SOCIETY OF BROWNFIELD RISK ASSESSMENT

Light Non-Aqueous Phase Liquid – Guidance Notes for their Assessment in Contaminated Land Scenarios in the UK

7. CHOOSING AN APPROPRIATE SUSTAINABLE REMEDIATION APPROACH

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PUBLICATION

This series of reports and tools is published by the Society of Brownfield Risk Assessment (SoBRA). It presents work undertaken by a SoBRA sub-group composed of volunteers listed in the acknowledgments below. This publication is part of a series of work packages designed to address various issues in data collection and evaluating risks associated with non-aqueous phase liquid (NAPL).

This guidance document is intended to provide the remediation decision making process and practical guidance whilst setting out industrial standard for managing risks associated with light non-aqueous phase liquid (LNAPL) effectively, in line with the current concepts, knowledge and guidance.

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Dr David Holmes	Geosyntec Consultants Ltd
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1 INTRODUCTION

The Society of Brownfield Risk Assessment (SoBRA) is a UK-based learned society that aims to:

- improve technical knowledge in risk-based decision-making related to land contamination applications; and,
- enhance the professional status and profile of risk assessment practitioners.

The society has a number of working groups (termed "sub-groups") comprising volunteer SoBRA members working on particular aspects to help achieve these aims. This report presents one of several outputs of the non-aqueous phase liquid (NAPL) sub-group.

The technical aims of the sub-group are to:

- support technical excellence in the assessment, estimation and evaluation of risks associated with NAPL; and,
- encourage best practice by delivering practical advice to support decisions regarding the appropriate management of NAPL risks.

It should be noted from the outset it is not the intention of the sub-group or any of its deliverables to replicate existing NAPL guidance. Instead, the overarching aim is to address gaps in current guidance, and to provide practical advice to SoBRA members when undertaking risk assessments at sites where NAPL could be or is present.

1.1 Evolution and Overall Strategy of Sub-Group

The evaluation of contaminated land risk relies on understanding sub-surface processes. NAPL can be difficult to measure, meaning conceptual site models (CSM) may be data deficient. Following several requests from our members, SoBRA created the NAPL sub-group in 2019 with a call out to the SoBRA membership for volunteers to participate.

Once the group of volunteers was assembled, initial sub-group meetings identified and prioritised areas where existing NAPL UK risk assessment guidance was lacking or would benefit from practical advice. As a result of this screening process, a series of seven working groups was formed, each tasked with producing a document or tool to address the identified need.

The overall approach developed by the sub-group to address NAPL risk assessment is summarised in Figure 1. The seven working groups cover all stages of risk assessment, ranging from establishing whether NAPL is likely to be present at a site or not through to designing an appropriate remediation strategy. The position of this particular document within this strategy is highlighted.

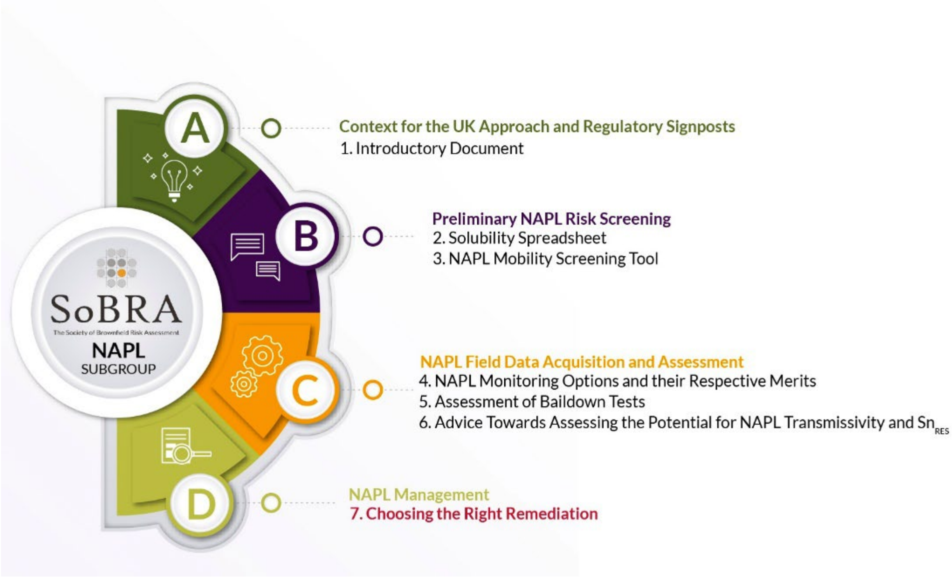

Figure 1. Publication Strategy for NAPL Sub-Group

1.2 Background

Selection of an appropriate light non-aqueous phase liquid (LNAPL) sustainable remediation approach is a vital part of the risk management process to mitigate identified risks. Understanding and determining LNAPL risks and drivers, remediation goals and objectives, and the remediation end-point through the development of a site-specific conceptual site model is central to the decision-making process. There is a lack of understanding and knowledge in the wider industry related to the LNAPL behaviour and remediation, which is largely attributed to the continuous evolution of LNAPL management and research in the last several years. New concepts, tools and technologies have emerged for developing a conceptual site model and subsequently assessing and evaluating associated risks and designing remediation. Therefore, the subject of this specific sub-group publication is to provide a decision-making process, including critical risks and considerations, for practitioners to use during the selection of an appropriate, effective, yet economical and sustainable remediation approach for LNAPL impacted sites.

1.3 Aims

The aim of this publication is to provide a decision-making process to help stakeholders manage LNAPL risks whilst setting a standard for managing risks associated with LNAPL. This publication will also aim to provide comprehensive, coherent, and transparent process for regulators to review remediation works carried out and assess whether remediation goals and objectives have been met at a site.

It is important to note that this publication solely focuses on LNAPL remediation. The risk assessment of dissolved phase contamination, including the selection of compliance points, or remediation of dense non-aqueous phase liquid (DNAPL), are outside the scope of this publication.

2 DECISION MAKING PROCESS FOR LNAPL REMEDIATION

The management and remediation of contaminated land in the UK is risk-based; LNAPL remediation should therefore adhere and follow the same risk-based approach. The complex nature of LNAPL fate and transport, together with rapid development of the LNAPL discipline in recent years, has provided an appreciation that understanding LNAPL behaviour and remediation is challenging. Many practitioners have struggled with the application and implementation of appropriate clean-up processes due to misconceptions about the behaviour of LNAPL. Therefore, this section describes the decision-making process for identifying the LNAPL risks and how to abate those risks systematically.

Figure 2, adapted from ITRC (2018) LNAPL Site Management: LCSM Evolution, Decision Process, and Remedial Technologies (LNAPL-3), illustrates an overview of decision-making process for the LNAPL risk management at a site.

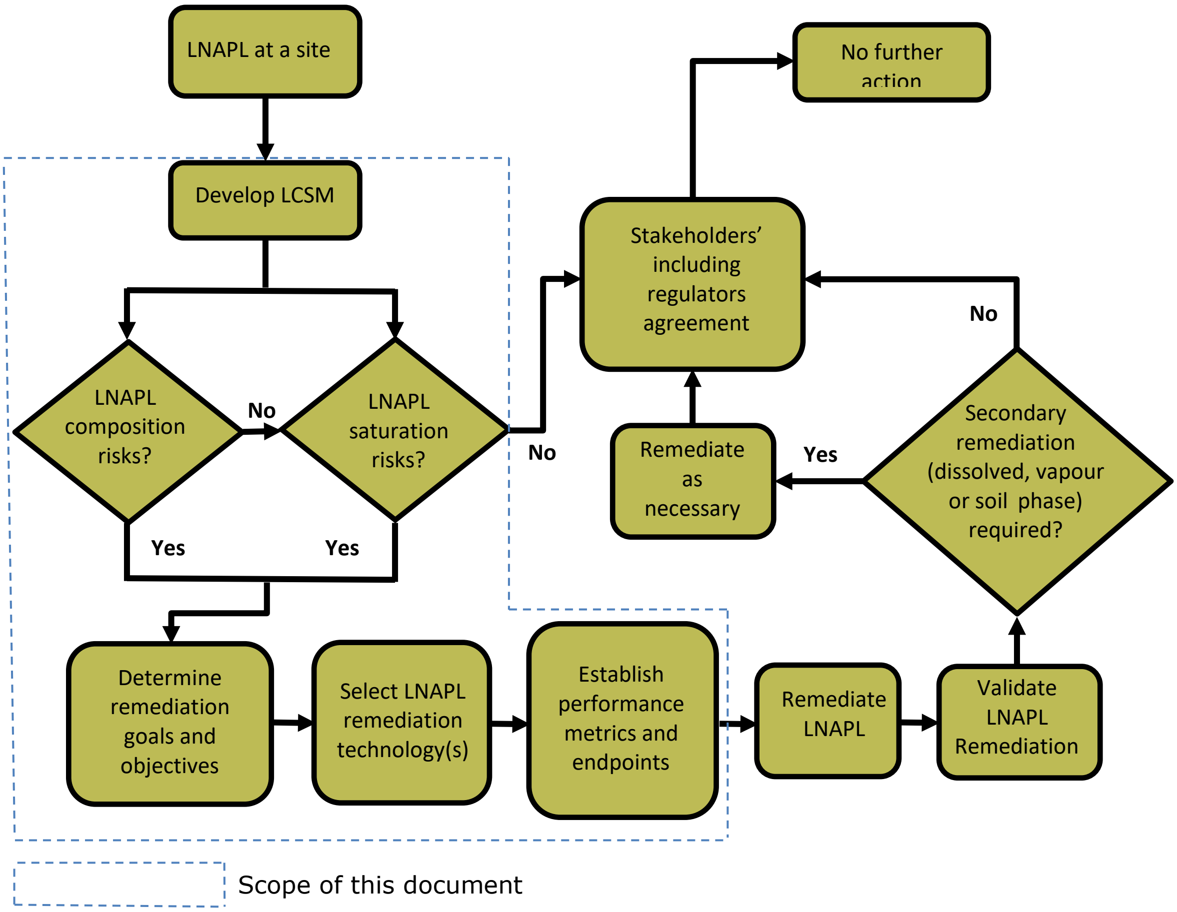

Figure 2. LNAPL Risk Management Overview (modified from ITRC, 2018)

As shown in Figure 2, the decision-making process starts with identification and verification of LNAPL risks with the development of an accurate LNAPL conceptual site model (LCSM), selection of LNAPL remediation goals and objectives, remediation technologies which are appropriate to address those risks, and finally ends with establishing remediation performance metrics and remediation endpoints.

