TECHNOLOGY DEMONSTRATION PROJECT REPORT: TDP20

DESIGN AND INSTALLATION OF A PERMEABLE REACTIVE BARRIER TO TREAT CARBON DISULPHIDE-CONTAMINATED GROUNDWATER

CONTAMINATED LAND: APPLICATIONS IN REAL ENVIRONMENTS

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

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DESIGN AND INSTALLATION OF A PERMEABLE REACTIVE BARRIER TO TREAT CARBON DISULPHIDE-CONTAMINATED GROUNDWATER

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This is a CL:AIRE Technology Demonstration Report. Publication of this report fulfils CL:AIRE's objective of disseminating and reporting on remediation technology demonstrations. This report is a detailed case study of the application of a permeable reactive barrier to remediate carbon disulphide. It is not a definitive guide to the application of permeable reactive barrier technology. CL:AIRE strongly recommends that individuals/organisations interested in using this technology retain the services of experienced environmental professionals.

EXECUTIVE SUMMARY

This project describes experience in the design, implementation and operation of a full-scale reactive iron permeable reactive barrier (PRB) for the treatment of groundwater contaminated with carbon disulphide (CS_2). This was the first application of zero-valent iron for the treatment of CS_2 and one of the few full-scale PRB implementations to date in the UK.

The site is a former chemicals manufacturing facility located in Stretford, Greater Manchester, and was inherited by Akzo Nobel in 1998. The principal chemical manufactured at the site over a 50-year period was CS_2, which was also the principal contaminant at the site.

Of primary concern was the presence of dense non-aqueous phase liquid (DNAPL) CS_2 in the sand aquifer and residual CS_2 in the unsaturated zone. A secondary concern was the presence of a small dissolved plume of CS_2, carbon tetrachloride (CCl_4) and the latter's primary biodegradation product, chloroform ($CHCl_3$), in the shallow sand aquifer.

The purpose of the PRB was to reduce the concentration of dissolved CS_2 in the shallow groundwater to a concentration that is protective of the identified downgradient controlled water receptors, whilst ensuring that there are no significant effects on regional groundwater flow. The evaluation, design and implementation of the system was undertaken in accordance with the Environment Agency's guidance, and the principal design specifications for the PRB system were to:

- Achieve at least a 90% reduction in the dissolved CS_2 concentrations crossing the site boundary having passed through the gates over the design lifetime;
- Have a mechanical design life of 20 years;
- Be suitable for monitoring the effectiveness of CS_2 remediation;
- Provide a robust, maintainable system, which may be cost-effectively decommissioned; and
- Have minimal environmental impacts other than the positive impact on the groundwater.

Hydrogeological modelling was used to establish the optimum location and extent of the "funnel" walls to ensure capture of the contaminant plume, whilst minimising the quantity of uncontaminated groundwater entering the system. It was also essential to ensure that future groundwater levels on the site would not have adverse consequences. A transient MODFLOW model was built for the pre-development conceptual model. The calibrated model of the current site was then used as the basis for developing a predictive model to simulate groundwater flow through the PRB.

A laboratory test programme was undertaken to determine the kinetics and degradation rate of CS_2, to confirm that no unacceptable degradation intermediates were formed and to provide design data. Column treatability tests were performed using site groundwater shipped to the laboratory. The objectives of the tests were to determine whether CS_2 was degraded under conditions of flow and whether the presence of other contaminants interfered with this. It was apparent from the laboratory based treatability studies that the proposed PRB technology would be effective in the degradation of the CS_2 from the groundwater at the site. Reactive iron was proven through laboratory tests to degrade CS_2, with half-lives varying from 0.35 to 2.63 hours at 23^oC, corrected to 0.63 to 4.63 hours at the ambient groundwater temperature of 12^oC.

The PRB met its key objective: it produced an effective remediation performance. The western PRB is efficiently removing CS_2 within the first reactor, resulting in concentrations below detection limit in the second vessel. Very little contamination presently reaches the eastern of the two gates.

This application was the first PRB used to successfully treat groundwater containing CS_2 (and lesser amounts of co-contaminants). Knowledge gained through this demonstration should improve confidence and aid uptake of this kind of solution at other sites elsewhere in the world where CS_2 is the main contaminant.

ACKNOWLEDGEMENTS

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ABBREVIATIONS

a-FeOOH	Goethite
AOD	Above Ordnance Datum
AWC	Available Water Capacity
BGS	British Geological Survey
CCl_4	Carbon Tetrachloride
CDM	Construction Design & Management (Regulations)
CEL	CEL International (formerly Courtaulds Engineering)
$CHCl_3$	Chloroform
Connelly GPM	Connelly (Gas Purifying Materials) Inc.
COS	Carbonyl Sulphide
CS_2	Carbon Disulphide
DNAPL	Dense Non-Aqueous Phase Liquid
E&RS	Environmental and Remediation Services Ltd (a member of the CEL International Group)
EA	Environment Agency
EDS	Euro Dismantling Services Ltd
EP	Effective Precipitation
ESI	Environmental Simulations International
ETI	EnviroMetal Technologies Inc
Fe_3O_4	Magnetite
$FeCO_3$	Siderite
FeOOH	Lepidocrocite
GC	Gas Chromatography
GC-MS	Gas Chromatography Mass Spectrometry
GIS	Geographic Information System
HSE	Health & Safety Executive
ICP-OES	Inductively Coupled Plasma - Optical Emission Spectroscopy
KGE	Keller Ground Engineering
m/d	metres per day
m/s	metres per second
m^3/s	metres cubed per day
mg/l	milligrams per litre
MIP	Membrane Interface Probe
ml/min	millilitre per minute
MNA	Monitored Natural Attenuation
MORECS	Met Office Rainfall and Evaporation Calculation System
PRB	Permeable Reactive Barrier
QUB	Queen's University Belfast
SEM	Scanning Electrode Microscopy
SEM-EDX	Scanning Electrode Microscopy - Energy Dispersive X-ray
TDP	Technology Demonstration Project
TDS	Total Dissolved Solids
VOC	Volatile Organic Compound
XRD	X-ray Diffraction
ZVI	Zero-Valent Iron

1. INTRODUCTION

1.1 SETTING THE SCENE

This project describes experience in the design, implementation and operation of a full-scale reactive iron Permeable Reactive Barrier (PRB) for the treatment of groundwater contaminated with carbon disulphide (CS_2). It was the first application of zero-valent iron for the treatment of CS_2 and was one of the few full-scale PRB implementations to date in the UK.

The PRB system was installed as part of the project to remediate the former Akzo Nobel site situated off Barton Dock Road, Stretford, Greater Manchester. The Barton Dock Road site (Figure 1.1) was the site of the manufacture of chemicals for approximately 50 years and has been redeveloped for office use. The principal chemical manufactured at the site was CS_2, produced by the reaction of sulphur with natural gas in the presence of a catalyst, which is generally used to manufacture viscose rayon and cellophane, or as a solvent for fats, rubber, resins and waxes. Carbon tetrachloride was also produced for a period of six years by the direct chlorination of CS_2. Contamination was present on the site as a result of historic operations with CS_2 being the predominant contaminant.

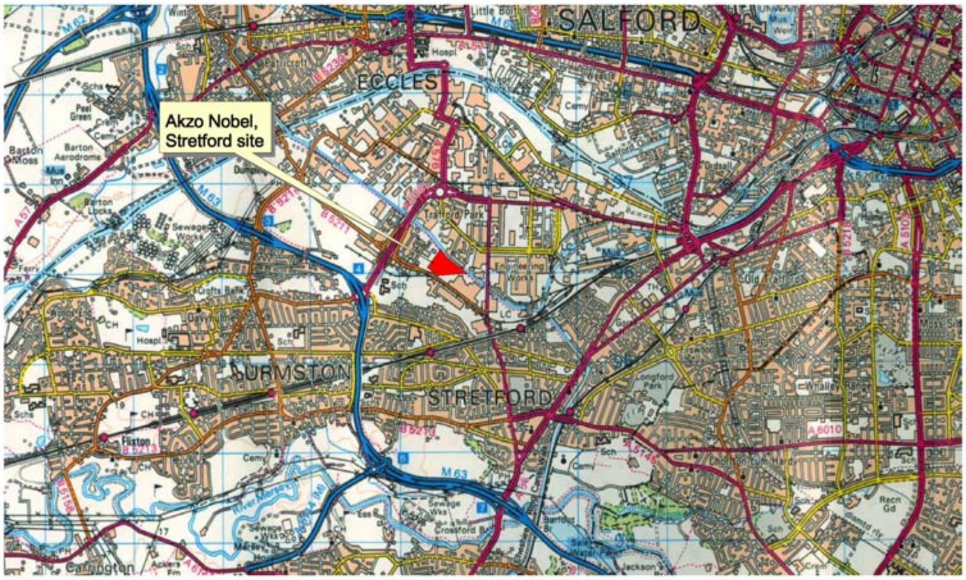

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Figure 1.1: Site location

CS_2 is a highly volatile and very flammable liquid, having a low flash point and a very wide explosive range (Table 1.1). Mixtures of CS_2 with air are highly explosive, being easily ignited by relatively low temperature sources, friction, compression and shock. In its pure state, it is clear and colourless but commercial products often have an unpleasant mercaptan-type odour and a yellowish colour. Material that has been in the ground will be black due to dissolution of soil organic matter and highly odorous.

A detailed site investigation programme and risk assessment had been performed voluntarily and was agreed by the local authority (Trafford Metropolitan Borough Council) and the Environment Agency. Some parts of the site were found to be contaminated with CS_2, including local areas of dense non-aqueous phase liquid (DNAPL). A significant area of placed waste was identified, which comprised a wide variety of site-derived materials.

Table 1.1. Physical properties of CS_2 (taken from Courtaulds Chemicals, 1998).

Physio-Chemical Property	**Value**
Density	1262 kg/m^3 at 20°C
Solubility in water	0.2% w/w at 20°C
Odour	Pure CS_2 virtually odourless Aged CS_2 has strong mercaptan odours
Boiling point	46°C
Flashpoint (closed cup)	-30°C
Autoignition temperature	80 – 102^{o}C
Ignition energy	0.010 - 0.015 mJ
Explosive limits	0.6 - 60 vol % in air

1.2 REMEDIATION OBJECTIVES & TECHNOLOGY SELECTION

Detailed quantitative risk assessment (DQRA) identified that remediation of CS_2 contamination was required to protect both human health receptors following redevelopment and ensure long-term protection of off-site sewers, a nearby stream and, ultimately, the Manchester Ship Canal. In addition, remediation of the areas impacted by waste material was necessary to enable construction and eliminate potential future human health risks.

The overall remediation strategy comprised:

- Removal of significant areas of CS_2 DNAPL by bentonite stabilisation of contaminated soil then excavation, prior to disposal to an authorised landfill;
- Excavation and removal of former waste materials deposited in one region of the site; and
- Remediation of shallow groundwater to reduce the off-site migration of dissolved CS_2 arising from minor residual soil contamination.

The remedial scheme was developed following a detailed evaluation of technology options. The evaluation was undertaken to identify technologies capable of achieving the specified remedial objectives and the following additional objectives:

- Capable of operation to meet the highest standards of health and safety, taking the specific hazardous properties of CS_2 into account;
- Minimum risk of significant detrimental effect on the wider environment;
- Minimum risk of nuisance odour complaints;
- Practicality of treatment;
- Cost-effectiveness and proportionality; and
- Ability to meet reasonable timescales to permit site redevelopment.

The primary emphasis was to treat the contamination source where technically and economically feasible.

The first stage of technology evaluation was the identification of potential remediation technologies for subsurface CS_2 contamination. Identified technologies were then subjected to a two stage ranking process:

1. A weighted screening process considering technical, environmental, safety and economic factors. Any technology that was demonstrably unsafe was automatically excluded from further consideration. The four top ranked options were taken forward for detailed consideration.

2. A more detailed examination of the proposed techniques was undertaken, including reference to laboratory test work on unproven techniques (where available) and order of magnitude cost estimates.

The outcome of the screening and detailed examination processes indicated that the overall and additional objectives would be best fulfilled by a combination of removal of the source, and installation of a PRB to treat the residual plume within the shallow groundwater. The overall remediation strategy is shown in Figure 1.2, with the remediation of the residual contamination through the application of a PRB being the focus of this report.

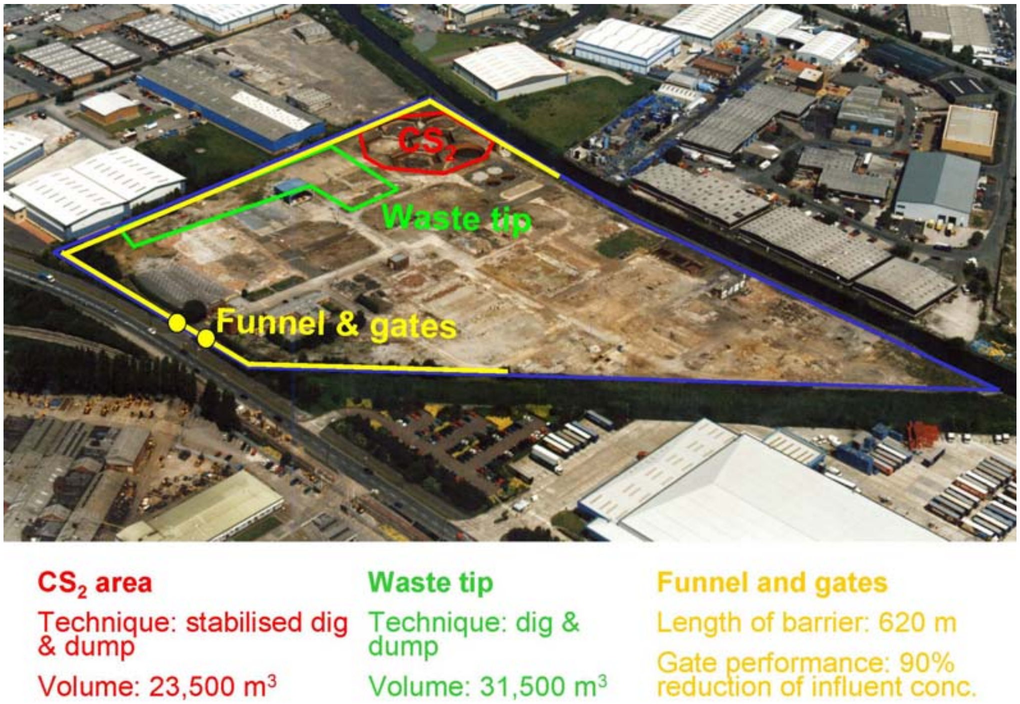


Figure 1.2: Overall Remediation Strategy

1.3 BACKGROUND TO TECHNOLOGY DEVELOPMENT

A PRB is an engineered treatment zone placed in the ground to remediate contaminated groundwater as it flows through. PRBs offer an effective treatment of a wide variety of contaminants yet result in minimal above-ground disturbance and have negligible overall effect on regional groundwater behaviour.

PRBs can be designed in a variety of configurations, depending on the contaminants to be treated, the layout of the area requiring remediation and the requirements of the land user(s). An example is provided in Figure 1.3. Although the detailed design will vary from site to site, two basic types of PRB can be recognised:

- Funnel-and-gate™: contaminated groundwater is directed to a permeable reactive zone by impermeable barriers; and
- Continuous wall: a reactive treatment zone is placed in the subsurface across the complete flow path of the contaminated groundwater.

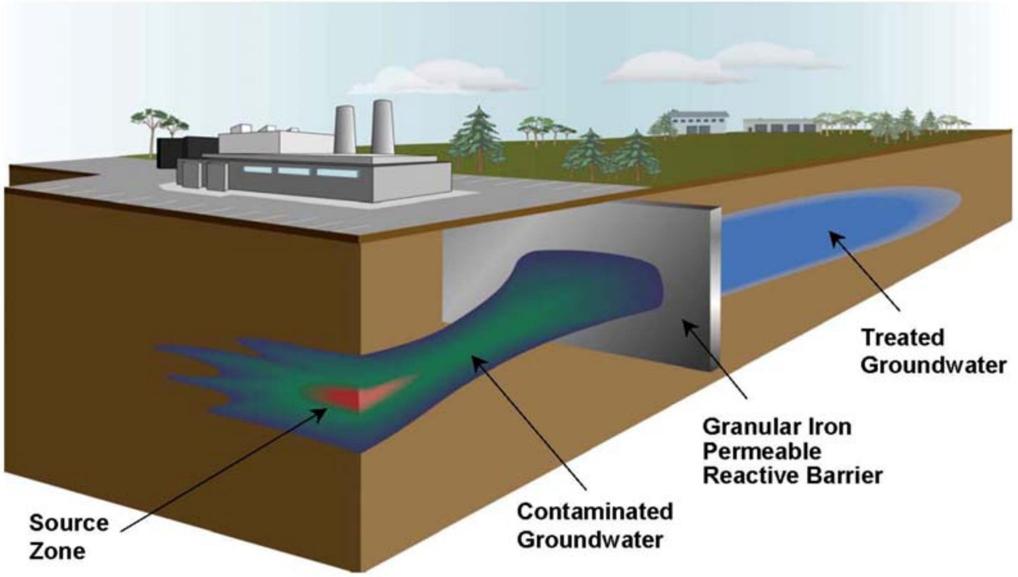


Figure 1.3: Example of a PRB (Source: EnviroMetal Technologies Inc.)

The use of different reactive media within the reactive zone of a PRB allows the treatment of a wide variety of groundwater contaminants, either alone or in combination, such as chlorinated solvents, petroleum hydrocarbons including polycyclic aromatic hydrocarbons (PAHs), phenols, cyanide, nitrate and heavy metals.

Due to their long history of operation in the USA, mainland Europe and elsewhere in the world (e.g. Japan), PRBs are recognised by regulatory authorities as an effective groundwater treatment technology. Their installation and use is underpinned by regulatory guidance in many locations, including the UK. PRBs can offer many advantages as a remediation technology, including technical efficiency and generation of innocuous end products, as well as being easy to maintain and monitor.

A PRB containing zero-valent iron to treat CS_2 had not been used before and, at the time, there were relatively few full-scale PRB implementations in the UK.

1.4 DESIGN OBJECTIVES OF PROPOSED PRB

The purpose of the PRB was to reduce dissolved CS_2 concentrations in the shallow groundwater, whilst ensuring that there was no significant effect on regional groundwater flow. The PRB was designed to:

- Achieve a 90% reduction of dissolved influent CS_2 concentrations from between up and downstream of the gates over their design lifetime (maximum envisaged influent concentration is approximately 100 mg/l). The treatment targets were specified to ensure no significant impact upon off-site receptors and eliminate any perception that “harm” could be caused by any residual dissolved CS_2;
- Have a mechanical design life of 20 years;
- Be suitable for monitoring to determine the effectiveness of CS_2 remediation and hence the treatment duration;

- Provide a robust maintainable system, which could be cost-effectively decommissioned; and
- Minimal environmental impacts other than the positive impact on the groundwater.

Although trace concentrations of other contaminants were present, particularly carbon tetrachloride (CCl_4) and chloroform ($CHCl_3$), these were only considered within the design as competing reactants. Discussions with the Environment Agency regarding the remedial objectives for the site concluded that monitored natural attenuation would be an acceptable strategy for the management of these low concentration contaminants, and this monitoring programme was therefore linked to monitoring of the PRB.

The installation commenced in April 2004 and was completed in December 2004.

The project team for these works comprised:

- CEL International Limited (‘CEL’), supported by dedicated staff from ESI Limited (‘ESI’), as Client’s Agent for the remediation programme;
- Euro Dismantling Services Limited (‘EDS’) as principal contractor for site remediation;
- A dedicated team of ESI staff responsible for hydrogeological modelling; and
- Queen’s University, Belfast (‘QUB’) responsible for laboratory trials and interpretation of results (QUB holds the worldwide patent for the use of reactive iron PRBs for the treatment of CS_2).

The applicability and design of the proposed PRB was evaluated using the Environment Agency’s guidance on PRBs (Figure 1.4) to:

- Confirm the viability of the technology for this application;
- Evaluate the site characterisation data to provide the necessary design information;
- Prepare a preliminary design, including choice of reactive medium;
- Prepare a preliminary implementation plan;
- Commence development of a monitoring programme to validate the design and monitor performance; and
- Develop a decommissioning plan for the system.

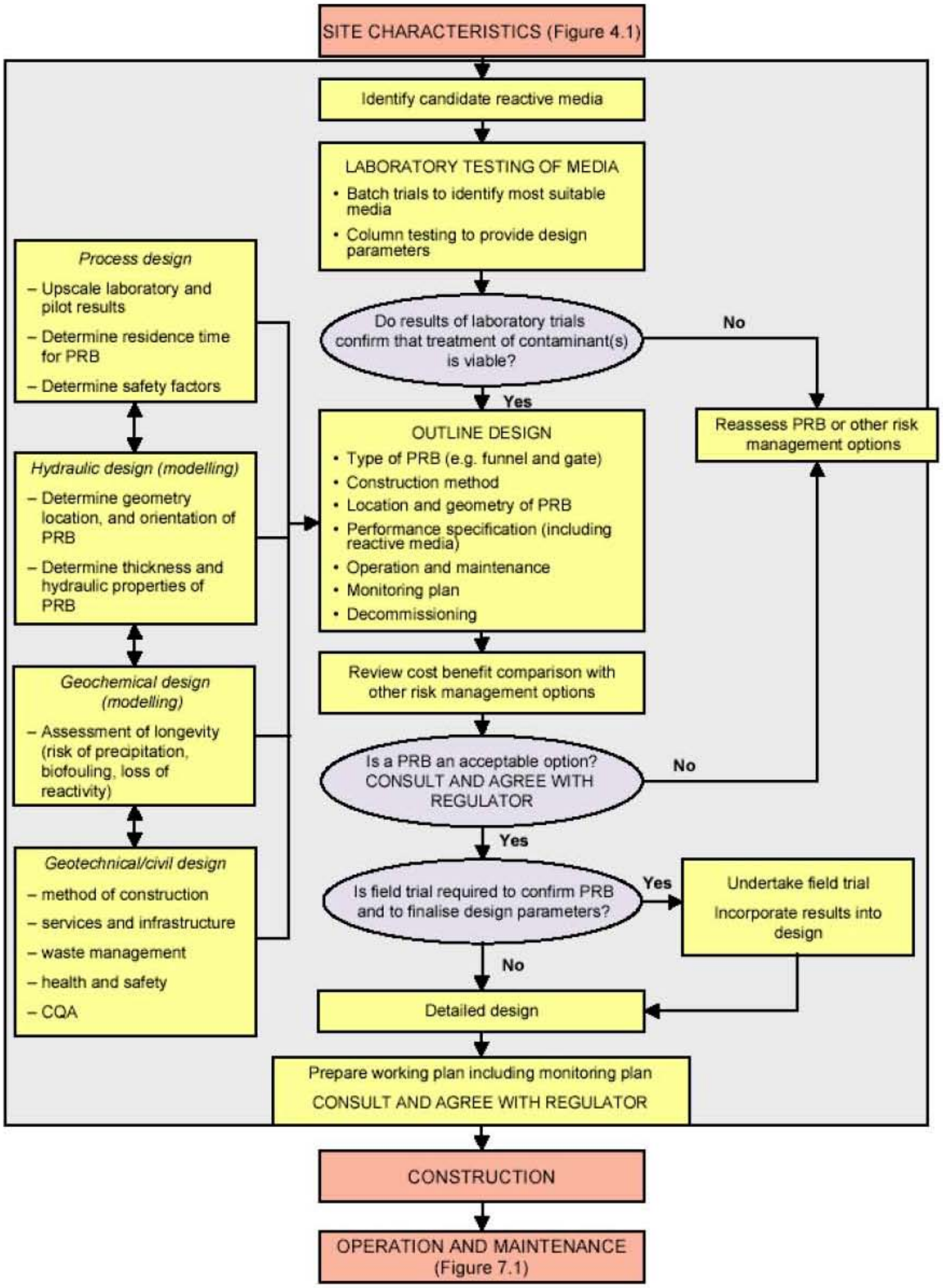


Figure 1.4: Design process for PRB (Source: Modified from Environment Agency, 2002)

The programme of work comprised:

- A laboratory treatability study to determine rates of CS_2 degradation, degradation products and potential gate performance under the site groundwater conditions;
- Hydrogeological modelling to determine the appropriate PRB configuration and the effect of this on local groundwater flow;
- Process design of the gate system to enable detailed technical assessment and preliminary design of the gate layout and constructability; and
- Preliminary specification of monitoring and decommissioning.

1.4 REPORT ORGANISATION

The project has been peer-reviewed and approved by CL:AIRE as a Technology Demonstration Project (TDP), and therefore the report has been written up as such. It is the intention of both Akzo Nobel and the project team to share learning from the various phases of the laboratory, design and implementation programmes to improve the uptake of PRB technology, to improve future projects and identify key areas of uncertainty that require further evaluation.

This report provides a description of the site, including history, condition and details of the contamination concerned. There is information on how the project was structured and organised, which includes contractual agreements between parties; health, safety and security implications; and regulatory compliance. The main part of the report details the experience of designing, operating and monitoring of the full-scale PRB, from initial planning, laboratory trials to commissioning and monitoring programme. The monitoring results from the first year's operation are presented and discussed. Finally, the project is evaluated against economic considerations, and conclusions are drawn regarding lessons learned and the PRB technology's applicability for future use for CS_2 treatment.

2. SITE DESCRIPTION

2.1 LOCATION

The former Akzo Nobel site occupied an area of approximately 7 hectares located off Barton Dock Road, Stretford, Greater Manchester, approximately 5.5 km south west of Manchester city centre (Figure 1.1), National Grid Reference SJ 784962. The site was situated in an industrial area with no residential or recreational areas in the close vicinity. Most of the site buildings and structures had already been demolished at the time of the project.

2.2 HISTORICAL INFORMATION

The site was formerly used to manufacture chemicals including CS_2, CCl_4 and fine organic sulphur chemicals. Originally the primary raw materials included sulphur, methane, chlorine and carbon briquettes.

Five CS_2 storage tanks were constructed in the north western corner of the site, located on a bunded concrete area (Plates 2.1a and 2.1b). CS_2 was also stored on a daily basis in three additional storage tanks, located on a bunded area to the north east of the site, along the canal boundary. A lagoon provided a reservoir for water used in the storage of CS_2 (for safety reasons, bulk CS_2 is stored under water within the tanks). This lagoon was constructed such that any free-phase CS_2 could be removed from the base. It was understood that leakage from the lagoon had been discovered and that the lagoon had since been repaired during site operation. CS_2 contaminated water was treated prior to discharge to the Davyhulme sewers.

Plate 2.1a: Site during operation

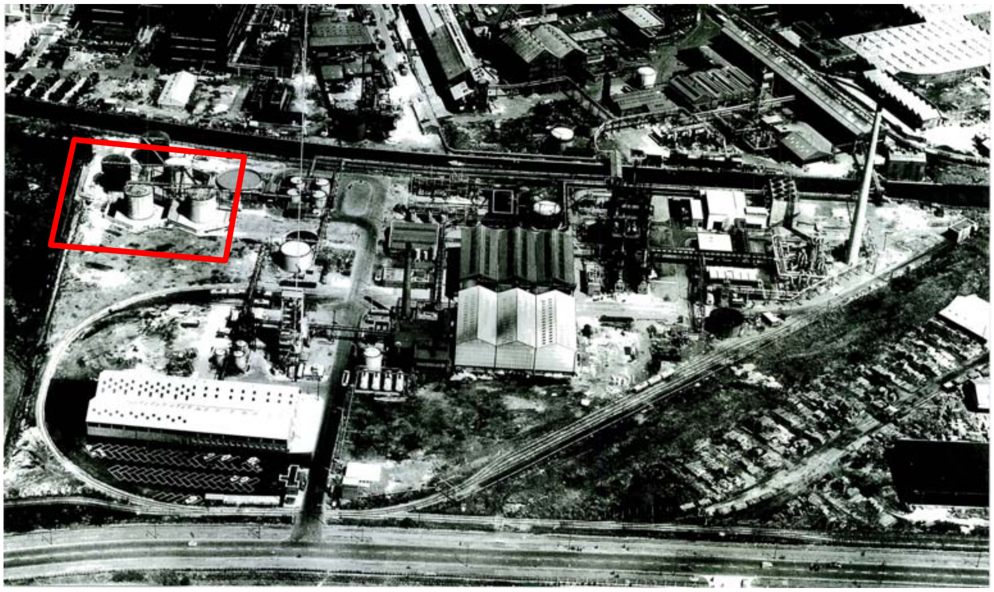


Plate 2.1b: Historical aerial photograph showing CS_2 storage tank area (outlined)

Waste generated at the facility included solid residues from tank and vessel cleaning, impure sulphur, concrete, general construction rubble, waste catalyst and scrap metal. Before about 1972, waste was deposited on the site waste tip. It was known that in the early history of the site, tank residues and impure CS_2 were deposited on the site and allowed to weather off.

CS_2 was a common contaminant but there was a relatively small number of locations at which it is the main contaminant of concern. CS_2 was known to be challenging to investigate and remediate because of its properties. It is extremely flammable, has a very low ignition energy, and can pose a vapour explosion risk. When impure, it has a strong, unpleasant odour. The planning and implementation of the site investigation and remedial works required a large team to ensure that all issues were addressed. This made the project particularly challenging and required collaboration between many specialist and research organisations.

The investigation programme was driven by the need to develop an appropriate understanding of site geology and hydrogeology, and a thorough understanding of the horizontal and vertical distribution of DNAPL, dissolved and vapour-phase contamination. A detailed programme of site investigations, employing a variety of techniques, was undertaken to achieve these goals.

2.3 GEOLOGY

The site and surrounding area were underlain with relatively recent deposits comprising alluvium with infrequent river terrace deposits and glacial gravel deposits, laminated clay and glacial till (BGS Sheet 85, Drift Edition, 1970). The site itself was underlain by late glacial flood gravels. Peat deposits were shown to the north of the site with glacial till beneath.

These drift deposits overlaid the Sherwood Sandstone group, although there were no exposures of sandstone near the site. Site data confirmed the regional geological sequence that comprised Made Ground, overlying peat in some areas (irregularly distributed), overlying the sand and gravel deposits, overlying the Glacial Till. Table 2.1 summarises the geological succession at the site.

Table 2.1: Proved geological succession at the site

Stratigraphy	Lithology	Thickness (m)	Hydrogeological characteristics
Made Ground	Bricks, sand, gravel, ash and clinker	0.3 – 3.8	Variable composition leads to heterogeneity in flow characteristics. Variable compaction and discontinuities associated with high permeability
Peat and clay	Clayey peat or peaty clay with plant fragments and rootlets	0 – 1.8	Thin low permeability horizon
Sand	Poorly sorted, fine sand to medium gravel, coarsening downwards	0.8 – 5.0	Minor aquifer Intergranular flow. Moderate permeability.
Glacial Till	Silty, sandy and stony clay, with occasional sand pockets and gravel	21.5 – 30.8	Low to very low permeability, but sand pockets will allow higher permeability in places
Sherwood Sandstone	Red-brown medium grained fissured sandstone	> 120	Major aquifer Inter-granular and fissure flow. High permeability related to fissure flow.

2.4 HYDROGEOLOGY

The site did not lie within any Source Protection Zones. Each hydrogeological unit is discussed separately below.

2.4.1 MADE GROUND

Made Ground deposits were variably saturated, being generally dry in the east and south of the site. In the north and west of the site, groundwater levels were observed on occasion to be above the base of the Made Ground.

