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Case Studies and Analysis of Sustainable Remediation Techniques and Technologies

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ABSTRACT

The concept of sustainable remediation has become well established in the remediation industry and its application has spread around the world. However, there is a recognised gap in the provision of detailed case studies documenting the practical implementation of sustainable remediation in the real world, particularly in a European context. A consequence of this gap is that the further refinement of guidance is impeded by a lack of knowledge of what aspects work well in practice, versus poorly.

Concawe commissioned a study to a) gather, prepare and publish ten European case studies that demonstrate sustainable remediation techniques and technologies and b) provide an analysis of the case studies to identify key success factors that facilitated the adoption and success of these projects at different sites.

A long-list of twenty case studies was identified. Each case study was scored by the project team on how closely it matched ISO Standard on Sustainable Remediation 18504:2017, its relevance to Concawe and its ability to be delivered to time. Ten case studies were recommended for selection, agreed by Concawe and a case study provider contracted. Case study information was then collected in a common template and reviewed by the project team, CL:AIRE's Technology and Research Group and Concawe. A series of ten detailed case study bulletins are freely available on-line from the CL:AIRE and Concawe web sites.

In addition, a cross comparison analysis of the ten case studies has been carried out, seeking to help practitioners compare these case studies to their own projects. The cross comparison analysis focused on the following attributes: site location and type of site (former use); saturated / unsaturated zone impact; targeted contaminants; risk drivers; envisaged land use; objectives for sustainability assessment; remediation options compared; stakeholder engagement; boundary conditions; scope (environmental, economic, social); key constraints / opportunities; and assessment type (qualitative, semi-quantitative etc).

Sustainable remediation techniques and technologies are being used on sites in Europe, particularly in the UK which has benefitted from the work of SuRF-UK and a pragmatic regulator. Working with a risk-based conceptual site model, effective engagement with stakeholders and a sound understanding of sustainable remediation practices are seen as key success factors from these case studies.

Based on this analysis and recently published guidance, a practical approach for deploying sustainable remediation on operational sites has been proposed.

KEYWORDS

Sustainable remediation, sustainability assessment, case studies, conceptual site model, sustainable and risk-based land management

INTERNET

This report is available as an Adobe pdf file on the Concawe website (www.concawe.eu).

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SUMMARY

The concept of sustainable remediation has become well established in the remediation industry and its application has spread around the world. However, there is a recognised gap in the provision of detailed case studies documenting the practical implementation of sustainable remediation in the real world, particularly in a European context. A consequence of this gap is that the further refinement of guidance is impeded by a lack of knowledge of what aspects work well in practice, versus poorly.

Concawe commissioned a study in 2021 to a) gather, prepare and publish ten European case studies that demonstrate sustainable remediation techniques and technologies and b) provide an analysis of the case studies to identify key success factors that facilitated the adoption and success of these projects at different sites.

A long-list of twenty case studies was identified. Each case study provider was invited to complete a questionnaire based on the ISO Standard on Sustainable Remediation 18504:2017. This was used to assess the suitability of all potential case studies for inclusion in the study.

Each case study was then scored by the project team on how closely it matched ISO 18504:2017, its relevance to Concawe and its ability to be delivered to time. Ten case studies were recommended for selection, agreed by Concawe and a case study provider contracted. Case study information was then collected in a common template and reviewed by the project team, CL:AIRE's Technology and Research Group and Concawe. A series of ten detailed case study bulletins are freely available on-line from the CL:AIRE and Concawe web sites.

Case studies that had undertaken a partial assessment of sustainable remediation were invited to complete a full sustainability assessment after the event (*post hoc* – six case studies). Case studies that had already undertaken a sustainability assessment as part of the decision making of the project, before the remediation (*ex ante* – four case studies), required no further action.

A cross comparison analysis was undertaken:

- Case studies represent a wide range of site types, including operational and development sites. Nine consider saturated zone impacts, with three also considering unsaturated zone impacts and two considering surface water impacts. The majority of case studies deal with hydrocarbon contaminants reflecting the primary concerns of Concawe members. Seven case studies are located in the UK, one each in Belgium and Spain, and one is confidential.
- The stated objective for all of the sustainability assessments is to compare available options.
- The case studies consider a broad range of remediation techniques including excavation and disposal (off site), on site containment (e.g. by excavation and capping under new building), ex situ bioremediation, in situ bioremediation, in situ chemical oxidation, natural source zone depletion, pump and treat, multi-phase extraction, monitored natural attenuation, skimming and extraction treatments and some novel permeable reactive barrier approaches to protect surface water resources.

- Four of the case studies use qualitative sustainability assessment only, five case studies use semi-quantitative sustainability assessment and one case study describes the use of qualitative assessment followed by a semi-quantitative stage (supported by cost benefit appraisal) to provide greater distinction between two options.
- All of the case studies consider a range of environmental, social and economic criteria, in nearly all cases drawn from the SuRF-UK indicator guidance. However, the sustainability assessments are limited to the "headline" categories of indicators, and do not drill down to the individual criteria provided in the guidance. The added value of these individual indicators is either not seen as useful or is not made sufficiently clear to guidance users.
- Stakeholder engagement is important to making robust sustainability assessments because in many cases the comparison made, whether qualitative or semi-quantitative is opinion based. Nine case studies report the stakeholder engagement they carried out. Six case studies describe engagement with regulators as a part of the sustainability assessment process.
- Drivers for undertaking sustainable remediation are: regulatory drivers; public ownership / funding drivers; benchmarking against sustainable development principles, as a part of both public and private sector corporate governance; emerging financial drivers. Many of these drivers are exemplified by the case studies, in particular client interests as part of wider sustainable development governance, and demonstrating sustainability gain to regulators. Six of the case studies highlight the specific importance of sustainability assessment in engagement with regulators and the agreement of an optimal site management approach.
- All of the case studies provide conceptual site models. Several of the case studies emphasise the importance of conceptual site models in remediation strategy discussion and development. Several also emphasise the importance of a collegiate or team approach to the work of site management towards achieving robust progress and agreed endpoints.

Analysis of the case studies and recently published guidance support a practical approach for deploying sustainable remediation on operational sites which should include the following:

- Consider changes in how remediation work is planned into the operational lifetime of a site to achieve sustainability gains at an early stage – e.g. "Stage A" (as defined by SuRF-UK).
- Consider the use of sustainable management practices (SMPs) to provide multiple opportunities to improve the sustainability of contaminated site management practice across the board.
- Encourage regulatory interest via collaboration in sustainability assessment to provide optimisation of remedial approach.
- Understand that the exact methodology and entry point for individual sustainability assessments can vary as long as they adhere to a robust basic "recipe" such as ISO 18504:2017 or SuRF-UK guidance.
- Pay greater attention to describing boundary conditions to ensure a reliable basis on which to compare options.
- Consider drilling down to individual sustainability criteria which may provide greater differentiation between options.

The value to Concawe members and the broader industry from this study is a greater awareness of sustainable remediation techniques and technologies, and the key enablers that will make the highlighted examples more relatable to other sites across Europe and beyond.

1. INTRODUCTION

1.1. BACKGROUND

The concept of sustainable remediation of contaminated soils and groundwater formally emerged over fifteen years ago when the Sustainable Remediation Forum (SURF) was established in the USA in 2006. Since then it has become well established in the remediation industry. Not only has sustainable remediation become the subject of both an International Organization for Standardization (ISO) standard (ISO, 2017) and an American Society for Testing and Materials (ASTM) standard guide (ASTM International, 2013), its application has spread around the world and guidance has been prepared in many countries to encourage appropriate application (Smith, 2019).

Though the progress to date has been laudable, there is a gap in the provision of detailed case studies documenting the practical implementation of sustainable remediation in the real world, particularly in the European context. Some organisations have produced relevant practical examples: sustainable remediation case studies are available from the CL:AIRE website[1], but they focus on demonstrating the effectiveness of the SuRF-UK framework in project decision-making, rather than highlighting sustainable remediation techniques and technologies per se; SURF (in the USA) has sixteen case studies on its website[2], but all but one fall within the USA. Equally, there are relatively few case studies highlighted in the wider literature. A consequence of this gap is that the further refinement of guidance is impeded by a lack of knowledge of what aspects work well, versus poorly, in practical deployment.

Against this background, this project aims to bring together a series of case studies that will help fill this gap in provision and inspire others to consider and adopt sustainable remediation approaches at their sites.

In addition to meeting an industry need, there are several European legislative drivers that provide a broader context for this project. The EU Soil Strategy for 2030 (European Commission, 2021a) is key to achieving the objectives of the European Green Deal (European Commission, 2019), which wants to see sustainability central to all EU policies. Related policies include the EU Action Plan: 'Towards Zero Pollution for Air, Water and Soil' (European Commission, 2021b), the EU Biodiversity Strategy for 2030 (European Commission, 2021c) and the proposed new Soil Monitoring Law which aims to protect and restore soils and ensure that they are used sustainably (European Commission, 2023). These case studies aim to promote adoption of sustainable soil management practices, accelerate the transition towards these practices and improve soil quality which are all actions that support this legislation.

There is no doubt that sustainable remediation is strongly aligned with these European policy drivers, however, the project also has a global policy resonance.

1.2. OBJECTIVES

The main objectives of this project were to i) gather, prepare and publish ten European case studies that demonstrate sustainable remediation techniques and technologies and to ii) provide an analysis of the case studies to identify key success

[1] https://www.claire.co.uk/supporting-materials/case-studies-and-bulletins
[2] https://www.sustainableremediation.org/case-studies

factors that facilitated the adoption and success of these projects at different sites. It is hoped that this will help Concawe members and the wider industry quickly compare the case studies and their own projects to promote adoption of these techniques and technologies but also note where they can be adapted and improved.

1.3. STRUCTURE OF THE REPORT

The report is structured as follows:

1. Introduction
2. Defining sustainable remediation
3. Case study collection and key features
4. Case study cross comparison
5. Experience-based protocol for deploying sustainable remediation in practice
6. Conclusions
7. References

Appendix 1: Individual case studies
Appendix 2: Certification of sustainable remediation assessment

In addition to forming an appendix to this report and to aid their dissemination, the case studies will also be reproduced as CL:AIRE Concawe bulletins and will be available to download from www.claire.co.uk/concawe.

2. DEFINING SUSTAINABLE REMEDIATION

2.1. DEFINITIONS

There are various different definitions around the concept of sustainable remediation which have often been adapted slightly to meet different regulatory needs and perspectives. These include terms such as green remediation; green and sustainable remediation; resilient remediation; sustainable and risk-based land management. The mostly commonly used terms are defined below.

Sustainable Remediation

The UK Sustainable Remediation Forum (SuRF-UK) defines the process of sustainable remediation as "the practice of demonstrating, in terms of environmental, economic and social indicators, that the benefit of undertaking remediation is greater than its impact, and that the optimum remediation solution is selected through the use of a balanced decision-making process" (CL:AIRE, 2010). The ISO 18504:2017 standard definition varies slightly as "elimination and/or control of unacceptable risks in a safe and timely manner whilst optimising the environmental, social and economic value of the work" (ISO, 2017).

Sustainable and risk-based land management is an analogous term that emphasises the importance of both risk management and sustainability (see section 5.1).

Green Remediation

Green Remediation is the practice of considering all environmental effects of remedial implementation and incorporating options to minimise the environmental footprints of clean-up actions (US EPA, 2008).

Green and Sustainable Remediation

Green and Sustainable Remediation (GSR) is defined as the site-specific use of products, processes, technologies, and procedures that mitigate contaminant risk to receptors while balancing community goals, economic impacts, and net environmental effects (ITRC, 2011).

Sustainable Resilient Remediation

Sustainable resilient remediation (SRR) is an optimised solution to cleaning up and reusing a hazardous waste site that limits negative environmental impacts, maximises social and economic benefits, and creates resilience against increasing threats (ITRC, 2021).

2.2. SUSTAINABLE REMEDIATION IN THE CONTEXT OF THIS PROJECT

In spite of the clear definitions available, there can still be ambiguity and confusion over whether a particular remediation technology or technique constitutes sustainable remediation. This is sometimes due to unsubstantiated claims by practitioners seeking to gain a market edge, but also simply due to a lack of understanding of the available information. This is captured by one of the eight myths of sustainable remediation described by Smith (2019), "Myth 2: Just saying a project is sustainable makes it so". Fortunately, international guidance about sustainable remediation is relatively consistent (e.g. ISO (2017), NICOLE/Common Forum (2013), SuRF-UK (2010)), and it is clear that to be classified as an example of sustainable remediation a project must:

- include an effective sustainability assessment (see section 5), which should be fit-for-purpose given the particular project boundaries and constraints; and
- adhere to certain key sustainable remediation principles as outlined, for example by SuRF-UK, in Box 2.1, which are broadly similar to those in ISO 18504:2017 (ISO, 2017).

Box 2.1: Key principles of sustainable remediation (from CL:AIRE, 2010).

Principle 1: Protection of human health and the wider environment.

Remediation [site-specific risk management] should remove unacceptable risks to human health and protect the wider environment now and in the future for the agreed land-use, and give due consideration to the costs, benefits, effectiveness, durability and technical feasibility of available options.

Principle 2: Safe working practices.

Remediation works should be safe for all workers and for local communities, and should minimise impacts on the environment.

Principle 3: Consistent, clear and reproducible evidence-based decision-making.

Sustainable risk-based remediation decisions are made having regard to environmental, social and economic factors, and consider both current and likely future implications. Such sustainable and risk-based remediation solutions maximise the potential benefits achieved. Where benefits and impacts are aggregated or traded in some way this process should be explained and a clear rationale provided.

Principle 4: Record keeping and transparent reporting.

Remediation decisions, including the assumptions and supporting data used to reach them, should be documented in a clear and easily understood format in order to demonstrate to interested parties that a sustainable (or otherwise) solution has been adopted.

Principle 5: Good governance and stakeholder involvement.

Remediation decisions should be made having regard to the views of stakeholders and following a clear process within which they can participate.

Principle 6: Sound science.

Decisions should be made on the basis of sound science, relevant and accurate data, and clearly explained assumptions, uncertainties and professional judgment. This will ensure that decisions are based upon the best available information and are justifiable and reproducible.

An important goal of this report is to provide clear illustrative examples of sustainable remediation practices.

There is also a great deal of consistency in how sustainable remediation is being approached in different countries (Rizzo *et al.*, 2016). When sustainable remediation networks first began some regulators were concerned that it replaced risk-based land management but as shown in section 5.1 the approaches are entirely integrated as sustainable and risk-based land management.

Indeed, looking at sustainable remediation allows the overall value of the project to be maximised by choosing options where negative impacts are the least and opportunities for benefits are optimised. It is also consistent with the revised EU Soil Strategy 2030 (European Commission, 2021b) as, for example, impacts on soil functionality can be explicitly considered as a sustainability criterion.

On a practical note, SuRF-UK has developed a "Sustainable Remediation Certification Sheet" that practitioners can elect to provide to their regulator/client. The signed sheet states that the sustainable remediation assessment complies with ISO 18504:2017 (ISO, 2017) and SuRF-UK (CL:AIRE, 2010) requirements (see Appendix 2). This may be helpful to Concawe. Practitioners can include the sheet in their reporting to clients as a matter of course. If it is absent, clients, regulators, and other stakeholders would be able to challenge "why not?".

In this project, in order to assess the suitability of potential case studies for inclusion, including whether a case study merited being classed as an example of sustainable remediation, and to undertake a transparent review and audit process, a template based on ISO 18504:2017 (ISO, 2017) was developed and this is described further in section 3.

3. CASE STUDY COLLECTION AND KEY FEATURES

3.1. COLLECTING CASE STUDIES

The extensive network of the project team was used to leverage relevant case studies. As well as implementing a broad marketing strategy to environmental consultancies, site owners, contractors, regulatory agencies and research institutions, direct approaches were made to individual organisations which were known to have potentially relevant examples.

A short briefing note about the project and a case study template were provided to organisations interested in providing case studies. The template, which is reproduced as **Table 1**, was developed using the ISO Standard on Sustainable Remediation 18504:2017 (ISO, 2017), which provides a description of sustainable remediation, developed with the active participation of sustainable remediation practitioners and networks from around the world. The template was used to assess the suitability of all potential case studies for inclusion in this project and to facilitate a transparent review and audit process, benchmarking all potential case studies against the ISO. Consideration of each case study's relevance to Concawe members' areas of operation was also factored in.

Table 1: Sustainable remediation case study audit and reporting template benchmarking against ISO 18504:2017.

Title of case study
Contact details - email address and phone number of the person(s) to contact about this case study.
Names & affiliations of authors
Brief summary of project (include relevance to Concawe)
Site description and project context
Describe confidentialities if applicable (e.g. restrictions to use of site name, site location, client name etc)
Remediation project (description and type: commercial, pilot etc)
Conceptual Site Model (CSM) If available / able to share at this stage, please include (diagrams and table of Source-Pathway-Receptor linkages, key site features) If unable to provide all details at this stage, please give a general description of Conceptual setting Note: A CSM will be required if your case study is selected
Do you have the necessary approvals to submit this case study? Yes / No If not, when can you get them by?
If the case study is selected, I would anticipate being able to complete the full Case Study write up by (please specify a date).
Please answer the 11 questions below to help us undertake a sustainable remediation assessment for the Case Study. • The sequence of questions follows the structure referenced in the ISO compliant guidance (ISO 18504:2017. www.iso.org/standard/62688.html). • An example is provided for information
1. Definition (e.g. ISO Chap 5) - A statement of why the case study should be considered as an example of sustainable remediation

2. Risk based (e.g. ISO Chap 6) - Clear explanation of linkage to a risk-based approach to contaminated land management
3. Assessment methodology (e.g. ISO Chap 7) - Identification of approach, qualitative, semi-quantitative, quantitative. Was a tiered approach used, if so, how?
4. Clear project framing (e.g. ISO Chap 8) - A clear description of the decision-making role of the sustainability assessment, the project and options being considered, the stakeholder engagement, the specific assessment objectives, boundary conditions, scope of sustainability and detailed methodology and interpretive approach.
5. Economic criteria (e.g. ISO Chap 9) - Clear rationale for economic criteria selection and statement of relevance and limitations
6. Social criteria (e.g. ISO Chap 10) - Clear rationale for social criteria selection and statement of relevance and limitations
7. Environmental criteria (e.g. ISO Chap 11) - Clear rationale for environmental criteria selection and statement of relevance and limitations
8. Indicators and metrics (e.g. ISO Chap 12) - Discussion of use of indicators or metrics (appropriate to the assessment tiers used)
9. Referencing to any bespoke “tools” or published methodologies (e.g. ISO Chap 13)
10. Approach to communication and engagement (e.g. ISO Chap 14) - Participants, consultees, audience and communication channels with them (if available - include a stakeholder engagement map).
11. Linkage to guidance, regulations, corporate governance (e.g. ISO Chaps 15 & 16) - Describe requirements for (and fit to) the sustainability assessment from local, regional, national policy and corporate policy as appropriate.

Following the case study collection phase, a long-list of twenty case studies were received (twelve from the UK, three from Belgium, two from Spain, one each from the Netherlands and Portugal, and one confidential site). Each case study was then scored by the project team on whether it was within scope (how it assessed sustainable remediation), its relevance to Concawe and its ability to be delivered to time. There was some iteration at this stage to ensure the relevant information had been provided to allow a fair comparison between case studies.

From these twenty submissions, ten case studies were recommended for selection and agreed by Concawe.

Case studies that had considered sustainable remediation principles and undertaken a partial assessment of sustainable remediation were invited to complete a full sustainability assessment after the event (*post hoc*). Case studies that had already undertaken a sustainability assessment as part of the decision making of the project, before the remediation (*ex ante*), required no further action.

3.2. CASE STUDY DRAFTING

Online briefings were held with the successful case study authors to discuss the requirements of the project and the review process. In order to maintain consistency across the ten case studies, each case study had to include the following key information:

- Title
- Introduction (scope, aims)
- Site description and project context. Include type of remediation project
- Conceptual site model (CSM)

- Assessment function (the contaminant linkages in the CSM being treated and the nature of the site)
- Sustainability assessment following an ISO 18504:2017-based template
- Project highlights
- Lessons learned
- Conclusions
- Author names and Contact details

To ensure that the information provided was concise, and based on CL:AIRE's bulletin publication experience, each case study was limited to a maximum of 4,500 words. It was also important that the content and style of writing was accessible to a broad range of stakeholders. The benefit of this approach was it used a tried and trusted approach and provided consistency across the case studies.

Once CL:AIRE had received the case studies (typically within 4-6 weeks), they were checked for completeness of information, accuracy, readability and either edited accordingly or the case study providers were asked to provide further details, as necessary. They were then reviewed by CL:AIRE's internal peer review group - the Technology and Research Group (TRG) - as the final case studies were to be published as individual CL:AIRE Concawe bulletins. After this, each case study was submitted to Concawe for review, comment and final signoff.

Once approval had been received, a cross comparison analysis of the ten case studies was carried out. This sought to identify trends and key success factors that facilitated the adoption of these technologies at different sites. The aim of the analysis is to help Concawe members and the wider industry compare these case studies to their own projects when they may be considering sustainable remediation techniques and technologies, both in terms of success factors and areas for improvement. The cross comparison analysis is presented in section 4.

4. CASE STUDY CROSS COMPARISON

4.1. RANGE OF CASE STUDIES

Table 2 provides a description of each of the ten case study sites in terms of their location; the site type; the contaminants targeted by the remediation and where they impact the surface or subsurface; risk drivers; and envisaged end land use.

The ten case studies selected are drawn from a wide range of site types: a vehicle maintenance facility; oil and gas infrastructure sites; industrial, manufacturing and distribution sites, and petrol retail sites. These include a range of operational and development sites, but primarily operational sites. Nearly all of the case studies (nine out of ten) consider saturated zone impacts, with three also considering unsaturated zone impacts and two considering surface water impacts. The risk drivers reflect this predominance of water impacts. The majority of case studies deal with petroleum hydrocarbon contaminants, and allied contaminants such as methyl tert-butyl ether (MTBE), reflecting the primary concerns of Concawe members. However, three of the case studies also include consideration of chlorinated hydrocarbons. Each case study includes a detailed CSM describing the risk management context and the source-pathway-receptor linkages being addressed. Most of the case studies relate to commercially applied remediation installations. However, several describe initial or pilot implementations which are to be scaled up, if effective. Seven case studies are located in the UK, one each in Belgium and Spain, and one is confidential. The predominance of UK-based case studies reflects the effectiveness of SuRF-UK at promoting sustainable remediation in the UK and how open the regulator is to sustainable thinking and actions, evidenced by how it has embedded sustainability within its Land Contamination Risk Management (LCRM) guidance (Environment Agency, 2020), which states that “We support a sustainable approach to land contamination risk management.” and directs readers to both SuRF-UK and ISO resources.

Table 2: Case study coverage.

Case Studies	Location	Type of site (former use)	Saturated / unsaturated zone	Targeted contaminants	Risk drivers	Envisaged land use
Case Study 1 - Sustainable Remediation of Former Vehicle Maintenance Facility for Mixed Use Development	London, UK	Vehicle maintenance facility	Saturated zone and unsaturated zone	Non-aqueous phase liquid (NAPL)	Human health and controlled waters (as defined in the UK)[3]	Mixed high-rise residential and commercial (retail) development as well as a school
Case Study 2 - Natural Source Zone Depletion Assessment: UK Large Scale Field Case Study	UK	Operational facility	Saturated zone and unsaturated zone	Light non-aqueous phase liquid (LNAPL)	Human health and controlled waters (as defined in the UK)	No change
Case Study 3 - Sustainable *In Situ* Thermal Remediation	UK	Manufacturing facility	Saturated	NAPL and dense non-aqueous phase liquid (DNAPL) (chlorinated solvents)	Human health and controlled waters (as defined in the UK)	No change
Case Study 4 - Sunshine on the Tyne - Sustainable Hydrocarbon Remediation	Gateshead, UK	Gas holder station, the project comprised the remediation of free phase hydrocarbon present in an infilled below ground tank structure.	Unsaturated zone	DNAPL (polycyclic aromatic hydrocarbons (PAH))	No direct risk driver, but the goal is mass removal before the structural containment of the contamination degrades.	Operational natural gas distribution site
Case Study 5 - Reactive Mat in Canal Catches Groundwater Contaminants	Ghent, Belgium	Canal impacted by contamination migrating from an adjacent former industrial site.	Saturated zone	Aliphatic and aromatic hydrocarbons, in particular benzene, xylenes, C6-C10 hydrocarbons and several PAH	Surface water quality	No change (canal and car dealer sites)
Case Study 6 - Sustainable Remediation of a Petrol Release in a Chalk Aquifer	UK	Petrol station	Saturated zone	Methyl tert-butyl ether (MTBE) and tert-amyl methyl ether (TAME), BTEX	Drinking water quality	Residential
Case Study 7 - Biosparge of Benzene and Orthodichlorobenzene in Groundwater: A Sustainable Remedy	UK	Industrial site	Saturated zone	1,2-dichlorobenzene, (DNAPL); benzene, (LNAPL)	Surface water (via groundwater)	Industrial
Case Study 8 - Sheen Mitigation Using an Oleophilic Bio Barrier - A New and Sustainable Remediation Technique	Confidential	Industrial facility	Saturated zone, impact on surface water	Hydrocarbon LNAPL	Surface water	Not applicable

[3] Controlled waters include 1) relevant territorial waters; 2) coastal waters; 3) inland freshwaters; and 4) ground waters (UK Government, 1990)

Case Studies	Location	Type of site (former use)	Saturated / unsaturated zone	Targeted contaminants	Risk drivers	Envisaged land use
Case Study 9 - Natural Source Zone Depletion in a Dismantled Petrol Station	Spain	Former petrol station now used for car parking	Saturated zone	LNAPL (petroleum hydrocarbons)	Groundwater	No change
Case Study 10 - Sustainability Assessment Case Study - Groundwater Remediation Close-Out	UK	Former chemical storage and distribution depot	Saturated zone	Chlorinated hydrocarbons	Groundwater	Ongoing industrial use

4.2. TRENDS IN THE PRACTICAL IMPLEMENTATION OF SUSTAINABLE REMEDIATION ACROSS THE CASE STUDIES

Table 3 and **Table 4** describe the framing (i.e. the preparation and definition) of the sustainable remediation assessments for each case study. **Table 3** describes the preparatory steps and **Table 4** how the sustainability assessment was defined (for example in terms of its scope). **Table 3 and 4** follow a concept of framing developed by SuRF-UK (CL:AIRE, 2020a), which is aligned with ISO 18504:2017 (ISO, 2017) on sustainable remediation.

Specifically, **Table 3** describes the preparatory steps of the assessments by summarising: the objectives of the sustainability assessment; the remediation options compared, and any key constraints/opportunities.

Four of the case studies describe sustainability assessment as part of a decision-making process before implementation of the remediation work (*ex ante* assessment), over the period of 2012-2020. The remaining case studies are *post hoc* assessments made to review the effectiveness of the implemented option against theoretical alternatives, carried out primarily over 2021-2022. The stated objective for all of the sustainability assessments was to compare available options, either *ex ante* or *post hoc*. Hence all of the case studies were at “Stage B” as defined by SuRF-UK (CL:AIRE, 2020a). In some cases there was a clear client interest or project driver, such as securing regulatory endorsement. This was particularly important for securing interest in the emerging technique of natural source zone depletion (NSZD). Case Study 6 is interesting as sustainability assessment was used on an *ex ante* basis at two points in the project. The first sustainability assessment was carried out in 2013 to find the most sustainable approach to remediation across a short-list of technically relevant options, the second was carried out in 2018 to decide when to terminate active remediation.

The case studies consider a broad range of remediation techniques including:

- Excavation and disposal (off site)
- On site containment (e.g. by excavation and capping under new building)
- *Ex situ* bioremediation (ESB)
- A range of *in situ* bioremediation (ISB) techniques
- *In situ* chemical oxidation (ISCO)
- NSZD
- Pump and treat (P&T)
- Multi-phase extraction (MPE)
- Monitored natural attenuation (MNA)
- Skimming and extraction treatments
- Some novel permeable reactive barrier (PRB) approaches to protect surface water resources.

The sites and projects themselves were subject to a variety of constraints, which impact the remediation options feasible for a site, and also their sustainability assessments. These were reported for seven of the case studies and comprised: residential properties near the site, the time and space available, operational site constraints, and health and safety risks.

Table 3: Case study preparations for sustainability assessment.

Case Studies	Date of sustainability assessment	Objectives for sustainability assessment	Ex ante / post hoc	Remediation options compared	Any key constraints / opportunities
Case Study 1 - Sustainable Remediation of Former Vehicle Maintenance Facility for Mixed Use Development	2020	Part of maximising the sustainability of this project	*Ex ante*	(1) Excavation and disposal of contaminated unsaturated zone soils and *in situ* bioremediation for the dissolved phase, (2) *Ex situ* bioremediation of excavated soils with containment on site of asbestos / PAH / metal contaminated soils, plus *in situ* bioremediation and MNA for the dissolved phase (3) as per option 2 but with off-site disposal of asbestos / PAH / metal contaminated soils (4) *In situ* bioremediation (ISB) linked to MNA for the saturated zone and ISB for the unsaturated zone where possible, with containment on site of asbestos / PAH / metal contaminated soils.	Limited available time, residential neighbours
Case Study 2 - Natural Source Zone Depletion Assessment: UK Large Scale Field Case Study	2021 - 2022	Selecting an optimal remediation approach	*Post hoc*	(1) Natural source zone depletion; (2) Dual phase extraction	Use of equipment in potentially explosive atmospheres
Case Study 3 - Sustainable *In Situ* Thermal Remediation	2012	Client interest in carbon footprint and wider sustainability impacts.	*Ex ante*	(1) Soil Excavation and Disposal (2 & 3) Multi-Phase Extraction (MPE) over 0.5 and 3 year operational periods (4) *In Situ* Thermal Remediation (ISTR) integrated with MPE	Working on an operational site
Case Study 4 - Sunshine on the Tyne - Sustainable Hydrocarbon Remediation	2022	The client's environmental strategy seeks to further the UN SDGs (in this case SDG 15 "Life on Land").	*Post hoc*	(1) Do nothing (baseline assessment position); complete source excavation; (2) Disposal and backfill; dewater tank of all liquids; (3) Dispose offsite and install low permeability cap to tank; (4) Targeted DNAPL removal using low energy (photovoltaic) system.	Limited space for remediation equipment due to ongoing large-scale demolition across the wider site; No readily accessible electrical supply or drainage within the works area on-site; Northern Gas Networks safety restrictions on 'live' gas sites precluded telemetry to remotely monitor remediation equipment; Constrained vehicle access to the site; and Wider mixed residential and industrial setting which is sensitive to vehicle movements, noise, dust and odours.

Case Studies	Date of sustainability assessment	Objectives for sustainability assessment	Ex ante / post hoc	Remediation options compared	Any key constraints / opportunities
Case Study 5 - Reactive Mat in Canal Catches Groundwater Contaminants	2021 (revised 2022)	Support the project's secondary objective which is to validate, on the basis of practical data, this technology is sustainable in relation to remediation alternatives.	*Post hoc*	(1) Removal of source by excavation, (2) Smart Pump and treat (geohydrological isolation); (3) Adsorption by a renewable adsorbent in a permeable barrier (reactive mat)	Constraint to the thickness of the reactive mat in relation to the required water discharge capacity of the canal. Opportunity is the draining force of the canal
Case Study 6 - Sustainable Remediation of a Petrol Release in a Chalk Aquifer	2013 & 2018	Identification of most sustainable remediation alternatives in line with client policy and gain regulatory endorsement of decisions made on sustainability grounds	*Ex ante*	**2013 assessment:** (1A) Continuing with the existing remedial systems; (1B) As 1A, but reduced duration of active source mass recovery focussing on hot-spot areas; (1C) As 1A, but more aggressive source area remediation (well replacement, increased vapour and groundwater abstraction, treatment and discharge); (1D) Continued operation of the hydraulic containment system combined with remediation of groundwater below three of the adjacent residential plots (well installation, total fluids abstraction, treatment and groundwater discharge); (1E) Stopping source-area remediation and continuing only with hydraulic containment system operation. **2018 assessment:** (2A) Switch off hydraulic containment system once the MTBE mass discharge remedial targets had been met (2B) Continue the hydraulic containment system to prevent periodic exceedances of BTEX at a compliance point	Not specified

Case Studies	Date of sustainability assessment	Objectives for sustainability assessment	Ex ante / post hoc	Remediation options compared	Any key constraints / opportunities
Case Study 7 - Biosparge of Benzene and Orthodichlorobenzene in Groundwater: A Sustainable Remedy	Finalised in 2022	Selection of optimal remediation approach	*Post hoc*	(1) Biosparging (2) Air sparging and soil vapour extraction (3) *In situ* chemical oxidation (4) Enhanced MNA	Not specified
Case Study 8 - Sheen Mitigation Using an Oleophilic Bio Barrier - A New and Sustainable Remediation Technique	2022	Implied as comparison with other potential solutions	*Post hoc*	(1) Oleophilic Bio Barrier (a form of permeable reactive barrier) (2) Pump and treat (3) Sheen capture in temporary booms (4) *In Situ* Stabilisation and Solidification (5) Excavation and disposal of soil source term	Space and access That the site was to be separately remediated Environmentally sensitive area Visual profile had to be maintained
Case Study 9 - Natural Source Zone Depletion in a Dismantled Petrol Station	2022	Apply systematic sustainability principles methodology to choose from various options; use as robust tool for discussion with regulators and other stakeholders	*Post hoc*	(1) Site wide NSZD (2) NSZD and passive skimmers (3) Site wide enhanced natural attenuation by oxygen injection and active and passive skimmers (4) Soil vapour extraction (SVE) with pump and treat (P&T).	Regulatory compliance for LNAPL removal The site is dismantled with no infrastructure Site is currently used as car parking and this needs to continue
Case Study 10 - Sustainability Assessment Case Study - Groundwater Remediation Close-Out	2014-2015	Review of the options for further groundwater remediation	Ex ante	(1) Pump and treat (2) ISCO (3) Combined pump and treat with ISCO (4) MNA	Not specified

Table 4 describes how the sustainability assessments were defined (i.e. the definition stage) by summarising the approach to the assessment (including the Tier as defined by SuRF-UK); boundary conditions; the scope of the assessment in terms of environmental, economic and social criteria; and any relevant stakeholder engagement and reporting specific to the sustainability assessment. These different elements are explained further below.

<u>Assessment approach</u>

Four of the case studies used qualitative sustainability assessment only (SuRF-UK Tier 1). Five case studies went straight into SuRF-UK Tier 2 using several variants of multi-criteria decision analysis (MCDA). One case study describes the use of qualitative assessment followed by a MCDA stage (supported by cost benefit appraisal) to provide greater distinction between two options, which were not well differentiated by the qualitative stage. This would be the typical approach foreseen by the SuRF-UK framework (CL:AIRE, 2010). The approach taken for the UK case studies, the confidential site (#8) and the Spanish case study (#9) followed that set out by SuRF-UK in Supplementary Report 1 (SR1) and Supplementary Report 2 (SR2) (CL:AIRE, 2020a,b), although a variety of tools were used. The Belgium case study (#5) used an in-house MCDA, but was broadly in line with the SuRF-UK approach.

As well as the assessment approach two other critical elements of defining a sustainability assessment are agreeing its boundary conditions (e.g. a system boundary) and defining its scope (i.e. the criteria to be included in the sustainability consideration).

Table 4: Case study definitions of sustainability assessment.

Case Studies	Assessment approach	Tier (as defined by SuRF-UK)	Boundary conditions	Scope - environmental	Scope - economic	Scope-social	Stakeholder engagement & reporting specific to the sustainability assessment
Case Study 1 - Sustainable Remediation of Former Vehicle Maintenance Facility for Mixed Use Development	In-house MCDA	Tier 2	Spatial Temporal Life Cycle boundaries specified.	Greenhouse gases Ground Air Quality Soil functionality Geotechnical properties Water uses Legally binding objectives Disturbance Energy & fuels use/generation Primary resources & waste	Direct costs/benefits Other costs Uplift in site value Liability discharge / ease of divestment Risk of damage Corporate reputation Duration/timing of benefit Chances of success Flexibility to change in circumstances	Long term risk management Direct risks Intergenerational equity Nuisance impacts Robustness & rigour Degree of uncertainty Validation/verification requirements	Early version of the SURE Tool used for this assessment and no stakeholder engagement (N.B. updated SURE Tool now includes stakeholder engagement section).
Case Study 2 - Natural Source Zone Depletion Assessment: UK Large Scale Field Case Study	In-house qualitative ranking	Tier 1	Not specified	Emissions to air; Soil and ground conditions; Groundwater and surface water; Natural resources and waste	Direct economic costs and benefits; Indirect economic costs and benefits; Project lifespan and flexibility	Human health and safety; Neighbourhoods and locality; Uncertainty and evidence	Sustainability benefits illustrated to internal project stakeholders

Case Studies	Assessment approach	Tier (as defined by SuRF-UK)	Boundary conditions	Scope - environmental	Scope - economic	Scope-social	Stakeholder engagement & reporting specific to the sustainability assessment
Case Study 3 - Sustainable In Situ Thermal Remediation	In-house MCA and quantitative tool (SiteWise)	Tier 2	Not specified	**Multi-Criteria Analysis (MCA):** Impact on water; Impact on soil; Impact on air; Natural resource use and waste generation; Intrusiveness **SiteWise:** GHG emissions; energy usage; water impacts; NOx emissions; SOx emissions; PM10 emissions.	**MCA:** Direct costs; Indirect costs; Employment opportunities & human capital; Gearing; Legacy and projects risks; Flexibility **SiteWise:** Not considered	**MCA:** Human health & Safety; Ethical and equity considerations; Policy and legislative compliance; Impact on surroundings; Uncertainty, evidence and verification; Community involvement & satisfaction **SiteWise:** Accident risk - fatality; Accident risk - injury	The sustainability assessment was discussed and reviewed with the regulatory authorities (both Local Authority and the Environment Agency), who agreed with the approach and the endpoints proposed.
Case Study 4 - Sunshine on the Tyne - Sustainable Hydrocarbon Remediation	In-house MCA	Tier 2	Project Boundary: Whole life, including capital and operational expenditure and impacts	Permanently remove environmental risks associated with DNAPL hydrocarbon contamination; minimise waste generation; minimise resource consumption; minimise greenhouse gas emissions (all assessed on the basis of quantifiable metrics).	No constraints to operation of gas infrastructure at any time; No significant constraints on wider gas holder demolition project; Whole life project cost (all assessed on the basis of quantifiable metrics).	Minimise local air quality impacts; Project vehicle movements; Minimise noise impacts; Minimise dust and odour impacts (all assessed on the basis of quantifiable metrics).	Detailed stakeholder mapping carried out: Client and site owner; site users (NGN operations); gas holder demolition contractor; site neighbours (residential); site neighbours (commercial) and environmental regulators (local authority and Environment Agency). The assessment was based on face to face discussions with stakeholders and general awareness of stakeholder priorities and expectations in relation to remediation works.

Case Studies	Assessment approach	Tier (as defined by SuRF-UK)	Boundary conditions	Scope - environmental	Scope - economic	Scope-social	Stakeholder engagement & reporting specific to the sustainability assessment
Case Study 5 - Reactive Mat in Canal Catches Groundwater Contaminants	In-house MCA	Tier 2	Not specified	Uplift in soil and groundwater quality Uplift in surface water quality Impact on air quality Physical landscape disturbance Biodiversity impact Climate adaptation impact Use of energy CO_2 footprint Use of virgin materials Production of waste	Cost for remediation Land use restrictions Business interruption Financial risks of the project Impact on brand value Time span Uplift in land value	Health and safety impacts Nuisance (noise, odour, dust etc) Community involvement Aesthetic appearance Site public value uplift (amenity, cultural etc)	No, executed by consultancy
Case Study 6 - Sustainable Remediation of a Petrol Release in a Chalk Aquifer	2013 Tier 1 qualitative sustainability assessment using AECOM Tool 2018 Tier 1 qualitative sustainability assessment using pairwise comparison approach supported by quantitative estimates of costs and benefits	Tier 1	Not specified	Emissions to air; Soil and ground conditions; Groundwater and surface water; Ecology; Natural resources and waste	Direct economic costs and benefits; Indirect economic costs and benefits; Employment and employment capital; Induced economic costs and benefits; Project lifespan and flexibility	Human health and safety; Ethics and equity; Neighbourhoods and locality; Communities and community involvement; Uncertainty and evidence	Iterative, client and consultant and then regulators invited to contribute

Case Studies	Assessment approach	Tier (as defined by SuRF-UK)	Boundary conditions	Scope - environmental	Scope - economic	Scope-social	Stakeholder engagement & reporting specific to the sustainability assessment
Case Study 7 - Biosparge of Benzene and Orthodichlorobenzene in Groundwater: A Sustainable Remedy	In-house MCA	Tier 1	Not specified	Linked to SuRF-UK SR2 checklist: 1 Effect on mobilisation of dissolved substances 2 Use of equipment that affects/protects fauna 3 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 4 Use of energy/fuels taking into account their type/origin and the possibility of generating renewable energy by the project	Linked to SuRF-UK SR2 checklist: 1 Direct financial costs and benefits of remediation for organisation 2 Costs associated with operation and any ongoing monitoring, regulator costs, planning, permits, licences, etc. 3 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 4 Factors affecting chances of success of the remediation / management works and issues that may affect works (community, contractual, environmental, procurement and technological risks)	Linked to SuRF-UK SR2 checklist: 1 Human health and safety - site workers 2 Human health and safety - Risk management performance on remediation works and ancillary operations (i.e. process emissions) 3 Duration of remedial works / avoidable transfer of contamination impacts to future generations 4 Effects from dust, light, noise, odour & vibrations during works and associated with traffic, including both working-day, night, weekend, etc.	Site owners, corporate client, regulators and stakeholders were involved in discussions, through the project duration. The option evaluation tool was used iteratively to agree on remediation strategy.

Case Studies	Assessment approach	Tier (as defined by SuRF-UK)	Boundary conditions	Scope - environmental	Scope - economic	Scope-social	Stakeholder engagement & reporting specific to the sustainability assessment
Case Study 8 - Sheen Mitigation Using an Oleophilic Bio Barrier - A New and Sustainable Remediation Technique	SuRF-UK spreadsheet	Tier 1	Not specified	Emissions to air Soil and ground conditions Groundwater and surface water Ecology Natural resources and waste	Direct economic costs and benefits Indirect economic costs and benefits Employment and employment capital Induced economic costs and benefits Project lifespan and flexibility	Human health and safety Ethics and equity Neighbourhoods and locality Communities and community involvement Uncertainty and evidence	Not specified
Case Study 9 - Natural Source Zone Depletion in a Dismantled Petrol Station	In-house	Tier 1 followed by Tier 2	Not specified in detail Only the site was considered in the assessment, except for vehicle transport, where full routes were considered.	Emissions to air Groundwater and surface water Natural resources and waste	Direct economic costs and benefits Indirect economic costs and benefits Project lifespan and flexibility	Human health and Safety Ethics and equity Neighbourhoods and Locality Communities and community involvement Uncertainty and Evidence	Regulator, petrol station operator
Case Study 10 - Sustainability Assessment Case Study - Groundwater Remediation Close-Out	In-house sustainable remediation tool developed by an AECOM legacy company	Tier 2	Sustainability assessment approach Life cycle assessment Spatial extent Timescale	Impacts on to air Impacts on soil and ground conditions Impacts on groundwater and surface water Use of natural resources and waste	Direct economic costs and benefits Indirect economic costs and benefits Project lifespan and flexibility	Impacts on human health and Safety Ethics and equity Neighbourhoods and Locality Compliance, uncertainty and Evidence	Client, Regulator

Boundary conditions

Few of the sustainability case studies provided information about the boundaries they considered. **Table 5** lists the boundaries described in the SuRF-UK SR1 guidance (CL:AIRE, 2020a). It is possible that this consideration is not fully understood by practitioners, which creates the risk that remediation approaches are not being compared on a "like for like" basis. Reliable comparison is dependent on all options under consideration being assessed under the same boundary conditions.