Adhering to the process outlined here will greatly assist practitioners in managing the identified risks and to resolve management and technical challenges within a consistent framework. In addition, regulators can also use this process to review the remediation work carried out and determine whether remediation goals and objectives have been fulfilled. The following sections detail each step which should be considered and answered during the decision-making process for effective management of LNAPL risks at a site.

2.1 LNAPL Conceptual Site Model (LCSM)

An accurate LCSM is the key for designing an effective remediation strategy. Therefore, the first point of review is to ask whether the LCSM developed for a site is appropriate and sufficient to answer the questions associated with the site. Should the LCSM be inadequate, further investigation may need to be conducted to collect the necessary data and refine the LCSM prior to the remediation decision making process. A lack of understanding caused by either data gaps or systematic misunderstanding of LNAPL results in a higher level of uncertainty and can lead to unnecessary excessive resources during remediation which may also not achieve the remediation end goals (Smith, 2019). An accurate and up to date LCSM allows the most appropriate management decisions to be made on the application and operation of remediation measures.

2.2 LNAPL Risks and LNAPL Drivers

Understanding LNAPL risks and associated drivers will allow the development of remediation objectives/goals specific to those drivers. An accurate and well-developed LCSM summarises the LNAPL conditions and can provide a guide to identify the LNAPL risks (e.g. vapour intrusion and off-site migration) associated with a site. Following identification of an LNAPL risks it is necessary, using site-specific information and other LNAPL related tools/methods, to verify whether the identified LNAPL risk has a potential to pose an unacceptable risk to identified receptors. This follows the source-pathway-receptor framework presented in Land Contamination Risk Management (LCRM) (Environment Agency, 2020).

There are two aspects of risk associated with LNAPL: composition and saturation. The presence of hazardous constituents (such as benzene, toluene, ethyl benzene and xylene, BTEX) in LNAPL are composition drivers, and the potential of LNAPL to move in the subsurface is a saturation driver (ITRC 2009a). Regulatory and aesthetic risks may be viewed as linked to either saturation, composition or both. Remedial corrective measures should be considered and implemented for complete LNAPL linkages which have been verified as presenting a potential risk to identified receptors.

2.3 Remediation Goals

Prior to remediation, appropriate remediation goals should be established for all LNAPL risks that pose an unacceptable risk to human health and the wider environment. Remediation goals are the desired, or acceptable LNAPL conditions required to be achieved at a site. They should also be relevant to the LNAPL risks and scientifically based.

2.4 Remediation Objectives

Remediation objectives should describe how remediation goals will be met at a site. These objectives should be combined with remediation technology performance metrics and a remediation end point. Therefore, remediation objectives should be "SMART" (**S**pecific, **M**easurable, **A**chievable, **R**elevant, **T**imely) (LNAPL-3, ITRC, 2018).

Appendix 1 compiles LNAPL risks/drivers, remediation goals and objectives extracted from ITRC LNAPL-3 (2018).

2.5 LNAPL Remediation Technology

Considering the LNAPL risks, drivers, goals and objectives, in principle there are three remediation technology groups for LNAPL:

1. Mass recovery – address saturation-based remediation goals;
2. Phase change – address composition-based remediation goals; and,
3. Mass control – address saturation-based remediation goals.

These groups are primarily based on the mechanisms by which a remediation technology manages LNAPL. The decision-making process should identify the appropriate technology group or groups required to manage LNAPL in accordance with the LNAPL risks, drivers, goals and objectives. Site conditions may dictate that more than one technology is used; therefore, consideration should be given as to whether combining two or more technology groups (a 'treatment train') could be more effective and economical at a site.

2.6 Performance Metrics and Remediation Endpoints

Performance metrics are measurable characteristics which link the remedial progress to reducing risk posed by LNAPL. Each performance metric may have a predetermined value or criteria to describe reaching the technology’s limit of benefit or it may be site-specific. This is then defined as the endpoint of the technology. An attempt should be made to identify an endpoint or criteria for assessing its utility for a given technology prior to application. Should a treatment train approach be adopted, it should be noted that the endpoint of a technology may not be the end of remediation. Upon reaching a technology specific endpoint, transition to another relevant technology may be required in order to manage the remaining LNAPL risks at a site. In some cases, the remedial objectives will remain unreached, and in these cases contingency measures should be considered.

3 REMEDIATON TECHNOLOGY EVALUATION

The outcomes of the decision-making process outlined in Section 2 should result in a list of identified remediation technologies potentially capable of achieving the remediation endpoints. Further evaluation can then be used to select the most appropriate remediation technology(s) for design and development of a pragmatic, sustainable and effective risk management strategy for a site. A remediation options appraisal should therefore be carried out for a site. During this options appraisal, remediation technologies and their strategies for implementation should be evaluated against technical, operational and commercial factors. A supplemental sustainability assessment, in line with UK Sustainable Remediation Forum (SuRF-UK) guidance (CL:AIRE, 2020a), is also recommended to determine the most sustainable way to mitigate the identified LNAPL risks at a site.

The details of remediation options and sustainability assessment are not within the scope of this publication. Published guidance and frameworks available to understand the correct procedure for remediation option and sustainability assessment are provided in the references (EA, 2020, API, 2004, EA, 2004, ITRC 2009b, CL:AIRE, 2020a, CL:AIRE, 2020b, NICOLE 2010, USEPA 1988, Smith, 2019).

To carry out a comprehensive remediation options appraisal, a number of factors are recommended for inclusion. These factors should be selected with consultation with all the stakeholders associated with the site. It should be noted that other factors in line with the site-specific and stakeholders' requirements, should be considered in the technology selection procedure. Please refer to the LCRM for further guidance on remediation option appraisal (EA, 2020).

Prior to implementation, an informed agreement from all stakeholders for the selected remediation strategy should be sought.

3.1 LNAPL Properties

The selected remediation technology should be appropriate for the characteristics of the LNAPL in both its physico-chemical properties and saturation. The use of an inappropriate technology may lead to little or no reduction of any of the risks associated with the presence of LNAPL, and remediation objectives will not be met. During a screening phase, some LNAPL properties can be estimated from published values, however, site-specific values should typically be measured wherever possible. Some of the most important NAPL properties are discussed in the SoBRA documents, '*Effective Solubility Tool*' (SoBRA, 2023a) and '*LNAPL Mobility Screening Tool*' (SoBRA, 2023b).

In addition, '*Note 1A: Conceptual site model development for the assessment of vapour intrusion linkages in the UK'* (SoBRA, 2022a) provides an overview of vapour intrusion risks.

3.2 LNAPL Distribution

Appropriate lateral and vertical delineation of the LNAPL distribution is an essential component of the LCSM. LNAPL remediation objectives are more likely to be met where there are fewer uncertainties concerning the vertical and horizontal distribution of LNAPL. The extent of the LNAPL zone has a significant impact on the technology selection and the scale of remediation. The associated costs, access limitations, physical barriers, timeframe, liabilities, and the technology limitations can vary with the size of the LNAPL body, and therefore, the feasibility of the remediation scheme will be determined by the extent of the LNAPL body. Delineation of the LNAPL body is therefore important not only for understanding LNAPL risks, but also remediation. Both the SoBRA document '*Baildown Test Guidance for Light Non-Aqueous Phase Liquids'* (SoBRA, 2022b) and forthcoming document '*NAPL Monitoring Options and their Merits*' (SoBRA, *in preparation*) describe current monitoring options and provide guidance for NAPL-impacted site investigations. In addition, direct push methods such as laser induced fluorescence can aid in mapping NAPL sites (Bujewski and Rutherford 1997, McCall et al., 2018).

3.3 Geology and Hydrogeology

Variations in the subsurface geology and degree of heterogeneity can complicate LNAPL plume delineation. Though often conceptualised as homogeneous, soils are highly heterogenous even at small scales. This is discussed further in the SoBRA document '*Advice Towards Understanding the Potential for LNAPL Transmissivity and Residual Saturation'* (SoBRA, *in press*). Therefore, all necessary investigation technologies and methods available in the industry should be considered and used as appropriate to limit the uncertainty of geology as much as practicably possible. Boreholes, trial pitting, cone penetrating testing, membrane interphase probing and 3D mapping can be used to understand the subsurface geology. Pumping tests and / or slug tests can also be used to understand the variations in the subsurface hydraulic conditions. The remediation strategy and system should be tailored specifically to the ground conditions beneath the site. For example, for effective LNAPL removal, it may be necessary to control or adjust the extraction air flow rate in a dual phase extraction system, depending on the bulk aquifer properties. LNAPL recoverability can also vary from one well to another on the same site, depending not only on groundwater level, but on which soil types are intercepted by the LNAPL in the well (Becket and Huntley, 2015) (i.e. extraction from soils with higher permeability is more feasible than from soils with lower permeability). There are significant benefits in spending more time and resources to fully understand the geological conditions. Each piece of evidence should be critically appraised to understand how it informs the LCSM to result in a correctly designed and effective remediation strategy.

