CL:AIRE

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Concawe bulletin

CL:AIRE's Concawe bulletins describe the deployment of sustainable remediation techniques and technologies on sites in Europe. Each bulletin includes a description of the project context and conceptual site model along with a sustainability assessment. This bulletin describes how sustainable remediation was applied to an active industrial site.

Biosparge of Benzene and Orthodichlorobenzene in Groundwater: A Sustainable Remedy

1. INTRODUCTION

This case study presents the implementation of a biosparge system for the remediation of volatile and chlorinated volatile organic compounds in groundwater at an active industrial site. The aim of the bulletin is to present the background and context, the site conceptual model, the basis for remedy selection including a sustainability assessment and the main lessons learned.

2. SITE DESCRIPTION

The project site, located in the United Kingdom, covers approximately 9 hectares and is part of a wider area that has been extensively used for industrial operations since the 1950s.

At present day, the site continues to be used for industrial purposes, though large expanses of the site are unoccupied space, e.g., grass fields, asphalted land, some trees or shrubs (see Figure 1). A regulated surface water body – an Area of Special Scientific Interest (ASSI) – is downgradient (north-east) of the site. It is expected that site use will remain commercial / industrial.

Lithology at the site is characterised by alluvial and glacial sediments. There is a general fining-downwards sequence with two defined hydrostratigraphic units (HSUs):

- Shallow HSU: Gravelly sands from approximately 5 metres below ground level (m bgl) transitioning into clean sands to approximately 20 m bgl.
- Deep HSU: Below 20 m bgl, the sands become interbedded with low-permeability silts. This HSU is strongly anisotropic.

Groundwater, typically encountered at 5 m bgl in the west of the site and at 7 m bgl in the east, flows eastward towards the ASSI surface water body. Vertical hydraulic gradients are downward between the shallow and deep HSUs, becoming upwards closer to the surface water body.

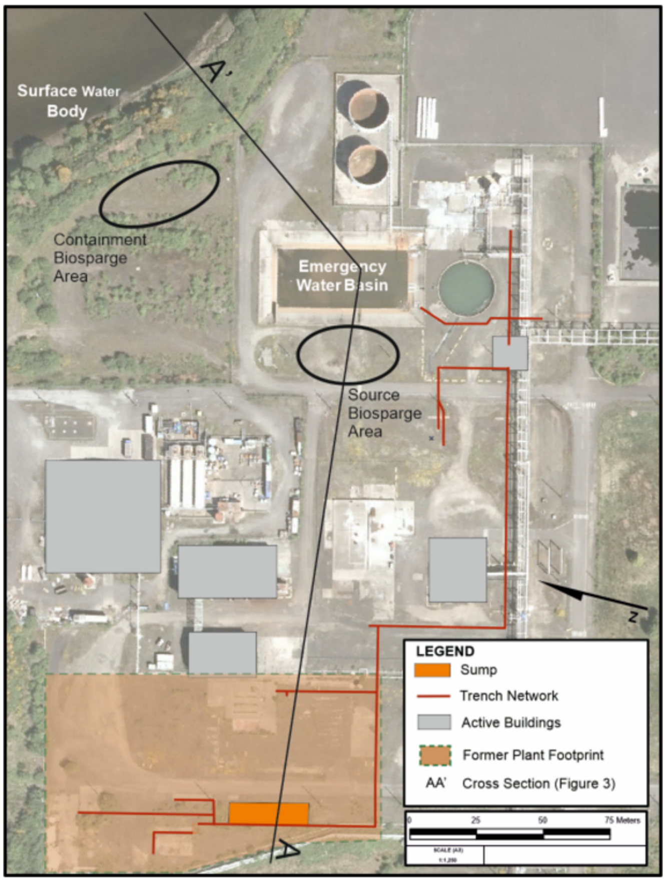

Figure 1: Site plan.

3. ENVIRONMENTAL LEGACY

Until the early 1980s, operations at the site included a plant manufacturing 1,2-dichlorobenzene, also known as ortho-dichlorobenzene (ODCB). Investigations in the 2000s identified legacy soil and groundwater impacts notably including ODCB and benzene, an ODCB breakdown product under anoxic conditions.

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Preliminary site investigations identified an abandoned sump and trench drainage network that still contained ODCB free product. In 2014, an initial remediation effort was undertaken to remove the free product and then abandon the drainage network. During these works, damage to the trench was noted and considered as likely "release points" for the present-day subsurface contamination. Noting that ODCB free product is a dense non-aqueous phase liquid (DNAPL), additional investigations subsequently undertaken to identify where ODCB had migrated from these release points included:

- Routine groundwater and surface water monitoring (routinely since 2007; targeted after 2014).
- Human health assessments including potential risks for vapour intrusion and potable water supply.
- Source investigation in 2013: real-time data collection using an on-site laboratory and groundwater vertical profiling using IsoFlow™ sampling techniques.
- Additional delineation investigation works in 2014: spike soil gas surveys, passive soil gas samplers and further soil and groundwater profiling.