Table 5: Boundaries for sustainability assessment (adapted from CL:AIRE, 2020a).

Boundaries Explained
The System Boundary. The system boundary encompasses the project goals for which options are being compared, and the options which might deliver these. It describes the "edges" of the system being considered, i.e. where it interfaces with the surrounding environment, society or economic processes or other systems. The system needs to consider all of the processes that are needed to deliver the project. This is so assessment can consider all impacts and benefits taking place as a result of the remediation work. *For example, the assessment will consider all remediation and ancillary work for [risk management objectives]. Movement of all materials to site, all operations to fully achieve agreed risk management objectives for the remediation. Removal and disposal of all residues. Management of all emissions.*
The "life cycle" boundary. "Life cycle" boundaries consider how far the option being considered should be broken down into sub-units requiring some sort of analysis. This boundary in effect sets a limit to the inputs and outputs that will be included in the assessment, in particular considering (a) how to deal with equipment that might be used on multiple projects; and (b) how do we deal with items that might be seen as trivial, for instance, what considerations might be *de minimis*. *For example, the assessment will consider what is consumed by the remediation; the effect of operations – such as emissions; the deterioration on capital equipment that will be reused and the impacts of capital equipment operation and maintenance.*
Optionally, **spatial boundaries** can be used to distinguish effects for different users / audiences according to their concerns (e.g. to provide a sub-assessment particularly focusing on concerns within 1 km of the site.
Optionally, **temporal boundaries** can also be used to distinguish effects for different users/audiences according to their concerns (e.g. to separate long term effects vs. temporary effects of operations).

Scope

All of the case studies considered a range of environmental, social and economic criteria, in nearly all cases drawn from the SuRF-UK SR2 indicator guidance (and its fore-runner). However, the assessments tended to be restricted to the "headline" categories of indicators, see **Table 6**, and do not drill down to the individual criteria provided in the SR2 guidance.

It is not known how far these individual criteria influenced the sustainability assessment comparisons made as they were not explicitly discussed in any of the case studies. However, they may have influenced thinking about the headline categories. Future practice should be encouraged to use the detailed checklist as it both explains and enhances the headlines, and may also facilitate mapping of the sustainability assessment against UN Sustainable Development Goals (SDGs) and also develop interests in wider social value considerations. For example, the Public Services (Social Value) Act requires all public sector organisations and their suppliers to consider how the services they commission and procure can improve economic, social and environmental benefits (UK Government, 2013).

Table 6: SuRF-UK Headline Categories for Indicators (CL:AIRE, 2020a).

Environmental	Social	Economic
ENV1: Emissions to air	SOC1: Human health and safety	ECON1: Direct economic costs and benefits
ENV2: Soil and ground conditions	SOC2: Ethics and equity	ECON2: Indirect economic costs and benefits
ENV3: Groundwater and surface water	SOC3: Neighbourhoods and locality	ECON3: Employment and employment capital
ENV4: Ecology	SOC4: Communities and community involvement	ECON4: Induced economic costs and benefits
ENV5: Natural resources and waste	SOC5: Uncertainty and evidence	ECON5: Project lifespan and flexibility

Stakeholder engagement

Stakeholder engagement is important to making robust sustainability assessments because in many cases the comparison made, whether qualitative or semi-quantitative is opinion based. This may be opinion-based evidence to support a comparison or, for semi-quantitative methods, to underpin any weightings used. Nine case studies reported the stakeholder engagement they carried out. In general the stakeholders involved in the sustainability assessments were consultants and site operators, although consultants may have tried to predict wider stakeholder perspectives to provide an assessment. In five cases this assessment was then used to support wider engagement. Case Study 4 carried out the most detailed stakeholder engagement mapping interests and soliciting opinions from external stakeholders. Case Study 6 stated that the regulators (local authority and Environment Agency) were involved in the sustainability assessment and decision-making process, and agreed with the approach and the endpoints proposed. Six case studies in total described engagement with regulators as a part of the sustainability assessment process.

Table 7 presents the range of guidance followed by the case studies. This was a requirement of the information requested from case study providers and links to sections 15 and 16 of the ISO 18504:2017 (ISO, 2017) guidance (see **Table 1**). All the case studies cited guidance from SuRF-UK, although two case studies used it along with other guidance to develop their in-house tool and methodology. Although the SuRF-UK framework was used in seven case studies this was typically supplemented by more specific and recent SuRF-UK guidance. The ISO guidance was cited by five case studies.

Table 7: Guidance documents cited by case studies.

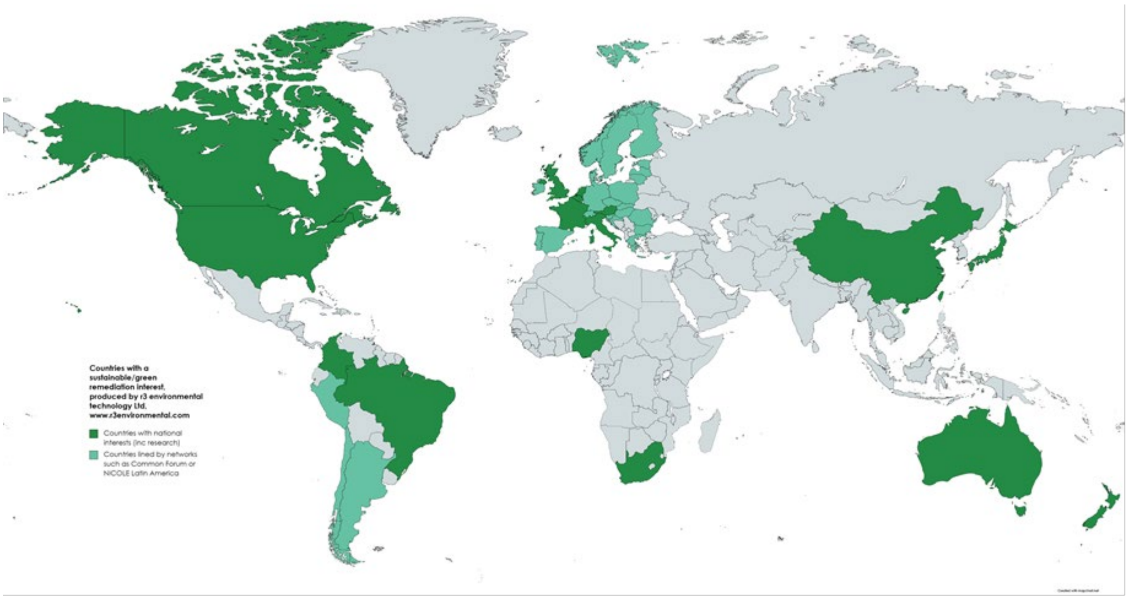
Name of guidance by issuer (listed alphabetically)	Cited by (number of case studies)
CL:AIRE	
2010. SuRF-UK framework for assessing the sustainability of soil and groundwater remediation	7
2011. The Definition of Waste: Development Industry Code of Practice	1
2011. Annex 1: The SuRF-UK Indicator Set for Sustainable Remediation Assessment (withdrawn 2020)	2
2020. Supplementary Report 1 of the SuRF-UK Framework: A general approach to sustainability assessment for use in achieving sustainable remediation (SR1)	4
2020. Supplementary Report 2 of the SuRF-UK Framework: Selection of indicators/criteria for use in sustainability assessment for achieving sustainable remediation (SR2)	3
2021. Sustainable Management Practices for Management of Land Contamination	1
Environment Agency (of England and Wales)	
Remediation Option Appraisal Matrix	2
Remedial Targets Methodology	1
Model Procedures for the Management of Land Contamination, Contaminated Land Report 11 (now superseded by Land Contamination Risk Management (LCRM) guidance.	2
ISO 18504:2017, 2017. Soil Quality – Sustainable Remediation	5
UN Sustainable Development Goals	2
US Environmental Protection Agency	
2008. Green Remediation: Incorporating Sustainable Environmental Practices in the Remediation of Contaminated Sites	1
2016. Green Remediation Best Management Practices	1
US Navy SiteWise tool	1

4.3. DRIVERS FOR UNDERTAKING SUSTAINABLE REMEDIATION AND KEY SUCCESS FACTORS TO THE ADOPTION OF SUSTAINABLE TECHNOLOGIES (THEMES OF GOOD PRACTICE)

Sustainable remediation is still considered an emerging practice in the management of contaminated sites in a global context (see **Figure 1**) and direct regulatory drivers have been relatively few (CL:AIRE and NICOLE, 2015; Rizzo *et al.*, 2016). However, there are now an increasing number of drivers towards its adoption, led by certain jurisdictions where it has become established practice. These drivers include:

- Regulatory drivers: for example, it is now a formal part of option appraisal under OVAM guidance in Belgium; SuRF-UK and ISO 18504:2017 (ISO, 2017) guidance is explicitly referenced by the regulator in the UK for land contamination risk management (Environment Agency, 2020).
- Public ownership / funding drivers: for example, in Austria application of public funding for site management must be accompanied by sustainability assessment and in the USA federally funded (e.g. US EPA) projects are expected to consider sustainability and resilience.
- Benchmarking against sustainable development principles, such as the UN SDGs as a part of both public and private sector corporate governance.
- Financial drivers are emerging, with financial institutions and pension funds that are investing in brownfield redevelopment being increasingly subject to mandatory disclosures in relation to climate change and sustainability. Globally, the Taskforce for Climate-related Financial Disclosures and Taskforce for Nature-related Financial Disclosures are gaining profile. In the UK, the Government has recently published Greening Finance: A Roadmap to Sustainable Investing (UK Government, 2021), which will require brownfield developments to be seen as sustainable from an investment perspective.
- Wider pragmatic benefits (CL:AIRE, 2020a) of applying sustainable remediation, including:
  - showing how early changes in the project design can avoid unnecessarily intrusive/intensive remediation.
  - providing a rigorous framework for predicting pinch points and potential areas of difficulty in delivering remediation and may also help identify secondary impacts which might then either be designed out or mitigated.
  - Providing a due diligence process for the overall understanding of the net benefit of the remediation work envisaged and a rigorous rationale for making choices between different approaches and methods that might be available/offered.
  - identifying beneficial opportunities for synergy, for example with other project activities.

Figure 1: Global development of sustainable remediation (Source: r3 Environmental Technology).



Many of the drivers are exemplified by the case studies, in particular client interests as part of wider sustainable development governance, and demonstrating sustainability gain to regulators (see **Table 3**). **Table 8** lists the key highlights each case study reported for itself and the main sustainability assessment outcomes. Six of the case studies highlight the specific importance of sustainability assessment in engagement with regulators and the agreement of an optimal site management approach. This was particularly important for NSZD as a relatively new remediation strategy. At least two case studies highlight the value of linking to UN SDGs. Case Study 5 used sustainability assessment *post hoc* to validate sustainability gains to Public Sector funders. However, as exemplified by Case Study 9, while sustainability assessment can be persuasive, it does not necessarily end a regulatory discussion. There may be “cultural” or other drivers that mean some form of compromise is needed; in the example of Case Study 9 it was agreed that some form of ongoing mass removal should continue, even though the sustainability argument was against this. The process of shifting risk-based land management to *sustainable and* risk-based land management is not complete, and potentially case studies like Concawe’s will help accelerate this shift.

Table 8 also demonstrates the practical or pragmatic use of sustainability assessment. Several points are notable, which are discussed below.

Several case studies did not undertake a qualitative stage but went straight to a semi-quantitative MCDA type of approach. This seems related to the preferences of the consultant and the consultant’s perspective of how to make the most persuasive and reliable arguments. There are clearly divergent opinions on the “entry point” for sustainability assessment, even if in general a tiered approach is broadly agreed. This is not really problematic as whatever approach is taken usable and pragmatic outcomes were achieved. However, several case studies showed a progression through tiers of sustainability assessment, for example qualitative to semi-quantitative, or the use of some quantitative data (such as carbon footprint) to support wider qualitative or semi-quantitative assessment across a broader range of considerations.

All of these case studies were at what SuRF-UK describes as “Stage B”, i.e. option appraisal, where risk management objectives are already set. The sustainability assessments all robustly supported effective site management decisions, such as remedy selection, or shifts in remediation strategy, such as for sites where remediation had been underway for some time already.

However, a gap in case study provision therefore remains for case studies looking at sustainable remediation applications for setting risk management specifications, for example in informing discussions of future re-use layout. This is partly to be expected as Concawe’s interests focus on operational sites, however it was also the situation for case studies where site use was to be changed. Potentially this reflects the majority of applications in general, with – thus far – only limited use of sustainability assessment at site planning stages or in consideration of longer term site stewardship, as defined by NICOLE/Common Forum (2018).

All of the case studies provided CSMs. Several of the case studies emphasised the importance of CSMs in remediation strategy discussion and development. Several also emphasised the importance of a collegiate or team approach to the work of site management towards achieving robust progress and agreed endpoints.

Table 8: Case study highlights and key findings.

Case Study	Case study highlights	Case study findings
Case Study 1 - Sustainable Remediation of Former Vehicle Maintenance Facility for Mixed Use Development	Sustainability of the short-listed options was assessed using a procedure based on the principles of ISO 18504:2017. *In situ* treatment processes were used to promote enhanced removal of free-phase oil contamination and enhanced biodegradation of residual hydrocarbons in soils and groundwater within a Secondary Aquifer. Regular groundwater monitoring and review of the DQRA during the works programme ensured that the remedial scope was optimised and practicable, but still achieved significant environmental betterment. Effective use was made of the CL:AIRE Definition of Waste Code of Practice initiative to plan, manage and implement a sustainable materials management solution with a zero materials balance being achieved. Site won hardcore from above and below ground demolition was processed into a high quality 6F2 graded aggregate and re-used for construction of a development platform. Coal tar-impacted macadam requiring removal from site was sent to a recovery facility to be recycled rather than to a landfill. General (uncontaminated) Made Ground arising from obstructions removal was processed to a suitable grading for re-use as engineered fill. A significant contribution to the overall success of the project was the collaborative spirit entered into by the client, consultant and contractor.	Remedial Option 2 (*Ex situ* bioremediation, *in situ* bioremediation, capping) delivered a good overall performance for each of the three sustainability domains, particularly Society, and made contributions to several UN Sustainable Development goals. Therefore, Remedial Option 2 was selected as the best approach and subsequently developed into a formal remediation strategy.
Case Study 2 - Natural Source Zone Depletion Assessment: UK Large Scale Field Case Study	The NSZD study was successful in proving the significance of natural mass depletion processes for the LNAPL plume and demonstrating that the monitoring of NAPL mass depletion rates could be achieved at an operational UK facility. The findings and conclusions of the study were accepted by the regulator and a phase of further data collection has been approved. Total CO_2 flux measured in the source zone was consistently higher than recorded at background locations, in line with the key assumption underpinning the evaluation approach. The trial recorded effective LNAPL mass depletion rates within the lower range of published research values, consistent with the wetter and cooler climate of the UK. As predicted, saturated zone mass flux was several orders of magnitude lower than vapour phase mass flux. The study was completed with full UK regulator engagement and acceptance of the study findings paves the way for development of a long term NSZD remedial strategy. With successful outcomes now reported back to both site operator and regulator, further NSZD monitoring data is being collected augmenting the initial dataset with a view to developing, and gaining endorsement for, a full NSZD strategy for the remediation of the LNAPL mass. The successful trial outcomes created the opportunity for more formal consideration of a highly sustainable ‘attenuation based’ remedial approach for this project.	NSZD (attenuation based) was chosen as the more sustainable approach. Across the environmental indicators, NSZD ranked better than Dual Phase Extraction for emissions to air, and natural resources and waste. Otherwise it ranked equally. Across the economic indicators for both direct and indirect economic costs and benefits NSZD ranked better, but was worse for lifespan and flexibility. Across the social indicators NSZD ranked better for human health and safety, and worse for uncertainty & evidence. For neighbourhoods and locality both options ranked similarly.

Case Study	Case study highlights	Case study findings
Case Study 3 - Sustainable *In Situ* Thermal Remediation	The importance of the development of rigorous CSMs early in the lifecycle of a remediation project was highlighted, so that remediation can be undertaken in a sustainable manner from design to implementation, and resources not be wasted through inefficient application of remediation technologies. There is also a need to continuously review remedial system effectiveness against performance data on a regular basis and to optimise these systems or revise the approach. The High Resolution Site Characterisation underpinned the sustainable remediation approach that was carried out at this site and demonstrated how the longer term pump and treat was inappropriate to achieve remedial targets. The remedial options appraisal was undertaken using a holistic sustainability approach, where environmental, social and economic indicators were evaluated to determine the most sustainable option and was one of the first examples of use of the SuRF-UK framework. The remedial design phase of the project focused on energy and hence carbon footprint reduction to the extent practical, including using gas-powered Thermal Conductive Heating to optimise energy use. This saved circa 82,000 kWh of power compared to if an electrically powered approach had been implemented. During the remedial implementation stage, the use of thermocouples to record temperature variations over time enabled the heating period to be reduced by ascertaining when the target treatment temperature had been achieved. Contaminant recovery continued for a period of 10 days without heating, saving another circa 42,500 kWh of energy.	The MCA assessment found that ISTR was the preferred remedial solution, as its overall MCA score demonstrated the greatest overall net sustainability benefit. The SITEWISE findings were used to inform related indicators used in the MCA. In addition to the sustainability assessment based decision making, the operation of the ISTR included making operational choices influenced by sustainability (e.g. choice of fuel type), informed by the US EPA Green Remediation Best Management Practices.
Case Study 4 - Sunshine on the Tyne - Sustainable Hydrocarbon Remediation	The remedial solution overcame site constraints and delivered a sustainable system which achieved permanent environmental betterment using only renewable energy to power remediation equipment with no significant impact on wider site activities or site neighbours. A supplementary ground investigation was undertaken to further characterise the spatial distribution of DNAPL and installed recovery wells for remediation. This informed the selection of potential remedial options which were subject to sustainability assessment to support the selection of the optimum solution. Assessment of site aspects, environmental, social and economic factors during the design process led to the development of a wholly sustainable, durable and robust remediation methodology. A 6 month remediation pilot trial provided an estimate of the potential DNAPL volume present and assessed the feasibility of consistently and robustly recovering DNAPL using pneumatic pumps installed in the recovery wells powered only by on site renewable energy generation. Following the remediation pilot trial, full-scale operation of the remediation system took place, with a total operating period of 22 months during which time 6,100 litres of DNAPL was recovered. This low intensity renewable energy driven approach provided multiple economic, social and environmental benefits.	The remediation options sustainability assessment identified the optimum solution to achieve both the project vision and stakeholder goals to be targeted DNAPL removal utilising a low energy system fuelled by renewable energy. This option was deployed successfully as part of the project. The sustainability assessment provided the project team with a suite of project metrics against which the success of the project could be assessed.

Case Study	Case study highlights	Case study findings
Case Study 5 - Reactive Mat in Canal Catches Groundwater Contaminants	Laboratory results on the adsorption capacity of green adsorbents matched well with field scale measurements. Direct measurements were made of vertical fluxes of individual contaminants through the waterbed, which assisted the design of the mat. The onsite deployment and customisation of the mat was relatively straightforward. Surface water quality was significantly improved compared to the initial situation. A *post hoc* sustainability assessment found that the reactive mat was the most sustainable alternative. There was successful international cooperation of several professional partners under the flag of EU Interreg that was initiated and facilitated by the Flemish OVAM.	The post hoc sustainability assessment found that the reactive mat was the most sustainable alternative.
Case Study 6 - Sustainable Remediation of a Petrol Release in a Chalk Aquifer	Regulator-endorsed closure of remedial activities on the petrol station was achieved through attainment of concentration-based remedial targets. The innovative use of mass discharge remedial targets achieved regulator-endorsed closure of remedial activities on all four properties adjacent to the petrol station, thereby allowing a return to residential use. Sustainability assessments were applied to inform future remedial strategy and to review the appropriate adoption of compliance points. Historical attenuation data were used to establish a road-map for closure of the hydraulic containment system.	In the 2013 assessment, Option 1D (targeted source reduction on adjacent residential properties combined with continued hydraulic containment system operation) was ranked highest when only the priority criteria were considered, hence it was selected as the preferred option. After implementation of option 1D a second (2018) sustainability assessment was carried out to decide whether hydraulic containment needed to continue. This concluded that switch-off was the best ranked option once MTBE mass discharge remedial targets had been met.
Case Study 7 - Biosparge of Benzene and Orthodichlorobenzene in Groundwater: A Sustainable Remedy	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 by-products – 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's compressed air supply. 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), which 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 & silts while minimising excessive lateral air migration.	The qualitative (Tier 1) sustainability assessment provided a clear finding favouring biosparge. Owing to the technical challenges in implementing this technology pilot testing of biosparging and air sparging with SVE was undertaken over 2016-2018. Full scale biosparging was installed in 2019/2020. The qualitative assessment provided a clear answer, so a more quantitative assessment was not undertaken.

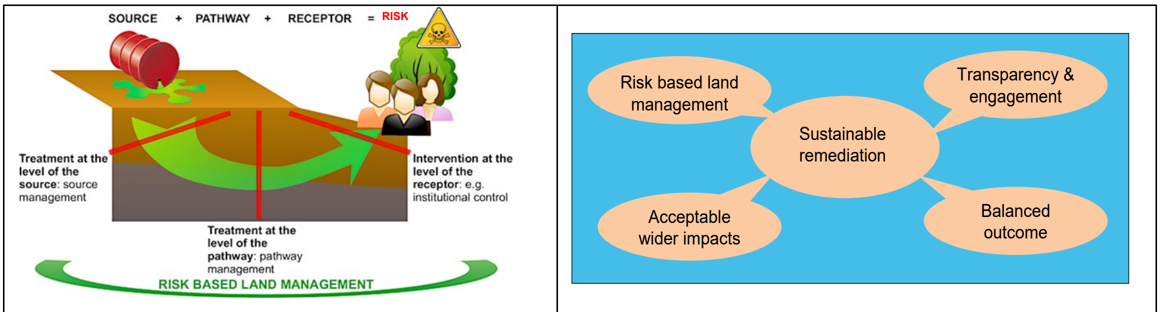
Case Study	Case study highlights	Case study findings
Case Study 8 - Sheen Mitigation Using an Oleophilic Bio Barrier - A New and Sustainable Remediation Technique	The implementation and installation works of the Oleophilic Bio Barrier represented a European first application. The installation works were successfully undertaken in highly challenging conditions and the project was completed safely, with no incidents or accidents and with no detrimental impact to the area. Overcoming the challenging significant tidal range of the river was achieved by working with a commercial diving team for in-water work and underwater excavation of trenches. Without the commercial diving team, the tidal range would have limited the working window to a few hours around the low tide event. It was notable that during discussions with key project stakeholders (e.g. local environmental protection and marine licensing authorities) with respect to working in an ecologically sensitive area within the marine environment that many of the key sustainable attributes of the solution, when compared to alternative approaches, were integral to attaining timely approvals for the proposed works.	The Oleophilic Bio Barrier was validated as having superior sustainability rankings overall and individually in 8 out of 15 headlines, compared with the other options being considered in the sustainability assessment.
Case Study 9 - Natural Source Zone Depletion in a Dismantled Petrol Station	A Tier 1 and Tier 2 sustainability assessment methodology was applied to identify the most sustainable remedial solution to address the impacts associated with the historical operation of a decommissioned petrol station. The assessment identified the optimal sustainable remediation approach for managing risks to people and the environment and achieving regulatory closure. The assessment was used to compare four options that would all achieve the remediation goals. The results from the sustainability assessment were useful when discussing the advantages and disadvantages of each option from a sustainability view with the regulators and other stakeholders. The results from the sustainability assessment can help justify the selected remedial approach.	After the Tier 1 evaluation, two options were discarded for being the least sustainable. Option 1 (NSZD) scored highest. However, the score obtained for options 1 and 2 (NSZD + Skimmers) was close. Therefore, a Tier 2 assessment was undertaken to obtain a higher level of confidence in the final choice. Although option 1 was identified as the preferred option by the sustainability assessment, the selected approach needed to align with the request from the regulators for active removal of LNAPL. Therefore, option 2 was selected as the preferred remedial option for the site.
Case Study 10 - Sustainability Assessment Case Study - Groundwater Remediation Close-Out	A sustainable remediation assessment was applied to inform the future remediation strategy and the requirement for further remediation. Regulators supported the use of MCA to assess the sustainability of the remediation options used on-site. Thorough carbon footprint analysis to inform the decision-making process when identifying the most sustainable remediation option. Regulators agreed that further active remediation of residual contamination was not sustainable.	MNA was the most sustainable remediation option, and this finding was robust to changes in the weightings used in the MCA. Carbon footprint analysis also indicated MNA favourably. MNA was considered the least resilient of the options to changes such as different land-uses or timescales; however, the Regulators agreed that further active remediation to treat residual contamination in the saturated sandstone was not sustainable and that the remediation strategy for the Site was complete.

5. EXPERIENCE-BASED PROTOCOL FOR DEPLOYING SUSTAINABLE REMEDIATION IN PRACTICE

5.1. PRINCIPLES AND BENEFITS OF SUSTAINABLE AND RISK-BASED REMEDIATION

Risk-based decision making is central to land contamination management. Decisions should be made based on risks to human health and the wider environment. For a risk to be present, a source (of hazardous substance or property), a receptor (which could be adversely affected by the contamination) and a pathway (linking the source to the receptor) must be present. This is referred to as a Source-Pathway-Receptor (S-P-R) linkage (CL:AIRE, 2020a), see **Figure 2**.

Figure 2: The elements of sustainable and risk-based land management.



Risk management (Tack and Bardos, 2013)	Sustainable Remediation (Bardos, 2023)

The remediation process itself is not free of impacts. Remediation is not intrinsically sustainable and poorly planned projects can have serious negative impacts. Therefore, risk management should also meet sustainable development principles. Together this constitutes ***sustainable remediation*, *or sustainable risk-based land management***, SRBLM (NICOLE/Common Forum, 2013; Bardos, 2023). SRBLM is recognised as the optimal approach for contaminated land decision-making, combining a risk-based framework for determining when harm (or potential harm) is unacceptable and where action is necessary, and ensuring sustainability is a part of deciding how such unacceptable risks are to be managed. In the best examples of SRBLM, significant improvements in project sustainability have been delivered, including concurrent reduction of the environmental footprint of the remediation, improved social performance, cost savings and/or value creation (CL:AIRE, 2020a).

5.2. WHEN AND HOW TO ACT (SUSTAINABILITY ASSESSMENT VERSUS SUSTAINABLE MANAGEMENT PRACTICES)

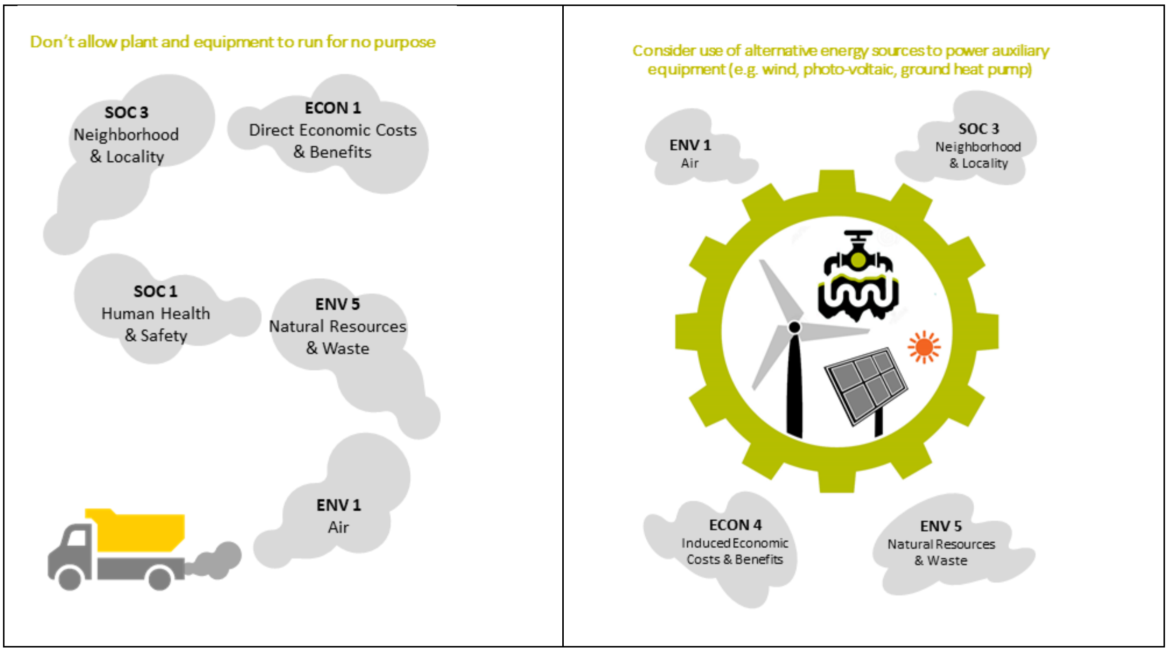
Key principles of sustainable remediation include the following: a focus on risk management as the main driver for remediation, seeking a net benefit from a transparent decision-making approach, looking at positive and negative impacts of remediation in a holistic and over-arching way, engagement with wider interest groups as necessary, clear procedures and reporting, and a sound evidential basis.

Underpinning this assessment-based design and decision making, is the potential sustainability gain from simple improvements for site management at any stage from site investigation through remediation and verification. These improvements may be as simple as simply switching off vehicles or machinery when not in use, and in the UK are known as "sustainable management practices or SMPs". In 2021, SuRF-UK issued updated "SMPs" guidance (CL:AIRE, 2021).

SMPs are "relatively simple, common sense actions that can be implemented at any stage in a land contamination management project to improve its environmental, social and/or economic performance". **Figure 3** illustrates two examples. SMPS can be applied at any point from site investigation onwards to improve sustainability performance, without requiring a formal sustainability assessment.

The concept developed from Best Management Practices (BMPs) first promoted by US EPA related to aspects of green remediation[4], i.e. achieving environmental gains.

Figure 3: SMP examples mapped to possible sustainability gains across the SuRF-UK indicator categories listed in **Table 6** (reproduced with permission from CL:AIRE).



5.3. PREPARING FOR, DEFINING AND EXECUTING A SUSTAINABILITY ASSESSMENT

One of the most detailed implementations of the ISO 18504:2017 (ISO, 2017) standard has been drawn up by SuRF-UK in its detailed procedural guidance for conducting a sustainability assessment - the SR1 and SR2 reports (CL:AIRE 2020a,b).

SR1 sets out some key messages on the role of sustainability assessment:

- Early action yields greatest benefit
- Sustainable risk-based land management is the optimal approach for contaminated land decision making

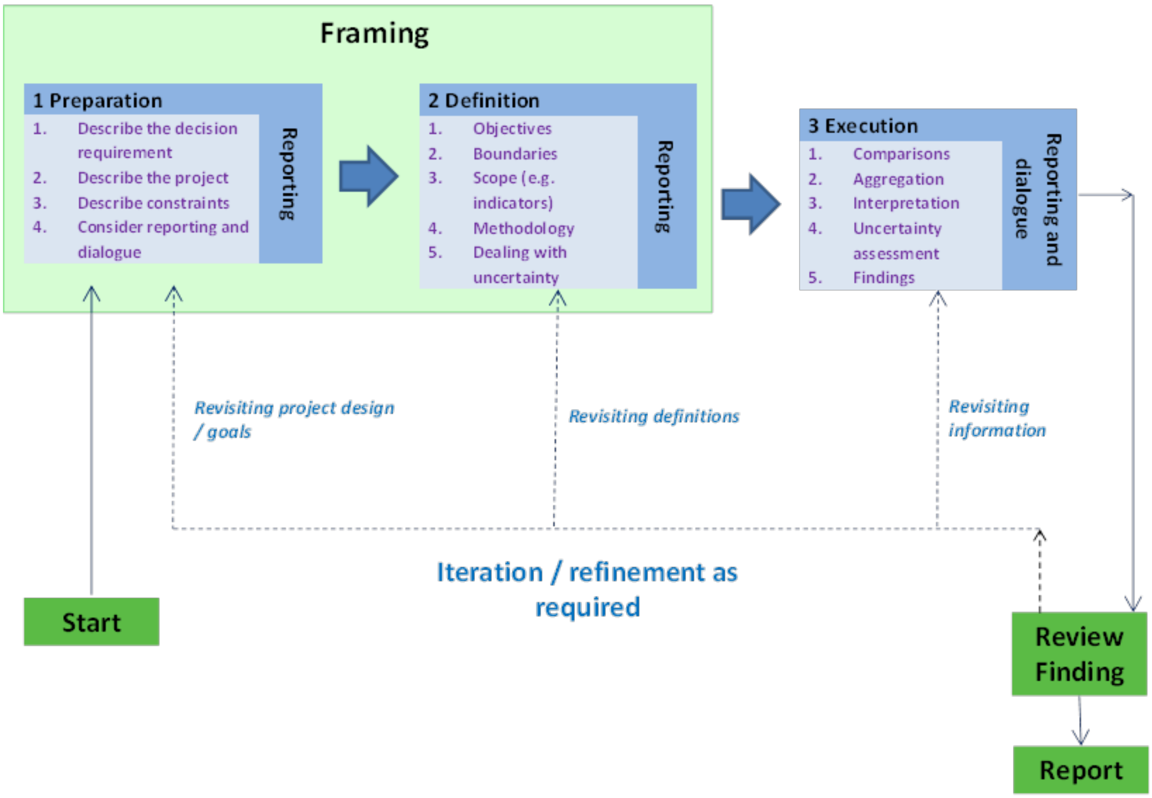
[4] https://clu-in.org/greenremediation/BMPs

- Sustainability assessment is multifactorial and site specific
- Sustainability is not capable of being reduced to simple metrics
- A tiered approach to sustainability assessment is recommended
- Sustainability assessment is subjective
- The usefulness of a sustainability assessment, its transparency, its resilience and its persuasiveness relies upon carefully preparing and defining the sustainability assessment approach so that it is fit for purpose for the particular site/project it is being applied to.

SuRF-UK summarises its approach to sustainability assessment as following three broad stages: *Preparation*, *Definition*, *Execution* (as shown in **Figure 4** and described in more detail in **Table 9**). The preparation and definition stages provide the 'framing' for the third, execution stage, as follows:

1. The preparation stage sets out the rationale for the assessment, the project or site being considered, the scenarios being compared, any opportunities and constraints that may apply, who will be consulted and when, and how the assessment will be reported and communicated.
2. The definition stage summarises and formats the preparation work as a series of objectives for the assessment, and then goes further to set careful boundaries for the work, how the comparison will be made, and how uncertainties will be dealt with.
3. The execution stage applies the framing developed to a sustainability assessment. The framing is specific to each site/project.

Figure 4: Sustainability assessment and its framing (reproduced with permission from CL:AIRE, 2020a).



A key feature of the sustainability assessment process, evident from **Figure 4**, is that it is iterative. This iteration may be a function of how stakeholders are engaged with the sustainability assessment process, or as a result of refinements which become evident as the process carries on.

This approach consists of simple steps and is intended to be used in conjunction with SR2 (CL:AIRE, 2020b), which provides more detailed guidance on the selection of indicators/criteria to set a site/project specific scope for sustainability assessment.

As previously noted, **Table 9** describes the three stages in more detail.

Table 9: Summary of the key steps within each broad task of SuRF-UK sustainability assessment (CL:AIRE, 2020a).

Task 1 - Preparation	Task 2 - Definition	Task 3 - Execution
Step 1.1: Describe the decision requirement Describe the decision the sustainability assessment is intended to support and how its outcomes will be used, and also the stakeholders who need to be engaged with it.	*Step 2.1: Summarise objectives* This activity reviews the preparation steps and consolidates them, especially since the preparatory and definition stages of framing may be separated in time.	*Step 3.1: Comparisons by indicator/criterion* Compare options for each individual sustainability indicator/criterion (identified in Step 2.3) in a way that is compliant with the methodology agreed (Step 2.4).
Step 1.2: Describe the project Clearly describe the project's remediation, risk management goals and any wider goals of importance. Specify the options to be compared using sustainability assessment.	*Step 2.2: Identify boundary conditions* Describe the assessment boundary conditions related to system, depth of consideration, proximity and timeframe.	*Step 3.2: Aggregation of individual comparisons* Aggregate individual outcomes, for example to overall comparisons by headline category, and from there comparisons for each of the three elements of sustainability, as set out in Step 2.4.
Step 1.3: Describe constraints & opportunities Identify constraints and opportunities. Constraints limit possibilities for remediation. Opportunities are where features of the site could create benefits, for examples synergies in energy or materials use.	*Step 2.3: Agree scope/indicators* Describe the range of individual sustainability considerations to be included in the assessment from the headlines summarised in Table 1 (of CL:AIRE, 2020a), which is set out in detail in *Supplementary Report 2*.	*Step 3.3: Interpretation* Initial conclusions are drawn from comparing options for "sustainability" in broad terms, and also for individual factors of special interest; discussion and review and ground truthing with wider stakeholders.
Step 1.4: Consider reporting and dialogue Plan how reporting and dialogue will involve the stakeholders identified in Step 1.1, in line with the SuRF-UK Framework's Key Principles, specifying who will be involved and when.	*Step 2.4: Agree methodology* Set out the methodology by which options are going to be compared for the different sustainability indicators/criteria being considered.	*Step 3.4: Understanding uncertainties* Sensitivity analyses can be applied to help stakeholders understand how uncertainties related to information/approach play out for the overall sustainability assessment outcome.
	Step 2.5: Agree how to deal with uncertainty Set out an approach for identifying uncertainties and reviewing their potential effect on sustainability assessment outcomes.	*Step 3.5: Presenting the findings* Check the clarity of the outcome, and determine conclusions. If the outcome is not clear consider a more detailed assessment (i.e. a higher "tier").

5.4. A PRACTICAL APPROACH FOR DEPLOYING SUSTAINABLE REMEDIATION ON OPERATIONAL SITES

Considering constraints

Operational sites are sites that are in functional use such as for manufacturing, and will continue in this function after remediation, as opposed to development sites. Many Concawe sites will be operational sites. These have particular constraints that affect remediation strategy development and its sustainability assessment:

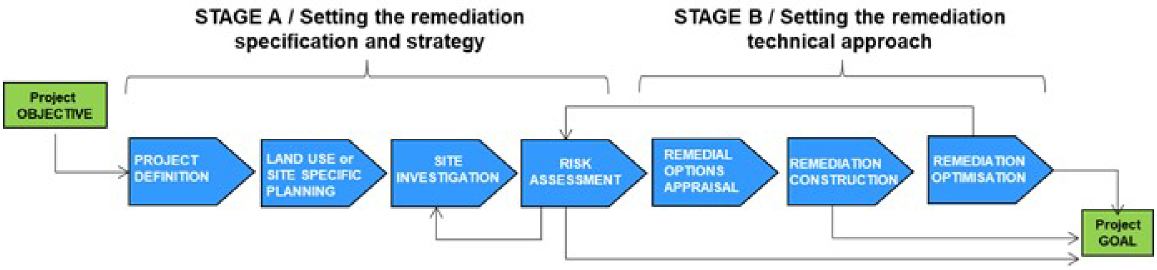
- There will be specific issues related to infrastructure and buried services;
- There may be limitations on access to source zones;
- There may be limitations on available space and on time;
- The future use of the site will not change greatly, if at all; and
- There may be wider neighbourhood issues which could be negatively impacted by remediation works.

Many of these constraints are apparent in the case study series.

There will also be opportunities, in particular the availability of energy, staffing and security. A particular opportunity might be the deployment of lower input / longer term remediation during site works for other purposes. This might allow for environmental liabilities to be reduced over the operational lifetime of a site to facilitate its future re-use at some point in the longer term. This approach is under investigation by the H2020 EiCLaR project[5].

Figure 5 links the opportunities for sustainable remediation to be carried out (i.e. at the stage of developing a strategy and/or at the stage of remedy selection for a concluded remediation strategy) with the trajectory of contaminated site interventions such as site investigation, remediation etc.

Figure 5: The life cycle of land contamination management and the SuRF-UK framework (adapted from CL:AIRE (2021)).



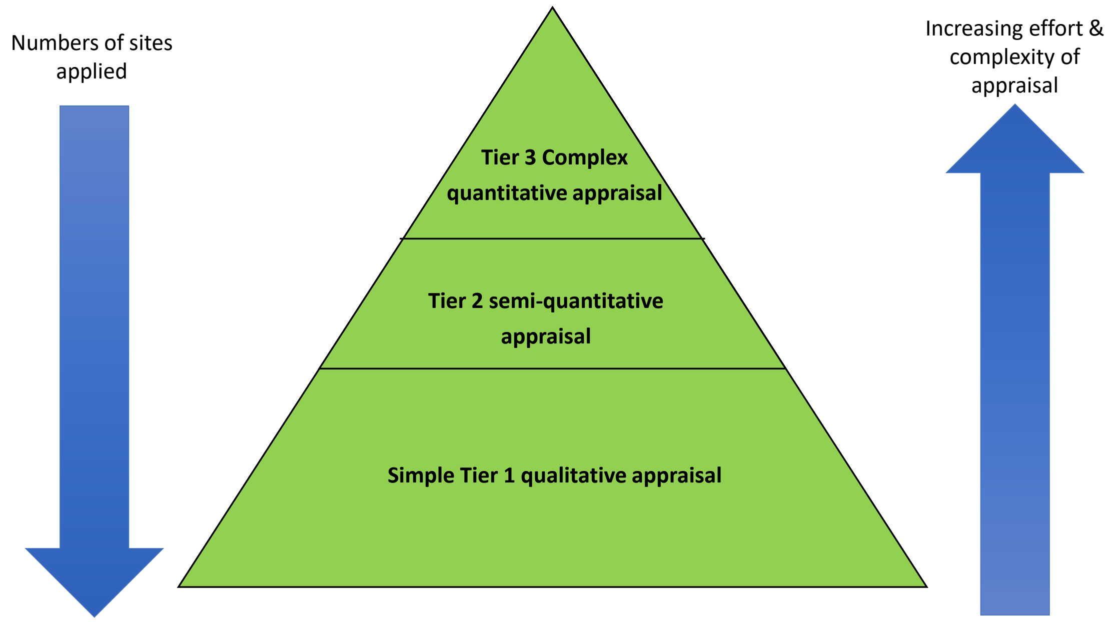
The prospects of changing the site layout or future use of different site areas is limited for operational sites compared with development sites. Hence the scope for considering strategic changes such as changes in land use, that would affect the setting of remediation targets is also limited, and in practice sustainable remediation assessment is limited to comparing different remedial options for a predefined risk management endpoint (Stage B). However, the opportunity for sustainability gains from the deployment of SMPs remains right from the start of the contaminated site management journey shown in **Figure 5**.

