



TECHNOLOGY DEMONSTRATION PROJECT REPORT: TDP17



A BIOLOGICAL SEQUENTIAL REACTIVE BARRIER (SREBAR):
DESIGN, INSTALLATION AND PERFORMANCE AT A FORMER MANUFACTURED GAS PLANT (FMGP) SITE IN SOUTH WEST ENGLAND

CONTAMINATED LAND: APPLICATIONS IN REAL ENVIRONMENTS

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SOUTH WEST ENGLAND**

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

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This is a CL:AIRE Technology Demonstration Project 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 a biological sequential reactive barrier to remediate contaminated groundwater. It is not a definitive guide to reactive barrier technology. CL:AIRE strongly recommends that individuals/organisations interested in using this technology retain the services of experienced environmental professionals.

EXECUTIVE SUMMARY

Gaswork activities at the study site were recorded back to the 19th century. The long-term activity of the gasworks plant had resulted in a present day requirement to manage the associated risks of contaminant transport. The remediation strategy chosen was one which would build on permeable reactive barrier techniques. Of particular interest is that this project was undertaken at an active industrial site. Therefore, not only was there a technological challenge associated with engineered *in situ* bioremediation, but also this demonstration applied PRB technology at an active site where most other remedial technologies could not be used to manage risk due to on-going activities.

During the initial site investigation, toxicity tests indicated a correlation between the toxicity and contaminant concentration. This permitted the rapid differentiation of contaminated areas from uncontaminated areas, potentially leading to a more focused sample collection. Chemical analysis revealed that on-site contamination consisted of a mixture of Polycyclic Aromatic Hydrocarbons (PAHs), Benzene, Toluene, Ethylbenzene and Xylene (BTEX), phenols, cresols, complex cyanide, and ammonium ions. These contaminants are common on former manufactured gas plant sites and were present in both the soil and groundwater under anaerobic conditions. Dense Non-Aqueous Phase Liquid (DNAPL) accumulated within the alluvial gravel aquifer at three locations of the site and provided the main source for groundwater contamination.

Based upon the human health and ecological risk assessment conducted for the site of study, it was decided that remediation actions should be undertaken to mitigate the significant risk to the groundwater resources posed by the high concentrations of PAHs and BTEX. The operational constraints posed by above and below ground installations prevented the use of many commonly used remediation strategies, such as excavation and disposal to landfill. The remediation option considered consisted of a SEquential REactive BARRier (SEREBAR) whereby the priority pollutants are removed by a combination of biodegradation/sorption processes.

Laboratory biodegradation studies revealed that the typical priority pollutants at Former Manufactured Gas Plant (FMGP) sites (naphthalene, BTEX and styrene), were readily utilized (removed) by indigenous microorganisms once aeration took place. This indicated that aerobic microorganisms were likely to be the main mediators of biodegradation in the SEREBAR, which is an aerated system. Furthermore, although complex cyanide was not a significant contaminant in relation to groundwater contamination at this site, microorganisms capable of its biodegradation were present. In fact microorganisms possessing the capability to degrade contaminants were present throughout the whole site and were not restricted to areas of historical contamination. Importantly, this finding provided evidence for a reduction in the number of samples taken for the microbial assessment of future sites.

Groundwater and contaminant flux modelling were used to predict both the mass of water/contaminants to be treated and the size of the cut-off wall required to capture/direct the contaminant plume to the zone of treatment (SEREBAR). Laboratory treatability studies were undertaken to determine rates of contaminant degradation and risk assessment models were used to agree contaminant discharge parameters with the Environment Agency (EA).

The treatability studies included laboratory experiments at different scales, going from bench-scale tests up to pilot bio-barriers. These experimental studies focused on the removal of all of the pollutants typically associated with FMGP sites: BTEX, styrene and naphthalene through both biodegradation and sorption processes, and cyanide (easily liberatable and complex) through biodegradation or chemical (Zero Valent Iron – ZVI) processes.

The rate of contaminant removal and/or degradation in the SEREBAR reactor is site specific. This is due to the unique geochemical conditions, contaminant mixture, hydraulic flows, location restrictions, and microbial ecology that may be present at a given site. The aims of the treatability study were therefore: 1) to determine reaction rates under expected and potential site conditions; and 2) predict reactive media longevity for the specific reactive media and combinations of reactive media to be used.

Groundwater for the treatability study was collected from two boreholes on-site. The selection of boreholes was based on the representative concentration of contaminants present, and their proximity to the envisaged SEREBAR placement. Study 1 focused on the removal of PAHs, (a) biotically (Lab-scale sequential anaerobic-aerobic biobox experiments) and (b) Granular Activated Carbon (GAC) sorption. Study 2 focused on the removal of cyanide (easily liberatable and complex) using (a) biotic (Lab-scale sequential anaerobic-aerobic biobox experiments) and (b) non-biological ZVI treatment columns. All of the treatability options researched demonstrated the removal of contaminants to agreed target levels. Biotically, the major organic contaminants were degraded within the artificially aerated section and further indicated the key limit to the efficient biodegradation of contaminants was oxygen availability.

Dependent on the site geology, hydrogeology, and the relative balance of installation and running costs, the SEREBAR system is able to operate under passive (installed beneath the water table), or semi-passive (installed underground but above the water table) groundwater flow conditions. The option chosen here employed semi-passive groundwater flow. Consequently, groundwater is pumped into the inlet of the SEREBAR system and then flows through the reactor downgradient due to gravity from inlet to outlet. The SEREBAR reactor was positioned at the head of the plume fringe where the viably active microbial population was uppermost. Construction of the SEREBAR reactor took place in May 2004. A 245 m long cement bentonite cut-off wall was installed through the gravel aquifer and keyed into the breccia underlying the site (sealed across active gas mains); this channelled groundwater into the SEREBAR treatment system. The SEREBAR is composed of an interceptor, for the separation of the non-soluble contaminants (non-aqueous phase liquids), and six treatment canisters in series (2 x non-aerated sand fill, 2 x aerated sand fill, and 2 x GAC). The presence of the GAC treatment step (sorption) at the rear of the SEREBAR system provides a final safety net prior to effluent discharge. It allows sufficient time for the establishment and maturation of the biodegrading community (biofilm) to occur without requiring recirculation of the effluent and also meant that the SEREBAR system was fully operational from day 1. ZVI was not necessary as a fill material due to the absence of significant levels of cyanide contamination within the groundwater.

Time course monitoring of geochemical and microbial ecology across the SEREBAR reactor took place every two months for a period of two years. The continued sample collection (non-specialist) developed during this project for geochemical monitoring is ongoing. The treatment option was studied under a variety of aeration (288-864 L/d) and groundwater flow rates (520-10,000 L/d) in order to assess its ability to deal with a variety of operational and contaminant pressures. This initial SEREBAR system is intended to be used as a demonstration and research system for groundwater remediation. Consequently, the sequence of non-aerated (anaerobic) and aerated (aerobic) canisters enables the comparison of biodegradation rates under different conditions. This also allows further optimization of future SEREBAR performance.

To date, monitoring has revealed a removal efficiency of >99.9%, of which 91% is due to the action of microorganisms. All changes in groundwater flow rates through the SEREBAR were adequately contained. The sequential design employed in the SEREBAR reactor enabled straightforward maintenance of the system.

The information collated from both the treatability study and latter performance monitoring of the SEREBAR reactor was utilized in the formation of four new models which are able to predict the operational performance and service life of the SEREBAR reactor. The models formulated focused on the variety of treatment options (fill material) able to be used within the novel

sequential treatment system and, as such, are transferable to remediate a variety of contaminants.

Although not employed in the chosen SEREBAR treatment system, information obtained from the ZVI treatability study, on the remediation of cyanide, as well as information on the dechlorination of trichloroethylene (TCE), was used in the development of a new model. Indeed, major advances in theory proposed by the new ZVI model are of significant importance, due to the numerous PRBs worldwide which utilize this remediation strategy.

The biotic treatment canisters represent the main treatment step within the SEREBAR. The project developed and solved a hydraulic model of flow through the SEREBAR reactor which raised questions relating to the aeration strategy employed. From the microbial investigation of biofilm formation within the SEREBAR, a preliminary finding was that the cells in the biofilm were more mobile than is usually accounted for in traditional models. Consequently, the developed and solved biofilm formation and kinetics model has led to the advancement of previous versions by accounting for the mobility of the cells in the biofilm.

Results from the GAC sorption experiments have also highlighted a potential complication, for which a model was designed. As the profile of the organic compounds present in the water changes with time it is plausible that the content of very strongly adsorbed organic compounds will increase. These may displace more weakly adsorbed organic compounds and result in both premature breakthrough and indeed breakthrough at higher than inlet concentrations. This whole effect is termed "roll up" and the developed model now provides information to highlight such problems.

This project has demonstrated the first implementation, from the laboratory to the field scale, of a sequential biologic reactive barrier for *in situ* bioremediation of groundwater at a FMGP site. The major benefit that SEREBAR brings, in contrast to virtually all the alternatives, is that the site can remain "active" during the remedial works and thereafter. The flexibility of the reactor design allows for easy modification of fill material in order to treat a variety of groundwater contaminants. For example, promote microbial proliferation via aeration and biofilm attachment - biodegradation; removal of contaminants via sorption – GAC; and chemical alteration of contaminants - ZVI.

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Abbreviations

BBSRC	Biotechnology and Biological Sciences Research Council
BTEX	Benzene, Toluene, Ethylbenzene, Xylene
CAT	Cable Avoidance Tool
CEH	Centre for Ecology and Hydrology
cfu/ml	Colony forming unit per millilitre
CL:AIRE	Contaminated Land: Applications in Real Environments
cVOC	chlorinated Volatile Organic Compounds
DGGE	Denaturing Gradient Gel Electrophoresis
DNA	DeoxyriboNucleic Acid
DNAPL	Dense Non-Aqueous Phase Liquid
DO	Dissolved Oxygen
DRO	Diesel Range Organics
DTI	Department of Trade and Industry
DWS	Drinking Water Standards
EA	Environment Agency
EERC	Environmental Engineering Research Centre
Eh	Redox Potential
EPA	Environmental Protection Agency
EPSRC	Engineering and Physical Sciences Research Council
EPH	Extractable Petroleum Hydrocarbons
EQS	Environmental Quality Standards
FID	Flame Ionisation Detector
FMGP	Former Manufactured Gas Plant
GAC	Granular Activated Carbon
GC	Gas Chromatography
GC-MS	Gas Chromatography-Mass Spectrometry
H&S	Health and Safety
HPLC	High Performance Liquid Chromatography
IC	Ion Chromatography
ICP-MS	Inductively Coupled Plasma - Mass Spectrometry
ICP-OES	Inductively Coupled Plasma - Optical Emission Spectrometer
k	First-order rate constant
LDPE	Low Density Polyethylene
LNAPL	Light Non-Aqueous Phase Liquid

MA	Malt Agar
m/d	metres per day
MG	Made Ground
mg/kg	milligrams per kilogram
mg/L	milligrams per litre
ml/min	millilitre per minute
MPN	Most Probable Number
NAPL	Non-Aqueous Phase Liquid
NGPH	National Grid Property Holdings
ORP	Oxidation-Reduction Potential
PAH	Polycyclic Aromatic Hydrocarbon
PB	Parsons Brinckerhoff
PCR	Polymerase Chain Reaction
PID	Photo Ionisation Detector
PPE	Personal Protection Equipment
P&TS	Pump and Treat System
ppb	parts per billion
ppm	parts per million
PRB	Permeable Reactor Barrier
QA/QC	Quality Assurance/Quality Control
QUB	Queen's University of Belfast
QUESTOR	Queen's University Environmental Science and Technology Research
SCA	Starch Casein Agar
SEREBAR	SEquential REactive BARrier
SSPH	Second Site Property Holdings
$t_{1/2}$	half-life
TOC	Total Organic Carbon
TPH	Total Petroleum Hydrocarbons
TSA	Tryptic Soy Agar
UKAS	United Kingdom Accreditation Scheme
USEPA	United States Environmental Protection Agency
VOC	Volatile Organic Compound
VW	Vibrating wire
ZVI	Zero Valent Iron
$\mu\text{g/L}$	micrograms per litre

1. INTRODUCTION

1.1. BACKGROUND

Past activities have resulted in elevated concentrations of organic compounds in soils and groundwater at a Former Manufactured Gas Plant (FMGP) site in South West England (UK). The organic contaminants of concern are primarily Polycyclic Aromatic Hydrocarbons (PAHs), Benzene, Toluene, Ethylbenzene, Xylene (BTEXs), as well as other organic compounds (phenols and cresols), some of which are acknowledged to be potential carcinogens. Based upon the human health and ecological risk assessment of the groundwater conducted for the study site, remediation works to address groundwater contamination were considered.

The preferred remedial action consisted of the installation of a SEquential REActive BARrier (SEREBAR) whereby the priority pollutants are removed *in situ* by a combination of anaerobic/aerobic biodegradation with the added protective measure of a sorption process.

The SEREBAR project was a collaborative research project between five academic partners and two industrial partners. The main aim was to implement a remediation solution that effectively removes organic contaminants and cyanide, which in turn would act as a flagship within the UK for companies interested in sequential treatment trains within permeable reactive barrier (PRB) technology.

1.2. PURPOSE AND OBJECTIVES

The purpose of the SEREBAR project was to remediate groundwater polluted with byproducts of the gas-making process using a SEREBAR system.

The overall objective of this report is to describe the major steps of the SEREBAR project. These include:

- Characterisation of the site where the SEREBAR has been installed. This comprises a description of the site geology as well as the nature and distribution of contaminants found in the soil and groundwater of the site.
- Identification and characterisation of the indigenous microorganisms and evaluation of their capacity of degrading the contaminants of concern.
- Design of the barrier, including laboratory experiments at different scales (going from bench-scale tests up to pilot bio-barriers) as well as modelling the hydrogeology of the site.
- Construction of the SEREBAR system and implementation of a monitoring plan.
- Evaluation of the overall performance of the system to verify that the SEREBAR system was operating as designed.
- Discussion of the costs associated with the SEREBAR project.

1.3. REPORT ORGANISATION

Chapter 2 introduces the PRB which has emerged as a promising technology in the *in situ* treatment of contaminated groundwater at a FMGP site. This includes a review of the experiences in the treatment of hydrocarbons, comprising the removal of hydrocarbons through biological degradation and sorption processes.

Chapter 3 describes the site at which the treatment system was to be installed. The site characterisation included an intrusive investigation focused on the geology, hydrogeology, and microbiology of the study area, as well as an exhaustive mapping of the contaminant plume. It sets the grounds to address the environmental risk before a remediation strategy was agreed and an action plan arranged. The latter is reported in chapter 4.

Chapter 5 examines the tasks carried out in the design of the treatment system. The tasks included exhaustive laboratory-scale experiments focused on the feasibility of removing the contaminants of concern through biological degradation and sorption using batch, column and pilot bio-barriers, as well as the design of the full-scale treatment system. The selected treatment system consisted of a sequential reactive barrier comprising of one single gate and two slurry walls acting as a funnel. An explanation of the components of the SEREBAR system is also provided.

Chapter 6 details the steps in the implementation of the system, focusing on the aspects relating to the construction of each of the components of the SEREBAR system.

Chapter 7 describes the operational parameters of the system (groundwater flow rate and air flow rate injected in the aerated canisters). It also addresses issues on the routine monitoring programme conducted following the SEREBAR installation, before discussing its performance in chapter 8.

Chapter 9 presents the costs for the tasks involved in the implementation of the SEREBAR system.

Chapter 10 and 11 provide the conclusions and the lessons learned from the SEREBAR experience.

2. BACKGROUND TO BIOLOGICAL PERMEABLE REACTIVE BARRIERS

2.1. PERMEABLE REACTIVE BARRIERS

The increasing awareness and concern about the environment has prompted hydrogeologists and engineers to develop alternative technologies for containing and treating subsurface contamination. Latterly attention has focused on the development of Permeable Reactive Barriers (PRB), which has now become a proven, *in situ* technology for the treatment of contaminated groundwater.

Essentially, a PRB consists of the installation, into the aquifer, of an appropriate reactive material able to remove the contaminants by abiotic (physical/chemical) and/or biotic (biological) processes as the contaminant plume flows through it. The mechanisms involved may be diverse, and include precipitation, sorption, oxidation/reduction, fixation, and biodegradation.

The abiotic and/or biotic remediation processes employed within a PRB depend primarily on the contaminant species to be removed, and in the case of biotic processes, the microbial ecology of the site. To date, the most commonly used reactive material in barriers has been granular Zero Valent Iron (ZVI) which has been used for the abiotic treatment of chlorinated solvents (Scherer *et al.*, 2000; CL:AIRE TDP3, 2001; Birke *et al.*, 2003) and carbon disulphide (CL:AIRE TDP20, in press). However, approaches comprising other materials (activated carbon, zeolite, organoclays, and organic substrates) and mechanisms (precipitation, sorption, biodegradation etc.) are increasingly under investigation. Among them, the removal of contaminant species by biologically-mediated processes (bio-barrier) has attracted great attention in the PRB field. This approach has been proposed for groundwater contaminated with organic and inorganic species (Scherer *et al.*, 2000), and although the development of bio-barriers is to date primarily studied at a laboratory-scale, field applications have been implemented. So far, bio-barriers have been installed for the treatment of organic contaminants (Guerin *et al.*, 2002; McGovern *et al.*, 2002), acid mine drainage (Benner *et al.*, 1997; Jarvis *et al.*, 2006; CL:AIRE TDP13, 2006) and nitrates (Robertson *et al.*, 2000; Schipper and Vojvodić-Vuković, 2001; USEPA, 2002).

The PRB technology basically offers two main configurations. The *continuous* PRB consists of an excavated trench backfilled with the reactive material. The *funnel-and-gate*[™] PRB employs low permeability cut-off walls (funnels) to direct groundwater towards the high permeability reactive zone (gate).

Figure 2.1 shows schematic diagrams of these two configurations.

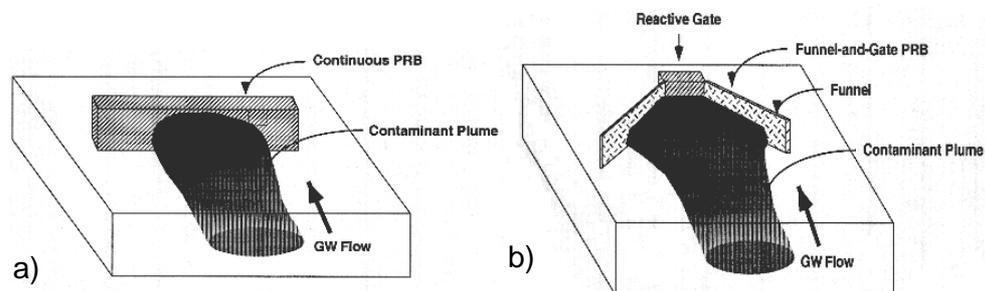


Figure 2.1: Schematic diagrams of PRB configurations a) continuous trenched system and b) funnel-and-gate system (Powell *et al.*, 1998)

More recent PRB designs may also incorporate additional measures or modifications to enhance the treatment efficiency of contaminated groundwater, such as *gravel trenches*, which act as a permeable corridor to homogenise contamination and groundwater flow to the reactive gate, *abstraction boreholes*, to increase both the rate of groundwater flow through the reactive cell and the likelihood of contaminated groundwater capture, and *reaction vessels*, which are engineered structures containing the reactive material, including sub-surface vertical flow reactors.

2.2. ADVANTAGES OF PRBs OVER CONVENTIONAL TREATMENTS

To date the traditional approach to treating groundwater is the pump-and-treat system (P&TS), whereby the contaminated groundwater is pumped through extraction wells up to the surface and treated by aboveground processes. The treated water is then either discharged into sewers or re-injected into the aquifer and the immobilised contaminants are either treated on-site or sent off-site for hazardous waste disposal or treatment.

Despite the long experience gathered with P&TSs, there are still some technical and economical limitations for their implementation at large-scale applications: 1) P&TSs typically require multiple wells to extract the contaminated water from the aquifer and the contaminants of concern (organic compounds in particular) are often not adequately captured or treated; 2) pump and treat techniques are accompanied with considerable costs associated with long term operation and maintenance; 3) P&TSs require aboveground structures that do not allow complete redevelopment of the site; 4) P&TSs may not be effective in removing or reducing contaminant concentrations to acceptable levels within the aquifer; and 5) it is often difficult to obtain regulatory agreement to cease operation of P&TSs.

PRBs potentially have several advantages over conventional P&TSs for groundwater remediation, including: 1) degradation or immobilisation of contaminants *in situ* without groundwater extraction to the surface; 2) they are potentially less expensive than P&TSs in the long term; 3) only periodic replacement of the reactive medium might be required after its capacity is exhausted or it has become clogged by precipitants and/or microorganisms; 4) sites can be used productively after the installation of a PRB; and 5) technical and regulatory issues related to ultimate discharge requirements of effluents from P&TSs are reduced.

2.3. POTENTIAL APPLICATION OF A BIOLOGICAL PRB IN FORMER MANUFACTURED GAS PLANT SITES

2.3.1. CONTAMINATION OCCURRENCE IN A FMGP SITE

Former manufactured gas plants (FMGP) (more commonly known in the UK as 'gasworks') sites can potentially be contaminated and may require remedial action to mitigate risk. The contamination would have been due to the operational procedures undertaken on the gasworks, accidental leakages, on-site disposal activities, and incidents which may have occurred when the sites were decommissioned.

Due to the potential risks posed by these substances and to the fact that gasworks are often located in urban areas, there is currently a significant interest in the development of technologies to remediate subsurface contamination at FMGP sites.

The primary organic pollutants of concern at FMGP sites are Polycyclic Aromatic Hydrocarbons (PAHs), Benzene, Toluene, Ethylbenzene, Xylene (BTEXs), and other organic compounds (styrene, phenols and cresols). Inorganic species such as cyanides, sulphur compounds and ammonium are also common constituents of interest. Once these contaminants enter the groundwater they may form a multi-component plume which can be difficult to treat.

2.3.2. EXPERIENCES IN THE TREATMENT OF HYDROCARBONS FOR APPLICATION IN PRBs

2.3.2.1. Biological degradation of hydrocarbons

Microbial degradation is considered as an effective and economical way to remove organic compounds from contaminated environments. This is based on the statement that the oxidation of hydrocarbons to less harmful compounds (e.g. CO₂ and H₂O) is thermodynamically feasible. The biological removal of BTEX and PAHs from wastewater, soils and surface waters has yielded a considerable amount of research.

Aerobic biodegradation has been successfully applied in bioremediation processes for a very wide range of hydrocarbon contaminants, including phenolics (Whiteley and Bailey, 2000), PAHs (Richard and Dwyer, 2001) and BTEX (Borden *et al.*, 1997). In such processes, aerobic microorganisms utilise hydrocarbons as the sole source of carbon and energy in the presence of oxygen. Oxygen is preferentially utilised over anaerobic electron acceptors because it yields more energy to the microbial community. It must be noted, however, that hydrocarbon-contaminated aquifers usually become anoxic due to the rapid consumption of oxygen by aerobic biodegradative microorganisms. Consequently, for aerobic biodegradation of aquifers to occur, a supply of air to the contaminated subsurface is required. Although the applications at a field-scale are still scarce, this approach has revealed to be successful in lowering concentrations of organic compounds to desirable levels (Gogoi *et al.*, 2003; CL:AIRE, 2005). Funnel and gate PRBs can capture all the contaminated groundwater and concentrate them into a smaller defined area for aeration.

Anaerobic treatment processes with nitrate, Fe(III), sulphate and carbon dioxide as electron acceptors are interesting alternatives for the bioremediation of anoxic hydrocarbon-contaminated sites. This approach has been proven to be efficient for a wide range of organic compounds, including BTEX, alkanes, some PAHs and some alkenes (Meckenstock *et al.*, 2004; Holliger *et al.*, 1996; Spormann and Widdel, 2000; Widdel and Rabus, 2001). However, other studies report only partial biodegradation of a few PAHs even under optimised conditions (Tiehm *et al.*, 1997; Sharak *et al.*, 1997). The availability of the above mentioned electron acceptors, which may either be present in the contaminant plume or supplied from above ground, largely dictates the physiological types of bacteria that can proliferate in the contaminated site of concern. The anaerobic treatment approach is at present widely explored at a laboratory-scale, whereby experiments are mostly conducted with artificially spiked water, pure cultures, either at higher temperatures or long residence times (Bidaud and Tran-Minh, 1998; Warith *et al.*, 1999; Rasmussen *et al.*, 2002), but applications at a field-scale, primarily through the injection of chemicals (nutrients, electron acceptors/donors) from the surface, are gaining attention (Madsen *et al.*, 1991; Durant *et al.*, 1995; Gersberg *et al.*, 1995; Guerin *et al.*, 2002). These studies concur that anaerobic biodegradation is generally slower than the rate of aerobic processes and that PAHs with 5 and 6 rings are persistent and recalcitrant (Abu-Salah *et al.*, 1996; Wilson and Jones, 1993; MacGillivray and Shiaris, 1994).

The use of PRBs for the management of complex contaminant groundwater plumes is at the very early stage of application. Few full-scale biological PRBs on FMGP sites are reported. Reports available detail a PRB containing peat for the removal of petroleum hydrocarbons (n-alkanes and BTEX) by a combination of sorption and aerobic biodegradation processes in Southeast Australia (Guerin *et al.*, 2002; McGovern *et al.*, 2002) and a PRB containing sand at a FMGP site in Portadown, Northern Ireland (CL:AIRE, 2005).

2.3.2.2. Adsorption of hydrocarbons

Since PAHs are hydrophobic compounds possessing low solubilities in water, they have a greater tendency to bind to surfaces, including natural organic matter in soil and aquifers. The sorption of high molecular weight PAHs has been demonstrated with a large range of materials, including granular activated carbon (GAC), zeolites, and peat. Thanks to its high surface area to volume ratio, GAC is acknowledged as one of the most powerful sorbents for the removal of organic contaminants from water and it has a long history of use in the treatment of industrial, municipal and hazardous waste (Koran *et al.*, 2001).

A PRB for the removal of PAH by sorption onto GAC has been installed in a FMGP in Karlsruhe, Germany (Birke *et al.*, 2003). GAC has also been used as filling material in PRBs for the removal of a variety of chlorinated volatile organic carbons (cVOCs) at Denkendorf and Reichenbach, Germany (Birke *et al.*, 2003).

2.3.3. EXPERIENCES IN THE TREATMENT OF CYANIDE FOR APPLICATION IN PRB

The main cyanide species present in environmental matrices are (i) easily liberatable cyanide (e.g. HCN, CN⁻, NaCN), which is reported to be highly toxic, and (ii) metal cyanide complexes (e.g. Fe₄[Fe(CN)₆]₃), which exhibit low toxicity (Shifrin *et al.*, 1996; Ebbs, 2004). The speciation of cyanide, thus, critically dictates its mobility and toxicity. Therefore, it is imperative to consider the cyanide species present in a contaminated site in order to not underestimate/overestimate the potential health risk.

Cyanide is a common contaminant present in soil and groundwater at FMGP sites. However, the majority of cyanide contamination is present as the metal cyanide complex, Fe₄[Fe(CN)₆]₃, and due to its low solubility results in its minimal infiltration of groundwater. Consequently groundwater research has focused on the less dominant but more mobile forms (easily liberatable cyanide).

The biodegradation of cyanide under both aerobic (White *et al.*, 2000) and anaerobic (Annachhatre and Amornkaew, 2000) conditions has been reported. Several studies have also demonstrated that combined anaerobic-aerobic reactor systems were capable of significant cyanide biodegradation (Oliveira *et al.* 2001; Chakraborty and Veeramani, 2002). Despite significant advances in the development of such biotechnologies, physical and economic factors still limit the application of cyanide biodegradation. Moreover, difficulties often arise when cyanide concentrations are above the maximum tolerance range for most organisms.

Laboratory-scale research has demonstrated that ZVI is effective in removing cyanide from solution to form iron-cyanide-hydrous ferric oxide precipitates. In contrast to the biotic approach, ZVI offers less sensitivity to actual cyanide concentrations, allowing higher inlet concentrations of cyanide to be remediated. Consequently the application of ZVI as the reactive material used in PRBs for the remediation of cyanide contaminated groundwater is feasible (Ghosh *et al.*, 1999).

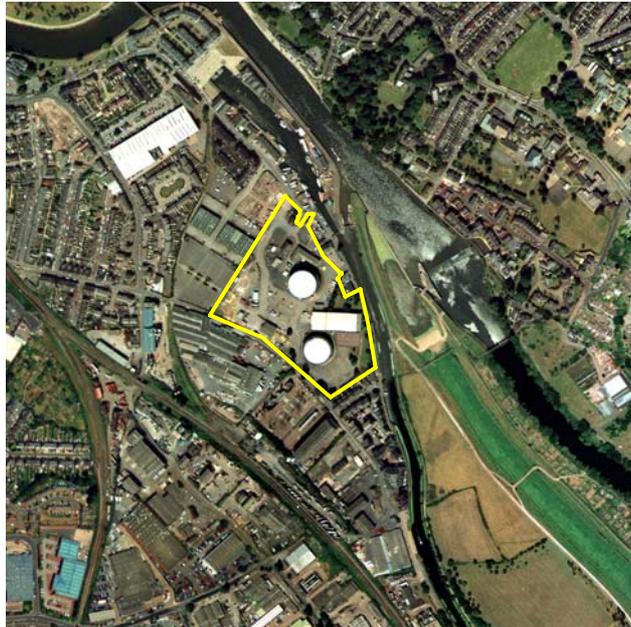
3. SITE DESCRIPTION

3.1. SITE USAGE

The site is located in South West England. It is roughly square in shape, bounded by a canal to the east and a road to the north and south west (total area of 3.4 ha). The canal expands into a marina immediately to the north of the site. It was constructed using puddling clay, forming a relatively impermeable barrier between the river, which can be found 120 m north, and the site.