The main contaminants of concern (COC) and depths of impact are summarised in Table 1.

Table 1: Summary of contaminants and lithology per biosparge area.

Contaminants of Concern	• ODCB as DNAPL • ODCB in dissolved phase with concentrations up to 78,000 µg/L • Benzene in dissolved phase with concentrations up to 119,000 µg/L
Primary Impacted Lithologies	• Sands (Deep) from 16-20 m bgl – ODCB in groundwater • Interbedded Sands/Silts from 20-30 m bgl – Benzene & ODCB in groundwater

4. CONCEPTUAL SITE MODEL

With the cleanout and abandonment of the trench network in 2014, the legacy free product source was eliminated, but ODCB DNAPL had already impacted the subsurface. Being an active site with an ASSI receptor downgradient, a conceptual site model (CSM) was developed. The CSM including sources, pathways and receptors and the concept of target treatment zones (TTZs) are illustrated on Figure 2.

TTZs were identified (based upon investigations and risk assessments) as follows:

- **TTZ1 - ODCB DNAPL near former plant.** Shallow soil sampling and observed staining near former sumps suggested that there had been spills or overflows. ODCB DNAPL is today found here in shallow gravels (~5-6 m bgl). There is no evidence that ODCB DNAPL migrated deeper than these shallow gravels. However, downward hydraulic gradients do take a dissolved-phase ODCB to depth (see TTZ2).
- **TTZ2 - Deep dissolved-phase plume of ODCB and benzene.** Downward hydraulic gradients take dissolved-phased ODCB from TTZ1 down to the Deep HSU. Then migrating eastward, the ODCB fully degrades, primarily by anaerobic dechlorination, to benzene.
- **TTZ3 - Deep ODCB DNAPL near Emergency Water Basin (EWB).** Damage to the trench network was found near the EWB with soil staining beneath failed segments. Investigations subsequently identified ODCB DNAPL in this area within the interbedded sand-silt unit at approximately 18-20 m bgl (TTZ3a). The highest measured ODCB dissolved-phase concentrations are downgradient at approximately 16-22 m bgl (TTZ3b).
- **TTZ4 - Combined ODCB and benzene plumes.** Approaching the surface water body, hydraulic gradients become upward and the interbedded nature of the deep sands and silts diminishes. This area where plumes begin to co-mingle is recognised as TTZ4.

