TECHNICAL REPORT NO.34

A practitioner’s guide for the analysis, management and remediation of LNAPL
Cooperative Research Centre for Contamination Assessment and Remediation of the Environment, Technical Report series, no. 34
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Enquiries and additional copies:
CRC CARE, PO Box 486, Salisbury South, South Australia, Australia 5106
Tel: +61 (0) 8 8302 5038
Fax: +61 (0) 8 8302 3124
www.crccare.com

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CRC for Contamination Assessment and Remediation of the Environment

Technical Report no. 34

A practitioner’s guide for the analysis, management and remediation of LNAPL

February 2015
### Abbreviations

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<tr>
<th>Abbreviation</th>
<th>Description</th>
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<tr>
<td>API</td>
<td>American Petroleum Institute</td>
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<tr>
<td>ASC NEPM</td>
<td>Assessment of Site Contamination National Environment Protection Measure</td>
</tr>
<tr>
<td>BTEX</td>
<td>benzene, toluene, ethylbenzene and xylene</td>
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<td>ASS</td>
<td>acid sulfate soils</td>
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<tr>
<td>CAPEX</td>
<td>capital expenditure</td>
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<tr>
<td>CRC CARE</td>
<td>Cooperative Research Centre for Contamination Assessment and Remediation of the Environment</td>
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<tr>
<td>CSM</td>
<td>conceptual site model</td>
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<tr>
<td>CUTEP</td>
<td>clean-up to the extent practicable</td>
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<tr>
<td>WA DEC</td>
<td>Department of Environment and Conservation (now the Department of Environment Regulation), Western Australia</td>
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<tr>
<td>DQO</td>
<td>data quality objective</td>
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<tr>
<td>DSI</td>
<td>detailed site investigation</td>
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<tr>
<td>ESA</td>
<td>environmental site assessment</td>
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<td>ESD</td>
<td>ecologically sustainable development</td>
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<tr>
<td>HERA</td>
<td>health and ecological risk assessment</td>
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<tr>
<td>HSL</td>
<td>health screening level</td>
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<td>ITRC</td>
<td>Interstate Technology and Regulatory Council</td>
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<tr>
<td>LCSM</td>
<td>LNAPL conceptual site model</td>
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<tr>
<td>LDRM</td>
<td>LNAPL distribution and recovery model</td>
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<tr>
<td>LNAPL</td>
<td>light non-aqueous phase liquid</td>
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<tr>
<td>OPEX</td>
<td>operating expenditure</td>
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<tr>
<td>QA/QC</td>
<td>quality assurance/quality control</td>
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<tr>
<td>RTEN</td>
<td>remediation to the extent necessary</td>
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<tr>
<td>SAQP</td>
<td>sampling, analysis and quality plan</td>
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<tr>
<td>SZNA</td>
<td>source zone natural attenuation</td>
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<tr>
<td>SVE</td>
<td>soil vapour extraction</td>
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<tr>
<td>TCEQ</td>
<td>Texas Commission on Environmental Quality</td>
</tr>
<tr>
<td>US EPA</td>
<td>United States Environmental Protection Agency</td>
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<tr>
<td>VOC</td>
<td>volatile organic compound</td>
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## Glossary of key terms