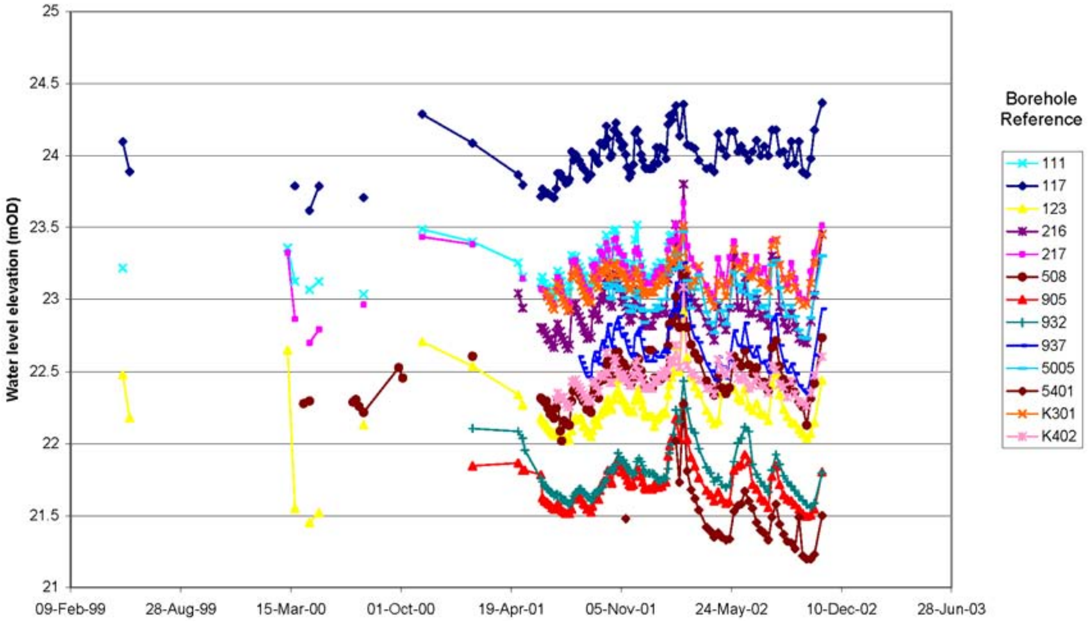
Made Ground at the site was generally a granular material and was therefore likely to have high permeability allowing movement of water and contaminants through the material. Within the Made Ground, localised low permeability units were found, such as the remains of concrete foundations. Localised perched water associated with these features was encountered.

2.4.2 PEAT AND CLAY DEPOSITS

The superficial peat and clay deposits at the site were localised in lateral extent but may have locally limited the vertical infiltration of water from the surface. It was noted that site boreholes monitoring groundwater within these deposits, were flooded on some occasions, indicating that these deposits may have been of relatively low permeability.

2.4.3 SAND AQUIFER

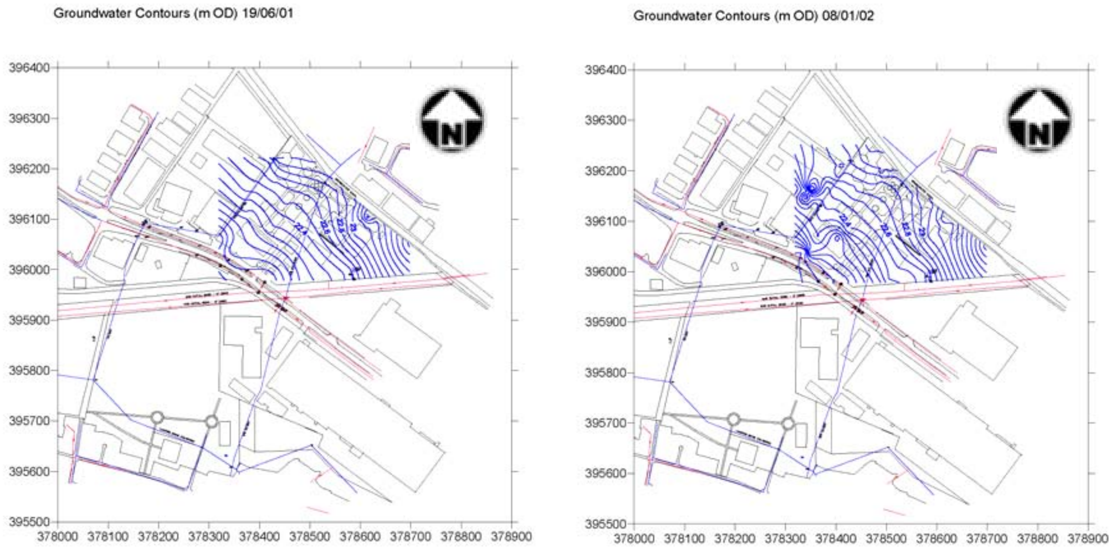
Figure 2.1 shows the variation in groundwater levels over time at selected locations in the sand aquifer. There was evidence of seasonal fluctuations with an amplitude of between 0.5 m and 1.3 m, indicating a local response to winter recharge.



NB Depth to groundwater varied from 0.01 m to 3.07 m with seasonal variations of up to 1.3 m.

Figure 2.1: Hydrograph showing variation of groundwater levels over time

Groundwater levels were contoured for selected dates, to examine the change in groundwater elevations and gradients across the site, and are shown in Figure 2.2 (19 June 2001 and 8 January 2002), and Figure 2.3 (2 July 2002 and 5 November 2002). These showed a general fall in groundwater levels from the northeast boundary (Bridgewater Canal) towards the southwest site boundary. The groundwater gradient was generally of the order of 0.004 to 0.006 to the southwest, but varied locally between 0.0017 and 0.01 with local spatial and temporal changes in direction. Groundwater levels were observed to rise during the winter with clear summer recessions.


Groundwater Contours (m OD) 19/06/01

Groundwater Contours (m OD) 08/01/02

Figure 2.2: Contours of groundwater elevation (m AOD) on 19 June 2001 and 8 January 2002

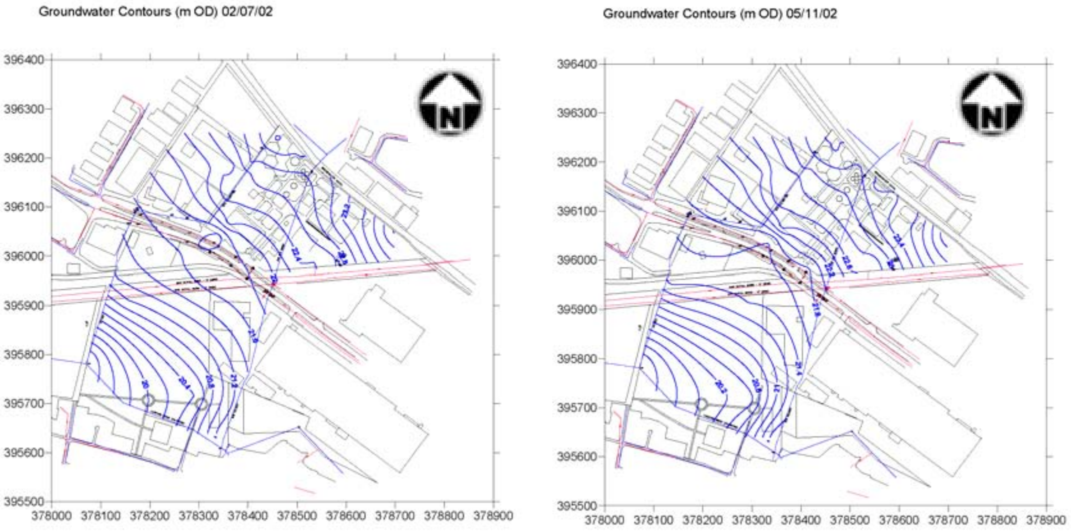


Figure 2.3: Contours of groundwater elevation (m AOD) on 2 July 2002 and 5 November 2002

At the northeastern boundary of the site, the average groundwater flow direction was approximately parallel to that boundary but locally there was possibly some variation, for example, see the observed water levels on 2 July 2002 (Figure 2.3). The observed spatial variability at these locations was small compared with the regional gradient to the southwest. Comparison with contours of groundwater levels from other dates indicated that the direction of flow across the boundary varied with time. These local changes were likely to be in response to local and seasonal variations in recharge.

Slug tests and pumping tests were carried out in the aquifer, giving hydraulic conductivities between 0.02 – 10.73 m/d and 9.5 – 36.6 m/d respectively. The larger volume of aquifer material tested during the pumping tests means that these results were more likely to represent the bulk properties of the aquifer.

2.4.4 GLACIAL TILL

The Glacial Till consisted mainly of clay but frequent sand partings and occasional pockets of thicker sand were present.

The Till was considered to behave as a low permeability layer separating the sand aquifer from the deeper Triassic Sandstone aquifer. Measurements of the hydraulic conductivity of the Till were made using field testing (rising/falling head tests and short duration pumping tests) and laboratory measurements. A weighted average estimate of the vertical hydraulic conductivity (Kv) of the Glacial Till was $9.1\text{x}10^{-5}$ m/d.

Water level data from the piezometers on site showed that a downward gradient existed from the groundwater in the Glacial Till towards the Sandstone. Water strikes were encountered between 3.9 m and 7.2 m below the top of the Till. This indicated that some groundwater might have been present in the sandy lenses within the Till.

2.4.5 SHERWOOD SANDSTONE

The Sherwood Sandstone is classed as a Major Aquifer by the Environment Agency. In the past, the aquifer was used to supply water to a variety of industrial users and the high demand caused a widespread lowering of water levels between the 1940s and 1960s. Reduction in groundwater abstraction (to approximately 20% of the peak demand) resulted in a recovery of groundwater levels in the Sandstone since the early 1980s, after which they were described as relatively stable (Stansbury 1994). These data were taken from three boreholes within 2 km of the site, SJ79/19 (SJ 7836 9773), SJ79/27 (SJ 7940 9730) and SJ79/60a (SJ 7999 9530). The average groundwater levels were about 17.8 m AOD. The nearest operating abstraction boreholes to the site were SJ 790 957 and SJ 791 957, approximately 700 m southeast of the site, with a combined annual abstraction rate of 755 megalitres per annum.

Current groundwater levels were approximately 16 m AOD, measured from the former site abstraction boreholes (the Lodge Borehole and the Norwich Union Borehole) and the more recently drilled borehole BH8203. The groundwater levels in the Sandstone indicated an overall groundwater gradient to the south-southeast of the order of 0.024. Water levels were observed to rise during the winter.

2.5 COMPARISON OF GROUNDWATER LEVELS BETWEEN THE AQUIFERS

Figure 2.4 presents the groundwater levels in the sand aquifer, the Glacial Till and the Sherwood Sandstone. Water levels in the Glacial Till were higher than in the Sherwood Sandstone at BH8203 and in the Lodge Borehole but lower than the Norwich Union Borehole.

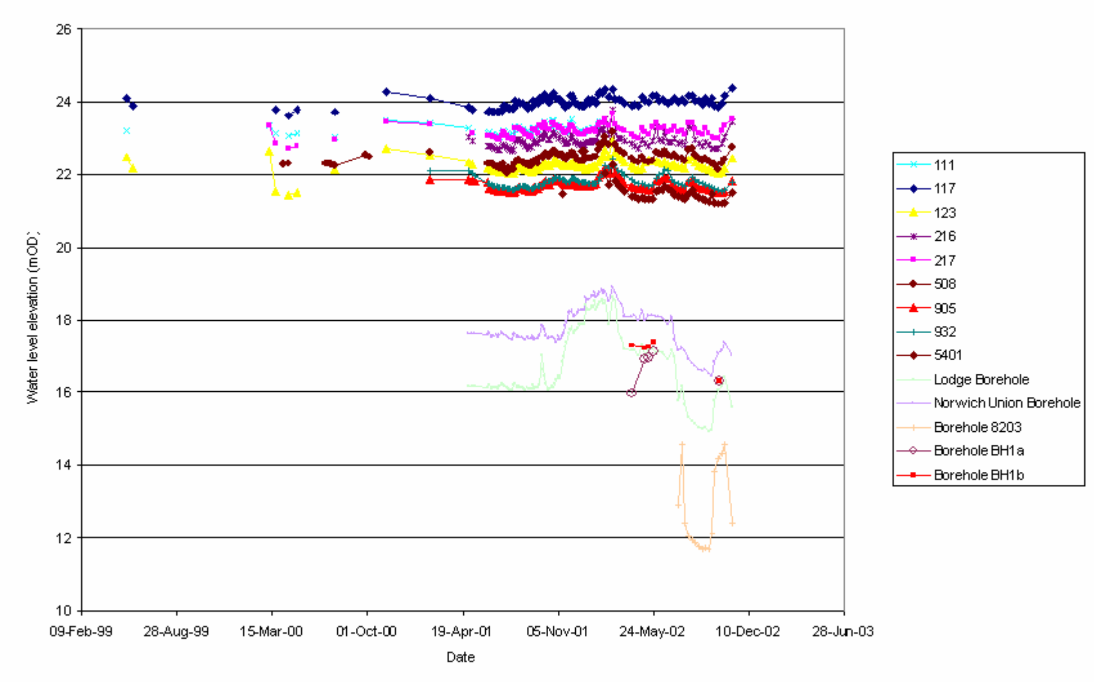


Figure 2.4: Comparison of groundwater levels in the sand, Glacial Till and Sherwood Sandstone

Water levels in both the sand aquifer and the Sandstone were observed to rise during the winter, with a clear summer recession in 2002, and a less marked recession in 2001. It was not clear to what extent the water levels in the Sandstone boreholes were affected by local abstractions.

As water levels in the sand aquifer were higher than in the Sandstone aquifer, a downward gradient existed from the sand aquifer to the Sandstone aquifer.

2.6 HYDROLOGY

The site was within the topographic catchment of Longford Brook (Figure 2.5), which flowed into the Manchester Ship Canal and then into Liverpool Bay. Topographic contours indicated that the ground fell to the south and west from a high point of approximately 27 m AOD in the northeast. The site itself was at an elevation of approximately 24.5 m AOD and was fairly flat. The Bridgewater Canal runs along the northeastern boundary of the site, in addition to a number of drains, culverts and sewers shown in Figure 2.5. The water level in the Bridgewater Canal was reported to be at 25.26 m AOD. This was above both the groundwater level and the ground level of the site.

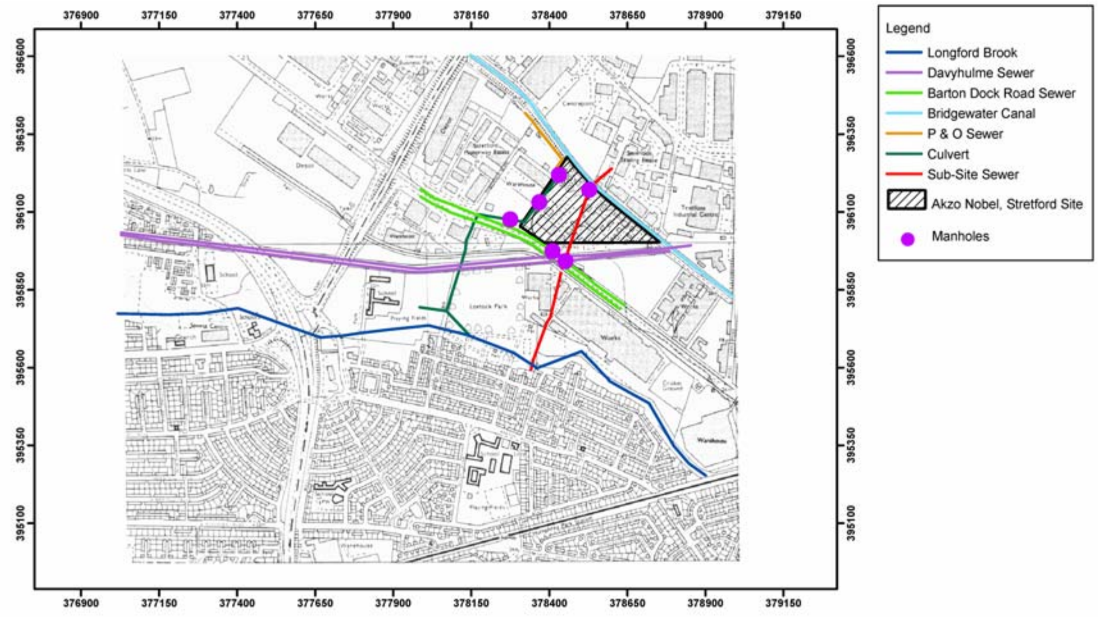


Figure 2.5: Locations of surface water features, sewers and drains

The Longford Brook (also known as the Bent Lanes Brook in its lower reaches) was approximately 300 m to the south of the site and flowed from east to west along the course shown in Figure 2.5 and was a fully enclosed culverted watercourse in the region of this site. Longford Brook was almost certainly the main natural discharge point for the local Drift groundwater system. The catchment area for the Brook lay between the River Mersey to the south and the Manchester Ship Canal to the north but it was difficult to make an estimate of the long-term average flow in the Brook.

The locations of the main drains and sewers in the vicinity of the site were obtained from maps from North West Water.

The sub-site sewer ran from the north side of the Bridgewater Canal across the site to the south, under the Davyhulme sewers (via a siphon) before entering the Barton Dock Road sewer. The Barton Dock Road sewer discharged to the main outfall sewers (Davyhulme sewers) immediately adjacent to the site.

The Davyhulme sewers were constructed in the late-19th to early-20th centuries. The southern sewer and northern sewer have diameters of 3.05 m and 3.96 m respectively. The sewers were about one third full under normal weather conditions. Davyhulme Sewage Treatment Works had an average intake flow of 4 m^3/s, a large proportion of which was likely to originate from the Davyhulme sewers. It was considered that a flow of 1 m^3/s was reasonable as a low flow estimate for each of the Davyhulme sewers.

2.7 METEOROLOGICAL DATA

The results of weekly rainfall monitoring undertaken at the Akzo Nobel site between January 2002 and July 2003 were recorded. The maximum weekly rainfall during this period was 40.7 mm per week, the minimum was 0 mm per week.

The long term annual average rainfall measured at the rainfall gauging station at the Davyhulme Sewage Works from 1941 to 1970 was 858 mm.

Met Office Rainfall and Evaporation Calculation System (MORECS) data provided weekly values of rainfall, effective precipitation (EP) and potential evaporation from January 1999 to July 2003. The soil type assumed for the evaluation of EP was grass with median available water capacity (AWC). During the mentioned period the maximum EP was 55.20 mm per week, the minimum was 0 mm per week.

2.8 NATURE AND EXTENT OF CONTAMINATION

Of primary concern was the presence of DNAPL CS_2 in the sand aquifer and residual CS_2 in the unsaturated zone. A secondary concern was the presence of a small dissolved plume of CS_2, CCl_4 and the latter's primary biodegradation product, $CHCl_3$, in the shallow sand aquifer. Also present in discontinuous but small discrete areas was sulphur, weathered fuel oil and various waste materials associated with chemical production furnace operation. In general, CS_2 contaminant concentrations were observed to decrease south and southwest of the CS_2 storage tank area (Figures 2.6 and 2.7). The low permeability Glacial Till acted as a barrier to downward vertical migration, although slightly elevated concentrations were observed indicating there may have been some localised migration of CS_2 within the Glacial Till.

Figure 2.6: Maximum concentrations of CS_2 (mg/kg) measured in Made Ground

Figure 2.7: Maximum concentrations of CS_2 (mg/l) measured in sand aquifer

The highest observed groundwater and soil CS_2 concentrations were from the CS_2 storage tank area and were 2344 mg/l and 9646 mg/kg respectively (Figures 2.6 and 2.7). Elsewhere on site the average groundwater CS_2 concentration was 15.38 mg/l and soil concentration was approximately 10.4 mg/kg, although the site was not uniformly affected by contamination.

A comparable CS_2 remediation project of this magnitude and complexity could not be found, despite exhaustive research. A worldwide search of remediation technologies potentially applicable for CS_2 DNAPL was undertaken. This required developing a detailed understanding of each technology to enable evaluation in a two stage process using ‘weighted rated matrices’, which included safety, environmental, technical, and economic considerations.

The selected remediation strategy was:

a) Removal of CS_2-contaminated soils by bentonite slurry stabilisation, excavation and disposal off-site to approved landfills. Stabilisation was essential to permit safe handling and transport of the material.

   The areas contaminated with DNAPL in the region of the former CS_2 storage tanks and waste tip were divided into individual ‘cells’, using temporary sheet piling, which served to contain the DNAPL during the stabilisation mixing process. The soils within the cells were mixed *in situ* with a proprietary bentonite clay-based material added in slurry form. Once this material had set, the contaminated soil was held within a physical matrix. The stabilised material was then dug out and removed to a suitable disposal facility, leaving clean material (mainly clay). The process is shown in Plates 2.1a, b and c. The excavated areas were backfilled with appropriate granular material. The remaining CS_2 groundwater and soil contaminant concentrations at the site are shown on Figure 2.8 and Figure 2.9 respectively.

Plate 2.2a: Mixing contaminated soil with bentonite clay-based mix.

Plate 2.2b: Transfer of stabilised soil to lorry for disposal in landfill

Plate 2.2c: Clean natural clay at base of treated ‘cell’

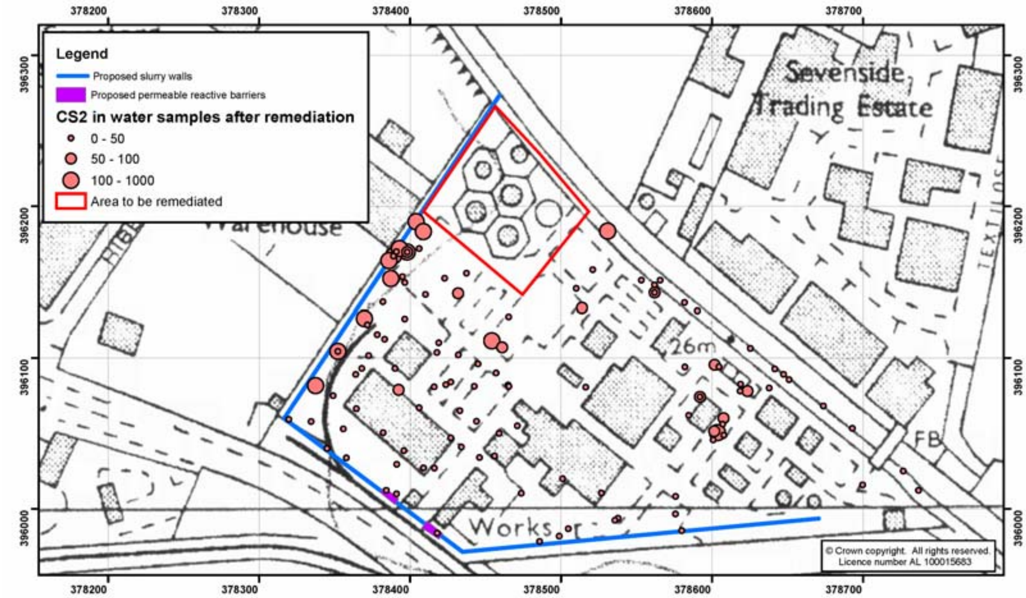


Figure 2.8: Groundwater sampling points after remediation of the site

Figure 2.9: Soil sampling points after remediation of the site

b) Reduce residual contaminant fluxes in shallow groundwater crossing site boundaries by means of a reactive iron PRB to protect off-site receptors from contamination by contaminated groundwater. This comprised an impermeable bentonite wall that directed groundwater flow to two reactive iron gates in which dissolved phase CS_2 is destroyed by chemical reactions that yield innocuous end-products (Figure 2.10).

c) Excavation of the waste dump and minor areas of mineral oil and sulphur contamination.

d) Monitored Natural Attenuation (MNA) for low concentration residual dissolved phase contaminants exiting the PRB gates.

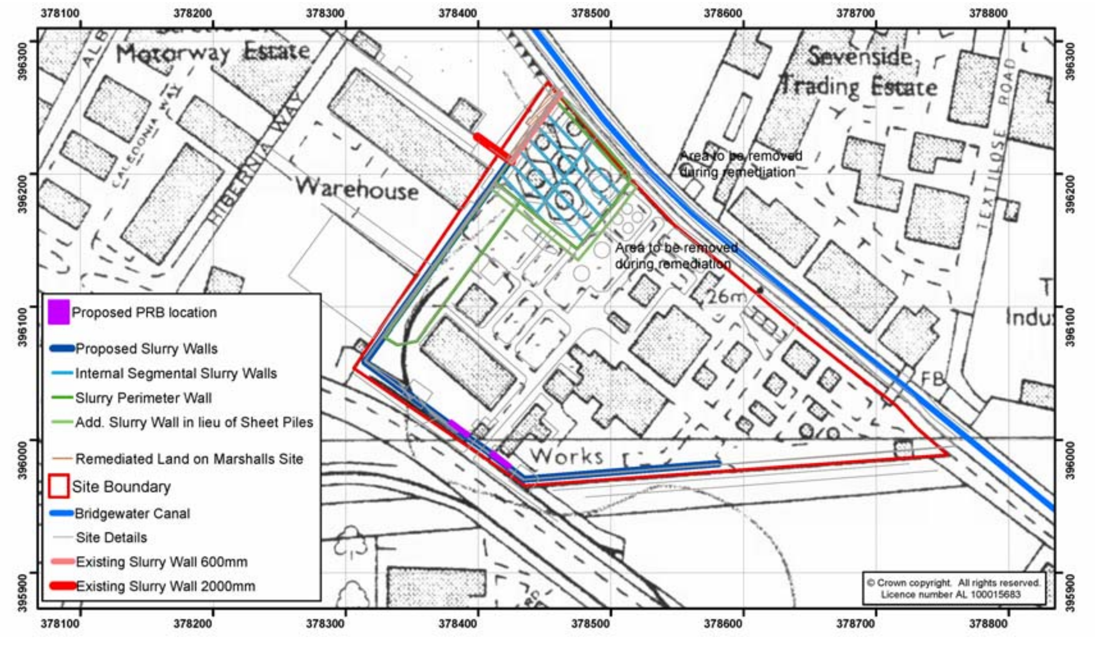


Figure 2.10: Layout of the site during remediation and development

The remainder of this report concentrates on the aspects of the remediation concerning the development and implementation of the PRB.

2.9 CONCEPTUAL MODEL

2.9.1 SOURCE-PATHWAY-RECEPTOR LINKAGES

Figure 2.11 shows the conceptual cross-section model for the Akzo Nobel site based on the pre-remediation site layout.

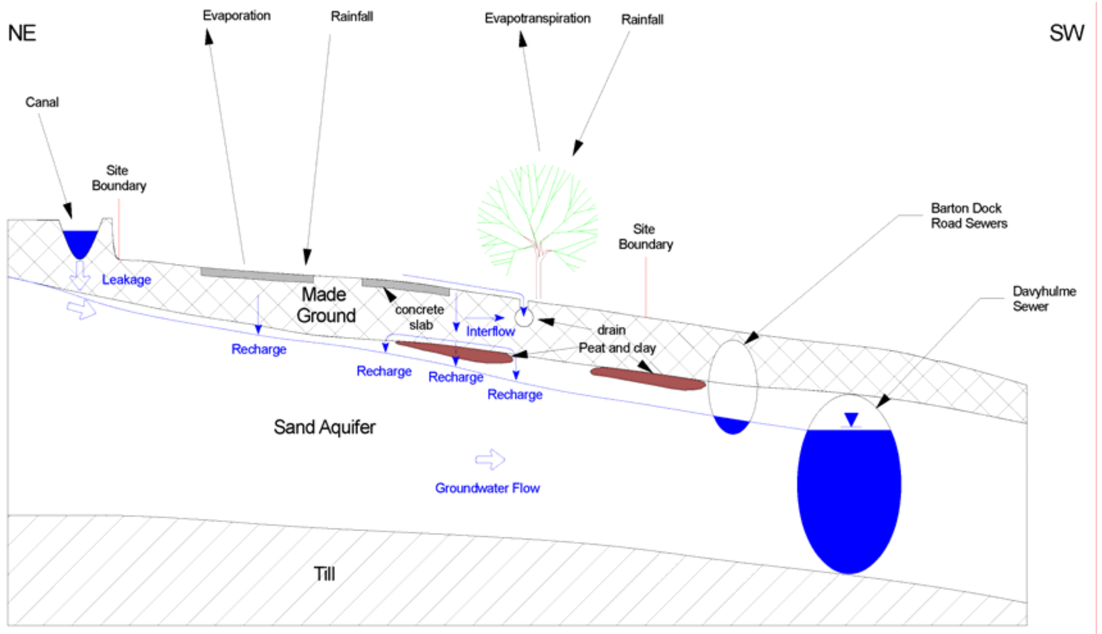


Figure 2.11: Conceptual cross-section

2.9.2 RECHARGE PROCESSES

Recharge was considered to occur via three processes: rainfall, canal leakage and drain leakage.

There were a number of pathways by which rainfall could enter the ground at the site. The pathway taken was dependent on the type and aspect of the surface the rain fell on, the nature of the rainfall event and seasonal influence on ground conditions. Three general land surface types were addressed.

1. **VEGETATION.** This comprised approximately 2% of the site land area, including a belt of trees along the south western boundary of the site. The vegetated areas were generally flat and would not have allowed rapid surface runoff to the site drainage system. Rainfall falling onto these areas would seep into the soil where it would evaporate or be transpired by plants i.e. evapotranspiration. It was considered that all the effective rainfall forms recharged to the sand aquifer within this land use area. Although the existing vegetation was removed to facilitate remediation, approximately the same density was replanted as part of the landscaping of the site redevelopment.

2. **BARE SOIL.** At the time this comprised approximately 60% of the site land area but was likely to be significantly reduced in the future development. The amount of rainfall able to infiltrate the soil depends on the compaction and saturation of the soil, rainfall intensity and effectiveness of the site drainage system to remove this water. Given the former land use at the site, it was considered that the soil was likely to be well compacted.

A proportion of the rain falling onto bare soil ran directly to the surface drainage system, where it was removed off site. The proportion was likely to be higher during the winter months when the ground may be saturated, limiting the potential for infiltration. The remaining water would probably pond on the ground surface, where it would be subject to evaporation. A proportion of the water would seep into the ground to form interflow (lateral flow within the unsaturated zone to the site drainage system) or recharge (downwards migration to the water table).

3. **HARDSTANDING.** This surface type comprised approximately 40% of the site area but was likely to significantly increase in the future development. Rain falling on the hardstanding would pond and then evaporate in light shower events. In heavier storms, and during the winter months when the potential evaporation rate is lower, rainfall would primarily runoff to the surface water drainage system. A proportion of the rainfall was likely to seep through cracks and joints in the concrete and infiltrate down into the soil zone below. This proportion would depend largely on rainfall intensity as the more intense rainfall events generated sufficient ponding to allow surface water flow to occur towards cracks and joints.

Most of the re-developed site was to comprise hardstanding, much of which would be covered by industrial units, but there was a possibility that this may change in the future. It was assumed that for the first 10 years of its life the hardstanding would be in good condition and the amount of recharge to the sand aquifer at the site would be significantly reduced, with remaining surface runoff drained from the site.

The canal lay above the groundwater table so there was potential for leakage from the canal to groundwater. The leakage flux was believed likely to be limited by the hydraulic conductivity of low permeability sediments beneath the canal and lining material.

The sub-site sewer was reported to be below the water table, therefore giving limited opportunity for leakage from the sewer to groundwater.

In the centre and south western parts of the site, the site culvert was considered to be in hydraulic continuity with the groundwater in the Drift. The flux of groundwater into the culvert was controlled by the hydraulic head gradient between groundwater and the culvert water level and the permeability of the culvert wall. There was potential for water in the culvert to recharge back into the groundwater at the blocked south western end.

There was a concern that the permeable backfill material around the culvert may act as a preferential pathway for groundwater flow that could continue off site to the southwest. To address this, following construction of the PRB system, the culvert and its backfill was cut and the bentonite slurry wall inserted across it, preventing any future flow along this pathway.

2.9.3 UNSATURATED ZONE

The water remaining after evapotranspiration losses and surface runoff should migrate through the unsaturated zone (Figure 2.11). Water movement would generally be downwards, but heterogeneity within the ground could result in some lateral movement of water. Where lateral flow (interflow) intersected drains, it was possible that some groundwater discharge to drains could occur.

