Introduction

ERM was commissioned to investigate and treat legacy contamination at a manufacturing facility in the UK. The site investigation activities, using High Resolution Site Characterisation (HRSC) techniques, identified impacts from Trichloroethene (TCE) within fractured bedrock, at concentrations suggesting the presence of DNAPL. The onsite TCE impacts relate to former degreaser locations within an operational building and the contaminant had migrated beyond the site boundary, being detected at downgradient receptors (*Figure 1)*. Following site characterisation, ERM partnered with Cornelsen to implement the chosen remedial approach.

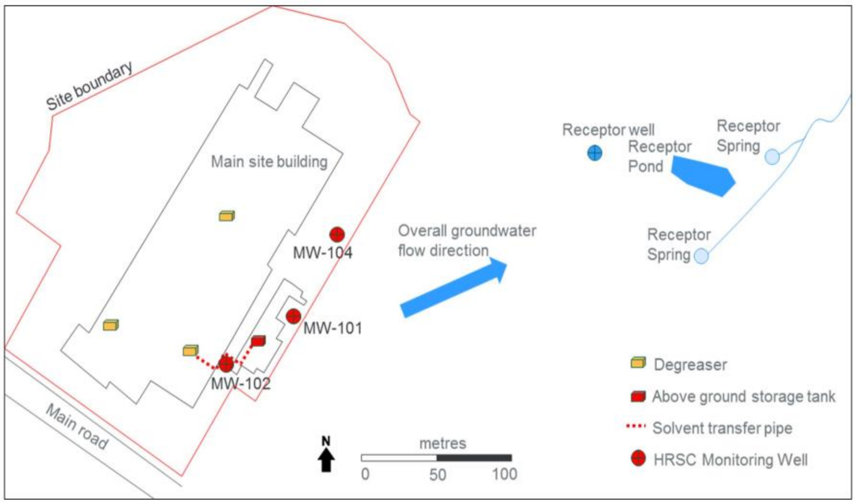

Figure 1: Source and Receptor Layout Plan

Site Characterisation

Due to the complex fractured bedrock geology, characterisation using traditional site investigation techniques was not feasible, so characterisation was undertaken via a complimentary suite of HRSC techniques including:

- **Detailed Geological Logging and Structural Frequency Analysis (SFA):** This involved traditional core logging to British Standards, but also logging of structure type, frequency and orientation. The site lies directly on slate bedrock, with sporadic weathered zones (See *Figure 2*).
- **Downhole Geophysics:** An optical televiewer was used to visually identify fracture zones (transport pathways).
- **Background Fluorescence Analysis (BFA):** This involves the analysis of groundwater samples with a fluorescence spectrometer, generating a unique fluorescence ‘fingerprint’ for each sample, allowing an assessment of hydraulic connectivity.
- **Discrete Fracture Network (CORE$^{DFN™}$):** The CORE$^{DFN™}$ allowed collection and on-site analysis of approximately 350 samples during a 2 week period, facilitating the identification of impacts in near real time and informing the drilling depth for subsequent locations, saving time, cost and energy consumption. Rock samples were analysed from both fracture surfaces and from the intervening rock matrix via microwave extraction (*Figure 3*) and GC/MS.

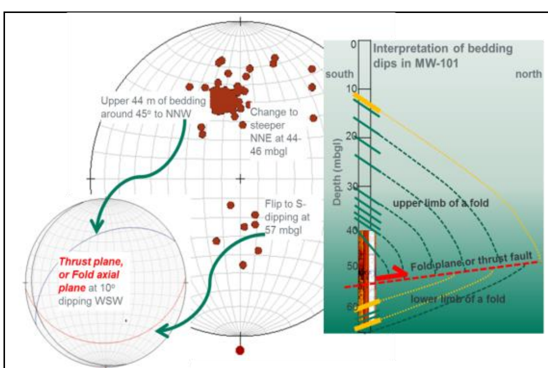

Figure 2: Structural frequency stereonets

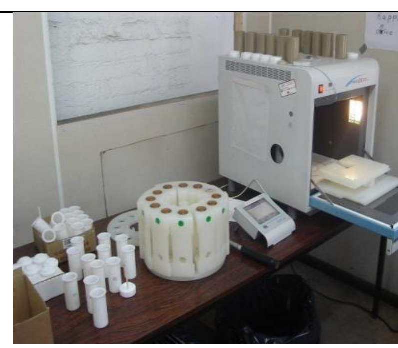

Figure 3: Microwave Assisted Extraction

Results

The integrated HRSC results allowed the creation of a fractured bedrock Conceptual Site Model (CSM) (*Figure 4*). The structural geological assessment determined that there were frequent bed-parallel fractures between 16-36m bgl, with some high angle cleavage fractures also present. The fracture locations identified correlated well with high TCE concentration data from the CORE$^{DFN™}$, confirming the migration of dissolved phase TCE and allowing the installation of targeted monitoring wells. Critical information gained from the structural geological assessment was the absence of open fractures below 40m bgl, which corresponded to trace TCE concentrations at these depths. This allowed the depths of impacts to be determined, providing key data for remedial design.