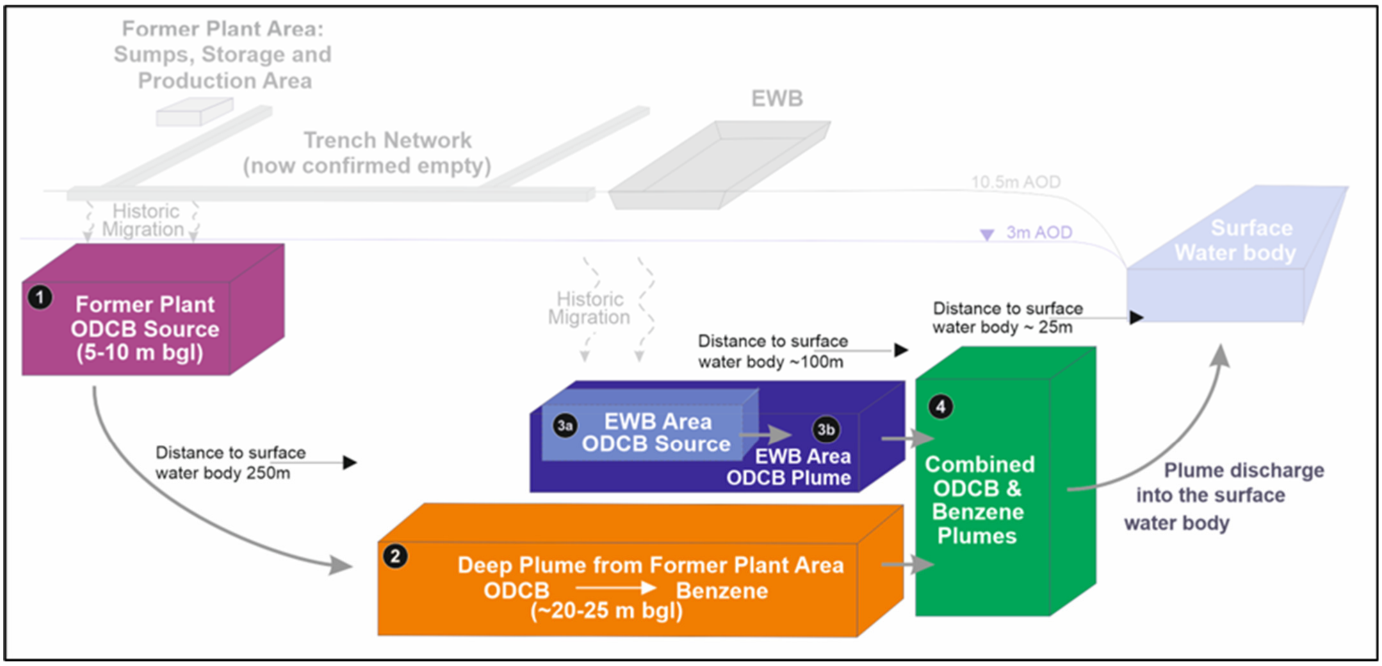

Figure 2: Conceptual site model showing target treatment zones.

Cross sections are illustrated in Figure 3. Note that the top cross section focuses on upgradient TTZ1 and does not show the downgradient ODCB plume that originates from near the EWB (i.e., TTZ3). Conversely, the bottom cross section focuses on TTZ3 and does not show the deep benzene plume that originates from near TTZ1.

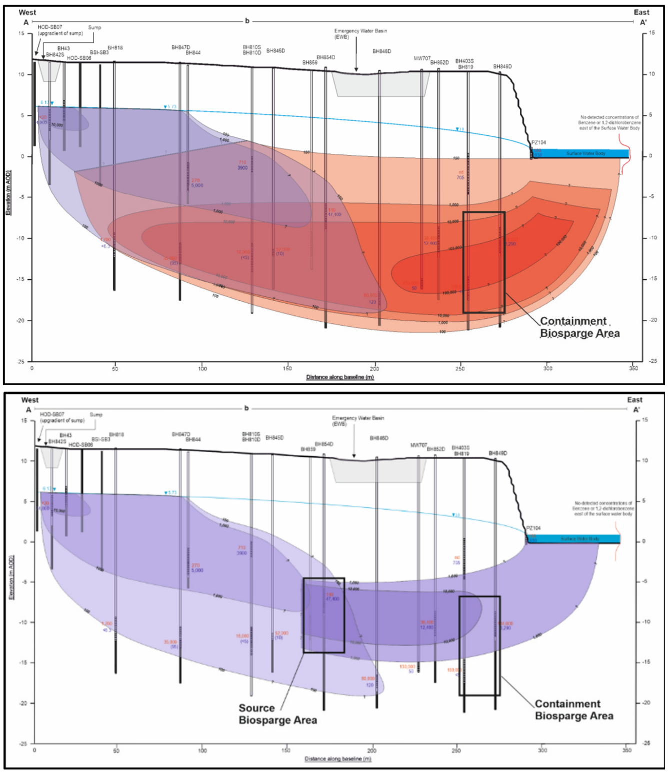

Figure 3: Cross section of ODCB and benzene plumes (top) and ODCB plumes (bottom). Purple = ODCB, Red = benzene. NB: Cross section A-A' location is shown on Figure 1.

Some key findings of the CSM included:

- Pressure driven migration of free product has effectively ceased. DNAPL migration (lateral or vertical) will not provide a significant future mechanism for contaminant transport.
- Contaminant leaching through the unsaturated zone is not considered significant. That is, the majority of the contaminant mass is understood to have already migrated into the saturated zone.
- Advective transport of dissolved-phase contamination through groundwater from the two identified source areas towards the regulated, off-site surface water body is a complete pathway.

5. ASSESSMENT FUNCTION

During investigations, CSM development, risk assessment and remedial options evaluation, regulators and stakeholders were kept engaged with, at minimum, annual reporting and annual on-site meetings. Key project decisions always sought stakeholder feedback. This section summarises the process to progress decision making, stakeholder endorsements and regulator approvals.

5.1 Risk assessments

Key outcomes of the risk assessments and regulator and stakeholder engagements include:

- Land will remain industrial and thus monitored and controlled.
- Potential risks to human health were evaluated and findings reported to regulators. No risks to human health were identified.
- No groundwater abstractions are known onsite or downgradient of the site. Only surface water is considered an ecological receptor, namely the ASSI located adjacent to / downgradient of the site.
- Quantitative risk assessment was undertaken for the adjacent surface water body calculating Level 4 remedial targets that considered Environmental Quality Standard (EQS) for transitional and coastal waters. (Note Level 4 takes account of any additional dilution available at the receptor.)

It is noted that present-day COC concentrations in groundwater are already less than the calculated Level 4 remedial targets. Similarly, years of surface water monitoring have not identified EQS exceedances within the main surface water body. However, the plume discharge has been mapped out using porewater and, given the value placed by stakeholders on the ASSI together with corporate core values, the decision was made to proceed with a voluntary remedial action.