3.4 Site Restrictions

Site restrictions can limit the number of feasible remediation options available and impact remediation implementation. Therefore, site restrictions such as physical, logistical, legal and regulatory, degree of disruption, site status (e.g. operational) and nearby sensitive receptors should be identified for design and implementation of a correct remediation strategy.

The availability and suitability of infrastructure, such as electricity supply and sewer system, should also be evaluated before selecting an appropriate remediation approach.

3.5 Pilot Testing

Correctly designed bench-scale and/or field-scale pilot testing, as necessary, is highly recommended. The site-specific information collected during pilot testing will inform the applicability and accuracy of the final design, resulting in a more effective remediation strategy for the site. This will also allow the development of suitable and appropriate remediation metrics (see Section 2.6). Depending on the outcome of the pilot testing, it may be necessary to revisit the remediation options appraisal.

3.6 Timescale

The required time to meet the remediation objectives/goals will greatly affect the selection of a remediation strategy at a site. Caution should be applied, as it can be technically challenging to predict the timeframes of LNAPL recovery endpoints (Sookhak Lari et al., 2020, Maini and Holmes, 2019). It is therefore important to understand and confirm any time constraints for achievement of the remediation objectives/ goals with all stakeholders. The shorter the timeframe available, (assuming no other variables change) the more aggressive the strategy that is required, resulting in a likely increase in cost. The required timeframe for a given technology is more likely to increase with an extensive distribution of LNAPL. Therefore, infrastructure requirements, modification to the remediation technologies, operating and monitoring requirements, and associated cost due to the variation of timescale should all be factored prior to remediation.

3.7 Regulations and Permits

The requirements for an environmental permit to operate the remediation system should be evaluated based on the scale and complexity of the remediation system. The time required to obtain a permit, together with the associated costs for both the permit and for the operation and monitoring, is determined by whether the proposed technology will be operated under standard rules or bespoke permit. Specific or complex technology (or innovative approach) is likely to require a longer timescale to gain permit approval. The associated cost for permitting and additional implementation to meet specific permitting requirements should be recognised.

It is also noted that the regulator policy objectives, particularly in Scotland should be considered during the decision-making process.

3.8 Sustainability

It is strongly recommended to carry out a sustainability assessment using the SuRF UK framework (CL:AIRE, 2020a; Smith, 2019) in order to identify the most sustainable remediation options/strategy for a site. A sustainability assessment will assist in identifying factors such as energy requirements, waste generation, and community concerns, which have possible impacts on the remediation and associated costs at a site. Resilience to climate change together with financial and institutional changes will also be evaluated during sustainability assessment.

Sustainability can be reviewed as an element in the remediation option appraisal. However, a separate sustainability assessment in line with SuRF UK framework can be performed for the top-ranked remediation technologies or strategies identified through a remediation option appraisal, without initially considering sustainability factors, for identification of the most sustainable remediation approach for a site.

This allows for a focused sustainability assessment of the selected remediation technologies or strategies that are deemed technically, commercially and operationally feasible.

3.9 Cost

Cost is often one of the primary decision-making factors in remediation. Each technology or strategy has different costs which widely depend upon the site-specific conditions, time frame and other factors discussed in this document. Attention should be paid to all of these factors during cost evaluation in order to estimate and optimise the potential total expenditure for the project. The decision-making process should also consider both capital and associated operation, maintenance and monitoring costs, to determine the total life cycle cost for the project.

3.10 Safety

Safety issues, which can vary from technology to technology and from site to site, may present a challenge for operating an effective remediation system. The implementation and operation of a remediation system will involve occupational, operational and environmental safety concerns and they should be managed appropriately for the safe operation of a system. The necessary regulations and ratings should be complied with during the design and building of the system. The potential for fire risk must be minimised and the critical safety devices should clearly be identified and listed in the operation manual. The system should have inherent basic safety features/functions for automatic shut down in an event of safety critical devices failure. All necessary compliance monitoring as requested by the environmental permit should be implemented and the generation of the waste stream should be managed appropriately. The LNAPL itself may pose a safety risk, not only from its hazardous properties but also if it has low flashpoint. This may necessitate ATEX (ATmosphères EXplosibles) areas which should be considered along with site constraints and operational risk assessments.

3.11 Operation and Monitoring

Operation and monitoring are crucial for successfully achieving remediation goals. The remediation system and strategy should be designed and implemented with equipment appropriate to the site conditions and remediation objectives. It should also be ensured that the final installation matches the system design. Incorrect or unsuitable equipment will greatly hinder the performance of the remediation system whilst presenting potential risks and/or nuisance to site users and neighbours.

In terms of system performance monitoring, LNAPL and water can become emulsified due to turbulent mixing in pumping operations. This can make measuring the precise quantities of the separate liquid phases prone to errors. Consideration should be given within the system design to allowing emulsions to separate. Over-estimating the volumes of LNAPL recovered will lead to a mischaracterisation of the site, and will impact the accurate recording of remediation system performance data which may in turn and lead to unnecessary operation of the remediation equipment beyond the originally anticipated endpoint.

Each remediation system will behave differently, and a comparable system's performance can also vary from one site to another depending on site conditions. This variability in system behaviour should be recognised and understood in order to develop an appropriate system performance monitoring programme. Regular monitoring to assess the operational performance and progress of the remediation is highly advisable. The morphology of an LNAPL zone is more likely to change rapidly during the initial stage of remediation. Therefore, regular monitoring, particularly immediately following system commissioning, is necessary to optimise the remediation system (e.g. adjusting pump depths, air extraction rates, target wells etc.) for correct, effective and safe operation. Based on the monitoring data, the remediation strategy and system design may need to be adjusted to improve the performance criteria at a site. It is therefore important that the system is monitored and the data interpreted by a suitably competent, skilled and experienced remediation engineer.

It is also important to consider the requirements of verification monitoring. Verification monitoring involves confirming that the risks associated with a site have been appropriately managed and that the site is suitable for its intended use. Therefore, having an initial discussion and reaching an agreement with all stakeholders, including regulators, regarding verification monitoring and the required lines of evidence will facilitate the site closure process and ensure compliance with regulatory requirements at the end of remediation.

It is important to note that the apparent NAPL thickness in monitoring wells will vary in response to seasonal and other drivers of groundwater fluctuation. The timing of verification monitoring is therefore critical, and best practice is to carry out between three and six post-remediation verification monitoring rounds spanning both low and high groundwater conditions.

Monitoring across ground highs and lows, interpreting LNAPL thickness alongside groundwater elevation and the use of multiple lines of evidence (E.g. no lateral migration of LNAPL, no increase in LNAPL areal extent, and stable of declining dissolved phase concentrations) can be used to address this limitation and demonstrate that remediation objectives have met at a site.

3.12 Data Collection and Review

As indicated in Section 2.6 and 3.5, it is recommended that performance metrics regarding system operation and ongoing LNAPL source behaviour are established prior to commencement of remediation. Depending on the system design, such data may include (but should not be limited to) LNAPL mobility, air extraction flow rate, mass recovery and dissolved phase groundwater concentrations etc. Collected data should be reviewed and assessed regularly by a suitably competent, skilled and experienced remediation engineer who is familiar with the remediation strategy. Regular review of performance metrics allows interpretation of the progress towards remediation goals. Review of the performance data also allows timely identification of any limitations of the remediation strategy, allowing corrective measures to be implemented, if necessary. In the treatment train approach, collection and review of monitoring data is vital to determine when to switch technologies.

Ultimately, the performance monitoring data will allow the determination of the achievement of remediation objectives and inform the cessation of the remediation operation at a site.

4 CASE STUDY

The following case study combines site data and various treatment scenarios, and has been created to illustrate how to apply the process given in this publication.

The information given here is for guidance purpose only.

Box 1 - LNAPL Remediation

LNAPL, which is likely to act as a continuous contaminant source beneath a site, creates a multi-phase system resulting in complex fate and transport among different phases. Therefore, a staged approach for remediation when encountering LNAPL, depending on site-specific conditions, may be more effective and economical. The first stage of remediation should focus on addressing and managing the LNAPL while the second stage, following the completion of LNAPL risk management, can focus on other aspects, such as the dissolved phase, if necessary. A staged approach is likely to give better control for practitioners, whilst allowing management of all identified risks and liabilities economically and effectively at a site.

4.1 Site Problem

A historical release of LNAPL from an underground storage tank in a petrol filling station was discovered during site redevelopment for high density residential end use. It appeared that the LNAPL leak had been occurring for more than a year. The initial investigation carried out at the site identified LNAPL in four monitoring wells at the site.

4.2 Development of LCSM

Development of an accurate LCSM is vital to evaluating and managing the associated risk at the site.