Data from the CORE$^{DFN™}$ and BFA further refined the CSM. The fluorescence ‘fingerprints’ obtained via the BFA showed potential hydraulic connections between the on-site and off-site receptors, supporting the data on groundwater flow direction gained from the geological assessment. The results of the CORE$^{DFN™}$ identified significant TCE concentrations were present within both the fracture network and rock matrix.

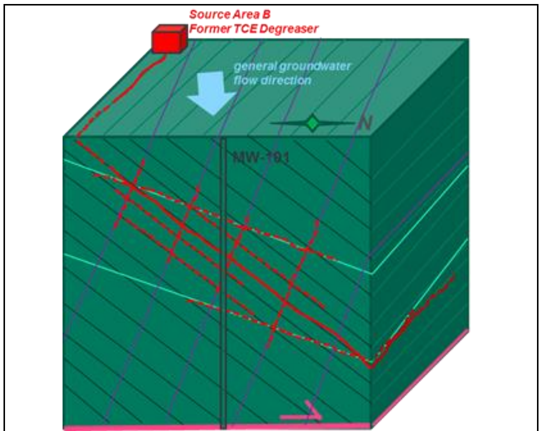

Figure 4: **Fractured Bedrock CSM**

Remedial Options Appraisal

Given the technical challenges of remediation of DNAPL in fractured bedrock, ERM carried out analysis of the significance of matrix diffusion (ie: contaminants may enter the rock matrix which can then ‘back-diffuse’ over long periods of time). PC based software (‘Matrix Diffusion Toolkit model’), was used to assist with the selection of the remedial technique by generating a model curve for diffusion into the matrix from a fracture where groundwater was saturated with TCE (1,100mg/l). The results showed matrix diffusion occurring within 0.5m of fractures, however this is of low significance given that DNAPL mass within fractures is dominant.

A Remedial Options Appraisal was undertaken using a holistic sustainability approach, where environmental, social and economic indicators were evaluated to determine the most sustainable option in accordance with CLR11, and the UK SuRF framework, incorporating sustainability as an integral part of the technology selection process.

The results of the ROA showed:

- Some techniques were unsuitable due to the nature of the fractured bedrock/depths of impact (excavation).
- Some techniques were not feasible as the source areas were located beneath operational manufacturing buildings (process based recovery techniques).
- Fluid-based remediation techniques were not feasible due to challenges of delivery in fractured bedrock and also the high TCE concentrations (In-Situ Chemical Oxidation).
- Given the limited options available due to technical and logistical constraints and the fact that downgradient receptors had already been affected the remedial goal was to reduce on-going impact to the receptors and contain the TCE. The understanding of matrix diffusion and containment distribution via the multiple HRSC techniques also suggested fracture mass should be targeted.
- Therefore hydraulic containment was the chosen solution to achieve these aims and meet client and regulatory expectations in the short to medium term.

A multiple well, field scale pumping trial was undertaken by ERM with Cornelsen to confirm Hydraulic Containment System (HCS) design parameters, such as radius of influence and flow rates. The remedial system was then designed by ERM and included creation of a groundwater flow model using Modflow and Modpath codes; the system comprises six pumping wells connected to recovery equipment (DNAPL collection tank, air stripper, chiller and liquid/vapour phase discharge via Granular Activated Carbon). The system has now been installed by Cornelsen and is currently being commissioned (*Figure 5* and *Figure 6*).

Figure 5: **Process Equipment**

Figure 6: **Equipment Container**

Best Practice

Best practice was demonstrated throughout the project:

- The HRSC techniques used were complimentary and provided a collaborative data set, creating a robust CSM. The HRSC techniques also produced a high quality data set in a short period of time and have related sustainability/costs benefits compared to traditional techniques. The data collected informed the depth of TCE impacts and the mechanisms for contaminant migration, with the data being used to inform the ROA and subsequent design.
- Innovative remedial design, including groundwater modelling and matrix diffusion assessment.
- Innovative system design:
    - The installation considered long term site operation/logistics. For example connections between groundwater extraction wells and the remediation equipment had to be buried underground to allow the site to remain operational. This was complex given the presence of numerous underground utilities.
    - The process system includes remote monitoring/telemetry/high level of control and monitoring from off-site (via remote access software and CCTV), with benefits of ease of use and reduced attendance costs.
    - The process equipment includes innovative security, such as finger print log in, passwords and different access rights (i.e. greater levels for Cornelsen for system maintenance).
    - High quality of plant, such as stainless steel high quality welds, efficient air stripper – this was particularly relevant given the plant was bought by the client which is unusual for many UK remediation projects.
    - Solenoid pump controls to allow pumps to operate lower than their normal operating rates.
    - Multi-mode groundwater pump control (i.e. drawdown, maximum volume or target flow rate can be set).
    - In-line PID to measure solvent vapours, enabling system optimisation in conjunction with the remote access.
    - Plant built into a container to allow full off-site construction and test running of the plant. This reduced the installation time on-site, making this process faster and more cost effective.
- ERM has created a Power BI dashboard to allow real-time data visualisation and interpretation. Data collected from the process equipment will be uploaded into the system via an EQuIS database, together with any manual data collection (using the EDGE field tool). This approach will significantly reduce data processing time and enable the system to be rapidly optimised.
- ERM has collaborated with Cornelsen to implement our conceptual design. However, unlike many traditional engineering design and build contracts this relationship has been leveraged to allow both parties to input into the detailed design from both an innovation and safety perspective, which ultimately has produced a higher quality product.
- A trusted advisor relationship has been built between the ERM/Cornelsen team and the Environment Agency (EA), with multiple discussions held and a 'remediation training' session to be scheduled for EA staff in the future.
- H&S approach: A HAZOP/process safety review was undertaken at the design stage (for example assessing material compatibility, critical safety devices, containment) with any mitigation measures being verified during system commissioning. This process will reduce operational risks significantly and also included liaison with site management on issues such as fire protection in the context of wider site activities.

Cost effectiveness and durability
The HRSC approach adopted minimised the duration of the site investigation and at this site finalised the CSM without the need for multiple phases of investigation that are typical with conventional drilling approaches. As duration was shorter, ERM estimates the cost of the investigation was 30 - 50% cheaper than using traditional techniques. The accurate delineation of the identified impact has also enabled the remedial strategy and design to be robustly assessed (for example the understanding of matrix diffusion could not have been achieved without HRSC) and this therefore increases the likelihood of achieving the remedial objectives. The remote system control and data management systems also mean site attendance can be reduced, saving cost. The innovative system design and data management protocols will also reduce downtime.

Significant reduction of the pollution burden
The HCS system is expected to reduce impacts to the off-site receptors by breaking the pollutant linkage. This approach has been selected due to the inaccessibility of the source zones and majority of the mass being in the relatively high permeability fractures, although some mass removal during the containment is still anticipated and will be assessed via monitoring to confirm the suitability of the strategy in the longer term.

Community and stakeholder acceptance
All project stakeholders were consulted throughout the project, as follows:

- **Regulators:** ERM kept the EA informed throughout the project and have received positive feedback from the regulator, who noted that the HRSC assessment had been completed to a level beyond that typically seen in the UK. The carefully designed remedial approach enabled endpoints to be agreed quickly with the regulators.
- **Client:** ERM held regular meetings with the client to discuss a wide range of issues, including H&S and integration of remedial activities with site activities.

The works were completed safely, on schedule, on budget and to the satisfaction of all stakeholders.

Compliance with Health and Safety
ERM and Cornelsen instigated a proactive, sustainable approach to H&S which frequently considered the risks in the context of an operational site. The work also fell under the CDM Regulations (2015), therefore the roles and responsibilities were clearly defined. In addition to typical risks considered for any in-situ remediation project, the following was also undertaken:

- Process safety was considered at the design stage with several reviews undertaken; the outcome of which added process safety features to the remedial equipment.
- A strong safety culture was embedded within the project team so any observed hazards were identified and addressed.
- Mentoring of junior staff was undertaken face to face throughout the works.
- Three project audits were undertaken in accordance with ERM’s global Active Safety Management approach, with lessons learnt fed back into the project and wider business.
- Use of the HRSC approach significantly reduced Health and Safety risks, given that accurate site characterisation can be undertaken more rapidly and with fewer intrusive locations, reducing the time spent on-site and hence the risks inherent with intrusive activities.
- Use of the data management and remote system operation will reduce travel to site, which is one of the biggest project risks.

Sustainability
Sustainability has been a key consideration throughout the project lifecycle, as summarised below:

- The use of innovative HRSC techniques has a lower carbon footprint than if multiple phases of traditional investigation had been undertaken.
- The remedial approach focussed on carbon footprint reduction to the extent practical, including:
    - Pumping trial and groundwater modelling during the design stage which identified the optimum pumping parameters to achieve capture and increase the overall efficiency for the commissioning and operations stage.
    - System build completed largely off-site, reducing travel to the facility.
    - Condensing of vapour stream using heat exchangers to dry vapour and minimise granular activated carbon use.
    - Use of remote monitoring technology to make system operation more efficient and reduce site attendance required.
    - Changeable pumping modes to maximise/target recovery with minimal power input.