Existing structures on the site include a former social club, a number of garages, stores, a number of portable office cabins and an operational office on-site. The site is predominantly covered in hardstanding, with two large car park areas along the southern boundary of the site. An area along the western boundary is used to stockpile fill materials and piping and to accommodate several container structures. The area along the eastern boundary of the site is landscaped with trees and grass cover.

Plate 3.1 shows an aerial photograph of the site and the surrounding area.



(Image copyright Getmapping plc www.getmapping.com)

Plate 3.1: Aerial photo of the site and the surrounding area

3.2. SITE HISTORY

Gasworks activities at the site are recorded back to the 19th century. In 1890 three gas holders existed on the site. The site underwent substantial works in 1905 to include an additional gasholder and railway sidings that extended to the north of the site. Small modifications continued until major rebuilding of the site was necessary after the area suffered bomb damage during World War Two. By 1963 major changes had occurred to the site with three gas holders in operation and buildings to the south and west that incorporated gas manufacturing and processing plant. Much of this plant had been demolished by 1980 and the area of the works was reduced to its current extent. Removal of a gas holder in 1989 and additional small changes resulted in the site being largely identical to its current layout by 1994.

3.3. SUMMARY OF ENVIRONMENTAL INVESTIGATIONS

In February 2001, SecondSite Property Holdings Ltd., (now National Grid Property Holdings Ltd.), commissioned Parsons Brinckerhoff Ltd. to undertake an intrusive ground investigation of the former gasworks site to assess potential environmental risks and to provide preliminary remediation cost estimates. A total of 39 trial pits and 14 boreholes were excavated and drilled. This enabled the geological and hydrogeological characterisation of the site to occur, and revealed the nature and extent of potential soil and groundwater contamination. The borehole locations are presented in Figure 3.1a.

Additional site investigations in February 2003 were undertaken by the EERC, the QUESTOR Centre - Queens University Belfast and Parsons Brinckerhoff Ltd for on-site hydrology, groundwater chemistry and soil and groundwater microbiology. The borehole locations are presented in Figure 3.1b.

Boreholes were extended to a maximum depth of 8 m below ground level (bgl) using a Technodrill and a Pioneer Drilling Rig from Geotechnical Engineering Ltd. Prior to drilling all borehole locations were hand dug to 1.2 m bgl and scanned using a Cable Avoidance Tool (CAT).

A total of 45 soil samples were taken during excavation of exploratory locations and scheduled for laboratory analyses. The analytical testing schedule focused on contaminants commonly found on former gasworks and coal carbonisation sites, including: PAHs, Volatile Organic Compounds (VOCs) (including BTEX compounds associated with hydrocarbon contamination), Total Petroleum Hydrocarbons (TPH), phenolic compounds, total, complex and easily liberatable cyanides, metals (arsenic, boron, cadmium, chromium, copper, lead, mercury, nickel, selenium, zinc), sulphate, chloride and ammonia. Analytical results are provided in Appendix 1.

A number of boreholes (34) were installed with monitoring standpipes to investigate and monitor the depth and quality of groundwater, and determine its flow direction. The remaining boreholes were either installed for gas monitoring only or sealed immediately.

Groundwater samples were collected from 25 boreholes during two monitoring visits and analysed for similar determinands to those detailed above for soils. Analytical results are provided in Appendix 2.

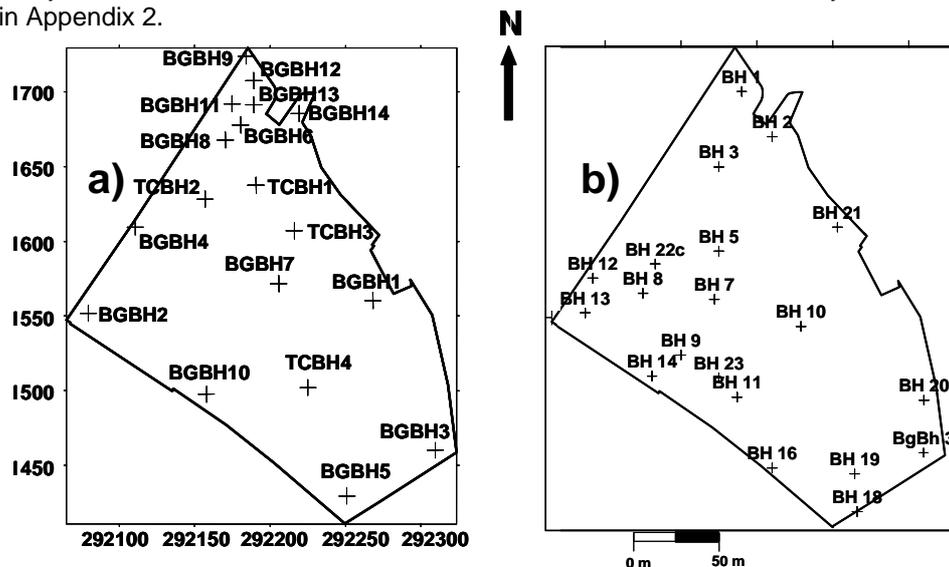


Figure 3.1: Location of boreholes drilled to investigate the extent of groundwater contamination within the site in (a) 2001, and (b) 2003

3.4. TOPOGRAPHY AND DRAINAGE

The site is generally flat with a slope towards the site boundary in the southern corner. A 0.5 - 0.7 m retaining wall maintains the slightly higher level of the lawns to the east and north of the office building, while a 2 m retaining wall gives the site an increased level in relation to the southern boundary of the site.

Approximately 60% of the site surface is impervious, although a substantial vegetated area exists by the main office building.

The site experiences an average annual rainfall between 750 and 1000 mm per year.

3.5. GEOLOGICAL AND HYDROGEOLOGICAL CONDITIONS

3.5.1. SITE GEOLOGY

Ground investigations indicated a clear sequence of made ground overlying and cutting into river terrace lithologies.

Made ground comprised a variety of different soil types with a number of different secondary constituents. The soils encountered during the site investigation ranged from sandy silts to gravels, with fragments of brick, tarmac, concrete, glass, coke, clinker, coal, asbestos and metal waste identified in the majority of the exploratory holes. The thickness of the made ground across the site varied from 0.9 m to 3.4 m, with the thickness of the made ground being smallest in the north corner of the site.

Natural ground encountered during the site investigation typically comprised of alluvial clay, silt or sand (2.5 m to 4.6 m thick). The alluvial gravels were typically present as small to medium sized and rounded with a maximum measured thickness of 3.0 m.

The site is underlain by a bedrock of Permian breccio-conglomerates, sandstones, with subordinate mudstones, occasionally with an argillaceous or calcareous matrix. Due to the low permeability of the weathered breccia, the underlying bedrock limits vertical hydraulic interaction and the overlying alluvial sediments can be regarded as a single unconfined layer. Representative borehole logs are provided in Appendix 3.

Figure 3.2 shows a typical stratigraphic sequence from borehole BH 16.

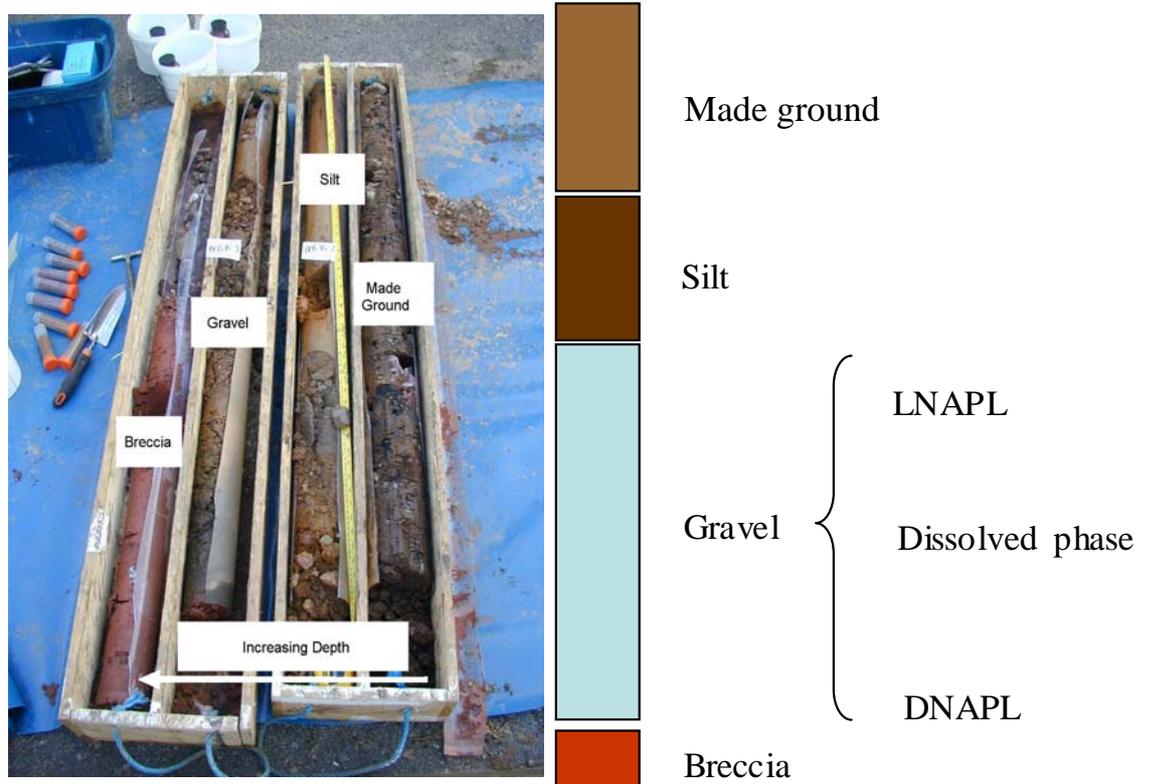


Figure 3.2: Stratigraphic sequence from borehole BH 16

3.5.2. SITE HYDROGEOLOGY

Groundwater monitoring indicated that groundwater flowed in a southerly direction in the alluvium, away from the canal and the river, in the north. This unexpected regime suggests that the canal may act as a hydraulic boundary between the river and the groundwater. The marina is not totally manmade in origin; historical maps suggest that it has been constructed from an oxbow lake. This suggests that there may be a hydraulic connection between the site and the marina, which would act as a recharge source.

Groundwater levels in January 2003 showed the groundwater to flow in a southerly direction with a hydraulic gradient at approximately 0.022 (Fig. 3.3). The hydraulic conductivity was determined by 11 slug tests carried out between the 28th April and 6th May 2003. The procedure involved the addition of a known volume to cause displacement of the head of groundwater and measurement of response using datalogging pressure sensors. The tests were carried out in accordance with BS6316:1992 Code of Practice for Test Pumping of Water Wells. The Bouwer-Rice and Hvorslev methods were used to calculate the hydraulic conductivity, which was quantified in a range of values of 3.0×10^{-6} m/s to 3.5×10^{-5} m/s to (0.3-3.0 m/d) (Table 3.1).

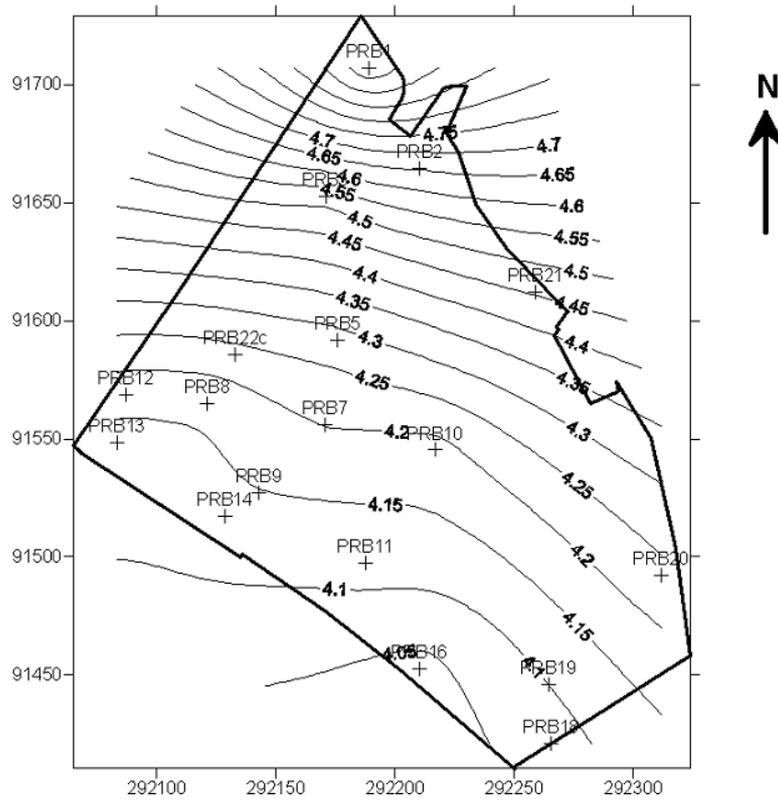


Figure 3.3: Groundwater levels (from monitoring carried out in January 2003)

Table 3.1: Data on site hydraulic conductivity following pump tests

Well name	Bouwer & Rice (Conductivity m/s)	Hvorslev (Conductivity m/s)
BH 3	1.82E-5	2.49E-5
BH 7	2.45E-5	3.46E-5
BH 8	1.47E-5	2.25E-5
BH 13	1.13E-5	2.18E-5
BH 14	6.73E-6	9.36E-6
BH 16	1.22E-5	1.89E-5
BH 17	1.11E-5	1.79E-5
BH 21	1.07E-5	1.61E-5
BH 23	3.04E-6	4.46E-6
BGBH 3	1.31E-5	1.77E-5
BGBH 9	1.20E-5	1.53E-5

3.6. NATURE AND EXTENT OF CONTAMINATION

The site investigation revealed elevated levels of contaminants in both soils and groundwater across the site that originated from a combination of sources located in the study site itself and in neighbouring areas.

Within the soils, the concentrations of the EPA 16-PAHs, easily liberatable and complex cyanide, phenols, cresols, benzene and xylene, zinc (Zn), mercury (Hg), arsenic (As), copper (Cu) and lead (Pb) were potentially a risk.

The contaminants of concern detected within the groundwater and exceeding Drinking Water Standards (DWS) and Environmental Quality Standards (EQS) comprised of EPA 16-PAHs, BTEX, phenol and cresol, and complex cyanide. The metals concentrations in groundwater were low.

The spatial distribution of the EPA 16-PAHs in the groundwater across the site revealed elevated concentrations towards the north-western boundary of the site, with values $>500 \mu\text{g/L}$ (Fig. 3.4a). A slight increase in concentration also seems to occur towards the south-western boundary. Two different contaminant profiles were observed across the site for both soil and groundwater matrices. In relation to the top soil (i.e. made ground), the distribution of the contaminants was widespread across the whole site reflecting the long and varied industrial history of the site. Contaminant hotspots within the soil do not serve as a major source for organic groundwater contamination. Instead, dense non-aqueous phase liquid (DNAPL) contamination from underground storage tanks and the bases of gas holders provided the main source for groundwater contamination. The non-aqueous phase liquids (NAPLs) were found to accumulate within a depression in the alluvial gravel aquifer (Gibert *et al.*, 2007). NAPLs were encountered at three locations BGBH11, TCBH2, and BGBH10 (Fig. 3.4b). These phases varied from yellowish light non-aqueous phase liquids (LNAPLs) to black DNAPLs.

The concentration of phenol (and to some extent cresol and total BTEX) followed the occurrence of NAPL coal tar product in the alluvial gravel aquifer on-site, with a decrease towards the south-eastern boundary. Figures 3.4c and 3.4d map the spatial distribution of Total Organic Carbon (TOC) and Total Petroleum Hydrocarbons (TPH), respectively. Both profiles show an increase in organic contaminants around BGBH11, TCBH2, and BGBH10, and can serve as indicators of the extent of the plume.

The concentrations of total cyanide exceeding the DWS were more widespread across the site than the other abovementioned contaminants (Fig. 3.5a). Relatively high concentrations were found around BGBH10 and are assumed to derive from the same sources as previously described for organic compounds, i.e. from the adjacent site. The environmental impact of cyanide contamination is directly related to its speciation. Easily liberatable cyanide is highly toxic, while complexed cyanide exhibits low toxicity. In this context, it is worth stating that iron is present in significant excess of the total cyanide concentration (Fig. 3.5a and 3.5b), and therefore complexed cyanide (iron ferricyanide) is expected to be dominant. This pattern has been reported to be common in FMGP (Shifrin *et al.*, 1996).

The spatial distribution of the redox potential (Eh) (Figure 3.5c) indicated reducing conditions towards the north-west and south-east area of the site. Eh measures the relative tendency for the aqueous solution to accept or donate electrons. Eh in groundwater containing organic compounds is usually biologically mediated and therefore Eh can be changed by biological activity. As electron acceptors and nutrients are depleted by microbial activity during biodegradation, Eh of groundwater decreases. There is close correlation between sulphide/sulphate (Fig. 3.6b and 3.6c) and Eh distributions. Locations where sulphate concentration is low have negative Eh, whereas locations where sulphate is dominant, Eh tends to be in the range of positive values. The comparison between sulphide and Eh should take into account that sulphide can precipitate in the presence of metals, as metal sulphides such as iron (Fig. 3.5b).

Ammoniacal nitrogen as N/nitrate follows a similar pattern, except in the southern corner of the site, where high contents of nitrate and low contents of ammoniacal nitrogen as N were found at Eh<400 mV (Fig. 3.6a and 3.5d).

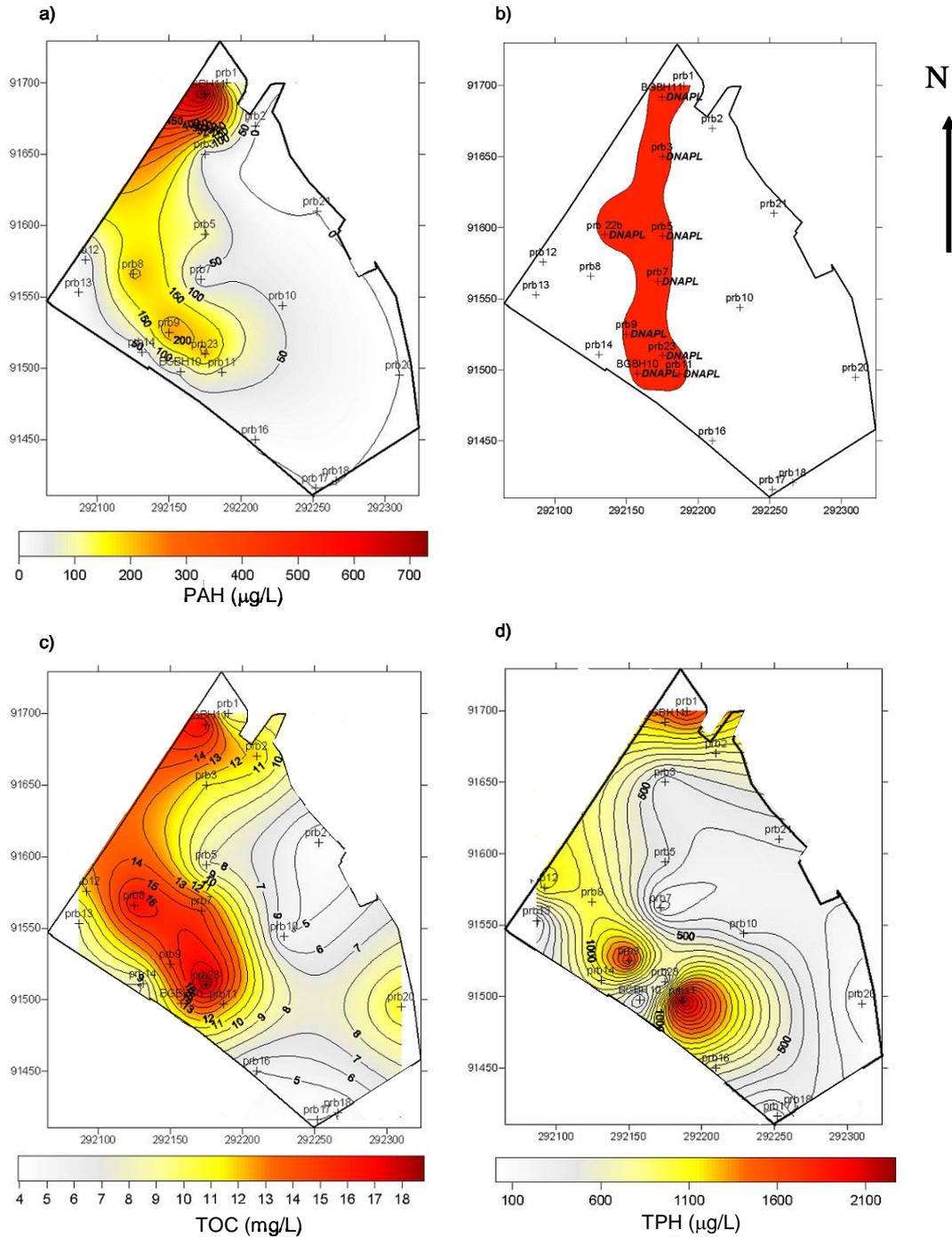


Figure 3.4: Site spatial distribution within groundwater of a) EPA 16-PAHs, b) NAPL, c) TOC, and d) TPH

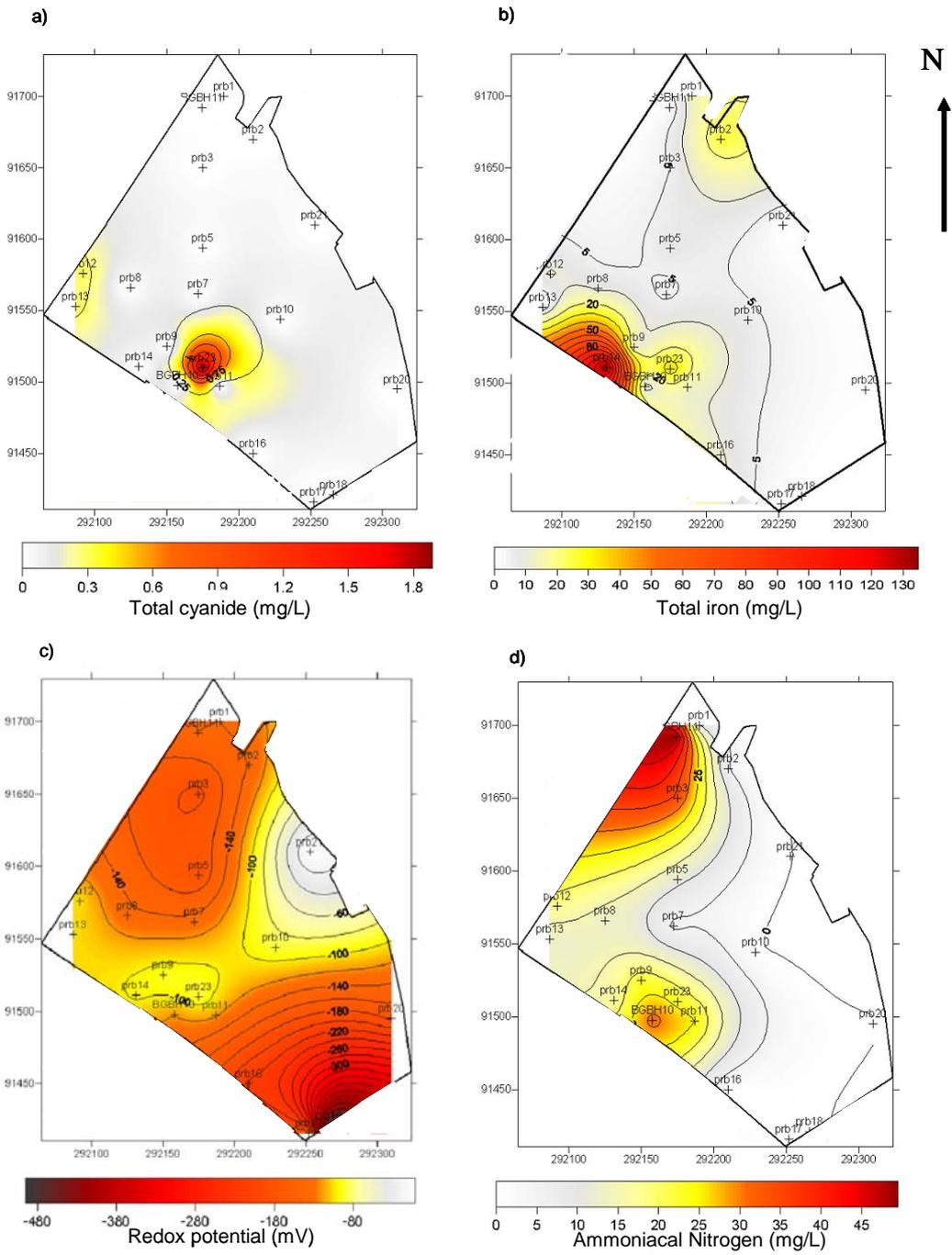


Figure 3.5: Site spatial distribution within groundwater of a) total cyanide, b) total iron, c) Eh, and d) ammoniacal nitrogen as N

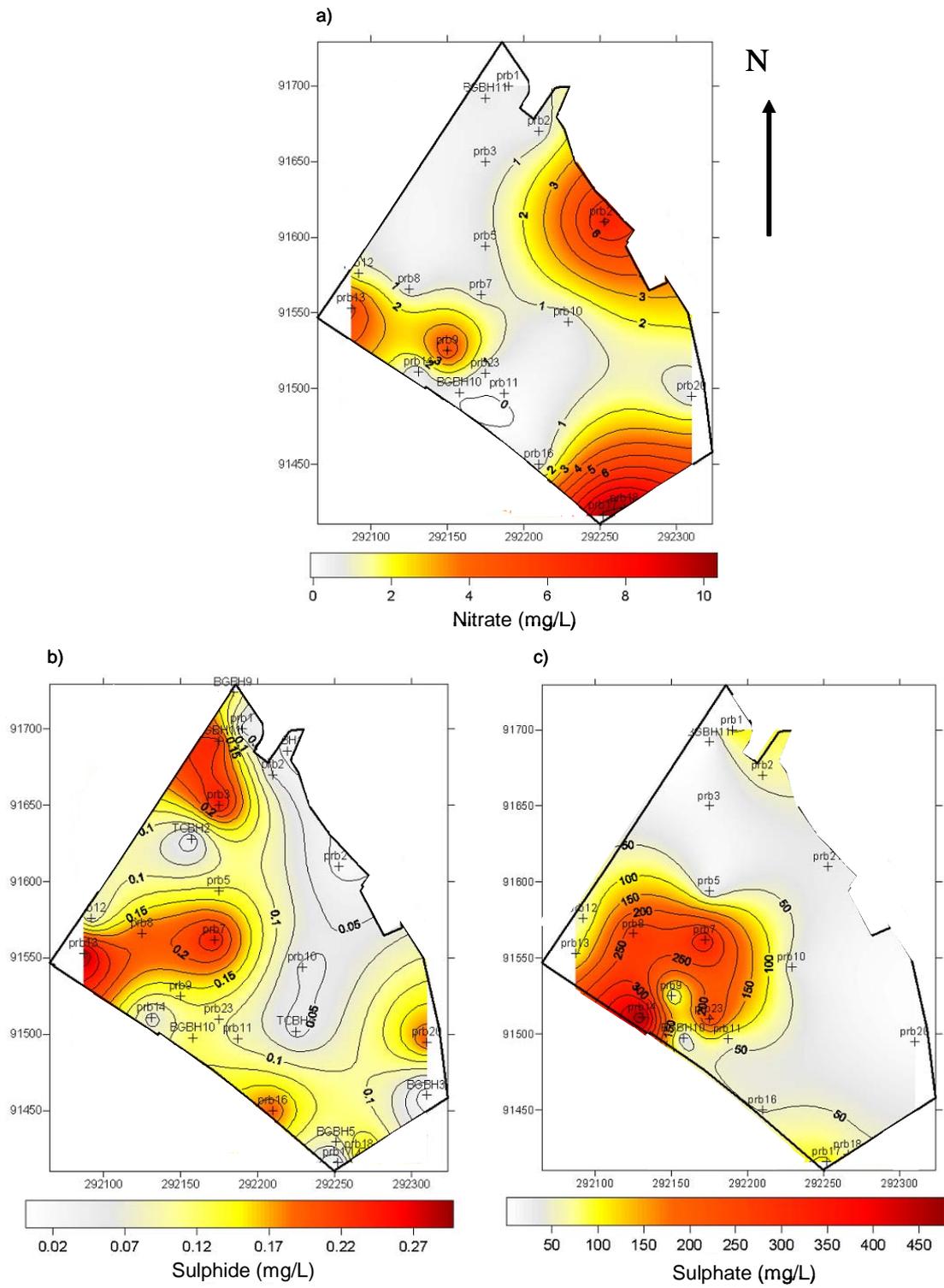


Figure 3.6: Site spatial distribution within groundwater of a) nitrate, b) sulphide and c) sulphate

A summary of analytical results for soil and groundwater on the whole site are provided in Appendices 1 and 2, respectively.