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<th>Definition</th>
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<tr>
<td><strong>Apparent (LNAPL) thickness</strong></td>
<td>The measured thickness of LNAPL in a screened monitoring well, as opposed to the actual formation thickness of LNAPL, which is governed by a number of factors including soil texture, wettability and capillary pressure characteristics, water table elevation fluctuations, and monitoring well design. Measured thickness in monitoring wells is therefore a poor metric for the amount of LNAPL present.</td>
</tr>
<tr>
<td><strong>Capillary fringe</strong></td>
<td>The lower region of the unsaturated or vadose zone immediately above the water table in which the pore spaces of a porous media are filled with water under pressure less than that of the atmosphere, being continuous with the water below the water table but held above it by capillary pressure.</td>
</tr>
<tr>
<td><strong>Capillary pressure</strong></td>
<td>A function of the (molecular-level) surface tensions between fluids and the solid phase of the soil or rock matrix, and the properties of porosity and pore ‘throat’ sizes, which are governed by grain shape and distribution.</td>
</tr>
<tr>
<td><strong>Conceptual site model (CSM)</strong></td>
<td>The overall aim of the CSM, which, from the perspective of contaminated sites management is integral to the process of risk assessment, is to enable source–pathway–receptor relationships to be assessed, to support the evaluation of the significance of plausible pollutant linkages. All three elements must be present for harm to be realised, triggering the requirement for further investigation, additional risk assessment or remediation.</td>
</tr>
<tr>
<td><strong>Data quality objective (DQO)</strong></td>
<td>The purpose of the DQO process is defined in Australian Standard AS 4482.1-2005 as ensuring that data collection activities are focused on the collection of information needed to make decisions and respond to relevant questions leading to such decisions.</td>
</tr>
<tr>
<td><strong>Economics (economics assessment)</strong></td>
<td>Cost alone is rarely a good indicator of the economic viability of remediation. In the context of this report, economics and economics assessment adopt the so-called triple bottom line or full-cost accounting approach. This approach considers, in addition to the financial aspects of the projects, the social and environmental benefits (or limitations) and an analysis of stakeholder values.</td>
</tr>
<tr>
<td><strong>Environmental site assessment</strong></td>
<td>Typically, a multistage approach to the investigation of (potentially) contaminated land and, if applicable, subsequent ‘tiers’ of risk assessment to address risks and liabilities. An essential component of CSM development and refinement</td>
</tr>
<tr>
<td><strong>Ganglia (LNAPL)</strong></td>
<td>Isolated disconnected globules of LNAPL trapped within pore spaces. Under natural conditions, they are likely to remain as immobile residue that cannot be practically removed</td>
</tr>
<tr>
<td><strong>Intergenerational equity</strong></td>
<td>A concept that says that humans hold the environment of the Earth in common with other members of the present generation and with other generations past and future, implying an obligation to pass the environment in reasonable condition to future generations</td>
</tr>
<tr>
<td><strong>In-well LNAPL thickness</strong></td>
<td>The observed thickness of LNAPL in a monitoring well, which relates to the pressure and spatial distribution of LNAPL in the subsurface, and varies with changes in groundwater elevation</td>
</tr>
<tr>
<td><strong>Light non-aqueous phase liquid (LNAPL)</strong></td>
<td>An organic or inorganic liquid that is not miscible with water and has a specific gravity less than 1.0 (e.g. petrol, diesel)</td>
</tr>
<tr>
<td><strong>LNAPL closeout</strong></td>
<td>The attainment of the LNAPL remedial objectives and remediation end points as agreed with stakeholders, enabling the focus of site management to be transferred from LNAPL to the adsorbed, dissolved and/or vapour phases, if applicable</td>
</tr>
<tr>
<td><strong>LNAPL conceptual site model (LCSM)</strong></td>
<td>Extension of the conventional hydrogeological CSM to include LNAPL-specific properties and parameters, such as intrinsic permeability, relative permeability and LNAPL transmissivity</td>
</tr>
<tr>
<td><strong>LNAPL remediation</strong></td>
<td>Application of an LNAPL mass recovery, phase change and/or source reduction technology to achieve a defined remediation objective</td>
</tr>
<tr>
<td><strong>LNAPL transmissivity</strong></td>
<td>The volumetric rate at which LNAPL can flow through a unit width of a mobile LNAPL layer driven by a unit LNAPL gradient</td>
</tr>
<tr>
<td><strong>Phreatic zone</strong></td>
<td>The saturated zone of the geological sequence below the water table at and above atmospheric pressure</td>
</tr>
<tr>
<td><strong>Pilot study</strong></td>
<td>Also referred to as pilot testing. Pilot studies, which can include small-scale bench testing on site-specific material, or preliminary field trials in advance of the full field-pilot study, are typically conducted to evaluate the effectiveness of the selected remediation technology and the scaling of the full system</td>
</tr>
<tr>
<td><strong>Receptor</strong></td>
<td>The concluding linkage within the source–pathway–receptor conceptualisation of exposure pathways. In contaminated sites management, the concept typically applies to human health or ecological receptors</td>
</tr>
<tr>
<td><strong>Relative permeability</strong></td>
<td>The effect known as relative permeability occurs during the multiphase flow of two immiscible fluids (e.g. LNAPL–water) when both fluids compete for available pore space, resulting in the cross-sectional pore space available for each fluid being less than the total pore space. In this instance, water saturation will reduce the cross-sectional area of the soil or rock matrix available for LNAPL flow</td>
</tr>
<tr>
<td><strong>Remediation end point (LNAPL)</strong></td>
<td>A realistic, achievable, measurable and agreed-upon LNAPL remedial technology–specific point at which active treatment can be terminated. The LNAPL end point is often based on declining recovery rates or asymptotic LNAPL recovery curves. In essence, the limit of practical LNAPL remediation of a particular technology that takes account of the inherent limits of the system</td>
</tr>
<tr>
<td><strong>Remedial objective (LNAPL)</strong></td>
<td>The LNAPL condition to be achieved by the remedial strategy or action that constitutes the desired or aspirational outcome of remediation</td>
</tr>
<tr>
<td><strong>Residual saturation (LNAPL)</strong></td>
<td>LNAPL trapped within pore spaces that has become immobile can also be described as the saturation of LNAPL, at which the relative permeability of LNAPL is zero. Residual saturation is likely to be greater in the phreatic zone. The residual LNAPL saturation in the phreatic zone or in the zone of fluctuating groundwater table will act as a source of continued dissolved phase impact</td>
</tr>
<tr>
<td><strong>Site sensitivity</strong></td>
<td>Site sensitivity in the context of this guidance relates to impact assessment – the potential risks that LNAPL poses to human health or sensitive terrestrial and aquatic ecology, and also to the economic value of the land, both in financial terms (e.g. real estate or productive value) and in terms of social and environmental values (e.g. amenity value)</td>
</tr>
<tr>
<td><strong>Smear zone</strong></td>
<td>The area where LNAPL has been smeared into the pores of a soil or rock matrix through groundwater level fluctuations. The smear zone is defined in soil or rock matrix irrespective of whether the zone is above the water table at any given point in time</td>
</tr>
<tr>
<td>-------------------------</td>
<td>--------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------</td>
</tr>
<tr>
<td><strong>Source zone natural attenuation</strong></td>
<td>The depletion of the LNAPL source through natural losses associated with the processes of volatilisation, dissolution, biodegradation and sorption</td>
</tr>
<tr>
<td><strong>Stakeholder</strong></td>
<td>A person, group or organisation that has an interest in the project, the derivation of the remedial objectives or the outcome of the remediation program. Stakeholders typically include state and territory regulators, site owners, site operators, contaminated site auditors (where applicable) and individuals within the environs of the site, including those who might be affected by the migration of contamination across a site boundary</td>
</tr>
<tr>
<td><strong>Sustainability</strong></td>
<td>There are many definitions of sustainability. In this technical guide and in the context of LNAPL remediation, sustainable refers to the principles of ecologically sustainable development, which is a provision in the contaminated sites legislation of several states and territories. 'Ecologically sustainable development' principles include the concepts of intergenerational equity and the precautionary principle. Sustainability and economics assessments merge when the full life-cycle costs and benefits of each LNAPL remedial approach are considered</td>
</tr>
<tr>
<td><strong>Triple bottom line</strong></td>
<td>A concept, philosophy or framework for promoting sustainability and corporate social responsibility, and an instrument to support institutional accounting and reporting (see Economics [economics assessment])</td>
</tr>
<tr>
<td><strong>Vadose zone</strong></td>
<td>The unsaturated zone between the land surface and the groundwater table</td>
</tr>
<tr>
<td><strong>Wettability</strong></td>
<td>The tendency of a fluid, based on surface tensions, in a multiphase system to preferentially coat or ‘wet’ the solid phase of a soil or porous rock medium. Typically, water has a preference for small pore spaces, air for larger pore spaces and LNAPL for intermediate-sized pores. Water is therefore described as the wetting fluid, air as the non-wetting fluid and LNAPL as the intermediate wetting fluid</td>
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Authors of technical report
Paul Hardisty, WorleyParsons Services Pty Ltd (now with CSIRO)
Ed Dennis, WorleyParsons Services Pty Ltd (now with ERM Pty Ltd)
Melanie Myden, WorleyParsons Services Pty Ltd
Geoffrey Borg, Shell Company of Australia Pty Ltd (now with Viva Energy Pty Ltd)

Other contributions
Neil Foster, WorleyParsons Services Pty Ltd

Technical working group
Dennis Monahan, Former Director, Environmental Science Division, EPA Victoria, Chair
Andrew Miller, Department of Environment Regulation, Western Australia
Anne Northway, Environment Protection Authority, Victoria
Geoffrey Borg, Shell Company of Australia Pty Ltd (now with Viva Energy Pty Ltd)
Stuart Rhodes, Rio Tinto
Prashant Srivastava, CRC CARE

Project advisory group
Dennis Monahan, Former Director, Environmental Science Division, EPA Victoria, Chair
Janet Macmillan, Department of Environment Regulation, Western Australia
Erwin Benker, Environment Protection Authority, New South Wales
Rebecca Hughes, Environment Protection Authority, South Australia
Anne Northway, Environment Protection Authority, Victoria
Mitzi Bolton, Environment Protection Authority, Victoria
Tony Bradshaw, Department of Environment and Heritage Protection, Queensland
John Howell, Department of Health, Western Australia
Andrew King, BP Australia Pty Ltd
Belinda Patterson, Caltex Australia Petroleum Pty Ltd
Dave Thomas, Chevron Energy Technology Pty Ltd
Introduction

The Cooperative Research Centre for Contamination Assessment and Remediation of the Environment (CRC CARE) has released a series of technical reports on the assessment, management and remediation of light non-aqueous phase liquid (LNAPL) petroleum hydrocarbons in the subsurface. These technical reports summarise comprehensive research on the strategies to assess and remediate LNAPL, as well as on the treatment of the vapour and dissolved phase components attributable to the LNAPL source.

This technical report is intended as a practical guide to LNAPL remediation in Australia and to accompany CRC CARE Technical Report no. 18, *Selecting and assessing strategies for remediating LNAPL in soils and aquifers* (Johnston 2010). This guide draws on the wealth of literature on LNAPL remediation globally, and on the documented experience of remediation practitioners in Australia, Europe and North America, where many of the approaches, terms and technologies discussed in this document have been developed.

The guide may also form a platform for a consistent, trans-jurisdictional approach to the management of LNAPL impacts across Australia, and the nexus for the series of CRC CARE technical reports addressing the management of LNAPL and subsurface petroleum hydrocarbons.

It is also intended that this report acknowledges the diversity of technical expertise required of the professions engaged in the management and remediation of LNAPL contaminated sites. By setting out the entire project life cycle – from problem characterisation through to risk assessment, decision making, engineering design and execution, and ultimately LNAPL closeout – the unified approach of this guide is intended to support specialists in any one area of the project life cycle with perspectives on other areas.

This guide is aimed at industry project managers, environmental consultants, remediation practitioners, owners and operators of contaminated sites, and state and territory regulators in Australia – that is, those with an interest in the effective, efficient and sustainable remediation of LNAPL contaminated sites. The guide provides a practical step-by-step approach to site characterisation, remedial decision making, technology selection and implementation of remediation in an Australian context.