5.2 Remedial objectives and scenarios

Remedial objectives were iteratively developed over a period of two years. While the proposed remedial action is voluntary, the remedial objectives were discussed with stakeholders and regulators during the annual meetings. Time-phased project remedial objectives are presented within Figure 4.

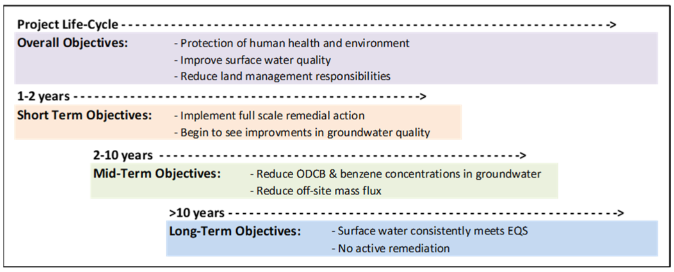

Figure 4: Remedial objectives.

5.3 Remedial scenario development

With the risk assessments largely completed and remedial objectives agreed, discussions began on potential approaches to take forward the remedial action. While considering available technologies, this process focused primarily on strategy or “scenarios”. The scenarios considered included:

- **Migration or plume control**. Leave sources and focus on plume and reduction of off-site mass fluxes.
- **Source removal / treatment**. Action the DNAPL sources only.

- **Plume control and source action.** Control plume immediately to reduce off-site mass flux while also actioning source area (s).

Plume control with partial source action was preliminarily selected with the following considerations:

- DNAPL sources left untreated can persist for decades. Plume containment alone would be unlikely to meet the objective of no active remediation beyond 10 years.
- ODCB DNAPL entered the environment from multiple release points and is in places at depths of over 20 m bgl. Remediation of source areas alone would be challenging and unlikely to reduce offsite fluxes in a reasonable timeframe.
- The ODCB source near the EWB is nearer to the surface water body than the source at the former plant area. The EWB source has DNAPL bound in interbedded sands and silts at approximately 20 m bgl and results in an ODCB dissolved-phase plume that migrates and reaches the surface water body as ODCB.

5.4 Identification and screening of potential technologies

Potential technologies for treatment of ODCB and benzene dissolved-phase plumes and DNAPL source were preliminarily screened. This qualitative screening considered technical feasibility, potential effectiveness, ease of implementation and cost effectiveness. The top seven technologies, further ranked as top, mid and lower, are presented in Table 2.

With the preliminary efforts to identify a strategy and potential technologies, it was decided to proceed with pilot testing of both Sparging + SVE (soil vapour extraction) and Biosparge to confirm whether these technologies are applicable for the site (Section 7). In addition, a sustainability assessment was undertaken to further progress the remedial options evaluation process (Section 6).

6. SUSTAINABILITY ASSESSMENT

The preliminary technology screening had identified seven technologies that could be variably used for plume and / or source treatment. The technology common to the top four (top and mid ranked) technologies was enhanced aerobic *in situ* biodegradation. A sustainability assessment was performed to evaluate the top and mid-ranked technologies and a relevant baseline as follows:

- Two top ranked alternatives: Biosparge and sparging + SVE.
- One conceptually feasible alternative: *In situ* chemical oxidation (ISCO) with activated persulfate or catalysed hydrogen peroxide.
- Monitored Natural Attenuation (MNA), considered as a relevant common baseline.

6.1 Methodology

A qualitative approach was chosen to perform the assessment that was considered appropriate for a robust evaluation considering project constraints and boundaries. The assessment considered the SuRF-UK framework (CL:AIRE, 2010) as well as requirements of CLR11 (Environment Agency, 2004).

Table 2: Results of preliminary technology screening.

Top Ranked. Technologies identified as likely being technically feasible for both source area and dissolved-phase plume treatment.		
1	Sparging + SVE	Well-established technology for dissolved-phase, volatile and chlorinated volatile organic compounds. Less frequently implemented for DNAPL. Concern about ability to implement in interbedded sands and silts. Often SVE is required to prevent transfer to atmosphere.
2	Biosparge	Similar to sparging + SVE (e.g., largely same infrastructure), but air injected at lower flow rates only to oxygenate groundwater and augment *in situ* degradation (i.e., no contaminant stripping and SVE not needed).
Mid Ranked. Technologies conceptually / technically feasible, but less likely to be effective, implementable or cost effective for both the source area and dissolved-phase plume treatment.		
3	*In situ* chemical oxidation (ISCO)	Implementation considered with activated persulfate or catalysed hydrogen peroxide (permanganate was also considered, though ranked even lower).
4	Enhanced aerobic biodegradation	Use of supersaturated groundwater, oxygen infusion technology, or oxygen releasing compounds.
Lower Ranked. Technologies unlikely to be effective, implementable or cost effective for both source area and dissolved-phase plume treatment.		
5	Groundwater extraction and treatment	Known commonly as "pump and treat", technology could likely be implemented quickly and be successful for the dissolved-phase plume. Applicable primarily for source. Preliminarily, poor considerations for sustainability and cost.
6	Anaerobic biological treatment	*In situ* chemical reduction using zero valent iron or other reductants. Uncertain feasibility, i.e., additional bench and pilot testing would be required.
7	*In situ* thermal / soil mixing treatment	Best applied to discrete sources; EWB source is relatively large / dispersed and extends to greater than 20 m bgl. Not suitable for dissolved-phase plume.