[5] www.eiclar.eu

Selection of assessment tier

Figure 6 shows the tiered approach recommended for sustainability assessment (CL:AIRE, 2010) with assessment commencing at a qualitative tier, and only progressing to more intensive analytical effort if the lower tier does not provide a sufficiently clear outcome (as exemplified by Case Study 9). There is evidence that this lowest tier, qualitative assessment, provides sufficient information for making choices based on sustainability in the majority of cases (Smith and Kerrison, 2013). In practice, the entry level is often at "Tier 2" reflecting the perspectives of consultants or other stakeholders on what might make the most robust or convincing sustainability assessment. The case studies tend to show that the sustainability assessments regardless of entry point were persuasive to regulators. However, it should be noted that in some jurisdictions regulators have limited resources and this may be a challenge to getting engagement on sustainability assessments.

Figure 6: Tiered approach to sustainability assessment.



It may also be helpful for site owners to include in their procurement processes a requirement for a "Sustainable Remediation Certification Sheet", as suggested in section 2.2 (see also Appendix 2).

Lessons learned and key suggestions

Table 10 links lessons learned across the ten case studies to the sustainability assessment steps described in **Table 9**.

Table 10: Sustainability assessment in practice – lessons learned from the case studies.

	Sustainability Step (from Table 9)	Lessons Learned
Preparation Stage	1: Describe the decision requirement	All of the case studies expressed clear rationales for the decision requirement.
	2: Describe the project	The use of CSMs greatly assisted the description of each case study (project). A wide variety of treatment based remediation strategies were included across the case studies.
	3: Describe constraints	Project constraints had a direct bearing on sustainability assessment considerations.
	4: Consider reporting and dialogue	Were it not for the case study process, reporting would not have been in the public domain. In all cases the sustainability assessment process included stakeholders close to the process (client, consultant and contractor). Where regulators were also included, they seemed able to commit to an active role. This is significant given the limitations of their organisational resources and shows strong regulatory interest and motivation to deploy sustainable remediation.
Definition Stage	1: Objectives	Objectives were not always specifically stated. However, rationales and motivations were provided (as mentioned above).
	2: Boundaries	There was little explicit consideration of boundaries across the case studies. While these considerations may have been implicit in the sustainability assessments carried out, this is a failure of transparency. Clear boundaries are essential to support like for like comparisons of different remediation options.
	3: Scope / Indicators	No case studies used the detailed individual criteria suggested by SuRF-UK in SR2 (CL:AIRE, 2020b), although the headline categories for these individual indicators were widely used. The added value of these individual indicators is either not seen as useful or is not made sufficiently clear.
	4: Methodology	Entry level may be at a qualitative tier or a semi-quantitative tier. A range of methods were used, but these were broadly consistent with ISO 18504:2017 (ISO, 2017).
	5: Dealing with uncertainty	One case study only considered possible uncertainties in the sustainability assessment. Sensitivity analysis has broadly been found to be unnecessary, perhaps because a range of opinions were already considered in the assessment process. Other case studies did not mention sensitivity analyses.

Based on the foregoing, the key suggestions for the deployment of sustainable remediation on operational sites are as follows:

1. It is worth considering if there are changes in how remediation work is planned into the operational lifetime of a site might allow for sustainability gains at “Stage A” (as defined by SuRF-UK). For example, the installation of longer term, lower input approaches during other planned maintenance to deal with a source term over time. This depends on having a good site understanding ahead of an urgent regulatory demand.
2. The use of SMPs provides multiple opportunities to improve the sustainability of contaminated site management practice across the board.
3. Regulator collaboration in sustainability assessment should be encouraged to select and optimise the remedial approach. There may also be opportunities to extend this collaboration into discussing the verification of whatever remedial approach is selected. Hence, active regulatory engagement should be encouraged, rather than solely relying on prediction of regulatory perspectives.
4. The exact methodology and entry point for individual sustainability assessments can vary as long as it adheres to a robust basic “recipe” such as ISO 18504:2017 (ISO, 2017) or SuRF-UK guidance.
5. Consultants and contractors should pay greater attention to describing boundary conditions, and also to drilling down to individual sustainability criteria which may provide greater differentiation between options and yield further improvement in sustainability outcomes overall.

6. CONCLUSIONS

Twenty actual European case studies have been reviewed, and ten were selected that demonstrate sustainable remediation techniques and technologies along with a cross comparison analysis of the case studies which seeks to help practitioners compare these case studies to their own projects, both in terms of success factors and areas for improvement.

Stakeholder engagement is important to making robust sustainability assessments because in many cases the comparison made, whether qualitative or semi-quantitative is opinion based. Positive engagement with regulators as a part of the sustainability assessment process is key to a successful outcome and is to be encouraged where possible.

The importance of conceptual site models (CSMs) in remediation strategy discussion and development is clearly shown by the case studies, as is the importance of a team-based approach to the work of site managers towards achieving robust progress and agreed endpoints.

Many of the drivers for sustainable remediation are exemplified by the case studies, in particular client interests as part of wider sustainable development governance, and demonstrating sustainability gain to regulators.

Analysis of the case studies and recently published guidance support a practical approach for deploying sustainable remediation on operational sites which should include the following:

- Consider changes in how remediation work is planned into the operational lifetime of a site to achieve sustainability gains at an early stage – e.g. “Stage A” (as defined by SuRF-UK).
- Consider the use of sustainable management practices (SMPs) to provide multiple opportunities to improve the sustainability of contaminated site management practice across the board.
- Encourage regulatory interest via collaboration in sustainability assessment to provide optimisation of remedial approach.
- Understand that the exact methodology and entry point for individual sustainability assessments can vary as long as they adhere to a robust basic “recipe” such as ISO 18504:2017 or SuRF-UK guidance.
- Pay greater attention to describing boundary conditions to ensure a reliable basis on which to compare options.
- Consider drilling down to individual sustainability criteria which may provide greater differentiation between options and yield further improvement in sustainability outcomes overall.

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APPENDIX 1 INDIVIDUAL CASE STUDIES IN FULL

CL:AIRE

CON 01
(November 2023)

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 a sustainable remediation approach was applied on a UK site.

Sustainable Remediation of a Former Vehicle Maintenance Facility for Mixed Use Development

1. INTRODUCTION

This bulletin discusses a project in the London area, where a sustainability assessment was conducted to select the most appropriate remediation option for a 1.71 ha brownfield site to be redeveloped for mixed use. The aim of the bulletin is to demonstrate how the most sustainable option was selected using a publicly available digital tool - SURE by Ramboll ('SURE') - and the way sustainable approaches were deployed during full-scale implementation. In this bulletin the background to the project is summarised, the conceptual site model is presented and the remedial options selection process is described. Highlights of the project are provided, and conclusions are drawn regarding the role of sustainability assessment in achieving project goals.

2. SITE DESCRIPTION AND PROJECT CONTEXT

The site, which is located within East London, had been occupied by a vehicle showroom with associated vehicle maintenance operations taking place over approximately 40 years. Prior to this, a tin plate works and railway sidings were present. The client LocatED, on behalf of the Department for Education, which had purchased the site, was granted planning permission for a scheme of mixed high-rise residential and commercial (retail) development as well as a school, as part of a wider community regeneration scheme. The site had undergone a series of site investigations by various parties and following a Phase II intrusive investigation, Ramboll conducted a Detailed Quantitative Risk Assessment (DQRA) to assess the requirement for remediation, based on the presence of compounds of potential concern.

A site plan is provided in Figure 1, illustrating the sources of contamination.

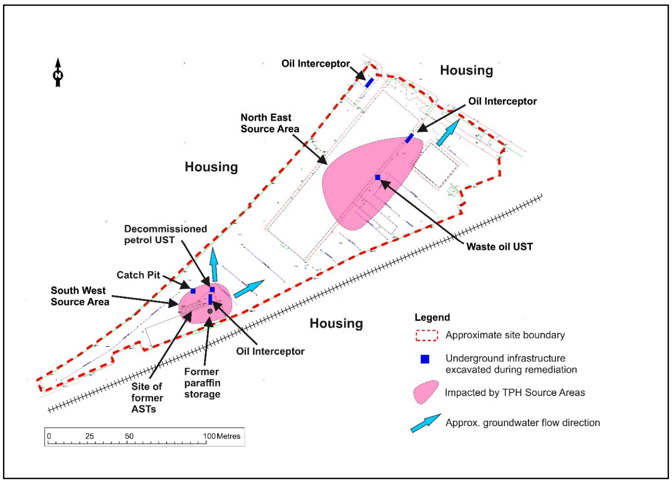

Figure 1: Site plan showing key source areas for remediation.

3. CONCEPTUAL SITE MODEL

The conceptual site model is summarised in Figure 2.

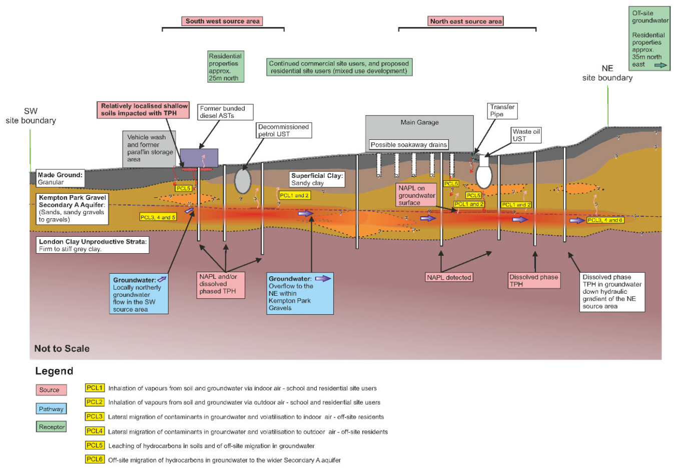

Figure 2: Conceptual site model (pre-demolition and remediation).

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There were three key sources of contamination, which together with the associated migration pathways, are described below:

Source Area 1 (north-east), diesel and lubrication grade petroleum hydrocarbons with Light Non-Aqueous Phase Liquid (LNAPL): The key source of contamination within this locality was a former waste oil Underground Storage Tank (UST). Leakage from this UST or its associated infrastructure had resulted in free phase lubricating oil and diesel migrating directly into the Kempton Park Gravel where on reaching the water table it had formed LNAPL. This has provided a continuing source of dissolution to the groundwater as dissolved phase contamination (measured as elevated Total Petroleum Hydrocarbons, TPH). Evidence of groundwater flow towards the north-east indicated that there was a potential for off-site migration of dissolved phase into the wider aquifer.

Additionally, potential leakage from the transfer pipelines may have impacted the made ground[1] and/or gravelly clay horizon directly above the overlying Kempton Gravels.

Source Area 2 (south-west), paraffin and diesel petroleum hydrocarbons with LNAPL: The assumed sources of contamination within this locality were likely to have originated from Above Ground Storage Tanks (ASTs) containing diesel and paraffin. Leakages and spillages from ASTs had resulted in localised hydrocarbon contamination in soil (particularly in made ground), whilst drummed paraffin storage in the former vehicle wash area is thought to have been a significant contributor to the groundwater impact as noted by the presence of NAPL characterised as kerosene. These hydrocarbons had impacted the made ground, then following downward migration through the Kempton Gravels had migrated laterally as NAPL, providing an ongoing source of dissolved phase hydrocarbons to the groundwater and presenting a theoretical vapour risk. Widespread hydrocarbons were present across a smear zone arising from groundwater fluctuations across the LNAPL impacted area.

Source Area 3, Diffuse made ground contaminants: The made ground contained low but diffuse concentrations of asbestos fibres together with elevated heavy metals and polycyclic aromatic hydrocarbons, collectively referred to as 'Made Ground Contaminants' (MGC) which posed a risk if they remained exposed at the surface after redevelopment.

The principal receptors to contaminants identified on site were therefore future site users, off-site residential site users and groundwater within the Kempton Park Gravel down hydraulic gradient of the site.

4. ASSESSMENT FUNCTION

Based on the above conceptualisation, the remediation requirements according to the substrata are set out in Table 1.

The Environment Agency's remediation option applicability matrix (Environment Agency, 2019) was used to screen potential remediation techniques for addressing the compounds of concern in each of the substrata identified in Table 1, based on the technical feasibility and practicability of implementation at the subject site. A number of the potentially applicable remedial techniques were combined into five remedial options, which were then short-listed for detailed assessment. These were as follows, the abbreviated title of the option highlighting the predominant remedial approaches (E&D: Excavation and off-site disposal; ESB: *Ex situ* bioremediation; ISB: *In situ* bioremediation; CAP: Capping (with minor off-site disposal)).

- **Remedial Option 1: E&D ISB**: Excavation and disposal of (i) made ground impacted by MGC and TPH, and (ii) deeper soil impacted by TPH and NAPL within smear zone and reinstatement with 'clean' imported backfill. Removal of residual NAPL by skimming pump or absorbent (depending on thickness) and treatment of dissolved phase by enhanced bioremediation through oxygen release, with a preliminary

Table 1: Summary of remediation requirements (receptors indicated in parentheses).

Contamination issue	Soil zone		
	Unsaturated zone	Smear zone	Saturated zone
MGC	Remove / treat source or interrupt pathway (on-site residents)	NA	NA
MGC & TPH	Remove / treat source or interrupt pathway (on-site residents)	NA	NA
TPH	Remove / treat source to achieve Site Specific Target Levels (SSTLs) (on-site residents)	Enhance oxidation status (during saturation phase) to enable natural attenuation to address residual concentrations (controlled waters)	NA
TPH as NAPL	No action required	Remove LNAPL as far as reasonably practicable (controlled waters)	NA
TPH as dissolved phase (various bands)	NA	NA	Achieve SSTLs as per DQRA (on & off-site residents)

NA: Not applicable

[1] Artificial man-made deposits such as fill material, re-worked soils and/or materials arising from previous demolition and importing.

Table 2: Short-listed options for review indicating target matrix.

Matrix/substratum	Options				
	Option 1 E&D ISB	Option 2 ESB ISB CAP	Option 3 ESB ISB E&D	Option 4 ISB CAP	Option 5 ISB E&D
Made ground (asbestos & heavy metals)	Excavation & disposal	Containment	Excavation & disposal	Containment	Excavation & disposal
TPH-impacted soil		*Ex situ* bio	*Ex situ* bio	*In situ* bio (proprietary-Gypsum & GAC)	*In situ* bio (proprietary-Gypsum & GAC)
LNAPL	Skimmer/ absorbent	Skimmer/ absorbent	Skimmer/ absorbent		
Groundwater	*In situ* bio/chem	*In situ* bio/chem	*In situ* bio/chem		

phase of chemical oxidation if necessary. Creation of reactive zone at site boundary to promote ongoing natural attenuation.

- **Remedial Option 2: ESB ISB CAP:** Excavation of (i) made ground impacted by TPH, and (ii) deeper soil impacted by TPH and NAPL within smear zone and treatment on site by ESB. Removal of residual NAPL by skimming pump or absorbent (depending on thickness) and treatment of dissolved phase by enhanced bioremediation through oxygen release, with a preliminary phase of chemical oxidation if necessary. Creation of oxidative reactive zone at site boundary to promote ongoing natural attenuation. Segregation of made ground with unacceptable levels of asbestos and disposal off-site. Reinstatement of remaining MGC-impacted soil on site under planned infrastructure, in landscaped areas, with suitable capping where appropriate.
- **Remedial Option 3: ESB ISB E&D**: As for Option 2 but with off-site disposal of all MGC-impacted soil instead of containment.
- **Remedial Option 4: ISB CAP**: Treatment of TPH-impacted soil, NAPL and groundwater using a proprietary ISB approach based on gypsum (as sulfate) combined with granular activated carbon (GAC). Limited ESB of unsaturated zone TPH. Creation of oxidative reactive zone at site boundary to promote ongoing natural attenuation. Segregation of MGC-containing made ground with unacceptable asbestos and disposal off-site. Reinstatement of remaining MGC-impacted soil on site under planned infrastructure, in landscaped areas, with suitable capping where appropriate.
- **Remedial Option 5: ISB E&D**: As for Option 4 but with off-site disposal of all MGC-impacted soil instead of containment.

The applicability of the various techniques comprising each option to the substrata for treatment is summarised in Table 2.

5. SUSTAINABILITY ASSESSMENT

5.1 Methodology and project framing

A sustainability assessment of the five short-listed options was undertaken in general accordance with the guidance provided by the Soil Quality-Soil Remediation Standard ISO 18504 (BSI, 2017). This was conducted using Ramboll's in-house tool which has subsequently been developed into SURE and now made publicly available (https://ramboll.com/sure). SURE has essentially three functions; to assess the options, engage with stakeholders and report the results using a digitally-based platform. The assessment has therefore been re-run using SURE, with a similar output (the main difference being that the previous assessment had used 15 indicator categories whereas the SURE assessment used 25 indicators as criteria drawn from the updated SuRF-UK listing (CL:AIRE, 2020).

SURE enables the project details and framing to be recorded, prior to indicator selection and weighting. The assessment was framed in terms of the relevant boundary conditions (relating to restrictions imposed upon the evaluation of impacts and benefits), these being spatial (whether within the immediate footprint or on a wider scale), temporal (the planning horizon over which benefits/impacts are considered) and life cycle (in terms of the plant and equipment components of the remediation) as presented in Table 3.

Table 3: Boundary conditions used in the SURE assessment.

Spatial	Temporal	Life Cycle
Global, based on client commitment to action on global heating and overall sustainability ethos.	Extending indefinitely into the future, as driven by overall sustainability issues and intergenerational equity considerations.	All elements of the remediation, except manufacture of plant, reagents and equipment.

5.2 Selection and weighting of indicators

The assessment then proceeded as follows. A total of 73 indicators based on the updated SuRF-UK listing were reviewed for their applicability to the site, of which 25 in total were selected, nine, seven and nine from the domains of Environment, Society and Economy respectively. The indicators were weighted according to their relative importance on a scale of 1 to 5 as set out in Table 4, which groups the indicators according to the categorisation of SuRF-UK.

Table 4 (a): Indicators used, relative weighting (W) and rationale: Environment Domain

Category/indicator	W	Rationale
Emissions to air		
Greenhouse gases	5	Climate emergency
Ground Air Quality	3	Impact on local environment
Soil & Ground Conditions		
Soil functionality	1	Suitable for use, but restricted to specific development
Geotechnical properties	1	Suitable for use, but restricted to specific development
Groundwater & Surface Water		
Water uses	1	Moderate potential for future use
Legally binding objectives	5	Compliance
Ecology		
Disturbance	1	Urban site, limited
Natural Resources & Waste		
Energy & fuels use/generation	5	Climate emergency
Primary resources & waste	5	Global importance

Table 4 (b): Indicators used, relative weighting (W) and rationale: Social Domain

Category/indicator	W	Rationale
Human Health & Safety		
Long term risk management	5	Ethical & compliance
Direct risks	5	Ethical & compliance
Ethics & Equity		
Intergenerational equity	3	Moderate relevance
Neighbourhood & Locality		
Nuisance impacts	5	Potentially significant for local residents
Uncertainty & Evidence		
Robustness & rigour	1	Reasonable degree of information available for options but just need to assess from stakeholder perspective
Degree of uncertainty	3	Moderate importance, particularly in relation to achieving objectives
Validation/verification requirements	5	Onerousness of importance in demonstrating achievement of objectives for stakeholder benefit

5.3 Evaluation of options and scoring

The five options were then scored according to their positive or negative impacts on each of the indicators on a 1 to 5 scale, five representing the best performance. Scoring was undertaken proportionately, with options being assigned equivalent scores where differences between them were marginal. SURE computed the total weighted score, normalised on a percentage basis to the maximum score achievable, provided a breakdown of option performance against indicator category and also identified the relative

Table 4 (c): Indicators used, relative weighting (W) and rationale: Economic Domain

Category/indicator	W	Rationale
Direct Economic Costs & Benefits		
Direct costs/benefits	5	Key issue for client
Other costs	1	Of lesser significance in relation to direct costs
Uplift in site value	1	Low significance
Liability discharge / ease of divestment	5	Key issue for client
Indirect Economic Costs & Benefits		
Risk of damage	1	Limited concerns over selected options
Corporate reputation	3	Moderate importance for client
Project Lifespan & Flexibility		
Duration/timing of benefit	3	Reasonably important in order to fulfil development programme requirements
Chances of success	5	Key to fulfilling objectives
Flexibility to change in circumstances	3	Flexibility of intermediate significance

contribution to each of the 17 United Nations Sustainable Development Goals (UN SDGs). The latter was based on the linkages between each of the selected indicators and the relevant UN SDGs as have been identified by SURF-UK (CL:AIRE, 2020) for which SURE pre-assigns a linkage weighting on a scale of 0 to 5, based on the number of linkages to a particular UN SDG for the selected indicator.

Figure 3 shows the output from SURE at domain level. Option 2, (ESB, ISB, CAP) returned the best overall performance followed by Options 1 (E&D, ISB) and 4 (ISB, CAP). Substituting excavation of the MGC in place of capping significantly reduced the sustainability of Option 3 (ESB, ISB, E&D) compared to Option 2, as it did for Option 5 (ISB, E&D), compared to Option 4.

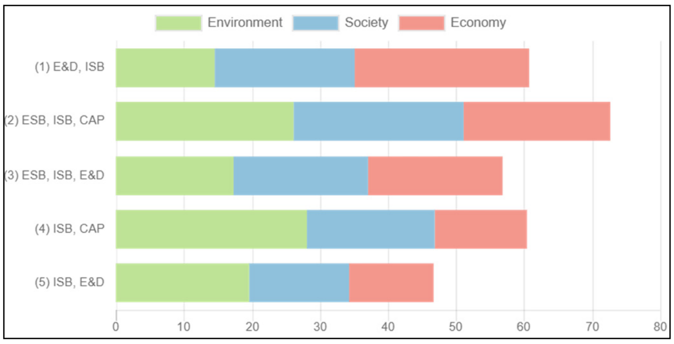


Figure 3: Total scores for each option, showing contribution of scores by domain. Normalised score expressed as a percentage of the maximum achievable score.

Remedial Option 2 delivered a good overall performance for each of the three domains, particularly Society, where it was also the best option, though Option 4 was marginally better for Environment, and Option 1 for Economy. Figure 4 provides a breakdown of the option scores for the indicator categories within each domain.

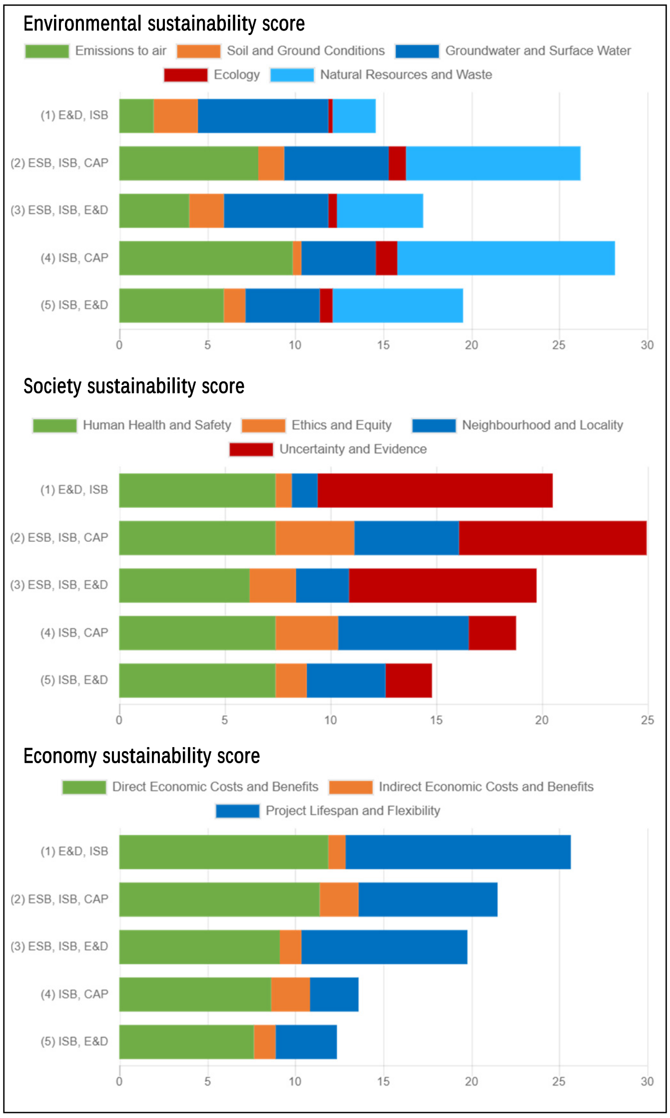


Figure 4: Option scores per indicator category for each domain.

For the Environmental criteria, the lowest scores were ascribed to the three Remedial Options (1, 3 and 5) involving excavation and off-site disposal, as this would likely have the biggest impact on carbon footprint, as well as representing relatively high waste generation, resource consumption and potentially other environmentally deleterious aspects such as releasing dust and volatiles. Remedial Option 4 avoids these issues through being an *in situ* approach, and whilst for such reasons it also scored better against the *ex situ* treatment option, it scored slightly less on soil and groundwater quality which Option 2 may address more efficiently and without imparting elevated calcium sulfate into the ground, as would be the case with the proprietary ISB approaches.

As noted in Table 3, the carbon footprint of the reagents used, including slow release oxygen or chemical oxidation was excluded due to such information not being readily available. Overall however, it is not considered that this would have made a significant difference to the outcome, given the magnitude of *ex situ* versus *in situ* differences driving the assessment and the fact that the same reagents were to be used in Options 1, 2 and 3 with Options 4 and 5 deploying an alternative approach, but also involving proprietary reagents.

For the Social criteria, Remedial Option 2 also scored highest, avoiding issues relating to vehicle movements that could impact neighbourhoods, and by using a destructive approach leaving less of a legacy for future generations than Option 1 (excavation). Whilst this was also the case for the two proprietary *in situ* approaches (Options 4 and 5) these performed less well regarding the uncertainty and evidence issue - inherent to *in situ* soil treatments to some extent but especially where NAPL is concerned and the difficulties of verification, particularly in the short term. The human health and safety category includes two indicators, one relating to the degree of mitigation of human health through the remediation process, the second relating to worker exposure and whilst the remedial options differed significantly for each of these indicators, the combined performances resulted in a similar overall score for each option.

Finally for Economic criteria, the off-site disposal option (Remedial Option 1) offered a more rigorous degree of mitigation in terms of contaminant removal, liability discharge, uplift in site value, and scored relatively well for indicators such as duration/timing of benefit, chances of success and flexibility. The best overall option, Option 2, however, is not far behind, but the proprietary approaches (Options 4 and 5) both perform less well due to the degree of uncertainty in treatment success, less flexibility and the extended time and costs required for laboratory treatability testing (including collection of additional samples).

A further means of assessing the relative performance of the options is through the UN SDGs. As examples, the relative contribution of Options 1, 2 and 5 to each of the 17 UN SDGs is presented in Figure 5 (overleaf), as respectively representing the best two and the worst performing options.

Whilst Remedial Option 2 performed better in the sustainability scoring than Option 1, the excavation-based option made greater positive contributions to the following UN SDGs:

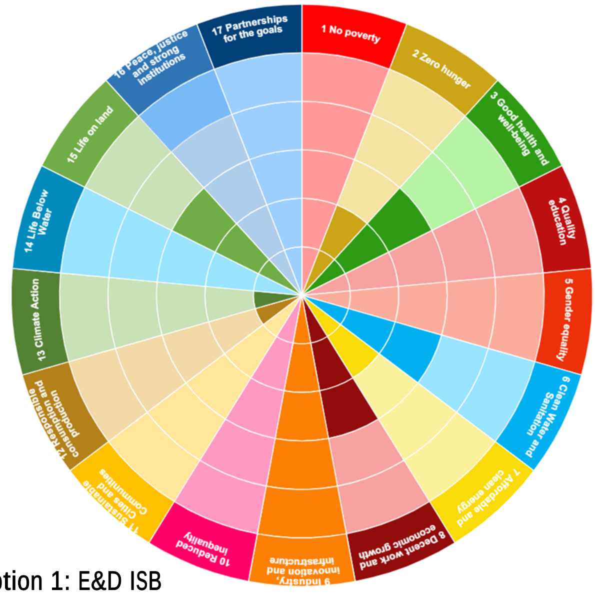
- SDG3 Ensure healthy lives and promote well-being for all;
- SDG6 Ensure availability and sustainable management of water and sanitation;
- SDG8 Promote sustained, inclusive and sustainable economic growth, full and productive employment and decent work for all; and
- SDG9 Build resilient infrastructure, promote inclusive and sustainable industrialisation and foster innovation,

than either Options 2 or 5. Both Options 2 and 5 did however make greater contributions to:

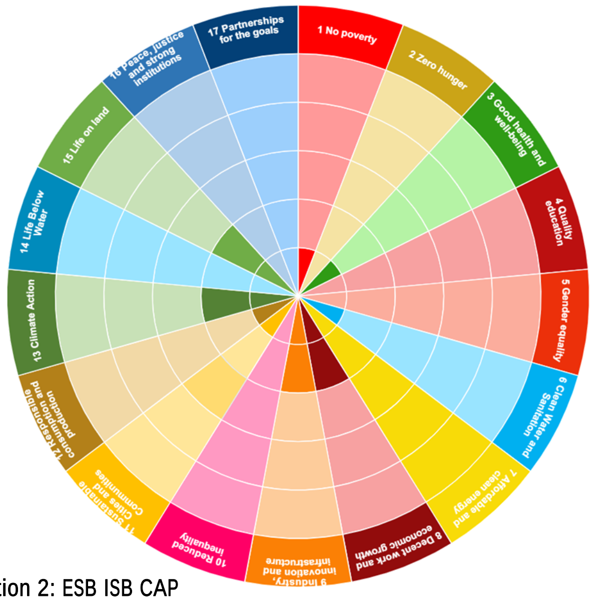
- SDG7 Access to affordable, reliable, sustainable and modern energy for all; and
- SDG13 Urgent action to combat climate change,

than Option 1. Option 2 also made a contribution to SDG 1 No poverty, unlike the other two and made equal or greater contributions to the remaining goals than Option 5, apart from SDG number 3 (health).

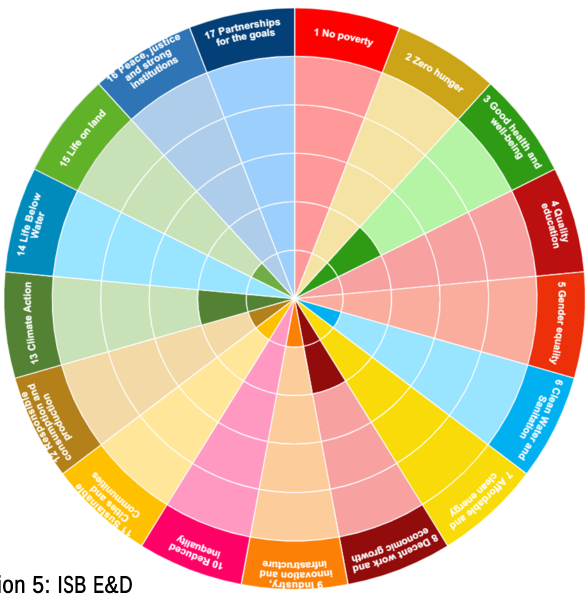
Based on the sustainability assessment undertaken using the SuRF-UK aligned indicators, Remedial Option 2 was selected as the best approach and subsequently developed into a formal remediation strategy.



Option 1: E&D ISB



Option 2: ESB ISB CAP



Option 5: ISB E&D

Figure 5: Comparative contribution to UN SDGs: Options 1, 2 and 5.

6. IMPLEMENTATION OF REMEDIATION WORKS

The remedial works were tendered and the contract awarded to Soilfix who implemented the following remedial actions in accordance with Ramboll's sustainable remediation strategy, based on Option 2:

- removal of decommissioned underground fuel and oil storage tanks and other potentially contaminative infrastructure including oil / water interceptors and catch pits, and sub-surface hydraulic rams;
- proof dig of the site to two metres below ground level to remove sub-surface obstructions and to handpick visible fragments of asbestos-containing material;
- excavation and on-site *ex situ* enhanced bioremediation of 1,074 m^3 of soils from two source areas;
- removal of 700 litres of LNAPL from groundwater via a series of horizontal recovery trenches (and disposed to a licensed waste management facility) and 224 m^3 of groundwater impacted with dissolved phase hydrocarbons (treated on site and discharged to foul sewer);
- in the saturated zone, *in situ* addition of proprietary reagents to promote desorption of free-phase hydrocarbons for enhanced recovery;
- enhanced aerobic bioremediation of residual hydrocarbons in the smear zone and saturated zone in two source areas using an extended oxygen release compound – using a combination of soil mixing and direct-push injection techniques.

All soil movements were completed in accordance with Soilfix's Materials Management Plan, compiled in accordance with Version 2 of the Definition of Waste: Development Industry Code of Practice (DoWCoP) (CL:AIRE, 2011), to achieve a zero materials balance. Opportunities for recycling of materials were maximised: demolition material was processed to create a high quality 6F2 graded aggregate for constructing the development platform, uncontaminated made ground arising from removal of obstructions was processed for re-use as engineered fill and 940 m^3 of coal tar impacted bituminous material was recycled at a dedicated recovery centre.

The remediation was verified in accordance with the requirements of the remediation strategy through:

- regular groundwater and ground gas monitoring from a network of monitoring wells across the site, including wells down hydraulic gradient of the source areas and comparison against site specific target levels (SSTLs) which are protective of on-site and off-site human health (volatilisation pathway);
- revision of the conceptual site model and SSTLs to more closely reflect the proposed development and conditions encountered during the remediation (whilst maintaining a level of conservatism in the assessment);
- collection of soil samples from excavations and comparison to SSTLs which are protective of on-site and off-site human health (volatilisation pathway) and groundwater;
- collection of soil samples during *ex situ* bioremediation and comparison to SSTLs which are protective of on-site and off-site human health (volatilisation pathway) and groundwater; and,

- collection of samples from materials to be re-used on site and comparison to SSTLs.

With respect to the clean cover system, this was to be undertaken as part of a separate construction phase remediation strategy, which would include an assessment of the ground gas and vapour monitoring data and the potential requirement (if any) for ground gas protection to be incorporated into the proposed development.

The scope of the remediation work as implemented was therefore fully consistent with the elements set out in Option 2.

7. PROJECT HIGHLIGHTS

The largest (north eastern) source area was impacted by significant quantities of free-phase weathered engine oil. Mass excavation and on-site treatment would have been logistically challenging and treatment to below SSTLs using bioremediation techniques unlikely to be viable within a realistic programme. The contractor, Soilfix therefore entered a non-compliant 'value engineered' proposal at tender stage that allowed for horizontal recovery trenches to be advanced across this source area to enable more efficient recovery of free-phase oils (Figure 6).

Figure 6: Recovery trench constructed in north eastern source area.

Following sufficient pumping to remove visible product, the NAPL recovery process was enhanced through direct push injection of Regenox® Part A (an *in situ* chemical oxidant) and Petrocleanze™ (a percarbonate-based reagent with detergent-like properties), both manufactured by Regenesis, at 50 injection points. Injection of these reagents promoted desorption of residual product and subsequent oxidation once mobilised in the dissolved phase. This was followed by residual polishing of the saturated zone by injecting, as well as *in situ* mixing, an oxygen release compound (ORC Advanced™, also manufactured by Regenesis) that promoted enhanced biodegradation of residual hydrocarbon contamination within soils and groundwater over a 12 month period.

This approach resulted in approximately 6,000 tonnes of soil being retained on-site rather than potentially requiring removal off-site for treatment or landfilling. Segregated hydrocarbon impacted soils from the south western source area (containing free phase paraffin/diesel impact) underwent bioremediation treatment before being reused on-site. Unnecessary over-excavation of this source area into the saturated zone was avoided through *in situ* soil mixing of a granulated oxygen release compound product (PermeOx® Ultra, manufactured by Evonik), to promote enhanced biodegradation of residual hydrocarbons within deeper soils and groundwater. Implementation of this activity is illustrated in Figures 7, 8 and 9.

Figure 7: Photo showing that the depth of the dig was just beneath the groundwater level to reduce over-excavation.

Figure 8: Photo showing the excavator adding the oxygenating compound. The machine used for subsequent mixing is seen in the background.

Figure 9: Photo showing mixing the reagent into the top layer of material using a specialist attachment on the arm of the excavator.

A combination of these approaches avoided removal of approximately 3,000 tonnes of hazardous waste from the site to landfill.

In total, across both the south western and north eastern source areas, the remediation techniques adopted saved 475 HGV loads (9,500 tonnes) of soil from being removed off-site to a permitted hazardous waste facility. As the site had a neutral material balance, this resulted in a further saving of 475 lorry loads of material imported into the site. In total around 950 lorry movements were therefore removed from the congested local highway network.

A view of the site post-completion is provided in Figure 10.

Figure 10: Photo showing the site following completion of works.

8. CONCLUSIONS

The following factors have been the primary contributors to maximising the sustainability of this project:

- Sustainability of the short-listed options was assessed using a procedure based on the principles of ISO 18504 (BSI, 2017).
- Effective use was made of DoWCoP (CL:AIRE, 2011) to plan, manage and implement a sustainable materials management solution with a zero materials balance being achieved.
- Site won hardcore from above and below ground demolition was processed into a high quality 6F2 graded aggregate and re-used for construction of a development platform.
- Coal tar impacted macadam requiring removal from site was sent to a recovery facility to be recycled rather than to a landfill.
- General (uncontaminated) Made Ground arising from obstructions removal was processed to a suitable grading for re-use as engineered fill.
- *In situ* treatment processes were used to promote enhanced removal of free-phase oil contamination and enhanced biodegradation of residual hydrocarbons in soils and groundwater within a Secondary Aquifer.
- Regular groundwater monitoring and review of the DQRA during the works programme ensured that the remedial scope was optimised and practicable, but still achieved significant environmental betterment.

A significant contribution to the overall success of the project was the collaborative spirit entered into by the client, consultant and contractor: the client being receptive to a sustainable strategy as developed by the consultant and the value-engineered proposal of alternative, less intrusive and more sustainable remedial methods for challenging contaminants (free-phase weathered engine oils and paraffin), as presented by the contractor. Going forward, the facility for online participation in the sustainability assessment process as is afforded by SURE, is expected to enhance the degree of stakeholder engagement in future projects.

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This project won the Best Application of Remediation Technologies category at the 2022 Brownfield Awards. It was also "Highly Commended" in the Best Sustainable Re-use of Materials category and the SURE tool was "Highly Commended" in the Best Research, Innovation or Advancement of Science in the Brownfield Sector category.

CL:AIRE

CON 02
(November 2023)

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 focuses on the assessment of natural source zone depletion on a UK site.

Natural Source Zone Depletion Assessment: UK Large-Scale Field Case Study

1. INTRODUCTION

This case study was undertaken at a large operational facility, with the purpose of quantifying the rates of Natural Source Zone Depletion (NSZD) from a stable Light Non Aqueous Phase Liquid (LNAPL) plume. The quantification of NSZD rates was designed to allow the consideration of an 'attenuation-based' remedial option for both LNAPL and dissolved phase constituents.

NSZD has the potential to represent a highly sustainable remedial option in favourable scenarios. To formalise the sustainability benefits an 'attenuation-based' approach, in this case implementing NSZD, was assessed against an alternative remedial option through qualitative comparison against the 15 headline indicators from the UK Sustainable Remediation Forum (SuRF-UK) (CL:AIRE, 2020).

This case study summarises the project context and conceptual site model that supported the consideration of NSZD as a potential remedial solution as well as the sustainability assessment completed. Key aspects of the approach to dialogue with key stakeholders including the client and Environment Agency are also presented.

2. SITE DESCRIPTION AND PROJECT CONTEXT

The site which is the subject of this NSZD case study is an operational facility. Continuation of current operations is expected for the site under existing ownership. LNAPL within the defined source zone:

- Lies within an unconfined aquifer beneath an area of predominantly unsealed ground;
- Primarily comprises a highly volatile mixed hydrocarbon product; and
- Is located within the seasonal groundwater smear zone, at depths of 3.5 to 5.0 m below ground level (m bgl).

Following multiple phases of intrusive investigation and several years of regular groundwater monitoring, the LNAPL body was identified as suitable for NSZD assessment. The key supporting pillars developed during the monitoring phase which allowed both the site operator and regulator to buy into the concept of NSZD as a potential remedial option were:

1. Data obtained during the extensive monitoring phase had provided high confidence in both LNAPL and dissolved phase plume stability.
2. Detailed quantitative Human Health and Controlled Waters risk assessments completed in advance of the NSZD assessment had established an absence of unacceptable risk to identified receptors (offsite residents, downgradient aquifers and surface water bodies). The outcomes from these assessments were reviewed and accepted by both the site operator and regulator.
3. During the delineation and monitoring phase, mass recovery via skimming had been undertaken from a groundwater monitoring well network within the LNAPL source zone. LNAPL recovery rates had markedly reduced during this period.

Consideration of the three concepts set out in Figure 1 (which underpin the basis for deciding an appropriate course of remediation for any site), identified NSZD as a potential remedial solution in this case.

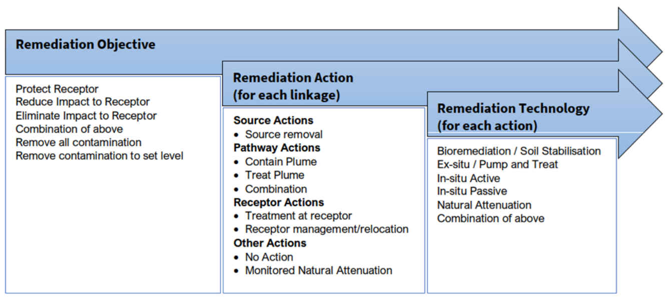

Figure 1: Relationship between remediation objectives, actions and technologies (WSP).

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Concawe
Environmental Science for European Refining

Remediation Objectives: The remediation objectives determine the overall technical intent of the project.
Remediation Action: The conceptual approach to achieving the identified remediation objective, defined specifically in terms of contaminant linkages which each action addresses.
Remediation Technology: The specific tools that will be employed to fulfil each remediation action.

Works completed throughout the NSZD assessment were designed to be compatible with requirements at an active facility and minimise impacts on routine site operations. Constraints such as the use of equipment in potentially explosive atmospheres (ATEX zones) had to be considered throughout the design and implementation of the NSZD monitoring programme. Such constraints will also need to be factored into the implementation of any future remediation strategy developed for the study area.

3. CONCEPTUAL SITE MODEL

At the outset of the trial phase NSZD represented a novel remedial option with very little track record of application in the UK. As such effective engagement with key project stakeholders (including the client and regulator) required clear and coherent communication of NSZD principles and a robust supporting conceptual model.

The comprehensive LNAPL conceptual site model for the project, developed through the site investigation, monitoring and testing phases, can be summarised as a series of building blocks (Figure 2). The principal data streams relating to each component in this project are described below Figure 2 (a-e).

Figure 2: LNAPL conceptual site model components (WSP).

a) Nature and Extent

The source zone related to a discrete release event >10 years before commencement of the NSZD study and covered a surface area of approximately 1 hectare. The majority of LNAPL mass within this source zone was present within the groundwater smear zone. The geology underlying the source zone consisted of unconsolidated granular material, predominantly comprising sands and gravels. Local heterogeneity was present within these shallow superficial deposits (including cohesive lenses). The ground surface in the source zone and downgradient areas was predominantly unsealed. Surface cover and geology in surrounding areas at the site was consistent with the source zone allowing background monitoring locations to be identified. Representative background locations are necessary to evaluate vapour phase mass flux attributable to LNAPL depletion when using certain surface based NSZD monitoring techniques (API, 2017).