It is important to note that terms used in this guide such as ‘remedial objective’, ‘remediation end point’ and ‘closeout’ generally only apply to the LNAPL component of site contamination. The overarching project objectives associated with LNAPL must be kept in mind. These are likely to include measures to address explosion risk, the effects on health of acute or chronic exposure to vapour intrusion, and the amelioration of dissolved phases.

In the management of an LNAPL contaminated site, attainment of the LNAPL remedial objective or the LNAPL remediation end point should be considered to be substeps of the overarching project objectives, since management of the adsorbed, dissolved or soil vapour phase hydrocarbon impacts is likely to continue beyond these stages.

To place this guide in context, LNAPL contamination is most often related to leaking underground petroleum storage systems and associated infrastructure. Legislation and
guidance are available in some states to promote testing and replacement of underground assets to foreshadow the likelihood of future losses of containment. The maxim of prevention being better than cure is apt in relation to the management of an LNAPL impacted site.

It is also essential to differentiate between a stable LNAPL plume and an actively spreading LNAPL plume. A stable plume may be the legacy of historical practices, or associated with leaking underground petroleum storage or transfer infrastructure, whereas an actively spreading plume might be associated with a catastrophic failure of petroleum handling infrastructure. This guide is primarily intended for use in the management and remediation of a stable plume, where the source of impact has been rectified. The guide assumes that the spreading plume scenario associated with catastrophic failure will be prioritised, triggering emergency response and pollution incident reporting in accordance with state and territory legislation.

Technical context

Petroleum hydrocarbon spills, accidental releases or failures of containment can result in explosion risk, risks to human health from contamination, devastation of groundwater or natural resources, direct or indirect economic impacts, and damage to the reputation of organisations and individuals associated with the release.

Surface releases of oil will be obviously visible and likely to demand a more immediate clean-up response from society – including people who are likely to be affected by the release – than subsurface releases. Depending on the magnitude of the release and environmental conditions, surface releases can generally be regarded as more tractable than subsurface releases. Further information on the response to surface spills is available in *Understanding oil spills and oil spill response* from the United States Environmental Protection Agency (US EPA) Office of Emergency and Remedial Response (US EPA 1999).

Given the more problematic nature of subsurface contamination, and the inherent challenges of soil and groundwater remediation following contamination, this document focuses on the remediation of subsurface LNAPL contamination.

Over the past several decades, a wealth of research and practical experience has led to a comprehensive understanding of the behaviour of immiscible liquids in the subsurface. Worldwide, billions of dollars have been spent on remediation. Accordingly, this guidance document does not seek to provide a comprehensive technical review of LNAPL fate and transport. Rather, it provides a straightforward framework to guide remedial practitioners through a series of critical steps that can help to ensure successful outcomes.

Once LNAPL has been released to the environment, it can be difficult and sometimes expensive to remediate. Even under ideal conditions, it is likely that a significant proportion of the LNAPL released will remain in the subsurface as an immobile residue. Many LNAPLs contain compounds that are partially soluble, and therefore mobile, in groundwater. As a result, LNAPL in the subsurface may be a long-term environmental liability because of its potential to contribute to a human health or environmental exposure pathway.

The technical challenges associated with LNAPL remediation have led to concepts such as ‘clean-up to the extent practicable’ (CUTEP), ‘remediation to the extent
necessary’ (RTEN) and technical impracticability (Johnston 2010). Most Australian state and territory regulators address LNAPL contamination concerns on a site-specific basis, without the benefit of broad technical guidance to assist in decision making.

Over the past few decades, LNAPL remediation technologies have evolved from conventional skimming, manual bailing, pumping or hydraulic recovery systems to encompass a variety of innovative passive, active and experimental approaches. These include methods that address the mobile and residual LNAPL fractions while simultaneously acting on the volatile and dissolved-phase components.

Research into the quantitative analysis, treatment and remediation of LNAPL continues. At the same time, a maturing of the understanding of risk-based approaches to the management of contaminated sites (including the principles of full-cost economics and sustainability) by regulators and other stakeholders is likely to lead to Australia-wide changes in approaches to the treatment of LNAPL.

Influenced by local conditions, policies for the treatment of LNAPL across Australia are continuing to develop. In a time of rapid technological change, it is envisaged that the process set out in this guide will apply in the future to sites that are affected by LNAPL.

**Emergency response and the structure of the guide**

This guide primarily addresses the management and treatment of a stable LNAPL plume to enable a measured and systematic response to LNAPL remediation. Emergency response and pollution incident reporting should be a priority in the scenario of a catastrophic failure of petroleum storage infrastructure and the presence of an actively spreading plume.

This guide describes a sequence of five principal steps (1 to 5) that provide a consistent, pragmatic and systematic approach to the management of an LNAPL impacted site in Australia, irrespective of changes in the science of LNAPL remediation or regulatory policy.

The five steps are presented sequentially, but there is overlap between steps and substeps, and indistinct boundaries between steps. For example, feedback from later steps (such as cost–benefit analysis or performance monitoring) can influence the selection or establishment of LNAPL remediation end points. The user is therefore encouraged to use this guide iteratively and incrementally to achieve the desired LNAPL remediation end point.

To inject an element of pragmatism into this guide, ‘practitioner’s tips’, based on the personal experiences of accomplished remediation practitioners, have been interspersed throughout the document.

The guide also includes three worked examples (in Appendix A), which illustrate the merits of a sequential approach to the prioritisation, assessment, management and remediation of an LNAPL impacted site. The worked examples are also intended to demonstrate the iterative and interdependent nature of the process – that is, information derived from subsequent steps or substeps can lead to a revision of the initially proposed management approach.

In keeping with the broadly accepted philosophy of management of contaminated sites adopted by most practitioners, the guide uses a phased and risk-based approach, and
emphasises the importance of full-cost economic and sustainability considerations at key steps in the process.

Site sensitivity and the principles of ecologically sustainable development (ESD) – which includes the concept of intergenerational equity (Fowler & Cole 2010) – are, or should be, key considerations in the decision-making process. Economics assessment and consideration of sustainability are also emphasised in the decision-making process surrounding the selection of remedial technologies.

Finally, the importance of early engagement and consultation with regulatory authorities on the optimum means of managing the LNAPL impacted site cannot be overemphasised.

The five principal management steps are set out in Figure 1.

![Figure 1. The five steps of LNAPL management and remediation](image)

The idealised five steps are intended to follow a sequential process, driven, from the bottom up, by the demands of emergency response [to a recent pollution incident], the sensitivity of the site, and integrity and reliability of data, particularly during the early stages of development of the LNAPL conceptual site model (LCSM). However, as with all dynamic processes, feedback mechanisms can influence decision making, or trigger reappraisals or changes in direction.

For example, a pollution incident in which petroleum product has entered the environment and is spreading through the subsurface and presenting immediate risks to people and the environment will need to proceed immediately to action to recover LNAPL (i.e. stop it from spreading further), and manage immediate exposure or explosive risks to the community and the environment. In such instances, there is no time to develop a detailed LCSM before selecting a remedial approach. Decisions will

---

1 The conceptual site model (CSM) is fundamental to the management of contaminated sites. Throughout this guidance document, because the focus is on management of LNAPL, the acronym LCSM is used for consistency. However the LCSM should be considered a subset of the greater CSM and should contain all the attributes of a conventional CSM, with particular focus on LNAPL.
have to be made on readily available information on the nature of the LNAPL release, and the geology and hydrogeology of the affected area. Once these immediate risks are controlled and the LNAPL plume is stable, the project will have to be reassessed using the standard process.

In another example, an unsuccessful pilot study would inevitably lead to reappraisal of the technology selection, system modification or redesign, or revision of the LNAPL end point. In some instances, steps or substeps may not be relevant or applicable.