3.7. SITE MICROBIOLOGY

An extensive microbiological survey was carried out in order to characterise the indigenous micro flora present on-site. The collection of solid sample cores during the installation of boreholes and the subsequent groundwater obtained from them allowed for a complete profile of the sites geomicrobiology (attached (biofilm) and free living (planktonic) microorganisms). Work carried out on all samples was:

- Traditional microbial ecology (Enumerating bacteria)
 - Heterotrophic bacterial counts – determines the total number of culturally viable aerobic microorganisms per ml or g of sample on nutrient rich plates, and the total number of culturable bacteria in minimal media containing the priority pollutants.
 - Total counts – determines the total number of microorganisms per ml of sample
 - LIVE/DEAD (BacLight, Invitrogen Molecular Probes) – determines the total number of viable and dead microorganisms per ml of sample
 - Most Probable Number (MPN) counts – based on presence or absence of growth on a specific carbon source in a series of dilutions. Useful when dealing with low numbers of microorganisms.

It is important to note that there are discrepancies between direct (culturally viable – heterotrophic bacterial and MPN) and viable (total – LIVE/DEAD) counts. Culturable microorganisms represent between 0.01-12.5% of the viable microorganisms within the environment (Pickup, 1995). Laboratory-based cultivation techniques are also highly selective, providing bias towards rapidly growing microorganisms. Consequently microbial ecology uses both culture and non-culture based techniques for the assessment of environmental sites.

- Microtox™ toxicity testing (Azur Environmental Ltd., Wokingham, UK) – A highly sensitive and rapid system for the assessment of groundwater contamination. Chemical characterisation is restricted by its detection limits and does not account for the complex chemical interactions (synergistic, antagonistic and additive) that occur in such heterogeneous systems (Ferguson *et al.*, 2003). *Vibrio fischeri* luminescence was measured after 5 min exposure with the unknown environmental sample. The degree of light loss shown by the organism is indicative of potential toxicity to microorganisms, which in turn can be expressed as an EC₅₀ value, i.e. the concentration of the tested material that reduces *Vibrio fischeri* light emission by 50%.
- Molecular microbial ecology (Identification of microorganisms that degrade the priority pollutants)
 - DNA extraction
 - Polymerase Chain Reaction (PCR) – The purpose of PCR is to make a huge number of copies of a gene. This is necessary to have enough starting template for sequencing.
 - Denaturing Gradient Gel Electrophoresis (DGGE) – Allows the determination of microbial community profiles. DGGE exploits the fact that otherwise identical DNA molecules, which differ by only one nucleotide within a low melting domain, will exhibit different denaturing characteristics. During DGGE the products of PCR are separated by electrophoresis through a gradient of increasing chemical denaturant. Differing bacterial DNA sequences will therefore denature at different chemical concentrations, resulting in a series of bands. The position of the band within the gel signifies a different microorganism.

- DNA sequencing – Procedures for determining the nucleotide sequence of a DNA fragment. This results in the identification of microorganisms.
- Tolerance and Mineralisation study – Determines the optimal conditions, capability, rates, and capacity of the indigenous microorganisms to tolerate different environmental conditions.

The survey revealed that a complex microbial community of microorganisms with the capability for naphthalene, styrene, acenaphthylene, phenanthrene, 2-methylnaphthalene, BTEX, thiocyanate, and cyanide (easily liberatable and complexed) degradation, was present throughout the whole site. Figure 3.7 shows the total viable plate counts, degradation counts for BTEX and naphthalene, and MPN counts on Diesel Range Organics (DRO), against toxicity for soil cores from two borehole locations (BH 1 and 9) at various depths. Proliferation of microorganisms was apparent even in zones where Microtox™ testing indicated that toxicity was high (e.g. BH 1-1: made ground) indicating the existence of a microbial population present on-site with the capability to tolerate a variety of organic and inorganic contaminants at high concentrations. Molecular community profiling also indicated differences in the microbial community structure associated with the concentration of contaminants, temporal (seasonal) variability, and whether or not the microorganisms were 'free living' planktonic or 'attached' in biofilm communities. The latter highlighted the importance of solid sample collection during borehole drilling or trial pit excavation for the identification and analysis of microbial samples. However, the ability for PAH biodegradation was not restricted to areas of historical organic contamination, providing strong evidence for a significant reduction in the number of microbial samples required in future site investigations.

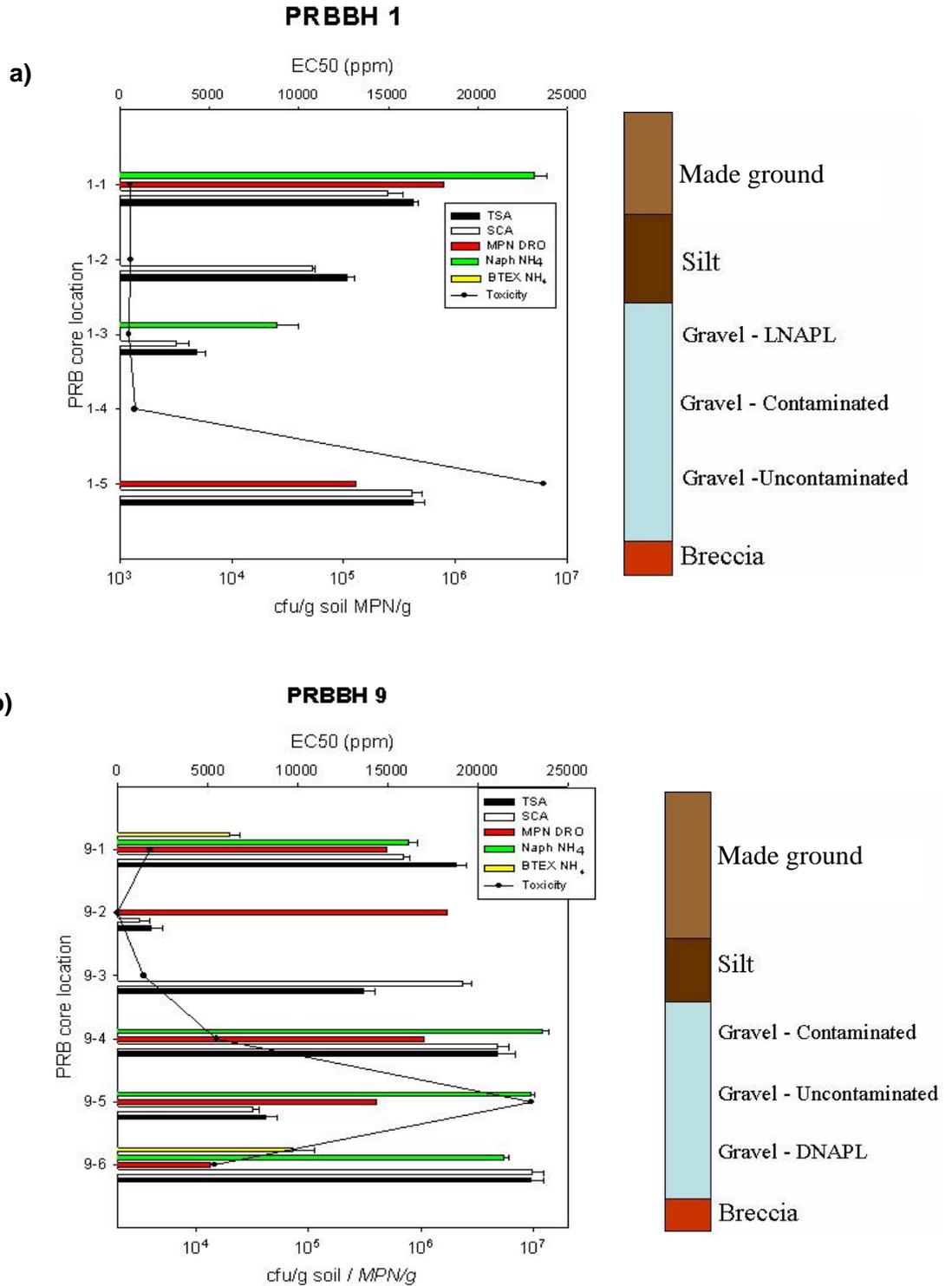


Figure 3.7: Soil core samples total viable heterotrophic counts, bacterial counts on minimal media containing naphthalene or BTEX as the sole source of carbon, and MPN counts on DRO against toxicity for a) BH 1, and b) BH 9. The PRB core location (Y-axis) signifies the sample identity within the named boreholes at various lithologies

The biogeochemical conceptual model correctly predicted that the greatest percentage of live bacteria occurs at the plume fringe (BH 11). Table 3.2 shows the % live/dead microorganisms within the groundwater at four different locations across the site (Fig. 3.8). Although the highest live % was observed at BH 11, in comparison with the unpolluted control location (BGBH 3), the microbial community appeared highly stressed. Differences in cellular morphology and also % live count for BH 9 and BH 11 were attributed to their position within the contaminant plume. BH 9 is situated within the head of the plume, whereas, BH 11 is located at the fringe head (refer to Fig. 3.8).

Table 3.2: % live/dead microorganisms (BacLight) within the groundwater at four different locations across the site

Borehole	% LIVE	% DEAD	S.D.
BGBH 3	82.8	17.2	3.59
BH 9	77.6	22.4	10.3
BH 11	93.0	7.0	2.91
BH 13	48.0	52.0	4.69

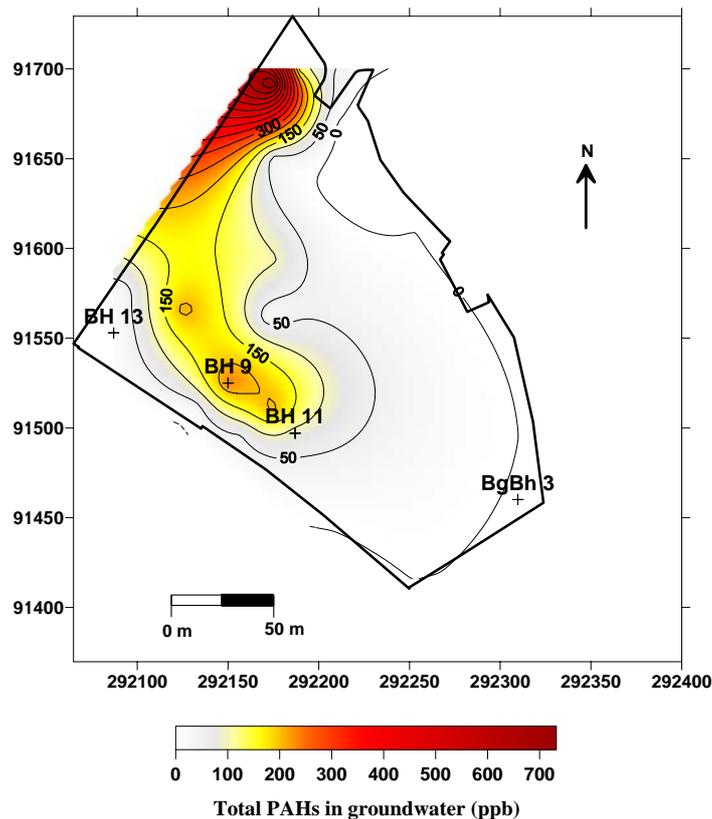


Figure 3.8: Site spatial distribution within groundwater of the EPA 16-PAHs and the position of boreholes in relation to the contaminant plume

Total microbial counts across the site ranged from 2.6×10^5 to 7.6×10^6 cells per ml. In general, the highest microbial populations were coupled with areas of low organic pollution, indicating that elevated concentrations of organic contaminants imposed a negative impact on the viability of microorganisms on-site. Figure 3.9 illustrates the influence of groundwater toxicity, determined by Microtox™ EC₅₀, on *in situ* microbial numbers for a selection of boreholes.

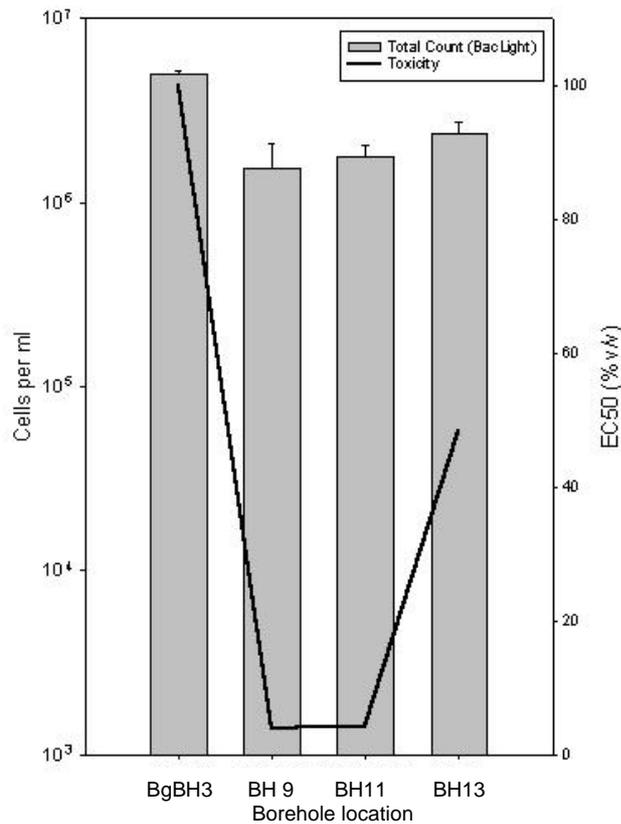


Figure 3.9: Total microbial counts for groundwater samples versus groundwater toxicity

The groundwater toxicity data also correlated with the chemical characterisation data for the site. The Microtox™ assay indicated no toxicity was associated with groundwater obtained from BGBH 1, 3, 5, 9, 14, and TCBH 4, whilst BGBH 10, 11, and TCBH 2 were highly toxic. NAPL was also found to occur at these locations. This pattern allowed contaminated areas to be differentiated from uncontaminated areas.

3.8. PRB FOR THE REMEDIATION OF CONTAMINATED GROUNDWATER IN A FMGP SITE: THE SEREBAR PROJECT

Based on the information gathered during the site characterisation, it was decided that remediation actions should be undertaken to mitigate the significant risk to the groundwater resources posed by the elevated concentrations of PAHs and BTEX.

An options appraisal was undertaken, but the associated operational constraints posed by above and below ground installations prevented the use of many commonly used remediation strategies, such as excavation and disposal to landfill. The risk of off-site migration of contamination was a key consideration and therefore PRB technology was selected to mitigate

this risk. A cost-benefit analysis was conducted on the installation and running of a PRB compared with shutting down the site and this concluded that a PRB was the most favourable option. The options appraisal resulted in the selection of a SEquential REactive BARrier (SEREBAR) whereby the priority pollutants are removed by a combination of biodegradation/sorption processes.

To date, there are not any reported full-scale sequenced biological barrier technology applications for the treatment of groundwater contaminated in a FMGP site in the UK. Globally, this approach is at very early stages of application. The SEREBAR project is thus presented as an innovative experience in the treatment of contaminated groundwater.

4. TECHNOLOGY DEMONSTRATION SUPPORT ISSUES

4.1. INTRODUCTION

This section discusses the supporting issues referring to the selection, installation and monitoring of the PRB, including:

- Project team
- Work plan
- Monitoring/Sampling plan
- Laboratory analytical methods
- Quality assurance/quality control
- Health and safety plan

4.2. PROJECT TEAM

The project was undertaken by the below-cited parties under the title “*In Situ* Bioremediation of Cyanide, PAHs and Organic Compounds using Engineered SEquenced REactive BARrier (SEREBAR) Techniques” under the LINK Bioremediation Programme, sponsored by BBSRC, EPSRC, EA and DTI.

SEREBAR was a large and complex project involving five academic and two industrial partners.

Academic Partners:

- EERC Research Provider of Queen’s University of Belfast (QUB) - Engineering, Hydrogeochemistry
- QUESTOR Centre Research Provider - Microbiology
- Oxford Centre for Environmental Biotechnology
- CEH Oxford Research Provider - Microbiology
- University of Surrey Research Provider - Design & Modelling

Industrial Partners:

- National Grid Property Holdings Ltd (NGPH) (formerly SecondSite Property Holdings Ltd (SSPH)) - Site Owner
- Parsons Brinckerhoff - Project Manager and Environmental Consultant to NGPH.

4.3. WORK PLAN

The project was split into two phases:

The first phase comprised a full characterisation of the site (involving geological, chemical, physical and biological characterisation), laboratory feasibility tests to ensure that the contaminated groundwater was suitable for the technology, with an emphasis on the microbiological component, negotiation with the Environment Agency (EA) and Local Authority contaminated land officer, and the evaluation of the data and production of an initial report.

The second stage proceeded on completion of successful results from stage one and consisted of the construction of a full-scale SEREBAR on the NGPH site. This phase also included long term testing and monitoring of the SEREBAR and the production of the corresponding report.

4.4. MONITORING/SAMPLING PLAN

The aim of the sampling regime was to determine the concentrations and distribution of groundwater contaminants across the SEREBAR system under normal operating conditions. The monitoring plan comprised continuous and intermittent monitoring as described below.

4.4.1 CONTINUOUS MONITORING

A fully automated continuous monitoring station was installed on-site to record basic parameters within the SEREBAR. The monitoring comprised water level, flow rate, conductivity, pH, air flow in the sparging system and gas analysis (CO₂, CH₄, O₂) at several points across the SEREBAR. The datalogger regularly downloaded and transmitted by telemetry the data to an off-site location, so that data could be provided in real time to a web page for remote access.

4.4.2 INTERMITTENT MONITORING

The monitoring/sampling plan specifies the type of monitoring performed during the SEREBAR evaluation and the methodology and equipment used for collection and analysis of samples.

The sampling programme started two months after completion of the SEREBAR installation and continued with decreasing frequency from once every two months during the first year to once every three months during the second year. The monitoring visits consisted of manual water collection for both on-site (in the field) and off-site (in the laboratory) analysis.

Because some of the chemical and physical parameters selected for the field measurements are unstable and subject to change during handling and transportation, they must be determined on-site. Field analysis during the SEREBAR monitoring comprised of:

- Water levels
- Physical/chemical basic parameters:
 - pH
 - Oxidation-Reduction Potential (ORP)
 - Specific conductance
 - Dissolved oxygen (DO)
 - Temperature
- Gas analysis

Water levels were manually determined with a dipmeter (Geotechnical Instruments Dipmeter). Water quality monitoring was carried out by pumping groundwater to a flow-through system (Waterra Sheffield cell), in which sensors for pH (Hanna Instruments electrode HI 9025C), ORP (Hanna Instruments electrode HI 9025C), Specific conductance (Hanna Instruments electrode HI 9835), DO (Hanna Instruments electrode HI 9145) and temperature (Hanna Instruments electrode HI 9835) were inserted for water analysis. Borehole gases from the interior of the canisters were analysed using a Gas Data LMSx Multigas Analyser and a Photo Ionisation Detector (PID). The gases analysed included CO₂, CH₄, O₂, H₂S, CO, HCN. Temperature and relative humidity were also recorded in this monitoring.

4.5. LABORATORY ANALYTICAL METHODS

All soil NGPH samples were analysed by Environmental Analysis Ltd. This laboratory was accredited under the United Kingdom Accreditation Scheme (UKAS). Groundwater samples were taken by Queens University Belfast (QUB) in collaboration with Parsons Brinckerhoff Ltd. and analysed by QUB and ALcontrol Geochem Laboratories, Chester, UK which was also UKAS accredited.

The chemical analyses comprised the analytes listed below.

- Metals (Cd, Cr, Cu, Fe, Pb, Ni, Se, Zn, As) by ICP-MS
- Anions (Cl⁻, SO₄²⁻) by Ion Chromatography
- Anions (NH₄⁺, S²⁻, HPO₃²⁻, NO₂⁻, F⁻) using a Kone Analyser
- PAHs by GC-MS
- BTEX by GC-MS
- Monohydric phenols by HPLC
- Extractable Petroleum Hydrocarbons (EPH) By GC-FID
- Total cyanide, free (easily liberatable) cyanide and thiocyanate using the "Skalar SANS+ System" Segmented Flow Analyser

The microbiological analysis comprised:

- Toxicity assessment, determined in accordance with the protocols outlined in the Microtox™ users manual (Azur Environmental Ltd., 1998)
- Total aerobic heterotrophic plate counts carried out on Tryptic Soy Agar (TSA), Starch Casein Agar (SCA), and Malt Agar (MA), which allowed for the categorization of total culturable bacterial counts, total culturable actinomycete counts and total culturable fungal counts, respectively.
- Total bacterial counts, performed using the LIVE/DEAD *BadLight* Bacterial Viability Kit (Invitrogen, Molecular PROBES)
- Most Probable Number
- Molecular microbial ecology
 - 16S rRNA gene, achieved using PCR (PTC-220 DNA Engine Dyad Peltier Thermal Cycler, M J Research Inc., USA) with the following universal primer pairs, 341F-GC clamped and 907R.
 - Microbial population profile: DGGE
 - DNA sequencing
- Tolerance and Mineralisation study using batch and biobox based microcosms – determines the optimal conditions, capability, rates, and capacity of the indigenous microorganisms to tolerate different environmental conditions.

4.6. QUALITY ASSURANCE / QUALITY CONTROL (QA/QC)

Quality assurance/quality control (QA/QC) protocols required the implementation of good field procedures and quality-control checks.

During site investigation, field methods carried out by Parsons Brinckerhoff (PB) complied with PB's Quality Management System, which operates within the standard outlined in ISO 9001 (BSI Certificate No. Q06143).

Boreholes were drilled and installed with monitoring standpipes in accordance with NGPH Guidance. The drilling equipment and rods were cleaned between boreholes using a steam pressure washer to reduce the risk of cross contamination. On completion of the drilling works, each borehole was fitted with a piezometer to measure the groundwater. All piezometers were designed, installed, and developed in general accordance with Code of Practice for Site Investigations, British Standard BS 5930:2003.

Representative soil and groundwater samples were collected and submitted for laboratory chemical analyses. Sample collection, storage and analyses were undertaken following quality control procedures specified in the NGPH Guidance Document.

Prior to sampling any groundwater from the monitoring wells, a minimum of three times the volume of groundwater contained within it was purged. This purging procedure ensures that samples collected from the well are representative of groundwater quality to be monitored.

The containers for groundwater samples were rinsed with groundwater prior to filling, unless preservative was used. Bottles were allowed to overflow, unless preservative was within the bottle, to ensure representative sampling, minimisation of aeration, and that there was no headspace within the bottle. Samples were labelled and stored in a coolbox with ice packs (4°C) before immediate despatch to laboratories for chemical analysis.

Samples for microbial analysis were collected in sterile 500 ml polypropylene containers (soil) and in sterile 1 L bottles (groundwater). Samples were stored at 4°C before immediate despatch to laboratories for analysis. Microbial samples taken for molecular profiling were stored on collection at -20°C. Enumeration of culturable bacteria always occurred within 72 hr of sampling.

Field instruments were calibrated daily and all manual recorded field measurement data were collected on field forms.

All personnel collecting samples had formal training and undertook a period of field apprenticeship covering how to correctly calibrate and operate field equipment, implement sampling procedures, and document the field protocols.

The QA/QC protocol of the electronic instrumentation included the sensor validation in the field, the time control for dataloggers and the precision and accuracy of sensors over time.

Field QA/QC procedures included the collection of field duplicates, field blanks and trip blanks; decontamination of all equipment that contacts the sample medium before and after each application; use of analyte-appropriate containers; and chain-of-custody procedures for sample handling and tracking. All samples to be transferred to the laboratory for analysis were clearly labelled and stored at 4°C.

Field blanks were collected to verify that the sample collection and handling process did not affect the quality of the groundwater samples.

Trip blanks were analysed to assess the effects of ambient conditions on sampling results during the transportation of samples. Trip blanks were prepared in the laboratory before each sampling event, and were transported inside each cooler like the other samples.

Duplicate groundwater samples were collected at a frequency of one every 20 or fewer samples. Each duplicate groundwater sample was collected concurrently with, and by the same method as, the primary sample.

As mentioned previously, all soil samples were analysed by UKAS accredited Environmental Analysis Ltd. Groundwater samples were analysed by both Queen's University Belfast (QUB) using in-house QA/QC procedures and ALcontrol Geochem Laboratories, Chester, UK, which was also UKAS accredited.

4.7. HEALTH & SAFETY PLAN

A Health and Safety (H&S) Plan was prepared and acknowledged by all parties involved in the project and kept on-site at all times during construction, maintenance and operation of the system.

Considerations addressed, as part of the H&S Plan, involved site investigation, installation of the SEREBAR and subsequent monitoring issues, including those listed below:

- Risk assessment
- Training for all project site workers and management personnel, including instructions of individual work practices
- Requirements for personal protection equipment (PPE)
- Periodical monitoring to ensure that any groundwater and localised air did not have hazardous impacts on human health or environment
- Responsible parties
- Details on general site procedures
- Emergency procedures
- Details of the location and nature of utilities and services, including emergency and fire fighting facilities
- Daily record of the condition of works carried out on-site

5. REMEDIATION DESIGN

5.1. INTRODUCTION

The design of the SEREBAR was determined using information obtained from batch, column and pilot-scale bioreactor experiments. The treatability study provided information on the degradation/sorption processes of typical organic pollutants of concern at former manufactured gas plant sites - BTEX, styrene and naphthalene.

The remediation design was split into three phases:

- Laboratory-scale feasibility studies;
- Numerical model and conceptual design of the cut-off wall and reaction vessel; and
- Design of the cut-off wall and reaction vessel.

5.2. LABORATORY STUDIES

5.2.1. OBJECTIVES

The laboratory-scale studies were undertaken to evaluate the feasibility of:

- The degradation of BTEX, styrene and naphthalene by microorganisms present in site groundwater;
- The degradation of cyanide (easily liberatable and complexed) by microorganisms present in site groundwater;
- Adsorption of BTEX, styrene and naphthalene onto granular activated carbon (GAC); and
- Abiotic precipitation of cyanide (easily liberatable and complexed) by zero valent iron (ZVI).

5.2.2. METHODOLOGY

The laboratory studies involved:

- Batch tests, used as a screening tool to provide initial confirmation of: 1) the capacity of the indigenous bacteria to degrade BTEX, styrene and naphthalene; and 2) the adsorption capacity of BTEX, styrene and naphthalene on GAC.
- Column tests were undertaken to evaluate the adsorption of BTEX, styrene and naphthalene on GAC in continuous flow systems and determine whether cyanides were efficiently removed by ZVI. It must be noted that parameters such as flow rate or residence time, not considered in batch systems, are key factors in the efficiency of sorption processes and should be used to obtain more accurate sorption data.
- Pilot-scale bioreactors, as a simulation of the barrier before full-scale implementation.

These experiments were carried out within the EERC and QUESTOR Centre - Queen's University Belfast (QUB) using pre-collected site groundwater. The groundwater collected for use in the treatability experiments represented the highest concentration of dissolved contaminants on-site. Any variation in the concentration profiles observed for the contaminated groundwater was attributed to the different batches collected from the FMGP site at different times. Boreholes BH 9 and BH 13 were chosen due to the high concentration of organic compounds and cyanide, respectively.

5.2.2.1. Microbiological degradation and toxicity assessments

A number of experiments were carried out to study the feasibility of the system from a microbiological point of view.

- The microbial degradation of the mixed priority hydrocarbon contaminants (BTEX, styrene and naphthalene) within groundwater from borehole BH 9;
- The microbial tolerance to the priority hydrocarbon contaminants (BTEX, styrene and naphthalene). In this case the concentration of BTEX, styrene and naphthalene within borehole BH 9 groundwater was increased approximately by a factor of 2, 4, 6, 8, 10, 15, and 20. Table 5.1 shows the concentrations of BTEX, styrene and naphthalene determined by GC-MS analysis after spiking. The naphthalene concentration was below that expected following spiking by a factor of 8 and attributed to headspace equilibration and analysis problems; and
- The microbial degradation of easily liberatable and complex cyanide within groundwater from BH 13.

Table 5.1: The concentration of contaminants within BH 9 following the addition of BTEX, styrene and naphthalene stock solution. ND signifies no data due to concentration of contaminants above the maximum measurable on the instrument

Contaminant	Supplementation factor and concentration (mg/L)						
	x2	x4	x6	x8	x10	x15	x20
Benzene	11.76	18.97	26.57	33.82	43.01	59.93	ND
Toluene	17.65	29.33	41.28	51.35	65.13	79.00	ND
Ethylbenzene	1.11	2.26	2.61	3.58	5.28	6.02	ND
o-Xylene	6.17	10.10	14.37	16.82	21.02	28.82	ND
m-Xylene	0.00	0.00	0.00	0.00	0.00	0.00	ND
p-Xylene	3.01	4.74	6.71	7.56	9.32	12.51	ND
Styrene	6.03	10.20	14.14	16.26	18.10	26.12	ND
Naphthalene	2.29	3.60	5.54	4.87	10.64	26.66	ND

All batch tests were carried out using 110 ml of BH 9 groundwater contained in 150 ml flasks, sealed with mini inert valves (VICI, Supelco UK). Samples were incubated in a Sanyo orbital incubator (180 rpm) at 25°C. Headspace samples (0.15 mL) were analysed by GC-FID.

5.2.2.2 Adsorption on GAC

The GAC, product name AquaSorb 101 (12 x 40 USS), was supplied by Jacobi Carbons. Two sets of experiments were carried out:

1. Batch tests using a known volume of spiked BH 9 groundwater (TOC concentrations ranging from 11.31 to 22.93 mg/L) were shaken for 72 hr with weighted amounts of dry GAC (0.001-2.000 g) in vials (40 mL, Teflon faced septa) using a rotary shaker. The amounts of each test are given in Table 5.2.