The long-term monitoring dataset indicated that the LNAPL was stable at the plume scale. A consistent footprint of measurable LNAPL was recorded over several years prior to the commencement of the NSZD trial. The groundwater smear zone was typically encountered from 3.5 m bgl. Seasonal variation in the depth to the saturated zone of +/- 1.0 m to 1.5 m was recorded. The LNAPL mass was present under unconfined conditions (Figure 3). The simultaneous variation of both the Air-NAPL and NAPL-Water interfaces in monitoring wells across the source zone, illustrated in the example diagnostic gauge plot are indicative of unconfined conditions (Hawthorne, 2011). Understanding the conditions under which LNAPL is present allowed refinement of the LNAPL conceptual model and prediction of LNAPL mass and behaviour.

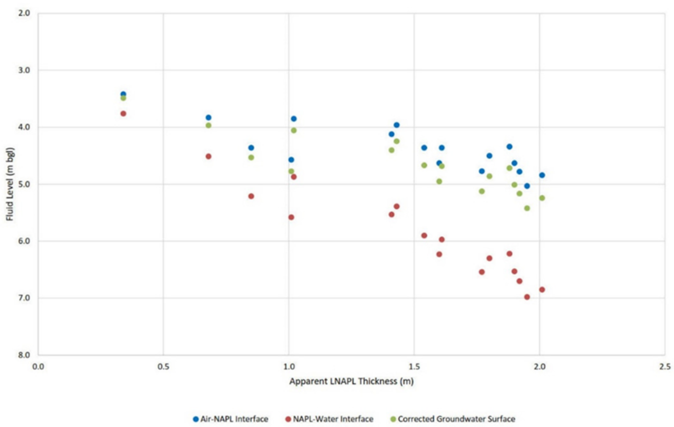

Figure 3: Diagnostic gauge plot - plume centre (WSP).

b) Composition

Data from multiple phases of product sampling prior to and during the NSZD trial identified a consistent source LNAPL composition, characterised by:

- Mixed source, predominantly C5-12 aliphatic and aromatic carbon chain fractions with some longer chain elements also present);
- Significant (but decreasing) benzene, toluene, ethylbenzene and xylene (BTEX) component;
- No oxygenates or chlorinated volatile organic compounds were identified (these components can drive risks to controlled waters).

Field observations recorded during the investigation and monitoring phases consistently demonstrated the volatile nature of the LNAPL source, through visual and olfactory evidence and field screening of soil samples (using a photoionisation detector) during phases of intrusive investigation.

The volatility of the source LNAPL highlighted potential for significant vapour phase mass degradation, via physical partitioning and biodegradation in the unsaturated zone. This represented a key component in the identification of NSZD as a potentially suitable remedial strategy.

Time series analysis of product sample analytical data highlighted LNAPL composition changes indicative of active degradation processes, most notably by the reductions in C17:pristane ratios shown in Table 1, which were reported as a significant indicator by Hurst and Schmidt (2005).

Table 1: Example nC17/pristane ratios 2016-2020.

	BH218	BH234
May 2016	2.34	2.73
January 2020	1.61	1.79
August 2020	1.76	1.88

c) Stability

Routine gauging and groundwater sampling data described the presence of a stable LNAPL and dissolved phase plume.

The stability of the LNAPL plume (Figure 4) remained consistent throughout the NSZD trial with the highest apparent LNAPL thicknesses (>1 m) restricted to five monitoring wells in the plume core and the extent of the measurable LNAPL footprint constant. Apparent LNAPL thickness in all monitoring wells remained within the historical ranges. Seasonal variation in apparent LNAPL thickness was observed consistent with data collected over multiple years during the pre-trial monitoring phase.

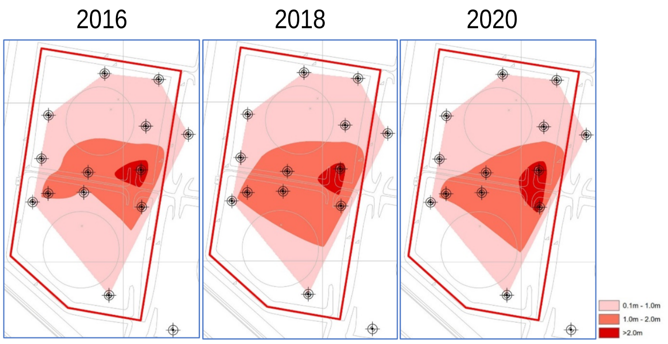

Figure 4: Median LNAPL thickness in monitoring wells (WSP).

d) Recoverability

LNAPL recovery was first implemented from a single well in 2008, then expanded to encompass multiple wells in 2009. The expanded system comprised multiple NAPL recovery pumps running continuously. Average recovery rates from the skimming system (initially 100s litres/day) exhibited a declining trend over time with rates reducing to approximately 10 litres/day by the end of 2014.

LNAPL transmissivity testing was undertaken at multiple wells in the source zone prior to the NSZD trial. Derived LNAPL transmissivity values (0.01 – 0.07 m^2/day) were consistent with the lower threshold for effective recovery based on published literature values (ITRC, 2009).

e) Degradation

Indicators of active LNAPL degradation were identified throughout the investigation and monitoring phases. The majority of the degradation evidence collected prior to the NSZD study was focused on saturated zone mass depletion processes.

In downgradient areas evidence indicative of active natural degradation of dissolved phase hydrocarbons was consistently recorded, directly through the reduction in concentrations of dissolved phase hydrocarbons over time and indirectly through the spatial distribution of electron acceptors.

Analytical data from LNAPL sample testing was indicative of high vapour phase degradation potential (consistent with field observations) with a relatively high abundance of volatile and higher solubility carbon chain lengths.

The NSZD assessment described below facilitated the quantification of the rates of LNAPL mass degradation and focused on vapour phase flux which was expected to dominate mass degradation.

CO_2 Flux Monitoring Programme

Following initial trials, the dynamic closed chamber (DCC) approach was selected as the primary method for evaluating vapour phase mass flux from the source zone, via the measurement of CO_2 flux from the ground surface (Figure 5).

The DCC method utilises short-term, non-steady state measurements (taken over 1-2 mins), to derive a total CO_2 flux. A Licor LI-8100A instrument was used to measure CO_2 flux throughout the study with the chamber mounted on dedicated soil collars that remained *in situ* for the duration of the assessment. In the initial testing phase 15 soil collar locations were utilised in the source zone before the network was expanded to 47 locations (including background locations) for the annual monitoring programme (Figure 6).

Figure 5: Field measurement using DCC method (using Licor LI-8100A) .

An initial commissioning phase was undertaken over a three week period using DCC to monitor diurnal CO_2 flux variations at individual locations and assess background locations. Diurnal variation in total CO_2 flux recorded by the DCC was typically between 30 and 50%.

In total >2,000 CO_2 flux readings were collected from the 47 monitoring locations, during nine monitoring events completed across an annual cycle (May-April).

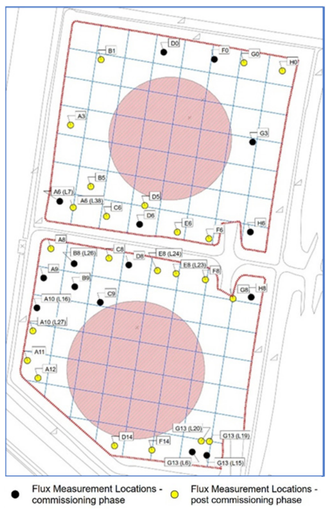

Figure 6: DCC monitoring locations.

Significant seasonality was observed in surface flux readings as expected with higher winter precipitation limiting observed surface flux in these months. An ongoing monitoring programme to further evaluate these variations is in progress with CO_2 flux monitoring events using the same method and test locations.

Soil Gas Monitoring

The DCC method utilised measured CO_2 flux only and interpretation for NSZD is based on the assumption that volatile hydrocarbons produced from the LNAPL plume are oxidised to form CO_2 in the unsaturated zone.

To verify this assumption soil vapour samples were collected throughout the trial from dedicated monitoring wells using vacuum canisters. The data obtained provided vertical profiles of soil gas concentrations. Results demonstrated that oxidation of methane and other volatile hydrocarbons being produced by the LNAPL plume was taking place (Figure 7). The oxidation of methane to CO_2 in the unsaturated zone is a key assumption underpinning NSZD assessment using the DCC method (API, 2017). Whilst the depth of the oxidation zone in the soil profile varied, the presence of a discrete oxidation zone above the LNAPL plume was consistent in all seasons.

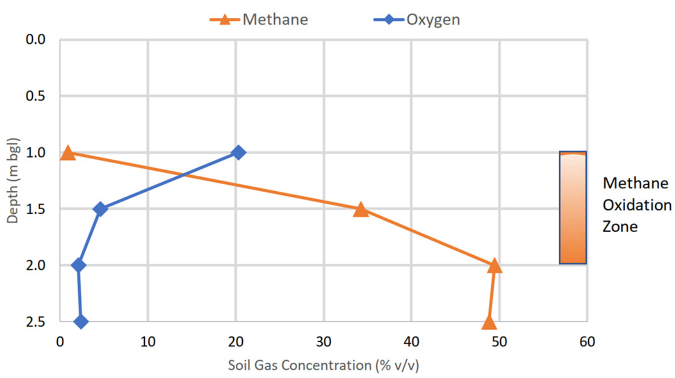

Figure 7: Typical soil gas profile, source zone (WSP).

Throughout the annual assessment period, soil gas samples continued to be collected from the source zone to provide conceptual support to the interpretation of surface CO_2 flux.

Soil gas profiles were vital in demonstrating that observed seasonal variations in surface CO_2 flux were not the result of concurrent large-scale reductions in the rate of LNAPL degradation at the base of the unsaturated zone.

4. ASSESSMENT FUNCTION

Based on the conceptual site model, the following plausible pollutant linkages (PPL) were identified:

- PPL1 - Leaching of contaminants in soil to groundwater;
- PPL2 - Lateral migration of LNAPL in the saturated zone; and
- PPL3 - Lateral migration of dissolved phase contaminants within the unconfined granular superficial deposits (assessed against agreed compliance points).

The remediation objective is to reduce impact to the receptor (the aquifer underlying, and downgradient of, the source zone). Remedial options were identified assuming current site use is maintained, and that risks to both human health and downgradient surface water receptors did not necessitate more active intervention.

Potential remediation technologies to benchmark against NSZD were taken from the Environment Agency's remediation option applicability matrix (Environment Agency, 2019). NSZD has the potential to be a highly sustainable remedial option for PPL1 and PPL2, and could be combined with a monitored natural attenuation (MNA) approach for PPL3, subject to a formal appraisal of the lines of evidence supporting an 'attenuation-based' approach.

Remedial options were screened for their feasibility (both technical applicability and practicality of implementation at the operational facility) to identify a lead case which would be compared against NSZD in the initial sustainability assessment.

Dual phase extraction was selected as the lead case for the initial sustainability assessment, given its successful application in an earlier phase of the project which provided a proven track record of implementation in the operational environmental specific to this study area.

Other potential remedial options including sparging, *in situ* chemical oxidation as well as physical or hydraulic barriers were considered to be non-viable due to the challenges of implementation in the operational setting, and as such were not carried forward for comparison. It should however be noted that a formal appraisal of remedial options is still expected to be undertaken following the conclusion of the NSZD trial.

The initial sustainability assessment, comparing the potential application of 'attenuation-based' approaches against dual phase extraction is presented in the following section.

5. SUSTAINABILITY ASSESSMENT

WSP employs a staged approach to sustainability assessment, this approach specifically comprises:

- **Preliminary Sustainability Assessment:** A qualitative assessment of the applicability of the SuRF-UK headline categories for sustainability indicators (CL:AIRE, 2020) to the proposed remediation of the site within the context of what can be influenced at an early stage in the project lifecycle.
- **Remediation Objectives and Actions Screen:** A qualitative assessment is then made of the remediation objectives and actions required to deliver remediation in the context of the proposed future use of the site.
- **Remediation Technology Screen:** This stage of the assessment considers suitability of available remediation technologies to meet the Remediation Objectives and Actions and includes assessments of applicability, technical feasibility, effectiveness, timescale and cost.

The tiered approach is designed to ensure that a balanced assessment is made of the possible remediation approaches and technological applications that could be taken forward during the remediation of the site and that a transparent record is kept of the decisions taken in line with the SuRF-UK guiding principles.

Table 2: Preliminary sustainability assessment.

SuRF-UK Sustainability Category	SuRF-UK Category Code	Relevance	Significance	Scope of Influence	Stakeholder Concern	Included in Assessment?
Environmental						
Emissions to air	ENV1	Yes	High	Medium	High	Yes
Soil and ground conditions	ENV2	Yes	High	High	High	Yes
Groundwater and surface water	ENV3	Yes	High	High	High	Yes
Ecology	ENV4	Yes	Low	Low	Medium	No
Natural resources and waste	ENV5	Yes	High	High	High	Yes
Social						
Human health and safety	SOC1	Yes	High	High	High	Yes
Ethics and equity	SOC2	Yes	Low	Low	High	No
Neighbourhoods and locality	SOC3	Yes	Medium	Low	Medium	Yes
Communities and community involvement	SOC4	Yes	Low	Low	Medium	No
Uncertainty and evidence	SOC5	Yes	High	Medium	Medium	Yes
Economic						
Direct economic costs and benefits	ECON1	Yes	High	High	High	Yes
Indirect economic costs and benefits	ECON2	Yes	Medium	Medium	High	Yes
Employment and employment capital	ECON3	Yes	Low	Low	Low	No
Induced economic costs and benefits	ECON4	Yes	Low	Low	Medium	No
Project lifespan and flexibility	ECON5	Yes	High	High	Medium	Yes

Following the initial NSZD trial, a period of further monitoring to refine the quantification of NSZD is ongoing to increase confidence in its technical feasibility to achieve the remediation objective. As part of the trial stage of the project a Tier 1 qualitative sustainability assessment was undertaken to consider how a fully implemented 'attenuation-based' remedial strategy would compare with the lead alternative (dual phase extraction).

A preliminary screening of the SuRF-UK indicators for sustainable remediation was carried out to determine their applicability to any future remediation of the study area and the priority each should be given for further consideration as part of the options appraisal. Commensurate with a Tier 1 assessment, only headline indicators were considered at this stage. Individual criteria checklists will be utilised in the formalised sustainability assessment, following completion of the trial phase.

Screening was completed by assigning a qualitative ranking (High / Medium / Low) to each indicator based on their relevance to the project, significance, scope of influence and stakeholder concern. The results of this screening are presented in Table 2 with comment on those indicators screened out at this stage provided below.

The ecology indicator (ENV4) was screened out as the study area is of low ecological value (given ongoing operational use) and its future ecological potential is likely to be dictated more significantly by any future changes in site use than the remediation in question.

Ethics and equity (SOC2) were screened out as any benefits or dis-benefits in this area were likely to be common to all remedial options considered technically feasible.

Community and community involvement aspects (SOC4) were not considered to be significant. The source zone wholly comprises private land under current site use. Any adopted remediation option is unlikely to noticeably alter the impact to the external community from existing site operations.

For both ECON3 and ECON4 indicators, the prospects for generating investment or employment capital are tied to the future site use and any potential re-development rather the remediation itself.

Following the preliminary screening the two remedial options being considered in this initial assessment, 'attenuation based' and dual phase extraction, were compared qualitatively for those sustainability indicators retained following preliminary screening. The project lifecycle has not yet reached the formal options appraisal phase so this comparison was completed qualitatively with each option assigned a ranking (better, worse or equal), relative to the alternative. Outcomes are presented in Table 3 with justification of qualitative rankings for each headline indicator. Table 4 summarises the assessment.

Table 3: Comparison of remedial options against selected indicators.

Assessment Criteria	SuRF-UK Category Code	Remediation Options for Assessment		Justification
		Attenuation Based	Dual Phase Extraction	
Environmental				
Emissions to air	ENV1	Better	Worse	Emissions to air will be greatest for dual phase extraction given the more intensive installation, commissioning and Operation & Maintenance regime required compared with an 'attenuation-based' approach.
Soil and ground conditions	ENV2	Equal	Equal	Both options expected to have comparable impact on soil quality. Neither is expected to significantly impact geotechnical quality of soil as ground disturbance will be minimal under either approach.
Groundwater and surface water	ENV3	Equal	Equal	Dual phase extraction will require groundwater abstraction. It is considered unlikely this would have an impact on the aquifer beyond the site footprint. Treated water could be discharged via existing site drainage facilities. Both approaches will result in long-term improvement in groundwater quality within the aquifer.
Natural resources and waste	ENV5	Better	Worse	Resource consumption is an aspect where 'attenuation based' approaches are always likely to rank more favourably against alternatives. Waste generation will also be reduced.
Social				
Human health and safety	SOC1	Better	Worse	Health and safety represents a key priority for all stakeholders given the operational nature of the facility. An 'attenuation based' approach will inherently offer a lower level of site exposure during its deployment, compared to an approach requiring a greater degree of Operation & Maintenance.
Neighbourhoods and locality	SOC3	Equal	Equal	Both options represent relatively low intensity remedial solutions and against the baseline of existing site operations, as such the impact of these to local communities is considered likely to be negligible.
Uncertainty and evidence	SOC5	Worse	Better	NSZD represents a novel remedial option with a limited track record as an applied remedial solution, particularly in the UK. Regulatory support to continue the assessment was obtained following the initial trial however, it is acknowledged that a formal 'attenuation based' approach carries a higher degree of uncertainty, compared to a more established approach.
Economic				
Direct economic costs and benefits	ECON1	Better	Worse	'Attenuation based' approaches represent a relatively low cost solution providing they can achieve the necessary soil and groundwater quality improvements.
Indirect economic costs and benefits	ECON2	Better	Worse	Indirect economic benefits associated with NSZD include the lack of disruption to routine site operations and the ability for the site owner to redeploy financial resources (due to the lower cost profile highlighted in ECON1), into other site wide improvements.
Project lifespan and flexibility	ECON5	Worse	Better	An NSZD based approach requires a significant timespan. The technical feasibility of the approach depends on the continuing satisfaction of a number of boundary conditions. Key amongst these for this project are the absence of a change in land use within or adjacent to the study area, as well as the conceptual site model continuing to support the strategy. A significant phase of data gathering was required to establish, with sufficient confidence (for both the client and regulator) that NSZD was a viable potential remedial option. It is anticipated that collection of such a supporting dataset would continue to be a key focus for all stakeholders on other such projects.

Table 4: Qualitative assessment summary.

Indicator Category	Attenuation Based	Dual Phase Extraction
Environmental	Better	Worse
Social	Equal	Equal
Economic	Better	Worse
Overall	Better	Worse

The results of the preliminary screening indicate that an 'attenuation-based' remedial strategy, founded on NSZD provides a more sustainable option than dual phase extraction. Sustainability benefits of an 'attenuation-based' approach were most significant for Environmental and Economic headline indicators.

6. PROJECT HIGHLIGHTS

The NSZD study was successful in proving the significance of natural mass depletion processes for the LNAPL plume and demonstrating that the monitoring of NAPL mass depletion rates could be achieved at an operational UK facility. Following the initial trial phase an annual mass depletion rate was quantified which benchmarked well with previously published mass depletion rates from global studies (Garg *et al*., 2017). The findings and conclusions of the study were accepted by the regulator and a phase of further data collection has been approved.

Principal Findings

Total CO_2 flux measured in the source zone was consistently higher than recorded at background locations, in line with the key assumption underpinning the DCC evaluation approach.

The trial recorded effective LNAPL mass depletion rates within the lower range of published research values (ITRC, 2009), consistent with the wetter and cooler climate of the UK, with a seasonal range of between approximately 950 – 6,500 l/ha/yr once background flux was subtracted. An annual average of approximately 3,300 l/ha/yr was calculated. The study was completed with full UK regulator engagement and acceptance of the study findings paves the way for development of a long-term NSZD remedial strategy.

As predicted, in line with published research, saturated zone mass flux was several orders of magnitude lower than vapour phase mass flux.

With successful outcomes now reported back to both site operator and regulator, further NSZD monitoring data is being collected augmenting the initial dataset with a view to developing, and gaining endorsement for, a full NSZD strategy for the remediation of the LNAPL mass. The successful trial outcomes created the opportunity for more formal consideration of a highly sustainable 'attenuation-based' remedial approach for this project.

7. LESSONS LEARNED

The following key learnings were obtained through the trial period regarding the design and implementation of NSZD assessment in a UK setting. It is recommended that these learnings are considered when NSZD is under consideration as a potential remedial option:

- Early engagement with the client is vital – NSZD is likely to represent a long-term commitment if pursued as a remedial technique.
- Be clear about uncertainties – time taken early in the process to increase confidence in the conceptual site model will provide value throughout the project lifecycle.
- Engagement with the regulator should be proactively sought, and is recommended as a key component in successfully implementing what is still at present a novel remedial option.
- On operational sites, ensure monitoring programmes are designed to manage all site constraints and critical safety controls.
- Contingency plans should be developed to specify actions and agreed responses in the event that changes to the conceptual site model are recorded that could potentially limit the applicability of an 'attenuation-based' remedial approach.
- A flexible field monitoring programme may be required to allow adaptation of the assessment as data are reviewed.

Following endorsement for the NSZD trial phase by internal stakeholders (client), a detailed consultation with external stakeholders (regulator) was undertaken focusing on achieving a consensus in relation to the following aspects:

1. The supportive LNAPL conceptual site model which underpinned the proposed NSZD assessment, including the outcome of detailed assessment of risks;
2. The technical theory underpinning NSZD and the proposed methodologies to be employed alongside performance indicators (what success looks like);
3. The relevant performance metrics and contingency measures that would be in place during the trial phase; and
4. A clear timetable including agreed reporting dates.

This consultation phase took several months but facilitated the development of a trusted relationship between stakeholders which is vital to support the application of an innovative technique.

8. CONCLUSIONS

The NSZD assessment presented in this case study, the first UK field-scale trial of these monitoring techniques (based on discussions with the regulator), resulted in enhanced understanding of:

- Deployment of NSZD monitoring techniques in an operational site setting; and
- Communication of NSZD data collection methods and results to external stakeholders.

The trial phase indicated that a flexible surface flux based method (DCC) can be successfully employed in a UK setting and that supporting vertical profiling of soil gas provides increased confidence in the interpretation of surface mass flux results.

The sustainability benefits that an NSZD based remedial option can provide should be considered early in the options appraisal process with the assessment of these benefits refined during any trial phase.

A mass flux range of approximately 950 – 6,500 l/ha/yr was recorded. At the plume scale depletion rates of this order can result in significant source mass removal. NSZD can represent a highly sustainable remedial option in supportive conditions where a volatile source LNAPL is present, even in the UK.

It is noted that observed surface flux was highly seasonal and care should be taken to fully characterise and understand the mechanisms for this in any assessment.

Before NSZD can be considered as a remedial option a significant period of investigation and monitoring is required to develop a sufficiently robust LNAPL conceptual site model.

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CL:AIRE

CON 03
(November 2023)

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 focuses on the application of *in situ* thermal remediation on a UK site.

Sustainable *In Situ* Thermal Remediation

1. INTRODUCTION

The site is an active manufacturing facility located in a mixed commercial/residential area (exact location confidential). Impacts from petroleum hydrocarbons and chlorinated solvents were identified in subsurface soil and groundwater, originating from multiple point sources.

Remedial actions were performed by a contracting company, that comprised installation and operation of a pump and treat system designed to extract impacted groundwater from underlying Chalk. However, in 2010 following operation of this system for over a decade, it became clear that mass recovery had declined to levels where further operation of the system would not have been sustainable. It was also clear that a significant contaminant mass remained beneath the site.

Given this, ERM carried out additional site characterisation and a revised sustainability-focused remedial options appraisal during 2011 and 2012. This led to the replacement of the pump and treat system with a source treatment approach using *In Situ* Thermal Remediation (ISTR) to remediate the main identified source zone; this was carried out in 2014. The remedial treatment zone was located within a warehouse building used for storage.

The operational phase was completed within a four-month period, safely, on schedule, on budget and to the satisfaction of all stakeholders (including the Environment Agency – regulator in England).

This solution was implemented following a sustainability-based options appraisal (using the then newly published SuRF-UK framework (CL:AIRE, 2010) that was then enhanced by the identification and incorporation, where feasible, of Best Management Practices (USEPA, 2008)[1] in the system design and operational phases. Particular focus was placed on power consumption optimisation.

2. CONCEPTUAL SITE MODEL

The site is underlain by fill material (i.e. Made Ground), typically 0.3 m in thickness and consisting of a concrete hardstanding, over varied cohesive and granular soils. The fill is underlain by heterogeneous natural deposits consisting of mostly silty clays with rootlets and slightly sandy silts and clays with chalk gravel clasts. At a depth of circa 6 m below ground level (bgl) is the Upper Cretaceous Chalk, which is highly weathered directly underneath the Drift deposits forming 'putty chalk'.

Shallow groundwater is present within the natural deposits at depths of circa 2 m bgl forming a perched aquifer. No clearly defined groundwater flow direction could be ascertained.

The Conceptual Site Model (CSM) was refined via additional investigation using High Resolution Site Characterisation (HRSC) techniques. These techniques included use of surface geophysics using resistivity profiling to identify contaminant transport pathways, together with passive soil gas sampling to qualitatively determine the presence or absence of contaminant source zones. These results and those collected from traditional borehole drilling and sampling were synthesised via sequence stratigraphic assessments to provide a more detailed geological and hydrogeological CSM that then enabled the risks to human health and the environment to be more accurately defined.

Impact to soil from total petroleum hydrocarbons was widespread within the treatment zone at concentrations of up to 2,300 mg/kg. Chlorinated Volatile Organic Compounds (CVOCs) were also detected, including chlorobenzene at a maximum concentration of 77 mg/kg.

The main contaminants of concern within groundwater were chlorobenzene, at up to 33 mg/L, dichloromethane and trichloroethene (both compounds at up to 300 mg/L). These concentrations are indicative of the presence of Dense Non-Aqueous Phase Liquid (DNAPL).

[1] The term Best Management Practices is used in this document as the work undertaken preceded the SuRF-UK introduction of Sustainable Management Practices in 2012.

Concawe
Environmental Science for European Refining

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3. RISK ASSESSMENT

The pump and treat system had been implemented based upon an assumption that contamination had migrated vertically from the Drift into the Chalk, which then represented a risk to a drinking water aquifer. However, the HRSC assessment concluded that pumping within the Chalk was making the situation worse, as it was inducing downward contaminant migration from the overlying Drift aquifer where the majority of the remaining impact was located.

The principal potential pollutant linkage was identified as between the Drift aquifer source and off-site surface water receptors, with most of the estimated contaminant mass present beneath a storage building. It was therefore agreed with the Environment Agency that the now defined contaminant source zone would be remediated on the basis of mass recovery to the extent technically and practically feasible. The remedial treatment zone comprised an area of circa 1400 m^2 (40 m x 35 m) and extended to a depth of 6 m bgl.

4. REMEDIAL OPTIONS ASSESSMENT

4.1 Identified remedial options

An updated remedial options appraisal was completed using existing UK guidance at the time (2011) including Contaminated Land Report 11 (Environment Agency, 2004) and Remedial Targets Methodology (Environment Agency, 2006) and the UK Sustainable Remediation Forum (SuRF-UK) framework (CL:AIRE, 2010), in two steps, as shown below:

- Step 1 – technology options were assessed initially by evaluating general feasibility (technical applicability). If an approach was not deemed to be technically effective, it dropped out at this stage.
- Step 2 – the technologies retained from Stage 1 that were deemed as generally feasible were taken forward for assessment of the technical effectiveness of detailed aspects of the remedial works to be carried out. The criteria at this stage were as follows and applied qualitatively:
  - ◊ Effectiveness on dissolved phase mass.
  - ◊ Effectiveness on DNAPL in soils.
  - ◊ Effectiveness on DNAPL in saturated zone.
  - ◊ Time to complete.
  - ◊ Cost range.
  - ◊ Surface infrastructure required.
  - ◊ Sustainability.

Three viable technologies were retained for more detailed evaluation, one of these being assessed for short and long term operation, giving a total of four assessments. These technologies comprised soil removal or *in situ* physical recovery processes. Injection based technologies were discounted because variability of the underlying lithology would have made subsurface delivery challenging. The presence of DNAPL would also have been expected to, at best, increase the timeframe or, at worst, inhibit the performance of either biological substrates or chemical oxidants. The retained technologies are summarised as follows:

1. Soil Excavation and Disposal: This technique would be constrained by the low headroom in some parts of the building, limited access, and the presence of foundation pads that would inevitably mean some contaminated soil would need to remain in place to maintain structural stability. Additional challenges included management of shallow groundwater and significant disruption to site activities in the context of an operational site.

2. Multi-Phase Extraction (MPE): This *in situ* technology involves simultaneous pumping of liquid and vapour from a series of wells, with contaminants removed in vapour, free and dissolved phase via in-well pumps and vacuum blowers connected to these wells. Recovered contaminants would be treated via a series of separators, air stripping and granular activated carbon technologies. MPE is a well understood technology and both short and long term approaches were considered in the assessment. However, given the variable nature of the geology, this technique would likely leave significant contaminant mass in place. MPE was assessed for both short term (6 months) and a long term (3 years) operation.

3. *In Situ* Thermal Remediation (ISTR): This technology is essentially a system that adds a heating component to a traditional ambient temperature MPE system. The heating process facilitates the liberation, mobilisation and/or degradation of contaminants. The benefits of this approach are that contaminants can be recovered independent of variations in lithology and the process can rapidly achieve a high percentage of volatile contaminant mass removal in both high and low permeability environments. This leads to greater certainty of success.

For the purposes of the sustainability assessment these retained techniques were carried forward into a semi-quantitative analysis using Multi-Criteria Analysis (MCA).

4.2 Sustainability assessment

The SuRF-UK framework describes two fundamental stages at which sustainability can be considered within a project: Stage A covers the plan/project design and Stage B is the remediation selection and implementation phase (CL:AIRE, 2010)[2]. This sustainability assessment relates to Stage B of the SuRF-UK framework, where the decision to undertake remediation has been made and the objective is to identify the most sustainable remedial option that can deliver the client's project objectives (CL:AIRE, 2010).

The technologies taken forward from the initial technical appraisal were assessed using a weighted quantitative MCA, informed by a comparative analysis of air impacts, energy and water consumption and worker safety using the US Navy SiteWise tool (US Navy, 2010). At the time of this appraisal there were few tools available and the SiteWise tool (also relatively newly published at the time) was used to provide a relative comparison of a number of predominantly environmental metrics that could inform the scoring in the MCA.

For this project, the key driver that influenced this assessment related to corporate policy and is defined as follows:

[2] The reader is referred to the SuRF-UK Framework document for a more comprehensive description of the each of the stages described here.

- Commitment to continual measurement and monitoring of its carbon footprint and to reducing this footprint through a carbon management programme.
- Sustainability as part of its Vision, Mission and Values, including:
  - ◊ To grow exceptional, long-term, sustainable value for all our stakeholders.
  - ◊ Being an employer of choice for empowered individuals in a safe and sustainable environment.

Works also had to be implemented within the context of an operational facility and the requirements of the facility and the workforce.

The sustainability assessment covers the 18 overarching categories of indicators described in the SuRF-UK framework across the three pillars of sustainability (CL:AIRE, 2010)[3], though after discussions within the project team the indicators were slightly adjusted to better reflect the key issues associated with the project (impacts on human health and safety were considered separately, impact on neighbours was renamed impact on surroundings – see Table 1).

Table 1: Overarching categories of indicators for sustainability assessment of remediation options (CL:AIRE, 2010).

Environmental	Social	Economic
• Impacts on air including climate change • Impacts on soil • Impacts on water • Impacts on ecology • Use of natural resources and generation of wastes • Intrusiveness	• Impacts on human health & safety • Ethical and equity considerations • Impacts on neighbours or regions • Community involvement and satisfaction • Compliance with policy objectives and strategies • Uncertainty, evidence and verification	• Direct economic costs and benefits • Indirect economic costs and benefits • Employment and capital gain • Gearing • Life-span and 'project risks' • Project flexibility

A relatively simple MCA was undertaken (summarised in Table 2) in which initially each of the sustainability indicators was given a weighting of 1 to 5 based on the judgment of the project team and reflecting the likely stakeholder interests. Within this site-specific context, criteria relating to impact to groundwater/air, human health risks, safety (as noted distinct from human health), legislative compliance and legacy risks were considered to be more significant indicators.

Following the weighting exercise, based upon the CSM and the identified drivers for action, each of the different remedial technologies was scored (again using the judgment of the project team) on a rating of -5 to +5 for overall net benefit (positive numbers) or cost (negative numbers) for each criterion.

In order to assist with the scoring (and in part to evaluate the usefulness of a quantitative approach within the context of an MCA) the SiteWise tool was used to quantify the relative impact of each of the short-listed options for a number of the environmental indicators. As noted above the SiteWise tool was used to help quantify the relative environmental footprint. A detailed description of the SiteWise tool is beyond the scope of this case study but the key features (as described in the SiteWise user manual) are summarised in Box 1.

Box 1: SiteWise tool summary (extract from user manual (US Navy, 2010)).

SiteWise™ is a stand-alone tool developed jointly by the U.S. Navy, U.S. Army Corps of Engineers (USACE), and Battelle that assesses the environmental footprint of a remedial alternative/technology in terms of a consistent set of metrics, including: (1) greenhouse gas (GHG) emissions; (2) energy use; (3) air emissions of criteria pollutants including oxides of nitrogen (NOx), sulfur oxides (SOx), and particulate matter (PM); (4) water consumption; and (5) worker safety. The assessment is carried out using a building block approach where every remedial alternative is first broken down into modules that mimic the remedial phases in most remedial actions, including remedial investigation (RI), remedial action constructions (RAC), remedial action operation (RA-O), and long-term monitoring (LTM). Once broken down into various modules, the footprint of each module is individually calculated. The different footprints are then combined to estimate the overall footprint of the remedial alternative. This building block approach reduces redundancy in the sustainability evaluation and facilitates the identification of specific activities that have the greatest environmental footprint. The inputs that need to be considered include (1) production of material required by the activity; (2) transportation of the required materials to the site; (3) all site activities to be performed; and (4) management of the waste produced by the activity. Materials usage is considered only for materials that are completely consumed (referred to as consumables hereafter) and cannot be reused during the application of the alternative.

For the purposes of the SiteWise assessment the default emission factors were first reviewed and adjusted where possible/practical to reflect UK conditions/practices. Then using the detailed anticipated scope and timescale associated with each alternative (using assumptions made during costing of each of the alternatives and based on a mixture of experience and initial engagement with contractors) the environmental footprint (and or other relevant metric) with each of the alternatives was calculated and the results are presented in Figure 1. The results were then used to inform the scoring used in the MCA assessment (noting that this primarily focused on environmental indicators but also included workers safety).

[3] Note that this assessment was undertaken prior to the publication of Annex 1: The SuRF-UK Indicator Set for Sustainable Remediation Assessment in late 2011.

Concawe bulletin

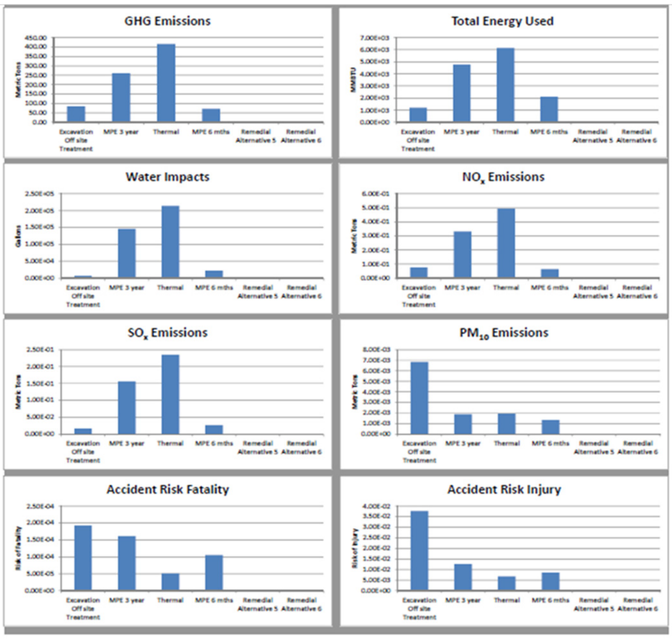

Figure 1: SiteWise outputs.

The results of the MCA are shown in Table 2 overleaf.

ISTR was selected as the preferred remedial solution, given that this was demonstrated to offer the greatest overall net sustainability benefit (+42 point score). This outcome was due to the high probability of the success due to a much higher maximum technically -achievable mass removal compared to ambient temperature MPE.

Short term ambient temperature MPE also scored highly but was lower than thermal due to lower achievable mass removal (20-30% of mass present).

Excavation scored the lowest due to health, safety and logistical challenges of soil excavation (source zone beneath a building and excavation hazards).

Although the environmental indicator for thermal remediation scored a net positive from an impact to soil and groundwater perspective, the negative scores relating to natural resource use and air emissions requires acknowledgement and was therefore focused upon during the remedial design and implementation phases.

The sustainability assessment was discussed and reviewed with the regulatory authorities (both Local Authority and the Environment Agency), who agreed with the approach and the endpoints proposed.

4.3 Thermal system overview

The ISTR system used Thermal Conductive Heating (TCH) as the heating methodology. This was selected principally due to the ability of TCH to heat the underlying lithology, irrespective of the variable permeability geology.

The system comprised 26 vapour/groundwater recovery wells and 14 gas-fired heating wells within the treatment area. 30 temperature monitoring points (thermocouples) were also installed to allow the heating process to be monitored and optimised.

The wells were linked to process equipment, which included pumps, soil vapour extraction blowers, a heat exchanger, inlet tanks and carbon vessels for treatment of vapour and liquid phase. The completed installation is shown in Figure 2.

Figure 2: Heating and recovery well array.

The system was operated for a period of 63 days, achieving the target treatment temperature of 80°C in the core of the treatment zone at depths where the majority of the contaminant mass was present (2-3 m bgl).

An estimated mass recovery of 380 kg of contaminant mass was achieved.

4.4 Further optimisation of the ISTR system to reduce carbon footprint

To reduce the carbon footprint of the remedial works, natural gas was selected as the fuel source for the TCH system. Total energy consumption for the gas used throughout the heating period was measured at 268,000 kWh (4,254 kWh per day). Had electrical power been used it is estimated that the energy consumption would equate to circa 350,000 kWh. This means that the use of gas has reduced the carbon footprint of the energy by approximately a third assuming the typical electricity generation mix in the UK at 2014.

Additionally, by the time the thermal treatment was implemented, best management practices for these technologies had been published (USEPA, 2012) and were implemented where possible. This included the use of thermocouples that allowed the subsurface heating process to be measured in near real-time, therefore enabling heating to be targeted in the areas where it was most needed or for the heat input to be reduced in zones that heated more rapidly. Once the thermocouples had shown that ground temperatures had reached the target treatment temperature in the areas of highest contamination, heating was discontinued and the pumping and vapour recovery system continued to extract in isolation for an additional 10 days.

Table 2: Results from MCA.

Sustainability criteria	Weighting (1-5)	Excavation	MPE 3 years	ISTR	MPE 6 months
Environment					
Impact on water	5	5	3	4	2
Impact on soil	1	5	3	3	2
Impact on air	5	-2	-3	-4	-1
Impact on ecology	3	5	3	4	2
Natural resource use and waste generation	4	-1	-2	-3	-1
Intrusiveness	3	-5	-1	2	1
Social					
Human health	5	-1	0	0	0
Safety	5	-4	-2	0	-1
Ethical and equity considerations	1	0	0	0	0
Policy and legislative compliance	5	4	4	4	3
Impact on surroundings	2	-2	0	1	1
Uncertainty, evidence and verification	1	3	0	0	0
Community involvement & satisfaction	3	-4	0	0	0
Economic					
Direct costs	3	-2	-2	-3	1
Indirect costs	3	-2	0	0	0
Employment opportunities & human capital	1	0	0	0	0
Gearing	1	0	0	0	0
Legacy and projects risks	5	5	3	4	2
Flexibility	1	0	0	0	0
Net environmental benefit		16	1	9	12
Net social benefit		-18	10	22	12
Net economic benefit		13	9	11	13
Overall net-benefit (Sustainability)		11	20	42	37
RANK		4	3	1	2

This led to a significant increase in VOC removal rates (10-20%) and associated mass recovery during this period, without use of additional energy for heating, saving approximately 42,500 kWh of gas. The continued recovery of VOCs from the ground without continuing to heat may have been due to reduction in steam accumulation in the vadose zone increasing the pore space available for vapour recovery, or enhanced by dissolved gas generation.

5. PROJECT HIGHLIGHTS

Good practice was demonstrated in several elements of the project, for example:

- This case study illustrates the importance of the development of rigorous CSMs early in the lifecycle of a remediation project, so that remediation can be undertaken in a sustainable manner from design to implementation, and resources not be wasted through inefficient application of remediation technologies (as occurred with the pump and treat system when the CSM was not fully understood). It also highlights the need to continuously review remedial system effectiveness against performance data on a regular basis and to optimise these systems or, as was the case here, revise the approach.
- At complex sites such as the one in this case study, HRSC tools are key to developing a robust CSM so that actual risks and, in this case, remedial approaches are designed and implemented appropriately. In this instance the HRSC underpinned the sustainable remediation approach that was carried out at this site and demonstrated how the longer term pump and treat was inappropriate to achieve remedial targets.
- The remedial options appraisal was undertaken using a holistic sustainability approach, where environmental, social and economic indicators were evaluated to determine the most sustainable option and is one of the first examples of use of the SuRF-UK framework.
- The remedial design phase of the project focused on energy and hence carbon footprint reduction to the extent practical, including using gas-powered TCH, to optimise energy use. This saved circa 82,000 kWh of power compared to if an electrically powered approach had been implemented.
- During the remedial implementation stage, the use of thermocouples to record temperature variations over time enabled the heating period to be reduced by ascertaining when the target treatment temperature had been achieved. Contaminant recovery continued for a period of 10 days without heating, saving another circa 42,500 kWh of energy.

6. LESSONS LEARNED

- It is recommended that sustainable management practices are considered at each stage of a project and ideally aligned with the overall sustainability objectives for the site.
- The SuRF-UK framework provided the means to improve the reliability and transparency of the remedial options appraisal process through consideration of a wide range of indicators. Subsequent remedial options appraisal processes have improved as familiarity with the framework has been gained and a workshop-type approach is now encouraged where stakeholders are directly consulted.
- Environmental footprinting can form a useful component of a sustainability appraisal but is not a sustainability appraisal in itself and its role in the context of the appraisal needs to be acknowledged. Appropriate and realistic design information and assumptions are needed to quantify each of the options and need to consider site-specific variables. The assumptions used in this process should be clearly documented.
- The ISTR solution selected via a sustainability-based options appraisal was enhanced by the identification and incorporation, where feasible, of best management practices in the system design by using gas as the energy source. Other best management practices incorporated into the systems operational phase included temperature tracking and post-heating contaminant recovery to optimise power usage. The best management practices used at the time focused on environmental indicators. Since 2012 (and updated in 2021) the Sustainable Management Practices as defined by SuRF-UK (CL:AIRE, 2021) would be the preferred approach and can be adopted to reflect the site investigation/risk assessment and remediation phases of the lifecycle.
- The HRSC approach adopted at the outset of the project was in itself a sustainable management practice but was not recognised at the time.