4.2.1 Geology and Hydrogeology

The desk study showed the geological and hydrogeological setting of the site, which was as follows:

- Superficial deposit: River Terrace Deposits (RTD) – Sand and Gravel;
- Bedrock geology: Chalk;
- Aquifer classification: Chalk – Principal aquifer, RTD – Secondary A aquifer;
- Site is in source protection zone (SPZ) III – Total catchment;

- Groundwater is unconfined;
- Resting groundwater level was 4.5 m below ground level (m bgl) and in the RTD, though the extent of any seasonal variations were not known;
- Both Secondary A and Principal aquifers are in hydraulically continuity; and,
- Depth to Chalk is 9 m bgl.

4.2.2 Receptors

Identified receptors were as follows:

- Intended site use is high density residential;
- Groundwater (site is within SPZ III - total catchment); and,
- Stream located approximately 75 m to the east of the site.

Box 2 – LNAPL Conceptual Site Model (LCSM)

A LCSM should be flexible and data-driven. It should continue to evolve through the entire project life cycle and mature through hypothesis testing. More investigation results in greater understanding of the LNAPL fate and transport. Insufficient investigations will lead to ineffective or inappropriate remediation approach, resulting in a higher project life cycle cost for a site. Therefore, it is vital to find the right balance of investigation for better understanding of a site and implementation of an effective remediation approach to meet end goals of the project.

4.2.3 Investigation Findings and Site Evaluation

Following the initial discovery of LNAPL, several phases of further investigations were required to collect site-specific details to inform the LCSM. A series of subsequent investigations at the site were implemented to gather the relevant site-specific data, which was combined with the environmental setting of the site:

- *LNAPL thickness*: The measured LNAPL thickness within the monitoring well network varied between 11 cm and 48 cm within the RTD (River Terrace Gravels). The potential depth of LNAPL penetration below the water table was estimated using the *LNAPL Mobility Screening Tool* (SoBRA, 2023b). The potential depth of penetration was in a range of 1.58 m to 1.65 m (estimated using the parameters given in Appendix 2 of the *LNAPL Mobility Screening Tool* for petrol and diesel in medium to coarse sands, together with site-specific data given in Table 1). This indicated that the LNAPL was unlikely to reach to the Chalk formation, and this was confirmed by intrusive site investigation data.

- *LNAPL mobility*: Transmissivity of LNAPL was measured using bail down tests and indicated that LNAPL beneath the site was functionally mobile and had potential for migration.
- *LNAPL extent:* Intrusive investigation including laser induced fluorescence (LIF) investigation, confirmed that lateral distribution of LNAPL within the unsaturated zone was limited. The size of the LNAPL body beneath the site was approximately 10 m x 30 m.
- *Groundwater quality*: Several rounds of groundwater sampling and analysis indicated majority of dissolved phase total petroleum hydrocarbons (TPH) concentrations above both drinking water and environmental quality standards, with an increasing trend.
- *Vapour monitoring*: Concentrations of contaminants measured in indoor air samples from onsite existing building were detected above the relevant generic assessment criteria (GAC), indicating a potential risk to human health.
- *LNAPL composition and properties*: Results of laboratory analyses of groundwater samples collected from beneath the site identified concentrations of TPH above the laboratory limit of detection (LOD). Laboratory analysis of the LNAPL revealed the following properties (see Table 1):

Table 1. Characteristics of the LNAPL

Sample ID	BH04	BH07	BH10	BH14
Carbon Range	C7-C25	C5-C24	C5-C24	C5-C24
Boiling Point Range	98-402^{0}C	36-391^{0}C	36-391^{0}C	36-391^{0}C
Fingerprint	Mixed Hydrocarbons	Mixed Hydrocarbons	Mixed Hydrocarbons	Mixed Hydrocarbons
Density at 10^{0}C (g/cm^3)	0.88	0.80	0.84	0.81

Kinematic Viscosity at 10^{0}C (cSt)	7.23	2.84	3.05	4.83

Box 3 – Effect of Viscosity on LNAPL Remediation

Viscosity, which is a measure of a fluid’s resistance to flow, significantly affects the LNAPL behaviour and the remediation approach at a site. The key implications for remediation are summarised below:

Aspect	**Low Viscosity LNAPL**	**High Viscosity LNAPL**
Mobility	Spread more readily; larger plume	Less migration; smaller plume
Recoverability	Easier to recover via physical remediation methods	Harder to recover via physical remediation methods
Volatility	Higher	Lower
Dissolution potential	Higher	Lower
Soil retention	Less likely	More likely

4.2.4 Application of the Field Data

The laboratory analysis of LNAPL properties provides critical information for remediation by determining the potential nature and behaviour (fate and transport) of the LNAPL. This in turn will inform assessment of risks and selection of appropriate remediation technologies, whilst ensuring compliance with environmental regulations.

Subsurface geology, aquifer hydrogeology, LNAPL properties and groundwater chemistry revealed through the subsequent investigations provided an improved understanding of the LNAPL at the site, allowing the development of an accurate LCSM which in turn aided the risk management strategy for the site. Figure 2 shows the LCSM developed for the proposed high density residential end use at the site.

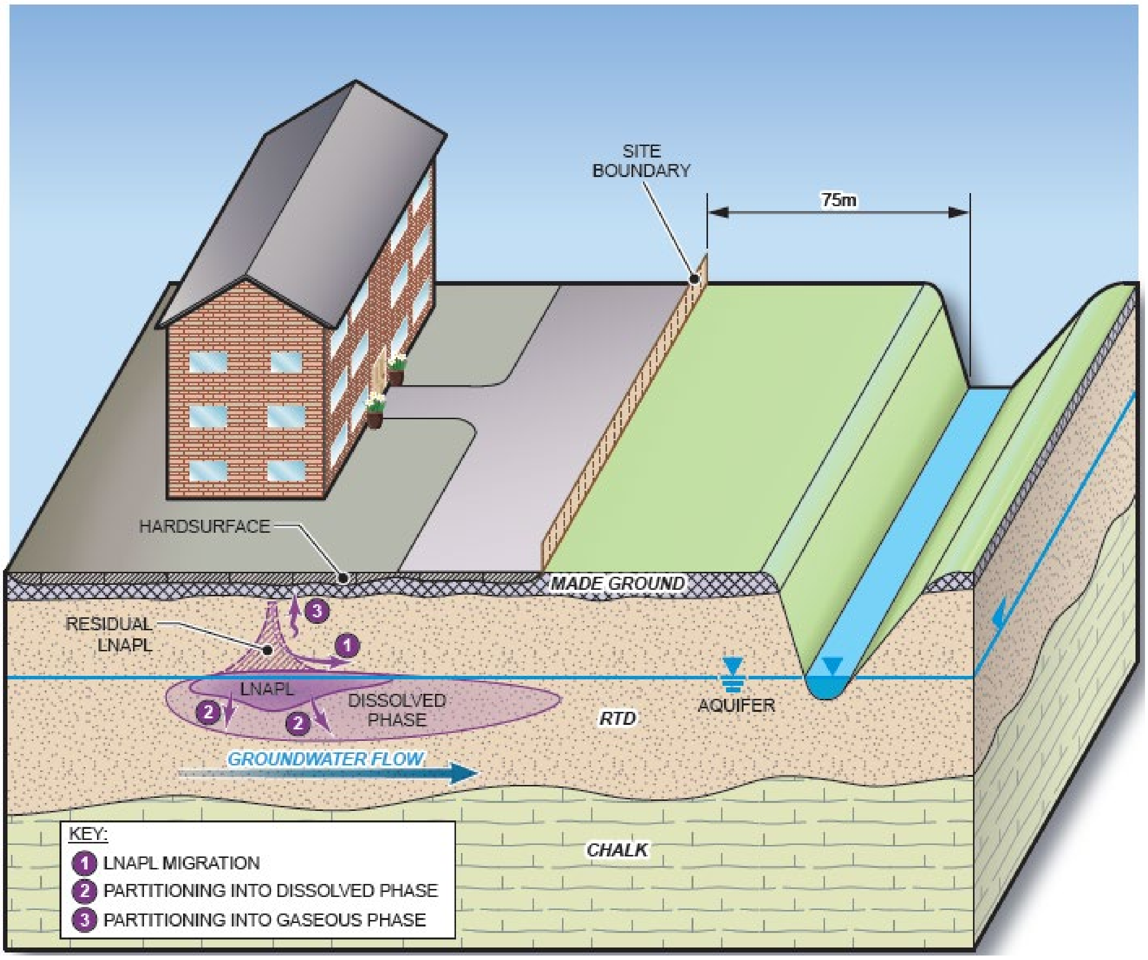

Figure 2. LNAPL Conceptual Site Model

4.3 LNAPL Risks and LNAPL Drivers

An accurate and well-developed LCSM will greatly assist with determination of LNAPL risks at a site. The LCSM, developed using the information collected through site investigations, revealed and confirmed the following LNAPL risks for the site:

Saturation drivers:

- LNAPL beneath the site was measured as locally mobile by the transmissivity analysis. This indicated that the LNAPL was at high saturation and recoverable in the capillary fringe. The potential for further migration of the LNAPL body was also estimated. The critical LNAPL thickness required for lateral spread was calculated as approximately 0.65 m to 1.0 m for petrol and diesel within medium to coarse sands using the *LNAPL Mobility Screening Tool* (SoBRA, 2023b). The measured LNAPL thicknesses across the site were below the calculated critical LNAPL thickness required for lateral migration, especially at the edges of the LNAPL body. The SoBRA tool uses literature values, so there will be a difference between the actual site-specific values and the parameters used. Therefore, good practice would dictate that site-specific data *should* be used, and model outputs validated by an LNAPL bail down or skimming test; and,

- LNAPL, held by capillarity, is likely to be present within the unsaturated zone.