Table 5.2: Description of the key parameters of batch tests. Variation in initial TOC for test 1 and 2 is due to temporal changes in groundwater sample collection

	Test 1	Test 2	Test 3
Water description	BH 9 ^a	BH 9 ^a	BH 9 + DNAPL ^b
Initial TOC conc (mg/L)	22.93	11.31	20.18
Adsorbent (g)	0.1-2	0.001-1	0.004-1.00

^a Water collected from BH 9

^b 1 L BH 9 water shaken with 50 mL DNAPL

Following a 72 hr period of agitation (the assumed time by which equilibrium should be reached) the concentration of PAHs in the remaining aqueous solution was determined using appropriate analytical techniques.

2. Column tests, whereby 3 columns containing GAC were run under three different conditions:

Column 1: BH 9 groundwater, unspiked, flow rate of 0.55 mL/min;

Column 2: BH 9 groundwater, spiked with BTEX, styrene and naphthalene, flow rate of 0.55 mL/min; and

Column 3: BH 9 groundwater, spiked with BTEX, styrene and naphthalene, flow rate of 1.81 mL/min.

Table 5.3: Concentration range of individual BTEX, styrene and naphthalene in the two waters prepared for the column tests. Variation in concentrations of contaminants is due to temporal changes in groundwater sample collection

Contaminant	Concentration of contaminants in BH 9 (mg/L)	Concentration of contaminants in BH 9 spiked with BTEX, styrene and naphthalene (mg/L)
Benzene	<0.01-19.5	0.03-25.1
Toluene	<0.01-13.1	0.05-39.9
Ethylbenzene	<0.01-0.03	<0.01-4.1
Total xylenes	<0.01-3.90	0.3-27.6
Styrene	<0.01-2.5	<0.01-21.0
Naphthalene	0.012-8.4	<0.01-23.4

Columns were constructed of clear Perspex, 50 cm in length with an internal diameter of 4 cm. Ten sampling ports were positioned along the length of the column, starting as close as possible to the influent end of the column and continuing at regular intervals on alternate sides of the column (Plate 5.1 and Fig. 5.1). In order to achieve the uniform packing of the column with the chosen reactive material, the column was first filled with approximately 100 ml deionised water; the GAC was then added in 50 cm³ portions, to avoid layering. Several pore volumes of deionised water were then flushed through the column to ensure complete saturation. The influent water was fed from a 20 L collapsible LDPE container through the column using a 205S Watson-Marlow peristaltic pump. Taking into account the column section and the filling GAC porosity (quantified as 0.59 by multiple measurements of volume displacement in water), the flow rates of 0.55 mL/min and 1.81 mL/min equalled an average residence time of 11.6 hr (694.1 min) and 3.5 hr (210.9 min), respectively. The three columns were sampled at the influent, effluent and port 3 (i.e. 12 cm from the influent) weekly for BTEX, styrene and naphthalene analysis (additional samplings at ports 6 (i.e. 27 cm) and 8 (i.e. 37 cm) in Column 3 were also periodically undertaken).



Plate 5.1: Experimental set-up for the treatability column experiments

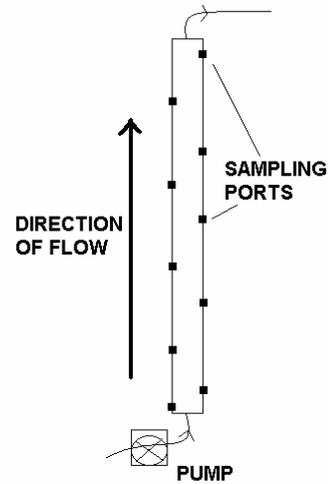


Figure 5.1: Schematic diagram of a column experiment

5.2.2.3. Zero Valent Iron

The iron used in the column studies (particle size 500-3000 μm) was supplied by Gotthart Maier Metallpulver GmbH and the product name was FG 0500/3000.

Three ZVI columns were set up:

- Column 1: BH13 groundwater, spiked to 1 mg/L (of both easily liberatable and complex cyanide), flow rate of 0.5 ml/min;
- Column 2: BH13 groundwater, spiked to 5 mg/L (of both easily liberatable and complex cyanide), flow rate of 0.5 ml/min; and
- Column 3: BH13 groundwater, spiked to 5 mg/L (of both easily liberatable and complex cyanide), flow rate of 1.8 ml/min.

The columns, packing method, and sampling strategy used in the ZVI treatability tests was the same as that for the GAC columns (see Fig. 5.1).

The porosity value of ZVI was 0.52. (Gotthart Maier 0.52 ± 0.03). Groundwater flow rates were set at 0.55 ml/min or 1.81 ml/min to represent normal or accelerated flow conditions. The residence time was calculated as 10.2 hours (611.6 min) and 3.1 hours (185.9 min) for the normal and for the accelerated flow, respectively.

Potassium ferricyanide (a complex cyanide) and sodium cyanide (an easily liberatable cyanide) were used to make up a stock solution (5 g/L for each compound (as CN^-) in solution).

5.2.2.4. Development of a laboratory-scale bio-barrier system

Two lab-scale bio-barriers were constructed to obtain biodegradation data for the design of the reactive cell of the SEREBAR. Each tank was constructed of clear Perspex sheets (12 mm thickness), with tank internal dimensions of length 145.5 cm, height 37.5 cm and width 10 cm. A 35 cm high Perspex plate was placed 5 cm from the influent end to act as a weir in order to create two separated compartments. The second compartment was provided with a sparging

system to supply air to promote aerobic conditions. This air-supplying system consisted of a cylinder of compressed air attached to a flow meter (Gilmont Instruments). This was connected to the nine sparge-heads placed along the floor of the tank via a looped tubing system. Airflow was regulated at 20 ml/min. The correct aeration of the aerobic compartment was ensured by a krypton tracer test described by Walsh (2000). Figure 5.2 shows a schematic diagram of this system.

The tank was filled with silica sand (average pore size 1.8 mm), which acted as support material for microbial communities during biofilm formation. All sampling ports were constructed by boring holes along the side of the bio-barrier and fixing 20 mm Viton Septa's in place (Fig. 5.2). Groundwater from BH 9 or BH 13 was passed through the bio-barriers. The influent water was pumped from a 20 L collapsible LDPE container at a flow rate of 1.81 ml/min (205S Watson-Marlow peristaltic pump). This rate was chosen to simulate, as closely as possible, flow conditions through the reactive barrier on-site. Residence time was determined through a dye tracer test and quantified as 136.8 hr (5.7 d).

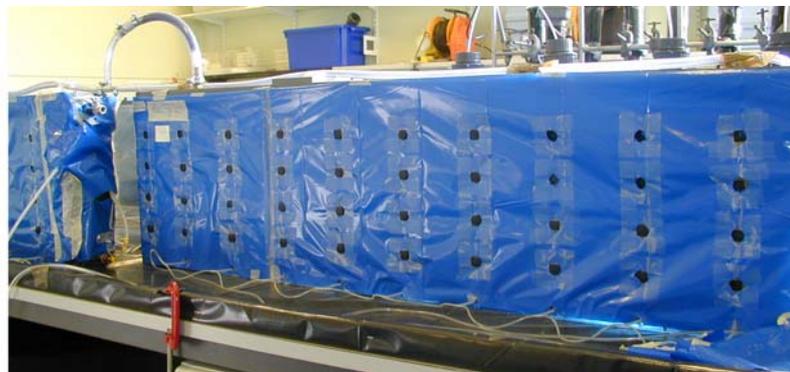


Plate 5.2: Experimental set-up for the bio-barrier experiments

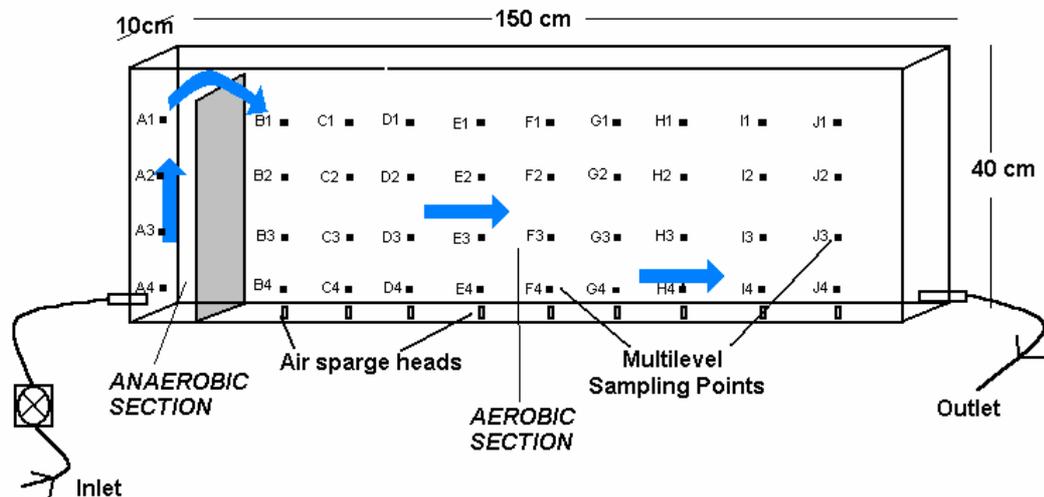


Figure 5.2: Schematic diagram of the bio-barrier

5.2.3. ANALYTICAL TECHNIQUES

Samples were analysed in the EERC Laboratory under the following QA/QC procedures where applicable. All machines are operated by trained/skilled operators in accordance with Standard Operating Procedures set out for each instrument.

5.2.3.1. Organic compounds analysis

BTEX, styrene and naphthalene were analysed by GC-FID (Focus, Thermo Finnegan).

TOC was analysed by means of a TOC Apollo 9000 (Teckmar Dohrmann).

VOCs were sent under Chain of Custody to a UKAS accredited laboratory (ALControl Geochem, Dublin) for analysis.

5.2.3.2. Inorganic species analysis

pH and ORP were carried out using an Orion Model 720A multimeter with microelectrodes (Diamond General Corp., MI, USA).

Anions were analysed by Dionex Ion Chromatography (IC) system, consisting of a CD20 Conductivity Detector, GP50 Gradient Pump and AS3500 Autosampler.

Alkalinity was measured using a Hach Digital titrator with phenolphthalein and bromocresol green – methyl red indicators.

Ferrous iron was analysed by the Hach 1.10 Phenanthroline Method.

Metals were analysed in-house by Inductively Coupled Plasma – Optical Emission Spectrometer (ICP-OES).

Total cyanide samples were sent under Chain of Custody to a UKAS accredited laboratory (ALControl Geochem, Dublin).

Easily liberatable cyanide was analysed by the Hach Pyridine-Pyrazole Method Number 8027.

5.2.3.3. Microbiological Techniques

The toxicity of the groundwater prior and subsequent to passage through the bio-barrier was determined in accordance with the protocols outlined in the Microtox™ users manual (Azur Environmental Ltd., 1998). The Microtox™ protocol for Basic Test was used for all groundwater samples analysed. *Vibrio fischeri* luminescence was measured after 5 min exposure with the unknown environmental sample. The degree of light loss shown by the organism is indicative of toxicity, which in turn can be expressed as an EC₅₀ value, i.e. the concentration of the tested material that reduces *Vibrio fischeri* light emission by 50%.

Total direct counts were performed using the LIVE/DEAD BacLight Baterial Viability Kit (Molecular PROBES). Samples were filtered onto a black stained 0.1 µm cellulose nitrate filter (Whatman) and viewed using fluorescence microscopy.

5.2.4. RESULTS

5.2.4.1. Biological treatability studies

Microbial degradation batch tests:

A reduction in the concentration of BTEX, styrene and naphthalene contaminants was observed during the initial batch experiments. The initial concentrations of contaminants are given in Table 5.4. The final concentrations achieved were 581 µg/L for benzene, 466 µg/L for xylenes (total o,m,p – xylenes), 54 µg/L for naphthalene, 28 µg/L for toluene and 10 µg/L ethylbenzene.

Plots of contaminant concentration versus time showed typical decay curves for first-order kinetics. Degradation rate parameters, rate constant (k-value) and half-life ($t_{1/2}$), were derived from linear least-squares regression analysis after plotting linearised curves versus time. The goodness of fit r^2 of the linear regression line was mostly >0.90, indicating that a first-order kinetics model described the data rather well. The k-value and $t_{1/2}$ for each contaminant are provided in Table 5.4.

Table 5.4: Maximum aerobic biodegradation rates for BH 9 groundwater at 25°C

Contaminant (initial concentration)	k-value (h^{-1})	$t_{1/2}$
		Hours
Benzene (1.60 mg/L)	0.011	61.88
Toluene (1.35 mg/L)	0.038	18.33
Ethylbenzene (0.22 mg/L)	0.156	4.44
p-Xylene (0.55 mg/L)	0.023	29.62
m-Xylene (0.34 mg/L)	0.021	33.81
o-Xylene (0.56 mg/L)	0.016	43.59
Styrene (0.71 mg/L)	0.058	12.05
Naphthalene (2.73 mg/L)	0.149	4.65

The biodegradation rates obtained provide an indication of the maximum rates achievable by the indigenous microbial population under fully aerobic conditions at 25°C. Consequently, a decrease in microbial activity and rate of biodegradation would be expected to occur on-site (average groundwater temperature is 13°C).

Contaminant tolerance studies:

The effect of increasing the level of hydrocarbon contaminants on the microbial population was investigated. The concentrations of contaminants following the addition of the BTEX, styrene and naphthalene spike are shown in Table 5.1. The k-value and half-life ($t_{1/2}$) for each contaminant are shown in Table 5.5. In general, half-life values increased in conjunction with contaminant concentration. However, when the concentration of contaminants was increased by a factor of 6 the degradation rates for benzene, toluene, ethylbenzene, o-xylene, styrene, and naphthalene were uppermost. This concentration corresponded to the highest percentage of viable microorganisms.

Table 5.5: k value (d⁻¹) and half lives (t_{1/2}) (d) for BH 9 groundwater supplemented with varying concentrations of BTEX, styrene and naphthalene contaminants

BH 9 BTEX, styrene and naphthalene supplementation factor	Benzene		Toluene		Ethylbenzene		p-Xylene		o-Xylene		Styrene		Naphthalene	
	k	t _{1/2}	k	t _{1/2}	k	t _{1/2}	k	t _{1/2}	k	t _{1/2}	k	t _{1/2}	k	t _{1/2}
x2	0.021	32.8	0.067	10.4	0.339	2.0	0.024	29.5	0.010	69.3	0.150	4.6	0.127	5.5
x4	0.008	82.5	0.012	59.2	0.128	5.4	0.009	77.9	0.007	93.6	0.031	22.3	0.089	7.8
x6	0.024	29.2	0.071	9.7	0.612	1.1	0.018	39.2	0.008	39.2	0.168	83.5	0.133	4.1
x8	0.006	108.3	0.011	66.0	0.191	3.6	0.005	144.4	0.002	301.3	0.037	18.7	0.102	6.8
x10	0.006	108.3	0.014	48.8	0.467	1.5	0.005	150.7	0.002	407.6	0.050	13.9	0.074	9.3
x15	0.003	247.5	0.002	407.6	0.007	105.0	0.006	115.5	0.007	101.9	0.007	93.6	0.065	10.7

The indigenous microbial population was found to tolerate and degrade high concentrations of BTEX, styrene and naphthalene, up to 15 times more concentrated than the original contaminated groundwater (Tables 5.1, 5.5 and 5.6). When the concentration of contaminants was increased above a factor of 10, the toxicity associated with such a mixed contaminant stream resulted in a reduction in viable microorganisms (Table 5.6), although degradation of the contaminants was still apparent (Table 5.5). A reduction in microbial diversity was also apparent as the concentration of the contaminants increased above a factor of six. This resulted in a reduction in degradation rate.

Table 5.6: % live/dead counts for BH 9 spiked with increasing concentrations of BTEX, styrene and naphthalene contaminants

BH 9 BTEX, styrene and naphthalene supplementation factor	% LIVE	% DEAD
Original	77.0	23.0
X2	89.4	10.6
X4	80.3	19.7
X6	88.6	11.4
X8	77.2	22.8
X10	51.0	49.0
X15	42.4	57.6
X20	0	0

5.2.4.2 Organic removal by sorption onto GAC

GAC batch tests:

Adsorption data were fitted to the Freundlich isotherm:

$$q = \frac{x}{m} = KC^n$$

where:

- q = the amount of adsorbate (x) per mass of adsorbent (m) at equilibrium (mg/g),
- m = mass of adsorbent in grams added to the reaction container (g),
- C = the solute concentration after exposure to the adsorbent at equilibrium (mg/L),
- K = Freundlich capacity parameter, taken as an indicator of adsorption capacity (L/g),
- n = Freundlich isotherm parameter, (dimensionless).

The amount of adsorbate taken up by the adsorbent was determined through a mass balance from liquid-phase measurements.

Experimental q and C data from each test were used to determine the constants (K and n) from a linearised form of the equation above. The summary of adsorption capacities obtained is tabulated in Table 5.7. The correlation coefficient r^2 showed a good linearity for all three batch tests.

Table 5.7: Adsorption capacity summary from batch tests

	1/n	log K	K	r^2
Test 1	2.3455	-1.2632	0.0545	0.987
Test 2	1.4682	0.4663	2.926	0.936
Test 3	0.4802	0.3397	2.186	0.928

GAC column tests:

Column 1: A total of 129.9 L of BH 9 groundwater passed through the column. Effluent concentrations for all BTEX and styrene were maintained under detection limits (<0.01 mg/L). Naphthalene showed effluent concentrations up to 0.179 mg/L, indicating that GAC was not effective in the removal of this contaminant to below the target values identified in the risk assessment for the site (0.015 mg/L). Samples from Port 3 (12 cm from the influent) showed low concentrations of BTEX and styrene, with sporadic peaks above the target values for benzene (peak up to 1.4 mg/L, target value 0.066 mg/L), toluene (0.3 mg/L; 0.2 mg/L), and total xylenes (0.4 mg/L; 0.066 mg/L). However, naphthalene was observed in port 3 from the start of the experiment with only a few analyses during the column experiment measured below the target value of (0.015 mg/L).

Column 2: Breakthrough did not occur at the effluent port for any BTEX or styrene after 116.4 L had passed through the column. However, breakthrough of naphthalene to concentrations greater than the target value (0.015 mg/L) occurred at both effluent and at Port 3, indicating again that GAC was not effective in the removal of naphthalene to below the target value.

Column 3: Benzene breakthrough at the effluent port to concentrations higher than the target value (0.066 mg/L) occurred after 75.6 L of groundwater passed through the column. However, at later sampling events the benzene concentration was frequently found lower than this value. Breakthrough did not occur at the effluent port for toluene, ethylbenzene, total xylenes and styrene after 380.5 L passed through. Again, breakthrough of naphthalene to concentrations greater than the target value occurred, indicating that GAC was not effective in the removal of naphthalene to below these target values. Samples from Port 3 showed breakthrough for benzene (after 91.2 L), toluene (after 166.8 L), ethylbenzene (after 218.9 L) and total xylenes (after 200.7 L). Samples from Port 6 showed breakthrough for benzene (after 166.8 L), toluene (after 166.8 L), ethylbenzene (after 166.8 L) and total xylenes (after 200.7 L).

It should be noted that naphthalene, BTEX and other highly volatile components are not the design target for GAC, as these compounds are easily and readily biodegraded. GAC is better used for PAHs, longer and branched chained aliphatic compounds and heterocyclics.

The calculation of the adsorption capacity of GAC in column tests was based on the assumption that GAC reached its adsorption capacity when the net mass of contaminants entering the column (or a portion of the column) was equal to the net mass of contaminants exiting the column (or a portion of the column), i.e. when the GAC surface was saturated with the organic contaminants adsorbed onto it.

As the feed solutions for GAC columns 1, 2 and 3 were a complex mix of organics (contaminants and background natural organics) at different concentrations, the first point of breakthrough for any one of the compounds was considered breakthrough for all the compounds. Therefore, calculations might underestimate the adsorption capacities of the individual compounds, especially those present in low concentrations in the influent feed.

Also, in instances where there was no breakthrough at the effluent or at intermediate ports the adsorption capacity measured was a minimum value and the GAC might have the capacity to adsorb a greater amount of organic contaminants. Table 5.8 summarises these results.

It is plausible that the content of very strongly adsorbed organics will increase, as the profile of the organics present in the water changes with time. Displacement of more weakly adsorbed organics and their premature breakthrough, and breakthrough at higher than feed concentrations, was observed. This phenomenon is known as roll-up and a model to predict its impact was developed. The effect is more commonly encountered when thermal waves are present in the reactor beds. However, the model was used to explain otherwise anomalous results from experiments where methanol had been used to bring low solubility materials such as PAHs into

solution but also proved to induce roll-up. It was clear that this phenomenon is important both at laboratory and full-scale.

Table 5.8: Adsorption capacity calculation data from column experiments

GAC Adsorption capacity (mg/g)	B	T	E	p-X	m-X	o-X	Styrene	Naphthalene
Column 1 – Entire column	4.54	3.69	0.18	0.43	0.80	0.74	0.72	1.56
Column 2 – Entire column	11.27	8.21	1.02	2.08	0.62	1.68	2.70	3.80
GAC 3 – Port 3	16.39	10.10	0.38	1.22	1.25	1.69	1.18	4.79
GAC 3 – Port 6	14.65	8.85	0.31	1.05	0.96	1.37	1.01	3.71

5.2.4.3 Cyanide removal

Column 1: The aim was to spike the influent groundwater to 1 mg/L for both complex and easily liberatable cyanide, however, results indicated high variability in the concentrations of these contaminants within the influent. This was attributed to biodegradation within the feed reservoir and/or degradation of the stock cyanide solution. As samples were not analysed in-house it was impossible to rectify this problem immediately, hence there were long periods of variable and low concentrations. The complete removal of both easily liberatable and complex cyanide was achieved following passage through the column.

Column 2: The influent solution concentrations of cyanide were again variable. The complete removal of both easily liberatable and complex cyanide was achieved following passage through the column.

Column 3: Under conditions of increased flow rate and elevated cyanide contamination levels, the complete removal of both easily liberatable and complex cyanide was still achieved following passage through the column.

Due to the large volume required for analysis, samples were not obtained from intermediate ports. Consequently the kinetics of cyanide removal by ZVI obtained will be underestimated as the concentrations close to method detection limits may have been achieved at ports closer to the influent, thus giving a lower half-life. The most accurate half-life data is obtained from Column 3 as this is at the faster flow rate (Table 5.9). Half-life values for total cyanide removal in Column 3 range from 0.44 to 1.17 hours. No decrease in removal rates (i.e. increase in half-life) for cyanide removal was achieved following the passage of over 651 pore volumes of spiked BH13 groundwater.

Table 5.9: Cyanide removal rates

Pore Volumes	Concentration (mg/L)		k-value (min ⁻¹)	Half-Life (hours)
	Influent	Effluent		
62	6.32	0.32	0.01605	0.72
116	4.76	0.42	0.01306	0.88
163	4.28	0.35	0.01347	0.86
225	1.89	0.30	0.0099	1.17
271	2.86	0.14	0.01623	0.71
442	3.59	0.05	0.02299	0.50
597	11.30	0.09	0.026	0.44
651	6.20	0.09	0.02277	0.51

5.2.4.4 Pilot-scale bio-barriers

Bio-barrier 1: to assess the biodegradation of BTEX, styrene and naphthalene

Due to the complex mixture of contaminants present within the groundwater, screening of the influent and effluent groundwater was carried out using the Microtox™ assay. Bio-barrier 1 was found to be operational after 7 days (i.e. toxicity measurements became stable after this point). After 38 days of operation, an increase in toxicity was observed in the effluent of the bio-barrier, from an EC₅₀ of 64.08% v/v to 4.39% v/v. At this time point the concentrations of benzene, toluene, *o*, *m*, *p*-xylene, and styrene increased within the influent groundwater, however, the concentration of these compounds within the effluent were below the respective GC-FID detection limits (0.01 mg/L) and also the remedial targets set. The increase in effluent toxicity at this time point was attributed to partial degradation of the priority BTEX, styrene and naphthalene contaminants (formation of toxic degradation products (e.g.) naphthoic acids and benzylsuccinic acid) as the microbial population acclimatized to the new conditions.

Influent groundwater concentrations were quite variable due to the differences in batches of BH 9 groundwater received at QUB. From days 21 to 150, toluene, ethylbenzene and total xylenes were all degraded to concentrations below their remedial target values by the effluent port. Benzene was degraded to concentrations lower than the remedial target level, apart from days 38 and 150.

Spiking experiments were conducted to reduce the influence of variable feed concentrations, as well as determine the tolerance and performance of the bio-barrier to higher levels of contaminants. The BTEX, styrene and naphthalene concentration was increased by a factor of 10 in BH 9 groundwater, for use as the influent feed solution. This solution was allowed to flow through the bio-barrier for a minimum of 5 days (i.e. one pore volume) prior to sampling (day 157). Several intermediate ports on the bio-barrier were sampled and analysed for BTEX, styrene and naphthalene. Samples taken on days 164, 178 and 192 indicated that the benzene, toluene, ethylbenzene and total xylene concentrations were less than their respective target values before intermediate port B1. Naphthalene concentrations, although decreasing, did not decrease to below its remedial target level on days 21 to 52, 59, and 74. An increase in path length or indeed residence time was concluded necessary for the complete remediation of these contaminants. These findings were used in the design of the SEREBAR.

Following 220 days operation, decommissioning of the bio-barrier, for the microbial characterisation of the biofilm, took place.

Bio-barrier 2: to assess the biodegradation of cyanide

As with Bio-barrier 1, screening of the influent and effluent water was carried out using the Microtox™ assay. Due to the low level of contaminants present in groundwater collected from BH 13, Bio-barrier 2 was operational from day one (i.e. effluent water was non toxic). Consequently, BH 13 groundwater was spiked with 1 mg/L of both easily liberatable and complex cyanide. Correlation between toxicity and chemical characterisation data for easily liberatable and complex cyanide within the influent water was apparent; however, following passage through Bio-barrier 2, removal of all toxic components occurred.

Both easily liberatable and total cyanide were being biodegraded as concentrations clearly decreased between the influent and effluent sampling ports. However, biodegradation to concentrations below the compliance targets set for total cyanide (0.143 mg/L) was not achieved through the length of the bio-barrier. Consequently an increase in path length or residence time was concluded necessary for the complete remediation of these contaminants.

5.3. DESIGN OF CUT-OFF WALL AND REACTIVE BARRIER SYSTEM

Field-scale implementation of a PRB requires careful design based on site specific hydrogeology and contaminant plume characteristics to appropriately determine the barrier location, configuration, and dimensions needed to capture and remediate the contaminated plume. With this purpose, a detailed numerical groundwater model was produced by QUESTOR-QUB and reviewed by Parsons Brinckerhoff Ltd. The groundwater model was based on the results from field investigations (See Section 3.3) and was produced using Visual MODFLOW. It provided a simple, single layer, unconfined representation of the groundwater system, within which to plot likely contaminant pathways.

5.3.1. BARRIER LOCATION AND CONFIGURATION

A series of simulations applying varying modifications were modelled using Visual MODFLOW and MT3DMS, to determine the best configuration to capture the plume for the subsequent treatment. The evaluated alternatives assessed various gate(s) positions, lengths of slurry walls, and the use of gravel trench(es). Both backward and forward particle tracking methods were used to simulate the transport of contaminants. Particle tracking simulates the advective transport using a Lagrangian method in which the particles move with the dominant flow velocity.

The preferred SEREBAR configuration dictated one single gate and two slurry walls acting as a funnel (Fig. 5.3). The first slurry wall extends along the southern site boundary (175 m) while the second runs along the site boundary in a north-easterly direction (70 m) to prevent off-site migration of contamination (Gibert *et al.*, 2007). With this configuration the cut-off walls (the funnel) modify flow patterns so that groundwater primarily flows through the high conductivity gap (the gate). The area of plume capture mimicked that of the TOC plume, overlaid onto the map in Figure 5.3. The design also incorporated two abstraction wells upgradient of the reactive gate for a more efficient capture of the plume and two recharge wells downgradient of the reactive gate.

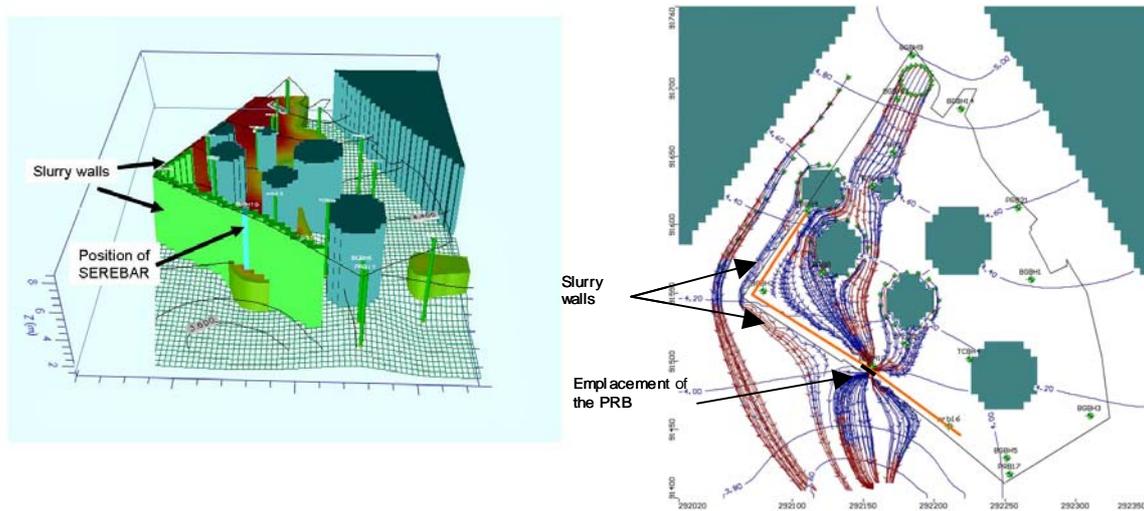


Figure 5.3: Plan of the site showing the position of the slurry walls (the funnel) and the reactive zone (the gate) in 3D (left) and 2D (right). TOC flow delineated as indicator of contamination plume

5.3.2. CONCEPTUAL REACTOR DESIGN OF THE GATE

The gate of the SEREBAR was designed to be entirely below ground level and composed of an interceptor and six steel canisters installed in series (Gibert *et al.*, 2007). This sequential design allows a number of different contaminants to be treated in a variety of ways. Consequently, this treatment strategy allows a highly adaptable approach to risk management. The site was chosen for use as a research and demonstration facility and consequently allowed the development of a novel treatment strategy. The risk assessment indicated that cyanide was not an issue for groundwater contamination at this site and, as a result, ZVI was not used as a treatment approach.