7. CONCLUSIONS

Whilst the use of ISTR is relatively energy intensive, this case study shows that the approach can be more sustainable than longer running pump and treat approaches, especially when HRSC is used to fully understand a CSM prior to its deployment and when best management practices are used to optimise energy consumption at design and implementation stages.

The energy reduction lessons learnt from the ISTR application at this site were that the energy source use and optimisation could be more widely applied to other sites to improve the sustainability of ISTR.

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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 a solar powered pump to recover hydrocarbon contamination.

Sunshine on the Tyne – Sustainable Hydrocarbon Remediation

1. INTRODUCTION

The project comprised the remediation of free phase hydrocarbon present in an infilled below ground tank structure. The objective was to achieve permanent environmental betterment in a sustainable manner and minimise the risk to groundwater and surface water. A remedial solution was designed that used solar powered down-borehole pumps and operated over a period of 22 months. A total of 6,100 litres of hydrocarbon was recovered during this period.

2. SITE DESCRIPTION AND PROJECT CONTEXT

Northern Gas Networks (NGN) own and operate a gas holder station in Redheugh (Gateshead, northern England) occupying an area of 2.1 ha. The site is an operational natural gas distribution site featuring above ground pressure reduction infrastructure, a network of below ground utilities, and three decommissioned gas holders. The site is located within a wider mixed residential and industrial area.

The site has been a gas holder station since the 1890s, originally comprising four gas holder structures used to store town gas (manufactured gas). The historical site layout is shown on Figures 1 and 2.

Gas Holder No. 3 was demolished and the below ground tank infilled during the late 1980s/early 1990s. Several phases of ground investigation were undertaken to characterise the dimensions of the gas holder and the distribution of contamination within it. This included supplementary ground investigation by Sweco to further characterise the spatial distribution of dense non-aqueous phase liquid (DNAPL) hydrocarbon and install recovery wells for remediation. Ground investigation identified significant hydrocarbon contamination (dissolved and non-aqueous phases) in the infilled tank of former Gas Holder No. 3. The structure has a diameter of approximately 48 m with a masonry wall and base. The base of the tank is up to 9.5 metres below ground level (mbgl). The DNAPL hydrocarbon present within the gasholder tank was considered to be contained and hydraulically isolated from the surrounding strata (alluvium and glaciolacustrine deposits over glacial till), but given its

Figure 1: Redheugh Gasworks, 1939.

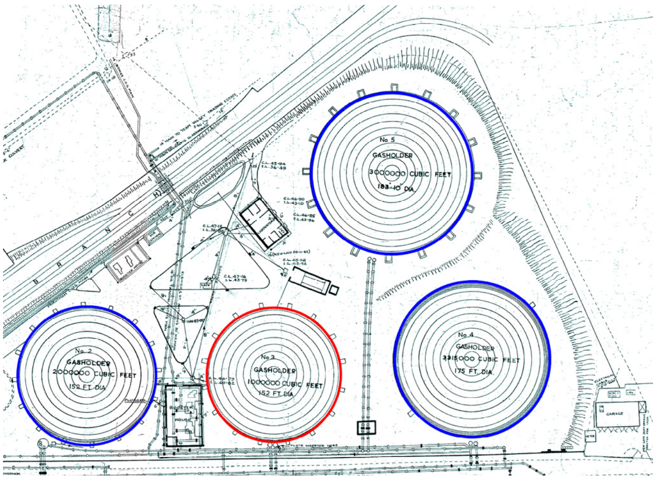

Figure 2: Extract from 1936 site layout plan showing the location of the four gas holders on site. Gas Holder No. 3 is the middle of the four gas holders shown and circled red. Gas Holders Nos 2, 4 and 5 are circled blue. Courtesy of National Gas Archive.

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Concawe
Environmental Science for European Refining

age, its integrity is expected to degrade to the point where this will no longer be the case in the future. NGN appointed Sweco to develop a remedial solution that would achieve environmental betterment by permanently reducing the quantity of DNAPL hydrocarbon and the associated risks posed to environmental receptors, including surrounding groundwater and surface waters.

Gas Holder Nos. 2, 4 and 5 were undergoing decontamination and dismantling during the Gas Holder No. 3 remediation project. The design of the remediation system (including the physical footprint occupied by equipment and frequency of maintenance visits) required liaison with the demolition contractor to ensure that the remediation works did not impact their programme.

The remedial solution comprised targeted DNAPL hydrocarbon recovery commencing with a 6 month pilot trial followed by full-scale operation of the remediation system (22 months in total).

Four self-contained remediation systems were deployed, each comprising a fenced compound which contained a 100 mm diameter, 9 m deep recovery well installed within Gas Holder No. 3 and associated remediation equipment. The location of the remediation system infrastructure is shown on Figure 3. The need for a small operational footprint was a key design consideration for the remediation system due to the space requirements for the gas holder demolition works being undertaken concurrently across the wider site. Each remediation system occupied an area of only 12 m^2.

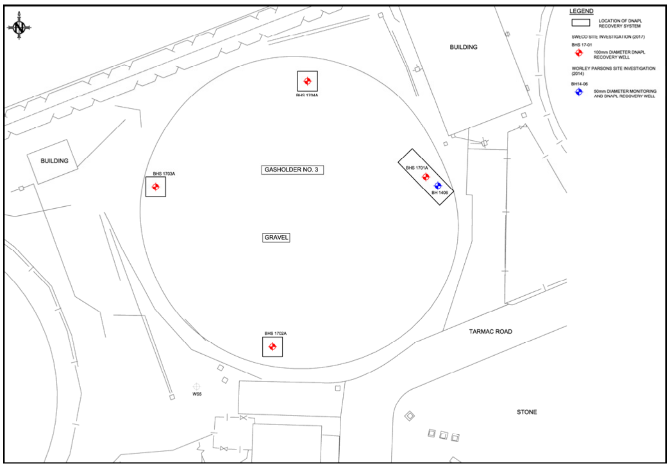

Figure 3: Remediation system layout.

The remediation systems each comprised a bottom loading pneumatic pump which recovered DNAPL hydrocarbon and contaminated water from the well into intermediate bulk containers stored within constructed bunded areas. Each pneumatic pump was powered by an individual receiver compressor connected to a battery and a timer/controller unit. The battery was charged via a 100 W photoelectric solar panel (only) thereby providing a solely renewable energy source. This was an important design aspect as there was no readily accessible electrical supply on the site. Examples of similar solar powered remediation systems in the UK are rare. Each pumping system could be set at user defined intervals to suit the recovery characteristics of each well and the DNAPL hydrocarbon being recovered at that location, whilst also balancing the power requirements from the battery. The treatment systems operated remotely without the requirement for permanent supervision. The remediation system at BHS17-04A is shown in Figure 4.

Figure 4: Remediation system at BHS17-04A.

3. CONCEPTUAL SITE MODEL

A conceptual site model is provided as Figure 5.

Several phases of ground investigation confirmed that the in-ground gas holder tank structure of Gas Holder No. 3 has a diameter of approximately 48 m with a masonry wall and base. The base of the tank is approximately 5.7 mbgl in the centre and 9.5 mbgl in the annulus (immediately inside the tank wall). Fill materials within the holder tank typically comprised made ground of clayey gravel to gravelly clay with some tarmacadam, plastic, wood, glass and metal. The in-ground tank contains water resting at between 0.2 mbgl and 0.5 mbgl.

Monitoring wells installed into the gas holder tank identified that DNAPL hydrocarbon in the form of coal tar/creosote is present within the base of the tank. DNAPL hydrocarbon was identified in all monitoring wells installed around the annulus of the tank, with thicknesses ranging between 0.12 m and 1.8 m.

Outside the tank structure, surrounding ground conditions typically comprise made ground of reworked natural material up to c.6 m deep overlying principally gravelly clay superficial deposits of alluvium and glaciolacustrine deposits identified to at least 23 mbgl (base unproven). The solid geology beneath the site comprises the Pennine Middle Coal Measures. The alluvium is classified by the Environment Agency as a Secondary A Aquifer and the

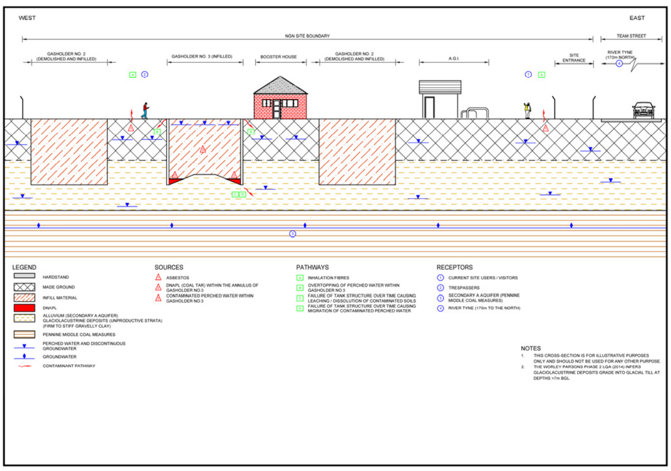

Figure 5: Conceptual site model.

glaciolacustrine deposits as Unproductive Strata. Perched groundwater was identified in the superficial deposits with no laterally continuous groundwater body identified. The Pennine Middle Coal Measures are classified by the Environment Agency as a Secondary A Aquifer. Surface watercourses are present within 200 m of the site.

The site environmental risk assessment identified that the hydrocarbon is substantially contained by the former tank structure of Gas Holder No. 3 and is considered to be hydraulically isolated from the water within the surrounding ground. As such, the contamination within the gas holder tank is not considered to pose a significant risk to environmental receptors under current site conditions and usage. However, it was noted that this assessment could change in the event of degradation of the in-ground former gas holder tank wall with potential for contaminant release and pollution of controlled waters.

4. ASSESSMENT FUNCTION

The assessment of the study site was undertaken through a tiered approach comprising several phases of ground investigation, with refinement of the conceptual site model after each phase to build up an understanding of the pollutant linkages and associated levels of risk. This approach ensured that the assessment was proportionate and robust. The contaminant linkages which were the focus of the project were those relating to controlled waters receptors (groundwater and surface water) and the potential migration of contamination from Gas Holder No. 3 to impact them. Whilst not considered to pose a potential statutory liability in its current condition, the hydrocarbon contamination (dissolved and non-aqueous phases) within the gasholder tank and the potential to cause pollution of controlled waters in the future was the driver for remediation. In line with NGN's Environment Strategy (that includes five main focus areas linked to United Nations Sustainable Development Goals and targeted at reducing NGN's environmental impact, with land remediation commitments covered under 'Improve Life on Land' aligned to Goal 15), the objective was to mitigate future risks associated with degradation of the below ground structure and achieve permanent environmental betterment in a sustainable manner.

5. SUSTAINABILITY ASSESSMENT

A sustainability assessment was undertaken following the approach set out in BS ISO 18504:2017 (ISO, 2017). This approach enabled the project team to identify the optimum methodology to achieve the remediation objective whilst adapting to the following identified site aspects:

- Limited space for remediation equipment due to ongoing large-scale demolition across the wider site;
- No readily accessible electrical supply or drainage within the works area on-site;
- NGN safety restrictions on 'live' gas sites precluded telemetry to remotely monitor remediation equipment;
- Constrained vehicle access to the site; and
- Wider mixed residential and industrial setting which is sensitive to vehicle movements, noise, dust and odours.

<u>Stakeholder Mapping</u>
A mapping exercise was undertaken to identify relevant project stakeholders and their sustainability goals for the duration of the remediation project. The outcome of the stakeholder mapping is presented in Table 1.

Table 1: Stakeholder mapping.

Project Vision: *Achieve voluntary environmental betterment by permanently reducing the quantity of DNAPL hydrocarbon present and the associated risks posed to environmental receptors, whilst still allowing the site infrastructure to operate*							
Project Boundary: *Whole life, including capital and operational expenditure and impacts*							
Stakeholder Goals	*Equivalent SuRF-UK headline sustainability indicator (CL:AIRE, 2020a,b)*	Stakeholders					
		S1. NGN (client and site owner)	S2. Site users (NGN operations)	S3. Site users (gas holder demolition contractor)	S4. Site neighbours (residential)	S5. Site neighbours (commercial)	S6. Environmental regulators (local authority and Environment Agency)
Environmental Goals							
Achieve permanent environmental betterment (Env1)	*ENV2 ENV3*	✓			✓		✓
Minimise whole-life project environmental impact (Env2)	*ENV1 ENV5*	✓					
Social Goals							
Minimal impacts on site neighbours / residents (Soc1)	*SOC1 SOC3*	✓		✓	✓	✓	✓
Economic Goals							
Minimal impacts on wider site activities (Eco1)	*ECON2*	✓	✓	✓			
Affordable whole-life project cost (Eco2)	*ECON1*	✓					

This process enabled the identification of five main project goals informed by project stakeholder priorities against which relevant project specific sustainable remediation objectives, indicators and metrics could be established to directly inform the remediation options sustainability assessment, and also identify material remediation performance criteria for use in verification reporting. These are summarised in Table 2.

Semi-Quantitative Remediation Options Sustainability Assessment
Semi-quantitative sustainability assessment of each potential remediation option was undertaken by assigning scores to each objective. This process ensured that the remediation options sustainability assessment identified the optimum solution to consciously achieve both the project vision and stakeholder goals. The assessment is presented in Table 3.

Table 2: Sustainable remediation objectives, indicators and metrics.

Project Goals (Stakeholders Goals / Relevant Stakeholders)	Sustainability Category and equivalent SuRF-UK headline sustainability indicator (CL:AIRE, 2020a,b)	Project Objectives*	Project Indicators	Project Metrics
Goal 1 (Env1) Achieve permanent environmental betterment (S1, S4, S6)	Environmental *ENV2* *ENV3*	1A. Permanently remove environmental risks associated with DNAPL hydrocarbon contamination inside Gas Holder 3	1A-1. Quantity of DNAPL Removed 1A-2. Thickness of DNAPL remaining	Litres removed Metres as measured in monitoring wells
Goal 2 (Env2) Minimise whole-life project environmental impact (S1)	*ENV1* *ENV5*	2A. Minimise waste generation	2A-1. Quantity of waste removed from site	Litres/tonnes removed
		2B. Minimise resource consumption	2B-1. Quantity of imported backfill material required	Tonnes
		2C. Minimise greenhouse gas emissions	2C-1. Operational emissions of greenhouse gases (equipment and transport fuel consumption)	tCO2e
Goal 3 (Soc1) Minimal impacts on site neighbours/ residents (S1, S3, S4, S5, S6)	Social *SOC1* *SOC3*	3A. Minimise local air quality impacts	3A-1. Project vehicle movements 3A-2. Project equipment fossil fuel consumption	Litres of fossil fuel consumed
		3B. Minimise noise impacts	3B-1. Noise rating of project machinery/equipment	dB
		3C. Minimise dust and odour impacts	3C-1. Site neighbour complaints	Number of attributable complaints received
Goal 4 (Eco1) Minimal impacts on wider site activities (S1, S2, S3)	Economic *ECON2*	4A. No constraints to operation of gas infrastructure at any time	4A-1. Complaints / issues from NGN Operations	Number of complaints received from NGN Operations
		4B. No significant constraints on wider gas holder demolition project	4B-1. Complaints / issues from demolition project team	Number of complaints received from demolition team
Goal 5 (Eco2) Affordable whole-life project cost (S1)	*ECON1*	5A. Minimise whole-life project cost	5A-1. Whole-life project cost	Total project cost (capital and operational - £ excluding VAT)

*Note that minimising health and safety performance was not included as a specific project objective as this is core to all NGN projects.

Table 3: Semi-quantitative remediation options sustainability assessment.

Potential Remediation Option	*Project Objectives / Category (equivalent SuRF-UK headline sustainability indicator (CL:AIRE, 2020a,b))*										*Total Score*	*Comments*
	Environmental (ENV1, 2, 3 and 5)				*Social (SOC1 and 3)*			*Economic (ECON1 and 2)*				
	1A	*2A*	*2B*	*2C*	*3A*	*3B*	*3C*	*4A*	*4B*	*5A*		
Do nothing (baseline assessment position)	1 *Fail*	3	3	3	3	3	3	3	3	3	*28*	Disregarded as objective 1A (permanent environmental betterment) not achieved.
Entire source excavation, disposal and backfill. (Includes dewatering and disposal of liquids off-site.)	3	1	1	1	1	1	1	1	1	1	*12*	Robust methodology enabling thorough contaminant removal but resource, waste, carbon and financially intensive. Social impacts anticipated.
Dewater tank of all liquids, dispose off-site and install low permeability cap to tank (such as clay or asphalt). (Includes drilling of boreholes to facilitate dewatering.)	2	2	2	2	2	2	2	2	2	2	*20*	Targeted waste removal with potential for some residual/ relcalcitrant contamination to remain, some resource requirement and some social impacts.
Targeted DNAPL removal using low energy system. (Includes drilling of boreholes to facilitate DNAPL hydrocarbon recovery.)	2	3	3	3	3	3	3	3	3	3	*29**	Targeted treatment to permanently remove only the necessary contamination with potential for some residual/ relcalcitrant contamination to remain. Minimisation of social and environmental impacts and costs.
*Potential remediation options were assessed against the baseline position of do nothing and assigned a 1 (poor) to 3 (good) rating of effectiveness or environment/social/economic impact (with reference to BS ISO 18504:2017, Section 7.4.3). Scores were then summed across all project objectives, with the most sustainable project remediation option being the highest scorer (as denoted by *).*												

The remediation options sustainability assessment identified the optimum solution to achieve both the project vision and stakeholder goals to be targeted DNAPL removal utilising a low energy system fuelled by renewable energy. This option was deployed successfully as part of the project. This assessment provided the project team with a suite of project metrics against which the success of the project could be assessed.

6. PROJECT HIGHLIGHTS

NGN appointed Sweco to develop a remediation solution which would achieve the remediation objective whilst working around the site aspects and constraints. The remedial solution overcame site constraints and delivered a sustainable system which achieved permanent environmental betterment using only renewable energy to power remediation equipment with no significant impact on wider site activities or site neighbours.

Sweco undertook supplementary ground investigation to further characterise the spatial distribution of DNAPL and installed recovery wells for remediation. This informed the selection of potential remedial options which were subject to sustainability assessment to support the selection of the optimum solution. Assessment of site aspects, environmental, social and economic factors during the design process led to the development of a wholly sustainable, durable and robust remediation methodology. A 6 month remediation pilot trial provided an estimate of the potential DNAPL volume present and assessed the feasibility of consistently and robustly recovering DNAPL using pneumatic pumps installed in the recovery wells powered only by on-site renewable energy generation. The remediation pilot trial confirmed the presence of significant quantities of DNAPL which could be freely recovered from monitoring wells installed within the former holder tank by *in situ* pumping techniques.

Following the remediation pilot trial, Sweco were commissioned by NGN to undertake full-scale operation of the remediation system, with a total operating period of 22 months during which time 6,100 litres of DNAPL was recovered. Operation ceased when recovery rates reduced to a level where continued operation was no longer considered beneficial in removing the contaminant source. The volume of DNAPL recovered and the rate of recovery were monitored during the operational phase to enable system optimisation and to measure the effectiveness of the remediation activities.

This low intensity renewable energy driven approach designed by Sweco and their contractor Geo2 Remediation Ltd provided multiple economic, social and environmental benefits as summarised in Table 4.

Table 4: Economic, social and environmental benefits.

Remediation System Feature	Environmental Benefit	Social Benefit	Economic Benefit
Use of entirely renewable energy source	Carbon savings and air quality benefits compared to use of electricity from mains or on-site generators. Four individual petrol powered generators to enable the same operation would have generated 61 tonnes of CO_2 equivalent, the same as the emissions from an average car driving 207,000 miles. Carbon saved has monetised societal value of £4,000.	Minimal impact on site neighbours with no complaints received during operation. Quiet system compared to use of traditional on-site generators. Alternative required four individual petrol powered generators for 50 hours per week each rated at 94 dB. No air quality impacts from emissions from generators or equipment.	No operational energy costs. Four individual petrol powered generators would have cost approx. £25,000 more in equipment and fuel than the solar power solution used.
In situ remediation targeting DNAPL	Waste generation minimised by targeted recovery of DNAPL. Vehicle movements associated with waste disposal minimised thereby limiting carbon and air quality emissions.	No significant odours, noise or dust during operation. Vehicle movements associated with waste disposal and associated nuisance and vehicle emissions minimised.	Waste disposal costs optimised.
Remote operation with minimal maintenance requirements	Monthly maintenance visits required only, thereby limiting carbon and air quality emissions from vehicles.	Vehicle movements associated with maintenance visits, and associated nuisance and vehicle emissions minimised.	Minimal maintenance costs (mechanically simple).

7. LESSONS LEARNED

This project demonstrates how a sustainable, low intensity remediation technique can be applied to remediate free phase hydrocarbon (Light Non-Aqueous Phase Liquid (LNAPL) or DNAPL) contamination in soil.

The remediation system at Redheugh Holder Station successfully recovered 6,100 litres of DNAPL during the 22 months of operation, powered solely by solar energy whilst having no significant impact on wider site activities or site neighbours. Whilst the operational interval of the remediation equipment had to be balanced against power generation from the solar panels, this project demonstrated it to be a successful approach to deploy on sites where the physical characteristics of DNAPL being removed require a slow sustained rate of recovery, and where there are no specific remediation time constraints such as in a development programme.

8. CONCLUSIONS

The remediation strategy that was developed provided permanent sustainable environmental betterment using technology powered only by renewable energy, examples of which are rare in the UK. There are numerous other situations in which this technique could be operated to deliver sustainable environmental betterment, including the remediation of remote or off-grid sites.

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CL:AIRE

CON 05
(November 2023)

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 the application of a reactive mat to protect a surface water resource.

Reactive Mat in Canal Catches Groundwater Contaminants

1. INTRODUCTION

This bulletin describes the application of a nature-based system variant of permeable reactive barriers for protecting a surface water resource called a "reactive mat". This installation was part of an EU-funded Interreg project called RESANAT (residual contamination remediation with nature-based techniques). The bulletin describes the design, implementation and the functioning of the reactive mat and provides a retrospective (*post hoc*) sustainability assessment comparing the reactive mat approach with alternatives that might have potentially been deployed.

2. PROJECT CONTEXT AND SITE DESCRIPTION

There are many European locations where a long-term inflow of contaminated groundwater reduces the quality of receiving (draining) surface waters. These inputs may lead to ecological and human impacts which breach the Water Framework Directive. In general, this also leads to environmental liabilities, reputational damage and a lower marketability of sites.

This case study is an example of this situation. It concerns a canal (the Lieve) that has been affected by an adjacent historically contaminated site. It is located near to the harbour of Ghent in Belgium. The contamination results from industrial production of tar and carbon black. Contaminants include aliphatic and aromatic hydrocarbons, in particular benzene, toluene, ethylbenzene, xylenes (BTEX), C6-C10 hydrocarbons and several polycyclic aromatic hydrocarbons (PAH). Contaminated groundwater from this site drains into the Lieve, causing surface water concentrations 70 to 300 times Flanders environmental quality standards for several PAH-components (e.g. acenaphthene: measured 18 µg/l; environmental quality standard 0.06 µg/l). In 2006 the site was partially remediated by excavation and removal of shallow soil, which allowed redevelopment of the site for two car dealerships. However significant residual soil and groundwater contamination remains. In 2019, at the start of the RESANAT-project, the site included the two car dealerships and a vacant plot. Figure 1 shows an aerial photo of the site in 2020. The vacant plot has since been redeveloped.

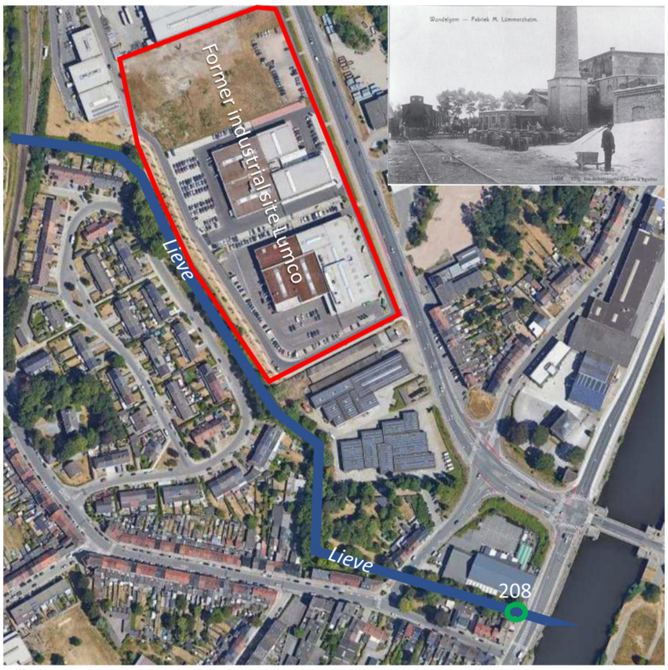

Figure 1: Aerial photo of the Lieve Canal and the former Lumco industrial site in 2020 (red outline). In 2021, a new car company was established at the bare land at the top of the picture. Inset photo is a factory in Ghent circa 1918.

Over many decades, the Lieve became clogged by a thick contaminated sediment layer. This layer was dredged and removed in 2019 as a climate adaptation measure by the water manager. As a result of dredging the draining capacity of the canal increased. In turn this increased flow has led to a higher influx of contaminated groundwater and so a further increase in the concentration of contaminants in the canal (surface) water. Moreover, following removal of the sediment, residual free product is locally (still) present in the current waterbed and thin 'rainbow' layers have been observed on the water surface.

Concawe
Environmental Science for European Refining

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TAUW proposed the concept of using natural materials as an adsorbent in a permeable barrier. It designed a mat structure which is placed on the bed of a surface water body to intercept the contaminated groundwater that drains into it. TAUW has named this technology ‘Natural Catch’ and it received the 2013 NICOLE Technology Award. The functioning of this reactive mat exploits three nature-based processes:

1. The natural drainage capacity of the canal, so no pump is needed;
2. The use of a naturally occurring renewable adsorbent in the mat that is inert and has a high adsorption capacity; and
3. A biologically active interface at the mat surface that provides aerobic biodegradation.

The RESANAT project (2019-2022) supported a full-scale proof of concept for the Natural Catch[TAUW] technology for the Lieve canal. The project was part funded by the EU, the Dutch Ministry of Economic Affairs and the project partners OVAM, Envisan, TAUW, iFlux, TTE and Witteveen+Bos. The project was led by TAUW. OVAM, the Flemish governmental agency responsible for waste policy and soil remediation, was closely engaged as initiator of RESANAT and its responsibility for the site. The City of Ghent was involved because it is regulator for the Lieve and its banks. The duration of the project was 3.5 years, and it is planned that the reactive mat will remain in place after the project.

3. CONCEPTUAL SITE MODEL

The soil east of the Lieve, at and near the former industrial site, consists of a fine silty sand to a depth of about 5 to 6 m below ground level (bgl) and below that of moderate sand alternated with loamy layers. The groundwater level is present at a depth of 1.5-2.5 m bgl, depending on seasonal fluctuation. The contaminated groundwater from the former industrial site to a depth of about 6 m bgl is drained by the canal (see Figure 2). The deeper groundwater contamination below 6 m bgl flows in the opposite direction. Representative groundwater concentrations on the east bank of the Lieve for some relevant contaminants are presented in Table 1 (measured March 2020). Initial surface water concentrations in the Lieve, after dredging the sediment layer, are presented in Table 2 (NB: measuring point 208 is depicted in Figure 1).

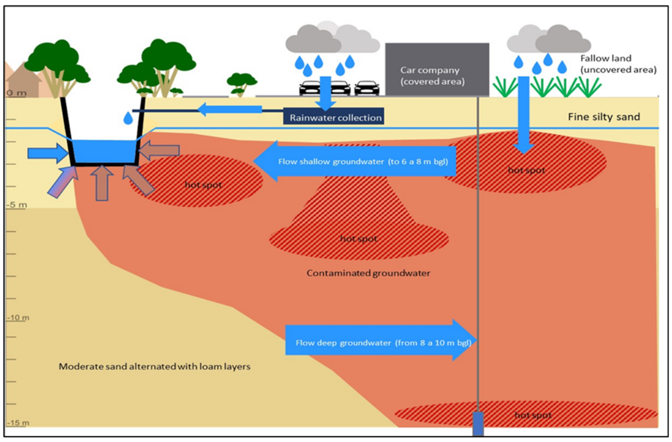


Figure 2: Conceptual site model.

Table 1: Measured groundwater concentrations (µg/l).

March 2020	Well 20 (3.2-5.2 m bgl)	Well 50 (3.15-5.15 m bgl)	Well 90 (3.2-5.2 m bgl)	Well 100 (2.4-4.4 m bgl)
Benzene (µg/l)	15	38,000	100	< 0.2
Toluene (µg/l)	15	11,000	1.2	< 0.5
Ethylbenzene (µg/l)	5.5	1,100	8	< 0.5
Xylenes (µg/l)	9.9	4,600	3.9	< 0.5
Naphthalene (µg/l)	240 / 270	6,100 / 7,200	13 / 16	0.14 / 0.2
Acenaphthene (µg/l)	1.1	280	41	0.1
C6-C10 (µg/l)	99	60,000	130	< 10

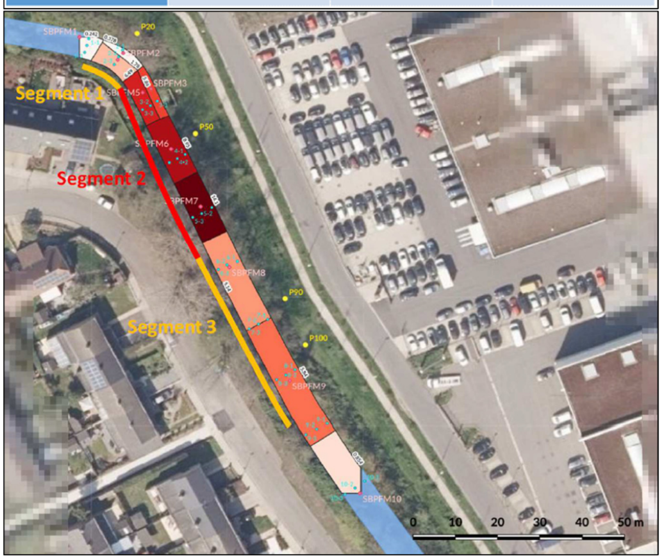
Table 2: Measured surface water concentrations (µg/l).

	201	202	203	204	205	206	207	208
Benzene	< 0.2	<0.2	180	140	100	83	75	3.5
Toluene	< 0.5	<0.5	56	30	20	16	16	8.2
Ethylbenzene	< 0.5	1	6.1	6.9	7	5.9	5.4	3.2
Xylenes	< 0.5	1.7	27	23	21	17	16	9.3
Naphthalene	0.2	12	46	57	60	54	53	26
PAH (16 EPA)	0.66	25	57	77	86	80	93	79
Acenaphthene	0.12	3.9	3.2	6.3	7.5	9.4	10	15
C6-C10	< 10	<10	280	210	160	130	120	61

iFlux used sediment bed passive flux meters to give an indication of the vertical influx of contaminants from the sediment to the surface water (Table 3). These measurements have led to an important insight into the contaminant loads that the canal receives daily, the distribution of influxes over the canal length and the influence of degradation and dilution downstream. The majority of flux to the canal was found at measuring points 202/203 to 204/205 through the bed (see image under Table 2).

Table 3: Measured influx of contamination from groundwater to surface water (mg/m²/day).

	Segment 1	Segment 2	Segment 3
Benzene	0,00	11.8	0.00
Xylenes (sum)	0.17	20.2	0.04
Naphthalene	2.36	28.4	0.35
Phenanthrene	7.93	17.8	5.17
Pyrene	2.21	4.59	4.83
Acenaphthene	4.98	7.24	2.24
C6-C10	0.00	3.02	0.00



Based on these findings the reactive mat needed to be installed at a 110 m long canal section with a total surface area of 660 m^2. The hydraulic head of the groundwater in the bank is about 1.5 to 2.2 m bgl (wells at 5 m bgl). The difference in the hydraulic head of this groundwater and the surface water level is 0.2 to 0.3 m, which supports the data of the vertical flux measurements that indicate a flow from groundwater towards the surface water as well. The implication is that shallow groundwater contamination flows from the former industrial site (source zone) into the Lieve (receptor). The draining depth of the Lieve is believed to be approximately 6 m bgl; below this the groundwater flows in the opposite direction.

4. PROCESS DESIGN AND INSTALLATION

The process of selecting absorbent material was based on a short-list identified following a literature study. Six materials were identified:

- Hazelnut shells (milled);
- Biogranulate (thermally treated sewage sludge);
- Carbon sludge (used pulverised activated carbon from drinking water treatment);
- Biochar (carbon from pyrolysed waste wood);
- Pine bark (shredded); and
- White peat (sieved).

These were tested in laboratory batch experiments using contaminated groundwater from the site to determine physical parameters and their adsorption capacity for key contaminants. The laboratory data were used to model the technical life expectancies of materials in a reactive mat for the Lieve canal. Biochar and peat were found to be the optimum materials: biochar recorded the highest adsorption capacity; peat had the second best adsorption capacity and is lower in cost.

To keep the adsorption material in place on the waterbed in the Lieve, a special geotextile construction was designed and produced (by TenCate Geosynthetics) to provide a replaceable system. It consists of a double fabric: a strong woven outer part and a fine non-woven inner part that keeps the fine adsorbent particles inside. Each mat element consists of several compartments to guarantee that the adsorption material is homogeneously distributed.

In September 2020 empty geotextile mat elements were transported to the site and filled with the adsorption material (either biochar or peat) and ballast (gravel) by the contractor Envisan (Jan de Nul Group). They were then hoisted into the canal and fixed to the banks (Figure 3). Biochar mats were placed at the canal section with the highest influx over a length of 65 m (segments 1 and 2, see image under Table 3), with peat mats used where the canal receives the lowest influx over a length of 45 m (segment 3). The mats were primarily deployed on the canal bed, with a small vertical fold part on the banks.

In January 2021 environmental monitoring of surface water quality and several other indicators began. The first three monitoring rounds after installation found that the surface water quality had improved substantially, particularly for the biochar section of the mats, where the highest influx of contaminants was measured. A high efficiency on the reduction of concentrations in the surface water was observed: 85-99% for PAH, 84-97% for benzene, 90-97% for xylenes and 92-100% for C6-C10.

Figure 3: Construction of reactive mat in the Lieve.

At the end of the fourth round of monitoring (September 2021), there was an unexpected increase in contaminant concentrations at the three measuring points furthest downstream. Vertical flux measurements taken in December 2021 demonstrated that the biochar mats were far from saturated with contaminants. On further investigation a visible gap was found between two mat elements and these were adjusted to close the gap. At the next monitoring round in January 2022, the contaminant concentrations had fallen back to earlier levels (Figure 4).

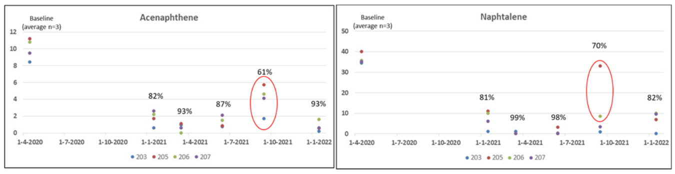


Figure 4: Concentration (µg/l) in surface water as function of time (Biochar mat - 203 & 205; Peat mat - 206 & 207).

Aerobic biodegradation is a key part of the Natural Catch[TAUW] concept and is being tracked in the Lieve Canal project. For this, in January 2021 the water at the mat surface was analysed by a qPCR-test to identify the presence of specific micro-organisms (Figure 5). In addition to anaerobic biodegraders, aerobic biodegraders of BTEX, PAH and alkanes were present at the interface in low to moderate numbers (10^1–10^4 cells/ml), which means aerobic biological degradation is taking place of residual contaminants that pass the adsorbent.

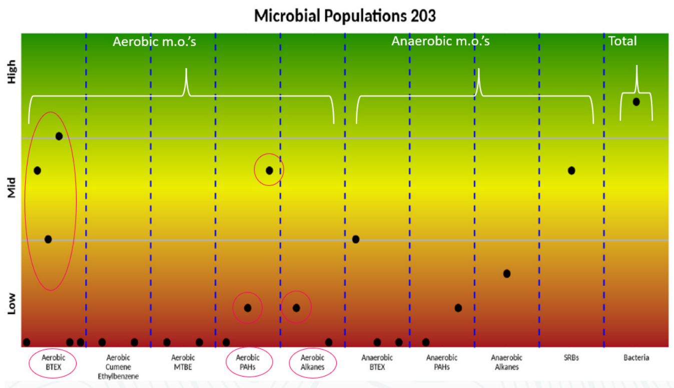


Figure 5: Overview of the microbial aerobic and anaerobic populations in sample 203, based on the quantified genes.

Monitoring continued until the end of the project in December 2022, including a further qPCR-test on micro-organisms on the mat surface and an analysis of the adsorption material in the mat to find out about the load of contaminants.

5. SUSTAINABILITY ASSESSMENT

5.1 Method and score

TAUW has developed an in-house tool for assessing the sustainability of remediation options by assigning weights and scores to sustainability indicators across the three dimensions of People, Planet and Prosperity (Society, Environment & Economy). The indicators are listed in TAUW's internal Guidance Document on Sustainable Remediation (2020) and the TAUW methodology is based on ISO 18504, the UN Sustainable Development Goals, SuRF-UK documents, other relevant literature resources and in-house experience. TAUW has already used the assessment tool at several commercial projects.

All sustainability indicators were given an initial weighting for perceived importance from 1 to 3. The maximum weight of 3 was given to the following indicators:

- 'Health and safety risks' and 'Nuisance' (dimension People);
- 'Uplift in soil and groundwater quality', 'Uplift in surface water quality' and 'CO_2 footprint' (dimension Planet); and
- 'Cost of remediation' and 'Uplift in land values' (dimension Prosperity).

These weightings were given because the ideal remediation alternative should be effective in tackling the soil and groundwater contamination and entail at least as low as possible health and safety risks, nuisance and costs (relatively). Other sustainability indicators have a weight of 1 or 2.

The individual score for each sustainability indicator can take a value from 0 to 5. The lowest individual score is 0, the best individual score is 5. A score of 0 means either no added value at all or a negative burden. The higher the score, the lower the burden or the higher the benefit in terms of sustainability.

The product of individual score and weight delivers a final value for each individual sustainability indicator. These values are summed to a give a total for each of the three dimensions. These totals are then used as a basis to compare remediation alternatives.

5.2 Remediation alternatives and assessment

The sustainability assessment for this case study of the Lieve was completed *post hoc*. It supports the project's secondary objective which is to validate, on the basis of practical data, this technology is sustainable in relation to remediation alternatives.

For the purposes of the sustainability assessment pump & treat (P&T) and excavation were considered as the alternative remediation approaches to using the reactive mat. P&T is the technically most obvious remediation alternative for the specific site circumstances. Excavation is prevented by ongoing businesses on top of the source zone. However, as excavation and removal of contaminated soil could be a potential effective option in other contexts (e.g. after demolition of a factory) it has been included as an additional comparator in the sustainability assessment.

The two comparators are based on the following designs:

1. The P&T alternative is considered to consist of three extraction wells to 5 m bgl (reaching groundwater to a depth of at least 6 m bgl by extraction), a groundwater extraction flow rate of 40 m^3/d (taking into account the natural flow rate) using an extraction pump and a treatment unit with an oil-water separator and water purification filters with activated carbon. Subsequently, the purified water is discharged directly into the Lieve. Replacement of system components takes place after 10 to 15 years and it takes at least 30 years for the contaminant concentrations to decrease to an acceptable level with regard to surface water quality protection.
2. The excavation alternative consists of soil excavation at a surface area of approximately 7,500 m^2 to an average depth of approximately 5 m bgl; an area that is supposed to be present within the radius of influence of the draining canal. Groundwater needs to be extracted in order to make soil excavation possible in the saturated zone and so a water treatment unit with the same components as for the P&T alternative is necessary. Sheet piles are necessary to be able to create a dry environment and for stability. The contaminated part of the soil, expected to be approximately 22,500 m^3, needs to be transported off site for thermal treatment, especially with regard to the presence of PAH and free phase product. Clean soil is needed for the backfill.

The reactive mat has a length of 110 m and is 5 m wide. A length of 65 m is filled with biochar (about 110 m^3) and the other part is filled with sieved peat (about 70 m^3). Every 10 years the adsorbent needs to be replaced, assuming that no biodegradation takes place (conservative assumption). The charged adsorbent is transported off site for thermal treatment. The geotextile and the ballast material are re-used and every 10 years the geotextile is refilled with fresh adsorbent and replaced. It takes at least 30 years for the contaminant concentrations to decrease to an acceptable level with regard to surface water quality protection.

Table 4 (overleaf) shows TAUW's scoring of the sustainability assessment for the three options, along with supporting rationales. If the assessment had been part of an advance decision-making process at a site, it would also have needed input from other stakeholders, such as the problem owner and local residents. As stakeholders may judge (weigh and score) sustainability indicators differently this would make a more robust assessment. This is particularly true for criteria which are not directly or fully measurable, such as 'Nuisance', 'Community involvement' and 'Aesthetic impact'.

The outcome of the assessment is as follows:

- On the 'People' dimension, both P&T and reactive mat have similar scores and better than excavation, due to the indicators 'Health and safety' and 'Nuisance'.
- On the 'Planet' dimension, the reactive mat scores best and excavation worst. This is mainly due to the indicators 'Impact on air quality', 'Use of energy', 'CO_2 footprint' and 'Use of virgin soil'.
- On the 'Prosperity' dimension, the reactive mat scores best and excavation worst. This is mainly due to the indicators 'Costs of remediation', 'Business interruption' and 'Financial project risks'.

Table 4: Sustainability assessment of reactive mat and two alternatives – excavation and pump & treat.