For the purposes of the groundwater model, it was assumed that all the Made Ground was unsaturated. The relatively low permeability of the underlying peat and clay, which were not laterally continuous, could locally restrict the downwards movement of infiltrating water to cause localised perched groundwater bodies.

2.9.4 GROUNDWATER FLOW

Shallow groundwater flow occurred mainly in the unconfined sand aquifer, which had a saturated thickness of approximately 2.6 m. The groundwater flow was predominantly lateral in a southwesterly direction.

Local groundwater flow direction in the sand aquifer was affected by a number of features:

- The Barton Dock Road sewers could receive flow from the sand, since the head in the sewers was lower than groundwater level. It was uncertain as to what quantity of groundwater typically flowed into the sewers from the sand, but when investigated the sewer was dry in some sections.

- Although the culvert on the eastern boundary of the site was blocked with concrete, it could have formed a preferential groundwater flow pathway. The culvert was therefore removed as part of the remediation project and the western bentonite wall was designed to follow its former course.

- There was potential for groundwater to discharge into the sub-site sewer. The flux into the sewer would be controlled by the hydraulic head gradient between groundwater and the sewer water level and the permeability of the sewer wall. The water in the sewer was assumed to be approximately at the invert level. Groundwater could also flow along preferential pathways in the backfill material around the sub-site sewer.

- Figure 2.10 shows that an existing bentonite wall consisted of two parts, one running along the site boundary and the second running perpendicular to the site boundary. Weirs were cut into the latter part to enable groundwater flow across the barrier.

- There was the possibility of building foundations or other low permeability features extending down below the water table that could affect local groundwater flow.

Groundwater flowed into the site across the northeastern site boundary at an estimated 180-190 m^3/d. This water was derived from recharge up the hydraulic gradient of the site. Groundwater then flowed to the southwest across the site boundary and continued until the Davyhulme Sewer was reached. The Davyhulme Sewer was considered to penetrate the entire thickness of the sand aquifer and act as a barrier to groundwater flow (Figure 2.11). Groundwater discharged into the sewer or the backfill material around the sewer.

The sand was underlain by Glacial Till which was laterally continuous under and adjacent to the site and was considered to significantly restrict the downward flow of groundwater into the sand. Given the proportionally small downwards flow, the Till was considered to form an effective aquifer base to the sand aquifer.

2.10 TRANSPORT OF CONTAMINATION

This conceptual model only considered the dissolved phase of CS_2; the non-aqueous phase was treated as the contaminant source, which was removed by excavation during remediation works.

The CS_2 DNAPL had seeped downwards through the Made Ground, peat and clay and sand aquifer and onto the underlying Till, where it was gradually dissolved into groundwater to form a dissolved contaminant plume. Site observations generally showed that elevated concentrations of dissolved CS_2 were not maintained downstream of the source area. This may be a feature of the partitioning behaviour of CS_2, which tends not to dissolve readily in the subsurface, despite its relatively high solubility.

Most of the contamination was found below the former CS_2 storage tanks, so the bentonite walls that were keyed into the Till in the northern corner of the site (Figure 2.10) would prevent contaminant flow across the north western boundary.

3. PROJECT STRUCTURE AND ORGANISATION

3.1 MANAGEMENT INTRODUCTION

The project team organigram is shown in Figure 3.1. The roles and responsibilities of the key members are presented below.

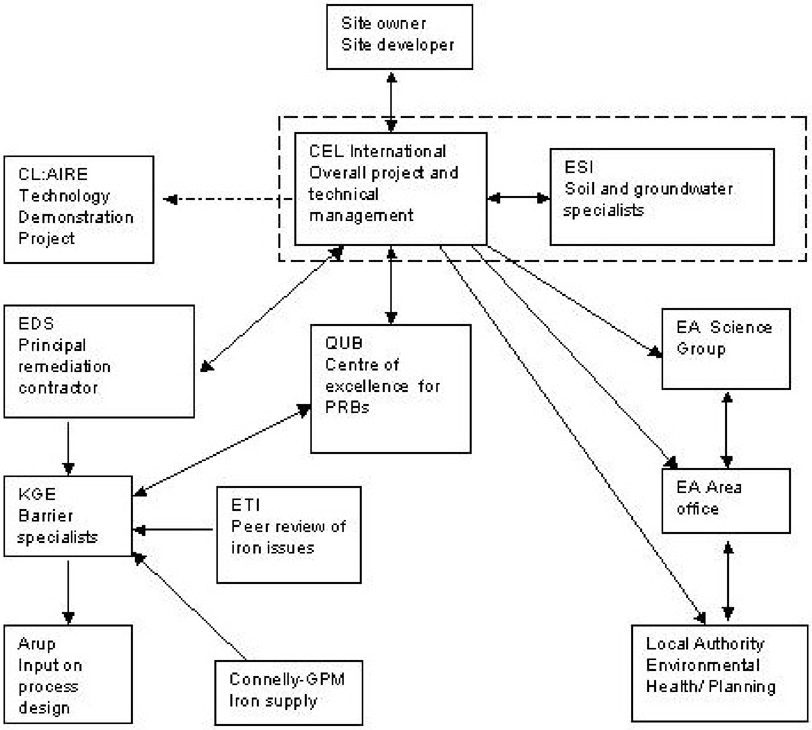


Figure 3.1: Project organigram

Environmental & Remediation Services (E&RS) Ltd (at the time named Cortex, the environmental consultancy at CEL International Ltd) led and managed the project on behalf of the site owner, Akzo Nobel. E&RS was responsible for the technical and project management of the overall project. It ensured liaison with the ultimate client and led all discussions with regulatory bodies and other third parties. Its further role was to ensure appropriate technology development for the optimum application of basic science.

ESI Ltd was lead environmental consultant for the soil and groundwater aspects of the project. ESI's main activities relevant to the PRB implementation were: site investigation and interpretation; risk assessment; regulatory negotiation support; groundwater modelling for PRB design programme; technical review of sub-contractor PRB design inputs; and specification of PRB monitoring.

Euro Dismantling Services (EDS) Ltd was the Principal Contractor on the project, responsible for the design and implementation of both the overall project and the PRB. Included in the remit of EDS were site health and safety, project management and site supervision.

Keller Ground Engineering (KGE) was the principal subcontractor responsible for the bentonite barrier and involved in the PRB design. Arup designed some of the process elements of the PRB.

Professor Bob Kalin led the research group in Environmental Engineering, within the School of Civil Engineering at Queen's University Belfast. This group was responsible for undertaking the laboratory treatability studies to determine rates of CS_2 degradation, degradation products and potential gate performance under the site groundwater conditions.

EDS provided standard contractor's insurance to cover normal contractor's activities on site. More unusually, insurance was taken out by the client, Akzo Nobel, in preparation for the deep excavations required next to the Manchester Ship Canal in case of catastrophe should there have been a breach of the canal.

The PRB's performance was warranted by E&RS under the site's remediation warranty, with defect liability provided by EDS and certain aspects of the design warranted by Arup.

3.2 REGULATORY APPROVAL

This was a voluntary remediation by Akzo Nobel, in conformance with its Corporate Social Responsibility programme, and as such it did not come under Part IIa of the Environmental Protection Act 1990. However, regulatory liaison was maintained throughout the project. The site investigation, risk assessment and remediation selection reports were distributed to and accepted by the regulatory authorities.

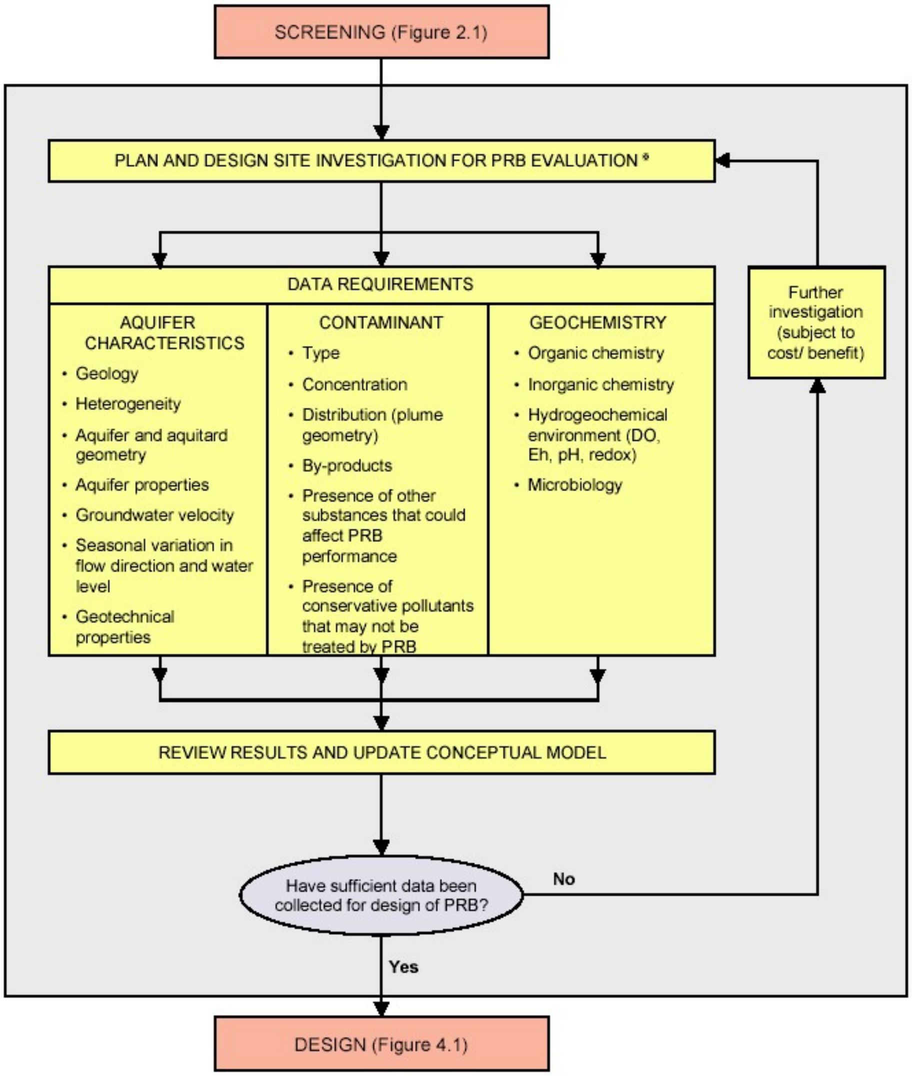
A detailed site investigation programme and risk assessment was performed for the site and agreed by the local authority, Trafford Metropolitan Borough Council, and the Environment Agency. The evaluation and design of the PRB was undertaken in line with the Environment Agency's guidance on PRBs (Environment Agency, 2002). Figure 3.2 is taken from this guidance document and shows the site characterisation processes followed. Site screening was carried out based on the appropriate risk assessment reports and is not discussed further here.

Some practical aspects of the remediation work required compliance with certain regulations. For example, planning permission was sought and achieved for the remediation works, excluding planning application submitted by the future site developer. This was a fairly complex process, requiring various trials to ensure all parties were satisfied that the remediation process would not itself cause environmental or public harm, and the approval of validation reports. All site activities complied with Construction Design & Management (CDM) Regulations (see Section 3.3).

Considerable effort was made to exceed compliance with legislation and to implement best practice wherever possible, whilst using value engineering and project management techniques to ensure the project remained cost effective. The benefits of this approach, along with maintaining a close relationship with the regulators resulted in the following accolades:

"The Agency has been encouraged by the quality of the investigations and remedial works carried out on this site, and is pleased that a satisfactory outcome has been achieved whereby the site has been successfully remediated to a suitable standard for future industrial use." Environment Agency, May 2005

"We are satisfied that the validation report demonstrates that the remediation has been carried out in a satisfactory manner and the target levels have been achieved." Trafford Metropolitan Borough Council, May 2005



✤ The necessary site characterisation data may have been obtained as part of the initial investigation

Figure 3.2: Refining site investigation for design of PRB (Source: modified from Environment Agency, 2002)

3.3 HEALTH AND SAFETY

The Health & Safety Executive (HSE) performance was the top priority of the overall remediation programme and was managed under CDM regulations (see roles within organigram below). Therefore all works were undertaken under a system of method statements and permits to work. Safety was considered at all stages of the project and significant design changes were incorporated to ensure safe construction of the PRB and during its operation and maintenance. The Planning Supervisor approved the site health and safety file on completion of site works. Making safety paramount paid off: there were no lost time accidents and only three minor accidents during the 48,570 site hours.

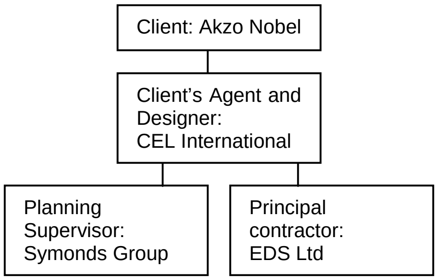


Figure 3.3: Roles under CDM

The PRB was designed to minimise vandalism, with the majority of the structure being underground, beneath a layer of gravel. Above-ground elements are within the perimeter of the site and are surrounded by heavy-duty steel fencing. Gas ventilation was steel plated, with protective cowling.

During the construction of the PRB, the site had 24-hour security, seven days a week, with a dedicated team of security staff. Only trained, briefed and authorised personnel were allowed access to the monitoring points. Access to the reactors (and monitoring points) was controlled by a secure fence, with keys held by the monitoring contractor.

Any maintenance works were carried out with the knowledge and agreement of the monitoring contractor. Method statements, safe methods of working, risk assessments, COSHH assessments and training records were reviewed prior to any works taking place. It was agreed that any future works would be carried out in accordance with the current construction and environmental legislation and guidelines in place at that time.

3.4 DEMONSTRATION WORK PLAN

The overall remediation works comprised:

- Removal of significant areas of CS_2 DNAPL by the excavation of contaminated soil after bentonite stabilisation, with disposal to authorised landfill sites;
- The installation of bentonite walls at the western and southern boundaries of the site to prevent off-site shallow groundwater flow, other than through the iron gates;
- The installation of two parallel reactive iron gates within the southern run of the bentonite wall to treat residual dissolved CS_2 in shallow groundwater; and
- Excavation and removal of former waste materials deposited on the site and localised areas of other contamination.

The design process applied to the PRB followed best-practice guidance (Environment Agency, 2002) and included the following activities:

1. **Determination of geology, hydrology, hydrogeology and contaminant distribution**
   An extensive programme of site investigation was carried out over a period of three and a half years to assess the geology, hydrology, hydrogeology and contaminant distribution. This investigation used a wide range of techniques, ranging from using a Membrane Interface Probe (MIP), to more classical invasive techniques, such as cable percussion rigs. The investigation was not limited to the site and in total more than 800 ground penetrations were made. All information was stored on a shared database and GIS.

2. **Detailed quantitative risk assessment for identified pollutant linkages**
   Based upon the site investigation data set, risk assessments for controlled water and human health receptors were undertaken and accepted by the local authority (Trafford Metropolitan Borough Council) and the Environment Agency. The conclusions of the risk assessment were that significant CS_2 terms required removal to protect the underlying groundwater and future site occupants. In addition,

treatment of shallow groundwater was required to reduce the flux of CS_2 crossing the site boundary. A 90% reduction of dissolved influent CS_2 concentrations in shallow groundwater crossing the site boundary was shown to provide effective protection of downgradient receptors. The maximum envisaged influent concentration was approximately 100 mg/l with normal concentrations being in the order of 10 mg/l.

3. **Evaluation and selection of remediation technologies using weighted-rated matrices, including environmental impact and economic analyses**
   The evaluation of remedial technologies was conducted in two phases, in accordance with Environment Agency guidance, using weighted-rated matrices. In the first phase, all potential technologies were considered, including those not proved at field scale but with significant potential. Particular emphasis was placed on health and safety aspects, both during and post remediation. Five technologies were shortlisted for fuller evaluation in Phase 2. The second phase considered in detail the technical and economic factors associated with each technology. At all stages cognisance was taken of both in-house knowledge and experience of CS_2 and reports of CS_2 remediation carried out by third parties.

4. **Laboratory testing**

5. **Establishment of ‘basis of design’ parameters, including constraints imposed by development and other issues (e.g., easements)**
   The broad responsibility shouldered by the managing contractor (CEL) facilitated a wide overview of key constraints and design parameters. Key constraints included historical covenants, developer future uses, planning requirements and underground structures. Critical influences to design parameters included ‘maintenance free’ operation and simple decommissioning, owing to the site changing ownership and the probable fractious arrangements that could result from multiple ownership of the site in future. A design basis document was prepared to record these factors.

6. **Development of conceptual models and numerical groundwater models for pre- and post-development cases**

7. **Determination of groundwater capture zones and design fluxes**

8. **Specification of gate hydraulic conductivity and porosity**
   Based on the laboratory testing, agreed design parameters for the gate were established and documented

9. **Determination and specification of PRB system design longevity**
   Based upon the requirements for minimum maintenance and high reliability, a design life of ten years was selected for the reactive iron to be installed in the gates. Value engineering processes concluded that this was a reasonable balance between capital and operating/maintenance costs, whilst ensuring effective treatment. Laboratory testing confirmed that such a design lifetime could be achieved. Mechanical and structural components of the gates were designed for a minimum twenty-year life to enable repacking with fresh reactive iron if required.

10. **Design and specification of bentonite slurry wall**
    The slurry wall had a design permeability of 1×10^{-9} m/s and other specification in accordance with the ICE Specification for the Construction of Slurry Trench Cut-off Walls (Institution of Civil Engineers, 1999). Slurry wall design lifetime was twenty years, which was the maximum warranty period available commercially.

11. **Preliminary design of gate reactors and infrastructure, including selection of materials of construction, off-gas treatment**
    Working from the design basis document, the engineering team developed a preliminary process and engineering design capable of satisfying all the design requirements of the PRB system. Gas generation was one of the key

considerations. Hydrogen is generated via a redox controlled reaction between iron and water, and is chemically stable under the redox state and pH conditions that are anticipated within the PRB. The reaction will progress until equilibrium is reached. Additionally, biological processes within the gate may generate odorous sulphur compounds. All off-gas from the gates is therefore directed via a passive venting system through activated carbon canisters and vents to atmosphere at a safe location. Special precautions were necessary in the design due to the risk of explosive hydrogen/air mixtures and specialist engineering support was employed to ensure a safe design.

12. Value engineering

The design of the gates was subjected to a thorough value engineering process, which considered many aspects of the gate design and construction, ranging from overall reactor design to constructability. The value engineering exercise involved all of the key team members, was systematic in its approach and sought the greatest savings from the least changes (Pareto rule).

13. Detailed design of gate reactors and infrastructure

The preliminary design was subject to a programme of peer review and value engineering to identify the most cost effective configuration, taking full account of design longevity and the constructability of the system. Detailed design documents were then prepared and, following final review, issued for construction.

14. Construction of the gates and iron

15. Commissioning and handover

This included a performance monitoring programme, which is discussed in Section 5.

4. PRB DEVELOPMENT AND DESIGN

4.1 LABORATORY TRIALS

Although the basic principles of reactive iron treatment of CS_2 had been established (Kalin & Myles, 2003), a laboratory test programme was essential to predict treatment performance under continuous flow conditions, to determine the effects of groundwater hydrochemistry on treatment performance, and to derive parameters for engineering design. This laboratory testing was performed by Queen's University Belfast.

Column treatability tests were performed using site groundwater shipped to the laboratory. The objectives of the tests were to determine whether CS_2 was degraded under conditions of flow and whether the presence of other contaminants interfered with this. Column tests were the favoured method of treatability testing, as they allowed the measurement of change in contaminant concentration with distance travelled, and half-lives calculated in this manner are usually more reliable than those from batch tests.

4.2 EXPERIMENTAL DESIGN

Groundwater samples were obtained from two site boreholes chosen to represent the typical variation in groundwater chemistry close to the likely location of the gates. Eight Perspex columns were used for the tests. Four of these operated under flow conditions approximating field groundwater flow velocity and were equipped with ten sampling ports at intervals along the length. These measured 50 cm x 4 cm internal diameter. The other four columns were operated at accelerated flow rates to determine the long-term effects of groundwater on the reactive media; these only had influent and effluent sampling ports. These measured 15 cm x 4 cm internal diameter.

Two types of iron (Connelly (ETICC-1004) and Gotthart Maier (FG 0500/3000)) were used in these tests to determine the most cost-effective treatment medium for the site. Table 4.1 summarises the experimental work performed.

Table 4.1: Experimental column configurations

Column	Iron supplier	Flow rate (ml/min)
S1	Connelly	0.154
S2	Connelly	0.154
S3	Gotthart-Maier	0.154
S4	Gotthart-Maier	0.154
S5	Connelly	0.796
S6	Connelly	0.796
S7	Gotthart-Maier	0.796
S8	Gotthart-Maier	0.796

All materials of construction were chosen to minimise losses of organic contaminants through sorption, which was tested in batch experiments before construction. Plate 4.1 shows two of the columns.

Plate 4.1: Two of the continuous flow laboratory test columns

4.3 METHODS

4.3.1 COLUMN PACKING

The columns were filled with deionised water and the reactive iron added in portions, to avoid layering. Several pore volumes of deionised water were then flushed through the column to ensure complete saturation.

The porosity was found to be 0.52 for both types of iron. A flow rate of circa 0.1 ml/min was obtained for the normal flow columns and a flow rate of circa 0.8 ml/min was obtained for the accelerated flow columns. The residence time (the time taken for one pore volume to pass through) was calculated as 36.4 hours for the normal flow columns and 2.1 hours for the accelerated flow columns.

4.3.2 GROUNDWATER PREPARATION

As background CS_2 concentrations in the groundwater collected from the site were less than 10 mg/l, and will have varied due to volatile losses in transit, the site groundwater required the addition of CS_2 to achieve higher concentrations. A concentration for CS_2 of 100 mg/l was chosen as representing the highest probable concentration that could reach the barrier during remediation works or immediately after.

4.3.3 ANALYTICAL TECHNIQUES

Water samples were analysed for:

- Organics (carbon disulphide, carbon tetrachloride, chloroform, dichloromethane and chloromethane) by Gas Chromatography - Mass Spectrometry (GC-MS);
- Methane by Gas Chromatography (GC);
- pH and redox potential;
- Alkalinity;
- Ferrous iron;
- Major ions; and
- Total dissolved metals by (Inductively Coupled Plasma - Optical Emission Spectroscopy (ICP-OES).

A proportion of samples were also sent to ALcontrol Laboratories for check analysis of the organic components.

Samples of iron were cored from the columns at the end of the test programme for analysis of passivation and mineralogical fouling using:

- Scanning Electron Microscopy (SEM);
- SEM- Energy Dispersive X-ray (EDX) to determine elemental analysis; and
- X-ray Diffraction (XRD; performed at the University of Edinburgh).

4.4 RESULTS AND DISCUSSION

4.4.1 CARBON DISULPHIDE DEGRADATION

Table 4.2 shows the results of half-life determination from the column testing. Columns 1 and 2, utilising Connolly iron, showed half-lives ranging from 0.35 to 2.63 hours. Columns 3 and 4, utilising Gotthart Maier iron, showed half-lives ranging from 0.35 to 1.75 hours.

Table 4.2: Summary of calculated half-life data for CS_2 degradation in standard flow column tests at ambient laboratory temperature (23^{o}C)

Column	Iron Source	Flow-Rate (ml/min)	Half-Lives (hours)			
			Min	Max	Mean	Median
S1	Connelly	0.10	0.53	2.63	1.50	1.49
S2	Connelly	0.10	0.35	1.50	0.81	0.69
S3	Gotthart Maier	0.10	0.35	1.75	0.98	1.00
S4	Gotthart Maier	0.10	0.43	1.17	0.70	0.61

Results for accelerated flow columns S5-S8 showed a trend toward passivation of the 50 cm thickness of iron in the columns after approximately 1700 pore volumes (Figure 4.1).

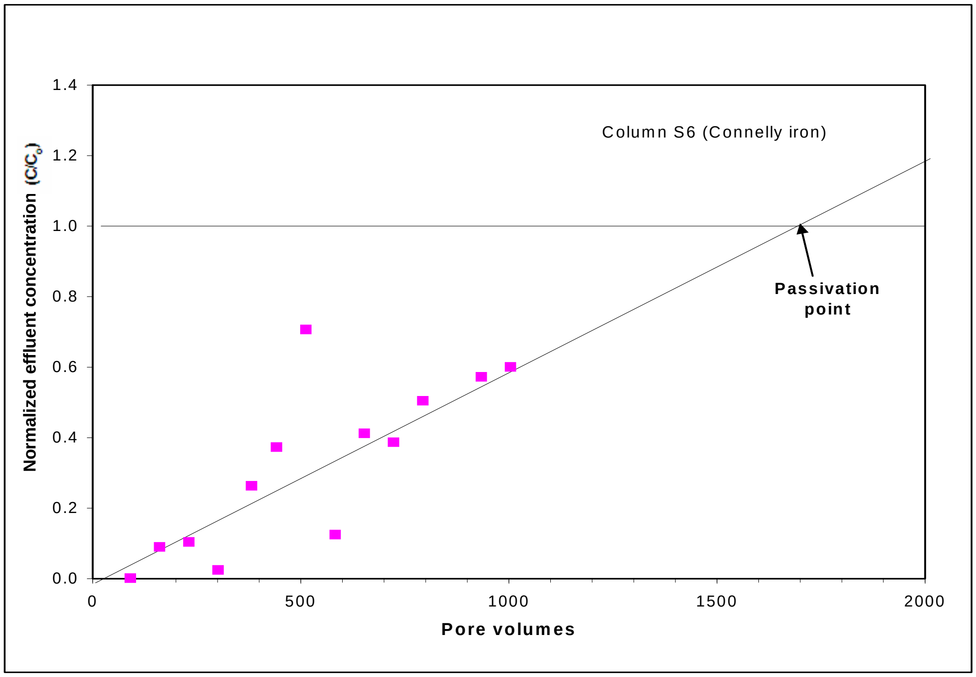
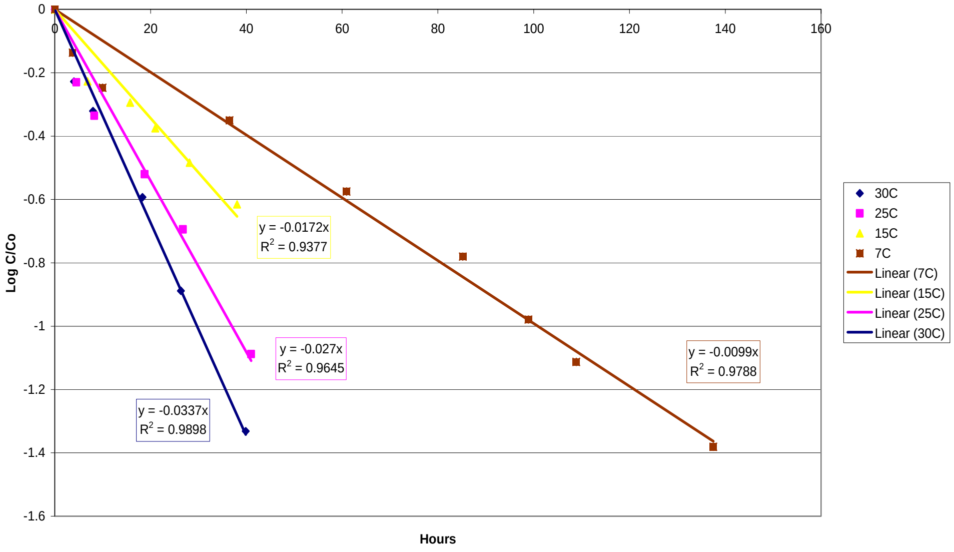


Figure 4.1: Determination of passivation point (number of pore volumes resulting in cessation of CS_2 degradation activity) for packed bed of Connelly iron

The results of columns S5 and S6 were also analysed on the basis of total weight of CS_2 degraded with time and compared to the weight of iron present. For S5 and S6, the total weights of CS_2 degraded were 5032 mg and 5389 mg. This gives a reactivity of 21,394 mg/kg and 22,913 mg/kg. A similar exercise was carried out for columns S1 and S2 by considering the first 4 cm of column bed length. The calculated reactivity was 15,170 mg/kg for S1 and 20,978 mg/kg for S2. As residence time was small for these cells, it was possible that the reactivity was less. It was concluded that a reactivity of 20,000 mg/kg could be safely applied for the long-term design of the gate reactivity.

4.4.2 TEMPERATURE CORRECTION

All laboratory tests were carried out at room temperature, therefore calculated half-lives needed to be adjusted to groundwater temperatures on-site. From batch test data (see Figure 4.2), it was concluded that the CS_2 degradation rates measured in the laboratory (23^oC) should be decreased by a factor of 1.8 to compensate for slower reaction rates at field temperature (12^oC).



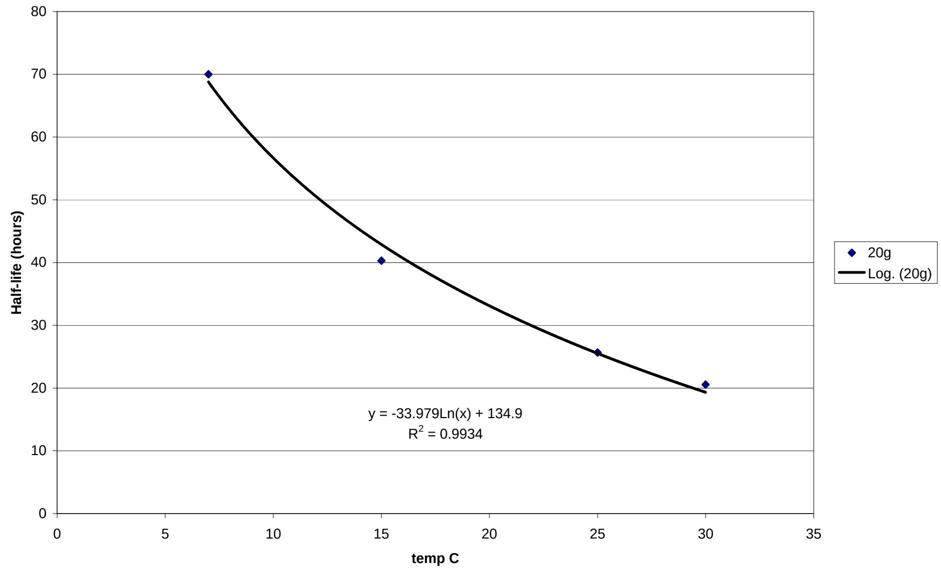


Figure 4.2: The effect of temperature on CS_2 degradation rate

4.4.3 PERMEABILITY DATA

Table 4.3 summarises permeability data obtained from falling head tests. It was clear that a reduction in hydraulic conductivity occurred over the number of pore volumes specified for each column; this was likely to be due to a build up of precipitates in the columns.

Table 4.3: Permeability data from column tests

Column	Hydraulic Conductivity, K (m/sec)			No. pore volumes
	Initial	Final	Reduction ratio	
S1	2.7×10^{-4}	5.4×10^{-5}	5.0	46
S2	2.7×10^{-4}	5.3×10^{-5}	5.1	46
S3	2.4×10^{-4}	1.2×10^{-4}	2.0	46
S4	2.4×10^{-4}	3.7×10^{-5}	6.5	46
S5	2.7×10^{-4}	2.5×10^{-5}	10.8	1004
S6	2.7×10^{-4}	1.8×10^{-5}	15.0	1004
S7	2.4×10^{-4}	3.8×10^{-5}	6.3	1004
S8	2.4×10^{-4}	1.5×10^{-5}	16	1004

For process design, a long-term permeability reduction factor was assumed.

4.4.4 CATIONS, ANIONS AND TRACE METAL DATA

The influent groundwater chemistry was quite variable, which meant the inorganic chemistry data were difficult to interpret. Generally, columns S1 to S4 displayed similar trends in that both the total dissolved Fe and the alkalinity decreased from the influent to effluent. No trends were seen for Ca^{2+} and Mg^{2+}. The groundwater had a very high sulphate concentration and a decrease in concentration between the influent and effluent was apparent in several samples but was not consistent.