The designed reactive barrier employed biodegradation and sorptive processes in the removal of contaminants. The actual design was:

- Interceptor: The reactive cells within the treatment canisters could not cope efficiently with Non Aqueous Phase Liquids (NAPLs), which can clog and render the barrier media ineffective. To deal with this an interceptor was designed to prevent NAPL transport into the treatment canisters. NAPLs would be separated from groundwater through differences in density;
- The first and second canisters (hereafter referred to as S0 and S1) were designed to promote anaerobic biodegradation of site groundwater. They would be filled with sand, which has been reported to be an efficient support material for microorganisms;
- The third and fourth canisters (S2 and S3) were designed to promote the aerobic biodegradation of site groundwater, achieving further degradation of compounds not sufficiently removed during the first zone. For this purpose, air would be supplied with an appropriate sparging system. Sufficient amounts of oxygen are required to achieve the efficient biodegradation of organic compounds in the SEREBAR, although slow anaerobic degradation might occur; and
- The fifth and sixth canisters (GAC1 and GAC2) were designed to contain granular activated carbon (GAC) for the sorption of groundwater contaminants during the time prior to the colonisation of canisters S0 to S3 with a community of microorganisms able to biodegrade the contaminants. GAC1 and GAC2 also provided a safety net for the removal of any undegraded compounds. An estimation of the amount of GAC required for a given period of time (in this case yearly) can be made from the flux of groundwater and the sorption capacity of GAC determined in column experiments. Such calculations show an amount of GAC ranging from 0.032 to 0.045 tonnes per year required.

This sequence (biodegradation-sorption) is justified by the fact that the majority of compounds are degraded within the biological zone; consequently there will be less competition for sorption sites within the GAC, further enhancing the longevity and sorption capacity within the system. The convenience of this sequence has been reported in laboratory studies (Rasmussen *et al.*, 2002). The presence of the GAC treatment step (sorption) at the rear of the SEREBAR system provides a final safety net prior to effluent discharge. It allows sufficient time for the establishment and maturation of the biodegrading community (biofilm) to occur without requiring recirculation of the effluent and also means that the SEREBAR system is fully operational from day 1.

The SEREBAR system was intended to be used as a demonstration and research system for groundwater remediation. Consequently, the sequence of non-aerated (anaerobic) and aerated (aerobic) canisters enables the comparison of biodegradation rates under different conditions. This also allows further optimization of future SEREBAR performance.

Figure 5.4 shows a conceptual design of the reactive cells in the SEREBAR.

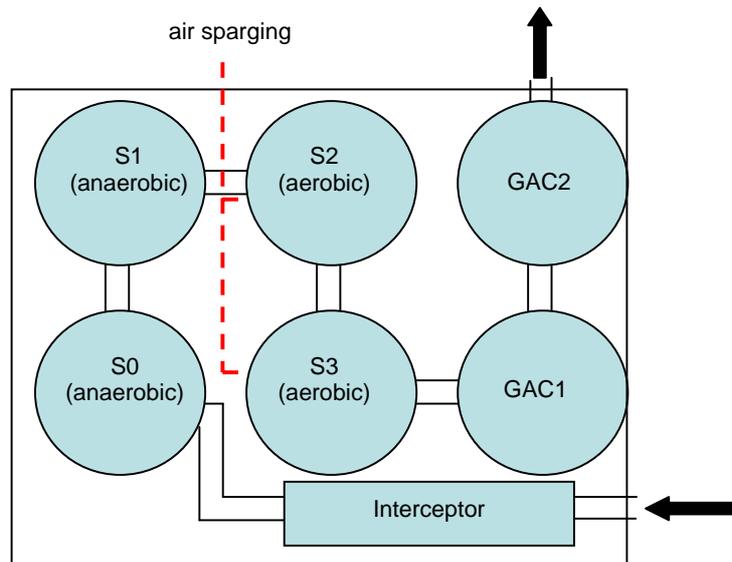


Figure 5.4: Conceptual design of the reactive cells in the SEREBAR

In general, groundwater flow to and through a PRB is designed to operate under passive conditions, i.e. rely entirely on gravity flow. The SEREBAR system is able to operate under passive (installed beneath the water table), or semi-passive (installed underground but above the water table) groundwater flow conditions. The option detailed here employed semi-passive groundwater flow. Groundwater was designed to be pumped by means of a submersible pump from the abstraction wells into the interceptor, from where it would flow through the six canisters under gravity. At the exit of canister GAC2, treated groundwater would be transferred to a discharge well downstream of the cement bentonite cut-off wall and discharged into a designed infiltration zone. The use of a pump allowed the direct control of groundwater flow into the SEREBAR barrier, enabling perturbations to the system to be assessed and future optimization of groundwater treatment.

Figure 5.5 shows a conceptual lateral view of the reactive canisters of the SEREBAR.

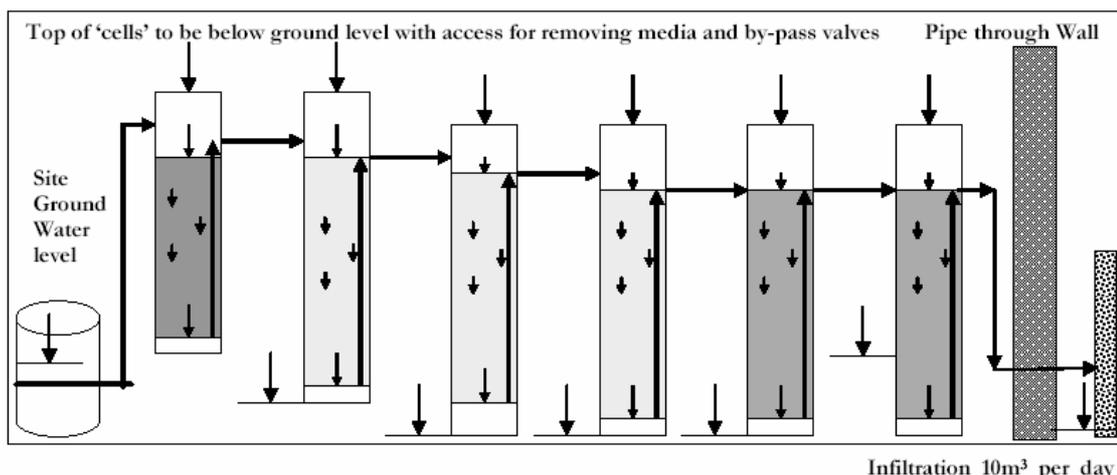


Figure 5.5: Conceptual lateral view of the reactive canisters of the SEREBAR (interceptor not shown).

6. INSTALLATION OF THE SEREBAR

6.1. INTRODUCTION

The SEREBAR was installed between February 2004 and May 2004. It was constructed and operated in accordance with the current Environment Agency guidance document “Design and Construction of Permeable Reactive Barrier Systems”.

The SEREBAR installation basically comprised the emplacement of two impermeable cut-off walls (to intercept and direct groundwater flow towards the SEREBAR), a submersible pumping system (to pump the groundwater to the inlet of the gate of the SEREBAR), an interceptor (for NAPL separation), a series of six canisters as the reactive zone (to treat the contaminated water) and a monitoring system.

This section discusses the aspects relating to the installation of each of these components. Plates 6.1 and 6.2 show images of the installation process of the SEREBAR barrier.

6.2. CUT-OFF WALL CONSTRUCTION

The funnel consisted of two cement bentonite impermeable barriers positioned vertically in the cut-off trench to capture and redirect groundwater over the length of the spill area (see Fig. 5.3). The cut-off wall was installed in accordance with the Institution of Civil Engineers “Specification for slurry cut-off walls”.

Excavation was performed with a conventional excavator (Plate 6.1a). The cut-off wall was generally 60 cm wide excepting within the area of the SEREBAR where it was locally widened to 1 m. The depth of the cut-off wall varied from 6 m to 8 m. Contaminated arisings were stockpiled on-site and then removed to a licensed landfill site. The wall was constructed from cement, Ground Granulated Blast Furnace Slag (GGBFS), bentonite and water, rendering a material with low permeability ($<1 \times 10^{-9}$ m/s). On completion of the cut-off walling, the upper 30-50 cm were trimmed from the wall and the site reinstated with either concrete or a combination of Type 1 stone and asphalt.

6.3. PUMPING SYSTEM

In general, groundwater flow to and through a PRB are designed to operate under passive conditions, i.e. rely entirely on gravity flow. The SEREBAR system is able to operate under passive (installed beneath the water table), or semi-passive (installed underground but above the water table) groundwater flow conditions. The option detailed here employed semi-passive groundwater flow. Consequently, the intercepted groundwater was directed to the reactive zone by means of a submersible pump, which lifts water to the interceptor (see Fig. 5.5). The submersible pump is capable of operating at groundwater flows of 0.5-10 m³/day. From the interceptor, groundwater flows under gravity vertically downward to the series of six reactive canisters, at the exit of which a pipe directs it through the impermeable slurry wall and discharges it into a designed infiltration zone (Plate 6.1b).

The use of a pump to control groundwater flow through the SEREBAR also meant that adequate groundwater flow to the canisters was maintained, and also that controlled experiments were able to be carried out under varying flow rates.

6.4. GROUNDWATER MONITORING WELLS

Seven groundwater monitoring wells were installed at locations throughout the SEREBAR. Each monitoring well contained a vibrating wire piezometer to measure groundwater level and a pH and conductivity probe to monitor groundwater quality. The instrumentation is linked to the monitoring system for the SEREBAR and is described in detail in Section 6.7.

6.5. REACTOR VESSELS

Excavation to a depth of approximately 3.6 m below existing ground level was conducted using a 25 t excavator. Soil from this excavation was reused for backfilling around the canisters, and was transferred to a separate stockpile. Following excavation works, a 0.2 m thick concrete slab (C40) with two layers of 8 mm mesh reinforcement was installed to provide support to the SEREBAR system.

The steel canisters for the SEREBAR were supplied prefabricated with all internal pipework in place. Only the external pipework, monitoring rods and valves were required to be fitted on-site by screwed connection – no hot works (welding, cutting, and burning) were permitted. The steel canisters (each 2.5 m diameter, 3.1 m height, 4.8 t weight) were carefully lifted into position using a 45 t mobile crane (Plate 6.1c). Once positioned directly onto the concrete slab, they were fixed in position using 20 mm holding-down bolts set into the concrete. After fixation of the canisters, backfilling around them was conducted using suitable excavated material (Plate 6.1d). This was carefully and evenly placed in 0.3 m layers with light compaction (hand-roller) to ensure no movement or damage to the canisters. A 50 mm blinding slab was constructed using ready-mixed concrete and placed by a 25 t excavator.

a)



b)



c)



d)



Plate 6.1: Sequential images of the installation process of the SEREBAR: a) excavation of the cut-off trench, b) installation of a deep well downgradient of the reactive gate, c) lifting canisters into position, and d) backfilling space around canisters

Following placement of the blinding concrete, the connecting pipework (40 mm polyethylene) and valves were installed (Plate 6.2a). These interconnecting pipes were provided with valves that allow bypass of individual canisters (allowing each unit to be isolated for maintenance) and with sampling taps that allow in-line water sampling to take place at points entering and exiting each canister.

Sparge pipes were installed in canisters S0 to S3, though the functioning of the SEREBAR reserves air sparging only to S2 and S3 to provide these canisters with aerobic conditions. The sparge pipes were fixed in a concentric circle and founded on coarse gravel (Plate 6.2b), and they were connected to the air sparge system.

Filling with the appropriate materials was then conducted. S0 to S3 canisters were filled with sand, GAC1 and GAC2 with granular activated carbon (GAC). In both cases the material was added using polypropylene bags (0.5-1.0 t), which were carefully lowered into the canister using the 25 t excavator with lifting strops and positioned on the base (Plate 6.2c). The bag was then cut, and the material discharged into the canister. Care was taken to ensure that no contamination of materials occurred during this operation.

Following the placement of materials, the lids were bolted onto the canisters and the ventilation pipework connected (Plate 6.2d). These pipes allow ventilation and monitoring of any gases that are produced during bioremediation in a safe manner. The canisters were also provided with piezometers permitting the measurement of water level and collection of water from the canister for analysis.

The interceptor was built to receive contaminated groundwater from the abstraction wells (Plate 6.2e). As discussed in Section 5.3.2, it is designed to isolate DNAPL and LNAPL contamination prior to entry into the first canister.

Once all the elements of the gate were completed, a steel mesh grillage was installed at ground level with an access facility for subsequent monitoring operations. This grillage was supported on a steel frame which was bolted to the top flanges of the SEREBAR canisters (Plate 6.2f).

6.6. TESTING OF SPARGING LINES

Canisters S2 and S3 were connected to an air sparge system supplied by Ecomesh Ltd, Ballymena, Northern Ireland. The sparge lines were tested using a hired compressor to prove that the airlines were open and aeration of the canisters was satisfactory. Spargers were tested at varying flow rates (100-500 cm³/min), which were measured with a datalogger.



Plate 6.2: a) connecting pipes, b) layout of the sparger system within a canister, c) filling the canisters with the reactive materials, d) vent pipework for collection of gases from the canisters, e) interceptor as a first stage prior to the entrance to the reactive canisters, and f) covering the canister system with a steel mesh grillage

6.7. INSTRUMENTATION FOR MONITORING SEREBAR OPERATION

An extensive instrumentation system was installed to monitor the following parameters:

1. Flow rate at inlet and outlet of the SEREBAR system (by means of a 15 mm electromagnetic flow meter)
2. Groundwater levels in all six canisters (with vibrating wire (VW) transducers)

3. Gas monitoring in each canister head space (O_2 , CO_2 and CH_4) (by means of a gas analyser)
4. pH and conductivity in GAC2 (pH & EC meter)
5. Air flow in sparging system
6. Groundwater level, pH and conductivity in the monitoring wells (with VW transducers and pH & EC meters).
7. LNAPL/DNAPL presence in the interceptor (by means of a LNAPL/DNAPL probe)

The electrical controls of this monitoring equipment including: (a) the two submersible borehole pumps; (b) the datalogger; (c) the two flowmeters; (d) the gas analyser; (e) the pH/conductivity; and (f) the LNAPL probe were located in a control cabin mounted on the boundary wall near the SEREBAR (Plate 6.3).



Plate 6.3: Control cabin mounted on-site for the automatic monitoring of the SEREBAR system

6.8. CLEANING AND MAINTENANCE

The design of the SEREBAR system enables straightforward maintenance. The control of groundwater flow rate, via the inlet pump, and the fact that individual canisters can be taken offline by means of isolation valves, means that repairs and maintenance could occur without having a detrimental effect on treatment performance (Figure 6.1). As well as periodical GAC replacement, the following routine maintenance schedule was specified:

1. Installed valves are stainless steel and are opened every six months to prevent seizure.
2. Interceptor and pipework are checked for leaks during each visit to the site for compliance monitoring and any leaks sealed.
3. All holding down and retaining bolts are loosened, greased and retightened annually.
4. Submersible pumps are inspected and cleaned as recommended by the manufacturer on an annual basis.
5. All installed sensors are checked for the presence of corrosion and, where possible, calibrated using a manual readout.
6. Grillage is carefully inspected and any damaged/corroded sections replaced as required.
7. Instrumentation cabinet is checked for ingress of water and corrosion and standby batteries checked for state of charge and replaced as necessary.
8. Mains electrical supply is checked annually by a qualified and certified electrician.

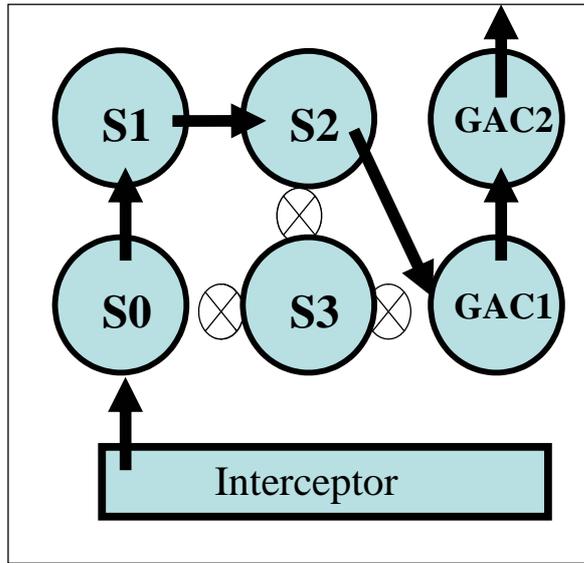


Figure 6.1: Conceptual design of the SEREBAR showing the redirection of groundwater flow following isolation of canister S3

7. OPERATION AND MONITORING

7.1. INTRODUCTION

This chapter describes the operational parameters of the SEREBAR system (groundwater flow rate and air flow rate injected in the aerated canisters) prior to discussing its performance in the next chapter. The present chapter also addresses issues during the routine monitoring programme conducted following the SEREBAR installation.

7.2. SEREBAR OPERATION

7.2.1. FLOW RATE

Flow rate through the barrier was initially fixed at 520 L/d, reduced in October 2004 to 320 L/d and subsequently increased to 520 L/d in December 2004. Taking into account the canister dimensions and the filling material porosity, the average hydraulic residence time (t_R) in each canister for these flow rates was 12 days and 19 days, respectively. In January 2005, the flow rate was increased to 10,000 L/d ($t_R=0.6$ d) and reduced after 2 weeks to 4000 L/d ($t_R=1.5$ d). At this time, the original interceptor was replaced. The new one was designed to prevent passive aeration by sealing the interceptor.

Plate 7.1 shows the installation of the new interceptor.



Plate 7.1: Installation of the new interceptor

In May 2005 the flow rate was set at 1700 L/d ($t_R=3.6$ days) until October 2005, when the pump malfunctioned. Following repair, the PRB ran again in November 2005 at a flow rate of 1700 L/d, which was later reduced to 1000 L/d in January 2006. Water level monitoring confirmed that groundwater was flowing under gravity through the six reactive canisters of the SEREBAR. This increase in flow rate allowed a more effective capture of the contaminant load within the reaction canisters, which led to a higher overall treatment efficiency.

7.2.2. AIR SPARGING

The air sparging system operated with a low air flow rate (200-400 mL/min) and was subsequently increased in December 2004 to 600 mL/min. In May 2005, the air compressor malfunctioned and aerobic conditions could not be maintained in canisters S2 and S3 until repairs were carried out in June 2005. From that month on, the air flow rate was set at 600 mL/min.

Table 7.1 summarises operational parameters (groundwater flow rate, residence time in each canister, air flow rate) of the SEREBAR barrier over time.

Table 7.1: Summary of the operational parameters of the barrier after two years

Sample date	Groundwater flow rate (L/d)	Residence time* (d)	Air flow rate (mL/min)
Jul 04	520	12	200-400
Oct 04	320	19	
Nov 04	320	19	
Dec 04	520	12	400-600
Jan 05	520 (10000)	19 (0.6)	600
Feb 05	4000	1.5	600
May 05	1700	3.6	0 (air compressor malfunction)
Oct 05	0 (pump malfunction)		600
Nov 05	1700	3.6	600
Jan 06	1000	6.1	600
Jul 06	1000	6.1	600

* Residence time in individual canisters.

7.3. MONITORING PLAN

A monitoring programme was planned to verify that the SEREBAR system was operating as designed. In general this monitoring was focused on the SEREBAR system, rather than the entire site. The programme was designed to verify proper installation of the system and identify its ability to deal with enforced perturbations in groundwater flow and/or chemical load.

7.3.1. AUTOMATIC MONITORING

As previously noted in Chapter 4, a fully automated continuous monitoring station was installed on-site to record the basic parameters within the PRB. The monitoring comprises water level, flow rate, conductivity, pH, air flow in the sparging system and gas analysis (CO₂, CH₄, O₂) at several points across the PRB. The datalogger regularly downloads and transmits by telemetry the information to an off-site location, so that the data can be provided in real-time to a web page for viewing by the project team.

7.3.2. MANUAL MONITORING

On-site visits were planned to manually monitor the water level within the canisters and also to collect groundwater samples for chemical analysis both on-site and off-site (in the laboratory). Procedures for the manual monitoring were detailed in Chapter 4.

7.3.3. SAMPLING POINT LOCATION

The interconnecting pipes were provided with valves that allow isolation of individual or multiple canisters (for maintenance purposes) and with taps for sampling water at the entrance and exit of each canister. Canisters were provided with two sampling points (referred to as A and B), each comprising two piezometers at approximately 1.6 m and 2.6 m deep (referred to as shallow and deep, respectively) (Figure 7.1).

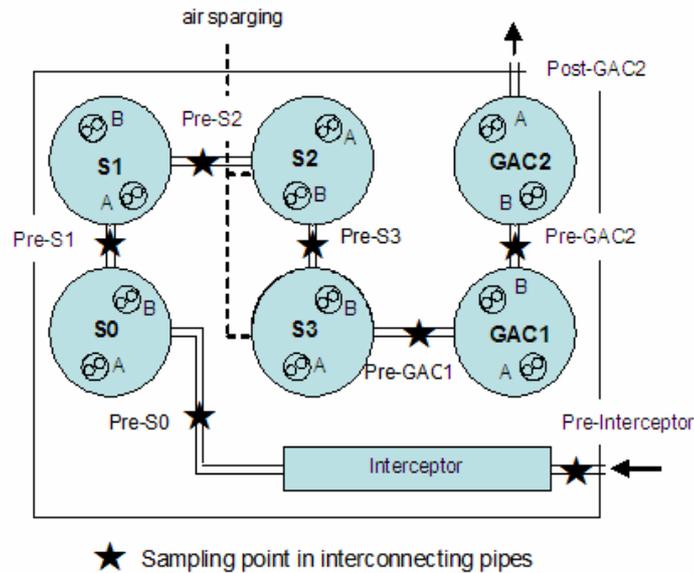


Figure 7.1: Conceptual design of the reactive gate in the SEREBAR system and location of the sampling points

7.3.4. SAMPLING FREQUENCY

The sampling programme started two months after the completion of the SEREBAR installation. Sampling continued with decreasing frequency from once every two months during the first year to once every three months during year two.

7.3.5. SAMPLING METHODS

Groundwater samples were collected from both inside the canisters and at the taps (Figure 7.2).

A peristaltic pump was used to collect groundwater from the canisters. Water quality measurements were taken using a flow-through cell (Waterra Sheffield cell), minimising contact of the groundwater with the atmosphere. Prior to sample collection, the volume of water contained within the monitoring well pipe was calculated, and a minimum of three times the calculated volume was purged from the monitoring well. In relation to groundwater sampling from between the canisters (taps), water quality measurements were taken directly using a 1 L container. Agitation of the samples during their collection at these points and exposure to the atmosphere must be taken into consideration when interpreting air-sensitive water parameters (Eh and DO). Once collected, the water samples were stored on ice at 4°C and analysed within seven days.

Biofilm samples for microbial analysis were collected using the developed solid sample collection system (Plate 7.2).



Plate 7.2: Solid sample collection for microbial biofilm analysis

8. RESULTS AND DISCUSSION

8.1. INTRODUCTION

This chapter describes the performance parameters of the SEREBAR system between its completed installation in May 2004 and August 2006 (see also Gibert *et al.*, 2007).

8.2. GROUNDWATER CHEMISTRY

Prior to entry into the interceptor, the major ion chemistry indicated that groundwater ionic chemistry was dominated by calcium bicarbonate with lesser but significant concentrations of sodium, potassium and sulphate (data not shown). The data were consistent with the background chemistry for upgradient wells proximal to the SEREBAR and sampled prior to its installation.

The pH was stable, with most values ranging from 6.7 to 7.7 for all sampling events (data not shown). No significant pH differences between the aerobic and anaerobic zones were detected. Electrical conductivities varied mostly in the range of 600 $\mu\text{S}/\text{cm}$ to 850 $\mu\text{S}/\text{cm}$, except in Jul-04, Oct-04 and Jan-06, when lower ranges were observed (430 $\mu\text{S}/\text{cm}$ to 630 $\mu\text{S}/\text{cm}$). Given these levels of electrical conductivities, pollution from dissolved solids such as minerals salts did not appear to be a threat to the quality of the groundwater at the site.

Prior to the replacement of the interceptor, initial measurements indicated that dissolved oxygen (DO) ranged between 2 mg/L and 4 mg/L prior to entering the first canister. This was reduced to <2 mg/L with the emplacement of the new covered interceptor (data not shown). DO declined as groundwater flowed through the anaerobic canister (<0.2 mg/L) in both S0 and S1. As the result of artificial aeration within canisters S2 and S3, DO concentrations increased (from <0.2 to 2 mg/L). No vertical profiles were observed at the top and bottom of the canisters.

Redox potential (Eh) was generally between -50 mV and +150 mV in canisters S0 and S1, with a general slight increase through the aerobic zone (Eh mostly between +170 mV and +350 mV) due to artificial aeration (data not shown). Eh in canisters GAC1 and GAC2 slightly declined to values between +150 mV and +250 mV. Similarly to DO, no significant differences were observed between Eh in shallow and deep monitoring wells within the canisters.

Groundwater temperature was between 5.5°C and 12°C in winter months rising to between 16°C and 19°C in summer months.

8.3. INLET CONCENTRATIONS

During a two year sampling period, the concentrations of the EPA 16-PAHs at the entrance to the interceptor fluctuated between 40 $\mu\text{g}/\text{L}$ and 401 $\mu\text{g}/\text{L}$ (Figure 8.1a). BTEX components were found between <0.01 $\mu\text{g}/\text{L}$ and 529 $\mu\text{g}/\text{L}$ (Figure 8.1b). Naphthalene, which was found to be the dominant PAH in the site groundwater (Ferguson *et al.*, 2007), entered the SEREBAR at concentrations between 1.4 $\mu\text{g}/\text{L}$ and 3.8 $\mu\text{g}/\text{L}$ (Figure 8.1c). Phenols and cresols were always below detection limits (<10 $\mu\text{g}/\text{L}$).

Low molecular weight (2-ring) PAHs accounted for more than 80% of the total PAHs entering the barrier. This predominance is not surprising since lower molecular weight PAHs exhibit lower hydrophobicities and are more soluble than heavier PAHs, which bind more tightly to the soil matrix (Haesler *et al.*, 1999). This is noteworthy because bi- and tri- cyclic PAHs are readily

biodegradable and are expected to be removed by biodegradation in the PRB more easily than heavier PAHs.

For the purpose of evaluating and discussing chemical changes across the barrier, a distinction was made between the original interceptor operating at low flow rates (320-520 L/d) (Jul-04 to Dec-04) and the new fully sealed interceptor operating at higher flow rates (1000-4000 L/d) (Jan-05 to Jul-06).

8.4. SEREBAR PERFORMANCE

8.4.1. ORIGINAL INTERCEPTOR OPERATING AT LOW FLOW RATES

Under the low flow rate conditions and prior to the replacement of the interceptor, the removal of the EPA 16-PAHs occurred primarily within the interceptor (reduced by >92%) (Figure 8.1a). This was undoubtedly due to the intrusion of air and subsequent development of a microbial community capable of PAH degradation (Ferguson *et al.*, 2007). The rapid removal of PAHs from groundwater, particularly of the 2-ring PAHs, is in accordance with reported laboratory experiments (Rasmussen *et al.*, 2002).

The passage of groundwater through the anaerobic zone (canisters S0 and S1) did not significantly decrease the concentration of the EPA 16-PAHs (with a contribution to the overall PAH removal <7%). The need to supply O₂ to achieve appreciable PAH biodegradation during the hydraulic residence time is in agreement with previous laboratory treatability tests and reported field-scale applications (McGovern *et al.*, 2002; Rasmussen *et al.*, 2002).

The entrance into the first aerobic canister (S2) resulted in the almost complete removal of the residual EPA 16-PAHs (Figure 8.1a). Dec-04 showed the lowest concentration of the EPA 16-PAHs at this sampling point, which was consistent with the increase of air flow (up to 600 mL/min) implemented that month (Table 7.1). Further passage of the groundwater through the second aerobic canister (S3) resulted in a decrease in the EPA 16-PAHs concentrations below 0.6 µg/L, indicating an overall removal through the gate of >99.5% (Gibert *et al.*, 2007).

Prior to discharge and following passage through the sorption zone (GAC1 and GAC2 canisters) the concentration of the EPA 16-PAHs was further reduced to <0.01 µg/L (resulting in an overall removal of PAHs >99.9%), which is well below the compliance level set (100 µg/L).