Assessment tool TAUW on sustainability indicators S&G remediation								
Dimension	Sustainability Indicator	Assessment score Excavation	Assessment score Pump&Treat	Assessent score Reactive Mat	Weight	Final score Excavation	Final score Pump&Treat	Final score Reactive Mat
People	Health & safety risks (regarding execution remediation)	2	5	4	3	6	15	12
	Nuisance (odor, noise, dust, movements, vibrations, light, road closure)	1	4	4	3	3	12	12
	Community involvement	2	2	3	1	2	2	3
	Aesthetic impact of works (permanent)	3	2	2	1	3	2	2
	Uplift in public value of site (leisure, cultural historic, etc)	0	0	0	1	0	0	0
	Subscore dimension People					**14**	**31**	**29**
Planet	Uplift in soil & groundwater quality	5	0	0	3	15	0	0
	Uplift in surface water quality	5	5	5	3	15	15	15
	Impact on air quality (fine particles (PM10) and NOx)	0	5	5	1	0	5	5
	Physical landscape disturbance (permanent)	3	3	3	1	3	3	3
	Biodiversity impact (macro and micro)	1	3	4	1	1	3	4
	Climate adaptation impact (incl extraction of groundwater resources)	1	3	3	1	1	3	3
	Use of energy (fossil or green fuel and electricity)	0	4	5	1	0	4	5
	CO2 footprint (energy, materials, chemicals, redox)	0	4	4	3	0	12	12
	Use of virgin soil (sand mining)	0	5	5	1	0	5	5
	Production of waste	2	3	4	2	4	6	8
	Subscore dimension Planet					**39**	**56**	**60**
Prosperity	Cost of remediation	0	3	5	3	0	9	15
	Land use restrictions (with respect to excavation and extraction)	5	2	2	1	5	2	2
	Business interruption	0	5	5	2	0	10	10
	Financial project risks	0	5	4	1	0	5	4
	Impact on brand value	1	1	4	2	2	2	8
	Time span (from start to end of remediation work)	5	0	0	1	5	0	0
	Uplift in land values (reclaim of land, marketability, etc)	4	3	3	3	12	9	9
	Subscore dimension Prosperity					**24**	**37**	**48**
© TAUW	**Total score**					**77**	**124**	**137**

Overall, the reactive mat has the best record on sustainability across the three dimensions. A brief explanation of the assessment of each indicator is given below:

People dimension

Health and safety risks
Due to the substantial excavation and backfill activities, the transport movements and the evaporation of volatiles, the excavation alternative has the lowest score.

Nuisance (for neighbourhood)
With regard to all transport movements on and off site and the accompanying noise, dust, movements, vibrations, light and road closure, the excavation alternative has the lowest score.

Community involvement
The community has not actively been involved in the realisation of the remediation. The neighbourhood was informed of the progress by periodic newsletters. What distinguishes the reactive mat is that because of its visibility and its innovative character, an information board for the public will be installed next to the Lieve to give information on the history of the site and the innovative approach.

Aesthetic impact of works (permanent)
The excavation alternative will not negatively influence the view of the site permanently. The other two alternatives will have some visible parts for the longer term.

Uplift in public value of site (leisure, cultural historic, etc)
The public value of the site does not increase as a result of the works.

Planet dimension

Uplift in soil & groundwater quality
In the short and medium term, the soil & groundwater quality will not (or hardly) increase by the P&T and reactive mat alternatives: neither are focused on the source, only on the path and receptor. The excavation is the only alternative that scores on this indicator.

Uplift in surface water quality
All alternatives equally score on this indicator, because they all positively contribute to the surface water quality (after all, this the purpose of the remediation).

Impact on air quality (fine particles (PM10) and NOx)
All the vehicles needed for excavation, transport and backfilling still use fossil fuels. This causes exhaust emissions such as fine particles and NOx. For the two other alternatives this is negligible in relation to the excavation alternative.

Physical landscape disturbance (permanent)
The landscape will not permanently be disturbed by any of the alternatives in a positive or negative way. The sand mining might disturb the landscape, but this is already dealt with under another indicator: 'Use of virgin soil'.

Biodiversity impact (macro and micro)
The excavation will cause loss of the current vegetation and biodiversity in the current soil. The P&T variant does not have any impact on biodiversity. The reactive mat has a slight positive impact on biodiversity in the water body as it forms a breeding ground for micro-organisms and some aquatic plants (N.B. periodically plants need to be removed to ensure the integrity of the mat).

Climate adaptation impact (including extraction of groundwater resources)
In all alternatives the removal of contaminated sludge and the increase of drainage capacity of the Lieve is incorporated, with which the surroundings can be dewatered in case of heavy rainfall. Nevertheless, for the excavation option a large active extraction of groundwater during a certain period of time is necessary. This leads to a temporary depletion of groundwater resources and local desiccation, which is an increasing issue in Flanders and The Netherlands.

(direct) Use of energy
The excavation alternative uses a lot of energy (green or fossil fuel or electricity) because of the use of excavators, trucks for transport of contaminated soil and clean sand, and machines for levelling after backfilling. For the P&T alternative extraction and purification pumps are necessary during a long period. The use of energy in the case of the reactive mat is negligible in relation to the other alternatives.

CO_2 footprint (energy, materials, chemicals, redox)
All the vehicles needed for excavation, transport and backfilling still use fossil fuels. This causes net CO_2 emission. The thermal treatment of the soil does not only need a lot of energy, but also causes oxidation of organic matter in the soil, leading to CO_2 emission. The production of sheetpiles, though reused at other locations (but not endlessly), causes a large part of the CO_2 emission as well. The final significant emission in the case of excavation is via the production of activated carbon and the regeneration of spent activated carbon used for water treatment.

In case of P&T green energy can be used for the pumps, which is almost CO_2-neutral. The largest CO_2 emission for P&T is via the production of activated carbon and the regeneration of spent activated carbon used for water treatment.

In case of the reactive mat, both biochar and peat are used. The biochar needs production energy, but less than activated carbon. The largest CO_2 emission in the case of the reactive mat is via the thermal treatment of spent biochar and peat after about 10 years (N.B. in practice there might be an alternative solution for thermal treatment of the spent biochar and peat by using white rot fungi for biological treatment). The CO_2 emission as a consequence of the production of the geotextile is negligible and the geotextile is reused as much as possible.

Use of virgin soil (sand mining)
For backfilling, the excavation alternative needs a large amount of clean soil, which is assumed to originate from a sand mine.

Production of waste
In the cases of excavation and P&T, waste in the form of piping material used for extraction of groundwater is produced, as well as free product from the oil-water separator. In the case of excavation, geotextile is used for temporary storage of soil piles, which needs to be destroyed afterwards.

In case of the reactive mats, the geotextile 'jacket' will eventually become waste (though in the first decades it can be reused by emptying and refilling).

Prosperity dimension

Cost of remediation
The costs of the excavation will be about EUR 3 million within a timeframe of a few months. The costs of the P&T alternative and the reactive mat alternative for 30 years will be about EUR 1 million and EUR 0.7 million respectively.

Land use restrictions (with respect to excavation and extraction)
Excavation scores best on land use restrictions, simply because almost all soil and groundwater contamination has been removed, at least above a depth of 5 to 6 m bgl to avoid the inflow of contaminants into the canal. In the case of both P&T and the reactive mat the current land use restrictions stay the same (under which the establishment of production and storage halls is still possible).

Business interruption
In the case of excavation, activities on site should be stopped for a couple of months. Business activities can proceed when P&T and the reactive mat are installed and operational.

Financial project risks
The financial impact of deviations in the dimensioning of excavation are much larger than for the other alternatives.

Impact on brand value
Any soil and groundwater remediation that is successfully executed contributes to the brand value of the problem owner. More impact can be generated when projects are carried out in an innovative and visible way, in combination with the link to their nature-based character. The latter is the case for the reactive mat, especially by communicating to the public by using an information board and a link to an online animation.

Time span (from start to end of remediation work)
The excavation alternative scores best on the time span of the works: months versus decades.

Uplift in land values (reclaim of land, marketability, etc)
For all alternatives there will be an uplift in economic land value, because of a reduction of the liability with regard to the contamination. In addition, the marketability is higher when all soil and groundwater contamination has been removed to a depth of 5 m bgl. Hence, excavation scores best.

6. PROJECT HIGHLIGHTS

- Laboratory results on the adsorption capacity of green adsorbents matched well with field scale measurements.
- Direct measurements were made of vertical fluxes of individual contaminants through the waterbed, which assisted the design of the mat.
- The ease of on-site deployment and customisation.
- The significant improvement of the surface water quality compared to the initial situation.
- A *post hoc* sustainability assessment found that the reactive mat was the most sustainable alternative.
- The international cooperation of several professional partners under the flag of EU Interreg that was initiated and facilitated by the Flemish OVAM.

7. LESSONS LEARNED

- Close consultation between environmental consultant, contractor and producer are essential for the design of an innovative construction.
- Design and construction of a reactive mat cannot be done without knowing the site characteristics (history, scale, environmental risks), flux measurements and adsorption characteristics (the chemical side), nor without reflection on the pros and cons of several potential construction types (the technical side) that should fit the specific situation.
- The connections between the mat elements are key: the watertight sheets on top of these connections should overlap both mat elements and be kept in place to prevent preferential flow paths of contaminated groundwater and/or free product. Otherwise, preferential flow paths would cause a reduction in surface water quality.
- Accumulation of gas in the construction (gas clogging) can occur, especially in shallow water applications. This might cause a decrease in the adsorption capacity of the mat and a decrease in residence time of groundwater contaminants. Initially encapsulated atmospheric air can be easily removed by temporary pressure on top of the mats. Gas formation (methane) as a result of anaerobic degradation of organic material in the aquatic soil underneath the reactive mat can be minimised by removing more sludge from the waterbed prior to installation.

8. CONCLUSIONS

- The use of a reactive mat filled with green adsorbents like biochar and peat can significantly improve the quality of a surface waterbody that receives groundwater contaminated with PAH, BTEX and C6-C10.
- Preliminary measurements on influx of contaminants and adsorption capacity of green adsorbents are of great value for the design and operation of a Natural Catch^{TAUW} construction.
- Following the ISO 18504 procedure for sustainable remediation assessment, the reactive mat was compared with two remediation alternatives: excavation and P&T. On this basis, the reactive mat had the best record on sustainability in the case of the Lieve.
- For similar situations with surface waters threatened by contaminated groundwater with oil-related components, the Natural Catch^{TAUW} construction can be a sustainable solution. Depending on the site-specific circumstances like depth and width of the surface water, the construction can be adapted (e.g. the installation technique and the type of ballasting).

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 a sustainable remediation approach on a UK petrol station site.

Sustainable Remediation of a Petrol Release in a Chalk Aquifer

1. INTRODUCTION

The dissolution of unleaded petrol leaking from an underground storage tank system at a petrol station impacted a public water supply well in 2002. The petrol station was subsequently determined as contaminated land in 2004 under Part 2A of the Environmental Protection Act 1990. Remediation works were guided by a Part 2A remediation statement and sustainability was a key consideration in accordance with statutory guidance (Defra, 2012).

Initial investigation works were undertaken in 2003 with remediation works commencing in 2005. In 2013, AECOM took over ongoing risk management, remediation and verification works at the former petrol station and associated nearby residential properties. AECOM's objective was to manage risks resulting from the historical fuel release, and to achieve regulatory agreement to the cessation of remedial works for the petrol station and adjacent properties in accordance with the sustainable and risk-based approach used for contaminated land management in the UK.

Sustainability assessments were completed by AECOM at two stages of the project: firstly, to inform the future direction of remediation upon taking over the project in 2013; and latterly, to review compliance points in 2018.

2. SITE DESCRIPTION AND PROJECT CONTEXT

Methyl tert-butyl ether (MTBE) and tert-amyl methyl ether (TAME), both additives to unleaded petrol, were detected during routine analysis of drinking water quality from a public water supply well (supply well) in 2002. The supply well abstracted groundwater from the White Chalk Subgroup (Chalk) and the overlying Quaternary weathered chalk deposits. The Chalk, a calcitic limestone, is a Principal Aquifer and is widely utilised for groundwater abstraction in England. During the first year of monitoring MTBE concentrations were detected within the supply well at concentrations above the taste and odour threshold, but well below human health criteria.

The subsequent site investigations confirmed an active petrol station located 750 m from the supply well was the source of the MTBE.

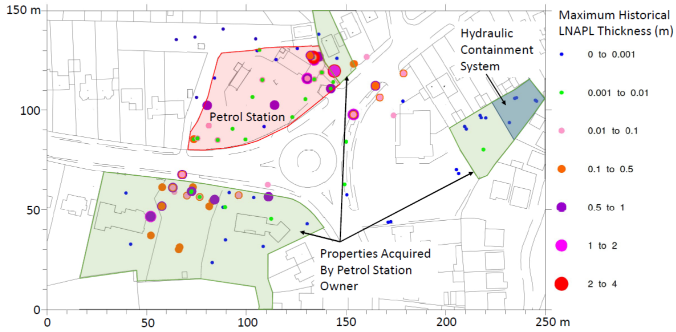


Figure 1: Site layout and historical LNAPL thickness.

Light-non-aqueous phase liquid (LNAPL) was identified beneath the petrol station which extended to off-site properties. Five of these adjacent properties were subsequently acquired by the petrol station owner to facilitate remediation activities. Figure 1 illustrates the historical LNAPL extent across the site and adjacent properties.

Dissolved-phase benzene, toluene, ethylbenzene, xylenes and naphthalene (BTEXN), MTBE and TAME were associated with the LNAPL. The BTEXN plume was primarily limited to the superficial deposits and extended a maximum distance of 80 m from the petrol station, in contrast to both MTBE and TAME, which were drawn into the abstraction and the plumes extended 750 m to the supply well. Figure 2 presents a schematic plan of the observed contaminant plumes extending from the petrol station to the supply well.

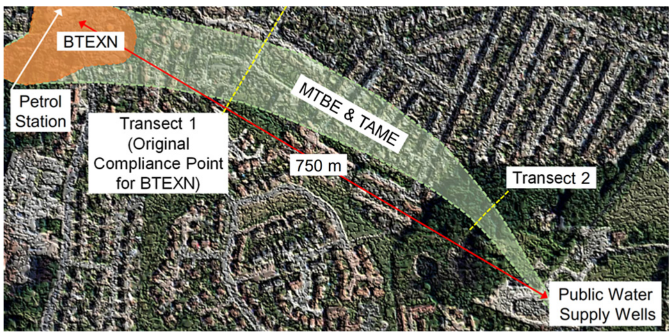


Figure 2: Schematic plan showing observed BTEXN and MTBE/TAME plumes.

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Concawe bulletin

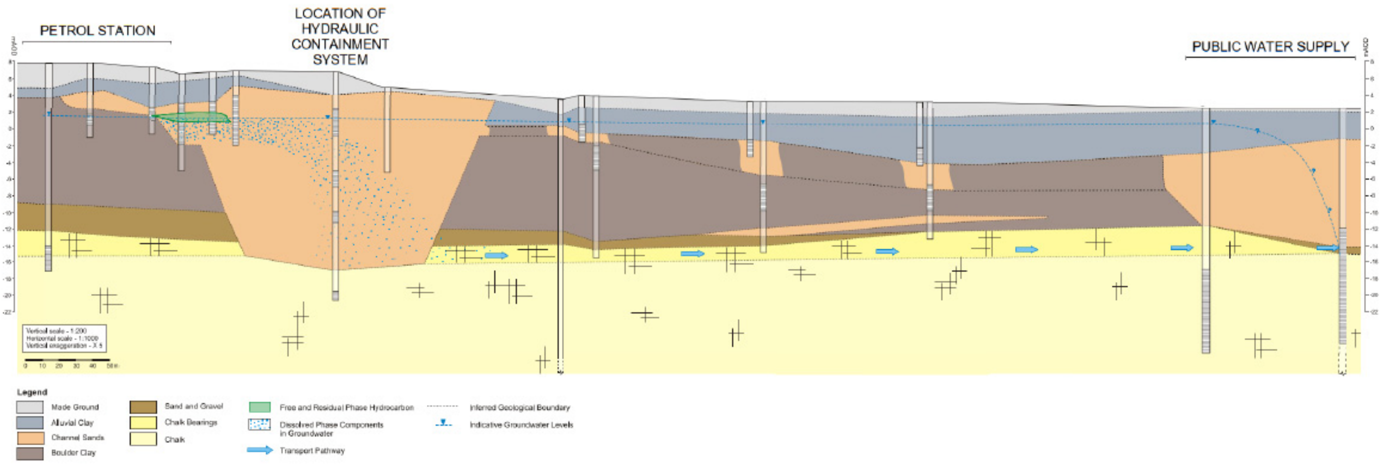

Figure 3: Conceptual site model (modified from Worley Parsons, 2012).

The site investigation and evidence of fuel leakage from the underground storage tank system led to the decommissioning of the petrol station in 2005 and removal of the tanks along with petroleum-impacted soil immediately surrounding the tanks.

3. CONCEPTUAL SITE MODEL

The petrol station was situated on made ground overlying the Devensian Till. Directly down hydraulic-gradient and adjacent to the underground storage tanks is a glaciofluvial channel comprising sands and gravels (referred to as the 'sand channel') which provides hydraulic connection between the petrol station and the underlying Quaternary weathered chalk deposits and the Chalk.

The primary potential groundwater transport mechanism between the petrol station and the supply well was downward movement through the sand channel into the weathered chalk deposits. The subsequent horizontal transport occurs via a relatively thin high transmissivity zone in the Quaternary weathered chalk deposits and is then captured by the supply well as illustrated in Figure 3.

4. REMEDIAL ACTIVITIES

A visual timeline of remedial activities is presented in Figure 4. Activities focused on source characterisation and pathway assessment, risk assessment, source remediation and pathway interception (to prevent further contaminant migration to the receptor).

Source remediation activities removed a significant volume of hydrocarbons through LNAPL skimming, soil vapour extraction and total fluids extraction on the petrol station and soil vapour extraction on one of the adjacent properties.

In 2010, an hydraulic containment system was installed approximately 100 m down hydraulic-gradient of the petrol station to break the pathway between the source and the supply well. The system was installed at a location where natural attenuation processes had already degraded the BTEXN and hence the abstracted groundwater (containing only MTBE and TAME) could be discharged to foul sewer.

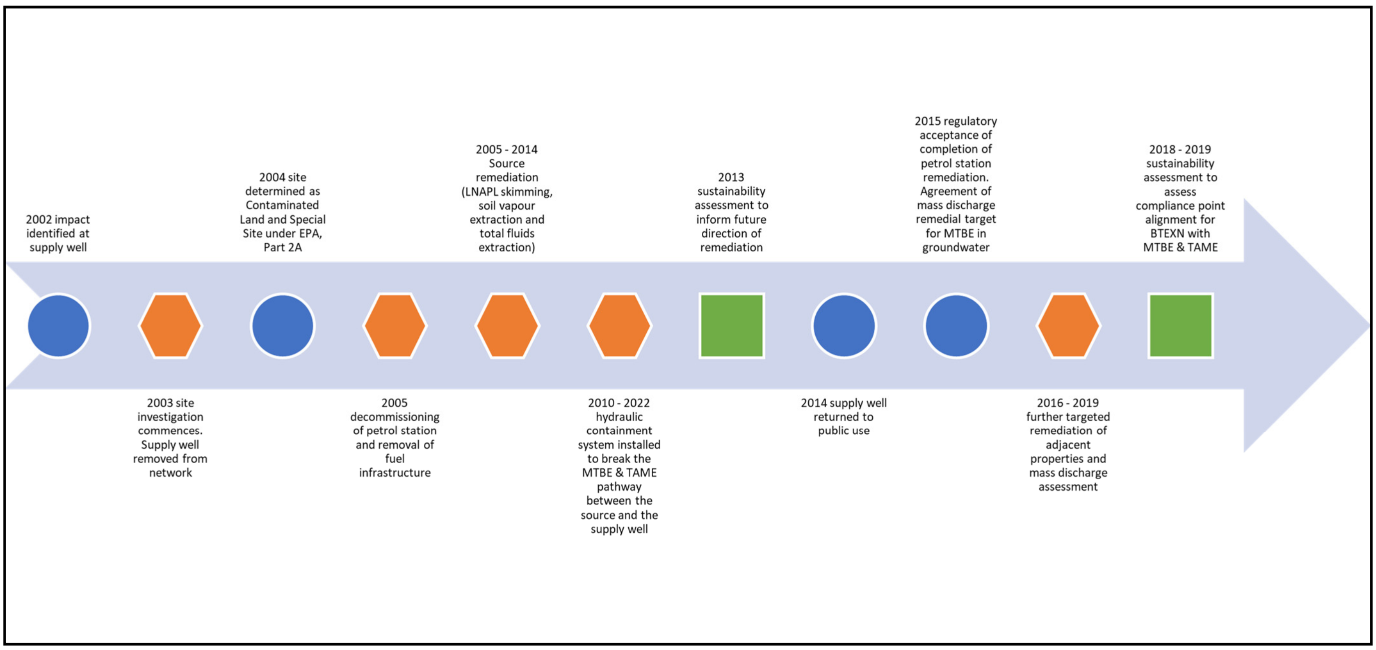

Figure 4: Timeline for remedial activities.

Upon commencement of the hydraulic containment system MTBE and TAME concentrations at the supply well rapidly reduced to below method detection limits within the year, and all abstracted water was able to be returned to public supply by 2014. The rapid reduction in concentrations at the supply well provided further support that the dominant migration pathway to the supply well was through the Quaternary weathered chalk deposits and not through the competent Chalk where matrix diffusion would have been expected to sustain the plume for a longer period following operation of the hydraulic containment system.

In 2012, remedial criteria were agreed with the Environment Agency which reflected the demonstrated natural attenuation capacity of the subsurface with respect to BTEXN. The subsequent focus of remediation was therefore on source reduction and ongoing pathway interception for MTBE and TAME.

5. INTEGRATION OF SUSTAINABILITY ASSESSMENTS WITHIN REMEDIATION

5.1 Initial sustainability assessment to support future remediation strategy

In 2013, a Tier 1 SuRF-UK-based sustainable remediation assessment was undertaken to identify the optimum risk management strategy to remediate the site. The principles of sustainable remediation were applied to the evaluation of the remedial options, which needed to meet three objectives:

- Achieving regulatory closure for remediation of the MTBE and TAME in the source area;
- Returning the petrol station site and associated acquired properties to beneficial use as soon as practically possible; and
- Mitigating any risks to human health, and to the future use of groundwater at the supply well based on taste and odour criteria.

Table 1 presents the five remedial options identified for achieving these objectives.

Table 2 presents the SuRF-UK sustainable remediation criteria, covering the three sustainability elements of environmental, social, and economic, which were chosen for the assessment.

Those criteria highlighted in bold were considered the most important by stakeholders but as this was a Tier 1 assessment the criteria were not weighted according to their importance. For each criterion, the assessment was based on comparison against an idealised situation or goal, (for example no emissions, minimise cost, maximise benefit), and the options were ranked accordingly from 1 (best) to 5 (worst). Where the differences between two or more options were marginal the options were ranked equally. The culmination of the assessment was therefore a comparison table which qualitatively ranked each option according to assessment criteria, together with the rationale for the ranking. The assessment was undertaken using a spreadsheet tool developed specifically for the assessment, and was latterly provided as the URS (a heritage AECOM company)-based SuRF-UK Tier 1 spreadsheet now available on the CL:AIRE website.

Implementation of the assessment process took place in two phases. The first assessment was completed by an Internal Stakeholder Team, consisting of the petrol station owner and their consultant URS. This assessment was then reviewed and amended by an External Stakeholder Team consisting of representatives from the Environment Agency, the Local Authority and the Water Company. The importance of stakeholder engagement was highlighted by the input from the External Stakeholder Team which increased the scoring associated with natural resources and waste, project lifespan and flexibility and ethics and equity for Option 1E (hydraulic containment only) resulting in this option moving from first to third place in the ranking of options. The increased scoring resulted from stakeholder concerns over the duration of this option and the ongoing discharge of groundwater to sewer from the containment.

Table 1: Remedial options evaluated.

Option	Details	Predicted duration of remedial activity (years)		
		Source mass recovery using soil vapour extraction and total fluids extraction	Groundwater remediation below three adjacent properties	Hydraulic containment system operation
1A	Continuing with the existing remedial systems	5	0	15
1B	As 1A, but reduced duration of active source mass recovery focusing on hot-spot areas	3	0	15
1C	As 1A, but more aggressive source area remediation (well replacement, increased vapour and groundwater abstraction, treatment and discharge)	2	0	10
1D	Continued operation of the hydraulic containment system combined with remediation of groundwater below three of the adjacent residential plots (well installation, total fluids abstraction, treatment and groundwater discharge)	0	2	5
1E	Stopping source-area remediation and continuing only with hydraulic containment system operation	0	0	20

Table 2: Criteria used to assess sustainability of options.

Environmental	*Economic*	*Social*
Emissions to air (minimise; air quality impact dominated by power consumption)	**Direct economic costs and benefits** (minimise cost, maximise benefit)	**Human health and safety** (maximise site safety and minimise potential for spills; hazard removal preferable to long term risk management)
Soil and ground conditions (maximise improvement in soil quality)	Indirect economic costs and benefits (return of properties to use in shortest time)	Ethics and equity (minimise transfer of impacts to future generations)
Groundwater and surface water (maximise improvement in groundwater quality)	Employment and employment capital (maximise)	Neighbourhoods and locality (minimise impact, maximise benefit)
Ecology (prevent deterioration in ecological systems)	Induced economic costs and benefits (minimise time for inward investment)	Communities and community involvement (maximise functionality of the impacted properties)
Natural resources and waste (minimise resource usage and waste generation)	**Project lifespan and flexibility** (most robust, most flexible, permanent solution, minimum operation period)	**Uncertainty and evidence** (minimise uncertainty and maximise quality of evidence)

The ranking of the options is illustrated graphically in Figures 5 and 6. Considering all 15 criteria, Options 1C and 1D were the highest-ranking (lowest scoring) option. Option 1D (targeted source reduction on adjacent residential properties combined with continued hydraulic containment system operation) was ranked highest when only the priority criteria were considered, hence it was selected as the preferred option.

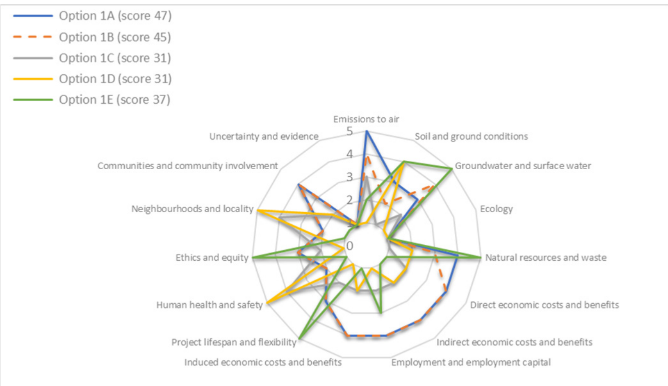

Figure 5: Individual and cumulative scores for all criteria – 2013 assessment. NB: low scores = most sustainable option.

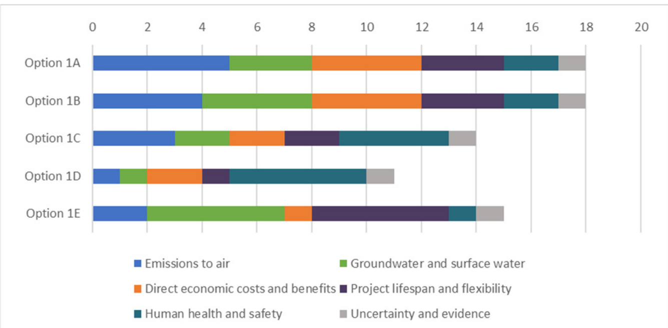

Figure 6: Cumulative scores for six priority criteria – 2013 assessment. NB: low scores = most sustainable option.

From the radar plot for each option it can be seen that Option 1D is highly ranked (lower scoring) in all criteria with the exception of the criteria for soil and ground conditions, human health and safety and neighbourhoods and locality. The sustainability assessment indicated that the additional improvement in these criteria provided by the alternative options was not justified by the additional benefits or impacts defined by the other criteria.

5.2 Implementation of Option 1D remediation solution

Cessation of active remediation on petrol station

In line with Option 1D, the soil vapour extraction and the total fluids extraction systems were removed from the petrol station site in 2014, once asymptotic recovery was reached. Regulatory approval for completion of remediation at the petrol station was received in 2015, following one year of post-remediation validation monitoring and confirmation that remedial criteria for the petrol station had been met.

Continued operation of the hydraulic containment system

Whilst the remedial targets were met for the petrol station, there was a continued need for operation of the hydraulic containment system to manage the remaining MTBE and TAME plume which was sustained by impacts that had migrated beyond the petrol station boundary.

Between 2014 and 2015 works focused on updating an existing numerical groundwater flow and contaminant transport model to assess the performance of the hydraulic containment system under a range of likely future abstraction regimes. The modelling supported field observations that the hydraulic containment system would continue to capture the dissolved MTBE and TAME plume as illustrated in Figure 7. It was therefore proposed that mass discharge at the hydraulic containment system provided a better metric than source zone groundwater concentrations to determine when concentrations of MTBE and TAME no longer presented a risk to the

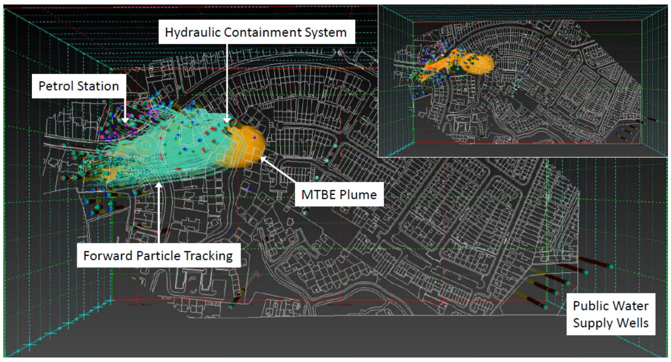

Figure 7: Modelled hydraulic containment system capture zone and MTBE plume.

public water supply. Continued operation of the hydraulic containment system was coupled with routine monitoring of groundwater quality within the source area, at the hydraulic containment system, at wells along two transects downgradient of the hydraulic containment system and at the supply well.

Mass discharge remedial targets for assessing remedial close-out for MTBE (and latterly TAME) were developed adopting the 10th percentile abstraction rate for the public water supply (i.e. 90% of the time the public water supply will be pumping at volumes greater than assumed target rate) and an agreed ceiling concentration based on conservative taste and odour thresholds within the blended public water supply. The MTBE target was agreed with the regulators and stakeholders, including the water supply company, in July 2015. The Environment Agency confirmed this was the first time a mass discharge remedial target had been agreed with them.

Since 2010 the hydraulic containment system has operated successfully with an operational efficiency of over 99%. By 2018 approximately 690 kg of MTBE and 315 kg of TAME had been removed in the discharge as a result of its operation and MTBE and TAME concentrations have continued to be below method reporting limits in the supply well.

Groundwater remediation below adjacent properties

The other element of Option 1D comprised the remediation of groundwater below three of the adjacent properties to accelerate the improvement in groundwater quality for MTBE and TAME to reduce the operational duration of the hydraulic containment system. Based on residual source concentrations and historical concentrations detected at the supply well, MTBE posed the dominant residual risk to the supply well. Focused short-duration source zone remediation works were undertaken at one of the adjacent residential properties in 2016 using total fluids extraction. Whilst the initial MTBE recovery rate was above that for the hydraulic containment system, within two months the mass recovery rate declined to rates of recovery below that achieved by the hydraulic containment system.

To focus further remedial activities the mass discharge of MTBE was assessed across a series of transects through the source area in 2017.

5.3 Further sustainability assessment to assess compliance points

A second sustainability assessment was completed in 2018 and looked specifically at whether the hydraulic containment system could be switched off once the MTBE mass discharge remedial targets had been met (Option 2A) or whether the hydraulic containment system should continue to be maintained to prevent periodic exceedances of BTEXN at a compliance point located upgradient of the supply well at transect 1 (Figure 2) (Option 2B). It should be noted that the supporting groundwater modelling and historical groundwater quality data at the supply well did not predict an exceedance for BTEXN at the supply well.

Both options included further short-duration targeted MTBE mass recovery from the one remaining residential property where MTBE mass discharge was calculated to exceed the mass discharge remedial target together with passive sulfate injection across the source area to stimulate anaerobic biodegradation of residual hydrocarbon mass.

Fifteen criteria across the three sustainability elements were selected again, and this time some of the criteria were supported by quantitative estimates of costs and benefits based on existing knowledge of system operational cost. A pairwise comparison of the two options was made with the options ranked again from 1 (best) to 5 (worst). The output of the Tier 1 assessment is presented in Figures 8 and 9.

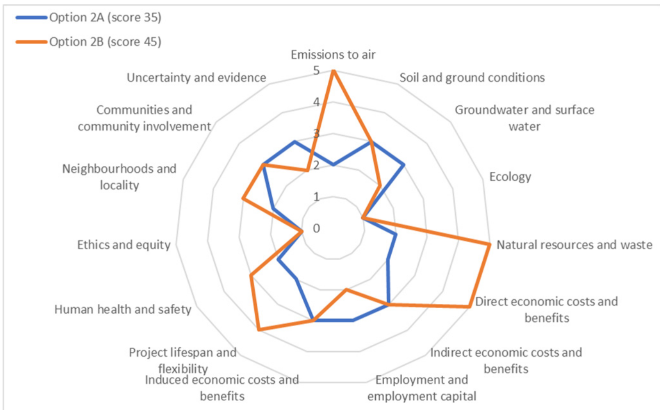

Figure 8: Individual and cumulative scores for all criteria – 2018 assessment. NB: low scores = most sustainable option.

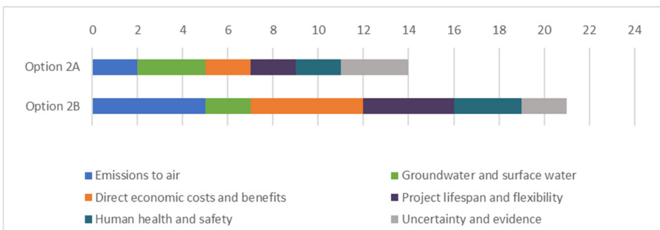

Figure 9: Cumulative scores for six priority criteria – 2018 assessment. NB: low scores = most sustainable option.

Considering all 15 criteria, Option 2A was the highest-ranking (lowest scoring) option. From the radar plot for each option it can be seen that Option 2A scored equal or better than Option 2B in all criteria with the exception of the criteria for groundwater and surface water, employment and employment capital and uncertainty and evidence. The sustainability assessment indicated that the additional improvement in these criteria provided by the alternative option (continuing to run the hydraulic containment system post-achievement of the mass discharge remedial target) was not supported by the additional benefits or impacts defined by the other criteria. The high scores for Option 2B were related to emissions to air, natural resources and waste, direct economic costs and benefits and project lifespan associated with continuing to run the hydraulic containment system. Impacts on these criteria relate to the electricity consumption, discharge of groundwater to sewer and operational and maintenance costs associated with the extended operation of the hydraulic containment system.

The results of this assessment were used to align the compliance point for BTEXN with that for MTBE and TAME i.e. the supply well. This approach was accepted by the regulators.

5.4 Additional remediation to support return of acquired properties to beneficial use

In accordance with Option 2A, further focused short-duration source zone remediation works were undertaken at the one adjacent residential property exceeding the MTBE mass discharge remedial target in 2018 using total fluids extraction. Similar to the previous trial, the MTBE recovery rate declined to rates of recovery below that achieved by the hydraulic containment system within 6 weeks of commencement. Given the additional water treatment required for abstracted groundwater from these pilot trials (due to the presence of BTEXN) as opposed to groundwater abstracted from the hydraulic containment system (predominantly BTEXN free as a result of natural attenuation), further source zone remediation of MTBE mass present below properties adjacent to the petrol station was not considered sustainable. In addition, the residual MTBE mass discharge from this property post-trial was calculated to be below the mass discharge target.

Following the reduction of MTBE within the source area, passive injection of sulfate was carried out to further stimulate anaerobic degradation of the residual hydrocarbon mass in this area to increase the availability of other electron acceptors for MTBE biodegradation (Figure 10).

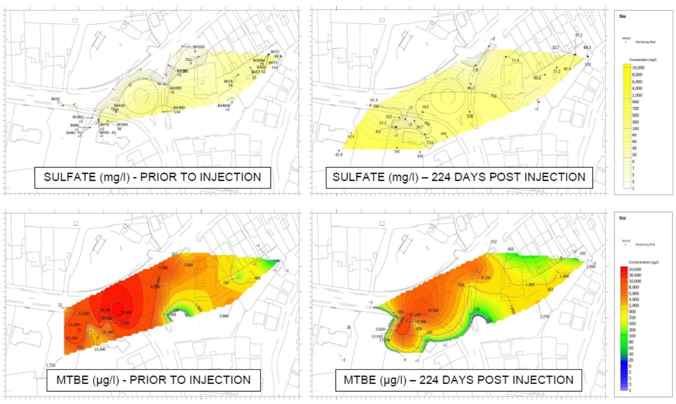

Figure 10: Sulfate and MTBE concentrations in groundwater prior to, and post, passive injection of sulfate.

Sulfate solution was successfully injected under gravity into selected wells to promote the attenuation of dissolved-phase hydrocarbons via biodegradation. Background sulfate concentrations were relatively low prior to the addition of sulfate. Approximately 6 weeks after completion of the sulfate injection, wells located outside of the main hydrocarbon impacted area where sulfate had been injected reported sulfate concentrations above background concentrations. The persistence of sulfate concentrations in these wells was inferred to be due to the lack of hydrocarbons restricting the activity of sulfate reducing bacteria.

In contrast, groundwater samples collected from wells located 5-10 m downgradient of the injection wells and located in areas of high concentrations of BTEX detected very low concentrations of sulfate. The low concentrations are understood to be a result of sulfate being utilised for the degradation of hydrocarbons by sulfate reducing bacteria. This was further supported by quantitative analysis of sulfate reducing bacteria and decreases in BTEX concentrations in these wells.

Concentrations of aerobic MTBE degrading bacteria were detected at locations across the project area but were clearly predominant in areas where BTEX concentrations were low or below the laboratory method detection limit. This indicated that where BTEX were not present to utilise oxygen for aerobic degradation the aquifer was sufficiently aerobic to support MTBE biodegradation by specialised MTBE degrading bacteria, which are already present within the aquifer. This was confirmed in laboratory microcosm experiments.

5.5 Regulator acceptance of source-zone remediation on acquired properties

MTBE mass discharge was assessed below four of the acquired properties to demonstrate whether the mass discharge target had been met. The hydraulic containment system was located on the fifth property and hence remediation continued at this property. The TAME mass discharge target had already been met at the hydraulic containment system and hence did not need assessment on a property-by-property basis.

The achievement of mass discharge targets for MTBE and TAME together with the achievement of concentration-based remedial targets for BTEXN below the four acquired properties led to regulator agreement that no further monitoring or remediation works were required at these properties. Each property could then be divested by the petrol station owner and returned to residential use.

5.6 Ongoing operation of the hydraulic containment system

The hydraulic containment system continued to operate to protect groundwater quality at the supply well from MTBE. To facilitate closure of the system, AECOM completed a review of historical MTBE attenuation between the petrol station and the supply well and developed a clear road-map for closure which was accepted by the Environment Agency.

6. PROJECT HIGHLIGHTS

Key project highlights include:

- Regulator-endorsed closure of remedial activities on the petrol station through attainment of concentration-based remedial targets;
- Innovative use of mass discharge remedial targets to achieve regulator-endorsed closure of remedial activities on all four properties adjacent to the petrol station, thereby allowing a return to beneficial use;
- Application of sustainability assessments to inform future remedial strategy and to review the appropriate adoption of compliance points; and
- Use of historical attenuation data to establish a road-map for closure of the hydraulic containment system.

7. LESSONS LEARNED

Sustainability forms part of the overall solution in complex cases - and often forms part of a final exit strategy. Prior to implementation the site conceptual model needed to be thoroughly understood through detailed on and off-site investigation, modelling and risk assessment - and closure could not have been achieved utilising sustainable assessment without this foundation.

These cases rarely are fast - and in the same way as traditional solutions they are not fit and forget. Successful implementation takes robust site characterisation, stakeholder engagement, adjustment and strategic flexibility.

8. CONCLUSIONS

Sustainability assessments were applied to identify the most sustainable remedial solution to address impacts to groundwater associated with the historical operation of a petrol station that had impacted a public water supply.

Tier 1 SuRF-UK-based sustainable remediation assessments were completed at two stages of the remediation works to identify the optimum risk management strategy for achieving regulatory closure for the ongoing remediation works, based upon the principles of sustainable remediation. The first assessment applied the principles of sustainable remediation to the assessment of five broad options for meeting remedial objectives. The second assessment was completed to evaluate the sustainability of additional remediation required to protect groundwater quality upgradient of the supply well. The assessments resulted in the adoption of the most sustainable remedial solution, were endorsed by the regulators and led to the cessation of monitoring and remediation works on the affected properties.

Key takeaways include:

- Proper characterisation of the situation is vital - closure cannot be achieved without good assessment and conceptualisation;
- Sustainability comes only after the situation is well understood and remedial options have been assessed;
- Stakeholder engagement is critical in shaping and ultimately endorsing the assessment findings; and
- Sustainability is an integral part of contaminated land management - from start to end, it was reassessed and all parties need to be kept engaged during this process.

REFERENCE

- Defra, 2012. Department for Environment, Food and Rural Affairs, Environmental Protection Act 1990: Part 2A Contaminated Land Statutory Guidance, April 2012.

CL:AIRE

CON 07
(November 2023)

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.

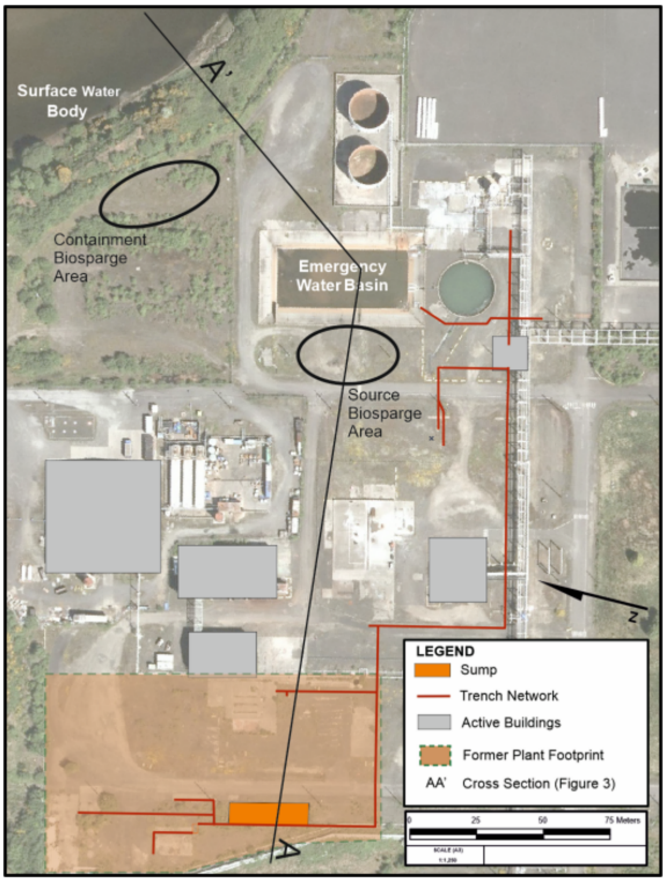

Figure 1: Site plan.

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.