In columns S5 to S8, the total dissolved Fe concentrations increased for the majority of samples. No trends were observed for Ca^{2+}, Mg^{2+}, SO_4^{2-}, and alkalinity. Once again, the variability in influent groundwater inorganic chemistry, combined with the short residence time, meant data were difficult to interpret. From SEM, SEM-EDX and XRD results it was clear that sulphur (as iron sulphide (pyrite) or possibly iron sulphate), calcium and carbonate (as calcite and siderite) were precipitated on the surface of the iron.

The principal precipitates identified by XRD were hydrated forms of ferric oxides such as goethite (hydrated iron oxide, a-FeOOH) and lepidocrocite (iron oxyhydroxide, FeOOH), magnetite (Fe_3O_4), and an iron carbonate mineral, siderite ($FeCO_3$). The minerals identified by XRD were also seen in SEM images (Figure 4.3). It was clear, from the comparison of sample SEM images, that more precipitates were formed at the influent end of the column, as less precipitates were seen in the Section from 12 to 13.5 cm up the length of the column. FeS was not detected by XRD in any of the samples, however the spherical shaped framboid structures appeared in several SEM images, in particular within the first 1.5 cm of all columns (where most CS_2 degradation took place). In a different case, Phillips et al. (2000) also visually determined FeS precipitates by SEM without being able to detect FeS by XRD for the same samples, probably due to the non-crystallinity of the FeS structure.

The reaction of CS_2 with iron was redox controlled. Figure 4.4 shows that CS_2 reactions with iron were most dominant within the iron-sulphide stability field and the rate of reaction of iron and CS_2 was reduced when the redox state was dominated by siderite or magnetite. Thus, the highest rate of reaction will take place in the reactor below the ‘rolling front’ of mineral precipitates in the field reactor.

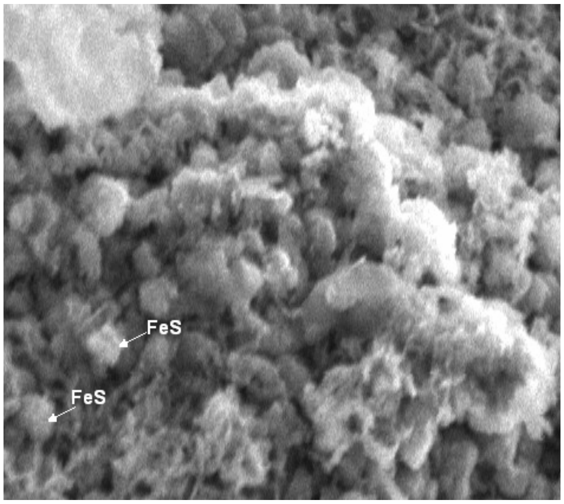


Figure 4.3: SEM micrograph of zero-valent iron filing taken from 0-1.5 cm from the influent of the accelerated flow column

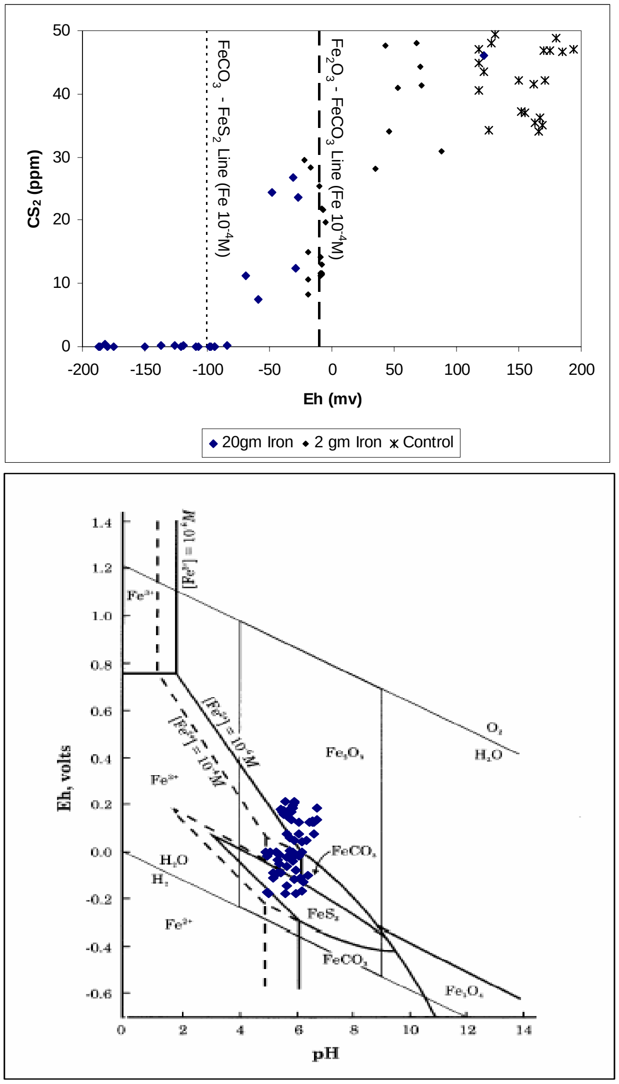


Figure 4.4: Carbon disulphide reactions with iron (Queen's University Belfast)

For all columns, the percentage calcium and sulphur decreased along the bed length. Gotthart Maier and Connelly iron were used as control samples and the analysis by SEM-EDX confirmed the absence of calcium and sulphur in the control columns, indicating that these elements were precipitating onto the zero-valent iron's surface in the columns.

Interpreting the data as a whole, under the anaerobic conditions prevailing in the columns, iron was oxidised by water:

$$Fe^0 + 2H_2O \rightarrow Fe^{2+} + H_2 + 2OH^-$$

The solution pH did not increase as a consequence of hydroxyl ion generation due to the formation of iron hydroxide precipitates:

$$Fe^{2+} + 2OH^- \rightarrow Fe(OH)_2$$

Roh *et al.* (2000) reported that $Fe(OH)_2$ can then convert to magnetite (Fe_3O_4).

Also, in waters with high alkalinity, some bicarbonate-carbonate buffering will have taken place.

$$HCO_3^- + OH^- \rightarrow CO_3^{2-} + H_2O$$

Carbonate may then have formed precipitates with calcium (calcite, aragonite), magnesium and ferrous ions (siderite) to produce carbonate precipitates:

$$Fe^{2+} + CO_3^{2-} \rightarrow FeCO_3$$
$$Ca^{2+} + CO_3^{2-} \rightarrow CaCO_3$$

Under the reducing conditions prevailing in the columns, the stable form of sulphur is sulphide, and as Fe^{2+} was produced due to water corrosion, the following reaction is likely to occur, causing hydrogen sulphide to precipitate as iron sulphide (FeS):

$$CS_2 + 5Fe \rightarrow 2FeS + Fe_3C$$
$$Fe^{2+} + HS^- \rightarrow FeS + H^+$$

As the main precipitates detected by the microscope techniques in the columns were goethite, lepidocrocite, magnetite, siderite and pyrite, the above reactions explain the main processes occurring in the formation of precipitates.

4.5 CONCLUSIONS

From the laboratory based treatability studies, it was apparent that the proposed PRB technology would be effective in the degradation of the CS_2 from the groundwater at the site. Reactive iron was proven through laboratory tests to degrade CS_2, with half-lives varying from 0.35 to 2.63 hours at 23^oC, corrected to 0.63 to 4.63 hours at the ambient groundwater temperature of 12^oC.

4.6 PROCESS DESIGN

4.6.1 BASIS OF DESIGN

4.6.1.1 Geology and Hydrogeology

A typical geological cross section for use in the design of the PRB was constructed from site characterisation data and the groundwater modelling and is summarised in Table 4.4.

Table 4.4: Shallow geology specification for PRB design

Stratigraphy	Lithology	Thickness (m)
Made Ground	Loose ash, sand, gravel and brick	1.3 to 2.4
Sand	Poorly sorted, fine sand and medium gravel	2.6 to 3.6
Glacial Till	Silty sandy and stony clay with occasional sand pockets and gravel	>10

4.6.1.2 Design configuration

A wall and barrier PRB configuration was selected as the only layout that could meet the constraints imposed by site development plans, the presence of the easement to the south of the site and the requirements for long-term monitoring and decommissioning of the system. A two gate configuration was selected as compatible with the site layout, whilst ensuring capture of all groundwater that may contain significant concentrations of CS_2 (Figure 4.5).

PRB above ground structures were to extend no more than 1 m above ground level, except for gas venting equipment. All structures and access points were to be tamperproof and integrated into the landscaping works to be performed during site redevelopment.

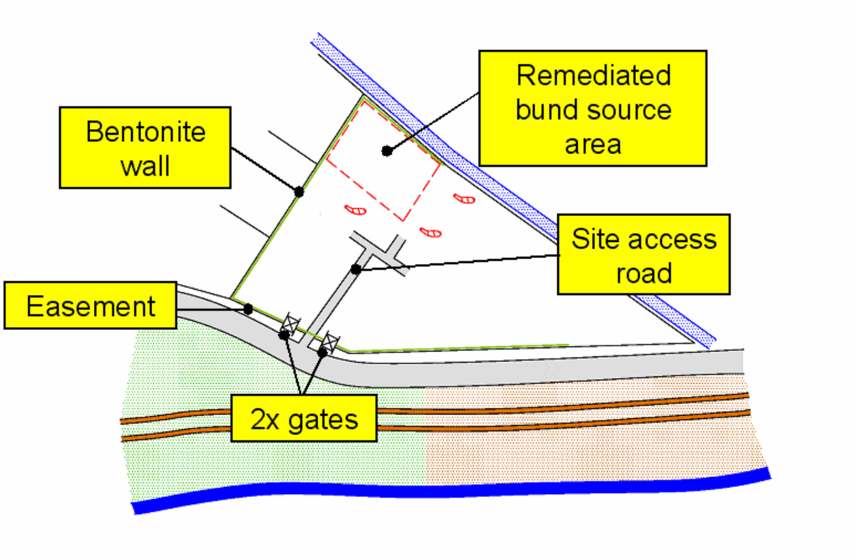


Figure 4.5: Schematic layout of PRB adopted for the basis of design

4.6.1.3 Slurry wall

The slurry wall was designed to be continuous and to extend to a depth of approximately 1.5 m below the surface of the Glacial Till along the entire design length. Each PRB gate was to be constructed by removing the part of slurry wall above the base of the sand and gravel. The flowpath through the Glacial Till will, therefore, be the same length under the gate as under the slurry wall, reducing the potential for underflow via the Glacial Till beneath the PRB gate.

Any junctions or contacts between the gate and the wall, and around the reactor vessel within a gate, were to be sealed appropriately and tested to ensure that preferential groundwater flow paths did not develop.

4.6.1.4 Direction of flow through reactor vessels

The internal arrangement of the reactors must not provide significant opportunities for parts of the water flow to bypass some or all of the reactive iron. To avoid this, the direction of the flow in each reactor is vertical. The direction of flow is downwards in the first reactor in each treatment line. Thus any significant clogging will occur at the upper surface, where replacement can easily be performed, if required.

4.6.1.5 Material durability

Appropriate materials were selected that will not be adversely affected by groundwater chemistry:

- Concrete structures have a design life of 30 years;
- Equipment items have a design life of 20 years; and
- Reactive media will have a design life of at least 10 years prior to replacement but could be reactivated at any time after 5 years.

The known low vertical permeability of the Glacial Till significantly reduced the risk of bypassing of the PRBs by underflow or vertical downward migration.

4.6.1.6 CS_2 half-life

The PRB reactive media was that produced by Connelly, for reasons of ready availability in the necessary quantity.

Based on the maximum CS_2 half-life of 2.63 hours on Connelly iron and a temperature correction factor of 1.8, a half-life of 4.7 hours was taken for the PRB gate design.

4.6.1.7 Reactive iron permeability and porosity

Information supplied by the manufacturers gives the permeability of the Connolly iron as around 5×10^{-4} m/s, whereas the column testing gave lower values in the range 2.4×10^{-4} to 2.7×10^{-4} m/s. It is concluded that the columns have been compacted to a higher density and that the field case should be taken to be the higher value.

Laboratory porosity was measured at 52%. However, the licence holders of reactive iron technology for chlorinated solvent application (ETI, pers. comm.) recommended a porosity value of 40% for full-scale reactors based on experience with reactive iron PRBs elsewhere.

4.6.1.8 Contaminant flux and vertical stratification

An estimate of worst-case contaminant flux can be derived by multiplying the gate flow rate by 10 mg/l, which is the estimated maximum long-term concentration reaching the PRB gates after other remediation works. Based on a 10 year total gate throughput of 75 m^3/day, this would equate to a total degraded CS_2 mass of 2.74 tonnes. This value is considered conservative for long-term conditions since some natural attenuation may occur (CS_2 is biodegradable at moderate concentrations; e.g., Smith & Kelly, 1988; Hartikainen et al., 2002; Jordan et al., 2002). The system was also designed to tolerate short-term peaks of up to 100 mg/l.

Groundwater contamination may exhibit vertical stratification, but this has not been monitored in the PRB gate area. To maximise efficiency and longevity of PRB the influent concentrations should be uniform. Homogeneity of the influent groundwater was enhanced by inclusion of a gravel-filled trench on the upgradient side of the PRB.

4.6.1.9 Passivation

The laboratory test data (Section 4.1) indicated that approximately 1500 pore volumes resulted in passivation of some of the iron column. In combination with estimates of fluxes through the PRB, a rate of passivation of the PRB is estimated as 20,000 mg CS_2 per kg iron, or approximately 2%. Calculations based on this assumption derived the total weight of iron necessary within the gates. This is a conservative assumption as it takes no account of natural attenuation by volatilisation, sorption or biodegradation.

4.6.1.10 Biofouling

The chemical environment within a packed bed iron reactor is moderately acidic and thus would normally reduce biological activity. Experience and literature sources suggest that upgradient diffusion of iron and redox conditions for continuous walls does enhance some microbial activity, and downgradient microbial activity has also been observed. Biofouling within a continuous wall or reactor has not generally been observed to be a significant effect (RTDF 2003; Gu *et al* 1999; Vidic 2001).

Microbial activity can, however, occur in the reactor. The design therefore limited the amount of open water with long residence times to minimise the generation of biofilms.

4.6.1.11 Mineral precipitation

The performance of any PRB system is affected by hydrochemically-induced changes. These were assessed in the laboratory trials and conservatism applied to these based upon the experiences of the design team.

Significant mineralogical fouling due to site water conditions was not observed during the treatability study.

The major risk of chemical fouling or a change in half-life is related either to:

- A significant increase in the Eh of the reactor; or
- A significant change in the pH of water entering the reactor.

Both of the conditions would require a significant external change in groundwater flow.

The basis of design was nevertheless specified to assume a clog zone thickness (0.2 m) and permeability (4.3 m/d) at the upgradient end of the PRB. Additionally, predictive modelling was carried out, based on an overall reduction in permeability by a factor of 10 during the operating lifetime of the gate media (10 year design life).

4.6.1.12 Gas production

Hydrogen is inevitably generated in PRBs via a redox-controlled reaction between iron and water and is chemically stable under the redox state and pH conditions that are anticipated within this system. The reaction will progress until equilibrium is reached.

Except for gas-tight systems, there is no evidence that reactive iron PRBs have suffered from excess hydrogen generation, which suggests that hydrogen is easily discharged by diffusion to atmosphere and dissolution into the surrounding groundwater. However, to prevent blinding of the iron bed with gas bubbles and ensure safety, some form of venting system is required.

The system must also consider the generation of odorous compounds, particularly mercaptans and other organosulphur compounds generated during anaerobic microbial activity. Although samples from the laboratory column tests indicated that there were no significant changes in mercaptan concentrations in water samples from the columns and effluent nor a significant difference in perceived odour, the potential for their presence in off-gas from the gate must be considered to avoid nuisance.

4.6.2 HYDROGEOLOGICAL DESIGN

A transient MODFLOW model was first built for the pre-development conceptual model (Figure 3.13). The model comprises a single unconfined aquifer layer, representing the sand aquifer, where there is no consideration of vertical flow. The model is 810 m wide and 850 m long, with cells of 10 m x 10 m, resulting in a grid of 85 by 116 cells. Recharge was applied to the top surface of the model. The underlying Glacial Till was assumed to be a no flow boundary. Sub-site structures that may represent fast flow pathways were represented in the model as high permeability cells.

Figure 4.6 shows selected modelled and observed hydrographs for the calibrated model.

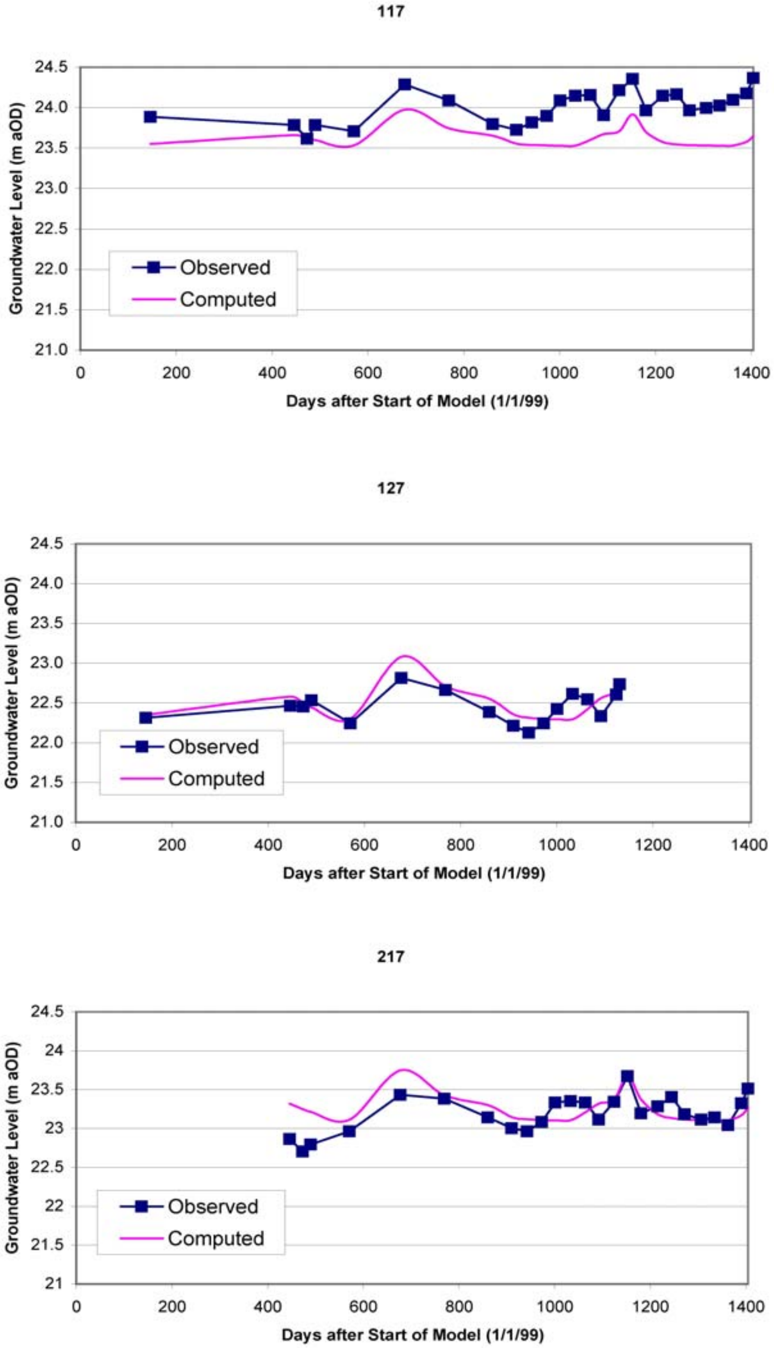


Figure 4.6: Example modelled and observed hydrograph from MODFLOW groundwater model and associated measured data

The hydrographs in general showed a good reproduction of average groundwater levels and amplitude of fluctuation. In particular, the behaviour at borehole locations 127 and 5052, up hydraulic gradient of the proposed location of the PRB, was simulated successfully. The water balance results for the transient calibrated model are shown in Table 4.5.

Table 4.5: Water balance for transient calibrated MODFLOW model

Flow Component	**Inflow to aquifer (m^3/d)**	**Outflow from Aquifer (m^3/d)**
Storage	41.5	0
Constant Head	70.0	277.9
General Head Boundary	112.9	0.8
River	136.6	0
Drain	0	82.3
Recharge	0	0
Total Inflow/Outflow	**361.0**	**360.9**
Percentage Error		**0.015**

The calibrated model of the current site was then used as the basis for developing a predictive model to simulate groundwater flow through the PRB. The objectives of the predictive model were to:

- Establish the optimum combination of location and extent of the impermeable slurry walls and size of the PRB gates to effectively capture the contaminant plume whilst minimising the capture of uncontaminated groundwater by the PRB.

- Estimate the hydraulic flux through the PRB gate(s) (initial and over the following 10 years), allowing for other scheduled remedial works and the currently envisaged future development plans.

- Estimate groundwater levels across the site after installation of the PRB (over the following 10 years), allowing for other scheduled remedial works and the currently envisaged future development plans.

Initial model runs were undertaken to assess the optimum combination of impermeable wall length and gate geometry. Following review of the model results and feedback from other parts of the design team regarding engineering requirements and reaction rates, the optimum geometry was selected:

- Impermeable bentonite slurry wall layout as per Figure 4.7, including a “kickback” length of circa 140 m to prevent by-pass flow of potentially contaminated groundwater around the eastern end of the wall, whilst minimising the capture of uncontaminated groundwater.

- Two reactive gates, each having a width (perpendicular to groundwater flow) of circa 7.5 m and a length (parallel to groundwater flow) of circa 6.25 m.

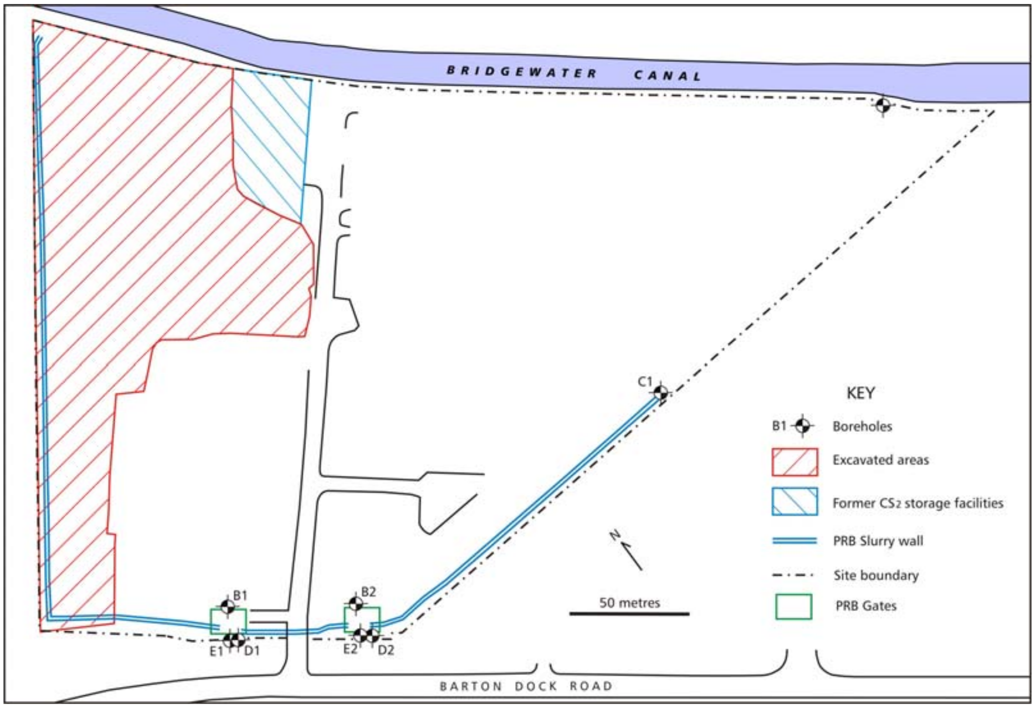


Figure 4.7: Final configuration of PRB system, based on engineering and hydrogeological design considerations

Based on this geometry, the predicted water balance for maximum and minimum-case hydraulic conductivity of the gates is presented in Tables 4.6 and 4.7. Figures 4.8 and 4.9 show the hydraulic head geometry behind the gates for these cases. As the gate flow rate used for the PRB gate design is a total of 75 m^3/day and the acceptable upgradient head increase was 1.2 m, the results demonstrated that the system would have no detrimental effect on site groundwater levels nor on regional groundwater flow.

Table 4.6: Water balance (m^3/d) for model with gate hydraulic conductivity set to 27 m/d

Component	In	Out	Percentage flow	
Recharge to the site	6.6		Around the eastern slurry wall	64
Inflow from the north	184.3			
Outflow in the east around slurry wall		121.7	Through the gates	34
Outflow from the left gate		34.7		
Outflow from the right gate		30.3	Through slurry wall	2
Flow through slurry walls		4.04		
Total	**190.9**	**190.7**	**Total**	**100**

Table 4.7: Water balance (m^3/d) for model with gate hydraulic conductivity set to 5.27 m/d

Component	In	Out	Percentage flow	
Recharge to the site	6.6	1	Around the eastern slurry wall	75
Inflow from the north	173.3			
Outflow in the east around slurry wall		34.5	Through the gates	22
Outflow from the left gate		20.9		
Outflow from the right gate		18.2	Through slurry wall	3
Flow through slurry walls		6.09		
Total	**179.9**	**179.7**	**Total**	**100**

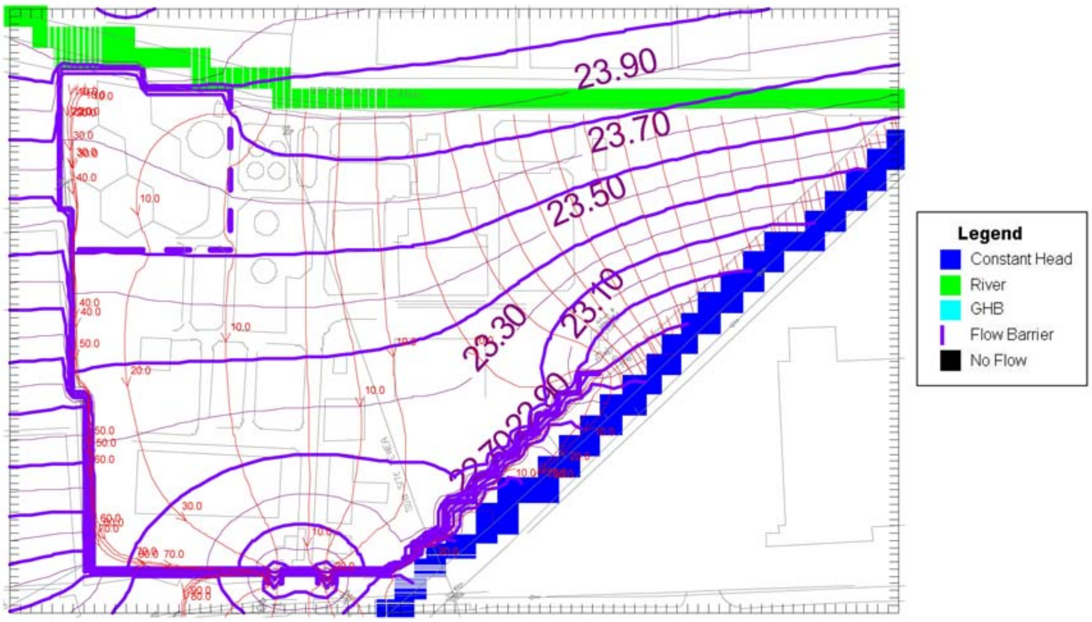


Figure 4.8: Modelled hydraulic head geometry behind PRB gate for gate hydraulic conductivity of 27 m/d

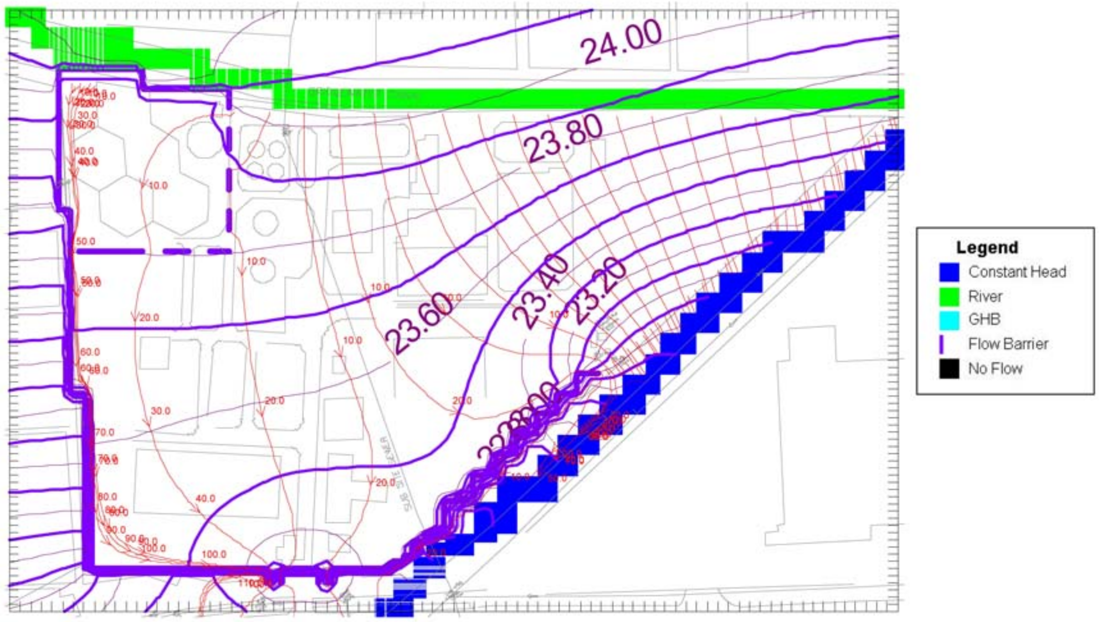


Figure 4.9: Modelled hydraulic head geometry behind PRB gate for gate hydraulic conductivity of 5.27 m/d

4.6.3 ENGINEERING DESIGN

The PRB was part of the overall remediation strategy, which involved removal of the source. The PRB system consisted of cement bentonite slurry walls that acted as a control to off-site migration of contaminant together with two reactive gates. The location of the slurry walls and gates are detailed in Figure 4.7.

4.6.3.1 Cement bentonite slurry wall

The cement bentonite slurry wall was constructed in line with the ICE Specification for the Construction of Slurry Trench Cut-off Walls (Institution of Civil Engineers, 1999).The slurry wall was installed as follows:

Length	-	550 m
Width	-	0.6 m (min)
Average Depth	-	6.5 m
Maximum Depth	-	8.5 m
Area	-	3575 m^2
Permeability	-	> 10^{-9} m/s at 90 days
Unconfined Compressive Strength	-	> 100 kPa at 28 days
Strain	-	no requirement in ICE Specification

The cement bentonite slurry was a mixture of ordinary Portland cement, ground granulated blast furnace slag, bentonite and water, which was weigh batched and mixed in high shear colloidal mixers. The slurry was pumped to the trench at an equal rate to excavation, which was undertaken using a modified 360° excavator.

The cement bentonite slurry wall was keyed into the underlying clay. Based on the site investigation data, it was concluded that a minimum penetration of 1.5 m into the underlying clay was required due to the presence of sand lenses in the top 0.5 m of the clay.

The use of cement bentonite slurry walls was preferred to alternatives such as sheet piling due to the slurry wall acting as a seal to the clay therefore eliminating downward flow paths for CS_2. Additionally, the slurry walls were constructed from a working platform with a minimum height of 1.5 m above the groundwater table and the slurry maintained close to working platform level to minimise the potential for trench collapse.

The cement bentonite trench raisings were coated in cement bentonite slurry and taken directly to holding cells with *ex situ* soil mixing under a Mobile Plant License to stabilise prior to disposal to landfill.