Naphthalene followed the same degradation profile set by the overall sum of the EPA 16-PAHs (Figure 8.1c). Its concentrations prior to the interceptor ranged from 1.9 µg/L to 23.2 µg/L, and fell below 0.4 µg/L at Pre-S0 (removal >96%). These values declined only very slightly through the biological canisters (S0 to S3), with an average concentration of 0.1 µg/L entering the sorption zone. Again, GAC was proved to be effective at reducing the residual dissolved naphthalene to very low concentrations (<0.01 µg/L).

The distribution of total heterotrophic and naphthalene utilising bacteria in samples obtained from the canisters was heterogeneous (Fig. 8.2). Under conditions of low flow rate, the enumeration of viable heterotrophic bacteria and also those utilising naphthalene as the sole carbon source showed a general decrease in microbial numbers from inlet to outlet. Highest microbial counts were observed within canister S0. Prior to the replacement of the interceptor with a fully sealed unit, and operation at low flow rates, the proliferation of viable naphthalene utilising microorganisms was primarily associated with the interceptor and canister S0. This was clearly consistent with the removal of naphthalene in the process.

BTEX concentrations showed a similar pattern to that of the EPA 16-PAHs (Gibert *et al.*, 2007). Removals through the interceptor were in the range of 77-98%, resulting in concentrations below

detection limits ($<2.5 \mu\text{g/L}$) at Pre-S0. These concentrations remained undetectable through the rest of the system (Figure 8.1b).

It is assumed that all of the biodegradative microorganisms entering the SEREBAR originated from the same source (intercepted groundwater). However, the microbial community that developed within the different canisters varied considerably. The ability to colonise a variety of different environments shows the highly adaptable nature exhibited by microorganisms.

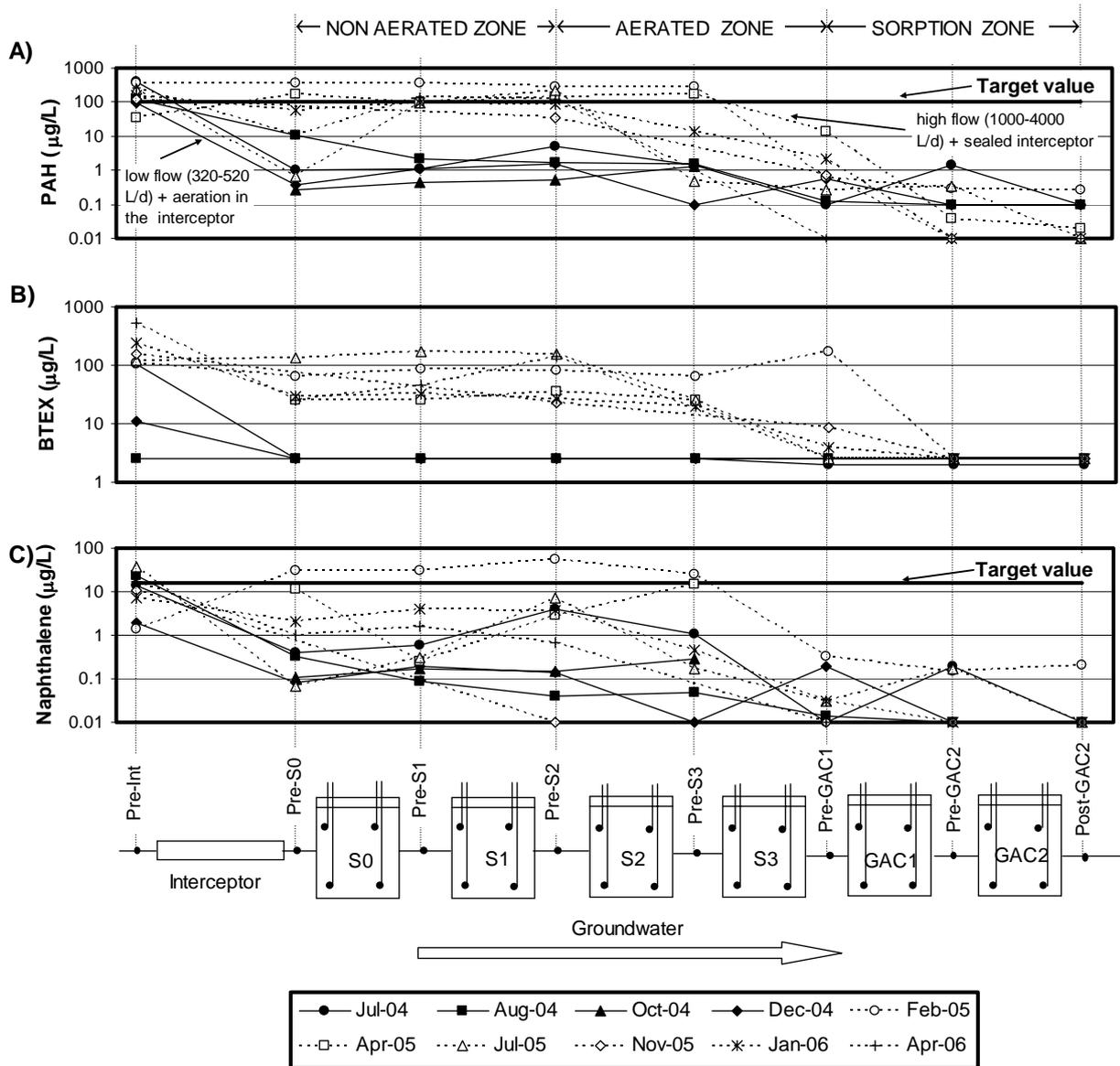


Figure 8.1: Concentration profiles of contaminants of concern through the SEREBAR reactors: A) EPA 16-PAHs; B) BTEX; and C) naphthalene across the barrier for each sampling event. Solid lines indicate concentrations with the original interceptor operating at the design flow rates (before Jan-05) and dashed lines indicate concentrations with the fully sealed interceptor operating at higher flow rates (Gibert *et al.*, 2007)

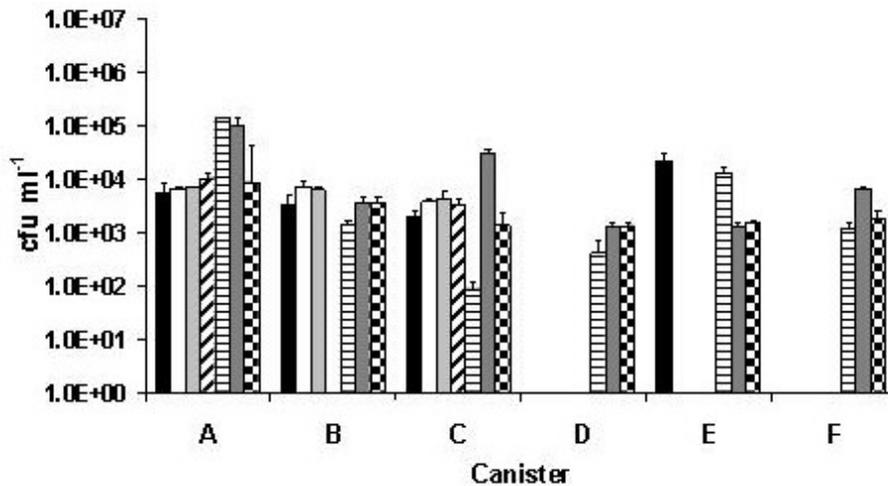


Figure 8.2: Total viable heterotrophic counts of bacteria using naphthalene as the sole carbon source across the SEREBAR reactor after 2, 3, 5, 6, 9, 11, and 14 months of operation. Groundwater flow rate was increased from 520 L/d to 4000 L/d after 7 months (Ferguson *et al.*, 2007). The counts are the mean of triplicates with standard errors indicated

8.4.2. FULLY SEALED INTERCEPTOR OPERATING AT HIGH FLOW RATES

In January 2005, the interceptor was replaced with a fully sealed unit to prevent passive aeration. Additionally, the flow rate was increased in February 2005 to 4000 L/d (Table 7.1). As shown in Figure 8.1a, these actions minimised biodegradation in the interceptor and the concentration of the EPA 16-PAHs entering Pre-S0 increased after this date from an average of 3.03 µg/L to an average of 104 µg/L. This rise was attributed to the more efficient capture of the contaminant plume at the higher flow rate. Following the increase in flow rate, <22% of the EPA 16-PAHs were removed across the anaerobic zone (Gibert *et al.*, 2007).

As groundwater travelled through the aerated canisters S2 and S3, a reduction in concentration of the EPA 16-PAHs was apparent (removals >91%), with concentrations at Pre-GAC1 averaging 2.92 µg/L (Gibert *et al.*, 2007). This finding is consistent with the increase in microbial numbers within the aerated canisters (S2 and S3) following the increase in flow rates through the SEREBAR (Ferguson *et al.*, 2007). A reduction in the concentration of PAHs within the aerated canisters occurred in S2 (Jul-05 sampling event), in S3 (Feb-05 and Apr-05) or in both S2 and S3 (Nov-05, Jan-06 and Apr-06). The differences in these profiles may rely on seasonal variations and on microbial adaptation to new flow rates. The subsequent passage through the GAC sorption zone led to a steady decline to concentrations <0.26 µg/L in Post-GAC2 before discharge. Similarly to the previous operational conditions, the overall removal of the EPA 16-PAHs through the SEREBAR barrier was >99.9% (Gibert *et al.*, 2007).

The BTEX degradation profile was similar to that observed for the EPA 16-PAHs. The replacement of the interceptor with a new fully sealed unit, resulted in an increase in BTEX concentrations entering the canisters (Pre-S0), from <2.5 µg/L to an average of 49.75 µg/L (Figure 8.1b). The passage of groundwater through the anaerobic canisters did not substantially decrease the concentrations of BTEX. Similarly to PAHs, anaerobic degradation of BTEX is widely reported, although biodegradation rates are known to be substantially slower in comparison to aerobic conditions (Landmeyer *et al.*, 1997). Consequently, at the retention times associated with such increased flow rate (1000-4000 L/d), a reduction in contaminant load within this section was not expected. However, as groundwater passed through the aerated canisters,

BTEX concentrations declined to an average of 4.38 µg/L, indicating BTEX removal >91%. An exception to this pattern was the Feb-05 sampling event, which showed a surprisingly elevated concentration of 172 µg/L. This may be due to an increase in flow rate prior to the sampling event (10,000 L/d), with the subsequent reduction of residence time within the canisters and the acclimation period of microorganisms to the increased flow rate. GAC removed the remaining BTEX contaminants (<2.5 µg/L at the post-GAC2 sampling location) producing an overall removal >95%.

Following this increase in groundwater flow rate and the replacement of the interceptor, an increase in microbial numbers present within the rear canisters (S2 and S3) was observed. This was attributed to increased microbial transportation, as the result of flow rate, relocation of microorganisms initially present within the front end (S0 and S1), and proliferation of microorganisms in new niches, due to the increased substrate availability and affiliation for aerobic degradation. It could also be due to the increased flux of nutrients.

The extent to which the PAH and BTEX contaminants are removed, following treatment within the SEREBAR, is comparable to a previous report for a biological PRB detailing the treatment of n-alkane and BTEX, where removal percentages varied from 63-96% for BTEX and 54-81% for different n-alkanes fractions (McGovern *et al.*, 2002).

8.5. GAS ANALYSIS

Headspace gas within the canisters generally presented a composition very close to that of air, with small increases in CO₂ to around 0.5% (v/v) but with sporadic peaks up to 2% (v/v) in S3 (Gibert *et al.*, 2007). It is postulated that the increase in CO₂ concentrations was indicative of microbial activity, especially within the aerated canisters. This finding is consistent with the EPA 16-PAHs and BTEX removals described above and with the higher microbial populations found in S2 and S3 (Ferguson *et al.*, 2007).

8.6. CHANGES IN POTENTIAL INDICATORS OF REDOX CONDITIONS IN THE SEREBAR

The development of anaerobic/aerobic conditions can be reflected in other redox sensitive species such as the sulphate/sulphide and nitrate/ammonium couples.

Sulphate concentrations remained largely unchanged for all sampling events (Figure 8.3a). This pattern was expected since Eh measurements were generally higher than those associated with sulphate reduction (Eh between -100 and -300 mV). Sulphide was always detected at low levels (<0.1 mg/L, mostly <0.05 mg/L).

The oxidised/reduced nitrogen species reflected well the anaerobic/aerobic conditions developed within the SEREBAR system. The overall profile of N-compounds along the barrier differed depending upon the intrusion of air in the interceptor (Gibert *et al.*, 2007). With passive aeration in the original interceptor (i.e. during the first 6 months of operation), NO₃⁻ and NO₂⁻ were sporadically found in Pre-S0 at concentrations around 5 mg/L (as N) (Figure 8.3b). It should be noted that these oxidised N-species were not originally present in the contaminant plume. Their presence is believed to be due to the biological oxidation of NH₄⁺ in the interceptor, due to the intrusion of air. Further passage of groundwater through the non-aerated canisters resulted in a gradual decrease of these oxidised N-species to <1.0 mg/L (as N), suggesting that denitrification was occurring in S0 and S1. The fact that NO₃⁻ removal occurred with no removal of target contaminants (Figure 8.1) may be due to the presence of other non-target organic compounds that are more readily degradable and exert a demand for electron acceptors. The NO₃⁻ decrease might also be partially due to NO₃⁻ assimilation into biomass (Robertson *et al.*, 2002).

As expected, the entrance into the aerated canisters led to an increase of NO_3^- and NO_2^- (up to 14 mg/L as N) and the concomitant decrease of NH_4^+ , making evident that biological oxidation of NH_4^+ contributed to the consumption of oxygen delivered in canisters S2 and S3 (Figure 8.3c). A molar balance between the decrease of NH_4^+ and the increase of NO_3^- and NO_2^- in the first aerobic chamber indicated that approximately 50% of the NH_4^+ was oxidised to NO_3^- and NO_2^- , suggesting that the rest could be converted to other species (e.g. gaseous N_2). It should be noted that these calculations are restricted to those sampling events with sufficient data (i.e. concentrations at Pre-S2 and Pre-GAC1 only).

Exceptions to these patterns occurred in Jul-04, when a decrease of NH_4^+ in the non-aerated canisters was observed, and Aug-04, when an unexpected increase of the oxidised nitrogen compounds was observed again in the non-aerated zone. The former indicated the existence of mechanisms responsible for NH_4^+ removal in anaerobic conditions (annamox: Jetten *et al.*, 1999), while the latter may be due to the intrusion of air and agitation of samples whilst collecting them from the pipework sampling locations.

Once the interceptor was replaced the profiles of N-compounds along the SEREBAR treatment train were simpler. With no oxidation of NH_4^+ in the interceptor, all nitrogen entered the anaerobic zone as NH_4^+ and as such crossed the anaerobic zone (Figure 8.3c). The entrance into the aerated canisters resulted in a drop in NH_4^+ accompanied by an increase of NO_3^- and NO_2^- (up to ~13 mg/L). A molar balance gave the same results are described above. Exceptions to this pattern were the Feb-04 sampling event, when NH_4^+ , NO_3^- and NO_2^- concentrations remained unchanged all along the SEREBAR, and the Jul-05 sampling event, when a decrease of NH_4^+ concentrations was observed in the interceptor. The former finding can be explained by the fact that the flow rate just before the sampling event in Feb-05 had been increased to the maximum of 10,000 L/d (Table 7.1) and an adaptation and relocation of microorganisms to the increased flow rate took place (Ferguson *et al.*, 2007). The removal of NH_4^+ in the interceptor in Jul-05 is not fully understood.

Figure 8.3d shows the profile of total inorganic nitrogen ($\text{NH}_4^+ + \text{NO}_3^- + \text{NO}_2^-$). The reduction in total N is achieved by the passage of groundwater through the SEREBAR, mainly as a result of nitrification and denitrification, as discussed above.

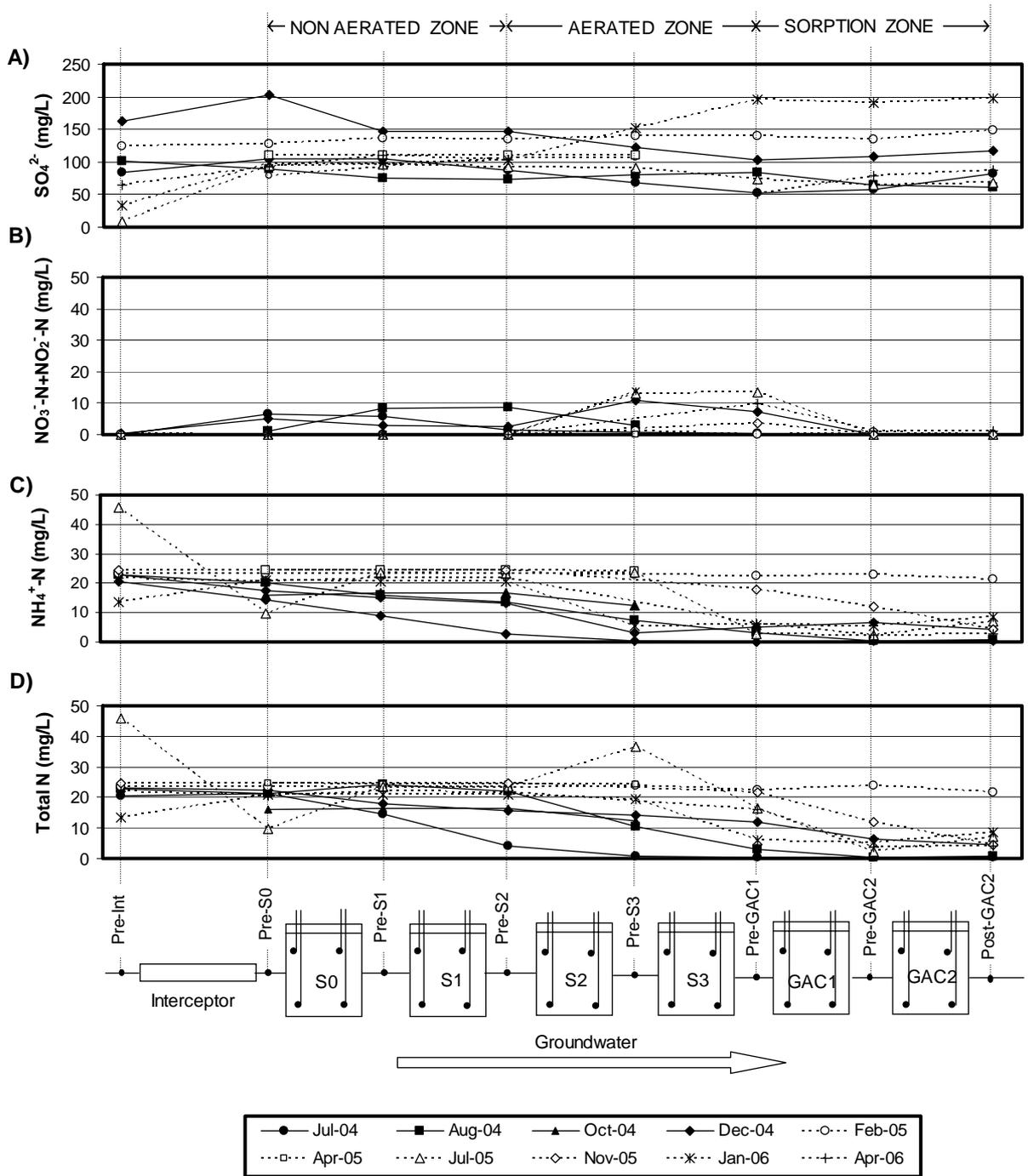


Figure 8.3: Concentration profiles of sulphate and inorganic nitrogen species through the SEREBAR reactors: A) sulphate; B) nitrate+nitrite; C) ammonium; and D) total N, across the barrier for each sampling event. Solid lines indicate concentrations with the original interceptor operating at the design flow rates (before Jan-05) and dashed lines indicate concentrations with the fully sealed interceptor operating at higher flow rates (Gibert *et al.*, 2007)

8.7. SEREBAR MODELS

A hydraulic model of the basic flow through the system was formulated and solved using gPROMS Version 3.0 for Windows XP (general PROcess Modelling System, from Process Systems Enterprise Limited, Hammersmith Bridge Road, London, England). This model included the small hydraulic head losses across the weirs in the reactors and the resistances to flow due to the canister fill materials and pipework.

This fully dynamic model was used to investigate the overall stability of flow through the SEREBAR. The modelling raised fundamental questions about the method of oxygenation of the reactors. Experimental studies on the reactors were conducted as a result of the modelling, and confirmed that the method of sparging air into the base or middle of the canisters S2 and S3 was inefficient.

Consequently, the aeration of subsequent SEREBAR systems should occur between the canisters and not within them. Such changes will reduce operational costs and simplify maintenance strategies, leading to a system that is more efficient, maintainable, predictable and robust.

Biotic canisters:

A new model of the biofilm formation and kinetics was formulated and solved. Preliminary results indicated that the cells in the biofilm were more mobile than is usually accounted for in traditional models. Consequently, the new model accounted for the mobility (convection and chemotaxis) of the cells in the biofilm, and also included the capture of new organisms by deep bed filtration and the *in situ* growth of the biofilm.

GAC canisters:

GAC played an important role early in the life of the SEREBAR process. More PAHs were captured in the carbon beds during start-up than was anticipated. The amount of microbial biomass observed within canisters GAC1 and GAC2 was greater than expected. A model of deep bed filtration of cells and biofilm fragments in the upstream sand beds found that there should be much less biomass than was actually observed in the GAC canisters. Thus the biomass in the GAC canisters could not be explained by deep bed filtration processes in the upstream canisters. The model developed here assumed that the cells of the biofilm were significantly mobile and had migrated to the GAC canisters where nutrients (groundwater contaminants) were concentrated in the adsorbed phase on the GAC.

The new analytical theory of roll-up was developed to account for the displacement of weakly and reversibly adsorbed species by more strongly adsorbed competitors (roll-up is the displacement of more weakly adsorbed organics and their premature breakthrough, and breakthrough at higher than feed concentrations as discussed in Section 5.2.4.2). This theory used a mathematical procedure called the method of characteristics. The analytical solution is a first approximation that can be used to estimate whether roll-up may be a problem in future GAC sorption strategies.

9. ECONOMIC CONSIDERATIONS

9.1. INTRODUCTION

The costs for the tasks involved in the implementation of the SEREBAR system were broken down into four general categories: (1) site characterisation, (2) design, (3) construction and (4) operation and maintenance (O&M). It is important to note that this project was research led and as such allowed optimization, investigation, demonstration and dissemination of the novel remediation process. Consequently the associated costs for future remedial works would be significantly reduced.

The cost elements associated with each task are summarised in Table 9.1:

Table 9.1: Summary of costs of the SEREBAR system

Item	Cost (£)
Site characterisation	
-Site characterisation (chemical/hydrogeological)	174,480
-Other site characterisation costs	15,000
Sub Total	189,480
Design	
-Bench-scale tests	128,940
-Engineering design (modelling and planning)	33,560
-Other design costs	2,030
Sub Total	164,530
Construction	
-Mobilisation, preparation, slurry wall installation	250,000
-Reinstatement	40,000
-Soil and construction disposal costs	134,500
-Monitoring wells installation within gate	8,000
-Treatment system, media, equipment and labour costs	189,500
-Other construction costs	80,000
-Report fees	48,000
Sub Total	750,000
Operation and Maintenance (O&M)	
-Monitoring (3 years research + 7 years compliance)	290,000
-Maintenance (10 years)	105,000
-Replacement of the reactive media	20,000
-Reporting costs (10 years)	50,000
-Other O&M costs (10 years)	15,000
Sub Total	480,000
TOTAL	1,584,010

The costs elements associated with each task are briefly discussed below in sections 9.2-9.5.

9.2. SITE CHARACTERISATION

As given in Table 9.1, the costs for the initial site characterisation were £189,480. This included:

- Drilling of 41 no. boreholes
- Gas analysis for some of them
- Sampling and analysis of 201 soil samples
- Installation of 37 monitoring wells

- 4 rounds of groundwater sampling and laboratory analysis from monitoring wells
- Reports on the site characterisation, including risk assessments

9.3. DESIGN

The design task comprised: 1) bench-scale tests (batch and column experiments); and 2) the engineering design (including modelling and planning) of the SEREBAR system. The costs of the design phase amounted to £164,530.

9.4. CONSTRUCTION

The largest single component of the £1,584,010 total cost was by far the SEREBAR construction cost. It totalled £750,000 and included the initial consents and report fees, the excavation and installation of the SEREBAR system, the monitoring system, the disposal of waste materials and the completion of a report.

9.5. OPERATION AND MAINTENANCE

The O&M costs were £395,000, primarily for performance monitoring. Performance monitoring included sampling and analysis of groundwater from the SEREBAR system and from the monitoring wells in the vicinity of the PRB at 58 sampling events performed over 10 years. The cost averaged £5000 per event.

Maintenance of the continuous, fully automated monitoring system accounted for £75,000. In addition, it is assumed (conservatively) that the GAC in the SEREBAR system would have to be replaced every 10 years at a cost of approximately £20,000.

9.6. COMPARISONS WITH ALTERNATIVE TREATMENTS

A principal advantage of the SEREBAR technology over the other remediation approaches is the reduced operation and maintenance (O&M) costs.

To date, PRBs have operated under entirely passive conditions (gravity fed). The SEREBAR system is able to operate under passive (installed beneath the water table), or semi-passive (installed above the water table) groundwater flow conditions. When the SEREBAR system is installed above the water table, as detailed here, a pump is used to transport groundwater to the inlet, followed by gravity flow through the canisters (termed semi-passive groundwater flow). In comparison with traditional PRBs the use of the inlet pump allows an increase in plume capture. The flexibility associated with the SEREBAR design (number of treatment canisters and fill material) and its installation depth, enable the most viable economic option to be sort. This selection process is influenced by the site geology, hydrogeology, SEREBAR maintenance and running, as well as the proposed site end use. The placement of the system underground also removes the requirement for any additional licences associated with pump and treat (above ground) remediation strategies.

An additional benefit that SEREBAR brings, in contrast to many of the alternatives, is that the site can remain “active” during the remedial works and thereafter. As with all PRB systems groundwater remediation takes place in an area which can be controlled, enabling accessible monitoring and in relation to the semi-passive SEREBAR system straightforward alteration of reactive material. The flexibility of the reactor design allows it to be located conveniently for the existing use of the site with groundwater managed by cut-off walls or pumping as appropriate.

10. CONCLUSIONS

1. Gasworks activities at the site of study are recorded back to the 19th century. The long-term operation of the gasworks plant has resulted in a need to manage the risk posed by the contaminants in the soil and groundwater beneath the site.
2. Ground investigations indicated that site stratigraphy is composed of a made ground layer 0.9 m to 3.4 m thick consisting of sandy silts and gravels with a number of waste materials (brick, tarmac, concrete etc) underlain by alluvial deposits 2.5 m to 4.6 m thick. These are in turn underlain by a bedrock of Permian breccio-conglomerates, sandstones, with subordinate mudstones, occasionally with an argillaceous or calcareous matrix of very low permeability, that limit vertical hydraulic interaction. Hence, the alluvial layer can be regarded as a single unconfined aquifer.
3. Groundwater monitoring indicated that the groundwater flowed in a southerly direction, with a hydraulic gradient of approximately 0.022. The hydraulic conductivity was determined by 11 slug tests and quantified in a range of values of 3.0×10^{-6} m/s to 3.5×10^{-5} m/s to (0.3-3.0 m/d).
4. The contaminants of concern detected within the soil and groundwater across the site comprised PAHs (measured as the EPA 16 PAHs; average concentrations of 1239 mg/kg in soil and 0.04 mg/l in groundwater, respectively), BTEX (11.5 mg/kg and <0.01 mg/l), phenol (1.4 mg/kg and 0.02 mg/l), cresol (5.6 mg/kg and 0.07 mg/l), and easily liberatable and complex cyanide (58.5 mg/kg and 12.1 mg/l). For some heavy metals (Zn, Hg, As, Cu and Pb), soil concentrations would be elevated for some land uses relative to the relevant Generic Assessment Criteria, although their groundwater concentrations were generally below the Drinking Water Standards and the Environmental Quality Standards (EQS).
5. Cyanide was found primarily in the low toxicity, complexed cyanide form. This finding was consistent with iron concentrations, which were found to exceed the concentrations of cyanide. This pattern has been reported to be common in FMGP sites. Hence, cyanide posed no risk and remediation was not required.
6. The spatial distribution of contaminants within the top soil was widespread across the site, reflecting the long and varied industrial history of the site. Dense non-aqueous phase liquid (DNAPL), accumulated within the alluvial gravel aquifer at three locations on-site, providing the main source for groundwater contamination. The spatial distribution of the contaminants of concern generally revealed elevated concentrations in groundwater towards the north-western edge of the site and slight increases towards the south-west boundary.
7. The microbiological survey revealed that a complex community of microorganisms capable of degrading a number of organic and inorganic (including easily liberatable and complex cyanide) contaminants was present throughout the site. Across the site total microbial counts within the groundwater ranged from 2.6×10^5 to 7.6×10^6 cells per ml. In general, the highest microbial populations were in areas of low organic pollution, indicating that elevated concentrations of organic contaminants produced a negative impact on the viability of microorganisms present on-site. Molecular community profiling also indicated differences in the microbial community structure associated with the concentration of contaminants, temporal (seasonal) variability, and 'free living' planktonic and 'attached' biofilm communities.