Acknowledging the potential for feedback mechanisms, the five key management steps are summarised below.

**Step 1: Undertake LNAPL project prioritisation and screen site sensitivity and risk**

Step 1 of the process considers project prioritisation and the critical question of whether emergency response is required (triggered by a recent pollution incident), or whether the project consists of a *mature* or *stable* LNAPL plume, where the primary source of impact has been rectified.

In the former case, it is of paramount importance that emergency response procedures, including statutory pollution incident reporting, are implemented to curtail the petroleum release and fast-track LNAPL recovery activities. This should take place before the more measured approach to LNAPL remediation – for which this guide is primarily intended – occurs.

For treatment of pre-existing or likely stable LNAPL plumes, site sensitivity screening and risk assessment are used to *rank* the significance of the LNAPL impact and all subsequent decision making.

The definition of site sensitivity, based on commonly used and widely accepted risk assessment and impact assessment practices, is used to classify the site and the significance of the LNAPL impact, together with the principles of ESD and economic considerations. Key parameters include quantified potential acute and chronic risks, the volume and physical extent of LNAPL in the subsurface, product volatility, and the relationship of the LNAPL with the potential pathways and receptors identified in the LCSM (which will be refined following completion of step 2).

Stakeholder considerations are also influential in ascribing or agreeing on site sensitivity. They can include the financial and productive value of the land, and concepts such as intergenerational equity and the ‘triple bottom line’ economic value of the land or other impacted assets. In step 1, the risks are appraised by the use of an LNAPL site sensitivity screening matrix to assign a sensitivity classification to the site: ‘low’; ‘medium’ or ‘high’. However, refinement of the LCSM is a dynamic process; at some stage following step 2, it may be necessary to reclassify the sensitivity of the site.

**Step 2: Undertake quantitative LNAPL analysis and LCSM development**

Step 2 expands on step 1. It consists of three substeps derived from detailed environmental site assessment (ESA):

- step 2(a) – desktop review and data gap analysis
- step 2(b) – detailed site investigation,
- step 2(c) – data collation, interpretation and visualisation.

When integrated, these substeps lead to the development of the LCSM.

The LCSM describes the three-dimensional extent, behaviour and recoverability of the LNAPL, and forms a foundation for subsequent decision making about the applicability of technologies to the site setting. In this context, the importance of scientific rigour and reliability of data cannot be overemphasised. It is also important to note that the LCSM should be considered a component of the overarching CSM, containing all the attributes of a conventional CSM, with particular focus on the LNAPL, its distribution and its recoverability.

**Step 3: Set LNAPL remedial objectives, define LNAPL remediation end points and select LNAPL remedial technology**

Based on the site sensitivity classification of step 1 and the refinement of the LCSM in step 2, step 3 guides users through a structured decision-making process. In consultation with stakeholders, this leads to the selection of the remediation or management measures for the site. Step 3 consists of four substeps:

- step 3(a) – setting LNAPL remedial objectives
- step 3(b) – establishing LNAPL remedial end points
- step 3(c) – technology selection, and
- step 3(d) – economic and sustainability analysis of the remedial options and technology selection, across the project life cycle (where applicable).

It should be emphasised that a site sensitivity classification of ‘low’ – as demonstrated by an absence of receptor risk, plume stability, compatibility with the principles of ESD or stakeholder agreement – is likely to support a non-active approach to LNAPL remediation. Under these circumstances, continuing the process beyond step 3(b) may not be required.

**Step 4: Undertake pilot testing and technology implementation**

Step 4 is the execution phase, where the selected remedial technology (or technologies) are designed, planned and installed. Depending on the magnitude of the LNAPL impact (and therefore the scale of the remediation system) and the site sensitivity classification established in step 1, pilot studies may be implemented to inform design of the final remediation system. Subject to the analysis of pilot study performance or other factors, a return to step 3(c) may be triggered.

**Step 5: System operation, performance monitoring and LNAPL closeout reporting**

Step 5, the final stage of the process, addresses system management, performance monitoring, system modifications as required, the attainment of the LNAPL remedial end points and system closeout. In this document, ‘closeout’ refers only to the LNAPL impact; closeout for the adsorbed, dissolved and vapour phases contamination, if applicable, may not occur at the same time.
Notes on use

This guide summarises and references common LNAPL characterisation approaches and available remediation technologies, including some more recent innovations. It is not, however, intended to provide a comprehensive guide of all available assessment methodologies and remediation technologies. Rather, the user is directed to the extensive literature available in these areas.

Beyond any immediate emergency response requirements that may be triggered by a pollution incident, the focus of this guide is leading practitioners through a rational, stepwise process, from initial site classification and characterisation through to LNAPL remediation system closeout (if applicable). Decades of remediation experience worldwide have shown that following such a process provides a sound basis for achieving positive remediation outcomes for all stakeholders.

As illustrated by the worked examples in Appendix A, it is also important to note that no two LNAPL impact scenarios are alike in terms of prioritisation, scale of the problem, site setting, product characteristics or ground conditions. While this document is intended as a general guide on the process of managing LNAPL remediation and primarily focuses on legacy LNAPL issues, the importance of emergency response to a recent pollution incident must be emphasised, with prioritisation of response the key message.

There is clearly a difference between the approach and response to management of a small-scale release (a few thousand litres or less) or a stable non-spreading LNAPL plume associated with a rectified historical incident and the emergency response that would be applied to a mega-litre impact scenario on an industrial scale, following a recent pollution incident. Professional judgement should therefore be exercised in each LNAPL remediation project. Figure 2 sets out a logic-based decision process for evaluating whether immediate risks require more urgent remedial action and consequently the development of an abbreviated LCSM.

Assessment and management of the hazards and risks presented by flammable and combustible liquids and gases, both in the ground and contained following recovery, is a unique and specialised area of contaminated site management and beyond the scope of this technical guide. It is imperative that practitioners working on LNAPL impacted sites are experienced in the occupational health and safety risks, and waste management risks posed by the work.
A sense of proportionality should be maintained in the use of this guide and in the management of LNAPL. As discussed above, site sensitivity, intergenerational equity
and the economics of remediation are key considerations in the decision-making process. The derivation of stakeholder-endorsed remedial objectives and the acceptance of LNAPL remediation end points rely heavily on the quality of the LCSM and the professional judgement of remediation practitioners.

**Practitioner’s tip: At which point should I talk to the regulators before addressing an LNAPL problem?**

The elimination or reduction of LNAPL impacts at contaminated sites is a universally held aim of regulators across Australia, to reduce any ongoing risks. A fundamental position is that there should be no unacceptable residual risk posed by any LNAPL remaining after remediation. To determine detailed approaches in specific jurisdictions, and to ascertain key local factors and risks, discussions should be held with regulators at an early stage of any remediation project.
Background – the Australian context and the behaviour of LNAPL in the subsurface

Before advancing to step 1 of the guide, this section provides background information on current LNAPL management guidance in Australia, the current positions of state and territory regulators, some key Australia-specific geochemical considerations, and the behaviour of LNAPL in the subsurface.

Relationship of this guidance document with other CRC CARE guidance documents

In addition to promoting a systematic process for the management of LNAPL and a uniform, risk-based approach to the treatment of LNAPL in Australia, this document aims to cross-reference the library of technical guidance produced by CRC CARE that is either directly or indirectly associated with the management of LNAPL.

Although this guide is primarily intended to provide a systematic process to accompany CRC CARE Technical Report no. 18 (Johnston 2010), it is also directly or indirectly relevant to the CRC CARE Technical Report series on the petroleum hydrocarbons (Technical Report nos. 2, 3, 4, 8, 10, 11, 12, 13, 15, 16, 18, 22 and 23). The reader is also encouraged to refer to these documents during the management of LNAPL and subsurface petroleum hydrocarbon impacts.