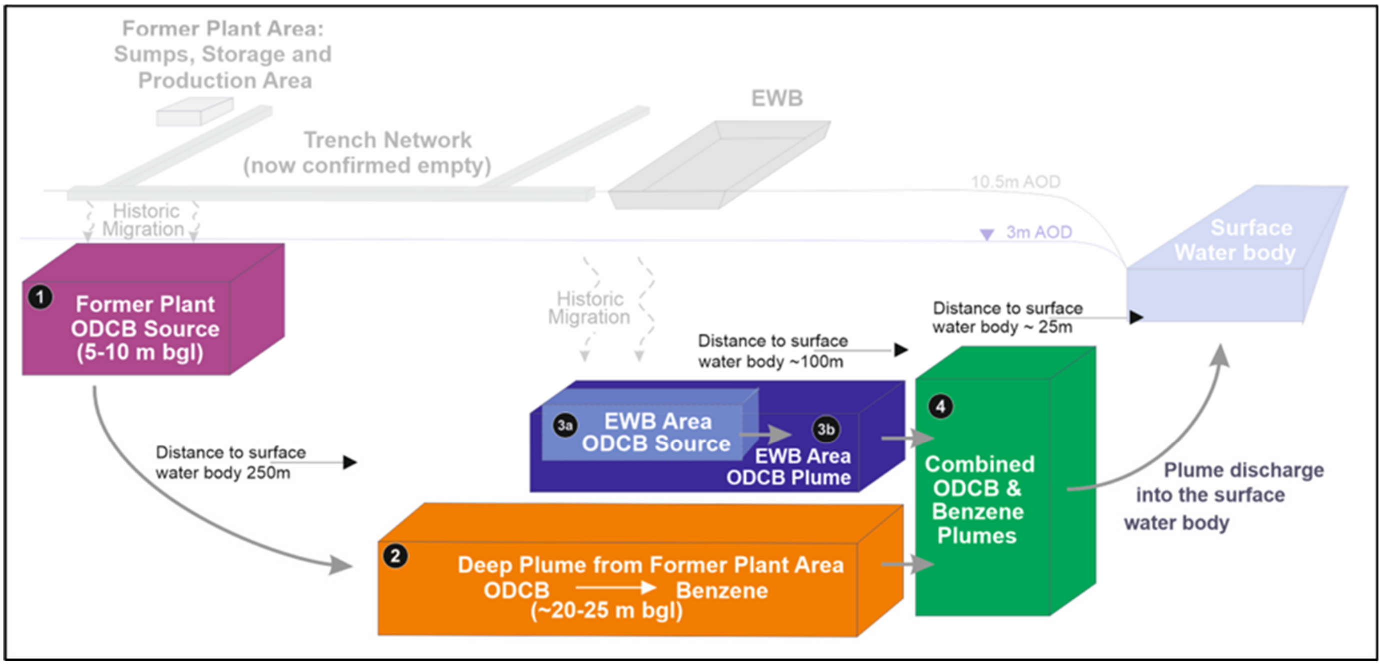

Figure 2: Conceptual site model showing target treatment zones.

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.

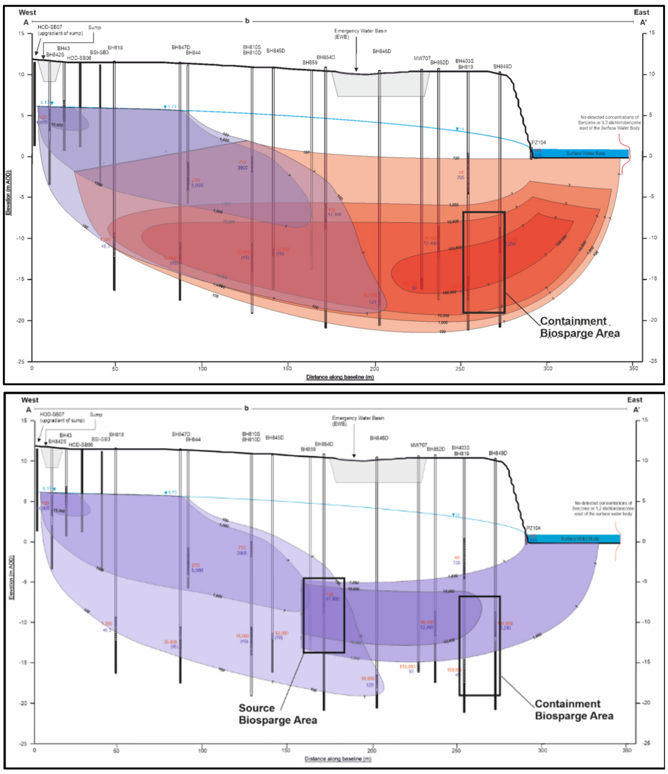

Figure 3: Cross section of ODCB and benzene plumes (top) and ODCB plumes (bottom). Purple = ODCB, Red = benzene. NB: Cross section A-A' location is shown on Figure 1.

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.

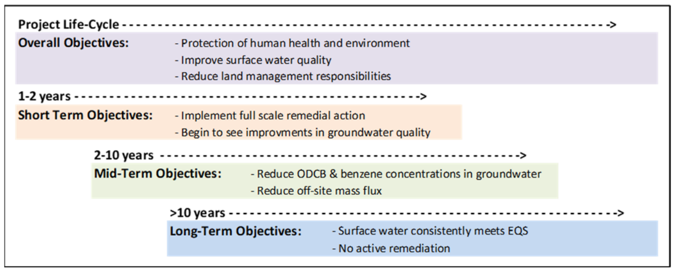

Figure 4: Remedial objectives.

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 →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
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
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**

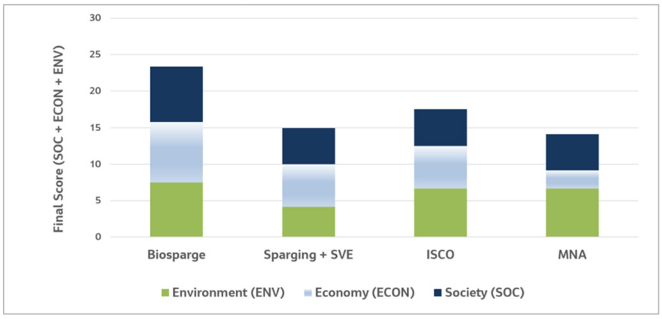

Figure 6: Sustainability assessment summary results.

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.

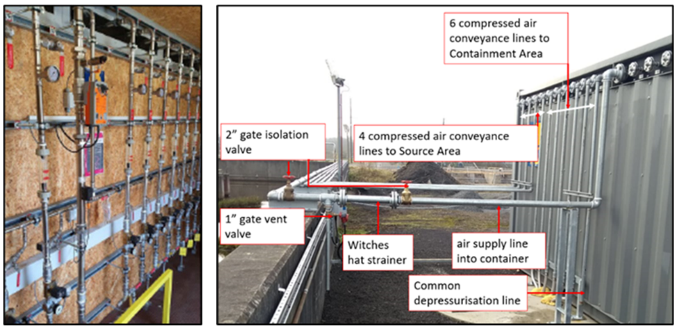

Figure 7: Biosparge system manifold and air supply conveyance pipes.

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.

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CL:AIRE

CON 08
(November 2023)

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 a novel and sustainable sediment remedy for mitigating sheens.

Sheen Mitigation Using an Oleophilic Bio Barrier - A New and Sustainable Remediation Technique

1. INTRODUCTION

This case study discusses a remediation project undertaken at a site, where historical hydrocarbon contamination was resulting in Light Non-Aqueous Phase Liquid (LNAPL) sheens appearing on the foreshore of the adjacent river. The works involved the application of a new sediment remedy for mitigating sheens through the innovative use of oleophilic geo-composites, which utilised the Arcadis developed and patented Oleophilic Bio Barrier (OBB) technology.

Herein, the project background is discussed, the Conceptual Site Model (CSM) is considered and the design and implementation of the OBB technology is described. Also included is a discussion on sustainability, project highlights, lessons learned, and conclusions. Sustainable remediation is further discussed within the UK Sustainable Remediation Forum (SuRF-UK) framework (CL:AIRE, 2010) and its Supplementary Report 1 (CL:AIRE, 2020).

2. PROJECT CONTEXT AND SITE DESCRIPTION

A "sheen" is a film with iridescent appearance, which can occur on the surface of water. Sheens can occur as a result of natural processes, such as decaying organic matter or bacterial processes, or from manmade pollution events. Petroleum sheens (Figure 1) can be encountered on the surface of water bodies adjacent or near to facilities where historical subsurface petroleum releases have occurred.

The industrial revolution led to the development of coastal and river transportation routes and the surrounding land. The historical development and associated industrial activities have, in some cases, resulted in land contamination. Where sites are contaminated with hydrocarbons, this can impact the adjacent water bodies. In these instances, many traditional forms of remediation are frequently found to be unsuitable solutions, being both unsustainable and costly. Traditional methods are often limited by such factors as:

- Access restrictions due to location of sheen instances (on water bodies);

Figure 1: Photograph of sheening.

- On-going active industrial practices restricting access;
- High costs associated with immediate solution of removal of source material; and
- Stringent remediation compliance criteria due to LNAPL impact on water bodies being unacceptable even at low levels, particularly due to visual impacts.

The site is planned to be remediated as part of a complex wider scheme, however the client required a separate remedial solution to address localised sheening events on the river. Arcadis worked closely with the client to understand the potential sources of the contamination and the mechanisms by which this sheen was being created in order to develop and design a robust solution.

3. CONCEPTUAL SITE MODEL

A detailed data review was conducted to develop a CSM to understand the potential source of the sheens, the mechanisms by which the sheens were being generated, and quantify the contaminant mass flux. Details of some of the information obtained and reviewed are included below.

Concawe
Environmental Science for European Refining

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Site generated data

- Time lapse photography
- Tidal observations
- Sediment sampling on the foreshore
- Directional drilling site investigation to gather data from beneath the inaccessible foreshore area

External sources of data

- National River Flow Archive (NRFA) Records
- Digital Marine Chart Published by GPS Nautical Charts
- Historical Weather Data (Figure 2)

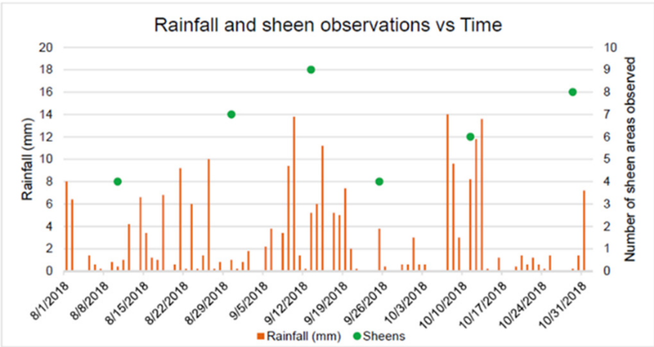

Figure 2: Weather data used with sheen observations prior to remedial works.

The data review concluded that the sheens were generated due to both seepage and ebullition (the release of LNAPL bubbles from sediments into overlying water), observed during rising and falling tides with increased prevalence around mid-tide levels.

The Bonn Agreement Oil Appearance Code (BAOAC; IPIECA-OGP 2015), which identifies categories of sheen appearance that have been correlated to sheen thickness, was used to characterise the observed sheen events. BAOAC ranges from silver (thinnest) to dark (thickest) sheen. Historical observations of sheens were primarily described as "slight", which were interpreted as BAOAC silver sheen, and were occasionally described as "widespread," which were interpreted as BAOAC dark sheen.

4. ASSESSMENT FUNCTION

Understanding the sources of the contamination and the mechanisms by which the sheen was being created was a key component in developing and designing a robust solution.

4.1 Oleophilic Bio Barrier concept

Arcadis developed a concept design for the installation of its patented OBB technology (Figure 3). This is a novel sediment remedy for mitigating sheens through the innovative application of oleophilic geo-composites (Figure 4).

The OBB is comprised of layers of Reactive Core Matting® (RCM®, as manufactured and trademarked by CETCO), and geo-composite mats (in this case manufactured by SKAPS).

[1] Drawing up and spreading of oil across the surface via capillary action.

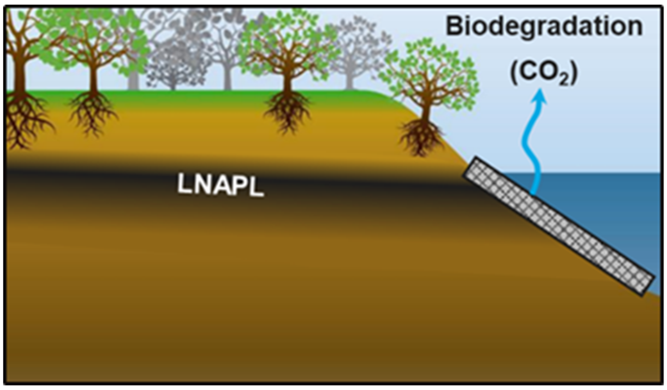

Figure 3: Concept design for OBB technology.

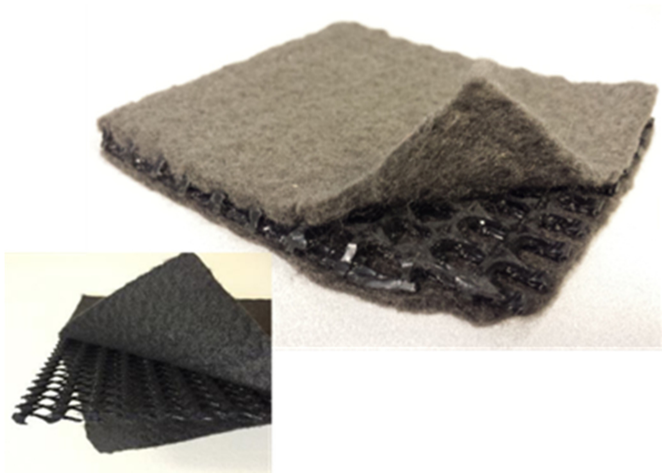

Figure 4: Geo-composite mats.

The RCM® contains an organophilic clay material that binds strongly with oils that flow into the mat without impacting water flow. These organophilic clays are manufactured using an ion exchange process that replaces sodium, calcium and magnesium ions of bentonite clay with quaternary amine compounds (Alther, 2010). This ion exchange process transforms bentonite clay from hydrophilic to oleophilic (meaning that instead of swelling / absorbing water, it absorbs oils). The RCM® also spreads, or wicks[1], the oils across its surfaces, which are constructed of polypropylene geotextiles that are also oleophilic in nature.

If the capacity of the RCM® is exceeded, the oils that pass through the mats are spread to a larger surface area, where they contact the geo-composite product. This product retains oils on its polypropylene geotextiles, while delivering oxygen and nutrients through its high density polyethylene core to microbial communities that populate the mat and degrade the retained oils.

4.2 Design of the barrier

The site-specific design of the OBB is included below and shown in Figure 5:

- Three layers of RCM®;
- One layer of geo-composite;
- Layer of 60 mm x 40 mm aggregate filter material; and
- Layer of 300 mm x 200 mm stone armour.

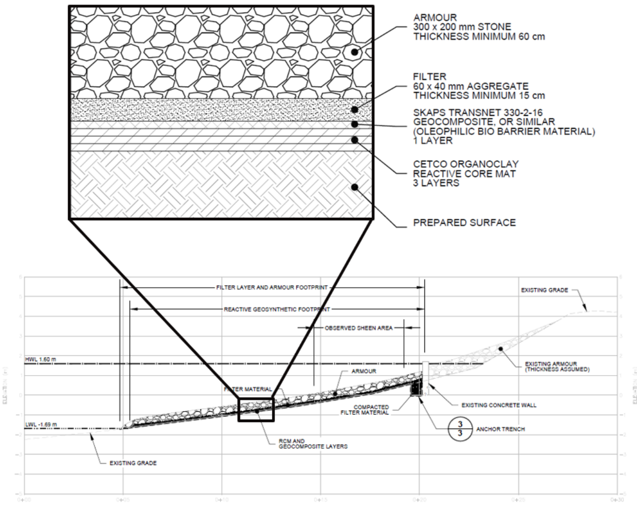

Figure 5: Layering and design of OBB.

The initial design details incorporated a number of assumptions such as rock armour thickness, construction make-up of the existing concrete wall structure, and the source of LNAPL, sheening mechanisms and flux estimates which were based on the previously developed CSM.

4.3 Installation process

The installation process took 5 weeks to complete on site and is outlined in the following sections.

4.3.1 Protection of the environment

During the installation of the OBB a number of environmental protection measures were deployed including:

- A floating containment barrier anchored to the foreshore (black and orange floating structure, Figure 6);
- Absorbents tied to the containment barrier to absorb any liberated LNAPL or sheen (white booms, Figure 6);
- Silt curtain deployed to riverbed to prevent turbidity generated by the works being released to the wider river environment (not visible in Figure 6);
- Ecologist Supervision – a trained and independently accredited individual deployed to observe the works and ensure protected birds and mammals in the area were not disturbed due to the works (this was also a permit requirement).

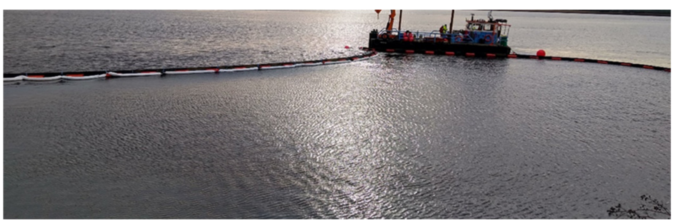

Figure 6: Floating containment and absorbents.

4.3.2 Rock armour removal and surface preparation

The rocky foreshore area was first prepared by removing the rock armour and exposing the contaminated sediments using a terrestrial-based long reach excavator, supported by marine-based plant situated on a 'spud legs' pontoon vessel. Rock armour removal was undertaken in a staged approach to allow assessment of the materials for potential reuse. Preparation of the sediment surface was undertaken to ensure that it was free of debris, protrusions and / or other potentially harmful materials that could otherwise damage the barrier during installation.

Following rock armour material removal, a number of trial pits were excavated to characterise the materials and environmental conditions. This revealed not a single point of sheen generation, but a layer of LNAPL impacted materials beneath the rock armour. Environmental samples were also taken to demonstrate baseline conditions present at the time of OBB installation.

4.3.3 OBB cutting and laying

RCM® and OBB geo-composite were rolled out (Figure 7) and cut to size into individual segments or panels and numbered, adjacent to the installation area. Cut panels were re-rolled onto plastic tube cores to allow a lifting bar and straps to be used for the installation works (Figure 8).

Figure 7: Rolled out RCM® and OBB geo-composite.

Figure 8: Cut and rolled up segments or panels.

The area of the OBB installation was within a significant tidal range of the river, dramatically limiting the working window on the foreshore to only a few hours per day around the low tide event. Individual panels (with plastic roll core) were lifted into position using lifting straps and a long reach excavator. The roll out of individual panels was positioned by hand, with pre-designed amounts of lateral and medial overlap.

4.3.4 Placement of anchor trench and filter stone

The strips of matting were lapped into trenches at the top and bottom of the barrier area, and concrete blocks were placed into the trenches to anchor the mats in place. At the low tide mark, this involved lowering concrete blocks using a HIAB crane installed on a specialist Multicat vessel, working alongside a diver to guide placement and disconnect the lifting tackle.

Following the deployment and installation of the OBB materials a layer of filter stone (Figure 9), followed by a layer of rip rap or rock armour was installed over the barrier area to complete the installation works and ensure the barrier was both secured in place and protected from the frequent storms that occur in the area.

4.4 Post-installation monitoring

Post-installation condition is shown in Figure 10. Observations were made during the demobilisation period to assess the initial conditions around the OBB. Notes were made at near low tide, high tide and during falling and rising tidal conditions, and no hydrocarbon-based sheen or olfactory evidence was noted.

Figure 9: Area of filter stone placement.

Figure 10: Post-installation condition.

A period of regular (minimum weekly) sheen and odour monitoring was undertaken by the client immediately following the installation, after which monitoring was undertaken on a less regular basis, but no less than twice per month. In the three-year period since the installation was completed no sheening events or olfactory evidence of hydrocarbon contamination have been noted at any of the tidal stages observed.

5. SUSTAINABILITY ASSESSMENT

5.1 Methodology

A retrospective, qualitative assessment of the sustainability of the remediation options considered as part of this project was undertaken in line with guidance outlined in the UK Sustainable Remediation Forum (SuRF-UK) framework (CL:AIRE, 2010) and its Supplementary Report 1 (CL:AIRE, 2020).

The SuRF-UK framework identifies six key principles of sustainable remediation, summarised below:

- Principle 1: Protection of human health and the wider environment
- Principle 2: Safe working practices (for workers and local communities)
- Principle 3: Consistent, clear and reproducible evidence-based decision-making
- Principle 4: Record keeping and transparent reporting (including assumptions and uncertainties)
- Principle 5: Good governance and stakeholder involvement
- Principle 6: Sound science

The sustainability assessment was completed using the Tier 1 Sustainability Assessment Spreadsheet Tool provided by SuRF-UK which enables assessment of the remediation project in accordance with SuRF-UK's guidance.

5.2 Framing of the sustainability assessment

The SuRF-UK framework recognises that in many circumstances, a practitioner does not have an opportunity to influence the design work. They are only asked to implement the remediation solution to deliver the design requirement. This represents a Stage B framework process. At this stage the remediation options appraisal can only seek to identify the technologies or techniques to achieve risk-based remedial objectives and also optimise the net (social, environmental and economic) benefit provided by the remediation.

This is the case for the project discussed herein in which the project goals required a solution to directly address and mitigate the sheening problem. Common options to address this issue were explored and are presented within the sustainability assessment below, alongside the technology implemented (i.e. OBB). The options were:

- Groundwater pumping and treatment of LNAPL (pump and treat);
- Sheen capture via installation of temporary sorbent booms;
- OBB technology to capture, retain and degrade sheen;
- *In Situ* Stabilisation and Solidification of impacted soils (ISS);
- Excavation and disposal of impacted soils ("dig and dump").

The main constraints of this project were as follows:

- Technology needed to address the sheening problem directly, as the site was planned to be remediated as part of a complex wider scheme.
- The location of the site, on a tidal riverbank, created space and access constraints.
- Sensitive environmental area, therefore, works required detailed planning and regulatory discussions to ensure that appropriate control and mitigation measures were in place.
- The site must be restored to a similar physical profile following works.

5.3 Evaluation of options and scoring

The sustainability assessment considered the potential environmental, social and economic costs and benefits in order to select the optimum remediation solution in terms of sustainable remediation. In the Tier 1 assessment, each indicator or criterion is unweighted (all indicators are perceived of equal importance).

Scoring was undertaken proportionately, with options being assigned equal scores where differences between them were marginal. A ranking scale ('0' denoting "worst" to '3' denoting "best") was applied to each sustainability indicator and the results aggregated.

5.4 Tier 1 sustainability assessment results

The output of the SuRF-UK Tier 1 Sustainability Assessment Tool is presented in Table 1. Justifications of assigned scores are discussed in Section 5.5.

Table 1: Tier 1 Sustainability Assessment Indicators and Scoring (Output of the SuRF-UK Tier 1 Sustainability Assessment Tool).

Technology		Sheen Mitigation - Remediation Technologies				
		Groundwater pumping and treatment of LNAPL	Sheen capture (installation of temporary sorbent booms	OBB to capture, retain and degrade sheen	ISS	Excavation and disposal of impacted soils
Social Indicators						
Human Health and Safety	Long Term	No Risk to Human Health Receptors based on existing Conceptual Site Model				
	Short Term, e.g. site workers	2	2	2	1	1
Ethics and Equity		1	2	3	1	2
Neighbourhood and Locality		2	2	3	2	1
Communities and Community Involvement		2	2	2	2	2
Uncertainty and Evidence		2	2	2	2	3
Social Score		**9**	**10**	**12**	**8**	**9**
Economic Indicators						
Direct Economic Costs and Benefits		1	2	2	1	1
Indirect Economic Costs and Benefits		1	1	3	3	3
Employment & Employment Capital		3	2	3	3	3
Project Lifespan		2	2	2	3	3
Project Flexibility		2	3	3	2	3
Economic Score		**9**	**10**	**13**	**12**	**13**
Environmental Indicators						
Air Quality / Climate Change		2	3	3	3	2
Soil and Ground Conditions		1	1	2	2	3
Groundwater and Surface Water		3	2	3	2	2
Ecology		2	2	2	1	1
Natural Resources and Waste		2	3	3	1	0
Environmental Score		**10**	**11**	**13**	**9**	**8**
Overall Summary						
Overall Score		**28**	**31**	**38**	**29**	**30**

5.5 Rationale of individual indicator scores

Social Indicators

Human Health and Safety (H&S)
Technologies scored higher where the technology effectively manages risks in the project (short term) in terms of delivery of mitigation of unacceptable human health risks to site workers, neighbouring residents and the public. ISS and excavation and disposal approaches both scored lower for social H&S elements due to the scale of earthworks plant and site works required in relation to the potential risks and increased H&S concerns.

Ethics and Equity
The OBB had the highest score as the remediation technology and timescales for remediation are more than proportionate to the level of improvement required, as it will directly target the sheening with long term effect.

Neighbourhood and Locality
Excavation of the impacted soils scored lowest due to the high impact expected with this technique in terms of impact to neighbourhood (e.g., dust, noise, light).

Communities and Community Involvement
All technologies scored similarly, whereby the implementation of all the considered remediation technologies would have a minor impact to the local community.

Uncertainty and Evidence
Excavation scored highest, due to the certainty that removal of the impacted soils would in turn reduce the likelihood of further sheening events. All other technologies considered would reduce or prevent sheening events, but with a lower level of certainty.

Economic Indicators

Direct Economic Costs and Benefits
Pumping and treatment of groundwater, ISS and excavation scored lower due to high costs associated with large scale plant and works (as noted above), operation and maintenance costs and waste disposal. The sheen capture would be low cost, however, would require regular maintenance. The OBB operation would incur moderate capital and low maintenance costs.

Further to the low maintenance costs, specific to the OBB, economic benefits would arise due to estimated design life for the OBB being at least 17 years. This is based on current site conditions, an infinite source mass, the retention capacity of the barrier components, and the estimated sheen flux. Once the planned wider remediation scheme is underway there will be a reduction in the up-stream source of the LNAPL with a corresponding reduction in the sheen flux at the OBB area. Therefore, resulting in an extension of operational barrier lifetime. The design of the rock armour installed over the barrier area also helps to ensure the barrier is both secured in place and protected from the frequent storms that occur in the area.

Indirect Economic Costs and Benefits
Pumping and treatment of groundwater and sheen capture scored lowest, as they may not enable site regeneration in the short term and would usually be used as a temporary or ongoing management solution. All other technologies scored highly due to the active treatment and / or removal of the affected soils / water allowing for regeneration and therefore indirect cost reduction in the short term.

Employment & Employment Capital
When considering this factor for job creation, employment levels (short and long term), skill levels before and after, opportunities for education and training, innovation and new skills - all technologies scored highly (and similarly) for this due to the need for 'employment' of specialists – either in active treatment and / or removal of the affected soils / waters. Sheen capture scored lowest as it is a short-term solution and may not enable site regeneration in the short term.

Whilst traditional bioremediation schemes are often seen to be a slower form of remediation, the OBB remediation scheme was developed to immediately address the sheening events on the adjacent river whilst creating an ideal environment for the microbial communities to establish and populate the mat to degrade the retained oils, allowing for site regeneration in the short term.

Project Lifespan
Excavation and ISS are well proven with stable timescales for application, so scored highly. The other technologies have timescales for implementation which can be reasonably estimated.

Project Flexibility
The technologies assessed can all be adaptable to changing conditions (on site, regulatory / local needs), however ISS can be adaptable at design phase only, so scored moderately along with groundwater pumping and treatment. The sheen capture, OBB and excavation and disposal scored highly as they are readily adaptable to changing conditions.

Environmental Indicators

Air Quality / Climate Change
Pumping and treatment of groundwater scored lowest due to the possible need to treat any vapour phase contamination associated with pumping of contaminated groundwater. Excavation and disposal scored moderately due to the associated emissions of plant and vehicles required for the works as well as the release of hydrocarbon vapour into the atmosphere during excavation works. The rest of the technologies scored highly as there would likely be negligible air emissions which do not require treatment.

Soil and Ground Conditions
Pumping and treatment of groundwater, as well as sheen capture, scored lowest due to limited positive impact on soil quality. Excavation scored highest, due to removal of impacted soils. The OBB and ISS would have an overall positive impact on soil quality due to removing or stabilising some of the impacted soils.

Groundwater and Surface Water
Pumping and treatment of groundwater, as well as the OBB, scored highest as these would have the most significant positive impact on groundwater quality or local surface water features. Other technologies would likely have an overall positive effect.

Ecology
The site is designated as ecologically sensitive. All technologies scored moderately or lower as the works could potentially impact ecology, and a management plan would be required. Excavation and disposal as well as ISS scored lowest due to the high impact of the works, which would likely require active mitigation. For the OBB, due to the ability to visually integrate the barrier into the surrounding area there was, and still is, a negligible disruption to the ecology in the vicinity with no visual impact as the works included restoring the disturbed foreshore to match the existing surroundings.

Natural Resources and Waste
Often, traditional remediation technologies will use higher levels of energy and create multiple waste streams, particularly with excavation and disposal, which scored the lowest. Sheen capture would be a low energy technique with negligible waste streams, so scored highly. The OBB also scored highly due to being low energy and able to minimise waste streams. The application of an OBB, in preference to a number of traditional sheen mitigation schemes that would require the wholesale or large-scale removal of impacted materials, minimises waste being generated on site and subsequent disposal to off-site sources.

5.6 Sustainability assessment conclusion

The sustainability assessment indicated that the OBB technology selected would provide the optimum remediation approach based on the assessment where potential social, economic and environmental impacts are considered of equal importance.

The selected remediation technology employed methods which minimised potential environmental, social and economic impacts at every stage throughout the project design and delivery, where possible and practicable to do so.

6. PROJECT HIGHLIGHTS

This project produced a number of highlights, including:

- Overcoming the challenging significant tidal range of the river, by working with a commercial diving team for in-water work and underwater excavation of trenches. Without the commercial diving team, the tidal range would have limited the working window to a few hours around the low tide event.
- Proactively managing the environmental challenges of working within an ecologically sensitive area through detailed planning and regulatory discussions, ensuring that appropriate control and mitigation measures were in place to prevent detrimental impact on the local environment and ecology.
- The implementation and installation works of the OBB representing a European first application. They were undertaken in highly challenging conditions, as referenced above, with no incidents or accidents.

7. LESSONS LEARNED

As would be anticipated from one of the first applications of a new remedial solution, there were lessons learned from the project identified in the design phase, pre-works and installation phases, with the main lessons learned summarised below:

Conceptual Site Model Uncertainty and Design Flexibility
The OBB design provided a barrier area and panel layout configuration. This required that each barrier panel be constructed from a continuous piece of fabric, reducing the ability to cut and reuse excess material. During installation works site conditions were found to be slightly different to those anticipated at the design stage and the coverage required for the OBB had to be increased to accommodate this variation. Allowing placement of excess cut materials (and specifying how to overlap these cut materials) could be added to the design to allow more flexibility during construction and minimise material wastage.

While the OBB design is inherently flexible and barrier coverage can be readily increased if required, this can lead to delays during the site works. As such it is desirable to undertake as much direct investigation of the target area as possible to aid the design process and ensure the area in question is as robustly understood as possible. While this would add expense to the design phase, it would add more certainty to the installation programme and potentially save on construction downtime costs, should it be necessary to increase the barrier area. However, it should be noted that typical locations for OBB installations can often mean that complete access is not possible in every instance (as was the case for this particular site) and as such the ability to flex the design to accommodate site specific variables encountered during installation works is a highly beneficial aspect of the OBB concept.

Licensing, Permitting and Technical Understanding of Stakeholders
Design and technical documents presented to stakeholders and non-technical consultees should be modified to account for variations in knowledge and understanding. Separation of interpretive or indicative drawings from technical design drawings would also help facilitate understanding by various stakeholders.

8. CONCLUSIONS

This design and build project represented the first application in Europe of the Arcadis patented OBB technology, with over 1,300 m^2 of oleophilic geo-composite and reactive core material installed during the project.

The installation works were successfully undertaken in highly challenging conditions and the project was completed safely, with no incidents or accidents and with no detrimental impact to the area.

It was notable with respect to working in an ecologically sensitive area within the marine environment that during discussions with key project stakeholders (e.g., local environmental protection and marine licencing authorities) many of the key sustainable attributes of the solution, when compared to alternative approaches, were integral to attaining timely approvals for the proposed works. For example, being able to limit or minimise disturbance and environmental impact in the area during the installation works, as well as the ability to integrate the barrier into the surrounding area with no visual impact or change to the foreshore area once completed, were important factors during the regulatory review period.

Following completion of the project initial evidence and observations indicate that the works have successfully mitigated the occurrence of sheen in the foreshore area and ongoing visual monitoring is continuing to ensure the demonstrable success of this OBB project. No sheens or olfactory evidence of hydrocarbon contamination have been observed in the three years of monitoring since installation.

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CL:AIRE

CON 09
(November 2023)

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 a sustainability assessment was used to help decide the remedial approach on a former petrol station site.

Natural Source Zone Depletion in a Dismantled Petrol Station

1. INTRODUCTION

In April 2009, a petrol station operated by bp was decommissioned. In 2010, bp hired AECOM to help manage the soil and groundwater hydrocarbon impact that was present at the site. Environmental works are currently underway.

These environmental works have been focused on improving the knowledge of the Conceptual Site Model (CSM) and the remediation options for the removal of the Light Non-Aqueous Phase Liquid (LNAPL) present at the site. The LNAPL is below the residual LNAPL saturation[1] in some areas of the site.

A human health quantitative risk assessment was undertaken in 2010 by AECOM which concluded that there were no unacceptable risks to receptors, and that groundwater was not used. Site characterisation efforts also determined that the LNAPL transmissivity is low and it is not feasible to hydraulically remove said LNAPL. However, the legal framework currently enforced mandates that LNAPL must be removed. Therefore, the primary remediation goal for the site is to remove the LNAPL, to the maximum extent possible. As a secondary objective, the dissolved hydrocarbon concentrations in groundwater should be reduced.

With the vast amount of information gathered, a decision had to be made on which remedial technique would be optimal to achieve the goals. This decision was made with the support of the results obtained from a sustainability assessment based on the SuRF-UK framework (CL:AIRE, 2010) and the ISO 18504:2017 standard (ISO, 2017). Following the tiered approach to the sustainability assessment (from Tier 1, qualitative, to Tier 3, quantitative), the remedial option was selected based on a Tier 2 assessment, which is detailed further herein.

In the following sections, the CSM, investigations undertaken at the site and the sustainable remediation assessment process are presented. Finally, the main conclusions can be found.

2. SITE DESCRIPTION

This site was occupied by a petrol station built in 1966 and decommissioned in 2009. The above-ground equipment and buildings were removed and the underground infrastructure was left in place but filled with solid foam (piping) and grout (tanks). The petrol station stored fuel in nine 20,000 L capacity underground tanks. The entire surface of the site is covered by asphalt hardstanding, which is currently in poor condition with many holes and cracks. A former abstraction well, used to supply a car washing tunnel, is located adjacent to the eastern border of the site. The well was decommissioned and sealed and is now paved over (Concawe, 2020).

The site is in an urban area and surrounded by a hotel to the west, an industrial area further west, commercial and industrial areas to the east and the south, agricultural land further to the south and a residential area to the north.

3. CONCEPTUAL SITE MODEL

3.1 Local geology

The geology is composed of anthropogenic fill material of gravels in a sandy matrix to a depth of 2 m below ground level (bgl). The fill material is underlain by natural soil of gravels and pebbles in a silty matrix to a depth of 12 m bgl. This material is underlain by compact loamy clays mainly in the western area, gravels in silty clay matrix mainly in the eastern area and sandstone from 15 m bgl (see Figure 1).

[1] Residual LNAPL saturation is defined as the saturation under which the LNAPL is "immobile under the applied gradient". LNAPL below residual saturation is neither mobile nor hydraulically recoverable; although a technology that changes the LNAPL physically or chemically may be capable of increasing contaminant mass recovery (EnvGuide, 2022).

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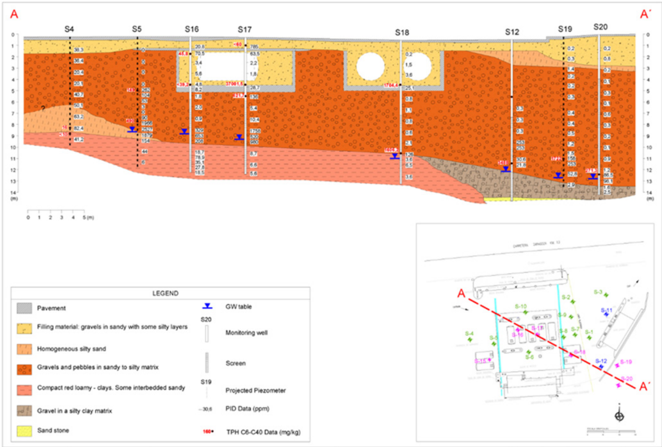

Figure 1: Site cross section.

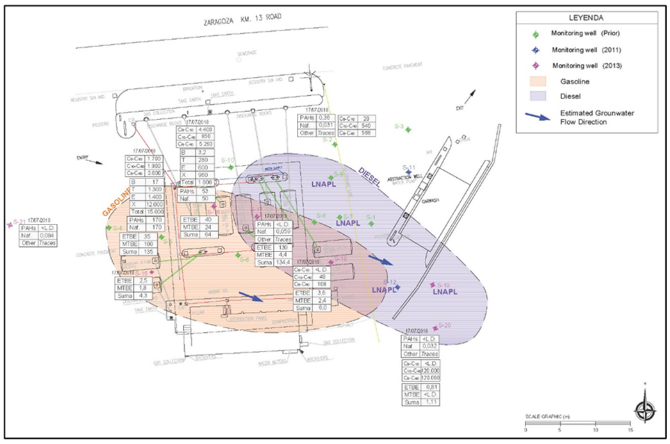

Figure 2: Groundwater contaminant concentrations (July 2018) and estimation of areas of gasoline and diesel impacts.

3.2 Hydrology

The main watercourse is a river located 400 m to the east. It flows towards the northeast. Also, several irrigation channels were identified, collecting surface water from a reservoir located 3.5 km to the west.

3.3 Hydrogeology

No groundwater bodies of regional interest were found in the literature, although there may be aquifers of local interest. Locally, the aquifer is in the gravel layer (quaternary terraces of the adjacent river). The permeability of the free alluvial aquifer is medium to high. However, the transmissivity is low due to the limited thickness of the saturated zone as was observed during the drilling of boreholes to install monitoring wells. The base of the aquifer is made up of clay and sandstone. The main hydrogeological features are:

- Groundwater table depth from 8 to 11 m bgl.
- Groundwater flow direction to the east-southeast.
- Hydraulic gradient from 1%, in the west and east of the site, to 5% in the central area.
- Low thickness of the saturated zone, between 1 and 2 m.

4. AREAS OF CONCERN

4.1 Hydrocarbon distribution

Figure 2 shows the baseline concentrations of Total Petroleum Hydrocarbons (TPH) measured in July 2018.

Two impacts were identified:

- A diesel-related impact in the eastern area, where LNAPL was identified. This area is shown in Figure 2 as a purple shaded area.
- A gasoline-related impact in the western and central area, where the concentrations of hydrocarbons are mainly due to the presence of lighter fractions of TPH, benzene, toluene, ethylbenzene and xylenes and the additives methyl tert-butyl ether / ethyl tert-butyl ether - orange shaded area in Figure 2.

The impacted areas of diesel and gasoline are estimated at 190 and 125 m^2, respectively.

In 2014, the LNAPL thickness distribution profile was estimated by taking well measurements (Figure 3).

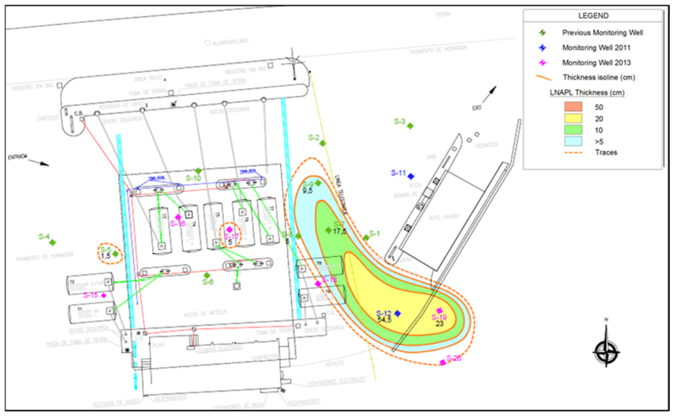

Figure 3: Thickness of the LNAPL plume, May 2014.

This study showed the plume was not expanding. Using the API Interactive LNAPL Guide[2] to estimate saturation, it was observed that LNAPL saturation at the edge of the plume was below the literature residual saturation values (between 5% and 10%, given the soil and LNAPL type and concentration (Brost and DeVaull, 2000)). Residual saturation can be defined as the value below which LNAPL is neither mobile nor hydraulically recoverable (EnvGuide, 2022), thus no further LNAPL migration processes were expected.

The total mass of LNAPL in the saturated zone was approximately 1200 kg (estimated from a volume of 1400 L of diesel, assuming a density of 0.86 g/cm^3).

5. NATURAL SOURCE ZONE DEPLETION STUDY

A detailed Natural Source Zone Depletion (NSZD) study was launched in 2016, including testing of several monitoring methods of NSZD to evaluate the most appropriate for a paved site. Naturally occurring processes of biodegradation were quantified with the estimation of a

[2] https://www.api.org/oil-and-natural-gas/environment/clean-water/ground-water/lnapl/interactive-guide

biodegradation rate. The following monitoring methods were included (Concawe, 2020):

- Gradient method based on measurement of O_2 and CO_2 concentration profiles.
- Thermal approach that quantifies NSZD rates based on heat generation in the source zone related to biodegradation of TPH.
- Passive CO_2 flux traps that capture CO_2 generated by microbial degradation of TPH as the CO_2 is discharged from the subsurface to the atmosphere.

All three methods provided strong qualitative evidence that biodegradation is taking place at significant rates at the site. While the quantitative estimations of biodegradation rates varied between methods, the results generally reflected the complexity of the processes responsible for NSZD, and the interferences that each method is subject to under the unique conditions at the site.

6. SUSTAINABILITY ASSESSMENT

Following the site assessment phase, work was undertaken to select the preferred remedial option. To support the decision, a sustainable remediation assessment was conducted to identify the optimal sustainable approach. The selected solution would address the impacted areas, minimise risks to receptors, and be accepted by stakeholders (regulators, land owner, bp, neighbourhood). As a first step, a Tier 1 SuRF-UK sustainable remediation assessment was undertaken. As a support document, the ISO 18504:2017 of Soil Quality – Sustainable Remediation was considered.

The following constraints (CL:AIRE, 2020a) were identified and considered in the process:

- The need to remove LNAPL (regulatory requirements).
- Although the permeability is medium to high, the transmissivity is low (low thickness of the saturated zone) and thus, hydraulic removal of LNAPL can be difficult in some areas of the site.
- The site is currently dismantled and has no infrastructures (water, energy, effluent discharge, etc.).
- The site is currently being used for parking and it is preferable that the remedial option chosen allows it to continue to be used as such.