8. Due to the apparent difference between the microbial community associated with 'free-living' and attached niches, the importance of both groundwater and solid sample collection was required for the complete assessment of microorganisms on-site.
9. Microtox™ toxicity tests showed a correlation between toxicity and chemical characterisation. The groundwater toxicity data also correlated with the chemical characterisation data for the site. The Microtox™ assay indicated no toxicity was associated with groundwater obtained from BGBH 1, 3, 5, 9, 14, and TCBH 4, whilst BGBH 10, 11, and TCBH 2 were highly toxic. NAPL was also found to occur at these locations. This pattern allowed contaminated areas to be differentiated from uncontaminated areas.
10. PAH biodegradation was not restricted to areas of historical organic contamination, providing strong evidence for a significant reduction in the number of microbial samples required in future site investigations.
11. Based on the information gathered during the site characterisation, it was decided that remediation actions should be undertaken to mitigate the risk to local groundwater resources posed by high concentrations of PAHs and BTEX contaminants. The associated operational constraints posed by above and below ground installations prevent the use of many commonly used remediation strategies, such as excavation and disposal to landfill. The remediation option adopted consisted of a SEquential REactive BARrier (SEREBAR) whereby the priority pollutants are removed by a combination of biodegradation/sorption processes.
12. Treatability experiments on the degradation/sorption processes of typical priority organic pollutants of concern (BTEX, styrene and naphthalene) were carried out to assess the design of the SEREBAR system. Batch experiments on the biodegradation of BTEX, styrene and naphthalene using groundwater collected at the site showed that the half-life ($t_{1/2}$) varied in a range of 0.18-2.58 days.
13. The effect of increasing the concentration of BTEX, styrene and naphthalene on the microbial population was investigated. In general, $t_{1/2}$ values increased with BTEX, styrene and naphthalene load. However, when the concentration of contaminants was increased by a factor of 6 in relation to the original concentration, the degradation rates for BTEX, styrene and naphthalene were uppermost. The indigenous microbial populations were found to tolerate concentrations of BTEX, styrene and naphthalene up to 15 times more concentrated than the original contaminated groundwater. However, when the concentration of contaminants was increased above a factor of 10, the percentage of microorganisms unable to tolerate the contaminant load increased above those with the capability to survive.
14. Batch and column experiments also demonstrated that GAC was effective at removing BTEX, styrene and naphthalene through adsorption onto its surface. The sorption capacity for the individual contaminants was quantified from column experiments to be in the range of 0.18-11.27 mg/g.
15. Although the remediation of cyanide was not a required element of the design of the SEREBAR, experiments revealed that ZVI was effective in removing cyanide. Kinetic parameters were determined through column experiments and the $t_{1/2}$ was calculated to be between 0.44 hr and 1.17 hr.
16. Two pilot-scale bioreactors were constructed as a simulation of the proposed barrier. Using groundwater collected on-site, the monitoring of these systems demonstrated that they were capable of degrading BTEX, styrene and naphthalene to concentrations below

- the remedial target values agreed with the EA and Local Authority contaminated land officer.
17. A series of simulations of the site hydrology, applying varying configurations of the SEREBAR system, were modelled using Visual MODFLOW and MT3DMS. The evaluated alternatives assessed various gate(s) positions, lengths of slurry walls, and the use of gravel trench(es). Both backward and forward particle tracking methods were used to simulate the transport of contaminants. The preferred PRB configuration dictated one single gate and two slurry walls, acting as a funnel. The design also incorporated two abstraction wells upgradient of the reactive gate for a more efficient capture of the plume and two recharge wells downgradient of the reactive gate.
 18. The gate of the SEREBAR system was designed to be entirely below ground level and was composed of an interceptor and six steel canisters installed in series to remove contaminants through aerobic/anaerobic degradation and sorption processes sequentially.
 19. Groundwater was pumped into the interceptor via the abstraction wells. The implementation of abstraction wells, controlling groundwater flow through the barrier, allowed perturbations within the system to be assessed. Additionally, the use of submersible pumps removed the need for barrier installation to occur, thereby reducing installation costs.
 20. Following the installation of the SEREBAR, a monitoring programme was implemented to verify that the system was operating as designed. In general this monitoring was focused on the SEREBAR system, rather than the entire site. The programme was designed to verify proper installation of the system and identify its ability to deal with perturbations in groundwater flow / chemical load.
 21. Major ion chemistry, prior to entry into the interceptor of the SEREBAR, indicated that the major water chemistry was dominated by calcium bicarbonate with lesser but significant concentrations of sodium, potassium and sulphate. The data were consistent with the background chemistry for upgradient wells proximal to the SEREBAR, sampled prior to its installation.
 22. Under low flow rate conditions (320-520 L/d) and passive aeration within the interceptor, the removal of the EPA 16-PAHs occurred primarily within the interceptor (>92%). BTEX contaminants were also removed below detection limits within the interceptor. This was likely due both to the intrusion of air and the subsequent development of a microbial community capable of degrading the organic contaminants and to volatilisation of BTEX components. The passage of groundwater through the anaerobic zone (canisters S0 and S1) did not significantly decrease the concentration of the EPA 16-PAHs, but further passage through the artificially aerated zone (canisters S2 and S3) resulted in the almost complete removal of the residual PAHs (overall removal >99.5%). Prior to discharge and following passage through the sorption zone (GAC1 and GAC2 canisters) the concentration of the EPA 16-PAHs were further reduced to <0.01 µg/L (resulting in an overall removal of EPA 16-PAHs >99.9%).
 23. Under the initial conditions of low flow rate, the enumeration of viable heterotrophic bacteria and also those utilising naphthalene as the sole carbon source showed a general decrease in microbial numbers from inlet to outlet. All of the biodegradative microorganisms entering the SEREBAR originated from the same source (intercepted groundwater). However, the microbial community that developed within the canisters varied considerably.

24. Increasing the flow rate (1000-4000 L/d) and replacing the interceptor with a fully sealed unit minimised biodegradation within the interceptor. Both the EPA 16-PAHs and BTEX concentrations were reduced following flow through the anaerobic zone (removal <22%). Bioremediation within the aerated canisters accounted for the majority of removal (91% of the EPA 16-PAHs). Subsequent passage through the GAC sorption zone led to reduction prior to discharge. Similarly to the previous operational conditions, the overall removal of the EPA 16-PAHs and BTEX contaminants by the SEREBAR barrier was >99.9% and >95%, respectively.
25. Following the increase in groundwater flow rate and the replacement of the interceptor, an increase in microbial numbers present within the aerated zone (canisters S2 and S3) was observed. This was attributed to increased microbial transportation, as the result of flow rate, relocation of microorganisms initially present within the front end (canisters S0 and S1), and proliferation of microorganisms in new niches, due to the increased substrate availability and potential for aerobic degradation. It could also be due to the increased flux of nutrients.
26. Increases in CO₂ concentrations (up to 2% v/v) were indicative of microbial activity within the aerated canisters. This finding was consistent with both the EPA 16-PAHs and BTEX removal, and with the higher microbial populations associated with the aerated zone.
27. Water level monitoring confirmed that groundwater pumped from the abstraction well into the interceptor was flowing under gravity through the reactive canisters of the SEREBAR system.
28. Based on contaminant concentrations present within the groundwater, and the sorption capacity of the system (GAC), replacement of the sorptive reactive media after exhaustion will not be necessary for at least 10 years. The life expectancy of the PRB can also be affected by possible losses of porosity due to biomass growth, which can negatively impact the hydraulic performance of the system. Further monitoring will be conducted biannually to ensure the long-term performance of the SEREBAR system.
29. The remediation costs using the SEREBAR system totalled £1,584,010. This included the site characterisation costs, the design and the construction of the barrier, and the operation and maintenance costs for a period of 10 years. It is important to note that this project was research led and as such allowed optimization, investigation, demonstration and dissemination of the novel remediation process. Consequently the associated costs for future remedial works would be significantly reduced.
30. Dependent on site geology, hydrogeology, and the relative balance of installation and running costs the SEREBAR system is able to work under passive - installed beneath the water table, or semi-passive – installed underground but above the water table conditions (detailed in this report).
31. This research has demonstrated the first implementation, from the laboratory to the field scale, of a SEREBAR biological reactive barrier for *in situ* bioremediation of groundwater at a FMGP site. The SEREBAR system has the potential to address groundwater contamination at a variety of sites with a variety of complex contaminant plumes, provided that the contaminant plume is well defined. Through discussions with industrial stakeholders, it has been estimated that there are over 400 sites in the UK alone that could benefit from SEREBAR technology.

11. LESSONS LEARNED

The SEREBAR system is so far the first Sequenced Biologic Barrier Technology for the treatment of contaminated groundwater at a FMGP site in the UK. The SEREBAR project is thus presented as an innovative experience in the treatment of contaminated groundwater.

The following lessons learned are based on the installation and demonstration of the SEREBAR technology:

1. Both groundwater and solid sample collection was important in the assessment of microbial populations within the SEREBAR and would be equally informative in the assessment of any biodegradation-based *in situ* remediation process. Work further emphasised that bacterial communities present within the soil and groundwater are highly adaptable, possessing a latent ability to deal with most conditions. Controlled spiking of contaminants to previously uncontaminated site groundwater revealed the bioremediation of the contaminants. As a consequence of these findings, future site investigations could reduce the number of samples required for microbial analysis before a site can be deemed suitable for a potential bioremediation strategy.
2. Potentially, microbial toxicity assays enable a rapid and cost-effective screening process for contaminant samples, allowing the differentiation of contaminated and uncontaminated samples, and leading to a reduction in the number of samples sent for full chemical analysis.
3. Operating costs associated with energy consumption, when using a pump for groundwater transport to the inlet, as well as those associated with running a compressor for aeration, could be removed with the employment of alternative energy sources (e.g. solar and wind power).
4. The importance of adequate aeration for the rapid biodegradation of contaminants by microorganisms within the SEREBAR was highlighted. Using the information obtained from the model of flow through the SEREBAR, it is recommended that aeration is altered, from within the canisters to between them. This would avoid both hydraulic problems and also the disruption of the biofilm, caused during passage of the air bubbles through the sand.
5. The presence of the GAC treatment step (sorption) at the rear of the SEREBAR system allows sufficient time for the establishment and maturation of the biofilm to occur without requiring recirculation of the effluent. It also acts as a safeguard in case the biodegradation process fails for some reason.
6. Under low contaminant loadings, passive aeration, due to groundwater flow over the interceptor weir, was sufficient for the complete elimination of contaminants. The requirement of artificial aeration is consequently removed; however, this was only realistic at low contaminant loadings.
7. Due to a reduction in contaminant load during groundwater flow through the original interceptor (attributed to passive aeration, microbial degradation, and volatilisation), it was replaced with a fully sealed unit to prevent passive aeration and the flow rate was increased from 320-520 L/d to 1000-4000 L/d. These actions clearly led to a reduction in the degradation of organic contaminants within the interceptor and an increased capture of the plume towards the reactive canisters.

8. The microbial investigation carried out on this project has revealed that much of the genetic material, relevant to the degradation of contaminants, may be mobile between species (Horizontal Gene Transfer). This has suggested that it is the gene population, as much as the species population, which requires modelling.
9. The cells of the biofilm were more mobile than was expected and more so than is usually accounted for in traditional models. From this finding a new model was developed to account for their greater mobility and used to predict the operational life of the reactor bed prior to biofouling and a requirement for cleaning.
10. GAC sorption experiments indicated that as the profile of the organics present in the groundwater changes with time it is plausible that the content of very strongly adsorbed organics will increase. These may displace more weakly adsorbed organics and result in both premature breakthrough and indeed breakthrough at higher than inlet concentrations. This effect is termed "roll up".

12. GLOSSARY OF TERMS

Acclimation (acclimatisation)

A dynamic response describing the capacity of an organism to adapt and tolerate a new environment.

Activated carbon

A black, highly porous adsorbent material, produced by the roasting of cellulose based substances, such as wood or coconut shells, in the absence of air, which is then crushed into granules. Thanks to its porosity, structure and very large surface area, activated carbon provides high adsorption capacity for a broad range of contaminants. The activated carbon must be replaced periodically as it may become saturated and unable to absorb.

Aeration

The process whereby air enters in intimate contact with water with the result of increasing the dissolved oxygen content and/or removing the dissolved gases and volatile substances.

Aerobic

In the presence of oxygen. Contrast with anaerobic.

Air sparging

In situ remediation technology where air is pumped into the ground to aid in the removal of volatile substances and/or to enhance aerobic biodegradation.

Anaerobic

In the absence of oxygen. Contrast with aerobic.

Anoxic

Literally "without oxygen." An adjective describing a microbial habitat devoid of oxygen.

Aquifer

A subsurface geological formation whose pore spaces are filled primarily with water and is sufficiently permeable to transmit water to wells and springs.

Bentonite

A very fine clay, capable of expanding to several times its normal volume when moist, commonly used in slurry walls.

Biobarrier

PRB in which organic or inorganic contaminants are biologically degraded or transformed. The biological process(es) may occur passively or may be enhanced by adding an electron acceptor or donor or nutrients.

Biodegradation

Breakdown, or destruction, of organic contaminants by microbial organisms into smaller compounds. Biodegradation processes vary greatly, but frequently the final product of the degradation is carbon dioxide or methane. Biodegradation is a key process in the mitigation of contaminants at hazardous waste sites. A related term is biotransformation.

Bioremediation

Process by which living organisms act to degrade or transform hazardous organic contaminants.

BTEX

An acronym for benzene, toluene, ethylbenzene and xylenes, a group of toxic, volatile aromatic compounds that are commonly found in crude oil and some petroleum products.

Chemotaxis

The movement of a microorganism or cell in response to a chemical stimulus.

Commissioning

The process during which systems and components of the PRB, having been constructed, are made operational and verified to be in accordance with the design and to have met the required performance criteria.

Conductivity

With regards to water quality refers to the amount of ionized substances in the water and is a numerical expression of the ability of an aqueous solution to convey an electric current. It is also an approximate indicator of total dissolved ions.

Confined aquifer

Aquifer in which the water is confined under pressure beneath impermeable or relatively impermeable materials.

Contaminants of Concern

Specific chemicals (usually the most hazardous ones) at a site that are chosen to be evaluated through a Risk Assessment. Some categories of chemicals, such as PAHs or VOCs, have dozens of individual constituents. Instead of evaluating each one, a few are chosen to represent the hazards posed by the whole group.

Downgradient

Direction toward an area of lower hydraulic head than point of origin, or point of interest.

Electron acceptor

In microbiology terms, compound undergoing reduction (accepting electrons) during cellular respiration. Oxygen usually serves as the final electron acceptor (aerobic respiration), but in its absence other species (such as nitrate or sulphate) can act as electron acceptors (anaerobic respiration).

Electron donor

In microbiology terms, compound undergoing oxidation (giving electrons) during cellular respiration, resulting in the release of energy. Organic compounds (such as petroleum hydrocarbons) can act as electron donors and, therefore, be biodegraded by microorganisms.

Former manufactured gas plant (FMGP)

Workplace for the production of gas from either coal or oil. FMGPs provided a local source of fuel for lighting, cooking and heating for residential and commercial consumers before the introduction of natural gas through the national gas transmission system. Although not currently in operation, many of them have left behind a legacy of impacted soil and groundwater at former locations.

Groundwater

Subsurface water, especially that found in the saturated zone below the water table or in aquifers, which supplies wells and springs.

Head

Head is the energy of a body of water produced by elevation, at a given pressure and temperature. In hydrologic terms, total head is the sum of the elevation head, the pressure head, and the velocity head at a given point in an aquifer. Fluids flow down a hydraulic gradient, from points of higher to lower hydraulic head

Hydraulic conductivity (K)

A measure of the capacity of an aquifer to transmit water, expressed in terms of velocity.

Hydraulic gradient

The change in total head with a change in distance in a given direction.

Hydrocarbons

A large group of chemicals containing carbon and hydrogen atoms. The carbon atoms may be arranged in a chain (aliphatic hydrocarbons) or in one or more six-atom rings (aromatic hydrocarbons). Hydrocarbons are generally associated with petroleum products (heating oil, gasoline, kerosene, asphalt, etc.), coal tars, creosote etc.

In situ remediation

Treatment of contamination at the site, in place, without removing it to another location.

Microtox™ test

In vitro bioassay that provides a rapid, and relatively inexpensive, assessment of chemical toxicity of a given test sample. It is based on the reaction of luminescent microorganisms to contaminants present in the sample. The organism used is *Vibrio fischeri*, a naturally occurring, non-pathogenic marine bacterium which gives off light as a byproduct of metabolic processes involved in its cellular respiration. Reduction in light output is generally proportional to the biological impact of the contaminated sample.

Monitoring wells

Specially constructed wells used exclusively for obtaining samples for testing water quality and for monitoring water levels.

Non-aqueous phase liquid (NAPL)

A chemical that does not dissolve well in water, typically an organic solvent. Dense non-aqueous phase liquids (DNAPLs) have a density greater than water. Light non-aqueous phase liquids (LNAPLs) have a density less than water. NAPLs, particularly DNAPLs can contaminate groundwater creating large underground plumes that persist for very long periods.

Oxidation-reduction potential (redox)

The loss (oxidation) and gain (reduction) of electrons by reactants expressed as electrical potential, Eh (volts)

Polycyclic aromatic hydrocarbons (PAHs)

Hydrocarbon compounds with multiple benzene rings. Typical components of fuels, oils, asphalts, greases, and coal tars, they are of environmental concern due to their persistence and toxicity. Several members are carcinogens.

Permeability

The capacity of rock or soil to transmit a fluid, usually water.

Permeable Reactive Barrier (PRB)

Engineered treatment zone of reactive material(s) that is placed in the subsurface in order to remediate contaminated groundwater as it flows through it.

Plume

A body of contaminated groundwater that extends from the source of contamination to another point in the direction of the groundwater flow.

Porosity

The ratio of the voids or open spaces in a material through which water or air can move.

Quality Assurance and Quality Control (QA/QC)

Systematic actions, procedures, checks, audits, and corrective actions applied to ensure that all research design and performance, environmental monitoring and sampling, field and laboratory analyses, and other technical and reporting activities satisfy given requirements for quality.

Recalcitrant

Resistant to biodegradation.

Slurry wall

Engineered subsurface structure that acts as an impermeable barrier to limit the lateral flow of groundwater. There are a number of construction techniques. At the SEREBAR site the slurry wall was formed by the single phase method; a trench was excavated to the required depth and during excavation a slurry of blast furnace slag, cement and bentonite clay was pumped into the trench to fill the excavation. The slurry was then left in the trench to set and harden to form a low permeability cut-off material.

Sorption

A phenomenon by which contaminants are taken from water and adhered onto (adsorption) or incorporated into (absorption) the physical structure of another solid. The term sorption is often used when the specific mechanism is not known.

Total Petroleum Hydrocarbon (TPH)

Term used to refer to the measurable amount of petroleum-based hydrocarbons present in a sample. The fraction includes a broad family of several thousand or more chemical compounds, and since its analysis does not distinguish between different constituents, the TPH value represents a mixture of chemicals.

Toxicity

Quantification of the degree of danger posed by a substance to animal, plant or microbial life.

Treatability study

Short-term investigation of how a particular technology will remediate a contaminated matrix. It will often run for several weeks or months.

Unconfined aquifer

An aquifer that is not bounded by an overlying layer of distinctly lower permeability (i.e. the upper layer or water table is at atmospheric pressure).

Upgradient

Direction toward an area of greater hydraulic head than point of origin, or point of interest.

Volatile Organic Compounds (VOCs)

Organic liquids, including many common solvents, that readily evaporate at temperatures normally found at ground surface and at shallow depths. Examples of volatile organic compounds include BTEXs.

Volatilization

Process of transfer of a chemical from the aqueous or liquid phase to the gas phase. Solubility, molecular weight, and vapour pressure affect the rate of volatilization.

Water table

The top of an unconfined aquifer where water pressure is equal to atmospheric pressure.

Well

A bored or drilled vertical excavation in the surface of the earth for the purpose of reaching underground water supplies to inject, extract or monitor water.

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APPENDICES

APPENDIX 1. SUMMARY OF ANALYTICAL RESULTS FOR SOIL ON THE WHOLE SITE

Determinand	No. of tests	Concentration (mg/kg)			
		Min.	Max.	Mean.	Median
pH	170	1.70	11.35	8.00	8.40
Cresols	170	0.10	116.70	5.64	0.40
Xylenols & Ethylphenols	170	0.10	141.30	6.55	0.30
Naphthols	170	0.10	24.00	1.69	0.40
Phenol	170	0.10	21.90	1.40	0.30
Trimethylphenol	170	0.10	32.60	3.18	0.55
Total Phenols	170	0.50	316.40	15.73	1.80
Naphthalene	170	0.50	13661.50	268.12	1.50
Acenaphthylene	170	0.60	4814.00	73.02	2.15
Acenaphthene	170	0.50	4313.20	77.38	2.50
Fluorene	170	0.50	13010.40	150.18	2.40
Phenanthrene	170	0.50	5496.50	108.84	6.70
Anthracene	170	0.50	31173.40	899.70	10.70
Fluoranthene	170	0.50	14244.60	203.76	8.20
Pyrene	170	0.50	12142.70	177.48	8.00
Benzo(a)anthracene	170	4.10	2373.60	191.76	18.00
Chrysene	170	0.60	15049.90	280.92	18.40
Benzo(b)fluoranthene & Benzo(k)fluoranthene	170	0.50	5653.70	75.44	4.60
Benzo(a)pyrene	170	0.50	2719.30	44.09	3.20
Indeno(1,2,3-cd)pyrene & Di-benzo(a,h.)anthracene	170	0.50	1535.20	31.55	2.43
Benzo(g,h,i.) Perylene	170	0.50	715.70	13.67	1.70
Total PAH	170	0.60	121217.00	1239.43	39.00
10 Dutch PAH	170	0.00	83218.10	828.08	22.50
Easily Liberatable Cyanide	170	1.03	559.69	15.48	2.37
Complex Cyanide	170	1.01	570.92	52.02	7.80
Total Cyanide	170	1.01	786.41	58.48	8.77
Elemental Sulphur	170	11.57	106395.66	3698.25	311.54
Water Soluble Sulphate	170	104.63	12155.85	944.88	250.27
Water Soluble Chloride	170	10.17	245.97	22.47	19.21
Exchangeable Ammonium	170	5.05	285.08	27.93	14.16
Arsenic	170	1.24	133.15	19.54	16.17
Cadmium	170	0.50	3.27	0.94	0.70
Chromium	170	1.54	79.43	17.76	16.25
Lead	170	3.09	3233.57	194.58	58.06
Mercury	170	0.21	13.73	0.88	0.41
Selenium	170	0.50	9.05	1.20	0.91
Copper	170	2.23	368.97	46.08	28.26
Nickel	170	1.90	100.72	35.73	34.20
Zinc	170	4.79	1249.45	105.26	82.82
Boron	170	0.53	6.25	1.18	0.99
Benzene	170	0.10	5.17	2.63	2.63
Toluene	170	0.08	8.96	2.42	0.33
Ethylbenzene	170	0.13	4.40	1.57	0.87
Xylene	170	0.07	26.95	4.87	0.62
Anthanthrene	170	0.50	244.70	8.58	1.30
Benzo(e)pyrene	170	0.50	1938.70	39.38	3.00
Catechol	170	0.10	10.70	1.67	0.30
Resorcinol	170	0.10	2.00	0.59	0.20
Total Petroleum Hydrocarbons	170	10.08	6706.42	915.69	325.35

APPENDIX 2.SUMMARY OF ANALYTICAL RESULTS FOR GROUNDWATER ON THE WHOLE SITE

Determinand	No of samples	Concentration (mg/L)			
		Min.	Max.	Mean	Median
pH	57	6.50	9.20	7.46	7.50
TOC	57	2.00	58.78	11.88	8.34
Suspended Solids	57	110.00	32210.00	5636.96	1855.00
Conductivity (µS/cm)	57	324.00	9600.00	1076.02	786.00
Cresols	57	0.00	0.24	0.07	0.03
Xylenols & Ethylphenols	57	0.00	0.82	0.17	0.02
Naphthols	57	0.00	0.25	0.04	0.01
Phenol	57	0.00	0.07	0.02	0.01
Trimethylphenol	57	0.00	1.51	0.25	0.15
Total Phenols	57	0.00	2.62	0.42	0.08
Naphthalene	57	0.00	0.14	0.03	0.01
Acenaphthylene	57	0.00	0.07	0.02	0.00
Acenaphthene	57	0.00	0.01	0.00	0.00
Fluorene	57	0.00	0.04	0.01	0.00
Phenanthrene	57	0.00	0.08	0.01	0.00
Anthracene	57	0.00	0.02	0.00	0.00
Fluoranthene	57	0.00	0.01	0.01	0.00
Pyrene	57	0.00	0.01	0.00	0.00
Benzo(a)anthracene	57	0.00	0.00	0.00	0.00
Chrysene	57	0.00	0.01	0.01	0.01
Benzo(b)fluoranthene & Benzo(k)fluoranthene	57	0.00	0.00	0.00	0.00
Benzo(a)pyrene	57	0.00	0.00	0.00	0.00
Indeno(1,2,3-cd)pyrene & Di-benzo(a,h.)anthracene	57	0.00	0.00	0.00	0.00
Benzo(g,h,i.) Perylene	57	0.00	0.01	0.01	0.01
Total PAH	57	0.00	0.38	0.04	0.01
Easily Liberatable Cyanide	57	0.50	2.10	0.93	0.55
Complex Cyanide	57	0.90	55.60	11.45	2.65
Total Cyanide	57	0.90	57.70	12.07	3.20
Thiocyanate	57	0.60	0.80	0.70	0.70
Elemental Sulphur	57	10.46	1115.83	259.36	45.92
Sulphate	57	13.61	779.25	131.01	70.28
Sulphide	57	0.00	0.00	0.00	0.00
Chloride	57	8.00	44.99	22.25	21.45
Total Ammonium	57	0.01	287.52	21.19	0.95
Arsenic	57	0.01	0.60	0.08	0.02
Cadmium	57	0.00	0.00	0.00	0.00
Chromium	57	0.01	0.03	0.02	0.02
Lead	57	0.02	0.08	0.05	0.07
Mercury	57	0.00	0.00	0.00	0.00
Selenium	57	0.05	0.05	0.05	0.05
Copper	57	0.01	0.25	0.09	0.02
Nickel	57	0.01	0.19	0.03	0.01
Zinc	57	0.01	0.18	0.05	0.06
Iron	57	0.03	40.70	2.54	0.52
Total Petroleum Hydrocarbons	57	0.15	44.60	6.09	1.87
Anthanthrene	57	0.00	0.00	0.00	0.00
Benzo(e)pyrene	57	0.00	0.00	0.00	0.00
Catechol	57	0.00	0.08	0.01	0.00
Resorcinol	57	0.00	0.04	0.02	0.01
Nitrate	57	6.00	46.80	14.40	9.83
Low Level Easily Liberatable Cyanide	57	0.01	54.38	1.48	0.02
Low Level Complex Cyanide	57	0.01	56.25	1.36	0.09
Low Level Total Cyanide	57	0.01	1.88	0.21	0.09



Job No. : BEN40102F/100.1
 Site Name :
 Client : Lattice Property Holdings

Record of Borehole **BGBH2**

Easting	292079.5	Start date	24/10/2000
Northing	91551.7	End date	24/10/2000
Ground level	7.69m AOD	Backfill date	24/10/2000
Final depth	9.00m	Page	1 of 1

Parsons Brinckerhoff Ltd, Queen Victoria House, Redland Hill, Redland, Bristol BS6 6US Tel. 0117-873-9090 Fax. 0117-823-7479

Progress				Samples & Testing				Strata				
Date	Hole	Casing	Water	Depths		Type	Field Record	Legend	Depth (Thickness)	Level m AOD	Strata Descriptions	Standpipe
				From	To							
				0.60	0.60	D			(1.30)		MADE GROUND comprising brown to black silty sand with abundant fragments of brick, concrete and Tarmacadam.	
				1.40	1.40	D			1.30 (0.30) 1.60	6.39 6.09	MADE GROUND comprising (stiff) orange to brown clay with few small subangular to angular gravel.	
				2.00	2.00	D			(1.30)		Brown silty SAND with abundant small to medium sized subrounded to rounded gravel.	
				4.00	4.00	D			2.60 (2.10)	4.79	Small to large rounded to subangular GRAVEL in a little sandy matrix.	
				4.50 4.5								
				5.00	5.00	D			5.00	2.69	(Stiff to very stiff - becoming moderately weak to weak below 7.5mbgl) dark red angular GRAVEL in a clayey matrix.	
				5.80	6.00	D			(4.00)			
									9.00	-1.31		

Diameters			General remarks				Equipment and Methods	
Depth (m)	Hole (mm)	Casing (mm)						
			1. Water strike at 4.5mbgl. 2. Installation details: Plain pipe GL-2.5mbgl Slotted pipe 2.5-5.5mbgl Bentonite GL-2.0mbgl, 5.5-9.0mbgl Gravel 2.0-5.5mbgl. 3. Borehole terminated in dry breccia. 4. Strong diesel odour to approximately 6.5mbgl. 5. No sample from 7.5mbgl to 9.0mbgl due to casing.				Pioneer	
Groundwater								
Depth struck	After 20 mins	Depth sealed	Notes: All dimensions in metres unless otherwise stated				Drilled by: Geotechnical	
4.50	4.50						Checked by:	

Issue 1 0/001



Job No. : BEN40102F/100.1
 Site Name
 Client : Lattice Property Holdings

Record of Borehole BGBH3			
Easting	292309.7	Start date	24/10/2000
Northing	91460.1	End date	24/10/2000
Ground level	7.96m AOD	Backfill date	24/10/2000
Final depth	6.50m	Page	1 of 1