Summary of available LNAPL management guidance in Australia

The management of contaminated sites in Australia is generally regulated by the states and territories. National standards and guidelines – such as those set out in the National Environmental Protection (Assessment of Site Contamination) Measure (ASC NEPM) (NEPC 1999, amended 2013a,b,c) – have also been developed to support a consistent national approach.

As with the management of contaminated sites in general, the treatment of LNAPL is considered differently among the states and territories, reflecting different approaches to the treatment of land and groundwater contamination. Friebel and Naderbaum (2011b), in discussing the limitations of health screening levels (HSLs) when LNAPL is present in groundwater, note that in most Australian jurisdictions the presence of free product requires management, irrespective of whether a risk is posed.

Regulatory approaches to the management of contaminated sites and treatment of LNAPL are dynamic. Principles such as RTEN and CUTEP may continue to be adopted, or they may evolve into risk-based approaches augmented with consideration of full-cost economics and the life-cycle sustainability of remediation. It is therefore recommended that, whenever LNAPL contamination is identified on a site, professional judgement is exercised, and engagement and consultation with the local regulatory authority is initiated as soon as practicable.

This guide is not intended to compromise the existing approaches or requirements of the states and territories, but rather to support a systematic and risk-based approach to the management of LNAPL in Australia.
Australian geochemical context

The geological history of the Australian continent extends from the beginning of the Archaean eon to the present, with all known rock types likely to be represented. From the hydrogeological and geochemical perspectives, diverse physical, hydraulic and chemical properties can be expected across the continent, which are attributable to the parent rock, and derived soils and sediments.

At the earliest stages of development of the hydrogeological CSM, characterisation of the properties of porous media, fractured media, and the associated relationships between higher- and lower-permeability soil and/or rock units is fundamental to understanding LNAPL behaviour and subsequent decision making about LNAPL management.

In this guide, brief mention of acid sulfate soils (ASS) is made. When they are disturbed, ASS pose a major geochemical threat to groundwater- and surface water-dependent ecosystems in many areas of Australia. ASS are naturally occurring soils and sediments, rich in iron sulfides (predominantly in the form of pyrite minerals), which are typically found in low-lying coastal or estuarine regions all around Australia. Further information on ASS can be found in CRC CARE Fact Sheet 6 (CRC CARE 2009) and WA Department of Environment and Conservation (now Department of Environment Regulation), Identification and investigation of acid sulfate soils and acidic landscapes (DEC 2013).

Since any LNAPL impacted site could lead to a program of product removal, trenching or dissolved phase extraction through dewatering, it is recommended that the geochemistry and the likelihood of ASS presence be established at an early stage of LCSM development to inform subsequent remedial decision making.

However, with the exception of pipelines traversing sensitive environments, sites of most LNAPL impact scenarios are likely to be industrial in nature and therefore in an environmental setting that has already been disturbed by the presence of site infrastructure.

Behaviour of LNAPL in the subsurface

An understanding of the behaviour of LNAPL in the subsurface is an essential part of successful site characterisation, and subsequent appraisal of the risks associated with LNAPL contamination and the suitability of available remedial technologies for reducing the risks.

This introductory section provides a basic summary of the main characteristics of LNAPL in the subsurface environment following loss of containment or accidental release.

More detailed information on the characteristics and behaviour of LNAPL in the subsurface can be found in:

- American Petroleum Institute (API) publications, which are summarised in API’s Interactive LNAPL Guide (API 2004)
- API’s LNAPL Resource Centre (www.api.org/environment-health-and-safety/clean-water/ground-water/lnapl.aspx)
- CRC CARE Technical Report no. 18 (Johnston 2010)
• Interstate Technology and Regulatory Council (ITRC)’s technology overview
  Evaluating natural source zone depletion at sites with LNAPL (ITRC 2009a)

• US EPA’s LNAPL groundwater issue (Newell et al. 1995)

• US EPA’s Residual saturation: What is it? How is it measured? How should we use it? (Adamski, Kremesec & Charbeneau 2003), and

• US EPA’s A decision-making framework for cleanup of sites impacted with light non-aqueous phase liquids (LNAPL) (US EPA 2005).

LNAPL occurrence in the subsurface

LNAPL compounds (such as petroleum hydrocarbons) may be present in the subsurface in four different phases:

• an immiscible or partitioning liquid phase (LNAPL)

• dissolved in groundwater as the aqueous phase

• volatilised into soil gas as the vapour phase, and

• adsorbed to soil particles in the solid phase (adsorbed phase) (Clements, Palaia & Davis 2009; Newell et al. 1995).

Once a subsurface hydrocarbon release occurs, it may undergo multiple phase changes from the original ‘free’ liquid phase: adsorption to solid soil particles, dissolution into pore water and volatilisation into the vapour phase. It is also important to note, as illustrated by Figure 3, that all four phases may be present in the vadose (unsaturated) zone. In the phreatic (saturated) zone, contaminants will not be present in the vapour phase (Newell et al. 1995) as water has displaced air from pore spaces. Compounds may also partition between the various non-liquid phases (vapour–dissolved; dissolved–adsorbed). This means that, while LNAPL may be the focus of remediation, much of the risk may be driven by compounds that have moved into other, more mobile phases.

This guidance document is primarily concerned with petroleum hydrocarbons in the liquid LNAPL phase. Practitioners must, however, be aware of the characteristics and behaviour of the other phases in which these compounds can occur in the subsurface.

Source: Newell et al. (1995)

Figure 3. The four phases of petroleum hydrocarbons in the subsurface
LNAPL mobility and longevity

Migration of LNAPL in the subsurface is controlled by the characteristics of the LNAPL (density, viscosity) and the subsurface materials at both the pore scale and macro scale (wettability, permeability, porosity, chemical composition, physical structure and heterogeneity). These factors, in turn, govern the capillary pressure and saturation relationships that determine LNAPL occurrence, distribution and mobility within a porous medium.

LNAPL released to the subsurface will generally migrate downwards under the influence of gravity until impeded by a low-permeability unit or by buoyancy forces near the water table (API 2004; Johnston 2010; Hardisty & Ozdemiroglu 2005). In summary, LNAPL in the subsurface is generally observed as:

- free-phase pooling at or near the capillary fringe, or within discrete fractures, or above low-permeability zones
- residual LNAPL in the vadose zone, and/or
- trapped LNAPL blobs or ganglia in the phreatic zone (Johnston 2010).

In the subsurface, LNAPL coexists with other fluids (water and air). This ‘multiphase’ conceptualisation describes LNAPL saturation as varying with depth (with a saturation peak occurring near the top of the capillary fringe), as depicted in Figure 4. This peak in saturation is sometimes reflected in the ‘depth to product’ measurement recorded in a monitoring well screened across the water table, and is a key metric in the assessment of contaminated sites and subsequent performance monitoring of LNAPL recovery systems.

The thickness of LNAPL in a monitoring well has been reported to exceed the actual LNAPL formation saturation thickness by a factor estimated to range between 2 and 10 (Johnston 2010). Based on this difference, the measured thickness in a monitoring well has been referred to as the ‘apparent thickness’. It is important to use the concept of apparent thickness to avoid overestimation of LNAPL volume. Many references describe the physical forces responsible for this phenomenon, and on using LNAPL thickness in wells as an indicator of LNAPL extent in a formation. For further information, see Charbeneau et al. (2000), Charbeneau and Chiang (1995), Farr, Houghtalen and McWhorter (1990) and Leonard and Parker (1990).

Johnston (2010), referencing ITRC (2009a), emphasises that the LNAPL in a well is only a reflection of the presence of the ‘free’ mobile LNAPL in a formation, and does not account for the residual saturations trapped within the soil and groundwater unit.