4.6.3.2 Permeable reactive gates

To some extent the placement of the PRB was constrained by the access road and easements. It was agreed that the location of the original site access road would continue to be used in the new development. Also, there were already some easements in place which affected the front entrance of the site. These factors partly influenced the decision to make the PRB a paired, rather than single, gate system, with the gates located either side of the access road, receiving an equal flow. New easements were established to protect the area where the PRB was sited and to allow for access once the site was redeveloped.

The gates were designed both to allow ease of construction and ease of access/decommissioning. Each individual gate consisted of two parallel treatment trains that allowed for ease of maintenance, as one treatment train could be taken off-line for maintenance. Each treatment train consisted of two in-line reactor vessels with the inlet reactor vessel having downward flow and the outlet reactor vessel having upward flow. This had the benefit of allowing for the future removal of fouled iron at the inlet, should this be necessary, by means of excavator at ground surface. The overall scheme was designed to produce a minimum head of 0.3 m between upstream and downstream of the gates with the reactor vessels working by gravity flow. At the upgradient and downgradient end of each gate was a gravel-filled bed with internal perforated pipes, connected to the appropriate reactors, to act as high permeability collectors and diffusers.

The reactors were pre-fabricated steel vessels of 5 m height x 3 m diameter into which 360 metric tonnes of reactive iron medium were placed (45 tonnes per canister). A highly permeable filter bed was placed under the iron within each reactor. The void above the upper surface of the iron in each reactor was not backfilled to allow easy access for maintenance or iron replacement. Pipework was minimal and valves were avoided to minimise future maintenance requirements. Vertical standpipe-type monitoring tubes were tapped into the pipework upstream and downstream of each reactor, enable monitoring of water quality and water level/pressure within the gate.

4.6.4 VALUE ENGINEERING

As some of the main costs of the PRB were attributed to capital expenditure, considerable time was spent reviewing the design to ensure it was as efficient as possible. Value engineering also improved safety on site, as well as constructability. The design was subjected to a thorough value engineering process, which considered many aspects of the gate design and construction, ranging from overall reactor design to constructability. The value engineering exercise involved all of the key team members, was systematic in its approach and sought the greatest savings from the least changes. Some examples of savings are provided below:

- The original design included a penstock valve based system to open and close the PRB. This was felt to be over-complex and open to an inherent problem of the flaps jamming over time. Instead, proprietary inflatable pipe plugs were placed into the interior of the PRB from the outside. When *in situ* and inflated, the PRB is closed. When deflated and removed for safe storage, the system is open.

- A decision was taken to pre-fabricate as much as possible off-site. One of the main components to be affected by this was the vessels that would contain the iron. Instead of concrete vessels being cast on site, steel canisters were pre-fabricated and imported onto site. This had many benefits as well as reduced construction costs. It minimised the risk to site personnel and made the structure relatively easy to dismantle, should this be required for unusual maintenance. The use of steel canisters also enabled the hydrogen offgas to be safely vented as it would not have been technically feasible to make concrete vessels gas tight.

- The initial design included a reinforced concrete wall between the slurry trench and the gravel. It transpired that this was only required as a temporary structural support until the slurry set, so timber bracing was used as a more cost-effective substitute.

- A reduction in time and improvement in safety was achieved by accurately pre-drilling the flange bases of the canisters, so that they could be easily aligned onto dowel pins. This minimised time required by site personnel in alignment and therefore time spent in the trench.

- In addition, 1-2% tolerance was built into the design of the flange faces, so that slight errors at the joints could be accommodated.

- The design of vents was simplified, reducing materials and improving the process.

- Where possible, proprietary equipment was specified, rather than custom-built.

4.6.5 CONSTRUCTION

The temporary works to allow installation of the reactive gate were designed around a sheet piled cofferdam with top and bottom propping. The propping systems employed were square hydraulic props without centre braces to allow installation of pre-manufactured canisters. The construction sequence was as follows:

- Initially, a 600 mm wide cement/bentonite slurry wall keyed 1.5 m into the underlying clay was installed around the perimeter of the 10 m square excavation with an enlargement at the joint with the site boundary slurry wall to eliminate potential flow paths that could be generated during the construction activities (see Plate 4.2a).

- Subsequently, interlocking LX16 sheet piles were installed through the slurry wall to a minimum depth of 9.5 m below ground level.

- The cofferdam was excavated to the top prop level at 2 m below ground level and proprietary (Mega Brace) hydraulic propping system installed.

- Excavation continued to 4.5 m below ground level and the bottom prop installed again using a proprietary (Mega Brace) hydraulic propping system.

- The excavation was continued to a datum level of 18.35 m AOD (approximately 6.1 m below ground level).

- The sheet pile pans were cleaned as the excavation progressed and the base of the excavation prepared for a concrete blinding layer.

- A 100 mm thick concrete blinding layer was laid over the entire excavation to seal the surface and allow for a safe working platform. The blinding layer was laid to a tolerance of +/- 10 mm.

- A reinforced concrete base 600 mm thick was designed to act as a base prop allowing the lower temporary prop to be removed and as a foundation base for the steel tanks. This concrete base was heavily reinforced and the reinforcement cages built in four sections at ground level, which were lowered into position and joined by overlapping steel bars. The steel reinforcement within the sheet pile pans was installed in place. This construction methodology allowed for minimal entry into the cofferdam and rapid construction.

- A C32/40 Pump & Plastic concrete, made with sulphate resisting portland cement (SRPC), was pumped into the base of the excavation and the surface of the slab finished with a power float to produce a flat surface for the canisters to sit.

- A specialist steel fabrication company supplied the PRB canisters, which were 5 m high by 3 m internal diameter with a steel wall thickness of 8 mm. The design of the canisters had to take into account both the lifting loads, installation loading and worst case loading of canisters being full without lateral support. The canisters were also primed and coated with a specially formulated paint to minimise potential corrosion. The canisters were supplied with all pipework and flexible couplings.

- The PRB canisters were lifted from the horizontal to the vertical using a ‘top and tail’ with two mobile cranes.

- The concrete slab was prepared by installing two positioning bolts for each canister. The canisters were lowered on to the positioning bolts and other holding bolt positions marked, drilled and set in resin. Subsequently, the canister was fixed using washers and nuts. The canisters and connecting pipework for each gate were installed in a single working shift.

- Shutters were installed against the upstream and downstream face of the gate. These were installed to allow for the zone around the canisters to be filled with cement/bentonite grout to minimise potential short-circuiting of the water. The cement/bentonite grout was installed in 1 m lifts with a minimum curing period of three days between successive pours. After each pour the external face of the shutter was infilled with 2 to 6 mm sand. A more robust system would have been to install a concrete or brick wall, which would have been a low maintenance option allowing increased production.

- The cement/bentonite grout was placed to 0.5 m below the top of the canisters and foam concrete placed to within 0.1 m of the top of the canister.

- The 2 to 6 mm sand was placed on the external face of the shutter to a depth of 2.5 m below ground level. Above this level clay was placed and compacted to ground level.

- The slotted high density polyethylene pipework that acted to connect canisters was placed into the base of each canister. These were prefabricated at ground surface and dropped into pre-cut holes in the canister stiffeners and clamped into place. A 6 mm single sized gravel was placed into the base of the canister to provide a 100 mm cover. A terram layer was placed as a geotextile separator between the gravel and zero-valent iron (ZVI).

- Subsequently, the canisters were filled with ZVI, which was produced by Connelly. The density of the delivered ZVI was calculated using delivered materials by a small-scale site test. The ZVI was emptied from the bags into a concrete skip with load cell. The concrete skip was lifted by crane and placed over the first canister and emptied into the canister. At regular intervals the ZVI was levelled and depth measurements taken which were assessed against mass placed to provide an indication of the density during placement. By careful placement the variation in density against that required by the design was minimal.

- The ZVI was placed to the required level and the lid placed on the canister. This process was repeated on all eight canisters.

- On the upstream and downstream face of the sheet piles a 5 m trench was installed and a sand/gravel mixture added to 2 m below ground level which was topped up to ground level with placed and compacted clay. This was to provide a permeable entrance/entry for the PRB gates.

- Subsequently, the sheet piles were removed using a crane hung vibratory hammer. However four sheet piles were left *in situ* at the joints between the PRB and the connecting slurry walls. These were left in place so as to minimise the potential for producing leakage paths.

- At all stages the inlet and outlet pipes were blocked using inflatable air bags.

- The gas venting pipework was installed and connected to the gas venting/treatment plant.

- The above ground civil engineering works, involving accesses, hardstandings, fencing and soft landscaping, were completed to provide a fully accessed compound designed to allow maintenance.

- The gas treatment plant involved mercaptan scrubbing using granular activated carbon (GAC) with appropriate water drainage points. Additionally, a passive gas venting stack with a flame arrestor was installed to deal with H_2 generated from H_2O/ZVI reactions. This system both removed odours from the gas and also minimised potential for flash back associated with ignition of the gas venting system.

- The system was opened by removing the inflatable pipe plugs and could be closed at any time by placing and re-inflating.

Plates 4.2a-g show the process of constructing the PRB.

Plate 4.2a: Line of slurry wall along western side of site

Plate 4.2b: Canisters *in situ* within a gate.

Plate 4.2c: PRB canisters

Plate 4.2d: Installation of filter bed

Plate 4.2e: Filling canisters with zero-valent iron

Plate 4.2f: Western gate close to completion

Plate 4.2g: Complete eastern gate

Constructability issues were developed to minimise health and safety risks both during construction and throughout the life of the gate, as required by CDM regulations. Specific issues addressed included:

- Minimisation of the need for groundwater control and the pumping of contaminated groundwater;
- Elimination of the requirement for complex construction activities;
- Use, so far as was practicable, robust and simple water industry technology to form the gate structures;
- Maximisation of the use of pre-cast or pre-assembled materials to reduce the intensity of on-site construction. This had additional benefits in terms of reduced procurement and construction timescales;
- Gate construction and commissioning to take place without the need for excessive temporary works; and
- Safety and cost-effectiveness in monitoring, maintenance and decommissioning, particularly, the need for human access into the reactor vessels was virtually eliminated.

Plate 4.3 shows the site during remediation works, prior to construction of the PRB. Approximate future PRB gate locations marked in red. Plates 4.4 and 4.5 show the developed site, post construction of the PRB, with the PRB positions also shown in red.

Plate 4.3: The site during remediation works, prior to construction of the PRB. Approximate future PRB gate locations marked in red.

Plate 4.4: The developed site, post construction of the PRB, with the PRB positions shown in red.

Plate 4.5: Entrance to the developed site, post construction of the PRB, with the positions of the eastern gate canisters shown in red (Photograph courtesy of Commercial Development Projects Ltd).

The gates were commissioned on 25 November 2004.

5. PRB OPERATION

5.1 MONITORING PROGRAMME

A monitoring plan was developed in line with Sections 6 and 7.3 of the Environment Agency (2002) guidance on PRBs and submitted for Environment Agency approval. The objectives of the programme were developed from trigger and operational control values that could indicate loss of PRB performance, specifically:

- Influent and effluent concentrations of contaminants and geochemical parameters;
- Hydraulic head build-up beyond operational limits; and
- Influent and effluent flow rates.

Measured values that exceed those specified in the approved monitoring plan trigger further investigation and defined corrective actions, including:

- Increasing monitoring;
- Review of conceptual model;
- Repair of PRB gate;
- Investigation of condition of media; and
- Reactivation of media or replacement.

The design of the monitoring points encompassed upstream and downstream groundwater monitoring boreholes, sample points within the PRB and a borehole placed to detect any bypass flow occurring around the eastern end of the impermeable barrier (Figure 5.1). Boreholes A, B, C and E were completed in the sand and gravel horizon to monitor upstream and downstream groundwater quality in the shallow aquifer. Borehole D is completed within the upper metre of the Glacial Till to confirm that no significant contaminant flow is occurring through this matrix. Borehole logs are provided in Appendix 1. Within the PRB itself, 12 monitoring points are installed (1PRB to 12PRB): 6 in the western and 6 in the eastern PRB. Within each PRB the wells are installed in pairs, such that two wells monitor the upgradient end of the PRB, two monitor the mid-section and two monitor the downgradient end (Figure 5.2).

The frequency of monitoring (Table 5.1) was intensive during the initial six months post-commissioning, at a lower frequency through to the third year of operation, with annual sampling anticipated from year four. The undertaking of significant maintenance works will trigger a period of more intensive monitoring to confirm resumption of design performance. This report solely considers the six month post-commissioning monitoring period, which was undertaken by the project team.

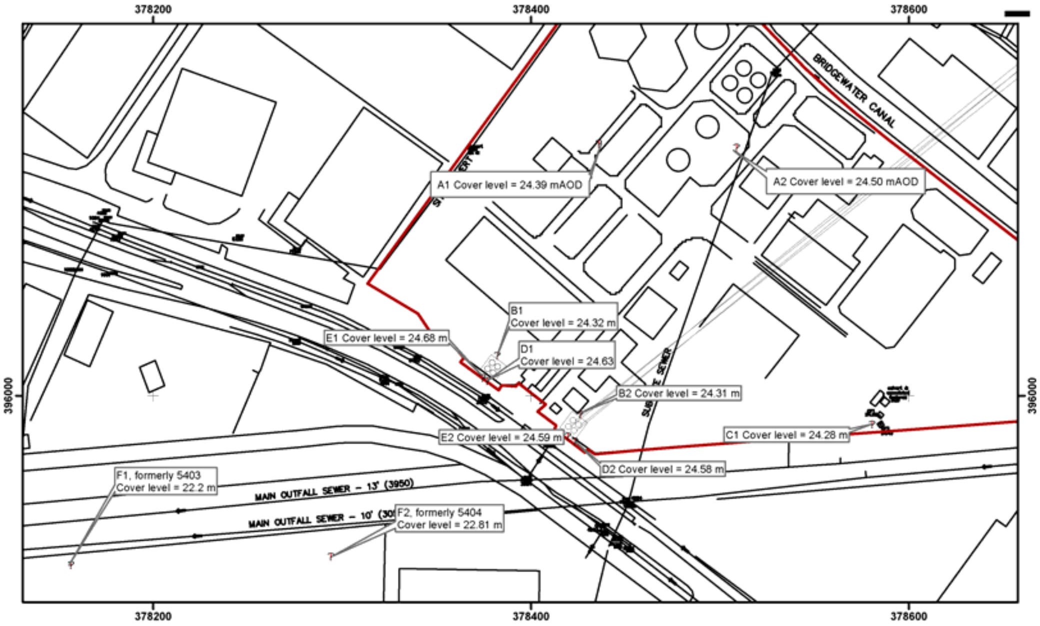


Figure 5.1: Location of monitoring boreholes

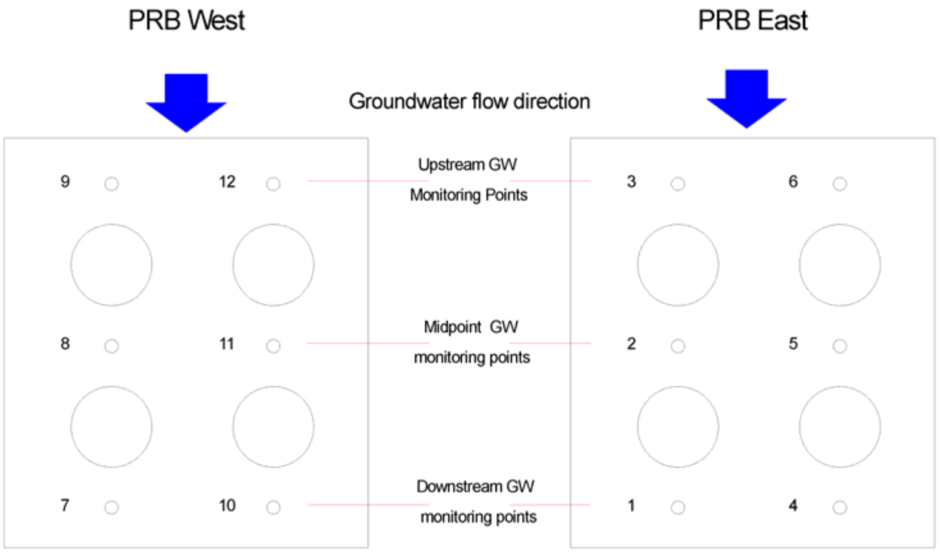


Figure 5.2: Monitoring points within the PRB

Table 5.1: PRB monitoring schedule

Time after commissioning	Measurement	Frequency
0 – 6 Months	Groundwater Levels	15 Mins (data logger) Monthly Download
	Field Measurements	Monthly
	Organic Suite	Monthly
	Inorganic Suite	Monthly
	Monitoring points within PRB	Monthly
6 Months – 2 Years	Groundwater Levels	Monthly
	Field Measurements	Quarterly
	Organic Suite	Quarterly
	Inorganic Suite	Quarterly
	Monitoring Points within PRB	Quarterly
2 Years - Decommissioning	Groundwater Levels	Quarterly
	Field Measurements	Quarterly
	Organic Suite	Annually
	Inorganic Suite	Annually
	Off-gas monitoring	Annually
	Monitoring points within PRB	Annually
Post-Maintenance[1]	All Parameters	Monthly measurements to be taken for 3 months after maintenance works to ensure effectiveness of works
Post-Closure	To be determined subject to review of operational monitoring data	

[1] Monitoring contingency to be undertaken in the event of significant maintenance works to PRB gates (e.g., partial or complete replacement of reactive iron)

5.2 POST-COMMISSIONING MONITORING

Post-commissioning monitoring took place on six occasions between January and July 2005:

- 12 – 13 January 2005 ("January" round);
- 25 February 2005 ("February" round);
- 31 March – 1 April 2005 ("March" round);
- 4 – 5 May 2005 ("May" round);
- 14 – 15 June 2005; and
- 14 – 15 July 2005.

5.2.1 METHODS

Prior to sampling each month, groundwater levels were measured by dipping. Thereafter, each well was purged, ideally by the removal of at least 30 l (or three well volumes) of groundwater. In some cases, this quantity could not be removed without the well running dry, so that samples were taken following purging of less than 30 l water. Groundwater level data logging was performed using Van Essen Diver DI240 loggers and a Solinst Barologger 3001 barometric pressure transducer. Data were downloaded at monthly intervals to PC.

Samples were taken and labelled with the sample location point, date and project number. Samples were stored, transported and delivered in a cool box to ALcontrol Laboratories in Chester either on the day of sampling or by overnight courier.

Following sampling, field parameters were determined using field meters attached to a flow cell, which in turn was connected to a battery operated whale pump. The pump was run for a period of at least two minutes and then an initial reading of the field parameters taken. A further reading was taken once the meters had stabilised. A limited number of boreholes ran dry during sampling. These wells were left to recover and a sample was collected using a bailer. Field parameters were measured from these bailed samples.

5.2.2 RESULTS

5.2.2.1 Groundwater elevations

Table 5.2 presents the data for groundwater elevations measured manually before sample collection and water levels from the post-commissioning monitoring and from through the PRB gates are shown in Figures 5.3 and 5.4 respectively.

5.2.2.2 Field determinations of water chemistry

The field data for pH, temperature, dissolved oxygen and electrical conductivity (Figures 5.5 and 5.6) appear broadly consistent across the sampling rounds. A limited number of outliers were obtained, namely:

- A few abnormally low pH readings in May;
- Apparently inconsistent Eh readings in February and March; and
- A few unrealistically elevated dissolved oxygen readings in May.

5.2.2.3 Results of chemical analyses

The results of the laboratory chemical analyses are also presented in Appendix 2 while hydrochemistry data is discussed fully in Section 5.2.3.3.

5.2.2.4 QA/QC samples

Blank samples (labelled PRB20 and PRB21) of deionised water were submitted to the laboratory following the sampling rounds of February, March and May. In general, these blanks confirmed the integrity of the analysis, returning values close to or below the detection limits for most analyses. The following minor discrepancies were noted:

- Iron. Blanks for February exhibited iron concentrations in range 30-60 µg/l, casting some doubt on the accuracy of groundwater samples showing low concentrations of iron.
- Chloride. Blanks consistently showed concentrations of 6-7 mg/l, suggesting either contamination of blank de-ionised water or residual signals in analytical apparatus.
- Total dissolved solids (TDS). Blanks for February exhibited elevated concentrations of TDS and higher than expected pH values for de-ionised water in atmospheric equilibrium.
- Volatile organic compounds (VOCs). Blanks from February and March were reported to contain 13-16 µg/l chloroform, suggesting either false analytical detects or minor sample contamination. These values are still well below those detected in the field samples, however.

Table 5.2: Pre-sampling "dipped" groundwater levels for the 2005 post-commissioning monitoring period

Sample point	**Jan**	**Feb**	**Mar/ Apr**	**May**	**Jun**	**Jul**
	m AOD	**m AOD**	**m AOD**	**m AOD**	**m AOD**	**m AOD**
Upgradient of PRB						
A1	22.80[1]	22.58	22.32	22.41	-	-
A2	22.47	22.30	22.19	22.22	22.15	22.04
C1	23.07	22.90	22.71	22.65	-	-
Eastern PRB						
B2		22.67	22.35	23.28	-	-
3PRB	22.87	22.66	22.36	22.49	22.27	22.14
6PRB	22.89	22.67	22.36	22.52	22.3	22.15
2PRB		21.77	21.76	21.77	21.77	21.78
5PRB		21.78	21.76	21.78	21.77	21.78
1PRB	21.96	21.65	21.41	No data	21.36	21.25
4PRB	21.95	21.66	21.41	No data	21.36	21.25
E2	22.02	21.61	21.37	22.49	21.34	21.24
D2	21.89	21.63	21.38	21.43	21.33	21.22
Western PRB						
B1		22.44	No data	22.22	-	-
9PRB	22.43	22.13	21.87	21.98	21.85	21.79
12PRB	22.42	22.13	21.88	22.03	21.84	21.8
8PRB		22.11	21.87	21.95	21.8	21.78
11PRB		22.10	21.85	21.94	21.79	21.75
7PRB	22.38	22.10	21.86	21.98	21.8	21.64
10PRB	22.38	22.11	21.88	21.95	21.8	21.67
E1	21.86	21.63	21.43	21.44	21.36	21.22
D1	21.84	21.63	21.43	21.73	21.44	21.43
Downgradient of Site						
F2	21.84	21.71	21.56	21.51	21.31	21.14
F1	21.58	21.47	21.20	21.25	21.06	20.9

[1] Water level measured during removal of data logger

Data are expressed as elevations in metres Above Ordnance Datum (m AOD).

Yellow shading shows monitoring points within the PRBs; blue shading shows monitoring wells screened into the Glacial Till.

5.2.3 DISCUSSION

5.2.3.1 Groundwater elevations

The observation wells generally show a steady decline in groundwater head both inside and outside the site from January to July. Several boreholes exhibit a limited recovery of level in May (Figure 5.3). Within the PRBs themselves, water levels reflect these broad seasonal trends.

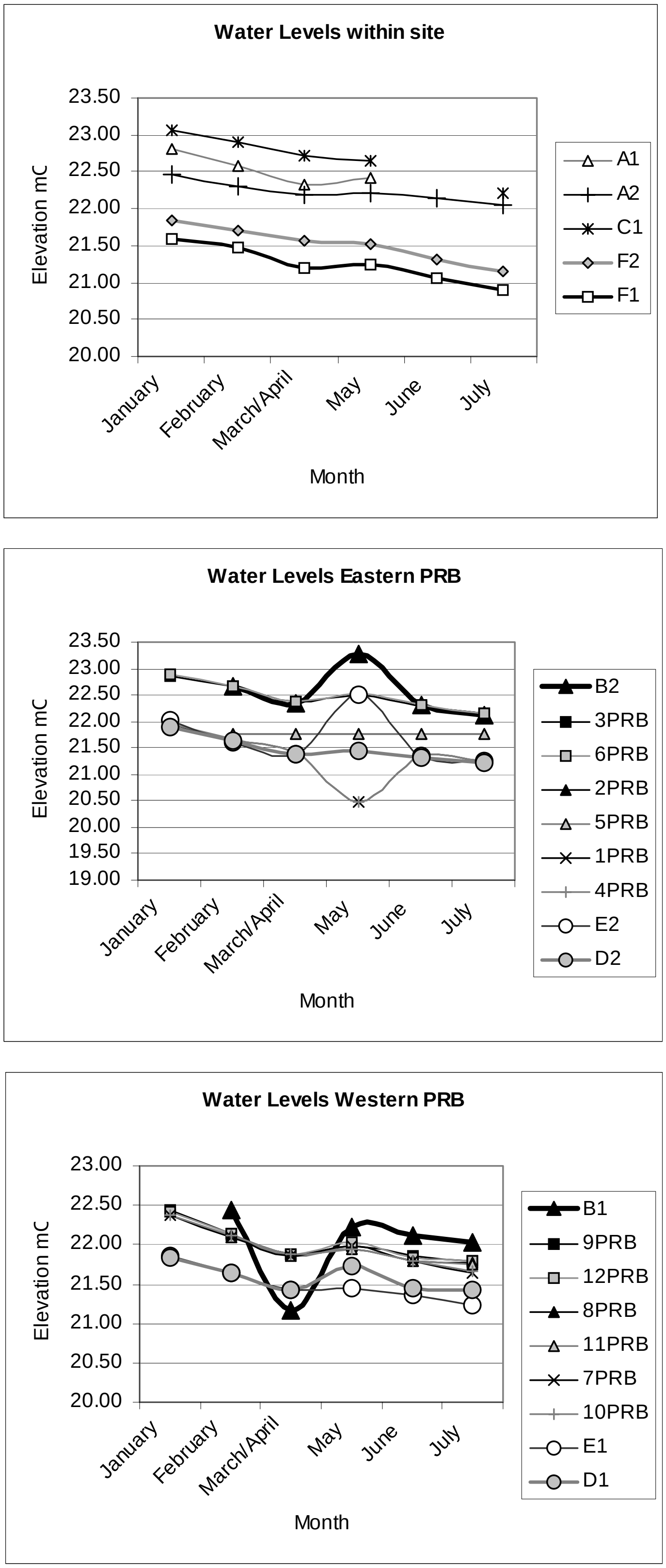


Figure 5.3: Measured groundwater elevations during the post-commissioning monitoring period

5.2.3.2 Hydraulic gradients through gates

Figure 5.4 plots the groundwater head gradients through the PRBs. Casting aside the dubious data points (highlighted in red), it will be seen that the desired southerly groundwater gradient is observed throughout the monitoring period in both gates. The gradient does not vary substantially: the absolute levels merely vary with seasonal trends.

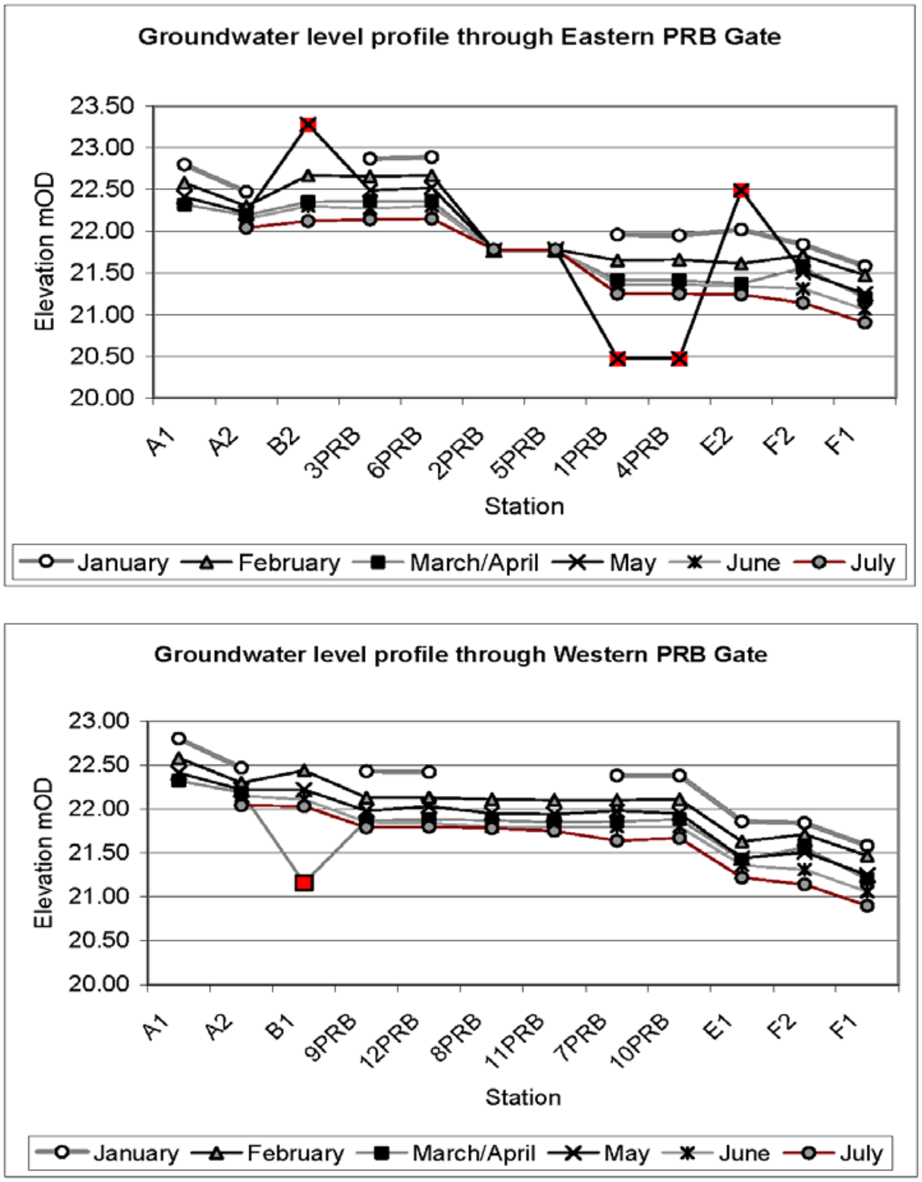


Figure 5.4: Hydraulic head gradients through the PRB gates

Firstly, the difference between the “B” and “E” Series boreholes can be used to calculate the overall gradient across the gates (Table 5.3). These are found to typically be around 0.06 for the western gate and 0.075 for the eastern gate.

Table 5.3: Calculation of hydraulic gradients through PRB gates based on data from B and E Series boreholes during the 2005 post-commissioning monitoring period.

	Feb	Mar/Apr	May	Jun	Jul
Western PRB					
B1 Elevation	22.44	21.16	22.22	22.11	22.03
E1 Elevation	21.63	21.43	21.44	21.36	21.22
Distance	13	13	13	13	13
Gradient	0.062		0.060	0.057	0.053
Eastern PRB					
B2 Elevation	22.67	22.35	23.28	22.30	22.12
E2 Elevation	21.61	21.37	22.49	21.34	21.24
Distance	13	13	13	13	13
Gradient	0.082	0.075	No data	0.074	0.068

Shaded cells indicate questionable data.

For each gate, the February, March/April, May, June and July data sets were considered to calculate the gradient within the PRB in more detail (Tables 5.4 and 5.5).

Table 5.4: Calculation of hydraulic gradients through Western PRB Gate based on data from PRB Monitoring Points.

	Feb	Mar/Apr	May	Jun	Jul
9PRB Elevation	22.13	21.87	21.98	21.85	21.79
8PRB Elevation	22.11	21.87	21.95	21.80	21.78
7PRB Elevation	22.10	21.86	21.98	21.80	21.64
Distance 8-9	4.7	4.7	4.7	4.7	4.7
Distance 7-8	4.0	4.0	4.0	4.0	4.0
Distance 7-9	8.7	8.7	8.7	8.7	8.7
Gradient 8-9	0.004	0.000	0.006	0.011	0.002
Gradient 7-8	0.002	0.003	-0.008	0.000	0.035
Gradient 7-9	0.003	0.001	0.000	0.006	0.017
12PRB Elevation	22.13	21.88	22.03	21.84	21.80
11PRB Elevation	22.10	21.85	21.94	21.79	21.75
10PRB Elevation	22.11	21.88	21.95	21.80	21.67
Distance 11-12	4.7	4.7	4.7	4.7	4.7
Distance 10-11	4.0	4.0	4.0	4.0	4.0
Distance 10-12	8.7	8.7	8.7	8.7	8.7
Gradient 11-12	0.006	0.006	0.019	0.011	0.011
Gradient 10-11	-0.002	-0.007	-0.002	-0.003	0.020
Gradient 10-12	0.002	0.000	0.009	0.005	0.015

Within the Western Gate (Table 5.4), gradients are very low. This indicates that the PRB fill is permeable relative to the natural aquifer material and most of the head loss across the gate appears to be taking place in the natural medium. There is a very slight tendency for gradients between the upstream pairs of monitoring points to be larger than the downstream pairs.