Box 4 – Mobile LNAPL vs Migrating LNAPL

Mobile LNAPL:

LNAPL that can move within existing pore spaces, but is not necessarily spreading laterally or vertically, is considered as mobile. Mobile LNAPL is at a saturation greater than residual and is potentially recoverable.

Migrating LNAPL:

LNAPL that is actively spreading laterally or vertically into new pore spaces (previously uncontaminated) is migrating LNAPL.

All migrating LNAPL is mobile, however, not all mobile LNAPL is migrating.

Composition drivers:

- Hydrocarbons from the LNAPL partitioning into the groundwater, thereby acting as a continuous contamination source; and,
- Hydrocarbon vapour intrusion, originating from LNAPL in the capillary zone and unsaturated zone.

In this scenario, the drivers for LNAPL remediation are both saturation and composition. Some of the LNAPL has been shown to be mobile and recoverable. However, a fraction will remain and continue to be a source of petroleum hydrocarbons in both the groundwater and soil vapour.

In addition, the presence of LNAPL beneath the site may create concerns for other stakeholders including regulators, particularly during site redevelopment and divestment (these include both aesthetic and regulatory concerns).

Box 5 - LNAPL Risks

Some LNAPL risks can also be mitigated by changing the end use of a site, implementing institutional or engineering controls. This should be a site-specific decision with collective agreement of all stakeholders.

4.4 LNAPL Remediation Goals and Objectives

LNAPL remediation goals and objectives for the confirmed LNAPL risks at the site are listed in Table 2.

Table 2. LNAPL Goals and Objectives

LNAPL Risks	LNAPL Remediation Goals	LNAPL Remediation Objective
Saturation Based		
Potential for LNAPL migration	Reduce LNAPL volume to reduce the mobility and/or terminate the LNAPL body migration	• Remove sufficient mobile LNAPL mass • Stop or minimise LNAPL migration either by physical or hydraulic barrier.
LNAPL in unsaturated zone soils	Reduce the LNAPL mass (TPH concentrations) in soils significantly	• Reduce soil concentrations to an acceptable level (based on published standards or outcomes of a detailed quantitative risk assessment)
Composition Based		
Dissolved phase impacts identified in groundwater beneath the site at levels indicating potential risks to controlled water receptors	Reduce unacceptable constituent concentrations partitioning from LNAPL to dissolved phase	• Reduce LNAPL mass • Change the LNAPL composition • Reduce dissolved phase concentrations to an acceptable level (based on published standards or outcomes of a detailed quantitative risk assessment)
Potential for vapour intrusion originating from LNAPL in unsaturated zone	Reduce unacceptable constituent concentrations	• Reduce LNAPL mass • Reduce unacceptable vapour accumulation by

LNAPL Risks	LNAPL Remediation Goals	LNAPL Remediation Objective
	partitioning from LNAPL to vapour phase	sufficient depletion of volatile constituents in LNAPL (LNAPL composition change) • Reduce vapour concentration to an acceptable level (based on published standards or outcomes of a detailed quantitative risk assessment) • Minimise vapour migration by physical barriers

4.5 LNAPL Remediation Technology Selection

Selection of appropriate remediation technology(s) to develop an LNAPL management strategy is a tiered approach. Initial LNAPL remediation technologies should be selected for further detailed evaluation through an option appraisal. Remediation option appraisal followed by (or with) sustainability assessment should be carried out to logically and systematically determine the appropriate remediation technology(s) for a site.

The initial LNAPL remediation technologies selected should be aligned with and be applicable to the LNAPL risks, goals and objectives identified for a site. Accordingly, remediation technologies initially selected, in line with remediation objectives, are summarised in Table 3.

Table 3. Initial Remediation Technology Selection

LNAPL Remediation Objectives	Remediation Technology Group	Remediation Technology
Reduce LNAPL Mass	Mass-Recovery	*For mobile mass:* • Skimming • Multi-Phase Extraction (MPE)

LNAPL Remediation Objectives	**Remediation Technology Group**	**Remediation Technology**
		• Total Fluid Pumping (TFP) *For reduced mobility/immobile mass:* • In-Situ Thermal Treatment • Surfactant Flushing
Change LNAPL composition	Phase-Change	• Soil vapour extraction (SVE) • Bioventing • MPE • Air sparging • Biosparging • In situ thermal treatment • Natural source zone depletion (NSZD)
Stop or minimise LNAPL migration	Mass-Control	• Slurry wall (hanging wall) • TFP • MPE
Reduce dissolved phase concentration	Mass-Recovery & Phase-Change	As above.
Reduce vapour phase concentration	Mass-Recovery & Phase-Change	As above
Minimise vapour migration	Phase-Change & Mass-Control	As above In addition, installation of vapour membrane within the final building design can also be considered to minimise the vapour migration, but not as a standalone mitigation measure.

Box 6 - Monitored Natural Attenuation (MNA) vs Natural Source Zone Depletion (NSZD)

As per the definition and screening criteria to assess the feasibility of natural attenuation (CL:AIRE 2024a) MNA is unlikely to be appropriate for use as a stand-alone technology for LNAPL management. However, MNA can be used as a remediation option to address other phases (e.g. dissolved phase) following the completion of LNAPL remediation.

In contrast, NSZD (CL:AIRE 2024b), depending on the site-specific conditions and LNAPL risks, remediation goals and objectives, is an appropriate remediation technology for LNAPL management at a site.

Both MNA and NSZD require long-term monitoring, potentially years, and therefore may not be suitable for use on sites with short timeframes such as typical development sites.

During remediation option appraisal, remediation technologies initially selected have been evaluated considering factors outlined in Section 3.0. Sustainability assessment was also performed for the first five remediation technologies ranked by the remediation option appraisal. Remediation option appraisal and sustainability assessment carried out for the site identified MPE as the most appropriate remediation approach for LNAPL management at the site.

Box 7 - Risk vs Sustainability

The aim of sustainability assessment is to determine the most appropriate remediation approach for managing identified, unacceptable risks, which requires remediation, in a sustainable way. Sustainability should not be used as a reason to avoid addressing these unacceptable risks. Instead, it should guide assessors in determining the most appropriate sustainable method for managing such risks.

Remediation technologies which are technically tested through an option appraisal should only be considered for sustainability assessment.

4.6 Performance Metrics and Remediation Endpoint

Performance metrics for determining the progress towards achieving the LNAPL remediation objectives at a site are specific to the remediation system in question. Therefore, performance metrics and endpoint should be determined in line with the remediation technology(s) selected. Based on the LNAPL remediation technology selected for the site, the performance metric and endpoints given in Table 4 are provided as common examples.

Table 4. Performance Metrics and Remediation Endpoints

Performance Metrics	Description	Endpoint	Challenges
LNAPL transmissivity	Indicator of LNAPL recoverability and potential for LNAPL migration	Should LNAPL transmissivity remain below the ITRC (2018) criteria (0.01 to 0.07m^2 /day), LNAPL recovery via simple hydraulic methods may not be viable.	LNAPL can be difficult to measure. The data gathered may be unclear. Transmissivity can vary with LNAPL position in the well, and not only LNAPL thickness. Groundwater fluctuations can lead to the LNAPL in the well intersecting highly permeable strata, leading to time-specific large variations in LNAPL mobility. This is discussed in '*NAPL Monitoring Options and their Merits'* (SoBRA, *in preparation*).
LNAPL recovery rate	Indicator of mobile LNAPL recoverability	Reaching towards zero or agreed threshold level.	The recovery method may create stable emulsions by turbulent mixing in extraction pumps making measurement of fluids difficult.

Performance Metrics	Description	Endpoint	Challenges
Performance of mass recovery	Indicator of mass recoverability	Performance of mass recovery reaches to an asymptotic level	It may be unclear whether LNAPL recovery is limited by LNAPL mobility, degradation/clogging in wells and/or remediation system limitations.
Decline curve analysis	Indicator of mass recoverability	Decline curve indicates that the time and effort for recovering the remaining LNAPL volume is not economical. This can also be considered as an indication to optimise the remediation system setup, or adjust the technology / approach being used.	It may be unclear whether LNAPL recovery is limited by LNAPL mobility, degradation/clogging in wells and/or remediation system limitations.
LNAPL body footprint	Indicator of LNAPL migration and recovery	Stable or shrinking LNAPL footprint after the remediation.	Requires an extended network of monitoring wells, which may not be practically possible.
Water/soil/vapour concentrations	Indicator of composition changes, hence reduction of partitioning	Reduce concentrations below the published standards or agreed site-specific assessment criteria determined by a detailed	Multiple rounds of monitoring are required. Measurements of dissolved phase concentrations on NAPL impacted site can be problematic due to presence of NAPL microdroplets in samples, particularly sites with small footprints such as petrol stations where down-gradient

Performance Metrics	Description	Endpoint	Challenges
		quantitative risk assessment.	boreholes cannot be located outside the NAPL footprint. Seasonal variation in water table can also make identification of trends difficult. The concentrations of TPH in groundwater (for example) may be stable until there has been significant mass reduction to reach required levels.

Box 8 - Remediation Criteria

Remediation completion criteria or endpoints should be clearly defined within the remediation strategy and secured through appropriate regulatory mechanisms (e.g. planning conditions, regulatory position statement) to provide objective and auditable endpoints.