The remediation goals for the site are to: 1) remove LNAPL and 2) reduce the dissolved hydrocarbons concentrations. To achieve these goals, the following options were evaluated, ranging from more passive to more active:

- **Option 1: Site wide NSZD**. Long-term low energy passive option (ITRC, 2011), including a long-term monitoring programme of dissolved TPH, temperature, oxygen, carbon dioxide and electron acceptors (such as nitrate, sulfate, methane, etc.) concentrations. The efficiency of naturally occurring biodegradative processes to ensure that both the LNAPL plume and the dissolved concentrations are reducing was assessed. This approach would require biannual visits.
- **Option 2: Site wide NSZD and passive skimmers in eastern area for LNAPL removal.** Long-term passive option, but timeframe could be reduced with passive skimming to remove LNAPL that accumulates in the monitoring wells of the eastern area. This approach would require a first stage of LNAPL removal with quarterly visits, which in a second stage could be biannual.
- **Option 3: Site wide enhanced natural attenuation by oxygen injection and active and passive skimmers in the eastern area for LNAPL removal.** Oxygen injection (through emitters, ceramic diffusers, etc.) would help to maintain an aerobic environment to facilitate contaminant biodegradation. Aerobic microorganisms utilise oxygen and contaminants as part of their metabolism and convert the contaminants into carbon dioxide, water, and microbial biomass. This technique would be applied site wide.
  In the eastern area, before the oxygen injection, active skimmers would be used to remove the hydraulically removable LNAPL and where LNAPL saturation is below residual saturation, passive skimmers would be installed. The system needs an air compressor for the active skimmers and a LNAPL storage tank.
  The removal of LNAPL would require monthly visits during the first year, which would be reviewed according to the volume of LNAPL recovered and the remaining concentrations in groundwater.
  The oxygen injection and active skimmers are expected to reduce the timeframe of the remediation when compared to the previous options.
- **Option 4: Soil vapour extraction (SVE) with pump and treat (P&T)**. This strategy combines two active techniques (SVE + P&T) which could help further reduce the timeframe required to achieve the remediation goals.
  The SVE consists of applying a vacuum to the unsaturated zone to induce the controlled flow of air and remove volatile contaminants from the soil. The gas leaving the soil is collected and treated.
  For its operation, a blower, an electrical connection or a generator, additional wells to achieve radius of influence and a granular activated carbon (GAC) filter to treat the extracted air before release to the atmosphere would be required.
  The P&T solution consists of installing submersible pumps to remove impacted groundwater site-wide and free-phase product in the eastern area. The mixture would be pumped to the surface and pre-treated on site. A hydrocarbon separator and effluent transport to an authorised treatment plant or connection to the municipal sewer network would be required. Also, external sources of water, energy, compressed air, etc. would be required. Finally, six additional wells would need to be installed, four in the eastern area and two in the central and western area. The implementation of this technology would require initially biweekly visits for maintenance and monitoring, and review of results in six months.

Following the Tier 1 SuRF-UK-based sustainable remediation assessment and the ISO 18504:2017 standard, the categories chosen as relevant from the sustainability indicators are provided in Table 1.

Table 1: Headline categories for sustainability indicators.

Environmental	Economic	Social
Emissions to air	Direct economic costs and benefits	Human health and Safety
Soil and ground Conditions	Indirect economic costs and benefits	Ethics and equity
Groundwater and surface water	Employment and employment capital	Neighbourhoods and Locality
Ecology	Induced economic costs and benefits	Communities and community involvement
Natural resources and waste	Project lifespan and flexibility	Uncertainty and Evidence

The categories in grey (Table 1) were excluded as they were not substantially different between remedial options for the following reasons:

- Soil and ground conditions: none of the options would change soil or geotechnical functionality.
- Ecology: no sensitive receptors were identified in the proximity of the site that would be affected.
- Employment and employment capital: the options will not have differentiating outcomes in the local opportunities for job creation in the community.
- Induced economic costs and benefits: this category is already covered in the indirect economic costs and benefits.

The criteria were all considered to contribute equally to the final classification (i.e. at this stage no weighting was used to prioritise any category over another category). Individual indicators were aggregated from each category and a ranking from 1 (best option) to 4 (worst option) was established for comparison. For example, the environmental category "Emissions to air" includes various indicators such as climate change-greenhouse gases (GHG), acid rain - emissions of NO_x and SO_x and ground air quality - particulates, volatile contaminants, etc. These were aggregated to give an overall comparison by the headline category.

Table 2 (on next page) presents the classifications obtained for the categories in each option. The lines of evidence (CL:AIRE, 2020b) are also included for a better understanding of the criteria used.

As can be observed, the best classified (lowest scoring) was option 1, followed closely by option 2. The worst classified is option 4 (Figure 4).

From Figure 4, it can be concluded that option 1 is strongest for the following reasons:

- Environmental indicator: emissions to air and natural resources. This option does not include emissions except the ones associated with light road traffic for monitoring; the only material used is for sampling.
- Social indicator: health and safety, neighbourhoods and locality and communities and community involvement. No civil works are required, no noise, vibrations or air emissions, and no machine/equipment installation and operation, minimising risk to workers and others. Regarding neighbourhood, there is little nuisance and the current use of the site as parking is not hindered.
- Economic indicator: direct economic costs and benefits and project lifespan and flexibility. This option is the least expensive and therefore could better resist eventual economic changes.

Option 1, however, has low scores in the following individual categories which must be discussed as to their influence on the final decision:

- Indirect costs reflect the local community's perception of the works undertaken, i.e., the more active the technical approach, the better the perception.
- Uncertainty and evidence: approach may not be acceptable to the regulators for not actively removing LNAPL.
- Ethics and equity: the LNAPL will be in the subsurface for a long period of time which may raise intergenerational equity issues.

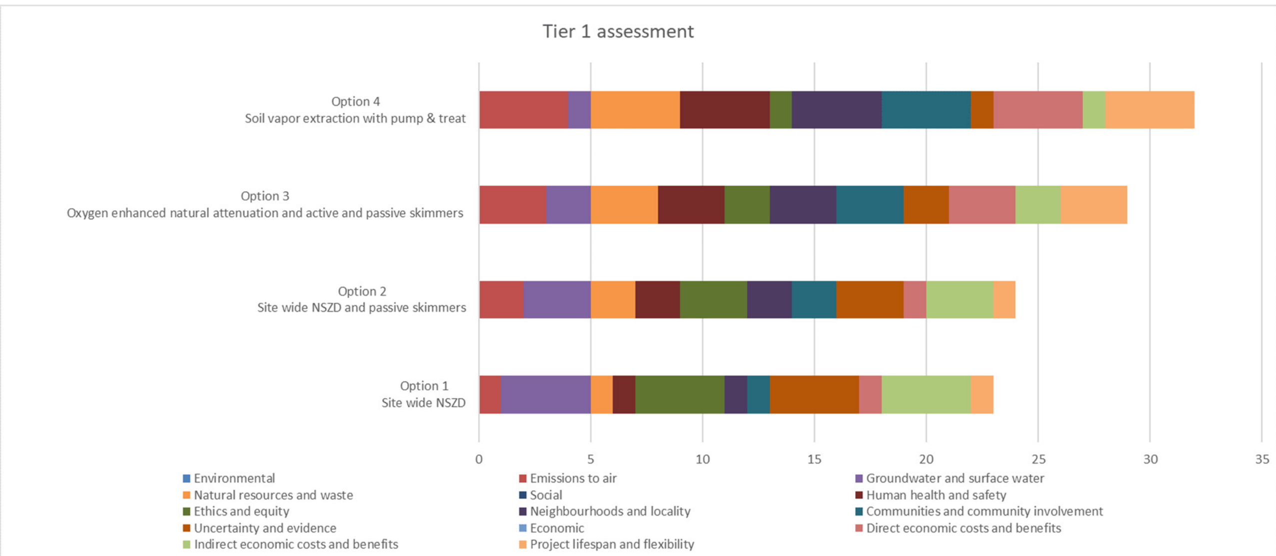

Figure 4: Tier 1 sustainable assessment cumulative scores.

Table 2: Final classifications of Tier 1 (Note: 1 – best option; 4 – worst option).

Categories	Lines of Evidence	Option 1: Site wide NSZD	Option 2: Site wide NSZD and passive skimmers	Option 3: Oxygen enhanced natural attenuation and active & passive skimmers	Option 4: SVE and P&T
Environmental Indicator					
Emissions to air	• Combustion from generators or other equipment / machinery • Emissions: ◊ volatile compounds (effluent and LNAPL storage, SVE system) ◊ transport of equipment / machinery ◊ particles, dust and GHG • Medium to long term occasional emissions of gases by vehicles	1	2	3	4
Groundwater and surface water	• Timeframe for achieving goals	4	3	2	1
Natural resources and waste	• Energy resources (compressor, pumps) • Waste generation and legacy impacts (LNAPL, GAC, contaminated personal protective equipment (US EPA, 2008), sampling disposable material, purge water) • Fossil fuels consumption	1	2	3	4
Social Indicator					
Human health and safety	• Machinery / equipment hazardous to workers (compressor, generator, etc.) • Road transport of machinery /equipment • Civil works • Transport of hazardous waste off-site	1	2	3	4
Ethics and equity	• Timeframe for achieving goals associated with probability of transferring contamination to future generations	4	3	2	1
Neighbourhoods and locality	• Noise from equipment / machinery • Heavy load traffic • Dust (civil works)	1	2	3	4
Communities and community involvement	• Restrictions of use of parking (civil works or equipment installation)	1	2	3	4
Uncertainty and evidence	• Likelihood of regulatory acceptance	4	3	2	1
Economic Indicator					
Direct economic costs and benefits	• Costs of installation, operation and maintenance (drilling, monitoring, permitting, etc.)	1	1	3	4
Indirect economic costs and benefits	• Corporate reputation: neighbourhood perception of the remediation is likely to be more favourable in the presence of permanent equipment and machinery, as the approach is perceived as more intense and faster	4	3	2	1
Project lifespan and flexibility	• Flexibility and resilience to cope with changing economic conditions and circumstances (if the pollutant - petrol station operator - has changes in its economic conditions)	1	1	3	4
Overall		23	24	29	32
		Best option	Better / average option	Worse / average option	Worst option

Table 3: Weighted categories for Tier 2 sustainability assessment.

Environmental		Economic		Social	
Category	Weight	Category	Weight	Category	Weight
Emissions to air	3	Direct economic costs and benefits	3	Human health and Safety	1
Soil and ground conditions	-	Indirect economic costs and benefits	1	Ethics and equity	0
Groundwater and surface water	0	Employment and employment capital	-	Neighbourhoods and Locality	1
Ecology	-	Induced economic costs and benefits	-	Communities and community involvement	1
Natural resources and waste	3	Project lifespan and flexibility	0	Uncertainty and Evidence	3

Option 4 (SVE and P&T), which is the most active and shortest-term, is the most penalised in the assessment, mainly due to the following individual categories / indicators:

- Greatest use of natural resources and waste generation.
- Greatest health and safety risks, due to the installation of machinery, increasing road traffic for equipment transport and monitoring, noise emitted by the machinery, need for civil works, etc.
- Greatest impact on the neighbourhood and locality, due to the higher nuisance caused (civil works, volatile compounds emissions, noise, loss of parking space, etc.).
- Greatest direct economic costs, given that this is the most expensive one, considering installation, operation and maintenance.
- Project lifespan and flexibility: this option is the most expensive one to implement and maintain and in case of economic changes, it is less resilient.

For the reasons mentioned above, options 3 and 4 were discarded as they are deemed to be less sustainable.

Overall, option 1 was the best classified, with a slight score difference from option 2. However, careful consideration was given to the timeframe associated with this technique and in ensuring the approach would be in line with regulatory requirements. Given these considerations and the closeness of scores between options 1 and 2, a Tier 2 evaluation was undertaken.

In the Tier 2 process, options 1 and 2 were further evaluated following a weighted multi-criteria comparison (Brinkhoff, 2011; United Kingdom Department for Communities and Local Government, 2009). The categories were weighted according to their relative importance in the final decision. Table 3 presents the weights for each category as 0, 1 and 3, with 0 being the lowest weight and 3 the highest.

The highest weight was given to the categories emissions to air; natural resources and waste; direct economic costs; and uncertainty and evidence, as these are considered to be most relevant to the stakeholders. Also, a numerical score from 1 to 5 was given to each category in both options. Preferred options (i.e. those options considered more sustainable) scored higher.

To compare the two options more accurately, the timeframe to achieve the remediation goals was estimated as 48 years in option 1 and 42 years in option 2. The same hydrocarbon mass removal was assumed for both options. The calculations were made considering the biodegradation rates that were estimated in the 2016-2020 NSZD field study. The timeframe was based on the hydrocarbon mass removal rate and the LNAPL volume removal considering the technical specifications of the skimmers.

The following parameters were chosen to be assessed for both options (Table 4) because of the lack of bias associated with their estimation:

- Carbon footprint;
- Waste volumes; and
- Direct costs.

Table 4: Quantitative estimations of carbon footprint and waste volume.

Remedial option	Carbon footprint (tonne CO_2)	Waste volume (kg)
Option 1	0.79	537
Option 2	0.96	779

Rationale
For the carbon footprint, the following assumptions were made:
- 3144 L of gasoline in option 1
- 3767 L of gasoline in option 2
- Waste in option 1 includes sampling waste (tube, gloves, absorbent paper, plastic bottles)
- Waste in option 2 includes sampling waste and LNAPL associated waste (skimmers, absorbents)

The carbon footprint calculation spreadsheet was developed by AECOM to calculate both direct and indirect GHG emissions of remediation works. The methodology is based on the ISO 14064:2019 and ISO 14069:2013. GHG emissions are calculated according to:

GHG emissions = Activity data factor * Emission factors

The activity data factor represents the operation generating GHG emissions (fuel consumption, distance travelled, etc.). Emission factors derive from the information published by the Spanish Ministry of Ecological Transition and Demographic Challenge (2021) and United Kingdom Department for Environment, Food & Rural Affairs (2021).

Table 5: Weighted scores and results of Tier 2 sustainability assessment (Note: the higher the score, the better the option, i.e. more sustainable).

Category	Weight	Option 1 Site wide NSZD		Option 2 Site wide NSZD and passive skimmers	
		Score	[Weight x Score]	Score	[Weight x Score]
Environment					
Emissions to air	3	5	15	4	12
Groundwater and surface water	0	-	0	-	0
Natural resources and waste	3	5	15	2	6
Social					
Human health and safety	1	4	4	4	4
Ethics and equity	0	-	0	-	0
Neighbourhoods and locality	1	5	5	5	5
Communities and community involvement	1	5	5	5	5
Uncertainty and evidence	3	1	3	3	9
Economic					
Direct economic costs and benefits	3	5	15	5	15
Indirect economic costs and benefits	1	1	1	2	2
Project lifespan and flexibility	0	-	0	-	0
Final result [Weight x Score]		63		58	

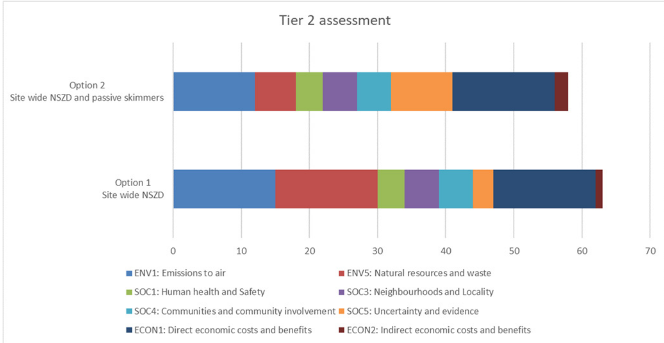

Figure 5: Tier 2 sustainability assessment cumulative scores.

The matrix and graphic results obtained are presented in Table 5 and Figure 5.

Tier 2 reinforces the results obtained in Tier 1, of option 1 as the most sustainable (highest global result and highest score in the categories with the highest weights) although the gap between both options is still slight.

There is however one high weighted category in which option 1 obtained the lowest score, which is Uncertainty and Evidence, related to the likelihood of acceptance by the regulator. This is a key factor in the final decision and for this reason, this option should be the least preferred.

In this case, the Tier 2 results, although not decisive, were useful to reflect and highlight the importance of the categories expected to be more relevant to the stakeholders.

7. CONCLUSIONS

A Tier 1 and Tier 2 sustainability assessment methodology was applied to identify the most sustainable remedial solution to address the impacts associated with the historical operation of a decommissioned petrol station.

The objective of the assessment was to identify the optimal sustainable remediation approach for managing risks to people and the environment and achieving regulatory closure. The assessment was used to compare four options that would all achieve the remediation goals. Each option had different resource requirements, timeframes and costs. Eleven individual categories were chosen from the fifteen proposed in the SuRF-UK framework and the ISO 18504:2017 standard for their relevance in this specific case.

After the Tier 1 evaluation, two options were discarded for being the least sustainable. Option 1 scored highest. However, the score obtained for options 1 and 2 was close. Therefore, a Tier 2 assessment was undertaken to obtain a higher level of confidence in the final choice.

In the Tier 2 assessment, the two options were further evaluated and compared against each other. The carbon footprint, waste volumes generated, and direct costs were quantified for each option. These were selected due to their lack of bias. A relative weight was given to each category that would represent the hierarchy of the criteria from the stakeholders' point of view. The assessment identified option 1 as the most sustainable, which reinforced the Tier 1 assessment results, although the scores were again close to each other. The weighted approach given by Tier 2 assessment was useful to highlight the categories that were expected to be more important to the stakeholders.

Although option 1 was identified as the preferred option by the sustainability assessment, the selected approach needed to align with the request from the regulators for active removal of LNAPL. Therefore, option 2 was selected as the preferred remedial option for the site.

The results from the sustainability assessment can be a useful tool when discussing the advantages and disadvantages of each option from a sustainability view with the regulators and other stakeholders. The results from the sustainability assessment can help justify the selected remedial approach.

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CL:AIRE

CON 10
(November 2023)

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 a sustainability assessment helped to close-out a remediation.

Sustainability Assessment Case Study – Groundwater Remediation Close-Out

1. INTRODUCTION

Between 2007 and 2013 AECOM carried out active groundwater remediation to treat chlorinated hydrocarbons (CHC) which were detected within a sandstone aquifer below the site. The works formed part of a longer-term, 15-year programme of investigation and remediation of the site, a former chemical storage and distribution depot located in the United Kingdom.

AECOM completed a Sustainable Remediation Assessment (SRA) as part of the close-out of the remediation at the site. The SRA supported a 'lines of evidence' approach agreed with the regulators to evaluate if residual risks to the aquifer were acceptably low and if remediation could then cease.

2. SITE DESCRIPTION AND PROJECT CONTEXT

Initial investigation and monitoring works carried out in 2000 were to assess the condition of the soil and groundwater at the site and the contamination risks associated with historical site-use. The site had previously stored organic and inorganic chemicals, including chlorinated solvents, which were kept in above-ground storage tanks (ASTs). Figure 1 illustrates the site layout and area.

The investigation works identified the following CHC within soil and groundwater at the site: tetrachloroethene (PCE); trichloroethene (TCE); cis-1,2-dichloroethene (DCE); trans-1,2-dichloroethene; and 1,1-dichloroethane. Potential risks to human health were identified from vapour intrusion studies, together with potential risks to groundwater quality within the underlying sandstone bedrock aquifer, a regionally important groundwater resource. To address these potential risks a remediation strategy was developed and implemented.

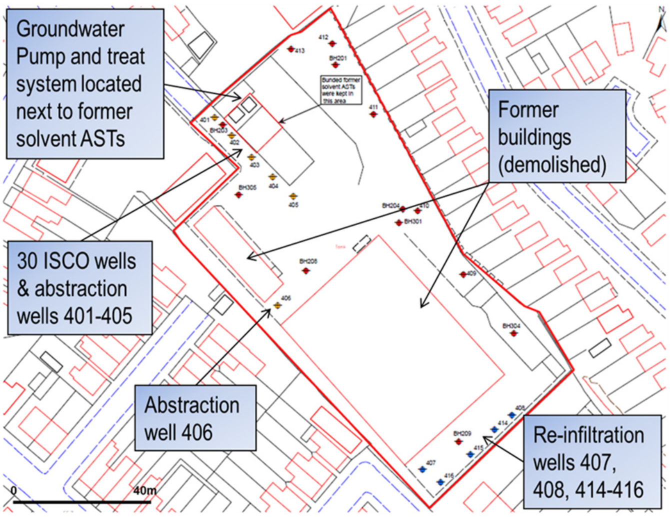

Figure 1: Site layout.

Initially a Soil Vapour Extraction (SVE) system was employed on-site, which operated from Spring 2002 until late 2003. SVE was used to mitigate potentially hazardous organic vapours and reduce contamination in the unsaturated soils in the area of the former ASTs. This remediated the unsaturated zone source and reduced the potential for further groundwater contamination. The system recovered approximately 2,100 kg of contaminant mass and was shutdown following a significant reduction in contaminant recovery rates, an updated assessment of the residual risk and agreement with the regulators that the SVE system had achieved its objectives.

To address the saturated zone impacts active groundwater remediation was undertaken from 2007 to 2013, which consisted of Pump and Treat (PT) and from 2011, *In Situ* Chemical Oxidation (ISCO). Active remediation was stopped at the end of 2013 to allow aquifer conditions to re-adjust before monitoring and further assessments were undertaken in Spring 2014.

Concawe
Environmental Science for European Refining

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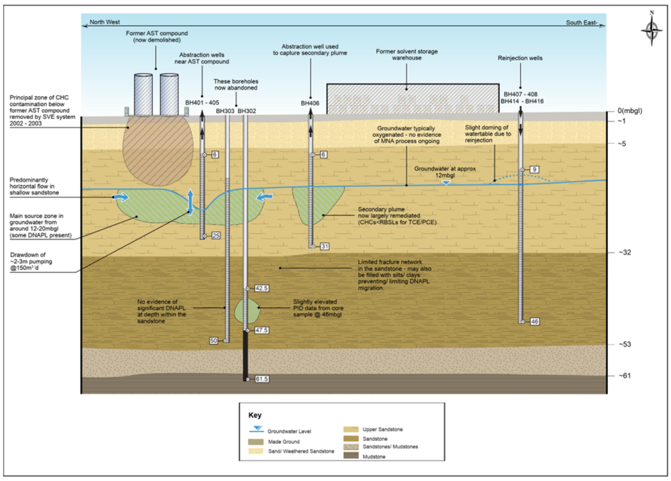
Concawe bulletin

3. CONCEPTUAL SITE MODEL

The site is situated on sandstone bedrock which is overlain by sand covered with Made Ground. The groundwater table is located within the sandstone at approximately 12 m below ground level (bgl) and varied between 9 m to 15 m bgl. The principal contamination source identified was below the former ASTs area, with CHC detected in both the unsaturated soils and within the saturated sandstone, where Dense Non-Aqueous Phase Liquid (DNAPL) was present. Figure 2 illustrates the conceptual site model prior to and during remediation.



MNA: Monitored Natural Attenuation; PID: Photo-Ionisation Detector; CHC: Chlorinated Hydrocarbons; DNAPL: Dense Non-Aqueous Phase Liquid; RBSL: Risk-Based Screening Level

Figure 2: Conceptual site model.

The sandstone aquifer was identified as the critical receptor. This supported a number of licensed abstractions for both potable and non-potable use in the wider area. The closest operational abstraction at the time of the SRA was located approximately 0.5 km from the site. Groundwater also provided base flow to local rivers, the closest of which was approximately 1 km down-hydraulic gradient of the site.

Potential human health receptors identified at the site were future site workers (assuming an on-going industrial site use) and occupiers of off-site commercial and residential buildings. These could potentially be exposed to and affected by CHC vapours volatilising from shallow contamination (subsequently remediated by the SVE system) or deeper, dissolved phase contamination (remediated by PT and ISCO).

4. ASSESSMENT FUNCTION

Following the completion of the SVE implementation, the works carried out from 2007 to 2013 focused on the sandstone aquifer, primarily on monitoring, assessment of potential migration pathways and risks, and then active remediation to mitigate these. To achieve the remediation objectives, PT and ISCO were used to reduce CHC impacts in the saturated sandstone present below the site.

PT remediation activities from 2007 to 2013 were estimated to have treated a total volume of groundwater of 158,863 m^3 (98 m^3 per day). As a result, 616 kg of contaminant mass was estimated to have been removed (of which approximately 400 kg was before the start of ISCO). The PT remediation gradually depleted CHC concentrations within the sandstone aquifer.

ISCO was carried out alongside PT between 2011 and 2013 to reduce the mass of CHC contamination via mobilisation of sorbed and DNAPL phases into groundwater, so that they were more easily recovered by the PT system, and through oxidation (breakdown) of a proportion of the CHC present in groundwater, and in doing so, enhance PT operation and shorten the duration of groundwater remediation. A total of 30 injection wells were installed at shallow and deeper levels in the saturated sandstone around the ASTs source area. Four rounds of sodium persulfate injection were carried out during which a total of 12,500 kg of reagent was injected. Monitoring indicated good distribution of reagents within the aquifer for treatment. It was estimated that the volume of sodium persulfate used was capable of destroying a CHC mass in the range of 1,100 kg to 3,200 kg, based on pre-injection, bench trial data. Results identified that using a combined approach of PT and ISCO preferentially removed TCE from the source area rather than PCE. Due to the removal of TCE and a reduction in PCE present within the source area the total combined mass discharge from the site was significantly reduced. When comparing the results of the groundwater monitoring from 2004 to 2014, the maximum detected concentration of TCE had dropped from 39.50 mg/l to 0.23 mg/l. It was conservatively estimated that 1,100 kg of CHC mass had been removed from the aquifer by the ISCO implementation, giving a total estimated mass removal of 1,716 kg by both PT and ISCO.

The cessation of active remediation and the scope of close-out monitoring, assessment and reporting were agreed with regulators in advance of the ISCO implementation. This included taking a 'lines of evidence' approach to reach an end point for the remediation, which would consider:

- concentrations of CHC remaining in groundwater;
- evidence of mass removed;
- evidence of effective distribution of ISCO reagent;
- assessment of source depletion;
- revised quantitative risk assessment (to show lower risk);
- lines of evidence that full breakdown of PCE and TCE had taken place; and
- cost benefit of further remediation.

Active groundwater remediation was stopped at the end of 2013 to allow aquifer conditions to stabilise. Following this, a close-out groundwater monitoring programme was completed in 2014 and 2015. A review of the lines of evidence described above was undertaken, including a SRA.

5. SUSTAINABILITY ASSESSMENT

A SRA was used to assess the cost/benefit of further groundwater remediation and to support and inform decision making. It was agreed with the regulators that a Multi-Criteria Analysis (MCA) approach would be taken due to the complicated nature of the conditions on-site. The SRA was carried out in 2014 post-completion of active remediation works and a monitoring period during which groundwater conditions were allowed to stabilise.

The overall objective of the SRA was to assess whether it would be sustainable to continue active remediation at the site or to change to passive Monitored Natural Attenuation (MNA). This objective was achieved through the completion of the following tasks:

- assessment of the potential options for further remediation for the site using the MCA approach with an in-house sustainable remediation tool; and
- quantification of carbon emissions and costs associated with active remediation options to support the MCA.

The SRA was completed using an in-house sustainable remediation tool developed by an AECOM legacy company. This adopted the UK Sustainable Remediation Forum (SuRF-UK) definition of sustainable remediation by addressing the three pillars of sustainability equally, which is considered to be vital for a truly sustainable assessment.

The sustainable remediation tool enabled comparison of different remediation options, by way of a semi-quantitative assessment, against a set of sustainability criteria and indicators. The indicators were grouped into assessment criteria, divided into economic, environmental and social categories. The criteria and indicators used were based upon those published by SuRF-UK (CL:AIRE, 2010). Furthermore, the sustainable remediation tool allowed quantifiable and qualitative data to be collected to inform decision making and cost analysis, including a high-level carbon footprint assessment.

Four remediation options were considered in this assessment including three active and one passive option. The active options comprised further application of the two technologies already employed at the site, PT or ISCO, either individually or in combination. The passive option comprised MNA i.e. no further action would be taken at the site to address the groundwater contamination following completion of an agreed period of post system-shutdown monitoring. Table 1 provides an overview of all four options.

Table 1: Summary of the remediation options.

Remediation Option	Description
1	Pump and Treat (PT). An active method designed to hydraulically contain contaminated groundwater on site, remove contaminant mass from the aquifer and then treat it by stripping out the contamination using blown air and activated carbon.
2	*In Situ* Chemical Oxidation (ISCO). An active method designed to destroy and mobilise CHCs, using a reagent e.g. sodium persulfate and activator e.g. iron citrate and controlled reagent delivery within the contaminated zone.
3	PT and ISCO. Enhancement of PT by the use of ISCO.
4	Monitored Natural Attenuation (MNA). A passive option, requiring no active works and relying on natural processes to clean up or attenuate CHCs in groundwater, as assessed by a limited programme of further monitoring before completion of the remediation is agreed with regulators.

The sustainable remediation tool allowed for qualitative and quantitative assessment of the sustainability assessment criteria and indicators. During this project, an initial review of criteria and indicators was undertaken, followed by a semi-quantitative assessment of indicators identified during the initial review as being relevant to the site.

Multi-Criteria Analysis

The first step of the SRA comprised an initial qualitative assessment that drew upon the project team's knowledge of the site and remediation techniques, and reflected key stakeholder preferences. The stakeholders considered in this SRA were:

- the client (considered in terms of the objectives for the remediation and for the site);
- the consultant (responsible for completing the SRA, whilst taking account of the other stakeholders' perspectives);
- regulatory authorities (which had been consulted on, and had agreed the use of the SRA and the methodology to be used); and
- occupiers of neighbouring residential and commercial properties (considered in terms of potential effects of the remediation options).

The project team reviewed the criteria and provided a justification of each one that was considered relevant to the site. Following the initial review, weightings were selected for each criterion, using key relevant indicators to help inform the scoring.

In addition to the criteria, the other limits, or boundaries to the SRA were:

- method of evaluation – the effect of each remediation option was assessed relative to each criteria and the associated indicators by considering performance against the indicator consistently, to provide a 'like for like' comparison of options;
- lifecycle – the SRA was limited to site-based remediation activities, and as described below for the carbon footprint assessment;
- spatial extent – this was limited to the site, the underlying aquifer and neighbouring land uses, as described in the conceptual site model; and
- timescale – this was the time needed for completion of further remediation.

Fifteen sustainable remediation criteria were used as part of the SRA with all of them defined as within either economic, social, or environmental categories (Table 2).

A weighting of "0" was applied by the project team to criteria that were not considered relevant to the SRA, a weighting of "1" reflected low importance and a weighting of "5" indicated the highest importance. If two or more assessment criteria were equally important they were given the same weighting. The criteria highlighted in bold in Table 2 were identified as those with the highest importance according to stakeholders and assigned the greatest weighting. Weightings are shown on Figure 3.

Table 2: Indicators used to assess the sustainability of remediation options.

Economic	Environmental	Social
Direct Economic Costs and Benefits	Impacts on Air	Human Health and Safety
Indirect Economic Costs and Benefits	Impacts on Soil and Ground Conditions	Ethics and Equity
Employment and Employment Capital	Impacts on Groundwater and Surface Water	Neighbourhood and Locality
Induced Economic Costs and Benefits	Impacts on Ecology	Communities and Community Involvement
Project Lifespan and Flexibility	Use of Natural Resources and Waste Generation	Compliance, Uncertainty and Evidence

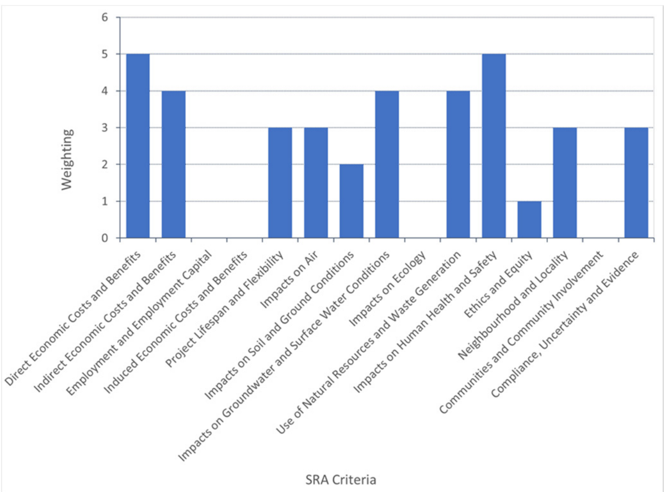


Figure 3: SRA criteria weighting for each social, environmental, and economic indicator.

The weighting process allowed the assessment criteria to be considered in relation to the site and the preferences of stakeholders. This enabled specific client or regulatory aims to be prioritised where necessary.

Following the weighting process, the project team held a workshop to review and select the scoring of the technology-specific remediation options. The workshop allowed subjectivity to be avoided as much as possible during the scoring process. The selection of scores was based on the project team's judgment of the degree to which the technology addressed the sustainability criteria, and the associated indicators, by considering performance against the indicator consistently for each remediation option.

The technology scores ranged from 1 to 5. A score of 1 indicated that the technology was the least favourable of the options at addressing the sustainability criteria. A score of 5 indicated that the technology was the most favourable alternative.

For each remediation option and assessment criterion, the technology score was multiplied by the sustainability weighting. The weighted scores are presented on Figure 4.

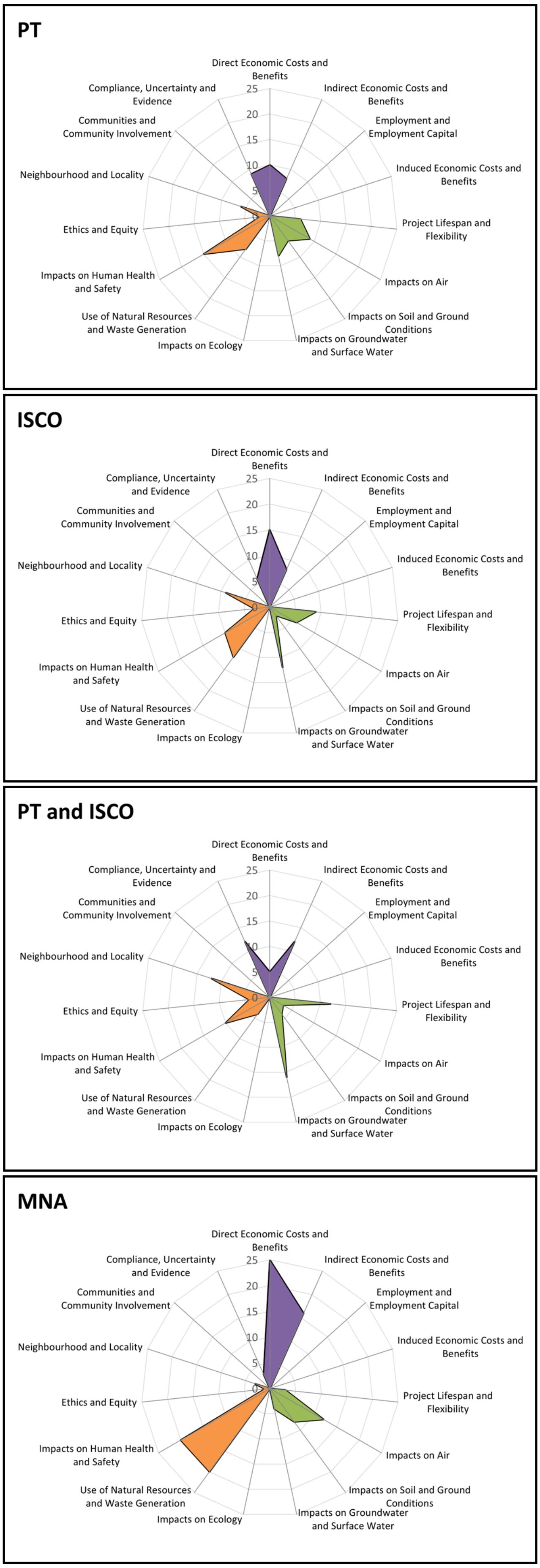


Figure 4: Weighted sustainability assessment scores.

The resultant weighted scores (Figure 4) were then expressed as a percentage of the maximum score possible and this was then normalised, to provide equal standing between environmental, economic, and social categories. These are presented in Table 3. This enabled a semi-quantitative assessment of the relative merit of each technology to be undertaken.

Table 3: Overall weighted score for each category (as a percentage of the maximum score possible).

Assessment Criteria	Maximum Score	PT	ISCO	PT and ISCO	MNA
Economic	60	40%	53%	48%	73%
Environmental	65	48%	49%	42%	68%
Social	60	53%	47%	63%	45%
% of Maximum Score (assuming 33% for each theme)		47%	50%	51%	62%

The assessment results were reviewed to ensure that the values were correctly reflecting the qualitative assessment. Values were then converted to percentage (%) with a higher percentage indicating a more sustainable remediation option. Figure 5 illustrates the results of the MCA.

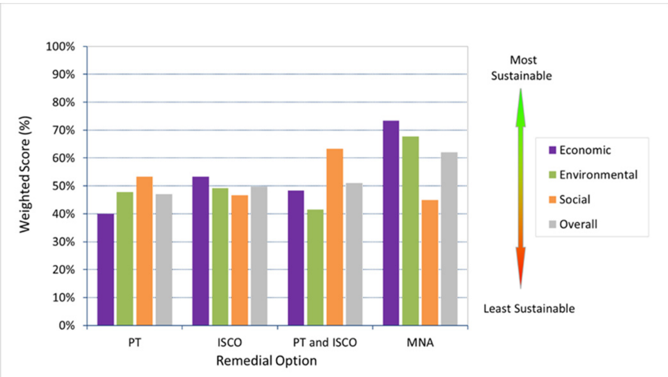


Figure 5: Normalised weighted sustainability assessment scores.

The MCA (as illustrated on Figure 5) identified that MNA was the most sustainable remediation option, with an overall weighted score of 62%. A combination of both PT and ISCO had an overall score of 51%, whilst ISCO alone scored 50%. The least sustainable remediation option identified was to use PT alone, with an overall weighted score of 47%.

The MNA remediation option scored well against economic and environmental indicators (scores of 73% and 68%), but for social indicators it was the lowest ranked of all remediation options, scoring 45%. A combined approach of using PT and ISCO scored the highest social sustainable factor, with 63%. This resulted from the technique able to remove greater contamination mass, returning the site to beneficial use more rapidly and with a reduced risk of regulators requiring further work.

A sensitivity analysis was performed on the MCA to see how changes to assessment criteria weighting and scoring would affect the overall weighted score for each of the four remediation options. The sensitivity analysis showed that the MNA option was not sensitive to changes in cost, project duration and flexibility and environmental impact. Whilst these changes resulted in a small percentage increase for each of the other three remediation technologies the weighted score of MNA remained greater.

Carbon Footprint Assessment

The second part of the SRA of remediation activities was to calculate the carbon footprints produced over the lifespan of the active treatment options (PT and ISCO) based on their implementation at the site to date. The passive option, MNA, was not assessed as no further action would be undertaken after the completion of the post-system shutdown monitoring. Inputs covered utilities (power and water), consumables (activated carbon and ISCO reagents), waste disposal, system operation and maintenance, and system performance monitoring. The footprint assessments were limited to site-based remediation activities, with emissions due to office or laboratory-based activities, or associated with consumables, such as tubing, gloves and laboratory testing equipment excluded.

Data were collected during monitoring rounds for utilities, waste, and equipment. Whereas for transport mileage data were used to estimate emissions for vehicular transportation of goods and site staff.

The emission factors were sourced from Government guidance for utilities and transport (Defra/DECC, 2012) and from the EcoInvent Database for materials (Swiss Centre for Life Cycle Inventories, 2009). Those for activated carbon assumed this would be re-activated carbon, originally sourced from coal. The relevant emission factors were applied to the data to give the carbon emissions arising for each activity. These were then summed to give the total carbon footprint for PT and for ISCO. The outputs enabled the carbon footprint to be compared to the cost of remediation, as well as the contaminant removal achieved at the site by each technology. Table 4 provides a summary of the carbon footprint assessment of PT and ISCO.

Table 4: Summary of carbon footprint assessment.

Remediation Option	Duration (years)	Contaminant Mass Removed (kg)	Total CO2e Emissions (kg)	Total Cost (£)	CO2e Emissions per 1 kg contaminant (kg)	Cost per 1 kg Contaminant (£)
PT	6.5	616	379,330	1,000,000	616	1,623
ISCO	2.5	1,100	43,695	500,000	40	455

Based on the carbon footprint calculations, ISCO was considered the better option, removing nearly twice the amount of the contaminant mass as PT, with lower carbon emissions and expenditure, and a shorter project duration. When comparing the above remediation options against MNA, it was considered that minimal emissions would be produced due to no further activities being carried out. However, MNA was the option considered least able to deal with changing circumstances at the site such as different land-uses or timescales.

The SRA was presented to the regulators in conjunction with the other lines of evidence including the results of further groundwater monitoring and solute concentration trend analysis, mass discharge estimation, update of the conceptual site model and updated quantitative risk assessments. Based on the remediation undertaken to date at the site, the results of the SRA and these other lines of evidence, further active remediation of the residual contamination in the saturated sandstone was not considered necessary, assuming on-site and off-site land uses did not change.

The regulators agreed that further active remediation to treat residual contamination in the saturated sandstone was not sustainable and that the remediation strategy for the site was complete.

6. PROJECT HIGHLIGHTS

Key project highlights include:

- application of a SRA to inform the future remediation strategy and the requirement for further remediation;
- regulators supported the use of MCA to assess the sustainability of the remediation options used on-site;
- thorough carbon footprint analysis to inform the decision-making process when identifying the most sustainable remediation option; and
- regulators agreed that further active remediation of residual contamination was not sustainable.

7. LESSONS LEARNED

A key lesson learned from this project was the value in using quantitative data to inform the decision-making process through estimating potential emissions for each active remediation option. Furthermore, this project illustrates the benefit of using a SRA, with other lines of evidence, to review the need for further active remediation.

8. CONCLUSIONS

A SRA was carried out to identify the most sustainable remediation option to address residual groundwater contamination following six years of active remediation comprising PT and ISCO. The assessment was based on environmental, social, and economic criteria and indicators using MCA and supported by an analysis of carbon footprints of potential options for further active remediation. The criteria and associated weightings reflected key stakeholder preferences. Findings from the assessment identified that the four potential remediation options varied in their sustainability impact, with MNA considered to be the most sustainable remediation option overall. Further active remediation of the residual contamination in the saturated sandstone was not considered justifiable, given the remediation undertaken to date at the site, the results of the SRA and the other lines of evidence. The regulators agreed that further active remediation to treat residual contamination in the saturated sandstone was not sustainable and that the remediation strategy for the site was complete.

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- CL:AIRE. 2010. A Framework for Assessing the Sustainability of Soil and Groundwater Remediation. Available at: www.claire.co.uk/surfuk
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APPENDIX 2 CERTIFICATION OF SUSTAINABLE REMEDIATION ASSESSMENT

SuRF-UK Sustainable Remediation compliance self-certification

Certification of Sustainable Remediation assessment

I hereby confirm that the sustainable remediation assessment presented in:

Author: ……………………………………………………………………………

Report title: ……………………………………………………………………………

Date: ……………………………………………………………………………

complies with ISO18504:2017 and guidance presented in the SuRF-UK Sustainable Remediation Framework (CL:AIRE, 2010).

The proposed remediation options are considered effective in managing identified human health and environmental risks, and the sustainable remediation assessment adopts the six principles of the SuRF-UK framework, namely that the best, or most sustainable, remediation is selected which achieves:

- Principle 1: Protection of human health and the wider environment.
- Principle 2: Safe working practices.
- Principle 3: Consistent, clear and reproducible evidence-based decision making.
- Principle 4: Record keeping and transparent reporting.
- Principle 5: Good governance and stakeholder involvement.
- Principle 6: Based on sound science.

Signature: ……………………………………………………………………………

Name: ……………………………………………………………………………

Professional Accreditation (e.g., Chartered institution): ……………………………………………………………

Chartership / Accreditation number: ……………………………………………………………………………

Date: ……………………………………………………………………………

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for European Refining

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