To avoid overestimation of LNAPL volume, it is imperative that users understand how to relate observed ‘in-well’ LNAPL thicknesses to estimated LNAPL saturation in the adjacent porous medium. An understanding of saturation estimates and areal extent of LNAPL occurrence provides the basis for calculation of LNAPL spill volume estimates, a key part of the LCSM.

It is also emphasised that, although LNAPL thickness is not a metric for LNAPL recoverability, it does support three-dimensional characterisation of the LNAPL mass. LNAPL recoverability is primarily governed by LNAPL transmissivity, which is best assessed by baildown testing (Lundy 2004).
Typically in porous media, as long as an LNAPL release continues, LNAPL in the subsurface continues moving. Once a release stops, the forces driving migration dissipate, and the rate of LNAPL migration slows, with a declining pressure head. With time, the force becomes insufficient to drive further LNAPL movement. This occurs when the pressure in the LNAPL is not enough to displace the water in pore spaces at the margin of the released LNAPL body. Johnston (2010) provides further discussion of LNAPL behaviour in porous media.

Lateral movement of the LNAPL is controlled by the LNAPL head gradient (Johnston 2010). Mobility and spreading of LNAPL may occur either within the body of the plume, as mobile LNAPL, or as part of the mobility of the plume itself (i.e. spreading of the plume). CRC CARE (2010) provides for further information on LNAPL migration and intraplume LNAPL mobility.

In fractured media, LNAPL mobility is governed principally by the geometry and interconnection of the fracture network, and the frequency and magnitude of groundwater fluctuations. Commonly used porous medium models may not apply. If LNAPL is detected in fractured media, special care must be taken during site characterisation and remediation to avoid inducing significant fluctuations in the groundwater surface, as this can drive LNAPL up- and cross-gradient in unpredictable ways. Hardisty et al. (2003) and CRC CARE (2010) provide a more detailed discussion of the behaviour and migration of LNAPL in fractured aquifers.

**Residual saturation and dissolved phase partitioning**

If the LNAPL release is large enough to reach the groundwater table, the LNAPL may begin to spread laterally and dissolve into groundwater. Dissolution into the aqueous phase is governed by the solubilities of the component compounds of the LNAPL and...
their relative proportions in the mixture. The ITRC (2009a) provides a useful account of
the processes governing LNAPL dissolution and biodegradation in the phreatic zone.

As the groundwater surfaces fluctuate, LNAPL is redistributed within the porous
medium, creating what is commonly referred to as a ‘smear zone’ (Figure 5). If
smearing occurs during a decline in groundwater elevations (e.g. due to natural water-
table fluctuations or fluctuations induced by pumping), residual LNAPL may be trapped
below the water table when groundwater levels rise again (NAVFAC 2010).

As LNAPL volume is depleted by dissolution, volatilisation or active remediation, the
proportion of pore space occupied by LNAPL (i.e. the saturation) decreases. As
saturation declines, LNAPL flow pathways become smaller and more tortuous. This
reduces the ease with which LNAPL can move (mobility). Ultimately, the LNAPL breaks
into isolated ganglia that are discontinuous and immobile, as a separate liquid phase
(Figure 5).

The saturation point at which LNAPL is immobile is referred to as residual saturation
(API 2003). At this point, the relative permeability of LNAPL is zero. Residual
saturations as high as 0.3 (30% of the pore space filled by LNAPL) are common in
porous media. LNAPL trapped as residual saturation can therefore provide an ongoing
source of dissolved phase contamination. Practitioners need to be aware that, even if
LNAPL is not present in monitoring wells, residual LNAPL may still exist in the adjacent
ground.

**Vapour phase**

When LNAPL is in physical contact with air contained in soil pores, the more volatile
fractions of the hydrocarbon constituents within the liquid phase may partition into the

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*Source: NAVFAC (2010)*

**Figure 5. Representation of LNAPL in the subsurface**

As LNAPL volume is depleted by dissolution, volatilisation or active remediation, the
proportion of pore space occupied by LNAPL (i.e. the saturation) decreases. As
saturation declines, LNAPL flow pathways become smaller and more tortuous. This
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source of dissolved phase contamination. Practitioners need to be aware that, even if
LNAPL is not present in monitoring wells, residual LNAPL may still exist in the adjacent
ground.

**Vapour phase**

When LNAPL is in physical contact with air contained in soil pores, the more volatile
fractions of the hydrocarbon constituents within the liquid phase may partition into the
vapour phase. Partitioning from liquid to vapour is governed by the partial pressure of the volatile organic compounds (VOCs) in the LNAPL, the corresponding mole fractions and other factors, such as soil temperature (Davis, Trefry & Patterson 2009).

The vapour phase can also partition from the dissolved phase, based on the Henry's Law partitioning coefficient between water and air, and other factors, such as the depth of the plume below the capillary fringe (Davis, Trefry & Patterson 2009). The vapour phase can also dissolve in soil moisture, leading to the formation of secondary dissolved phase plumes (Mendoza, Frind & Hughes 1990).

The primary concern with the development of a vapour phase in the vadose zone, as illustrated in Figure 6, is human health risks associated with vapour intrusion into buildings, sewers, other enclosed spaces or outdoor air. Fire and explosion hazard may also be a concern.

Although the discussion of vapour phase hydrocarbons is limited in this guidance document, it is important to understand that LNAPL volatilisation can significantly affect LNAPL losses, which contribute to source zone natural attenuation (SZNA), changes in physical characteristics (including density, viscosity and interfacial tension), and changes in chemical composition, which ultimately may affect the process of remediation (API 2004; ITRC 2009a). Vapours may also pose safety risks during remediation.

![Figure 6](image.png)

**Figure 6. Schematic of subsurface vapour migration from an LNAPL plume**

**Remediation**

The theory of LNAPL behaviour and multiphase flow in a granular or fractured media is complex and beyond the scope of this guide. Numerous literature sources are available for further reading, including ASTM (2007) and CRC CARE (2010). The ultimate
success of LNAPL remediation efforts will depend to a large extent on practitioners’ understanding of these concepts. How LNAPL moves and behaves in the subsurface determines the risks it poses, the remedial objectives that may be required to deal with it and the technologies that can best be used to achieve these objectives.

Remediation of LNAPL is rarely straightforward, and can often be time-consuming and expensive. The remainder of this document provides a step-by-step process for putting this understanding of LNAPL behaviour to use in remediation.

The history of LNAPL remediation globally is littered with examples of ill-conceived and poorly planned remedies that actually made the contaminant situation worse. Following the key steps in this guidance (which are based on several widely accepted and tested methodologies, mostly developed in North America and Europe) will help ensure that LNAPL remediation undertaken in Australia is successful, is economically viable, is sustainable in terms of considering the full social and environmental cost, and delivers real benefits to stakeholders.

The key steps, which are expanded upon in the remainder of this guide, are:

1. Undertake LNAPL project prioritisation and screen site sensitivity and risk
2. Undertake quantitative LNAPL analysis and LCSM development
3. Set LNAPL remedial objectives, define LNAPL remediation end points and select LNAPL remedial technology
4. Undertake pilot testing and technology implementation, and
5. System operation, performance monitoring and LNAPL closeout reporting.
Step 1: Undertake LNAPL project prioritisation and screen site sensitivity and risk

The definition of site sensitivity is likely to be pivotal in negotiations and consultation with stakeholders. Site sensitivity forms the basis of decision making in economic and sustainability assessment, the derivation of LNAPL remedial objectives, the agreeing of LNAPL remedial end points, and, integrated with a refined LCSM, the selection of remedial technology (if required).