A colour scale was used to rank the relative performance of each alternative against the other alternatives for a number of specific indicators. Descriptive qualitative comparisons are included as inputs into the tool and provide a basis to assign and discuss the colour code, which is used to attribute a numeric ranking for each field of the matrix (see colour scale in Figure 5).

The coloured matrix with descriptive text is a reasonably simple Excel spreadsheet with some Visual Basic. It was used iteratively and collaboratively with the client, the regulator and stakeholders for this specific site on numerous occasions to interactively present, discuss and agree upon strategies and technologies.

As an output, an overall score (normalised to a maximum score of 10 and based on individual rankings per indicator) for each dimension (society, environment, and economy) was derived for each of the four alternatives. The tool then provided a final score for each alternative (maximum possible final score of 30). For this qualitative Tier 1 assessment, weights were not assigned to indicators because the project team agreed to initially give equal importance to all indicators.

6.2 Selection of sustainable remediation indicators

Sustainability indicators were selected using the SuRF-UK list of headline categories (also updated considering CL:AIRE, 2020 and ISO 18504:2017). A positive inclusion approach was applied and a set of 12 out of the 73 SuRF-UK indicators was chosen. For example, indicators that showed no differentiation across the technologies were eliminated. An equal number of indicators was selected for each dimension to ensure a balanced consideration of environmental, social, and economic benefits and impacts of each alternative, while avoiding double counting.

The project specific indicators derived for each dimension / category and the selection rationale are illustrated in Table 3.

Table 3: Sustainability indicators per category / dimension and selection rationale.

Dimension	Category[1]	Indicator[1]	Justification for Selection
Environment	Groundwater and surface water	Effect on mobilisation of dissolved substances	Reduce mass flux to surface water
	Ecology	Use of equipment that affects / protects fauna (e.g., bird / bat flight, or animal migration)	Protect sensitive ecological species near / within project site
	Natural resources and waste	Use of primary resources and substitution of primary resources within the project or external to it, rates of recycling, rates of legacy waste generation, use of other recyclates	Focus on climate issue
		Use of energy / fuels taking into account their type / origin and the possibility of generating renewable energy by the project	Focus on climate issue
Society	Human health and safety	Site workers (construction activities)	Implement client core value considering implementation and long-term operation & maintenance
		Risk management performance on remediation works and ancillary operations (i.e. process emissions)	Implement client core value
	Ethics and equity	Duration of remedial works / avoidable transfer of contamination impacts to future generations	Manage business risks, compliance and integrity
	Neighbourhoods and locality	Effects from dust, light, noise, odour & vibrations during works and associated with traffic, including both working-day, night, weekend, etc.	Manage business risks, compliance and integrity
Economy	Direct economic costs and benefits	Direct financial costs and benefits of remediation for organisation	Ensure cost effectiveness requirement
		Costs associated with operation and any ongoing monitoring, regulator costs, planning, permits, licences, etc.	Ensure cost effectiveness requirement
	Project lifespan and flexibility	Duration of the risk management (remediation) benefit, e.g. fixed in time for a containment system / length of time taken for beneficial effects to become apparent	Comply with key remedial objective $\rightarrow$ability to stop active remediation after 10 years
		Factors affecting chances of success of the remediation / management works and issues that may affect works (community, contractual, environmental, procurement and technological risks)	Manage risks effectively while selecting most favourable remedial approach

Note: [1]Sustainability category and indicators updated to reflect SuRF-UK Supplementary Report 2 (CL:AIRE, 2020).

6.3 Sustainability assessment results

The outputs from the sustainability assessment tool are presented for the environment, society, and economy domains within Figure 5.

The sustainability assessment summary results are presented in Figure 6. With an overall ranking significantly higher than the other alternatives evaluated, biosparge is the technology that ranks the highest. In summary:

- Biosparge ranked the most favourable in each of the environmental, society and economy domains.
- ISCO ranked at least tied for second in each domain and second overall.
- Sparging + SVE ranked the lowest of the active treatments, just marginally above the baseline MNA.

While the qualitative (Tier 1) sustainability assessment provided a clear finding favouring biosparge, there were still technical challenges to implement this technology. Notably, it had been decided to progress with a pilot test to validate the feasibility of the technology.