Parsons Brinckerhoff Ltd, Queen Victoria House, Redland Hill, Redland, Bristol BS6 6US Tel. 0117-973-9080 Fax. 0117-823-7479

Progress				Samples & Testing				Strata				
Date	Hole	Casing	Water	Depths		Type	Field Record	Legend	Depth (Thickness)	Level m AOD	Strata Descriptions	Standpipe
				From	To							
				1.00	1.50	D		(1.00)	6.96	MADE GROUND comprising brown sandy silt with abundant whole bricks and half bricks and fine to medium sized concrete gravel.		
				1.60	2.50	D		(0.25) 1.25 (0.31) 1.56	6.71 6.40	MADE GROUND comprising red sand with abundant fine gravel.		
				2.90	4.00	D		(1.44)	4.96	MADE GROUND comprising (soft to firm) black very sandy clay with occasional medium sized gravel and some clay fragments at base. Moderate hydrocarbon odour. (Soft to firm) light brown SILT.		
				3.70	3.7			(1.00)	3.96	Light brown very sandy fine to medium sized GRAVEL becoming more sandy with depth.		
								(0.25) 4.00 4.25	3.71	White QUARTZ boulders. Light brown sandy GRAVEL.		
				5.50	6.50	D		(2.25)	1.46			

Diameters			General remarks 1. Borehole hand-dug to 1.0mbgl. 2. Water strike at 3.70mbgl. 3. Installation details: Plain pipe 0.0-3.0mbgl Slotted pipe 3.0-5.5mbgl Bentonite GL-3.0mbgl, 5.5-6.5mbgl Gravel 3.0-5.5mbgl.				Equipment and Methods	
Depth (m)	Hole (mm)	Casing (mm)					Dynamic sampling	
Groundwater			Notes: All dimensions in metres unless otherwise stated				Drilled by:	Geotechnical
Depth struck	After 20 mins	Depth sealed					3.70	3.70
Checked by:						Logged by:		

TABLE 10101



Record of Borehole **BGBH4**

Job No. : BEN40102F/100.1

Site Name

Client : Lattice Property Holdings

Easting	292110.6	Start date	25/10/2000
Northing	91609.5	End date	25/10/2000
Ground level	7.72m AOD	Backfill date	25/10/2000
Final depth	5.80m	Page	1 of 1

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Progress				Samples & Testing			Strata				Standpipe	
Date	Hole	Casing	Water	Depths		Type	Field Record	Legend	Depth (Thickness)	Level m AOD		Strata Descriptions
				From	To							
				1.00	1.00	D			(2.20)		MADE GROUND comprising sand with many fragments of brick and concrete and some whole bricks. Concrete slab at 0.75mbgl, blue stained concrete and blue sandy patches becoming clayey from 1.3mbgl with fragments of coke and coal. Strong coal tar odour.	
				2.50	2.50	D			2.20 (0.30) 2.50 (0.30) 2.80	5.52 5.22 4.92	MADE GROUND comprising concrete rubble Brown to orange coarse sandy GRAVEL. Gravel is fine to coarse and rounded. Black coarse sandy GRAVEL. Gravel is fine to coarse and rounded. Very strong diesel odour becoming stronger towards base, free phase visible on gravel surface.	
			▼	3.24 3.4 3.50	3.50	D			(2.60)			
				5.30	5.40	D			5.40 (0.40)	2.32	(Firm to stiff) red CLAY. Moderate coal tar odour.	
				5.80	5.80	D			5.80	1.92		

<table border="1"> <thead> <tr> <th colspan="3">Diameters</th> </tr> <tr> <th>Depth (m)</th> <th>Hole (mm)</th> <th>Casing (mm)</th> </tr> </thead> <tbody> <tr> <td></td> <td></td> <td></td> </tr> </tbody> </table>			Diameters			Depth (m)	Hole (mm)	Casing (mm)				<p>General remarks</p> <p>1. Water strike at 3.42mbgl. 2. Trial pit hand dug to 1.0mbgl. 3. Installation details: plain pipe 0.0-2.2mbgl slotted pipe 2.2-5.6mbgl BentoniteGL-2.0mbgl, 5.6-5.8mbgl Gravel 2.0-5.6mbgl.</p> <p>Notes: All dimensions in metres unless otherwise stated</p>	<p>Equipment and Methods</p> <p>Dynamic sampling</p>
Diameters													
Depth (m)	Hole (mm)	Casing (mm)											
<table border="1"> <thead> <tr> <th colspan="3">Groundwater</th> </tr> <tr> <th>Depth struck</th> <th>After 20 mins</th> <th>Depth sealed</th> </tr> </thead> <tbody> <tr> <td>3.24</td> <td>3.42</td> <td></td> </tr> </tbody> </table>			Groundwater			Depth struck	After 20 mins	Depth sealed	3.24	3.42			
Groundwater													
Depth struck	After 20 mins	Depth sealed											
3.24	3.42												
			<p>Drilled by: Geotechnical</p> <p>Checked by: <i>[Signature]</i></p> <p>Logged by: EB</p>										

Issue 1 01/01



Job No. : BEN40102F/100.1
 Site Name :
 Client : Lattice Property Holdings

Record of Borehole		BGBH5	
Easting	292250.9	Start date	26/10/2000
Northing	91429.4	End date	26/10/2000
Ground level	8.16m AOD	Backfill date	26/10/2000
Final depth	5.70m	Page	1 of 1

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Progress				Samples & Testing				Strata				
Date	Hole	Casing	Water	Depths		Type	Field Record	Legend	Depth (Thickness)	Level m AOD	Strata Descriptions	Standpipe
				From	To							
									(1.00)		Grass over MADE GROUND comprising brown very sandy silt with fine to coarse gravel, concrete gravels and rare fragments of clinker.	
				1.10	2.00	D			1.00 (0.10)	7.16	CONCRETE HARDSTANDING	
									1.10 (0.90)	7.08	MADE GROUND comprising (soft to firm) light brown clay with occasional fine to medium sized gravel, black silty sand at 1.25mbgl, occasional brick fragments, patches of yellow cemented sand and rare fragments of clinker and bands of black sandy silt. Moderate diesel odour.	
									2.00 (0.80)	6.16	MADE GROUND comprising pink to red fine to medium gravel.	
				3.00	3.30	D			2.80 (0.20)	5.36	MADE GROUND comprising (soft to firm) light brown clay with occasional gravel.	
									3.00 (1.00)	5.16	Light brown SAND with abundant fine gravel.	
				4.00	5.40	D			4.00	4.16	Light brown sandy GRAVEL. Slight petrol odour.	
				4.30					(1.40)			
				4.3					5.40 (0.30)	2.76	(Very stiff) red sandy CLAY.	
				5.40	5.70	D			5.70	2.46		

<table border="1"> <thead> <tr> <th colspan="3">Diameters</th> </tr> <tr> <th>Depth (m)</th> <th>Hole (mm)</th> <th>Casing (mm)</th> </tr> </thead> <tbody> <tr> <td></td> <td></td> <td></td> </tr> </tbody> </table>			Diameters			Depth (m)	Hole (mm)	Casing (mm)				General remarks 1. Borehole hand-dug to 1.0mbgl. 2. Standing groundwater at 4.3mbgl. 3. Installation details: Plain pipe 0.0-3.2mbgl Slotted pipe 3.2-5.5mbgl Bentonite GL-3.0mbgl, 5.5-5.7mbgl Gravel 3.0-5.5mbgl.	Equipment and Methods Dynamic sampling
Diameters													
Depth (m)	Hole (mm)	Casing (mm)											
<table border="1"> <thead> <tr> <th colspan="3">Groundwater</th> </tr> <tr> <th>Depth struck</th> <th>After 20 mins</th> <th>Depth sealed</th> </tr> </thead> <tbody> <tr> <td>4.30</td> <td>4.30</td> <td></td> </tr> </tbody> </table>			Groundwater			Depth struck	After 20 mins	Depth sealed	4.30	4.30			
Groundwater													
Depth struck	After 20 mins	Depth sealed											
4.30	4.30												
Notes: All dimensions in metres unless otherwise stated													

Checked by: Drilled by: Geotechnical
 Logged by: SP

Issue 1 01/01

Job No. : BEN40102F/100.1
Site Name
Client : Lattice Property Holdings

Easting	292170.3	Start date	25/10/2000
Northing	91674.4	End date	25/10/2000
Ground level	7.48m AOD	Backfill date	25/10/2000
Final depth	5.50m	Page	1 of 1

Progress				Samples & Testing				Strata				
Date	Hole	Casing	Water	Depths		Type	Field Record	Legend	Depth (Thickness)	Level m AOD	Strata Descriptions	Standpipe
				From	To							
									(0.20)	7.28	MADE GROUND comprising medium sized angular gravel in some sandy matrix above tarmacadam hardstanding and brick layer.	
									(1.40)		Dark brown black ashy silty sand with fine to coarse gravel and brick fragments	
									1.60	5.88		
									(0.40)		Dark brown silty SAND with brick cobbles and fine to coarse gravel. Strong diesel odour.	
									2.00	5.48		
				2.40	2.40	D			(0.50)		(Soft) light brown CLAY with some black gravel and much black mottling. Strong diesel odour.	
				2.50	2.50	D			2.50	4.98		
									(0.30)		Dark brown SAND with black gravel. Sand layer at 2.7-2.8 mbgl. Strong diesel odour.	
									2.80	4.68		
									(2.20)		Black sandy GRAVEL. Gravel is small to medium sized and rounded. Very strong tarry odour.	
				4.00	4.00	D						
				4.32								
				4.3								
				4.60	4.70	D						
				4.80	4.90	D						
									5.00	2.48		
									(0.50)		(Firm to stiff) dark red CLAY with occasional sand bands and rare angular gravel. Slight coal tar odour.	
									5.50	1.98		

Diameters			General remarks 1. Borehole terminated at 5.5mbgl. 2. Water strike at 4.32mbgl. 3. Borehole closed with bentonite.	Equipment and Methods Dynamic sampling
Depth (m)	Hole (mm)	Casing (mm)		
Groundwater			Notes: All dimensions in metres unless otherwise stated	Drilled by: Geotechnical Checked by:  Logged by: EB
Depth struck	After 20 mins	Depth sealed		
4.32	4.32			

Job No. : **BEN40102F/100.1**
 Site Name :
 Client : **Lattice Property Holdings**

Easting	292199.9	Start date	26/10/2000
Northing	91548.5	End date	26/10/2000
Ground level	8.06m AOD	Backfill date	26/10/2000
Final depth	5.40m	Page	1 of 1

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Progress				Samples & Testing			Strata				Standpipe	
Date	Hole	Casing	Water	Depths		Type	Field Record	Legend	Depth (Thickness)	Level m AOD		Strata Descriptions
				From	To							
				1.00	2.00	D			(1.00)	7.06	MADE GROUND comprising brown sandy silt with abundant angular gravel.	
									(0.10)	6.96	MADE GROUND comprising brown to black very gravelly sand with occasional black clinker	
									(0.60)	6.36	MADE GROUND comprising fine to medium concrete gravel	
				2.00	2.10	D			(0.30)	6.06	MADE GROUND comprising white fine to medium sized angular gravel with abundant clinker in a fine to coarse yellow sandy matrix	
				2.10	2.35	D			(0.10)	5.96	MADE GROUND comprising white fine to medium sized angular gravel with abundant clinker in a fine to coarse yellow sandy matrix	
				2.35	3.10	D			(0.25)	5.71	MADE GROUND comprising white concrete gravel	
									(0.75)		MADE GROUND comprising (firm to stiff) brown black sandy clay with silt patches. Slight diesel odour.	
				3.10	3.15	D			(0.05)	4.96	MADE GROUND comprising orange to red gravel with clayey patches and occasional diesel staining	
				3.15	3.30	D			(0.15)	4.76	CONCRETE HARDSTANDING	
				3.60	5.00	D			(0.30)	4.46	MADE GROUND comprising white and black concrete gravel and sand. Slight diesel odour	
									(1.40)		CONCRETE holder base 0.30m thick	
				5.00	5.40	D			(0.40)	3.06	Black sandy GRAVEL. Moderate to strong diesel odour	
									(0.40)	2.66	(Very stiff) red sandy CLAY.	

Diameters Depth (m) Hole (mm) Casing (mm)			General remarks 1. Borehole hand-dug to 1.0mbgl. 2. Borehole closed with bentonite from 5.4-0.5mbgl.	Equipment and Methods Dynamic sampling
Groundwater Depth struck After 20 mins Depth sealed				
Notes: All dimensions in metres unless otherwise stated				
Checked by: <i>[Signature]</i>			Drilled by: Geotechnical	Logged by: SP



Job No. : BEN40102F/100.1

Site Name

Client : Lattice Property Holdings

Record of Borehole BGBH8

Easting	292163.1	Start date	25/10/2000
Northing	91663.4	End date	26/10/2000
Ground level	7.50m AOD	Backfill date	26/10/2000
Final depth	5.50m	Page	1 of 1

Parsons Brinckerhoff Ltd., Queen Victoria House, Redland Hill, Redland, Bristol BS6 6US, Tel. 0117-873-9090 Fax. 0117-823-7479

Progress				Samples & Testing				Strata				Standpipe	
Date	Hole	Casing	Water	Depths		Type	Field Record	Legend	Depth (Thickness)	Level m AOD	Strata Descriptions		
				From	To								
				1.00	1.00	D			(0.25) 0.25 (0.75)	7.25	MADE GROUND comprising medium sized angular gravel in some sandy matrix above tarmacadam hardstanding and brick layer.		
									1.00 (0.30) 1.30	6.50 6.20	MADE GROUND comprising dark brown to black ashy sand with much fine to coarse gravel and brick, coke and coal fragments. Slight hydrocarbon odour.		
				2.00	2.00	D			(1.20)			MADE GROUND comprising light brown to yellow sand with cobble sized fragments of brick and fine gravel.	
									2.50	5.00		(Soft to firm) brown CLAY with large black patches. Strong diesel odour.	
				3.00	3.00	D			(1.50)			Black sandy GRAVEL. Product leaving yellowgreen stain.	
				3.20									
				3.4									
				4.00	4.00	D			4.00	3.50		Black sandy GRAVEL. Gravel is medium sized and rounded. Tar product.	
				4.80	4.90	D			(1.00)				
				5.00	5.00	D			5.00	2.50		(Very stiff) red sandy CLAY.	
									(0.50)				
									5.50	2.00			

Diameters Depth (m) Hole (mm) Casing (mm)			General remarks 1. Water strike at 3.2mbgl falling to 3.42mbgl overnight. 2. Borehole closed with bentonite.	Equipment and Methods Dynamic sampling
Groundwater Depth struck After 20 mins Depth sealed				
3.20 3.42				
Notes: All dimensions in metres unless otherwise stated			Drilled by: Geotechnical	Checked by:
			Logged by: EB	

Issue 1 01/01

Job No. : BEN40102F/100.1
 Site Name
 Client : Lattice Property Holdings

Record of Borehole BGBH9

Easting	292184.2	Start date	30/10/2000
Northing	91724.0	End date	30/10/2000
Ground level	7.76m AOD	Backfill date	30/10/2000
Final depth	5.50m	Page	1 of 1

Parsons Brinckerhoff Ltd, Queen Victoria House, Redland Hill, Redland, Bristol BS6 6US Tel. 0117-973-9090 Fax. 0117-923-7479

Progress				Samples & Testing				Strata				
Date	Hole	Casing	Water	Depths		Type	Field Record	Legend	Depth (Thickness)	Level m AOD	Strata Descriptions	Standpipe
				From	To							
				1.00	1.00	D			(1.00)	6.76	MADE GROUND comprising concrete over hardcore of brick and limestone, black fine to medium coal and clinker gravel and red to brown silty sandy gravel with occasional brick fragments	
				1.00	1.25				(0.25)	6.51	MADE GROUND comprising (soft to firm) red occasionally black very clayey silt with occasional medium sized clinker gravel	
				1.75	1.75	D			(0.75)			
				2.00	2.00	D				5.76	(Soft to firm) brown to black very sandy SILT with occasional black coaly patches becoming slightly clayey with depth	
				2.6								
				2.58								
				3.00	3.00	D					Yellow to brown sandy GRAVEL.	
									(2.75)			
				5.00	5.00	D			4.75	3.01	(Very stiff) red sandy CLAY.	
									(0.75)			
										2.26		

<table border="1"> <thead> <tr> <th colspan="3">Diameters</th> </tr> <tr> <th>Depth (m)</th> <th>Hole (mm)</th> <th>Casing (mm)</th> </tr> </thead> <tbody> <tr> <td> </td> <td> </td> <td> </td> </tr> </tbody> </table>			Diameters			Depth (m)	Hole (mm)	Casing (mm)				General remarks 1. Borehole hand-dug to 1.0mbgl. 2. Water strike at 2.55mbgl. 3. Installation details: Plain pipe 0.0-2.3mbgl Slotted pipe 2.3-4.8mbgl Bentonite GL-2.15mbgl, 5.5-4.70mbgl Gravel 2.15-4.7mbgl.	Equipment and Methods Dynamic sampling
Diameters													
Depth (m)	Hole (mm)	Casing (mm)											
<table border="1"> <thead> <tr> <th colspan="3">Groundwater</th> </tr> <tr> <th>Depth struck</th> <th>After 20 mins</th> <th>Depth sealed</th> </tr> </thead> <tbody> <tr> <td>2.58</td> <td>2.55</td> <td> </td> </tr> </tbody> </table>			Groundwater			Depth struck	After 20 mins	Depth sealed	2.58	2.55			
Groundwater													
Depth struck	After 20 mins	Depth sealed											
2.58	2.55												
Notes: All dimensions in metres unless otherwise stated													
Checked by: 		Drilled by: Geotechnical Logged by: SP											



Job No. : BEN40102F/100.1
 Site Name :
 Client : Lattice Property Holdings

Record of Borehole **BGBH10**

Easting	292157.6	Start date	30/10/2000
Northing	91497.5	End date	30/10/2000
Ground level	7.99m AOD	Backfill date	30/10/2000
Final depth	7.30m	Page	1 of 1

Parsons Brinckerhoff Ltd, Queen Victoria House, Keeloland Hill, Keeloland, Bristol BS30 8JG. Tel: 0117 973 9090 Fax: 0117 973 7479

Progress				Samples & Testing				Strata				
Date	Hole	Casing	Water	Depths		Type	Field Record	Legend	Depth (Thickness)	Level m AOD	Strata Descriptions	Standpipe
				From	To							
				1.00	1.00	D			(0.10) 0.10	7.89	CONCRETE HARDSTANDING MADE GROUND comprising brick sub-base with tarmacadam layer over dark brown silty sandy gravel with many brick and tarmac fragments, coal and concrete cobbles at base.	
									(1.70)			
									1.80	6.19	MADE GROUND comprising dark brown coarse sandy gravel. Gravel is medium to coarse rounded to sub-rounded with rare quartzite cobbles and black staining at base.	
									(1.60)			
									3.40	4.59	(Soft) dark brown SILT with black staining and some rounded gravel.	
				4.00	4.00	D			(0.90)			
				4.90 4.9 5.00	5.00	D			4.30	3.69	Black coarse sandy GRAVEL. Moderate hydrocarbon odour.	
									(2.50)			
				6.00	6.00	D			6.80	1.19	(Firm to stiff) red SILT/CLAY with occasional grey sandy patches. Slight odour.	
				6.60	6.60	D			(0.50)			
				7.00	7.00	D			7.30	0.69		

Diameters			General remarks 1. Borehole hand-dug to 1.0mbgl. 2. Installation details: Plain pipe 0.0-4.4mbgl Slotted pipe 4.4-7.1mbgl Bentonite GL-4.4mbgl, 7.1-7.3mbgl Gravel 4.4-7.1mbgl.	Equipment and Methods Dynamic sampling
Depth (m)	Hole (mm)	Casing (mm)		
Groundwater			Notes: All dimensions in metres unless otherwise stated	Checked by:
Depth struck	After 20 mins	Depth sealed		
4.90	4.90			Logged by: EB

Issue 1 01/01



Job No. : BEN40102F/100.1
 Site Name :
 Client : Lattice Property Holdings

Record of Borehole **BGBH11**

Easting	292174.8	Start date	30/10/2000
Northing	91691.9	End date	30/10/2000
Ground level	7.39m AOD	Backfill date	30/10/2000
Final depth	5.30m	Page	1 of 1

PARSONS BRINCKERHOFF LTD, SUITE 1 VICTORIA CROSS, NEWBURY MILL, NEWBURY, DISTRICT OF SOUTH OXFORD, OX5 1JF, OXFORD, OX5 1JF

Progress				Samples & Testing				Strata				Standpipe
Date	Hole	Casing	Water	Depths		Type	Field Record	Legend	Depth (Thickness)	Level m AOD	Strata Descriptions	
				From	To							
									(1.00)	6.39	MADE GROUND comprising (soft) black very sandy silt with abundant brick and half brick fragments.	
				1.50	1.50	D			(1.10)	5.29	MADE GROUND comprising (soft) black very fine sandy clay with occasional gravel. Very strong coal tar odour.	
				1.5					2.10		Black sandy GRAVEL. Strong coal tar odour.	
				2.50	2.50	D			(1.90)			
				3.00	3.00	D			4.00	3.39	(Soft) black CLAY.	
				4.50	4.50	D			(0.60)			
				4.65	4.65	D			4.60	2.79	Black SANDY GRAVEL.	
									(0.20)	2.59	(Very stiff) red sandy CLAY becoming highly compact sand with large pockets of reduced iron and some seeping of black contamination.	
				5.30	5.30	D			4.80			
									(0.50)	2.09		
									5.30			

Diameters Depth (m) Hole (mm) Casing (mm)			General remarks 1. Borehole hand-dug to 1.0mbgl. 2. Groundwater at 1.5mbgl with some DNAPL at 4.6-4.8mbgl. 3. Installation details: Plain pipe 0.0-2.3mbgl Slotted pipe 2.3-4.8mbgl Bentonite GL-2.20mbgl, 4.85-5.3mbgl Gravel 2.2-4.85mbgl.	Equipment and Methods Dynamic sampling
Groundwater Depth struck After 20 mins Depth sealed				
1.50 1.50				
Notes: All dimensions in metres unless otherwise stated			Checked by:	Drilled by: Geotechnical Logged by: SP

Issue 1 01/01



Record of Borehole **BGBH12**

Job No. : BEN40102F/100.1
 Site Name
 Client : Lattice Property Holdings

Easting	292190.7	Start date	30/10/2000
Northing	91706.8	End date	30/10/2000
Ground level	7.63m AOD	Backfill date	30/10/2000
Final depth	1.70m	Page	1 of 1

Parsons Brinckerhoff Ltd, Queen Victoria House, Redland Hill, Redland, Bristol BS6 6US Tel. 0117-973-9090 Fax. 0117-923-7479

Progress				Samples & Testing			Strata					
Date	Hole	Casing	Water	Depths		Type	Field Record	Legend	Depth (Thickness)	Level m AOD	Strata Descriptions	Standpipe
				From	To							
				1.00	1.00	D			(0.65) 0.05 (0.95)	7.58	CONCRETE HARDSTANDING	
									1.00	6.63	MADE GROUND comprising red to brown to black very sandy gravelly silt with abundant whole and half brick fragments, occasional fragments of concrete and tiles and patches of red sand and gravel.	
									(0.70) 1.70	5.93	MADE GROUND comprising red to brown to black very sandy gravelly silt with whole and half brick fragments, occasional fragments of concrete and tiles and patches of red sand. Gravel becoming more sandy and gravelly with depth.	

<table border="1"> <tr> <th colspan="3">Diameters</th> </tr> <tr> <th>Depth (m)</th> <th>Hole (mm)</th> <th>Casing (mm)</th> </tr> <tr> <td> </td> <td> </td> <td> </td> </tr> </table>			Diameters			Depth (m)	Hole (mm)	Casing (mm)				General remarks 1. Refusal at 1.7mbgl. 2. Borehole closed with bentonite.	Equipment and Methods dynamic sampling
Diameters													
Depth (m)	Hole (mm)	Casing (mm)											
<table border="1"> <tr> <th colspan="3">Groundwater</th> </tr> <tr> <th>Depth struck</th> <th>After 20 mins</th> <th>Depth sealed</th> </tr> <tr> <td> </td> <td> </td> <td> </td> </tr> </table>			Groundwater			Depth struck	After 20 mins	Depth sealed					
Groundwater													
Depth struck	After 20 mins	Depth sealed											
Notes: All dimensions in metres unless otherwise stated			Checked by: <i>[Signature]</i>	Drilled by: Geotechnical Logged by: SP									

Issue 1 01/01



Job No. : BEN40102F/100.1
 Site Name
 Client : Lattice Property Holdings

Record of Borehole **BGBH13**

Easting	292189.6	Start date	01/11/2000
Northing	91664.6	End date	01/11/2000
Ground level	7.33m AOD	Backfill date	01/11/2000
Final depth	4.20m	Page	1 of 1

Parsons Brinckerhoff Ltd, Queen Victoria House, Redland Hill, Redland, Bristol BS6 6US Tel. 0117-973-9090 Fax. 0117-923-7479

Progress				Samples & Testing			Strata			Standpipe			
Date	Hole	Casing	Water	Depths		Type	Field Record	Legend	Depth (Thickness)		Level m AOD	Strata Descriptions	
				From	To								
									(0.08) 0.08 (1.12)	7.25	TARMACADAM HARDSTANDING (Soft) black very fine sandy SILT with occasional gravel.		
									1.20 (0.10) 1.30 (0.50) 1.80 (0.20) 2.00	6.13 6.03 5.53 5.33	Black sandy GRAVEL (Soft) light brown mottled dark brown to black slightly silty CLAY. (Soft) grey to brown mottled sandy SILT.		
									(1.15)	3.15	4.18	Brown to black fine to medium sub-rounded to sub-angular GRAVEL in some of a coarse sandy silt matrix. Black colouration of gravel with tar odour from 2.7mbgl.	
									(1.05)	4.20	3.13	Black medium sized very angular to sub-angular GRAVEL in very coarse sandy matrix. Very strong tar odour and free product.	

<table border="1"> <thead> <tr> <th colspan="3">Diameters</th> </tr> <tr> <th>Depth (m)</th> <th>Hole (mm)</th> <th>Casing (mm)</th> </tr> </thead> <tbody> <tr> <td> </td> <td> </td> <td> </td> </tr> </tbody> </table>			Diameters			Depth (m)	Hole (mm)	Casing (mm)				General remarks 1. Borehole hand-dug to 1.2mbgl. 2. Borehole flooded at 0.5mbgl. 3. No samples due to poor sample return and casing jammed in borehole. 4. Borehole closed with bentonite.	Equipment and Methods Dynamic sampling
Diameters													
Depth (m)	Hole (mm)	Casing (mm)											
Groundwater													
Depth struck	After 20 mins	Depth sealed											
			Notes: All dimensions in metres unless otherwise stated	Drilled by: Geotechnical Logged by: TG									
			Checked by:										

Issue 1 01/01



Record of Borehole **BGBH14**

Job No. : BEN40102F/100.1
 Site Name
 Client : Lattice Property Holdings

Eastings	292219.2	Start date	01/11/2000
Northing	91685.5	End date	01/11/2000
Ground level	6.99m AOD	Backfill date	01/11/2000
Final depth	5.50m	Page	1 of 1

Parsons Brinckerhoff Ltd., Queen Victoria House, Redland Hill, Redland, Bristol BS6 6US Tel. 0117-973-9080 Fax. 0117-923-7479

Progress				Samples & Testing				Strata				
Date	Hole	Casing	Water	Depths		Type	Field Record	Legend	Depth (Thickness)	Level m AOD	Strata Descriptions	Standpipe
				From	To							
										6.89	TARMACADAM HARDSTANDING	
									0.10		MADE GROUND comprising (very soft) dark brown silt with abundant small to large angular to sub-angular gravel and abundant fragments of brick and coke with some clinker and coal.	
									1.20	5.79	(Soft) light to mid brown very fine SILT.	
				1.50	1.50	D			(0.55)			
				1.75					1.75	5.24		
									(0.05)	5.19	Brown very coarse SAND with occasional small to medium rounded gravel.	
									1.80	5.09	Fine silty CLAY.	
									(0.10)		Brown small to medium sized sub-angular to rounded GRAVEL with some black inclusions in much of a sandy silt matrix.	
				3.20	3.20	D			1.90			
									(1.30)		Brown small to medium sub-rounded to rounded occasionally angular GRAVEL in some coarse sandy matrix.	
				3.7					3.20	3.79		
									(1.00)			
									4.20	2.79	(Firm to stiff) light brown SILT with few small rounded gravel.	
									(0.20)	2.59	(Very stiff) brown to red purple CLAY.	
				4.80	4.80	D			4.40			
									(1.10)			
									5.50	1.49		

Diameters			General remarks			Equipment and Methods		
Depth (m)	Hole (mm)	Casing (mm)	1. Borehole hand-dug to 1.2mbgl. 2. Installation details: Plain pipe GL-2.5mbgl Slotted pipe 2.5-4.5mbgl Bentonite GL-2.2mbgl, 4.5-5.5mbgl Gravel 2.2-4.5mbgl.			Dynamic sampling		
Groundwater			Notes: All dimensions in metres unless otherwise stated			Drilled by: Geotechnical Logged by: TG		
Depth struck	After 20 mins	Depth sealed						
1.75	3.70							
			Checked by: <i>[Signature]</i>					

Issue 1 01/01