Within the Eastern Gate (Table 5.5), gradients are similar to those in the natural aquifer material and most of the head loss across the gate appears to be taking place within the PRB itself. There is a significant tendency for the gradients between the upstream pairs of monitoring points being larger than the downstream pairs.

Table 5.5: Calculation of hydraulic gradients through Eastern PRB Gate based on data from PRB Monitoring Points

	Feb	Mar/Apr	May	Jun	Jul
3PRB Elevation	22.66	22.36	22.49	22.27	22.14
2PRB Elevation	21.77	21.76	21.77	21.77	21.78
1PRB Elevation	21.65	21.41	20.47	21.36	21.25
Distance 2-3	4.7	4.7	4.7	4.7	4.7
Distance 1-2	4.0	4.0	4.0	4.0	4.0
Distance 1-3	8.7	8.7	8.7	8.7	8.7
Gradient 2-3	0.189	0.128	0.153	0.106	0.077
Gradient 1-2	0.030	0.088	---	0.103	0.133
Gradient 1-3	0.116	0.109	---	0.105	0.102
6PRB Elevation	22.67	22.36	22.52	22.30	22.15
5PRB Elevation	21.78	21.76	21.78	21.77	21.78
4PRB Elevation	21.66	21.41	20.47	21.36	21.25
Distance 5-6	4.7	4.7	4.7	4.7	4.7
Distance 4-5	4.0	4.0	4.0	4.0	4.0
Distance 4-6	8.7	8.7	8.7	8.7	8.7
Gradient 5-6	0.189	0.128	0.157	0.113	0.079
Gradient 4-5	0.030	0.088	---	0.103	0.132
Gradient 4-6	0.116	0.109	---	0.108	0.103

Shaded cells indicate dubious data quality.

Finally, it should be noted that, while there is a dominant southerly gradient through the PRB gates, the groundwater heads noted at A1 and A2 (within the contaminated site) are typically slightly lower than the heads recorded at the B series wells and at the inlet to the PRBs (particularly relative to the Eastern gate). This suggests that the main areas of contamination may not be migrating significantly.

5.2.3.3 Hydrochemistry data

The PRBs contain a medium, zero-valent iron, which is strongly reducing, itself being oxidised in groundwater to ferrous iron and, maybe, further to ferric species, in essence:

$$Fe^{o} \rightarrow Fe^{2+} + 2\varepsilon^{-}$$
$$Fe^{2+} + 3H_2O \rightarrow Fe(OH)_3 + 3H^{+} + \varepsilon^{-}$$

This oxidation can be coupled to a number of possible reducing reactions, for example, the reduction of oxygen (O_2) to water. As alternative electron acceptors, nitrate and sulphate can be reduced (the latter to sulphide, which can then precipitate as a ferrous sulphide within the PRB).

When the full equation for these redox reactions is written, it will be seen that they typically lead to consumption of protons and a rise in pH, e.g.:

$$4Fe^{o} + 8H^{+} + SO_4^{2-} \rightarrow FeS_{\downarrow} + 3Fe^{2+} + 4H_2O$$

Thus, through the PRB one would expect to observe:

- Decreasing O_2, NO_3^- and SO_4^{2-} concentrations;
- Decreasing redox potential;
- Increasing pH; and
- Concentrations of dissolved iron being potentially limited by formation of ferrous sulphides or ferric oxyhydroxides.

In terms of removal of contaminants, the basic reaction has been established (Section 4.4.4) to be:

$$CS_2 + 5Fe^0 \rightarrow 2FeS + Fe_3C$$

The iron sulphide and carbide produced would be subject to a series of complex, redox-sensitive reactions to yield iron hydroxides, sulphides and carbonates. Side reactions with chlorinated hydrocarbon co-contaminants present will also yield chloride on the site.

Figures 5.5 and 5.6 present graphically a selection of the data shown in Appendix 2. It will be observed that the predicted hydrochemical gradients are in fact observed in practice.

The field data show a degree of fluctuation between the various months of monitoring. However, within the core of the PRBs, measured dissolved oxygen contents are typically low (<4 mg/l), indicating removal of oxygen by oxidation of ZVI. At the centre and downstream ends of the PRB, very low Eh values of -200 to below -300 mV are observed in samples, indicating a more highly reducing environment than the dissolved oxygen data might suggest. In some sampling rounds, the lowest oxygen concentrations and Eh values are observed in the centre of the PRB, which may conceivably indicate diffusion of oxygen or other oxidising species into the PRB from the southern sides, as well as by advection from the northern side.

pH values are variable between monitoring rounds, and may be somewhat disturbed by ingress of surface water to the monitoring points. However, in most rounds, one may distinguish the predicted rise in pH through the PRB. For example, in May the field pH in the Western PRB rises from around 7.5-8.0 to almost 11 at the downstream end of the PRB.

Field electrical conductivity measurements are reflected by the laboratory determinations of TDS. In most sampling rounds, there appears to be an initial increase in electrical conductivity between the B series wells and the upstream PRB monitoring points, and then a decline between the upstream and mid-point pairs of monitoring points. The data in Figures 5.5 and 5.6 offer some explanation for this, as sulphate, manganese, magnesium and calcium appear to be removed within the first half of the PRB. Sulphate is presumed to be removed by reduction to sulphide. Dissolved sulphide was, in fact, detected at trace levels in the PRBs in the sampling rounds of February. Sulphide, once formed, is, however, likely to be removed by precipitation as iron sulphide. Calcium is likely to be removed by precipitation as calcium carbonate, due to pH elevation through the PRB.

Nitrate concentrations are generally below detection limits within the PRBs, and the nitrate concentrations present in the inlet water of the Eastern PRB appear to be removed by reduction within the first half of the PRB.

Mobile, conservative ions such as potassium, sodium and chloride are relatively unaffected by their passage through the PRB.

Iron concentrations in the "A" Series wells and B1 are rather high, possibly due to reductive mobilisation of ferrous iron in the reducing environment generated by the natural degradation of organic contaminants. The iron present in the water of B1 appears efficiently removed within the first half of the Western PRB, however, and dissolved iron concentrations within the PRBs are generally low (and, in some cases, undetectable), presumably due to iron being immobilised as insoluble sulphide or oxyhydroxide phases.

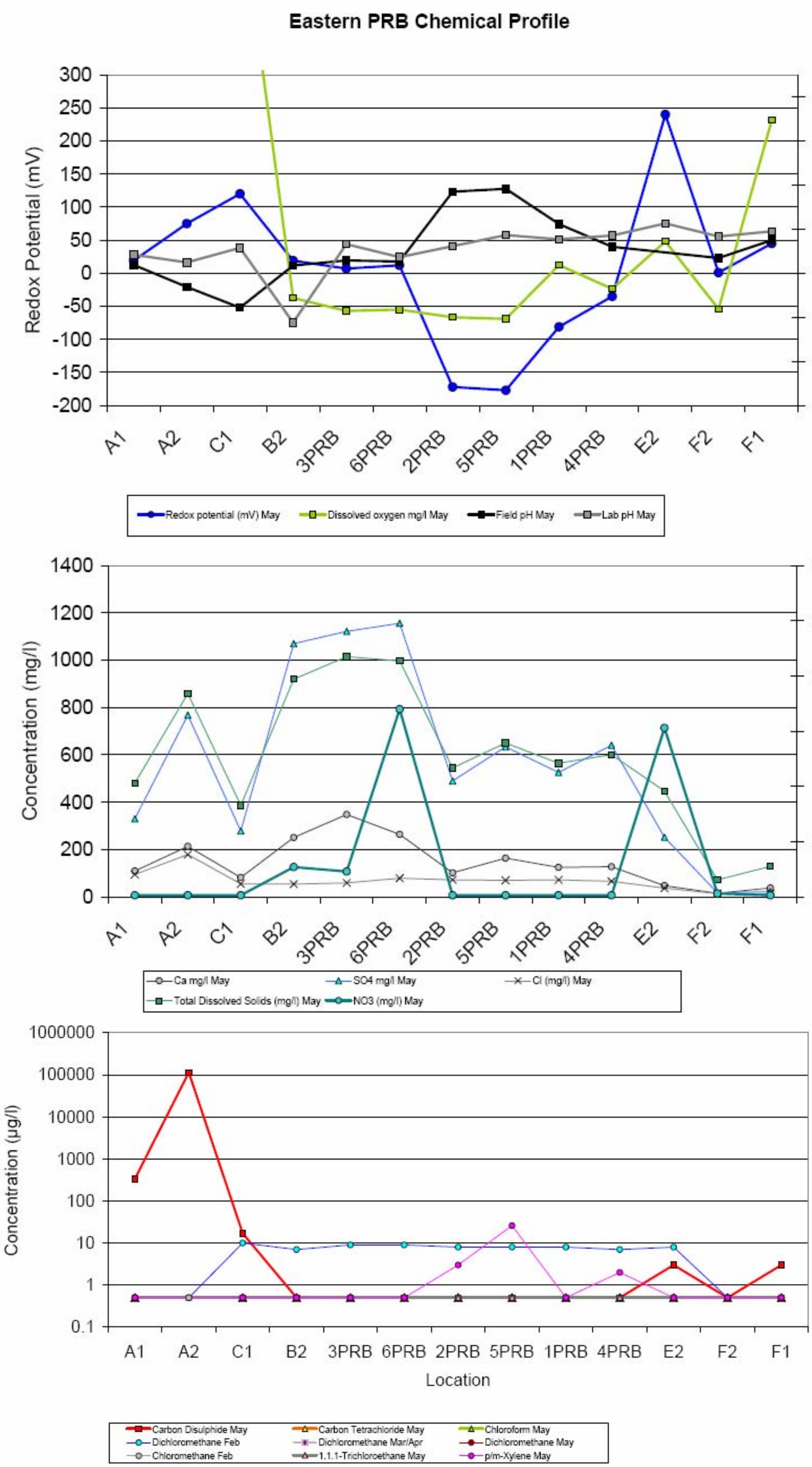

Eastern PRB Chemical Profile

Figure 5.5: Hydrochemical profiles of selected parameters through the Eastern PRB Gate

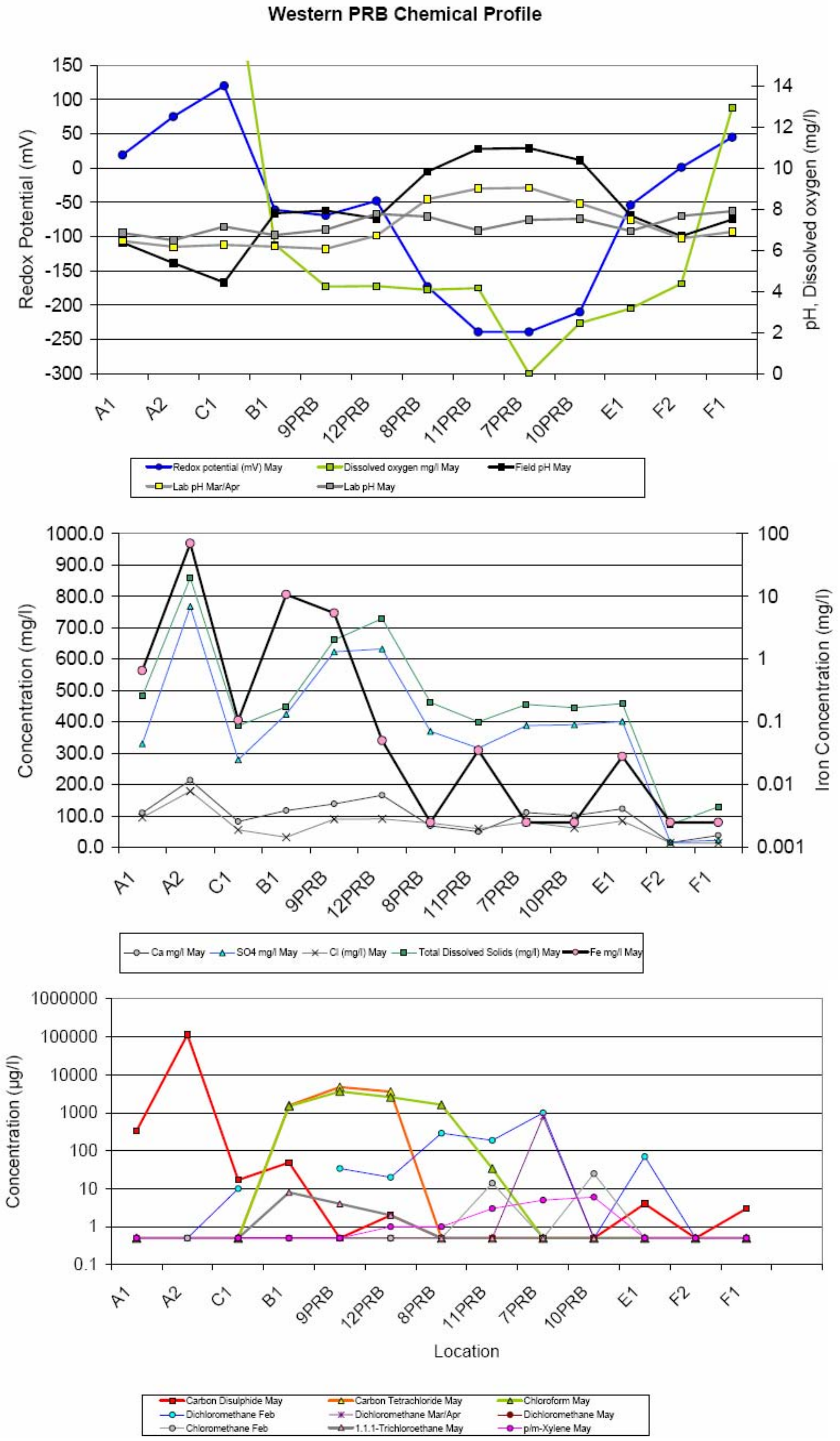


Figure 5.5: Hydrochemical profiles of selected parameters through the Western PRB Gate

5.2.3.4 Carbon disulphide data

CS_2 is present in the main part of the site in wells A1 and A2 at measured concentrations of up to 15 mg/l in A1 (although concentrations vary strongly from month to month) and up to 114 mg/l in A2. Only low concentrations (up to 17 µg/l CS_2) are observed in the lateral observation well C1, indicating that no bypass of CS_2 contaminated water has taken place.

Little CS_2 contamination appears to have migrated towards the Eastern PRB Gate, with concentrations below detection limit (<1 µg/l) being consistently reported from the PRB sampling points and well B2.

At the Western PRB Gate, concentrations of several tens of µg/l are observed in well B1. These concentrations appear to be very efficiently removed during passage through the PRB. Several detects (2 and 4 µg/l) were reported from the mid-point and downstream monitoring points.

At both D2/E2 and D1/E1, traces of CS_2 were detected on some individual sampling rounds (for example data, see Figure 5.7). In all cases, concentrations are <10 µg/l, well within the performance targets and considered a reflection of variability rather than a function of system performance. Low concentrations (up to 11 µg/l) of CS_2 were detected on three individual sampling rounds at F1/F2.

.

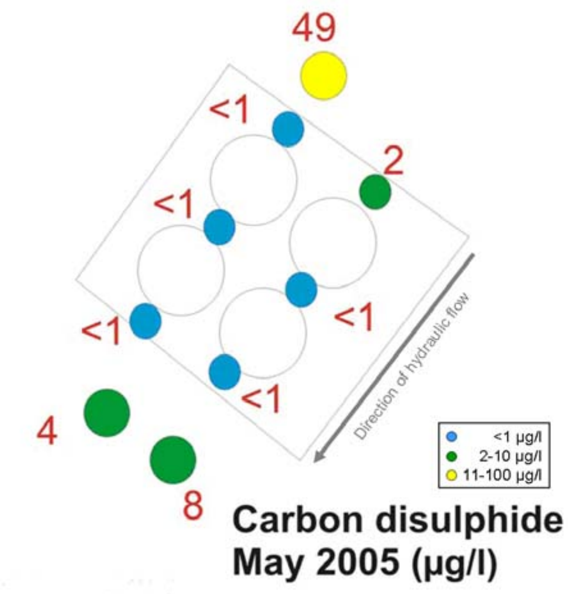


Figure 5.7: Concentrations of CS_2 in the monitoring points of the Western PRB Gate, May 2005

Groundwater concentrations upstream of the gate were generally 1 to 2 orders of magnitude higher than those taken from the downstream gates, where concentrations below 10 µg/l were standard, and frequently measured below 1 µg/l.

To estimate the flux of water (Q) through the PRB gates, one may apply Darcy's Law:

$$Q = K.i.A$$

where: K = hydraulic conductivity
i = hydraulic gradient
A = cross sectional area of gate

Assuming the cross-sectional area of the parallel treatment trains in each gate is 52 m^2 and a reactive iron bed hydraulic conductivity of 23 m/d (see Section 4.6.2), and taking for the Western PRB Gate, which receives the great majority of the detected CS_2 contamination, the mean of the hydraulic gradients measured (Tables 5.3 and 5.4; 0.006), then the estimated groundwater flux is:

$$Q = 23 \text{ m/d} \times 0.006 \times 52 \text{ m}^2 = 7.2 \text{ m}^3\text{/day}$$

Taking the average CS_2 concentration entering the Western PRB Gate as being 33 mg/l (Appendix 2), this equates to a contaminant flux of 0.12 kg/day, which is >99% removed by the PRB. Uncertainty in values of both hydraulic gradient and (especially) ZVI hydraulic conductivity, suggest a factor of uncertainty in estimated fluxes of 2 to 4.

5.2.3.5 Other contaminants

Carbon tetrachloride and chloroform are minor contaminants arising from manufacturing processes that were located in the south of the site and are consequently not detected in the "A" Series of observation wells. These compounds are also essentially absent from the Eastern PRB Gate, with only occasional detects of maximum 2 µg/l occurring. In the Western PRB Gate, however, concentrations of up to 4-6 mg/l carbon tetrachloride and up to 3-5 mg/l chloroform are consistently observed at the upstream end of the Gate (B1, 9PRB, 12PRB, see Figures 4.5 and 4.6). Carbon tetrachloride appears to be efficiently removed by the PRB, concentrations having fallen to below 1 µg/l by the mid-point sampling wells (8PRB, 11PRB). Chloroform is less rapidly removed, still being detectable in the mid-point wells, but having been essentially removed to <1 µg/l by the downstream points (7PRB, 10PRB).

Although BTEX (benzene, toluene, ethylbenzene, xylene) compounds were not detected in the "A" or "C" series wells, nor in the inlet water to the PRBs ("B" Series), they were occasionally detected in the mid-point or downgradient sampling points in the PRBs. Concentrations up to around 20 µg/l of para and meta xylene were detected in the mid-point wells of the Eastern PRB Gate, and up to 6 µg/l in the downstream wells of the Western PRB Gate. The fact that concentrations were relatively modest and that no detects were made in the "D" or "E" series wells, however, suggests that these detected compounds are of little practical significance.

5.2.4 CONCLUSIONS

Six rounds of groundwater level monitoring, field hydrochemical determination and hydrochemical sampling were carried out during the immediate post-commissioning period.

The highest concentrations of the main contaminant of concern, CS_2, were highly variable and were measured at up to 114 mg/l in Well A2 and 15 mg/l in A1. Concentrations reaching the gates were significantly lower and very little contamination reached the eastern of the two gates.

In Well C1, concentrations did not exceed 17 µg/l, showing that there was negligible bypass of contaminated groundwater around the impermeable barrier wall. Modest concentrations of some few tens of µg/l were shown to be entering the Western PRB Gate.

Hydraulically, the desired southerly water level gradients appeared to be maintained through the two gates, with water level differences of 0.8 to 1.0 m typically measured between the "B" and "E" wells. Site groundwater levels did not changed significantly following the installation of the PRB. In the Western PRB Gate, the hydraulic gradient within the gate itself was relatively flat. This indicates that the ZVI within the Western PRB Gate had a hydraulic conductivity similar to the aquifer material. In the Eastern PRB gate, the main head loss took place within the gate itself, suggesting that the hydraulic conductivity of the ZVI fill was much higher than the aquifer material.

Within the gates themselves, the expected hydrochemical profiles were observed. As one progresses downgradient, one notes:

- A reduction in concentration of sulphate (reduction to sulphide) and nitrate;
- A reduction in dissolved oxygen and declining redox potential;

- Increasing pH; and
- A reduction in concentrations of Ca, Mg, and Mn (maybe related to precipitation of carbonate phases with elevated pH).

The Western PRB Gate was shown to be efficiently removing carbon disulphide within the first reactor, resulting in concentrations below detection limit in the second vessel. Both hydraulic and hydrochemical evidence also suggest that the reaction front was largely within the first vessel.

6. ECONOMIC CONSIDERATIONS

6.1 INTRODUCTION

This section provides indicative costs for installing a similar PRB to this example at Stretford. The costs specifically exclude:

- Extensive site investigation works undertaken; and
- Other remediation costs e.g. stabilisation and landfill of contaminated soil and waste on site

The costs presented are therefore associated with the PRB's design and installation.

A summary of the costs is shown in Table 6.1.

Table 6.1: Summary of costs of the PRB

MAIN ACTIVITIES	COST £
Soil removal from PRB area	15,000
Pilot trial	110,000
Design and Value Engineering	75,000
Cut off wall and PRB	1,080,000
Supervision	130,000
Reporting	20,000
Sub Total	**1,430,000**
Groundwater monitoring (10 years) and decommission	220,000
TOTAL COSTS	**1,650,000**

6.2 DESIGN AND INSTALLATION OF THE PRB

An extensive exercise was undertaken to determine the most appropriate remediation technique for the main source zone of the site, which resulted in a decision to stabilise then remove the soil for disposal at a suitable landfill. In addition, a robust approach was required, to ensure that there was no potential for migration off-site of any residual CS_2, by installing an impermeable bentonite slurry wall, which would also channel the groundwater passing through the site into the PRB that would passively treat any traces of CS_2.

6.3 COST EFFECTIVENESS

There were no alternatives with which to compare this technique. Indeed, installing a PRB at this site required an additional outlay, without reducing the cost of remediating the land because the same amount of landfill was still required. However, the value of installing a PRB was that it provided increased and ongoing confidence for all parties concerned, particularly the regulators, that the contamination, and hence the liability, of the site was reduced to a minimum. This in turn gave the client the confidence that the contamination was being satisfactorily dealt with, in line with its Corporate Social Responsibility policy, and that any potential future liability at the site was minimised. This also added value for the developer, particularly when applying for planning permission to develop the site.

As the majority of the PRB costs were attributed to capital expenditure and construction, considerable time was spent reviewing the design to ensure it was as efficient as possible. The design was subjected to a thorough value engineering process (see Section 4.6.4).

In addition to the two main exclusions given at the beginning of this section, some costs associated with this project may be able to be reduced or excluded in similar future PRB installations:

- Bentonite cut-off walls were much longer than would be necessary in most cases, as they were also required to prevent off-site migration of contaminants, as well as to funnel groundwater towards the PRB.

- Laboratory trials would be unlikely to be required to the same extent again, as there was a considerable technology development element that could be bypassed.

- Particularly high standards were required for the security of the PRB once operational, as well as landscaping as the PRB was quite visible at what would be the front entrance of a new industrial site.

- A highly conservative approach was taken with regard to the low quantity of hydrogen that would be generated by the PRB, thus it was built to the principles of the American Petroleum Institute.

6.4 MONITORING AND MAINTENANCE

In terms of ongoing operation, there are relatively low costs; as the system is passive - groundwater is naturally channelled towards and through the PRB - no pumping or energy input is required.

The only ongoing operational costs are those of monitoring the groundwater, for ten years, and maintenance. The PRB was designed specifically to be low maintenance, with some minimal parts may require changing. It is highly unlikely that the reactive iron will need to be replaced during the lifespan of the PRB. In addition, given the results to date, it is likely that the PRB itself will not require replacement once its lifespan has expired, as there appears to be little remaining CS_2 on site.

7. CLOSE OUT

As required by the Environment Agency PRB Guidance (Environment Agency, 2002) a decommissioning plan will be developed and submitted for Environment Agency approval at the appropriate time.

Decommissioning will be triggered when remediation is complete. Completion of remediation will be determined by PRB inlet concentrations being below target values for an agreed period of time and calculations showing that these values are unlikely to be exceeded thereafter.

The PRB was designed to cause “minimum disturbance” to the current and future occupants of the site through its life-cycle and to provide cost-effective operation, maintenance and decommissioning. The use of vessels to contain the reactive medium facilitates the easy removal and disposal of the spent iron.

PRB decommissioning will involve removal of all reactive media and appropriate disposal. Since decommissioning will occur at some point in the future, it is impossible to speculate at this time about the most sustainable disposal route for the spent iron. Above ground infrastructure will be removed and the reactors backfilled with a suitably compacted clean, granular material. In addition, upstream and downstream bentonite walls will be breached at intervals to allow free passage of groundwater across the site.

8. CONCLUSIONS & LESSONS LEARNED

8.1 INTRODUCTION

This chapter describes the project conclusions, applicability and limitations of the PRB installation.

This PRB formed part of an overall scheme for the remediation of CS_2 contamination in soil and groundwater to enable beneficial development of a brownfield site. The remedial scheme was developed to deal with the identified pollutant linkages, site-specific requirements and the physical-chemical properties of CS_2 (particularly its volatility and flammability). Bearing these factors in mind, the following conclusions can be drawn from the project:

1. The PRB met its key objective: it produced an effective remediation performance. The western PRB was shown to be efficiently removing CS_2 within the first reactor, resulting in concentrations below detection limit in the second vessel. Very little contamination reached the eastern of the two gates.

2. This application was the first PRB used to successfully treat groundwater containing CS_2 (and lesser amounts of co-contaminants). It has therefore demonstrated the technology, which can now be applied to other sites where this CS_2 is the main contaminant throughout the world.

3. There are considerable benefits to be gained by testing the technology in a laboratory, before full-scale implementation. Even if it is a reasonably basic trial, it will save time and costs. Intensive laboratory testing of zero-valent iron treatment of site groundwater provides fundamental scientific data as well as design parameters.

4. There was no detrimental effect on local or regional groundwater properties as a result of the installation.

5. Evidence for the PRB's ultimate performance will be gained through a long-term monitoring programme. Although this commitment may be perceived as a disadvantage (see below), it requires minimal resources and provides useful data on the technology, which may be used in the development of successive applications.

6. There was considerable benefit gained by engaging with the regulators at an early stage. A close, constructive relationship was particularly developed with the Environment Agency and Trafford Metropolitan Borough Council, who provided helpful advice and supported the project throughout.

7. A critical success factor in the project was the positive team dynamics which led to effective communication and a wealth of constructive suggestions.

8. The project was multi-disciplinary: it was based on both civil and chemical engineering principles, which provided reassurance to all concerned, combined with cutting edge research and technology, which made it a stimulating and challenging project for those involved.

9. Value engineering was an effective step in the design process, both in reducing costs and improving the design itself.

10. Lab to field scale-up helps to address uncertainty and reduces technical and economic risk (warranties).

11. The PRB was installed and commissioned in parallel with the site's remediation works and development programme, allowed rapid realisation of economic benefit as well as effectively managing the site owner's residual liability.

12. PRBs can work well in the development context. They can enable use of brownfield sites and the PRB can be installed in conjunction with site development works.

13. Minimum life expectancy of the PRB is 10 years for materials and 30 years for structural design life.

8.2 APPLICABILITY

Opportunities for improved technical and project execution performance were identified during the project lifetime, exploitation of which is intended in future remediation works. These include options to minimise further the capture of uncontaminated groundwater, additional simplification of gate design and the use of staged media, splitting groundwater flow, variation in packing material and *in situ* cleaning.

The intention is to share learning from the various phases of the laboratory, design and implementation programmes to improve the uptake of PRB technology, to improve future projects and identify key areas of uncertainty that require further evaluation.

The Water Framework Directive (WFD) (European Commission, 2000), makes reference to diffuse sources of pollution and the importance of protecting surface and groundwater bodies, in terms of ecological, chemical and quantitative status. PRBs have a major role to play in the realisation of the WFD goals as a measure to prevent off-site contaminant migration and minimise impacts on surface and groundwater receptors. This technology has been applied for the treatment of a wide range of contaminants including chlorinated and non-chlorinated hydrocarbons, heavy metals, radionuclides and inorganic nutrients. Unlike other more conventional groundwater treatment methods, PRBs can treat complex mixtures of contaminants through the use of multiple reactive matrices within a single reactive barrier. Although the funnel-and-gate and continuous trench are the predominant PRB configurations, novel designs have been applied thereby overcoming constraints and allowing the realisation of treatment goals, site developments plans, health and safety and regulatory requirements. The use of metal canisters as reactive vessels at this site dealt not only with health and safety issues associated with the treatment of CS_2, but also contributed to the value engineering of the system and budget control.

PRBs can be used at sites of different sizes mainly as they can be designed to fit in with site development plans. The relatively short time period required for the installation of PRBs allows the site to be brought into beneficial use within a much shorter time span than if other remedial techniques are employed. Although PRBs have been predominantly used on commercial or mixed-use sites in the UK, they have also been used in residential areas in North America and Europe. PRBs additionally can be used for the treatment of landfill leachate, with some of the earlier North American PRBs installed for this application.

8.3 LIMITATIONS

The depth to which a PRB can be installed is dependent on the geology of the site. That, in turn, impacts on the type of PRB and installation method employed. The majority of PRBs are installed to treat contaminants within shallow aquifers within 10 m of ground level and have conventionally involved excavation, using standard excavating equipment with associated shoring. The development of new installation techniques such as biopolymer slurries, which circumvent the need for shoring, has allowed the installation of PRBs to depths in excess of 20 metres below ground level (mbgl). PRBs have not been extensively used for the treatment of contaminants in deeper aquifers (>30 mbgl.), although hydraulic and pneumatic fracturing techniques do exist for the injection of reactive materials such as emulsified ZVI into bedrocks.

The presence of underground structures, cobbles or boulders can also present problems for many of the conventionally used construction techniques, including trenching and sheet piling.

As PRBs are designed as a long-term remedial strategy, there is a requirement for access for monitoring and maintenance over the life-span of the PRB. The monitoring requirements are site specific and in most cases less onerous than those for pump-and-treat systems. Following installation and commissioning, monitoring may comprise a single yearly sampling event, with frequency decreasing with increasing operational lifespan.

The requirement for access should be taken into account in the design phase of the PRB as a number of measures can be incorporated into the engineering design to facilitate maintenance. For example, the use of metal canisters with manhole covered access points allows quick access to the PRB for maintenance and monitoring. These measures will also facilitate the decommissioning of the PRB should this be required.

The requirement to decommission a PRB is site specific and dependent on the contaminants being treated and the reactive media employed. Reactive media which sorb or concentrate contaminants and background anions/cations may, at a later stage, serve as a source of contamination. PRBs containing such reactive media may require decommissioning. Reactive materials which chemically degrade the contaminants to innocuous end-products may not have a requirement for decommissioning. The need for decommissioning needs to be discussed at the conceptualisation and design stage and may preclude particular PRB designs or the use of a PRB itself, especially if there are issues with the long-term access to the PRB, for example if decommissioning requires structures and facilities to be excavated in order to gain access to the PRB.

9. GLOSSARY OF TERMS

Bentonite
Bentonite is an absorbent aluminium phyllosilicate generally impure clay consisting mostly of montmorillonite commonly used as a drilling mud or a sealant due to its unique thixotropic and rheological properties.

