CL:AIRE

CON 02
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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 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.

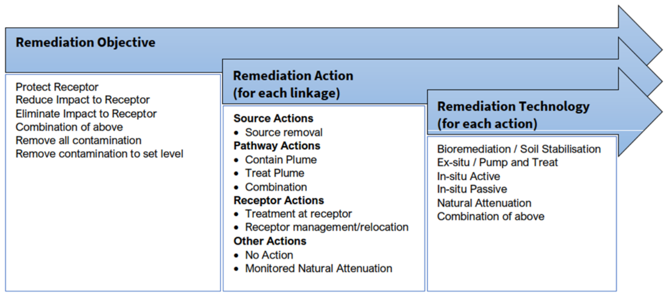

Figure 1: Relationship between remediation objectives, actions and technologies (WSP).

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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.

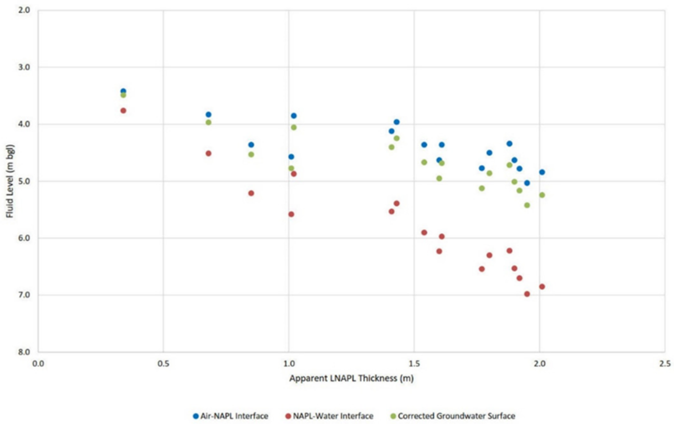

Figure 3: Diagnostic gauge plot - plume centre (WSP).

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.

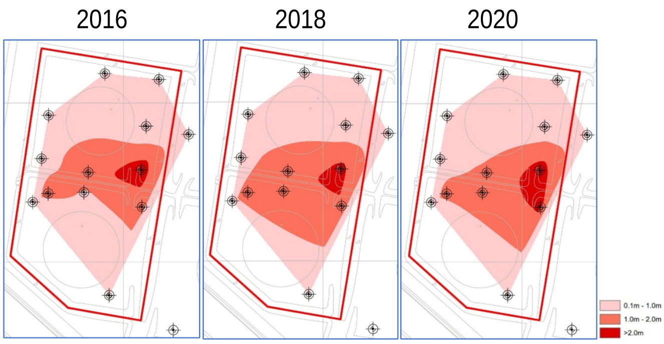

Figure 4: Median LNAPL thickness in monitoring wells (WSP).

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).

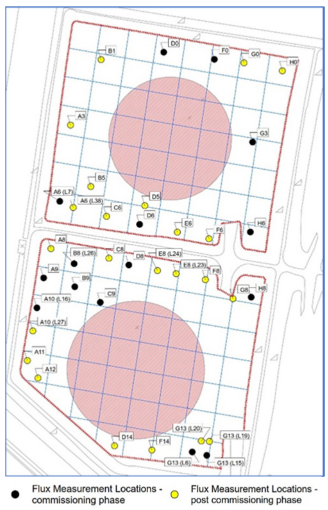

Figure 6: DCC monitoring locations.

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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.

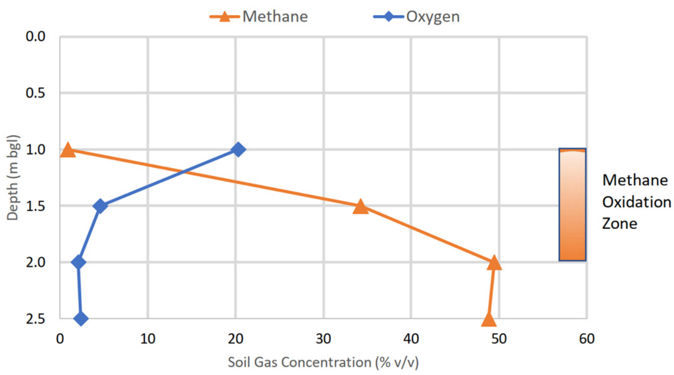

Figure 7: Typical soil gas profile, source zone (WSP).

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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