In addition, the qualitative assessment provided a clear answer, so a more quantitative assessment was not undertaken. However, if the pilot testing of the biosparge technology were to prove unsuccessful, semi-quantitative (Tier 2) or quantitative (Tier 3) sustainability assessments would be undertaken to better explore the other options.

	Category	Indicator	Target Treatment Zone -->	ODCB and Benzene Plume + EWB ODCB Source Area			
			Technology -->	Biosparge	Sparging + SVE	ISCO	MNA
Environment	Groundwater & Surface Water	Effect on mobilization of dissolved substances		Slight risk to promote migration of CoC via introduction of air in saturated zone	Risk to push dissolved contamination towards receptor with air injection at higher rate	Unknown but not expected	No effect expected since no active remediation, only GWM
Environment	Ecology	Use of equipment that affects/protects fauna (e.g. bird/bat flight, or animal migration)		Drilling during construction. During operation limited use of equipment (use plant air)	Drilling during construction. During operation, need additional equipment to extract air	Drilling during construction. During operation limited use of equipment (oxidants injection)	Only GWM equipment, but much longer term than other options
Environment	Natural Resources & Waste	Use of primary resources and substitution of primary resources within the project or external to it, rates of recycling, rates of legacy waste generation, use of other recyclates		Limited once system is operating	Generation of waste from SVE treatment, but expected to be recycled	Limited, from production of oxidants	No natural resource use but allows continued degradation of surface water quality with potential ecological risk to sensitive receptor
Environment	Natural Resources & Waste	Use of energy/fuels taking into account their type/origin and the possibility of generating renewable energy by the project		OM&M: use existing air supply from the plant	OM&M: use existing air supply from the plant, need additional energy for SVE	OM&M: minimal use, procurement/ transport of oxidant	No active remediation, only GWM, minimal energy use

	Category	Indicator	Target Treatment Zone -->	ODCB and Benzene Plume + EWB ODCB Source Area			
			Technology -->	Biosparge	Sparging + SVE	ISCO	MNA
Society	Human Health & Safety	Site workers (construction activities)		Drilling works, ongoing OM&M	Drilling works, ongoing OM&M	Drilling works, handling of persulfate or hydrogen peroxide	GWM only, but during much longer period than other alternatives
Society	Human Health & Safety	Risk management performance on remediation works and ancillary operations (i.e. process emissions)		Potential venting of air (limited amount of emission expected)	Need to control extracted air	Use of process reagents	Continued mass flux impacting surface water
Society	Ethics and Equity	Duration of remedial works / avoidable transfer of contamination impacts to future generations		Pilot test confirmed feasibility, expected to reduce contaminant mass within reasonable timeframe (<10yrs)	Likely to reduce contaminant mass within reasonable timeframe if successful (<10yrs), but aquifer overpressure risk	Uncertainty on effectiveness and implementability (multiple injections most likely required)	No active remedy continues to allow degradation of surface water receptor
Society	Neighborhood & Locality	Effects from dust, light, noise, odour & vibrations during works and associated with traffic, including both working-day, night, weekend, etc.		Drilling works	Drilling works, install SVE management system	Drilling works	GWM only

	Category	Indicator	Target Treatment Zone -->	ODCB and Benzene Plume + EWB ODCB Source Area			
			Technology -->	Biosparge	Sparging + SVE	ISCO	MNA
Economy	Direct Economic Costs & Benefits	Direct financial costs and benefits of remediation for organisation		Appropriate costs for benefits	Appropriate costs for benefits, but higher than biosparge	Reasonable cost but uncertainty as to result	Cheapest of alternatives however least potential benefit to client as no source depletion
Economy	Direct Economic Costs & Benefits	Costs associated operation and any ongoing monitoring, regulator costs, planning, permits licenses, etc.		OM&M costs	OM&M cost, higher than biosparge (need to manage extracted air)	Reagents costs for multiple injections	Only GWM cost, but indefinitely
Economy	Project Lifespan & Flexibility	Duration of the risk management (remediation) benefit, e.g. fixed in time for a containment system/length of time taken for beneficial effects to become apparent		Expected duration ~10 yrs	Expected duration =<10 yrs	If technology proven feasible, potentially faster than biosparge & sparging	Greatest duration for MNA
Economy	Project Lifespan & Flexibility	Factors affecting chances of success of the remediation / management works and issues that may affect works (community, contractual, environmental, procurement and technological risks)		Pilot test successful	Potential issues with sparging in anisotropic lithology	Greatest uncertainty compared to biosparge and sparging	No active remediation, cost of natural resource degradation

Colour Scale				
	Ranking = 3 - Most Favorable	Ranking = 2	Ranking = 1	Ranking = 0 - Least Favorable

Figure 5: Sustainability assessment results (GWM – groundwater monitoring; OM&M – operation, maintenance and monitoring).