For LNAPL remediation, such criteria may include:

- Demonstration that mass recovery rates have declined to an asymptotic level based on trend analysis, indicating that further active recovery would not result in a material reduction in risk;
- Confirmation of a stable or reducing LNAPL footprint over a defined monitoring period; or
- Achievement of dissolved phase contaminant concentrations below relevant published standards or agreed site-specific assessment criteria.

Performance against these criteria should be used to inform optimisation, transition between remediation phases and closure decisions.

In addition to agreed remediation endpoints, remediation work may continue until one of the following criteria has been attained at a site:

- Having carried out remedial works to manage unacceptable risks posed by LNAPL, a revised LCSM demonstrates the residual risks are now acceptable; or
- A cost benefit analysis, supported by site-specific data collected during the operation of the remediation system alongside any other relevant data, demonstrates that the additional improvement of on-site conditions cannot be justified.

4.7 Remediation

Figure 4 shows the anticipated LNAPL distribution and the extraction well network to address the LNAPL identified beneath the site.

A correctly designed remediation system is critical for achieving end goals of a risk management strategy effectively and economically. Results of TFP and SVE pilot tests carried out at the site in question were used to design a MPE system for the site. A MPE remediation system, utilising 12 extraction wells as shown in Figure 3, was operated for 18 months at the site with regular performance monitoring and maintenance for the safe and correct operation of the system.

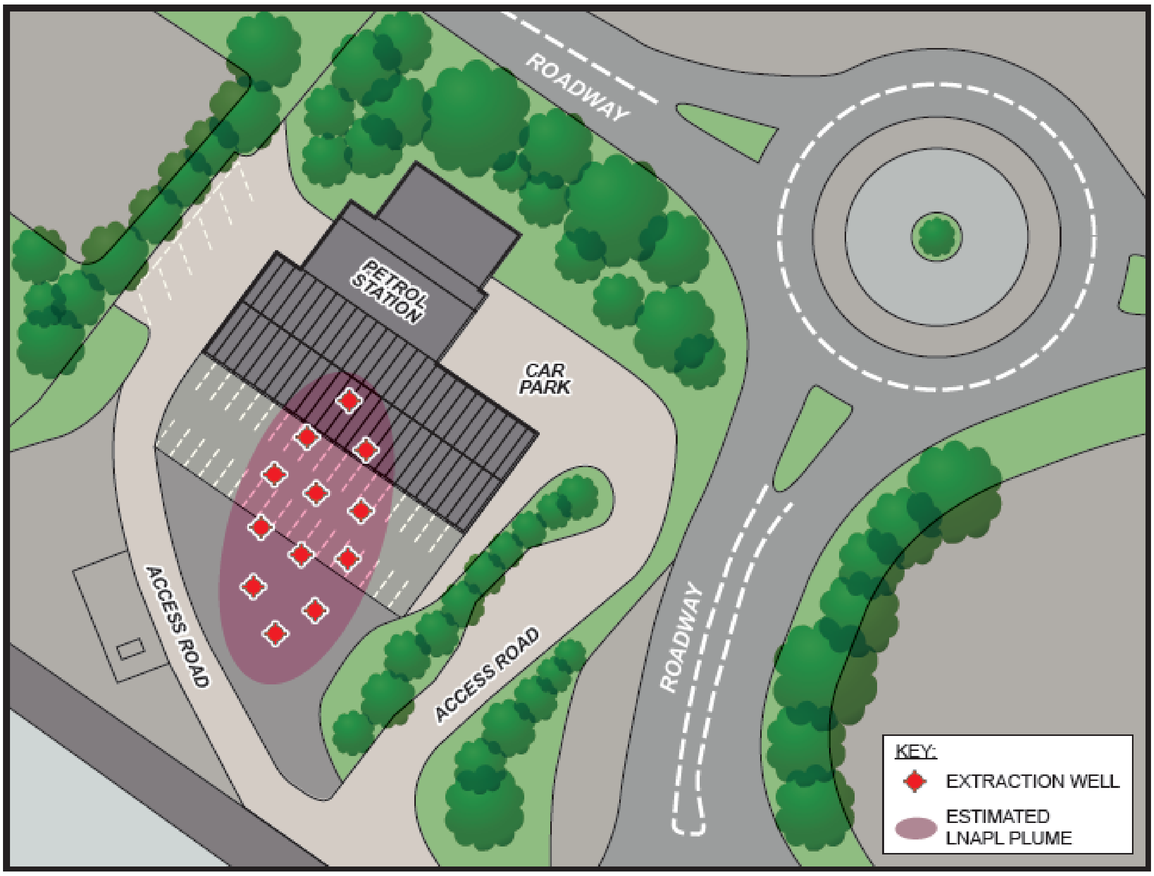

Figure 3. Anticipated LNAPL Distribution and Extraction Well Network

Box 9 - Treatment Train Approach

Sequencing or combining remediation technologies at different stages of the remediation life cycle is likely to be a more practical and cost-effective strategy for achieving remediation goals and objectives, depending on the complexity of the site. The selection and sequencing, or combining of remediation technologies, should be specific to the LNAPL risks, goals, and objectives, and must be a deliberate and considered aspect during the decision-making process.

4.8 Remediation Results

Necessary and appropriate site-specific data should be collected to provide lines of evidence to robustly demonstrate the achievement of remediation objectives and hence the mitigation of associated LNAPL risks.

Direct measurements of quantitative data for each LNAPL risk are preferable.

4.8.1 LNAPL Saturation

Figure 4 shows the cumulative LNAPL volume removed from the site.

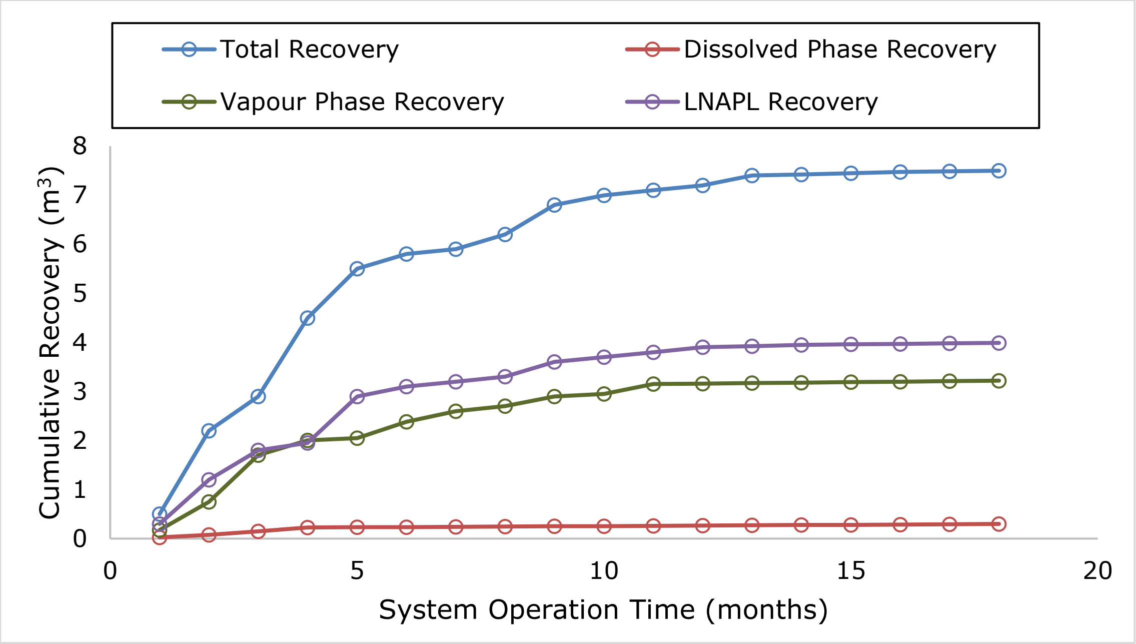

Figure 4. Cumulative LNAPL Recovery by the MPE System

A total volume of approximately 7500 litres (7.5 m^3) of hydrocarbons was removed by the MPE system over 18 months of operational time at the site. Of this volume, 53% was recovered as LNAPL; in addition, the soil vapour extraction system removed 43% of this volume as gaseous phase whilst only 4% was removed as dissolved phase.

Figure 4 shows that the cumulative LNAPL volume removed by the MPE system had reached the asymptotic level, indicating that continued operation of the system may be of limited benefit. Reaching the asymptotic level is indicative of the endpoint of MPE. However, this should be validated by on-site testing to eliminate remediation system limitations, as well as having exhausted all system optimisation options (i.e. adjusting targeted well array, air extraction rates and extraction regime etc). Therefore, further site-specific evidence should be presented to justify and demonstrate that remediation goals and objectives were met at the site.

The decline curve analysis for LNAPL recovery is shown in Figure 6. The best fit line through the LNAPL recovery rate data indicates the maximum recoverable LNAPL volume from beneath the site has been reached.

Box 10 - Asymptotic Recovery and Remediation Validation

Inadequate design of remediation system and limitations of its operation may also result asymptotic level of mass removal at a site. Therefore, multiple site-specific evidence should be provided to justify an asymptotic level at a site.

Regulators and stakeholders should request multiple evidence at a site to confirm and validate the remediation endpoint at a site and *should not* rely on the thickness of LNAPL in wells.

LNAPL thickness is a very poor metric and can vary with water table fluctuations: analysis of transmissivity should be used on a well-specific basis to provide the most robust measurement of the effectiveness of remediation.