Overview

The notion of site sensitivity is fundamental to the LNAPL management decision-making process, as it guides the setting of LNAPL remedial objectives, the scaling of the remediation program and the management of stakeholder expectations.

The definition of site sensitivity is a qualitative matter for stakeholder participation and professional judgement. From that perspective, determining site sensitivity can and should be a multi-stakeholder process in which agreement of the parties is critical. Site sensitivity extends beyond the potential risks the LNAPL poses to human health or sensitive terrestrial and aquatic ecology to include the economic value of the land – this includes both financial value (e.g. real estate or productive value) and social and environmental values (e.g. amenity value). As with the development of the LCSM and associated site characterisation, which is set out in step 2, Schedule B(2) of the ASC NEPM (NEPC 1999, amended 2013b) provides an excellent reference to support site sensitivity assessment.

To support classification of site sensitivity and the risk ranking of sites, an LNAPL site sensitivity screening matrix is presented in Figure 7. The screening matrix poses a series of questions about the prioritisation of the project, the regulatory regime, stakeholder requirements, the potential for human exposure, the sensitivity of the natural environment (including surface water and groundwater), and the social, environmental and economic value of the land. The result is a relative or arbitrary classification of low, moderate or high sensitivity. The screening matrix is not intended to be all-encompassing; it is primarily intended as a framework to promote stakeholder discussion.

Figure 7 provides a simple, logic-based flowchart to support the classification of site sensitivity. The user first considers the questions along the left-hand margin of the matrix. Depending on the response, the user proceeds through the flowchart, as directed by the responses to the questions, until a relative site sensitivity classification is obtained. This screening process relies on the user’s experience and sense of proportionality when comparing the significance of LNAPL impacts at the subject site with other sites and site settings. As discussed earlier, it is also important to distinguish between the emergency response and reporting requirements triggered by a pollution incident and the management of a stable LNAPL source (which this guide is primarily intended to address).

The site sensitivity screening process is intended to be logical. For a site to be considered of relatively low sensitivity, the path through the screening matrix needs to be downwardly vertical without deviating into the moderate- or high-sensitivity column. If the responses to any of the questions elicit a moderate or high response, a moderate
or high relative site sensitivity classification should be assigned for use in the decision-making phase in step 3, unless refinement of the LCSM in step 2 indicates an alternative approach or site classification.

This relative site sensitivity classification system is not aligned with any particular state, territory or national system in use in Australia. It is recommended that a balance of opinions from stakeholders should also be sought before the final assignation of site sensitivity.

**Temporal context**

The screening matrix in Figure 7 has been designed to consider site sensitivity in advance of LCSM interpretation and completion of the detailed site characterisation of step 2. However, the temporal context should also be considered, to accommodate future changes in land use, regulatory stance, demographics, social factors, environmental factors, financial land value and so on, to support the derivation of a pragmatic, realistic and sufficiently conservative site sensitivity classification.
Step 1. LNAPL project prioritisation site sensitivity and risk screening matrix

OVERVIEW

The determination of site sensitivity, integrated with the LCSM, is likely to be pivotal in subsequent negotiations and consultation with stakeholders. Site sensitivity forms the basis of decision making in economic and sustainability assessment, the derivation of remedial objectives, the agreeing of LNAPL remediation end points, and the selection of remedial technology.

Figure 7. LNAPL project prioritisation, site sensitivity and risk screening matrix
## Step 2: Undertake quantitative LNAPL analysis and LCSM development

The development and refinement of a robust and defensible LCSM is fundamental to the success of any LNAPL remediation project. Step 2 sets out the requirements of quantitative LNAPL analysis and LCSM development, as a basis to support subsequent decision making.

### Overview

The fundamental importance of establishing a robust and defensible LCSM cannot be overstated. All subsequent decision making surrounding the management of LNAPL will be based on the detailed analysis and interpretation of field and laboratory data collected during site characterisation. It is therefore imperative that experienced field personnel are engaged from the onset of site investigation to ensure the acquisition of the right data of high quality.

LCSM development continues through the life of an LNAPL remediation project. Sometimes, development of a detailed LCSM will have to wait until decisions have been made on technology to recover LNAPL (the LNAPL spreading after a recent release) or to mitigate risk from LNAPL (causing explosive atmospheres or acute health risks from direct exposure). The LCSM needed for making these decisions must be based on readily available information (desktop sources and direct observation) by experienced practitioners, without losing time in conducting detailed investigations. Critical information for the detailed LCSM will be collected during any such rapid response, and the practitioner must be ready to collect all data needed for assessment and management of long-term or chronic risks.

Where there are no acute and immediate risks to be managed, the development of a detailed LCSM has a defined data collection and interpretation phase (step 2 in this guideline), but it will not necessarily be confined to this step. Observation and data collection are continuous, from initial identification of LNAPL, through selection and operation of remediation systems, to project closure, resulting in continual refinement of the LCSM over the life of the LNAPL project. Quantitative LNAPL analysis and the production a reliable, three-dimensional LCSM require a combination of desktop research, field data acquisition and laboratory analysis. These data are integrated through data interpretation to establish the spatial extent and behaviour of the LNAPL plume, and its associated dissolved, vapour and adsorbed phase contaminants.

The LCSM describes the physical, chemical and biological processes that control the transport, migration and interaction of the LNAPL in the subsurface, associated with either a specific area of potential environmental concern or the entire site. The LCSM should also define the key hydrogeological and chemical conditions that determine Szna and LNAPL losses, including movement or migration, volatilisation and dissolution (Johnston 2010; ITRC 2009a).

The LCSM is typically developed to collate all site information, identify data gaps and determine whether additional information needs to be collected at the site. Schedule B(2) of the ASC NEPM (NEPC 1999, amended 2013b) provides the starting point for site characterisation. The American Society for Testing Materials Standard guide for
The development of conceptual site models and remediation strategies for light nonaqueous-phase liquids released to the subsurface (ASTM 2006), CRC CARE Technical Report no. 2 (Davis, Merrick & McLaughlan 2006) and CRC CARE Technical Report no. 11 (Clements, Palaia & Davis 2009) also provide excellent guides for LCSM development.

The key elements of step 2 (after ensuring that the LNAPL release has been stopped) are presented in Figure 8. These substeps and their associated requirements are expanded in Figure 9 and the accompanying text.

Figure 8. Key elements in LCSM development
Practitioner’s tip: Fire and explosion safety

The hazards and risks presented by flammable and combustible liquids and gases are considerable and unusual. It is therefore imperative that practitioners conducting work on LNAPL impacted sites are experienced in the management of workplace health and safety risks, including the safe management of wastes. Comprehensive health, safety and environmental planning is required before undertaking any work on an LNAPL site. Specific tasks should be supported by personal safety risk assessments and/or job hazard analysis. Specific requirements permitting hot work or cold work are likely to be required – these should be confirmed with the site’s owner or operator. Gas clearance certificates, real-time gas monitoring, and prevention of unpermitted entry to confined spaces are also fundamental.

For the management of safety and explosion risk on petroleum sites, the Workplace Clearance Group operates and manages the Workplace Clearance Program. The program is responsible for training and accrediting contractors in the planning and implementation of safe systems of work on such sites.

Whether the subject site is a petroleum site or otherwise, under the employer’s common law duty of care, and relevant state/territory or Commonwealth workplace health and safety regulations, suitable planning is necessary to ensure a safe place of work, as well as the provision of safe and suitably maintained plant and equipment, and appropriate training and supervision. In the planning of any works on a site potentially impacted by LNAPL, it is expected that any existing site-specific emergency procedures are identified, in addition to works-specific supplementary emergency procedures, emergency service contact numbers, and the location of the nearest appropriate medical facility. Further guidance is available in the National code of practice for the storage and handling of dangerous goods (NOHSC 2001).