Target Treatment Zone -->	ODCB and Benzene Plume + EWB ODCB Source Area			
Technology -->	Biosparge	Sparging + SVE	ISCO	MNA
Summary				
SOC Score (max 10)	7.5	5.0	5.0	5.0
ECON Score (max 10)	8.3	5.8	5.8	2.5
ENV Score (max 10)	7.5	4.2	6.7	6.7
Final Score (max 30)	**23.3**	**15.0**	**17.5**	**14.2**

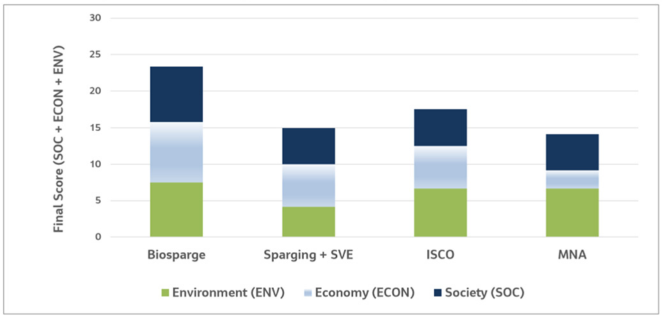

Figure 6: Sustainability assessment summary results.

7. IMPLEMENTATION OF REMEDIAL ACTION

7.1 Pilot testing of sparging + SVE and biosparge

Between 2016 and 2018, both sparging + SVE and biosparge were pilot tested onsite. Both technologies can be tested largely with the same infrastructure, except that sparging often requires SVE to manage release of generated gases to atmosphere. Objectives of the pilot trials were to evaluate:

- Air injection rates that can be achieved for sparging (together with SVE to recover COC vapours at the ground surface) noting the potentially problematic interbedded sands and silts.
- Biosparge flow rates to sufficiently enhance *in situ* degradation of ODCB and benzene dissolved-phase plumes that exist singly and comingled (which can complicate the biogeochemistry).
- If biosparge is a viable technology for effectively treating an ODCB DNAPL source.
- Critical design parameters (e.g., well spacing, flow rates) required for full-scale implementation.

Key highlights and findings from the pilot testing were:

- Sparging + SVE injection rates could be achieved for relatively short durations, but there was inadequate recovery with SVE to consider the test successful. As anticipated, the lithology created barriers to vertical air migration making recovery by the shallow SVE points ineffective.
- Even at lower biosparge injection rates, the interbedded lithology resulted in excessive lateral air migration. While a large radius or zone of influence (ZOI) is desirable, the goal is to distribute oxygen to groundwater within this ZOI (i.e., become dissolved and available for reaction). Injection rates had to be kept low to prevent the release of air and groundwater at distant monitoring wells.
- Within the containment area, and within the deeper interbedded sands and silts, there were positive observations that biosparge effectively oxygenated groundwater, promoted biodegradation within the aquifer, and reduced contaminant concentrations (both ODCB and benzene). Results shallower indicated that the interbedded lithology prevented delivering oxygen to the overlying strata.
- Within the source area, there was strong evidence of increased bioactivity during the longer operation of the biosparge pilot, i.e., orders of magnitude increase of key biomarkers, indicating significant mass degradation and microbial growth.

Conclusions and takeaways from the pilot testing were:

- Sparging + SVE was potentially feasible, but significant design considerations would be needed.
- Even at lower sparge flow rates, preventing the short-circuiting of air to monitoring wells would be critical for the safe operation of a full-scale system even at the lower biosparge injection rates.
- There were multiple indicators that biosparge could achieve remedial objectives for both the containment and the source area. However, achieving oxygen delivery across the full range of interbedded sands and silts from a single well screen would be challenging.

7.2 Full-scale biosparge system

Following the largely successful biosparge pilot test, a full-scale biosparge system was designed and installed. The full-scale implementation was phased given the challenges identified by the pilot getting air / oxygen distributed across the interbedded sands and silts. The "Phase 1" full-scale biosparge system includes:

- An air supply provided by the operating facility at up to 6 bars. Leveraging the site air supply is a sustainable way to provide the air (i.e., does not require running a separate compressor).
- A biosparge unit with stainless steel manifolding that divides, controls and measures the air to individual sparge wells. This approach allows for optimisation of air injection rates to specific wells and depths.
- Nested sparge wells installed at 2 locations in the source area and 3 locations within the plume containment area. At several locations, screens have been placed at 3 depths to allow targeted and controlled air delivery across the interbedded sands and silts at rates that do not induce short-circuiting.
- Vent wells installed across the interbedded sands and silts and the overlying sands. These wells allow pressure and air to migrate across the lithology and they are also completed at surface with pressure and flow monitoring to identify pressure build up or flow in a controlled manner.

The biosparge system manifold (inside container) and air supply conveyance lines are illustrated in Figure 7.