The combination of LNAPL recovery decline curve analysis (Figure 5) and decline in LNAPL transmissivity measured in the wells (Figure 6) across the site confirmed the maximum practicably recoverable LNAPL volume had been achieved. As a result, it was confirmed that asymptotic conditions had been reached because the maximum recoverable LNAPL volume had been successfully extracted from beneath the site, and not because of system operation limitations or inadequate design.

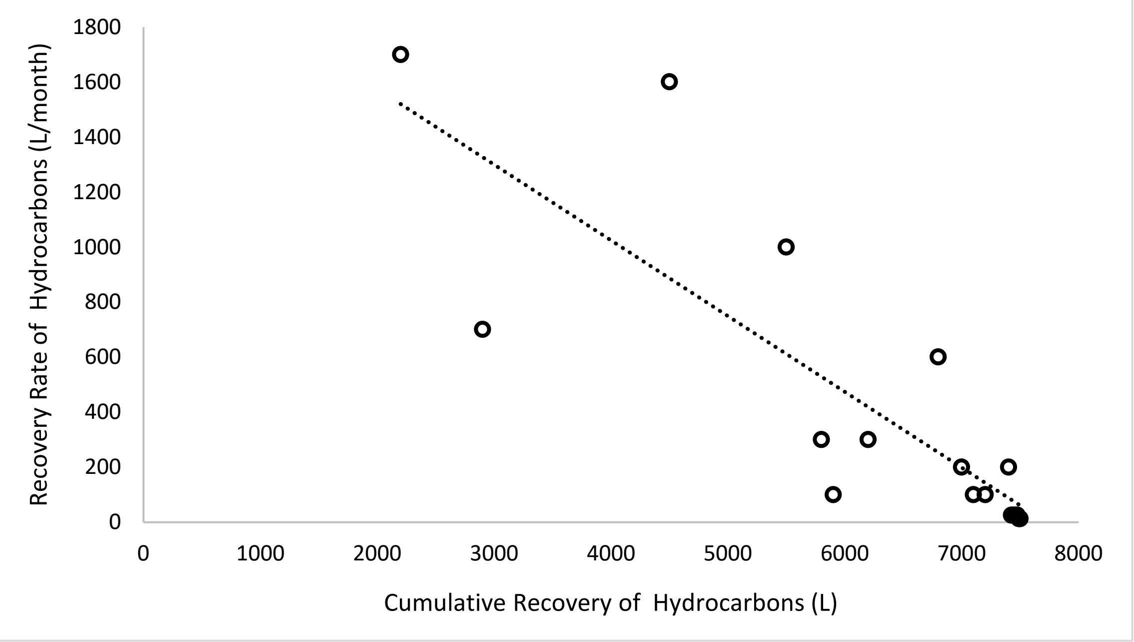

Figure 5. Decline Curve Analysis for Hydrocarbon Recovery

Note that early-time data may not fit.

This data can therefore be used to justify cessation of the active LNAPL remediation, subject to the LNAPL risks having been addressed.

Recovery of maximum LNAPL volume should reduce the LNAPL mass (saturation) beneath the site. As a result, LNAPL risks associated with LNAPL mobility and migration should be successfully addressed. LNAPL thickness was formerly used as a measurement of LNAPL saturation and mobility. However, LNAPL transmissivity analysis will provide a better understanding of the LNAPL mobility at a site. It is a direct measurement of mobility and can be used to corroborate the asymptotic recovery. This is discussed in greater detail in the SoBRA document '*Advice Towards Understanding the Potential for LNAPL Transmissivity and Residual Saturation'* (SoBRA, *in press*).

The viscosity of the LNAPL, based on the measured data is considered low. Low-viscosity LNAPLs (like in this case study) can be reduced to the very lowest transmissivity values in a relatively short time period. Conversely, higher viscosity LNAPLs can take longer (several years) recovery periods to produce the same effect.

Figure 6 shows the average LNAPL transmissivity across the site over the period of operation of remediation. LNAPL transmissivity decreases with LNAPL recovery: the LNAPL saturation falls and so too does the LNAPL mobility. To aid in a robust demonstration that hydraulic recovery has reached its practical endpoint, the transmissivity should be measured in all wells where LNAPL can accumulate.

The removal of 75% of the maximum recoverable LNAPL volume resulted in the average LNAPL transmissivity reaching the defined upper practical limit for hydraulic recovery of 0.07 m^2/day (as defined by ITRC, 2018). Subsequent continued recovery of LNAPL reduced the LNAPL transmissivity at the site to below 0.01 m^2/day, which is the lower limit defined by the ITRC for hydraulic recovery of LNAPL. The transmissivity of the residual LNAPL remains below the practical limit, therefore, further recovery of LNAPL by hydraulic methods is unlikely to materially change either the mobility or the saturation of the LNAPL.

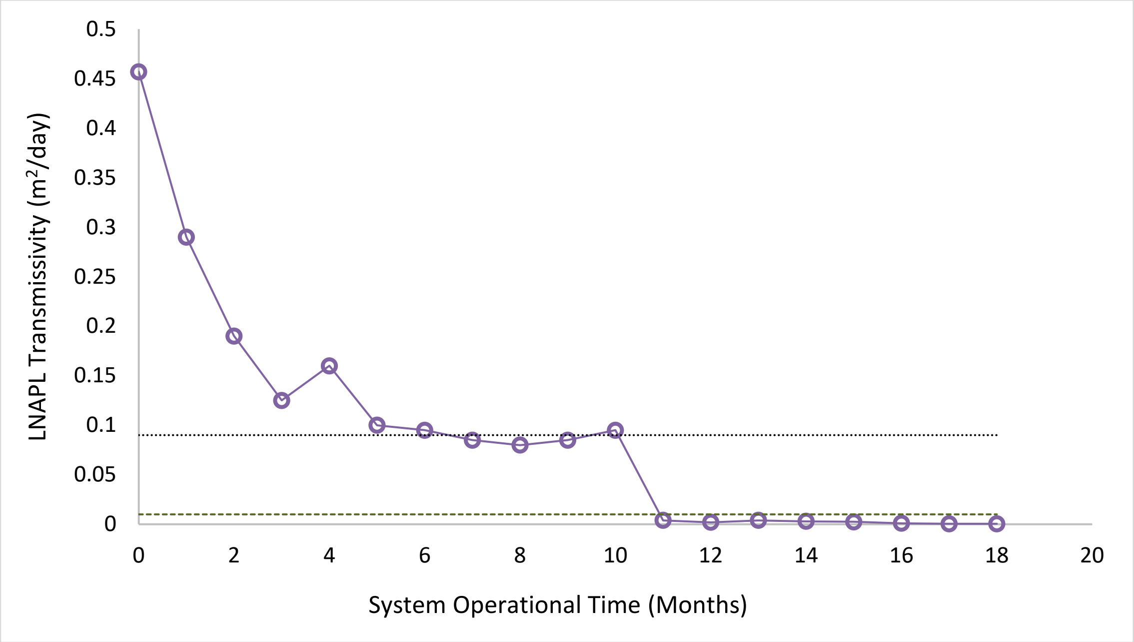

Figure 6. LNAPL Average Transmissivity over the System Operational Time

The final measurement of the LNAPL transmissivity in the monitoring wells at the end of recovery was below the ITRC (2018) cut off value (0.01 m^2/day). This demonstrated that while LNAPL could accumulate in the monitoring wells, it was not mobile and therefore not recoverable.

The combination of all the site specific monitored and analysed data discussed above demonstrated that remediation carried out at the site successfully addressed the LNAPL risks related to the saturation and met the remediation goals and objectives in this respect. As such the risks and drivers presented by the LNAPL saturation were addressed.

4.8.2 LNAPL Composition

Vapour phase

Figure 7 shows the results of indoor air samples collected prior to the LNAPL remediation. The measured concentrations of hydrocarbon in indoor air samples collected at the end of the remediation remained below the laboratory LODs and relevant assessment criteria, indicating that the partitioning of LNAPL into the gaseous phase and then vapour migration are no longer significant and are unlikely to present an unacceptable risk.

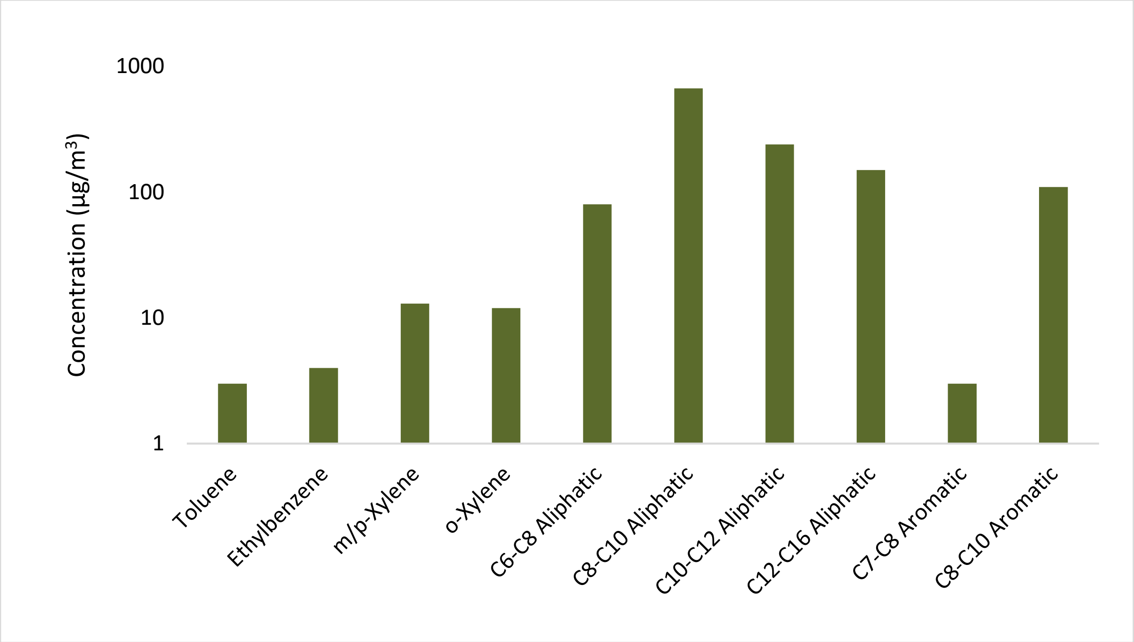

Figure 7. Results of an Indoor Air Sampling Event Collected Prior to Remediation.