Carbon Disulphide
Carbon disulphide is a colourless, highly volatile and flammable liquid with the formula CS_2. It is produced by the reaction of sulphur with natural gas in the presence of a catalyst which is chemical generally used to manufacture viscose rayon and cellophane, or as a solvent for fats, rubber, resins and waxes. Mixtures of CS_2 with air are highly explosive, being easily ignited by relatively low temperature sources, friction, compression and shock.

Column Treatability Tests
Laboratory based studies which involve passing a liquid through a column packed with porous medium. In the case of Stretford, a column treatability study was conducted on granular iron using groundwater flow rates and chemistry expected to occur at the site to establish design specifications for the PRB system.

DNAPL
Dense non-aqueous phase liquids. These are heavier-than-water organic liquids that have been widely used in industry since the 1900s. DNAPLs are only slightly soluble in water and so exist in the subsurface as a separate fluid phase, immiscible with both water and air. Common types of DNAPLs include wood treating oils such as creosote, transformer and insulating oils containing polychlorinated biphenyls (PCBs), coal tar and a variety of chlorinated solvents such as trichloroethene (TCE) and tetrachloroethene (PCE). DNAPLs have the ability to migrate to significant depths below the water table where they slowly dissolve into flowing groundwater, giving rise to aqueous phase plumes. A release of DNAPL at the ground surface can therefore give rise to long-term contamination of both the saturated and unsaturated zones at a site.

Flux
A rate of flow or discharge passing through a defined area, such as infiltration reaching the water table or precipitation reaching the ground, both for predefined areas

Glacial Till
Geological term for the unsorted, unconsolidated material deposited directly by glacial ice which is sometimes called boulder clay because it is commonly composed of clay, boulders of intermediate size, or both. Till can therefore have quite low permeability due to its clay content however, due to its unstratified, unsorted nature, its permeability is also likely to be highly variable depending on the deposited material. Drift is another term for the overall glaciofluvial deposited material from the melting of glaciers which includes glacial till, but also includes stratified material from glacial meltwaters.

Hydraulic Conductivity
The measure of how easily a medium can transmit a specified fluid. In groundwater terms it relates to an aquifer's ability to transmit water and is often expressed in terms of metres/sec.

***In Situ* Remediation**
In situ remediation is the process of making a site fit-for-purpose through destruction, removal or containment of contaminants in the ground, without the need for excavation. *In situ* treatments by nature are less intrusive than *ex situ* treatments but need to demonstrate that they can sufficiently deal with contamination in soils with greater heterogeneity and less efficient soil contact.

Made Ground
Manmade soil that is lying on top of the natural ground and often consists of natural soil mixed with clinker, ash, concrete and brick.

Mercaptan
Any one of series of compounds, hydrosulphides of alcohol radicals, in composition resembling the alcohols, but containing sulphur in place of oxygen, and hence also called the *sulphur alcohols*. In general, they are colourless liquids having a strong, repulsive, garlic odour. The name is specifically applied to ethyl mercaptan, C_2H_5SH, so called from its avidity for mercury, and other metals. Also called thiol.

PRB (Permeable Reactive Barrier)
A PRB is an *in situ* passive treatment system used to remediate contaminated fluids such as groundwater. It consists of a permeable wall of reactive material which is installed across the flow path of the contaminated fluid. As the fluid flows through the permeable barrier, the contaminant comes into contact with the reactive material and depending on the nature of the reactive material, is degraded to non or less toxic forms or its rate of transport is retarded.

Pareto Rule
The Pareto rule (also known as the 80-20 rule) states that, for many events, 80% of the effects come from 20% of the causes. Business management thinker Joseph M. Juran suggested the principle and named it after Italian economist Vilfredo Pareto, who observed that 80% of income in Italy went to 20% of the population. It is a common rule of thumb in business; e.g., "80% of your sales come from 20% of your clients."

Passivation
To render passive; to reduce the reactivity of a chemically active metal surface by electrochemical polarization or by immersion in a passivating solution. Reactive iron within a PRB is susceptible to passivation and may lead to reactive site saturation and thus concentration-dependent reaction rates.

Permeability
A measure of the ability of a material to transmit fluids, measured by hydraulic conductivity.

Piezometer
A non-pumping well, generally of small diameter, for measuring the elevation of a water table.

Recharge
The process by which water is added to a zone of saturation, usually by percolation from the soil surface; e.g., the recharge of an aquifer.

Redox
Redox (shorthand for reduction/oxidation reaction) describes all chemical reactions in which atoms have their oxidation number (oxidation state) changed. Redox potential is the tendency of a chemical species to acquire electrons and thereby be reduced and is measured (in volts) based on of the affinity of a substance for electrons. Each chemical species has its own intrinsic redox potential; the more positive the potential, the greater the species' affinity for electrons and tendency to be reduced. Substances more strongly electronegative than (i.e., capable of oxidizing) hydrogen have positive redox potentials. Substances less electronegative than (i.e., capable of reducing) hydrogen have negative redox potentials.

Remediation
The process of making a site fit-for-purpose through destruction, removal or containment of contaminants.

Unsaturated Zone (Vadose Zone)
This refers to the portion of the soil between the land surface and the water table (saturated zone). Movement of water within the vadose zone is studied within soil physics and hydrology, particularly hydrogeology, and is of importance to agriculture, contaminant transport, and flood control. .

Zero-Valent Iron
The elemental form of iron, Fe^0, with a valence state of zero.

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11. APPENDICES

Appendix 1	Borehole Logs
Appendix 2	Combined Chemical Data

APPENDIX 1
BOREHOLE LOGS

ESI

Telephone:
Fax:

BOREHOLE LOG

Environmental Simulations International Ltd

Project Stretford				BOREHOLE No **A1**
Job No 6333	Date 08-10-04	Ground Level (m) 24.39	Co-Ordinates () E 378,436.2 N 396,133.9	
Contractor Paul Blackledge Drilling				Sheet 1 of 1

SAMPLES & TESTS			Water	STRATA						Geology	Instrument/ Backfill
Depth	Type No	Test Result		Reduced Level	Legend	Depth	(Thick- ness)	(Thick- ness)	DESCRIPTION		
				23.19	▨	1.20	(1.20)		Compact grey colliery spoil		
				22.09	▨	2.30	(1.10)		Soft black peaty soil and brick fill		
				21.89	— —	2.50			Soft yellow brown clay		
				19.89	○ ○	4.50	(2.00)		Greyish brown sand and fine gravel		
				19.59	— —	4.80			Soft brown laminated clay		

Boring Progress and Water Observations						Chiselling			Water Added		GENERAL REMARKS
Date	Time	Depth	Casing Depth	Casing Dia. mm	Water Dpt	From	To	Hours	From	To	

All dimensions in metres Scale 1:50	Client	Method/ Plant Used	Logged By

ESI

Telephone:
Fax:

Environmental Simulations International Ltd

BOREHOLE LOG

Project Stretford				BOREHOLE No **A2**
Job No 6333	Date 07-10-04 08-10-04	Ground Level (m) 24.50	Co-Ordinates () E 378,508.7 N 396,132.3	
Contractor Paul Blackledge Drilling				Sheet 1 of 1

SAMPLES & TESTS			Water	STRATA					Geology	Instrument/ Backfill
Depth	Type No	Test Result		Reduced Level	Legend	Depth	(Thick- ness)	DESCRIPTION		
				24.10	▨	0.40	(0.40)	Concrete and brick rubble		▨
				22.20	▨	2.30	(1.90)	Compact grey clay, stone and brick fill		■
				21.80	▨	2.70	(0.40)	Crushed brick, soil and concrete		
				20.20	∘	4.30	(1.60)	Grey sand and fine to medium gravels		
				19.90	≡	4.60		Soft brown laminated clay		

Boring Progress and Water Observations						Chiselling			Water Added		GENERAL REMARKS
Date	Time	Depth	Casing Depth	Casing Dia. mm	Water Dpt	From	To	Hours	From	To	

All dimensions in metres Scale 1:50	Client	Method/ Plant Used	Logged By

ESI

Telephone:
Fax:

BOREHOLE LOG

Environmental Simulations International Ltd

Project Stretford				BOREHOLE No **B1**
Job No 6333	Date 11-10-04	Ground Level (m) 24.32	Co-Ordinates () E 378,382.3 N 396,021.4	
Contractor Paul Blackledge Drilling				Sheet 1 of 1

SAMPLES & TESTS			Water	STRATA				Geology	Instrument/ Backfill
Depth	Type No	Test Result		Reduced Level	Legend	Depth (Thick- ness)	(Thick- ness) DESCRIPTION		
				21.32	▩	(3.00) 3.00	Compact soil, stone and clay fill		
				20.82	⁘	(0.50) 3.50	Greyish brown sand and fine to medium gravels		
				19.42	⁘	(1.40) 4.90	Brown sand and fine to medium gravels		
				19.12	☰	5.20	Soft brown laminated clay		

Boring Progress and Water Observations						Chiselling			Water Added		GENERAL REMARKS
Date	Time	Depth	Casing Depth	Casing Dia. mm	Water Dpt	From	To	Hours	From	To	

All dimensions in metres Scale 1:50	Client	Method/ Plant Used	Logged By

ESI

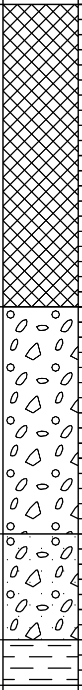
Telephone:
Fax:

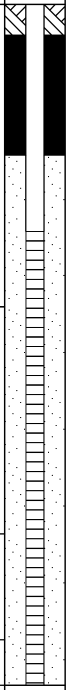
BOREHOLE LOG

Environmental Simulations International Ltd

Project Stretford				BOREHOLE No **B2**
Job No 6333	Date 11-10-04	Ground Level (m) 24.31	Co-Ordinates () E 378,426.1 N 395,990.2	
Contractor Paul Blackledge Drilling				Sheet 1 of 1

SAMPLES & TESTS			Water	STRATA				Geology	Instrument/ Backfill
Depth	Type No	Test Result		Reduced Level	Legend	Depth (Thick- ness)	DESCRIPTION		
				22.31	▩	(2.00) 2.00	Loose soil, ash, stone, brick and clay fill		
				20.81		(1.50) 3.50	Loose pea gravel fill		
				20.11		(0.70) 4.20	Brown sand and fine to medium gravels		
				19.81		4.50	Brown laminated clay		





Boring Progress and Water Observations						Chiselling			Water Added		GENERAL REMARKS
Date	Time	Depth	Casing Depth	Casing Dia. mm	Water Dpt	From	To	Hours	From	To	

All dimensions in metres Scale 1:50	Client	Method/ Plant Used	Logged By

ESI

Telephone:
Fax:

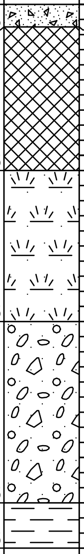
BOREHOLE LOG

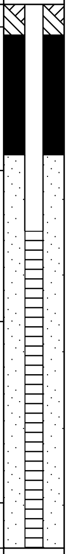
Environmental Simulations International Ltd

Project Stretford				BOREHOLE No **C1**
Job No 6333	Date 12-10-04	Ground Level (m) 24.28	Co-Ordinates () E 378,580.8 N 395,984.9	
Contractor Paul Blackledge Drilling				Sheet 1 of 1

SAMPLES & TESTS / STRATA

Depth	Type No	Test Result	Water	Reduced Level	Legend	Depth (Thick-ness)	DESCRIPTION	Geology	Instrument/ Backfill
				24.13		0.15	Reinforced concrete		
				23.18		(0.95) 1.10	Loose black ash		
				22.18		(1.00) 2.10	Brown peaty sand		
				20.98		(1.20) 3.30	Grey and black sand and fine to medium gravels		
				20.68		3.60	Brown laminated clay		





Boring Progress and Water Observations						Chiselling			Water Added		GENERAL REMARKS
Date	Time	Depth	Casing Depth	Casing Dia. mm	Water Dpt	From	To	Hours	From	To	

All dimensions in metres Scale 1:50	Client	Method/ Plant Used	Logged By

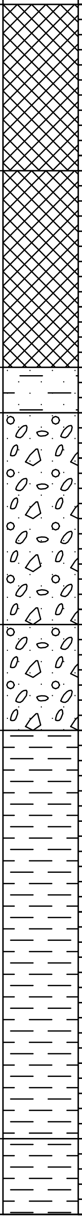
ESI

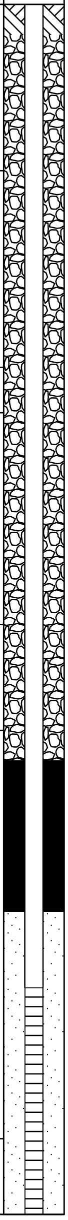
Telephone:
Fax:

BOREHOLE LOG

Environmental Simulations International Ltd

Project Stretford				BOREHOLE No **D1**
Job No 6333	Date 08-10-04	Ground Level (m) 24.63	Co-Ordinates () E 378,376.9 N 396,007.8	
Contractor Paul Blackledge Drilling				Sheet 1 of 1





SAMPLES & TESTS			Water	STRATA					Geology	Instrument/ Backfill
Depth	Type No	Test Result		Reduced Level	Legend	Depth	(Thick- ness)	DESCRIPTION		
				23.53		1.10	(1.10)	Compact black ash		
				22.23		2.40	(1.30)	Soft black peaty soil and brick fill		
				21.93		2.70		Brown clayey sand		
				20.53		4.10	(1.40)	Brown sand and fine gravels		
				19.83		4.80	(0.70)	Grey sand and fine to medium gravels		
				17.13		7.50	(2.70)	Soft brown laminated clay		
				16.63		8.00	(0.50)	Firm brown boulder clay		

Boring Progress and Water Observations						Chiselling			Water Added		GENERAL REMARKS
Date	Time	Depth	Casing Depth	Casing Dia. mm	Water Dpt	From	To	Hours	From	To	

All dimensions in metres Scale 1:50	Client	Method/ Plant Used	Logged By

ESI

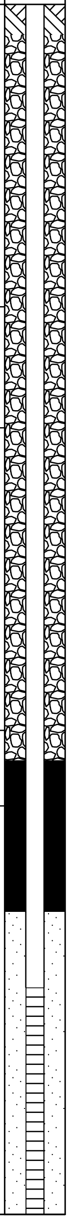
Telephone:
Fax:

BOREHOLE LOG

Environmental Simulations International Ltd

Project Stretford				BOREHOLE No **D2**
Job No 6333	Date 11-10-04	Ground Level (m) 24.58	Co-Ordinates () E 378,423.4 N 395,975.6	
Contractor Paul Blackledge Drilling				Sheet 1 of 1

SAMPLES & TESTS			Water	STRATA					
Depth	Type No	Test Result		Reduced Level	Legend	Depth (Thick-ness)	(Thick-ness) DESCRIPTION	Geology	Instrument/ Backfill
				22.58	▩	(2.00) 2.00	Loose black ash, soil, clay and brick fill		
				21.78	⁚	(0.80) 2.80	Brown sand		
				19.78	∘	(2.00) 4.80	Brown sand and fine to medium gravel		
				19.28	═	(0.50) 5.30	Soft brown laminated clay		
				16.58	═	(2.70) 8.00	Firm brown clay		



Boring Progress and Water Observations						Chiselling			Water Added		GENERAL REMARKS
Date	Time	Depth	Casing Depth	Casing Dia. mm	Water Dpt	From	To	Hours	From	To	

All dimensions in metres Scale 1:50	Client	Method/ Plant Used	Logged By

ESI

Telephone:
Fax:

BOREHOLE LOG

Environmental Simulations International Ltd

Project Stretford				BOREHOLE No **E1**
Job No 6333	Date 08-10-04	Ground Level (m) 24.68	Co-Ordinates () E 378,374.5 N 396,009.5	
Contractor Paul Blackledge Drilling				Sheet 1 of 1

SAMPLES & TESTS			Water	STRATA					Geology	Instrument/ Backfill
Depth	Type No	Test Result		Reduced Level	Legend	Depth (Thick-ness)	(Thick-ness)	DESCRIPTION		
				23.68		(1.00) 1.00		Compact black ash		
				22.28		(1.40) 2.40		Soft black peaty soil		
				21.88		(0.40) 2.80		Brown clayey sand		
				19.98		(1.90) 4.70		Brown sand and fine to medium gravel		
				19.28		(0.70) 5.40		Soft brown laminated clay		

Boring Progress and Water Observations						Chiselling			Water Added	
Date	Time	Depth	Casing Depth	Casing Dia. mm	Water Dpt	From	To	Hours	From	To

GENERAL REMARKS

All dimensions in metres Scale 1:50	Client	Method/ Plant Used	Logged By

ESI

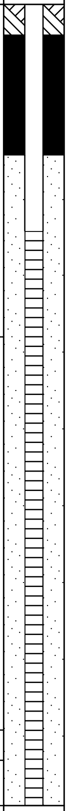
Telephone:
Fax:

BOREHOLE LOG

Environmental Simulations International Ltd

Project Stretford				BOREHOLE No **E2**
Job No 6333	Date 11-10-04	Ground Level (m) 24.59	Co-Ordinates () E 378,419.7 N 395,978.4	
Contractor Paul Blackledge Drilling				Sheet 1 of 1

SAMPLES & TESTS			Water	STRATA				Geology	Instrument/ Backfill
Depth	Type No	Test Result		Reduced Level	Legend	Depth (Thick-ness)	DESCRIPTION		
				22.39	▨	(2.20) 2.20	Loose black ash, soil, grout clay and brick fill		
				19.79	▨	(2.60) 4.80	Loose pea gravel fill		
				19.59	° o ° o	5.00	Brown sand and fine to medium gravel		
				19.29	— —	5.30	Soft brown laminated clay		



Boring Progress and Water Observations						Chiselling			Water Added		GENERAL REMARKS
Date	Time	Depth	Casing Depth	Casing Dia. mm	Water Dpt	From	To	Hours	From	To	

All dimensions in metres Scale 1:50	Client	Method/ Plant Used	Logged By

APPENDIX 2
COMBINED CHEMICAL DATA

Table A. Summary of laboratory results for dissolved metals

Sample Identity	Ca mg/l	Ca mg/l	Ca mg/l	Ca mg/l	Ca mg/l	Ca mg/l	Mg mg/l	Mg mg/l	Mg mg/l	Mg mg/l	Mg mg/l	Mg mg/l	Na mg/l	Na mg/l	Na mg/l	Na mg/l	Na mg/l	Na mg/l	K mg/l	K mg/l	K mg/l	K mg/l	K mg/l	K mg/l	Fe mg/l	Fe mg/l	Fe mg/l	Fe mg/l	Fe mg/l	Fe mg/l	Mn mg/l	Mn mg/l	Mn mg/l	Mn mg/l	Mn mg/l	Mn mg/l
	Jan	Feb	Mar	May	Jun	July	Jan	Feb	Mar	May	Jun	July	Jan	Feb	Mar	May	Jun	July	Jan	Feb	Mar	May	Jun	July	Jan	Feb	Mar	May	Jun	July	Jan	Feb	Mar	May	Jun	July
Up-gradient of PRB																																				
A1	258.9	341.7	286.4	109.6	224.3		33.65	20.61	17.64	6.61	26.34		121.5	60.0	78.8	75.0	138.8		10.5	11.3	12.8	11.6	10.4		68.62	27.35	7.77	0.65	36.2		6.97	5.07	4.40	1.50	4.088	
A2	360.0	244.5	223.8	213.5		208.2	26.42	29.10	28.19	27.96		29.29	79.5	108.8	127.5	150.0		165.0	11.7	9.0	11.3	10.1		8.0	39.14	46.53	37.92	69.89		47.95	5.76	5.09	4.72	4.65		4.368
C1	100.7	86.6	81.2	82.1		113.4	12.46	12.87	11.15	13.48		22.77	76.5	39.0	46.5	57.0		100.5	11.0	8.4	9.9	8.3		6.9	1.74	2.25	0.14	0.11		0.125	0.82	0.60	0.50	0.52		0.771
Eastern PRB																																				
B2		165.1	219.6	250.9	280.3	260.1		6.37	11.07	20.85	15.7	15.46		86.3	61.5	78.0	60.0	55.5		18.0	14.9	12.2	10.5	7.2		0.10	0.15	7.98	0.337	13.97		0.13	1.34	2.79	2.457	1.864
3PRB		291.9	308.8	348.1	449.3	351.5		23.00	28.05	32.67	36.84	29		56.3	52.5	63.0	63.0	52.5		10.5	11.3	12.0	13.1	10.1		0.11	0.04	0.05	0.028	0.02		3.14	5.92	7.14	9.21	5.134
6PRB	344.2	327.7	298.7	264.2	352.2	345.8	27.34	27.12	25.92	24.49	27.88	30.47	60.0	52.5	60.0	56.3	55.5	58.5	12.2	12.9	12.6	13.7	12.0	5.3	0.06	0.13	0.04	<0.005	0.033	0.018	4.84	4.30	4.61	3.827	5.685	5.065
2PRB		92.8	162.4	101.8	203.4	193.5		3.57	4.37	2.24	2.936	6.228		33.8	60.0	84.0	49.5	52.5		7.1	10.7	10.8	14.0	10.4		0.12	0.03	<0.005	0.019	0.023		0.002	0.012	0.001	0.004	<0.001
5PRB		87.0	189.2	163.8	199.2	158.3		2.44	3.97	2.50	1.78	1.684		25.5	64.5	56.3	61.5	54.0		7.4	12.0	12.5	11.1	5.6		0.11	0.04	0.07	0.005	0.028		0.004	0.02	0.016	0.02	0.021
1PRB	170.7	168.1	141.5	124.8	206.5	149.1	3.33	2.66	1.51	0.91	0.824	1.005	75.0	71.3	79.5	52.5	54.0	69.0	10.2	9.9	10.4	10.8	11.7	9.5	0.07	0.17	0.04	0.014	<0.005	0.025	0.02	0.13	0.11	0.26	0.061	0.146
4PRB	296.3	217.0	156.3	127.6	156.1	72.85	2.14	1.53	1.17	0.75	0.635	0.662	252.0	52.5	69.0	81.0	63.0	75.0	12.3	11.1	11.4	12.9	12.2	23.3	0.14	0.14	0.03	0.07	0.019	0.101	0.03	0.12	0.04	0.20	0.263	0.308
E2	134.2	116.8	37.8	47.6	38.5	60.17	2.84	2.33	0.81	1.67	0.815	1.209	135.0	97.5	112.5	161.3	55.5	99.0	22.5	12.5	8.4	21.8	37.5	12.9	0.06	0.11	0.13	2.79	0.088	0.015	1.29	1.21	0.57	0.31	0.273	0.567
D2	106.1	86.1	83.0	55.4	NDP	NDP	13.38	12.04	9.96	1.57	NDP	NDP	146.3	120.0	116.3	157.5	37.5	130.5	12.5	7.7	13.8	18.0	14.9	9.8	0.10	0.11	<0.005	3.71	NDP	NDP	0.44	0.98	0.46	1.00	NDP	NDP
Western PRB				55.4																																
B1			141.4	117.4	186.6	193			12.10	10.28	9.275	12.44			36.0	46.5	33.0	75.0			11.6	12.5	11.3	9.6			9.91	10.70	0.035	6.838			2.09	1.69	2.048	2.466
9PRB	196.6	175.8	222.6	137.9	212.5	215.9	15.83	14.52	19.65	12.68	16.02	19.27	40.5	49.5	54.0	55.5	43.5	51.0	11.0	11.0	11.9	11.9	11.7	9.0	15.98	10.96	7.61	5.38	5.506	25.99	3.28	3.19	4.21	2.54	3.71	4.044
12PRB	187.2	236.5	226.8	165.9	203.2	220.9	13.75	13.56	13.34	11.01	12.47	15.31	70.5	66.0	76.5	78.8	64.5	70.5	14.9	14.7	16.5	18.0	15.8	18.0	3.47	0.04	0.78	0.050	<0.005	0.037	3.95	4.25	4.67	3.29	4.413	4.773
8PRB		61.9	108.3	68.1	75.19	48.98		3.70	13.64	9.84	11.34	9.478		28.5	45.0	55.5	39.0	46.5		9.8	11.7	12.2	11.1	9.5		0.03	0.006	<0.005	<0.005	0.019		0.007	0.06	0.03	0.001	0.009
11PRB		29.9	52.3	49.3	71.98	60.94		2.86	5.80	4.87	6.059	4.891		34.5	57.0	69.0	60.0	69.0		9.2	12.5	14.9	14.3	18.0		0.04	0.18	0.04	<0.005	0.012		0.002	0.09	0.012	<0.001	0.002
7PRB	173.8	132.9	109.6	111.0	86.5	72.34	13.91	12.83	12.83	14.66	11.56	10.88	48.0	26.3	51.0	62.3	40.5	45.0	11.0	11.1	12.2	11.3	12.2	9.6	0.010	<0.005	<0.005	<0.005	0.015	0.015	0.005	0.001	<0.001	0.001	0.002	0.12
10PRB	94.0	94.2	95.6	101.7	89.92	82.99	6.44	6.65	5.50	4.76	3.682	3.144	70.5	75.0	60.0	75.0	60.0	66.0	13.7	14.4	14.3	15.8	14.9	14.7	0.04	0.03	<0.005	<0.005	0.012	0.049	0.003	0.005	0.02	0.006	0.002	0.036
E1	169.0	156.8	116.3	122.6	93.95	79.93	11.02	7.97	10.69	11.19	7.638	10.37	43.5	49.5	60.0	60.0	100.5	48.0	12.3	12.2	10.5	11.6	11.0	9.8	0.08	<0.005	<0.005	0.028	0.037	0.031	0.71	0.51	0.18	0.33	0.187	0.226
D1	125.9	127.5	127.1	131.7	123.3	112	10.24	10.04	8.95	15.86	11.04	11.98	79.5	45.0	48.0	67.5	145.5	75.0	9.2	10.1	13.7	9.0	8.3	7.1	0.012	<0.005	0.012	<0.005	0.018	0.026	0.28	0.83	0.41	0.23	0.151	0.186
Downstream of Site				131.7																																
F2	19.6	16.6	17.8	15.1	18.13	18.23	2.92	2.28	2.52	2.25	2.276	2.553	4.4	4.1	4.4	5.4	4.1	5.4	2.9	0.8	2.3	2.0	2.1	1.7	0.03	0.03	<0.005	<0.005	<0.005	0.021	1.46	1.18	1.12	1.00	1.385	1.229
F1	38.7	37.2	34.4	37.8	41.57	41.74	4.09	3.36	3.77	4.09	4.005	4.375	5.1	4.7	4.5	5.4	4.7	5.6	3.3	1.4	2.9	2.9	2.7	2.4	0.38	0.23	0.03	<0.005	0.243	0.078	1.14	0.98	1.06	1.08	1.23	1.363
20PRB		0.2	0.1	0.1	210.9	59.62		0.04	0.01	0.01	25.21	4.828		<0.2	0.3	0.5	121.5	60.0		<0.2	0.6	<0.2	9.8	18.8		0.06	<0.005	<0.005	67.16	0.019		0.002	<0.001	<0.001	4.445	0.002
21PRB		0.2			0.069	0.115		0.03			0.008	0.043		<0.2			0.6	0.3		<0.2			<0.2	<0.2		0.03			<0.005	0.02		0.002			0.002	0.001

Table B. Summary of laboratory results for anions (Alk = Total alkalinity in meq/l)

Sample Identity	Alk (meq/l)	Alk (meq/l)	Alk (meq/l)	Alk (meq/l)	Alk (meq/l)	Alk (meq/l)	NO3 (mg/l)	NO3 (mg/l)	NO3 (mg/l)	NO3 (mg/l)	NO3 (mg/l)	NO3 (mg/l)	SO4 mg/l	SO4 mg/l	SO4 mg/l	SO4 mg/l	SO4 mg/l	SO4 mg/l	Cl (mg/l)	Cl (mg/l)	Cl (mg/l)	Cl (mg/l)	Cl (mg/l)	Cl (mg/l)	PO4 (mg/l)	PO4 (mg/l)	PO4 (mg/l)	PO4 (mg/l)	PO4 (mg/l)	PO4 (mg/l)	Sulphide (mg/l)	Sulphide (mg/l)	Sulphide (mg/l)	Sulphide (mg/l)	Sulphide (mg/l)	Sulphide (mg/l)
	Jan	Feb	Mar	May	Jun	July	Jan	Feb	Mar	May	Jun	July	Jan	Feb	Mar	May	Jun	July	Jan	Feb	Mar	May	Jun	July	Jan	Feb	Mar	May	Jun	July	Jan	Feb	Mar	May	Jun	July
Up-gradient of PRB																																				
<0.05	2.40	5.30	3.70	1.90	2.4		<0.3	<0.3	<0.3	<0.3	<0.3		895	819	730	330	727		146	126	139	95	232		<0.08	<0.08	<0.08	<0.08	<0.08		<0.05	0.05	<0.05	<0.05	<0.05	
A2	5.10	2.80	4.10	3.00		1.8	<0.3	<0.3	0.3	<0.3		<0.3	887	824	805	768		754	141	143	170	179		229	<0.08	<0.08	<0.08	<0.08		<0.08	<0.05	0.05	<0.05	<0.05		<0.05
C1	1.30	1.40	1.30	2.60		2.7	11.3	2.0	1.8	<0.3		<0.3	462	343	326	279		393	58	45	44	55		98	<0.08	<0.08	<0.08	<0.08		<0.08	<0.05	0.05	<0.05	0.07		0.05
Eastern PRB																																				
B2		5.00	1.70	-	0.06	-		3.6	8	2.7	6.1	5.0		507	690	1070	901	956		73	59	54	54	49		<0.08	<0.08	<0.08	<0.08	<0.08		0.05	<0.05	<0.05	0.07	<0.05
3PRB		1.50	2.00	2.70	1.6	1.9		4.6	4.1	2.3	3.1	5.4		885	1206	1122	1160	998		76	62	59	62	60		<0.08	<0.08	<0.08	<0.08	<0.08		<0.05	<0.05	<0.05	0.08	<0.05
6PRB	1.10	0.18	1.70	0.42	1.2	0.3	16.7	17.5	17.4	17.0	15.4	16.0	1023	1010	1043	1156	1107	1079	62	69	64	79	70	66	<0.08	<0.08	<0.08	<0.08	<0.08	<0.08	<0.05	<0.05	<0.05	<0.05	0.06	<0.05
2PRB		0.26	2.20	0.34	1.1	0.32		<0.3	<0.3	<0.3	<0.3	<0.3		343	564	490	577	617		59	68	72	63	60		0.14	0.08	<0.08	<0.08	<0.08		0.05	<0.05	<0.05	0.08	<0.05
5PRB		1.00	8.90	1.20	1.3	0.68		<0.3	<0.3	<0.3	<0.3	<0.3		243	682	634	553	514		46	64	70	71	68		<0.08	<0.08	<0.08	<0.08	<0.08		0.05	<0.05	<0.05	0.08	<0.05
1PRB	1.20	0.44	4.30	1.20	1	1.6	0.3	<0.3	<0.3	<0.3	6.4	3.1	430	540	481	526	606	473	90	86	83	72	61	47	<0.08	<0.08	<0.08	<0.08	<0.08	<0.08	<0.05	0.05	<0.05	<0.05	0.08	<0.05
4PRB	1.00	1.10	7.80	1.30	2.3	3	0.5	<0.3	<0.3	<0.3	3.9	1.9	752	658	631	641	457	277	69	70	66	66	63	37	<0.08	<0.08	<0.08	<0.08	<0.08	<0.08	<0.05	0.07	<0.05	<0.05	0.09	<0.05
E2	1.40	1.40	3.90	3.60	3.3	3.6	5.1	0.5	0.6	15.3	19.1	2.8	470	452	269	252	268	270	75	75	53	37	39	33	<0.08	<0.08	<0.08	<0.08	0.10	<0.08	<0.05	0.05	<0.05	<0.05	0.07	<0.05
D2	3.50	4.30	3.60	4.00	4.2	4.1	0.7	<0.3	1.3	7.0	11.7	<0.1	539	357	322	292	166.4	98.2	67	61	66	60	45.42	53.83	<0.08	<0.08	<0.08	<0.08	<0.1	<0.1	<0.05	0.05	<0.05	<0.05	<0.05	<0.05
Western PRB																																				
B1			1.70	2.00	4.6	2.9			<0.3	<0.3	<0.3	<0.3			482	424	434	495			44	32	33	36			<0.08	<0.08	<0.08	<0.08			<0.05	<0.05	0.06	<0.05
9PRB	3.10	1.80	1.70	2.00	1.9	1.6	<0.3	<0.3	<0.3	<0.3	<0.3	<0.3	554	567	637	623	607	654	79	79	91	89	85	90	<0.08	<0.08	<0.08	<0.08	<0.08	<0.08	<0.05	0.05	<0.05	<0.05	<0.05	<0.05
12PRB	2.90	2.60	3.10	2.90	2.7	2.8	<0.3	<0.3	<0.3	<0.3	<0.3	<0.3	553	662	674	632	622	674	68	53	69	90	82	81	<0.08	<0.08	<0.08	<0.08	<0.08	<0.08	<0.05	<0.05	<0.05	<0.05	<0.05	<0.05
8PRB		0.42	0.54	0.48	1.3	0.38		<0.3	<0.3	<0.3	<0.3	<0.3		160	366	370	301	175		76	79	77	82	78		<0.08	<0.08	<0.08	<0.08	<0.08		0.05	<0.05	<0.05	<0.05	<0.05
11PRB		0.50	0.44	1.00	0.34	0.32		<0.3	<0.3	<0.3	<0.3	<0.3		79	246	316	299	252		76	64	59	69	69		<0.08	<0.08	<0.08	<0.08	<0.08		0.05	<0.05	<0.05	<0.05	<0.05
7PRB	1.10	0.34	0.44	1.00	1.1	0.36	0.3	<0.3	<0.3	<0.3	0.8	<0.3	524	472	445	388	312	249	96	82	82	80	84	77	<0.08	<0.08	<0.08	<0.08	<0.08	0.17	<0.05	0.05	<0.05	<0.05	<0.05	<0.05
10PRB	1.30	0.34	0.48	1.10	1.1	0.44	<0.3	<0.3	<0.3	<0.3	<0.3	<0.3	370	395	375	391	349	308	72	67	68	62	72	69	<0.08	<0.08	<0.08	<0.08	0.11	0.12	<0.05	0.05	<0.05	<0.05	<0.05	<0.05
E1	1.30	<0.04	2.90	1.10	1.1	0.34	2.4	0.4	0.4	<0.3	<0.3	<0.3	517	472	373	401	318	257	91	82	112	84	85	78	<0.08	<0.08	<0.08	<0.08	<0.08	<0.08	<0.05	<0.05	<0.05	<0.05	0.07	<0.05
D1	1.90	2.00	1.00	3.00	2.9	2.7	<0.3	<0.3	0.5	<0.3	5.5	1.3	390	367	452	341	302	244	98	85	88	109	113	117	<0.08	<0.08	<0.08	<0.08	<0.08	<0.08	<0.05	<0.05	<0.05	<0.05	0.07	<0.05
Downstream of Site																																				
F2	1.40	1.30	1.50	1.50	1.2	1.1	0.5	0.5	0.6	0.3	0.6	0.4	15	14	16	17	40	17	19	16	15	14	11	7	<0.08	<0.08	<0.08	<0.08	<0.08	<0.08	<0.05	<0.05	<0.05	<0.05	<0.05	<0.05
F1	2.40	2.10	1.20	2.60	2.6	1.8	1.5	0.4	0.3	<0.3	<0.3	0.3	22	20	22	22	21	21	18	14	15	13	9	7	<0.08	<0.08	<0.08	<0.08	<0.08	<0.08	<0.05	<0.05	<0.05	<0.05	<0.05	<0.05
20PRB		-	0.10	1.00	1.4	3.2		<0.3	<0.3	<0.3	<0.3	<0.3		4	<3	<3	770	252		6	6	7	183	69		<0.08	<0.08	<0.08	0.09	<0.08		0.05	<0.05	<0.05	<0.05	<0.05
21PRB		-			1.3	0.06		<0.3			<0.3	<0.3		4			<3	<3		7			4	<1		<0.08			<0.08	<0.08		0.05			<0.05	<0.05