The Phase 1 full-scale system began operation in 2021. Operational results will be available in 2023 and system performance assessed. Continuing with the phased approach, Phase 2 may involve the installation of additional biosparge wells, either at specific depth ranges or at closer lateral spacings, as determined by the Phase 1 results. If excessive lateral migration in certain depth intervals proves challenging, additional vent wells could also be considered.

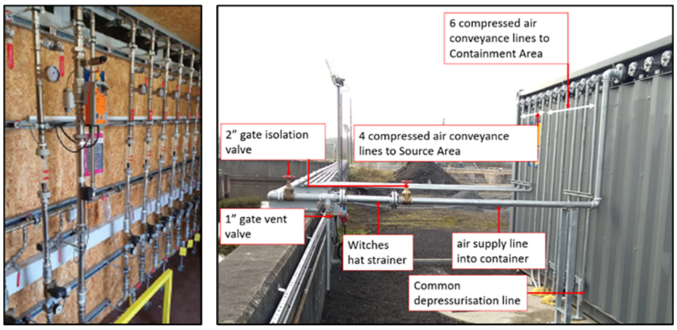

Figure 7: Biosparge system manifold and air supply conveyance pipes.

8. PROJECT HIGHLIGHTS

Highlights of the project include:

- Biosparge technology ranked highest in the sustainability assessment in part because it requires no chemical use and creates no waste. The technology oxygenates groundwater to enhance *in situ* biodegradation with contaminants eliminated – converted to simple, safe byproducts – not transferred elsewhere or to another media.
- Implementation is occurring in a phased manner to allow for operational flexibility and possible future expansion, e.g., additional sparge wells at different depth ranges or lateral spacing.
- The biosparge technology is itself flexible and the installed system has already been leveraged to support remediation of a separate part of the site (addressing a diesel spill from the 1980s).
- Connection to the existing plant compressed air supply simplified the design and eliminated the need for a dedicated compressor with its associated power and maintenance requirements. Even though the biosparge system does consume energy, its carbon footprint is reduced by efficiently using the plant compressed air supply.

9. LESSONS LEARNED

From initial strategy development to sustainability assessment, to pilot testing and now Phase 1 full-scale, the following are lessons learned:

1. Routine stakeholder and regulator engagement, including annual reporting and meetings, provided regular feedback that has facilitated decision making. Utilising tools and approaches that facilitate discussion and are familiar to regulators (e.g., SuRF-UK framework) helps get endorsements.
2. At this site the interbedded sands and silts are challenging for biosparge and many other technologies. Pilot testing was essential to understand whether technologies would work given the site-specific conditions.
3. The pilot test was successful while also identifying technical challenges. Rather than continue to pilot test, a phased approach was decided for full-scale implementation.
4. Leveraging the plant air supply reduced complexity and increased the sustainability. However, the system is now dependent on plant operation. For example, an unexpected plant air supply shutdown resulted in liquid backflow. The biosparge system required upgrades and was offline while redundancy in the backflow prevention was installed.

10. CONCLUSIONS

The preliminary steps to address legacy ODCB free product at the site were undertaken in 2014 with the clean out of the historic sump and trench network. Ecological and human health risk assessments were then undertaken for legacy impacts to soil and groundwater and no risks were identified. However, given the value placed on the adjacent ASSI surface water body and corporate core values, voluntary remediation was progressed.

Following technology screenings, remedial options evaluation, sustainability assessment and pilot testing, a biosparge system was designed and installed. The first year of full-scale (Phase 1) operation was completed in 2022 allowing an assessment of the technology performance. Key conclusions include:

- Routine stakeholder and regulator engagements throughout the decision-making process resulted in a voluntary remediation project with broad endorsement.
- Remedial options assessments and sustainability assessments were done progressively from early and simple screenings to interactive tools familiar to and accepted by the client and regulator alike (e.g., SuRF-UK) helped support timely decision making.
- Biosparge wells are effectively oxygenating groundwater and promoting biodegradation within the plume and source area as evidenced by reduced concentrations and increased microbial activity. However, challenging lithology has required nested biosparge wells at each location, with each well at a lower flow rate, to deliver oxygen across the interbedded sands and silts while minimising excessive lateral air migration.
- Additional system operation and monitoring will confirm reductions in COC concentrations, reductions in offsite mass flux and the expedition of DNAPL / source zone depletion. It is anticipated that requirements for system expansion, i.e., Phase 2, will be assessed in 2023.

REFERENCES

- CL:AIRE, 2010. SuRF-UK framework for assessing the sustainability of soil and groundwater remediation.
- CL:AIRE, 2020. Supplementary Report 2 of the SuRF-UK Framework: Selection of indicators / criteria for use in sustainability assessment for achieving sustainable remediation.
- Environment Agency, 2004. Model Procedures for the Management of Land Contamination. Contaminated Land Report 11.
- ISO 18504:2017, 2017. Soil Quality – Sustainable Remediation.