All fractions were below the limit of detection at the end of remediation

Dissolved Phase

Concentrations of average TPH fractions as relative percentages, measured in dissolved phase, prior to remediation and at the end of the remediation are shown in Figure 9.

The change of the TPH composition in dissolved phase can be used as a proxy for the change of LNAPL composition. Whilst it is noted the extent of LNAPL composition change would be different to the composition change observed in the dissolved phase, comparison of dissolved phase concentrations is still valid to infer LNAPL composition change beneath the site, as post remediation LNAPL data is generally not available.

The results clearly show the change of composition of dissolved phase contamination (and hence LNAPL composition) due to the remediation. Most of the lighter and mid-range carbon fractions have significantly decreased, and the majority of the residual LNAPL is comprised of the heavy-end TPH fractions.

- Prior to remediation, concentrations of C5-C12 comprised 90% of TPH composition in the dissolved phase.
- By the end of the remediation, the TPH composition has changed significantly, with C5-C12 now representing 44% of the composition, and C12-C35 comprising 56%.

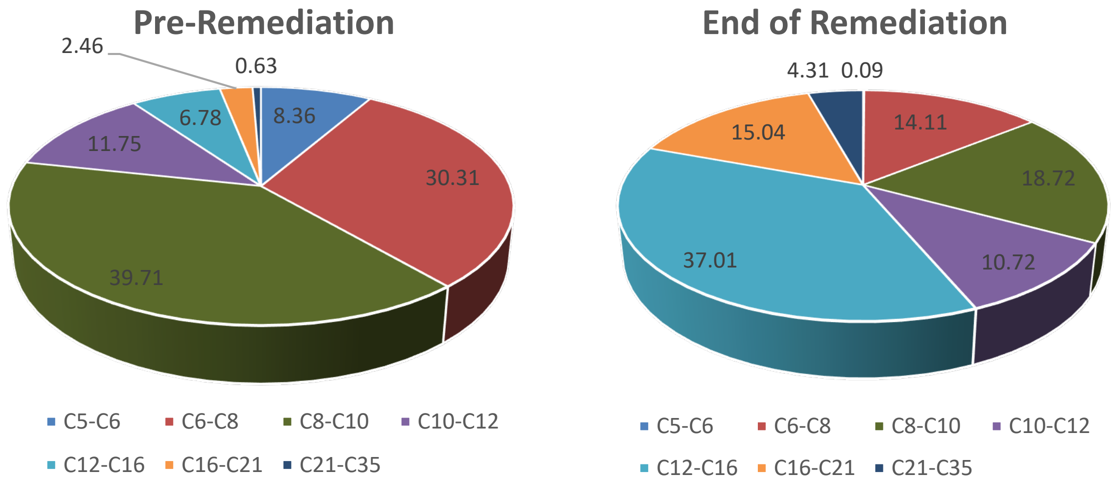

Figure 9 – Variation of the LNAPL Hydrocarbon Components over the Remediation Period

The partitioning of C5-C12 TPH fractions has significantly decreased due to the change of the LNAPL composition, modified by increased rates of volatilisation via soil vapour extraction. As a result, the composition of residual LNAPL by the end of the remediation primarily comprised lower volatility and lower solubility constituents, with associated reduced partitioning into the gaseous and dissolved phases. Results of both indoor air and groundwater samples confirm the limited partitioning of residual LNAPL, indicating that the potential risks to identified receptors are unlikely to be unacceptable. The measured concentrations of TPH in groundwater samples decreased during remediation, remaining below the site-specific assessment criteria (SSAC), by the end of remediation.

It should be noted that no post remediation soil investigations and analyses were carried out at the site. Other results collected (indoor air sample and dissolved phase concentrations measured together with contaminant removal by soil vapour extraction) were sufficient to confirm that residual LNAPL within the unsaturated zone was unlikely to present an unacceptable risk at the site and that remedial objectives had been achieved. When necessary, results of post remediation soil investigation can also be used to justify and demonstrate the meeting of remediation goals and objectives at a site.

4.8.3 Summary

Multiple site-specific lines of evidence collected over the period of remediation confirm the mitigation of all LNAPL risks and demonstrate that remediation goals and objectives at the site were met. The lines of evidence collected during the remediation are summarised below:

Saturation Risk:

- volume of LNAPL removed during the remediation - A significant LNAPL volume was recovered. The rate of recovery has decreased and reached an asymptotic level, indicating that continued operation of the system may provide limited benefit;
- decline curve analysis for LNAPL recovery - The best fit line through the LNAPL recovery rate data indicates that the maximum recoverable LNAPL volume from beneath the site has been reached; and,
- variation of LNAPL transmissivity throughout the remediation - LNAPL transmissivity decreases with LNAPL recovery: the LNAPL saturation decreases and so too does the LNAPL mobility.

Composition Risk:

- measured vapour phase concentrations – comparison of pre and post remediation indoor air samples results indicates that the partitioning of LNAPL into the gaseous phase and then vapour migration are no longer significant and are unlikely to present an unacceptable risk; and,
- measured dissolved phase concentrations – results of pre and post remediation dissolved phase concentrations indicate a change in TPH composition and a reduction in partitioning into dissolved phase.

4.9 Remediation Verification Monitoring

Remediation verification monitoring was commenced following the cessation of the MPE system operation and continued for a further four months on a monthly basis, capturing a range of representative groundwater conditions, to confirm that remediation goals and objectives have continued to be met at the site with no unexpected rebound. While LNAPL accumulated in the monitoring wells following cessation of active remediation, bail down testing confirmed the mobility was negligible and that the remaining LNAPL was functionally immobile.

There was a slight increase in dissolved phase concentrations measured during the first verification monitoring, however, concentrations measured in groundwater subsequently decreased during second and third verification monitoring events. Dissolved phase concentrations measured throughout the verification monitoring remained below the SSAC, indicating unacceptable risks to identified receptors are unlikely. Results of indoor air sampling carried out during remediation verification monitoring remained below the laboratory limits of detection.

Site specific details collected during remediation verification monitoring further confirmed that remediation goals and objectives were consistently met and no further work was required at the site. Following the agreement with the regulators and other stakeholders, remediation at the site was ceased and all the monitoring and extraction infrastructure was decommissioned.

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APPENDIX 1

Links between LNAPL Risks, LNAPL Remediation Goals and Objectives

APPENDIX 1: Links between LNAPL Risks, LNAPL Remediation Goals and Objectives (ITRC, 2018).

	LNAPL Risks	Potential Threshold Metrics	LNAPL Remediation Goal	LNAPL Remediation Objectives
LNAPL saturation-based goals	LNAPL in wells	LNAPL transmissivity to assess recoverability	Significantly reduce LNAPL saturation and therefore mobility	Recover LNAPL to a practicable limit
	LNAPL in soils	Soil TPH regulatory standards	Significantly reduce soil TPH concentrations	Reduce soil concentrations to below soil regulatory limits
	Potential LNAPL migration	LNAPL body footprint stability	Terminate LNAPL body migration and reduce potential for LNAPL migration	Remove potential LNAPL body migration by physical removal of mobile LNAPL
				Stop LNAPL migration by physical barrier
LNAPL composition-based goals	Groundwater impacts from an LNAPL source	Dissolved -phase regulatory standards	Significantly reduce unacceptable constituent concentrations in dissolved phase from LNAPL source	Control or treat soluble plume to Significantly reduce dissolved-phase concentrations. Contain LNAPL body and affected groundwater to prevent groundwater impacts at compliance points(s)
	Petroleum vapour intrusions overlying dissolved plume aside from the LNAPL source	Vapour intrusion screening distances	Significantly reduce unacceptable constituent concentrations in dissolved phase from groundwater source	Reduction of groundwater and vapour concentrations beyond acceptable levels
	Petroleum vapour intrusion overlying LNAPL source		Reduce unacceptable constituent concentrations in soil vapour and/or LNAPL source	Significantly reduce unacceptable vapour accumulations by sufficient depletion of volatile constitutes in LNAPL
	LNAPL occurrence in soil	Soil regulatory standards	Significantly reduce unacceptable soil concentrations even if/when LNAPL is within residual saturation range (e.g., TPH concentration)	Reduction of risk from specific components
Other LNAPL goals (E.g. Geotechnical, aesthetic-based)	Geotechnical instability of LNAPL-affected soil	Geotechnical structural tests	Restore soil stability (saturation-based goal)	Significantly reduce geotechnical soil instability
	Stains and odours	Field inspection	Remove aesthetic concerns (composition-based goal)	Significantly reduce offensive odours
		Odour-based screening levels		
	Sheens on surface waters	Field inspection	Remove aesthetic concerns (composition-based goal), or break pathway	Sheens no longer evident