Table C. Summary of laboratory results for other non-VOC parameters (TOC = total organic carbon; TDS = total dissolved solids)

Sample Identity	NH4-N (mg/l)	NH4-N (mg/l)	NH4-N (mg/l)	NH4-N (mg/l)	NH4-N (mg/l)	NH4-N (mg/l)	TOC (mg/l)	TOC (mg/l)	TOC (mg/l)	TOC (mg/l)	TOC (mg/l)	TOC (mg/l)	TDS (mg/l)	TDS (mg/l)	TDS (mg/l)	TDS (mg/l)	TDS (mg/l)	TDS (mg/l)	Fe(II) (mg/l)	Fe(II) (mg/l)	Fe(II) (mg/l)	Fe(II) (mg/l)	Fe(II) (mg/l)	Fe(II) (mg/l)	Fe(III) (mg/l)	Fe(III) (mg/l)	Fe(III) (mg/l)	Fe(III) (mg/l)	Fe(III) (mg/l)	Fe(III) (mg/l)	Free S (mg/l)	pH	pH	pH	pH	pH
	Jan	Feb	Mar	May	Jun	July	Jan	Feb	Mar	May	Jun	July	Jan	Feb	Mar	May	Jun	July	Jan	Feb	Mar	May	Jun	July	Jan	Feb	Mar	May	Jun	July	Jan	Feb	Mar	May	Jun	July
Up-gradient of PRB																																				
A1	3.3	2.0	2.6	3.1	2.2		10	10	9	17	8		793	495	878	481	928		8.26	<0.05	<0.05	<0.05	<0.05		60.36	27.35	7.77	0.65	36.20		<0.05	7.43	6.45	6.84	6.53	-
A2	1.4	1.4	2.5	3.0		2.2	7	9	7	10		8	777	219	732	859		889	<0.05	<0.05	<0.05	<0.05		7.10	39.14	46.53	37.92	<0.05		40.85	<0.05	6.71	6.17	6.49		-
C1	2.0	1.6	1.9	2.2		2.7	9	13	10	13		12	504	386	370	387		560	0.06	<0.05	<0.05	<0.05		<0.05	1.68	2.25	0.14	<0.05		0.13	0.2	6.43	6.26	7.15		-
Eastern PRB																																				
B2		1.7	2.4	3.1	2.6	1.2		11	5	4	4	4		592		920	823	817		<0.05	<0.05	1.7	<0.05	3.78		0.1	0.15	6.28	0.34	10.19		8.33	6.6	3.76	4.03	-
3PRB		2.0	2.5	2.3	3.3	2.1		3	3	4	3	3		812		1015	1032	835		<0.05	<0.05	<0.05	<0.05	<0.05		0.11	<0.05	<0.05	<0.05	<0.05		6.71	6.43	7.32	7.58	-
6PRB	2.4	2.7	3.0	3.5	3.5	2.6	3	3	3	3	3	3	967	895		997	981	877	<0.05	<0.05	<0.05	<0.05	<0.05	<0.05	0.06	0.13	<0.05	<0.05	<0.05	<0.05		5.07	4.98	6.73	4.85	-
2PRB		1.0	1.3	1.3	1.6	1.0		1	1	1	1	2		393		545	615	575		<0.05	<0.05	<0.05	<0.05	<0.05		0.12	<0.05	<0.05	<0.05	<0.05		7.4	7.57	7.23	7.36	-
5PRB		1.5	2.4	2.6	2.8	2.2		2	3	3	2	3		316		650	628	548		<0.05	<0.05	<0.05	<0.05	<0.05		0.11	<0.05	<0.05	<0.05	<0.05		7.97	8.05	7.73	7.80	-
1PRB	1.0	1.1	1.4	1.2	1.7	1.3	1	2	1	2	3	9	655	586		565	629	525	<0.05	<0.05	<0.05	<0.05	<0.05	<0.05	0.07	0.17	<0.05	<0.05	<0.05	<0.05		7.35	7.06	7.54	7.60	-
4PRB	2.6	2.3	3.0	2.7	2.8	3.3	2	7	4	6	12	30	768	617		601	570	421	<0.05	<0.05	<0.05	<0.05	<0.05	NDP	0.14	0.14	<0.05	<0.05	<0.05	NDP		7.61	7.64	7.71	8.02	-
E2	1.1	2.5	1.7	3.4	3.6	3.5	9	14	46	35	26	17	647	516	442	447	484	449	<0.05	<0.05	0.13	<0.05	<0.05	<0.05	<0.05	0.11	<0.05	<0.05	0.09	<0.05		7.71	7.66	8.26	8.14	-
D2	2.4	1.6	1.9	4.7	4.6	4.3	20	17	16	55	121	242	670	520	481	492	541	413	0.06	<0.05	<0.05	0.2	NDP	NDP	0.05	0.11	<0.05	3.51	NDP	NDP		7.96	7.66	8.03	8.17	-
Western PRB																																				
B1			3.4	3.0	3.7	2.8			4	4	6	6			452	448	555	540			<0.05	<0.05	<0.05	<0.05			9.91	<0.05	<0.05	6.84			6.18	6.74	8.11	-
9PRB	3.1	3.4	3.4	3.2	3.4	3.4	5	5	4	4	4	4	560	519	597	661	675	628	0.17	0.19	<0.05	<0.05	<0.05	4.34	15.82	10.96	7.61	<0.05	5.51	21.65	<0.05	6.99	6.07	7.00	8.03	-
12PRB	3.1	2.9	3.0	2.6	2.6	2.5	5	5	6	6	5	5	575	134	755	729	697	657	<0.05	<0.05	<0.05	<0.05	<0.05	<0.05	3.47	<0.05	0.78	<0.05	<0.05	<0.05	<0.05	8	6.71	7.77	7.89	-
8PRB		2.6	2.9	2.8	2.8	2.1		1	2	2	2	2		284	434	462	429	319		<0.05	<0.05	<0.05	<0.05	<0.05		<0.05	<0.05	<0.05	<0.05	<0.05		7.51	8.48	7.64	7.55	-
11PRB		2.2	2.1	1.8	1.6	1.7		2	2	2	2	2		886	349	400	413	377		<0.05	<0.05	<0.05	<0.05	<0.05		<0.05	0.18	<0.05	<0.05	<0.05		7.63	9	6.97	7.48	-
7PRB	3.2	2.9	3.0	2.8	2.8	2.3	2	2	2	2	2	3	534	645	469	455	446	375	<0.05	<0.05	<0.05	<0.05	<0.05	<0.05	<0.05	<0.05	<0.05	<0.05	<0.05	<0.05	<0.05	7.54	9.04	7.48	7.29	-
10PRB	2.7	2.1	2.5	2.1	2.3	2.0	2	2	2	2	2	3	429	84	436	445	464	415	<0.05	<0.05	<0.05	<0.05	<0.05	<0.05	<0.05	<0.05	<0.05	<0.05	<0.05	<0.05	<0.05	7.41	8.28	7.53	7.39	-
E1	2.9	2.7	2.7	2.8	2.9	2.4	4	5	3	4	4	4	526	12	499	458	433	379	<0.05	<0.05	<0.05	<0.05	<0.05	<0.05	0.08	<0.05	<0.05	<0.05	<0.05	<0.05	<0.05	7.37	7.48	6.94	7.26	-
D1	2.7	2.3	3.1	2.6	2.7	2.3	5	4	3	5	3	4	511	14	475	548	510	485	<0.05	<0.05	<0.05	<0.05	<0.05	<0.05	<0.05	<0.05	<0.05	<0.05	<0.05	<0.05	<0.05	8.14	6.79	8.09	8.23	-
Downstream of Site																																				
F2	0.3	0.3	0.3	0.3	<0.2	<0.2	2	3	2	2	3	3	78	457	77	72	75	75	<0.05	<0.05	<0.05	<0.05	<0.05	<0.05	<0.05	<0.05	<0.05	<0.05	<0.05	<0.05	<0.05	7.74	6.58	7.67	7.65	-
F1	0.3	0.3	0.4	0.4	<0.2	<0.2	4	5	4	4	4	4	143	684	130	129	138	133	0.12	<0.05	<0.05	<0.05	<0.05	<0.05	0.38	0.23	<0.05	<0.05	0.24	0.08	<0.05	8.11	6.9	7.90	8.00	-
20PRB		<0.2	0.3	0.3	2.8	1.6		1	<1	<1	5	2		507	<5	11	857	378		<0.05	<0.05	<0.05	4.79	<0.05		0.05	<0.05	<0.05	62370.00	<0.05		7.14	5.7	5.76	6.19	-
21PRB		<0.2			0.3	<0.2		1			<1	<1		489			<5	<5		<0.05			<0.05	<0.05		<0.05			<0.05	<0.05		6.64			5.95	-

Table D. Summary of laboratory results for VOCs (i): Carbon disulphide and chlorinated methanes (all in µg/l)

Sample Identity	Carbon Disulphide	Carbon Disulphide	Carbon Disulphide	Carbon Disulphide	Carbon Disulphide	Carbon Disulphide	Carbon Tetrachloride	Carbon Tetrachloride	Carbon Tetrachloride	Carbon Tetrachloride	Carbon Tetrachloride	Carbon Tetrachloride	Chloroform	Chloroform	Chloroform	Chloroform	Chloroform	Chloroform	Dichloromethane	Dichloromethane	Dichloromethane	Dichloromethane	Dichloromethane	Dichloromethane	Chloromethane	Chloromethane	Chloromethane	Chloromethane	Chloromethane	Chloromethane
	Jan	Feb	Mar/Apr	May	Jun	July	Jan	Feb	Mar/Apr	May	Jun	July	Jan	Feb	Mar/Apr	May	Jun	July	Jan	Feb	Mar/Apr	May	Jun	July	Jan	Feb	Mar/Apr	May	Jun	July
Up-gradient of PRB																														
A1	15067	5133	<1	336	61282		<1	<1	<1	<1	<10		<1	<1	<1	<1	<10		<1	<1	<1	<1	<10		<1	<1	<1	<1	<10	
A2	8630	13219	24165	113803		6210	<1	<1	<1	<10		<1	<1	<1	<1	<10		<1	<1	<1	<1	<10		<1	<1	<1	<1	<10		<1
C1	<1	<1	6	17		<1	<1	<1	<1	<1		<1	<1	4	<1	<1		<1	<1	10	<1	<1		<1	<1	<1	<1	<1		<1
Eastern PRB																														
B2		<1	<1	<1	<1	<1		<1	<1	<1	<1	<1		<1	<1	<1	<1	<1		7	<1	<1	<1	<1		<1	<1	<1	<1	<1
3PRB		<1	<1	<1	<1	<1		<1	<1	<1	<1	<1		1	<1	<1	<1	<1		9	<1	<1	<1	<1		<1	<1	<1	<1	<1
6PRB	<1	<1	<1	<1	<1	<1	<1	<1	<1	<1	<1	<1	<1	<1	<1	<1	<1	<1	<1	9	<1	<1	<1	<1	<1	<1	<1	<1	<1	<1
2PRB		<1	<1	<1	<1	<1		<1	<1	<1	<1	<1		2	<1	<1	<1	<1		8	<1	<1	<1	<1		<1	<1	<1	<1	<1
5PRB		<1	<1	<1	<1	<1		<1	<1	<1	<1	<1		1	<1	<1	<1	<1		8	<1	<1	<1	<1		<1	<1	<1	<1	<1
1PRB	<1	<1	<1	<1	<1	<1	<1	<1	<1	<1	<1	<1	<1	<1	<1	<1	<1	<1	<1	8	<1	<1	<1	<1	<1	<1	<1	<1	<1	<1
4PRB	<1	<1	<1	<1	<1	<1	<1	<1	<1	<1	<1	<1	<1	<1	<1	<1	<1	<1	<1	7	<1	<1	<1	<1	<1	<1	<1	<1	<1	<1
E2	<1	<1	<1	3	<1	<1	<1	<1	<1	<1	<1	<1	<1	<1	<1	<1	<1	<1	<1	8	<1	<1	<1	<1	<1	<1	<1	<1	<1	<1
D2	<1	<1	<1	4	<1	<1	<1	<1	<1	<1	<1	<1	<1	<1	<1	<1	<1	<1	<1	8	<1	<1	<1	<1	<1	<1	<1	<1	<1	<1
Western PRB																														
B1			17	49	<1	<1			4611	1558	927	1713			2421	1486	855	996			<1	<1	<1	<1			<1	<1	<1	<1
9PRB	<1	4	<1	<1	<1	<1	3896	5979	3763	4765	4014	6040	4121	5089	3026	3652	3163	5650	<1	34	<1	<1	<1	<1	<1	<1	<1	<1	<1	<1
12PRB	<1	<1	<1	2	4	2	3214	2289	3413	3592	8634	3247	3062	1617	2161	2573	8431	3431	<1	20	<1	<1	<1	<1	<1	<1	<1	<1	<1	<1
8PRB		<1	<1	<1	<1	2		<1	<1	<1	<1	3		336	1796	1627	953	351		290	<1	<1	<1	367		<1	<1	<1	<1	20
11PRB		<1	<1	<1	4	2		<1	<1	<1	<1	2		84	138	34	<1	10		188	<1	<1	<1	321		14	<1	<1	<1	20
7PRB	<1	1	<1	<1	<1	2	<1	<1	<1	<1	<1	<1	<1	1	<1	<1	40	48	1195	997	793	<1	<1	420	<1	<1	<1	<1	<1	27
10PRB	<1	<1	<1	<1	<1	2	<1	<1	15	<1	23	<1	<1	<1	18	<1	45	6	611	<1	<1	<1	<1	259	<1	25	<1	<1	30	22
E1	<1	<1	<1	4	<1	<1	<1	<1	<1	<1	<1	<1	<1	<1	<1	<1	4	3	<1	70	<1	<1	<1	<1	<1	<1	<1	<1	<1	<1
D1	<1	2	<1	8	<1	<1	<1	<1	<1	<1	<1	<1	<1	<1	<1	4	5	5	426	108	<1	<1	<1	<1	<1	<1	<1	<1	<1	<1
Downstream of Site																														
F2	<1	3	<1	<1	<1	<1	<1	<1	<1	<1	<1	<1	<1	<1	<1	<1	<1	<1	<1	<1	<1	<1	<1	<1	<1	<1	<1	<1	<1	<1
F1	<1	<1	<1	3	<1	<1	<1	<1	<1	<1	<1	<1	<1	<1	<1	<1	<1	<1	<1	<1	<1	<1	<1	<1	<1	<1	<1	<1	<1	<1
20PRB		<1	<1	<1	36540	2		<1	<1	<1	<10	2		16	13	<1	<10	9		<1	<1	<1	<10	315		<1	<1	<1	<10	20
21PRB		<1			<1	<1		<1			<1	<1		16			16	15		<1			<1	<1		<1			<1	<1

Table E. Summary of laboratory results for VOCs (ii): Chlorinated ethanes and ethenes (all in µg/l)

Sample Identity	1.1.1-Trichloroethane	1.1.1-Trichloroethane	1.1.1-Trichloroethane	1.1.1-Trichloroethane	1.1.1-Trichloroethane	1.1.1-Trichloroethane	Tetrachloroethene	Tetrachloroethene	Tetrachloroethene	Tetrachloroethene	Tetrachloroethene	Tetrachloroethene	Trichloroethene	Trichloroethene	Trichloroethene	Trichloroethene	Trichloroethene	Trichloroethene
	Jan	Feb	Mar/Apr	May	Jun	July	Jan	Feb	Mar/Apr	May	Jun	July	Jan	Feb	Mar/Apr	May	Jun	July
Up-gradient of PRB																		
A1	<1		<1	<1	<10		<1		<1	<1	3		<1		<1	<1	<10	
A2	<1		<1	<10			<1		<1	<10			<1		<1	<10		
C1	<1		<1	<1			<1		<1	<1			<1		<1	<1		
Eastern PRB																		
B2			<1	<1	<1				<1	<1	<1				<1	<1	<1	
3PRB			<1	<1	<1				<1	<1	<1				<1	<1	<1	
6PRB	<1		<1	<1	<1		<1		<1	<1	<1		<1		<1	<1	<1	
2PRB			<1	<1	<1				<1	<1	<1				<1	<1	<1	
5PRB			<1	<1	<1				2	1	1				<1	<1	<1	
1PRB	<1		<1	<1	<1		<1		<1	<1	<1		<1		<1	<1	<1	
4PRB	<1		<1	<1	<1		<1		<1	<1	<1		<1		2	<1	<1	
E2	<1		<1	<1	<1		<1		<1	<1	<1		<1		<1	<1	<1	
D2	<1		<1	<1	<1		<1		<1	<1	<1		<1		<1	<1	<1	
Western PRB																		
B1			10	8	<1				6	3	<10				<1	<1	<1	
9PRB	5		4	4	5		4		5	6	7		<1		<1	<1	<1	
12PRB	4		3	2	3		5		6	6	15		<1		<1	<1	<1	
8PRB			<1	<1	<1				<1	<1	<1				<1	<1	<1	
11PRB			<1	<1	<1				<1	<1	<1				<1	<1	<1	
7PRB	<1		<1	<1	<1		<1		<1	<1	<1		<1		<1	<1	<1	
10PRB	<1		<1	<1	<1		<1		<1	<1	<1		<1		<1	<1	<1	
E1	<1		<1	<1	<1		<1		<1	<1	1		<1		<1	<1	<1	
D1	<1		<1	<1	<1		<1		<1	<1	<1		<1		<1	<1	<1	
Downstream of Site																		
F2	<1		<1	<1	<1		<1		<1	<1	<1		<1		<1	<1	<1	
F1	<1		<1	<1	<1		<1		<1	<1	<1		<1		<1	<1	<1	
20PRB			<1	<1	<10				<1	<1	<10				<1	<1	<10	
21PRB					<1						<1						<1	

Table F. Summary of laboratory results for VOCs (iii): BTEX Compounds (all in µg/l)

Sample identity	Benzene	Benzene	Benzene	Benzene	Benzene	Benzene	o-Xylene	o-Xylene	o-Xylene	o-Xylene	o-Xylene	o-Xylene	Ethylbenzene	Ethylbenzene	Ethylbenzene	Ethylbenzene	Ethylbenzene	Ethylbenzene	p/m-Xylene	p/m-Xylene	p/m-Xylene	p/m-Xylene	p/m-Xylene	p/m-Xylene
	Jan	Feb	Mar/Apr	May	Jun	July	Jan	Feb	Mar/Apr	May	Jun	July	Jan	Feb	Mar/Apr	May	Jun	July	Jan	Feb	Mar/Apr	May	Jun	July
Up-gradient of PRB																								
A1	<1		<1	<1	<10		<1		<1	<1	<1		<1		<1	<1	<1		<1		<1	<1	<1	
A2	<1		<1	<10			<1		<1	<10			<1		<1	<10			<1		<1	<10		
C1	<1		<1	<1			<1		<1	<1			<1		<1	<1			<1		<1	<1		
Eastern PRB																								
B2			<1	<1	<1				<1	<1	<1				<1	<1	<1				<1	<1	<1	
3PRB			<1	<1	<1				<1	<1	<1				<1	<1	<1				<1	<1	<1	
6PRB	<1		<1	<1	<1		<1		<1	<1	<1		<1		<1	<1	<1		4		<1	<1	<1	
2PRB			<1	<1	<1				2	<1	<1				1	<1	<1				17	3	2	
5PRB			<1	<1	<1				2	2	3				2	3	<1				21	26	26	
1PRB	<1		<1	<1	<1		<1		<1	<1	<1		<1		<1	<1	<1		<1		<1	<1	<1	
4PRB	<1		<1	<1	<1		<1		<1	<1	<1		<1		<1	<1	<1		<1		<1	2	<1	
E2	<1		<1	<1	<1		<1		<1	<1	<1		<1		<1	<1	<1		<1		<1	<1	<1	
D2	<1		<1	<1	<1		<1		<1	<1	<1		<1		<1	<1	<1		<1		<1	<1	<1	
Western PRB																								
B1			<1	<1	<1				<1	<1	<10				<1	<1	<10				<1	<1	<10	
9PRB	<1		<1	2	2		<1		<1	<1	<1		<1		<1	<1	<1		<1		<1	<1	<1	
12PRB	<1		<1	<1	<1		<1		<1	<1	<1		<1		<1	<1	<1		<1		<1	1	<1	
8PRB			<1	<1	<1				<1	<1	<1				<1	<1	<1				<1	1	<1	
11PRB			<1	<1	<1				<1	<1	<1				<1	<1	<1				<1	3	10	
7PRB	<1		<1	<1	<1		<1		<1	<1	<1		<1		<1	<1	<1		<1		2	5	5	
10PRB	<1		<1	<1	<1		<1		<1	<1	<1		<1		<1	<1	<1		<1		<1	6	4	
E1	<1		<1	<1	<1		<1		<1	<1	<1		<1		<1	<1	<1		<1		<1	<1	<1	
D1	<1		<1	<1	<1		<1		<1	<1	<1		<1		<1	<1	<1		<1		<1	<1	<1	
Downstream of Site																								
F2	<1		<1	<1	<1		<1		<1	<1	<1		<1		<1	<1	<1		<1		<1	<1	<1	
F1	<1		<1	<1	<1		<1		<1	<1	<1		<1		<1	<1	<1		<1		<1	<1	<1	
20PRB			<1	<1	<10				<1	<1	<10				<1	<1	<10				<1	<1	<10	
21PRB					<1						<1						<1						<1	

Table G Summary of field parameter results

Sample Identity	Dissolved oxygen (mg/l)	Dissolved oxygen (mg/l)	Dissolved oxygen (mg/l)	Dissolved oxygen mg/l	Dissolved oxygen mg/l	Dissolved oxygen mg/l	pH	pH	pH	pH	pH	pH	Redox potential (mV)	Redox potential (mV)	Redox potential (mV)	Redox potential (mV)	Redox potential (mV)	Redox potential (mV)	Temperature (°C)	Temperature (°C)	Temperature (°C)	Temperature (°C)	Temperature (°C)	Temperature (°C)	Electrical Conductivity (µS/cm)	Electrical Conductivity (µS/cm)	Electrical Conductivity (µS/cm)	Electrical Conductivity (µS/cm)	Electrical Conductivity (µS/cm)	Electrical Conductivity (µS/cm)
	Jan	Feb	Mar/Apr	May	Jun	Jul	Jan	Feb	Mar/Apr	May	Jun	Jul	Jan	Feb	Mar/Apr	May	Jun	Jul	Jan	Feb	Mar/Apr	May	Jun	Jul	Jan	Feb	Mar/Apr	May	Jun	Jul
Upgradient of PRB																														
A1	2.57	3.40		22.60	-	-	6.44	6.49	6.36	6.38			-49	27.8	36.3	19			8.8	8.9	8.6	9.5	-	-		1689	1488	967	-	-
A2	3.70	6.40		25.70	0.40	1.55	6.36	6.34	6.05	5.38		6.00	-29	28.5	53.1	75			10.7	9.2	10.1	10.7	10.4	11.1		1595	1632	1873	1800	1865
C1	11.69	8.56		22.90	-	2.55	6.44	6.27	6.07	4.44		6.20	37	32.6	54.7	120			7.3	7.5	8.1	11.8	-	12.5		750	665	710	-	961
Eastern PRB																														
B2		5.26		4.88	0.63	0.53		6.48	6.34	6.35		4.50		20.9	23.4	19				9.8	9.6	10.4	11.9	13.4		1537	1468	1480	1503	1367
3PRB	1.14	7.32		4.29	2.45	0.51	5.87	6.60	6.54	6.58		6.00	-23	13.8	26.8	7			11.1	7.1	9.6	10.7	11.7	12.0		1631	1722	2326	1990	2104
6PRB	7.11	2.87		4.35	2.34	2.96	5.54	6.58	6.39	6.53		5.00	167	15.4	34.4	12			11.7	10.8	9.4	10.7	11.8	13.2		2093	1692	2176	1984	1724
2PRB		1.15		4.00	0.30	0.16		7.07	7.05	9.70		9.50		12.5	-2.1	-172				14.6	12.4	11.6	11.8	12.0		1139	792	1258	1281	1148
5PRB		1.76		3.93	0.26	0.27		7.07	6.88	9.83		9.60		-12.8	7.6	-177				10.0	12.0	11.9	12.1	12.9		1443	1222	1254	1170	955
1PRB	0.63	5.31		6.37	2.30	0.62	8.83	6.92	6.69	8.23		8.10	-347	-3.8	18.6	-81			11.5	13.2	10.8	11.7	12.8	13.1		1169	1055	1071	1205	988
4PRB	0.50	5.86		5.29	0.64	0.63	9.48	6.94	6.65	7.20		8.80	-274	-5.4	20.1	-35			11.6	8.4	11.0	11.4	12.1	12.3		885	1239	1119	1100	894
E2	0.98	2.99		7.44	0.29	0.16	7.06	6.60	6.59	2.46		7.20	79	13.8	23.6	240			11.6	7.2	10.6	11.1	11.8	12.8		1032	430	877	861	753
D2	8.18	5.89		17.14	5.40	4.01	7.03	6.71	6.58	0.78		7.30	65	7.9	33.9	341			13.2	7.2	11.8	13.0	12.4	12.7		-	100	973	947	738
Western PRB																														
B1				6.28	0.27	0.40			6.47	7.80		6.20			31.4	-61					10.2	14.7	11.5	13.1			963	958	905	990
9PRB	1.62	3.82		4.24	0.48	0.24	6.10	6.58	6.47	7.93		5.90	-87	15.4	31.1	-69			12.2	11.0	10.7	10.8	11.4	12.0		1419	1293	1435	1556	1757
12PRB	1.19	2.13		4.26	0.58	0.43	6.58	6.66	6.50	7.55		6.30	-114	10.8	28.7	-48			12.6	11.8	10.7	11.0	11.6	12.1		1781	759	1622	1826	1715
8PRB		1.96		4.08	0.22	0.15		6.87	6.75	9.82		9.7		-0.9	15.2	-173				11.3	11.0	11.0	11.7	12.5		1069	863	896	830	525
11PRB		2.80		4.16	0.23	0.16		6.90	6.81	10.93		9.80		-2.3	12.0	-239				11.7	11.2	11.2	11.8	12.5		896	677	740	834	682
7PRB	0.88	4.21		0.00	1.80	0.35	10.38	6.94	6.77	10.97		9.80	-276	-4.6	13.7	-239			12.2	8.8	11.0	14.2	11.8	12.9		944	867	890	813	624
10PRB	8.15	3.69		2.46	2.15	0.14	9.56	6.93	6.56	10.39		10.00	-231	-4.4	25.3	-210			12.1	8.3	11.0	12.4	12.2	13.2		920	782	867	850	685
E1	11.26	6.67		3.17	0.38	0.41	8.34	6.27	6.25	7.69		7.20	-121	32.6	41.7	-54			9.4	10.7	10.8	11.2	11.8	13.1		1034	879	906	821	644
D1	6.08	10.10		8.66	5.76	8.05	7.86	6.19		1.07		7.50	-2	37.1		315			11.3	11.4		14.5	12.7	12.6		1046		995	967	824
Downstream of Site																														
F2	2.92	7.43		4.38	0.38	0.30	6.62	6.21	6.01	6.69		6.40	53	35.1	57.1	1			8.7	11.3	8.7	11.3	10.6	11.8		247	138	151	159	163
F1	2.82	7.13		12.94	0.31	0.67	7.03	6.22	6.61	7.50		6.60	71	35.7	22.1	45			8.3	8.6	8.7	11.6	10.7	12.1		168	221	266	272	250
20PRB	-	-			-	-	-	-	-	-			-	-	-	-			-	-	-	-	-	-			-	-	-	-
21PRB	10.40	-			-	-	5.35	-					171	-					6.0	-			-	-					-	-
Field Blanks		11.58						6.37						26.8						8.8						2				