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2 The Workplace Clearance Group comprises BP Australia Pty Ltd, The Shell Company of Australia Pty Ltd and Caltex Australia Limited.
Step 2: Undertake quantitative LNAPL analysis and LCSM refinement

OVERVIEW

The development of a robust and defensible LCSM is fundamental to the success of any LNAPL remediation project. Step 2 sets out the requirements of quantitative LNAPL analysis and LCSM development as a basis to support decision-making going forward. The importance of scientific rigour and reliability of data that are used to characterise the three-dimensional extent and recoverability of the LNAPL source at this stage of the process cannot be overemphasised.

Step 2(a): preliminary site investigation (PSI)

The initial stage of desktop study is primarily concerned with the collation of facts and the analysis of data gaps to support the development of a preliminary LCSM. The ultimate aim of this element is to define the characteristics of the DQOs required to support the characterisation of the site and the prediction of likely LNAPL recovery rates.

- The LNAPL release history in context with the site setting and history
- Hydrogeological conditions and the identification of data gaps
- Site and subsurface infrastructure including potential preferential LNAPL migration pathways
- LNAPL physicochemical properties and data gaps
- Source-pathway-receptor relationships

Step 2(b): detailed site investigation (DSI)

All subsequent decisions on the management and/or remediation of the site will be based on the integrity of field and laboratory data acquired through the implementation of the SAP. Key aspects to consider include:

Field data acquisition fundamentals
- Engage experienced field personnel
- Drilling and sampling—continuous coring techniques
- Conduct detailed soil and/or rock classification
- Construct high-quality LNAPL specific monitoring wells
- Complete frequent P/D measurements
- Undertake specialty core to support core analyses
- Conduct L/D borings
- Complete 3-D spatial delineation
- Complete LNAPL baloon testing to support detailed transmissive zone assessment
- Conduct an assessment of temporal changes

Laboratory analysis fundamentals
- Use high quality NATA-accredited laboratories
- Validate data with a rigorous program of QA/QC
- LNAPL source physicochemical characterisation including density, viscosity, composition, and, if applicable, product ageing forensic analysis
- LNAPL saturation profiling
- Specialised core/petrophysical tests including:
  - LNAPL saturation
  - Capillary pressure assessment
  - Moisture retention assessment
  - Residual saturation assessment

Step 2(c): data interpretation

Undertake a detailed interpretation of field and laboratory data, building on the foundations of the preliminary LCSM, to develop a comprehensive 3-D characterisation of site conditions. The finalised LCSM should be built in layers and include the following elements:

- Context within the source-pathway-receptor framework
- Determination of hydrogeological properties
- LNAPL physicochemical properties
- Spatial extent of the LNAPL(s) and consideration of multiple sources
- Potential co-solvency effects of interacting LNAPL types
- LNAPL transmissivity determination and identification of transmissive zones
- LNAPL natural causes
- LNAPL volumes and recovery estimations—consider the A*LP's LNAPL Distribution and Recovery Model (LRM)

Figure 9. Quantitative LNAPL analysis and LCSM refinement
Step 2(a): Desktop review and data gap analysis

The initial stage of desktop review is primarily concerned with the collation of information and the analysis of data gaps to support the development of a preliminary LCSM. The ultimate aim of this substep is the definition of the data quality objectives (DQO) required to support the characterisation of the site and the prediction of likely LNAPL recovery rates. Table 1 sets out typical requirements of preliminary LCSM development.

Table 1. LNAPL desktop review information requirements

<table>
<thead>
<tr>
<th>LCSM information</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>Site setting (historical and current)</td>
<td>• Land use (historical, current and future)</td>
</tr>
<tr>
<td>Hydrogeological information</td>
<td>• Surficial and bedrock geology characterisation, including presence of aquifers</td>
</tr>
<tr>
<td></td>
<td>• Groundwater characterisation, including depth to groundwater, groundwater flow direction and velocity, hydraulic conductivity and transmissivity</td>
</tr>
<tr>
<td>Site structures</td>
<td>• Mechanism of release</td>
</tr>
<tr>
<td></td>
<td>• Subsurface infrastructure</td>
</tr>
<tr>
<td></td>
<td>• Potential migration conduits and preferential pathways</td>
</tr>
<tr>
<td>LNAPL physical properties*</td>
<td>• Density</td>
</tr>
<tr>
<td></td>
<td>• Dynamic viscosity</td>
</tr>
<tr>
<td></td>
<td>• Interfacial tensions</td>
</tr>
<tr>
<td></td>
<td>• Vapour pressure</td>
</tr>
<tr>
<td></td>
<td>• Henry’s Law Constant</td>
</tr>
<tr>
<td>LNAPL chemical properties</td>
<td>• Constituent solubilities and mole fractions</td>
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<tr>
<td></td>
<td>• Weathering profile and breakdown products</td>
</tr>
<tr>
<td></td>
<td>• Hydrocarbon compound ratios</td>
</tr>
<tr>
<td>LNAPL mobility and body stability information</td>
<td>• Depth to LNAPL, water levels and LNAPL–water interface measurements</td>
</tr>
<tr>
<td></td>
<td>• Diurnal and seasonal water level fluctuations</td>
</tr>
<tr>
<td></td>
<td>• LNAPL thickness in wells</td>
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<tr>
<td></td>
<td>• LNAPL transmissivity</td>
</tr>
<tr>
<td></td>
<td>• Losses, including SZNA</td>
</tr>
<tr>
<td></td>
<td>• Evidence of migration</td>
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<tr>
<td></td>
<td>• Stable/shrinking dissolved phase plume associated with LNAPL</td>
</tr>
<tr>
<td>Potential receptors</td>
<td>• Identification of receptors and potential complete exposure pathways</td>
</tr>
</tbody>
</table>

\* CRC CARE (2010) provides a useful reference source on the relevant properties of LNAPL.
It is important to note that the LCSM should be regarded as a dynamic document, to be augmented or revised on the basis of increasing site knowledge and the results of subsequent phases of site investigation or research.

The outcome of the desktop review and data gap analysis will be development of a sampling, analysis and quality plan (SAQP). The SAQP will comprise the instruction set for the detailed site investigation (DSI) that is designed to acquire field and laboratory data, sufficient in number and quality to be suitable for interpretive purposes.

**Step 2(b): Detailed site investigation**

Implementation of the SAQP through DSI consists of three aspects: development of a comprehensive site safety plan, acquisition of field data, and laboratory analysis of samples collected during the DSI. This section elaborates on the importance of sound data collection and laboratory analytical techniques in the refinement of the LCSM and in the prediction of LNAPL recovery rates.

**Safety**

Safety should always be of paramount concern. A site investigation safety plan should be designed and put in place before field activities start. All personnel should have appropriate training for the tasks they are undertaking. When LNAPL is present, an additional level of safety preparedness is required to prevent exposure of workers to toxic or carcinogenic compounds in soil, water and air, and to prevent fire and explosion hazards.

**Drilling and well design**

In addition to the importance of using experienced field personnel for DSI on an LNAPL impacted site, the use of the correct drilling techniques, which are capable of obtaining continuous cores for subsequent core analysis, cannot be overemphasised. Drilling techniques capable of supporting continuous coring include Geoprobe® or direct push rigs, sonic rigs, rotary core barrel drilling techniques and shely tubes.

Drilling on LNAPL sites also requires specialist drilling techniques and the engagement of drillers experienced in the investigation of contaminated sites. Avoidance of cross-connection between groundwater units and aquifer is of paramount importance. Strict decontamination protocols for down-hole drill tools need to be followed and, depending on the hydrogeological regime, the use of telescopic drilling techniques may be necessary to isolate LNAPL and water-bearing units. Detailed literature is available on groundwater well design and completion in suspected LNAPL contaminated strata (Environment Agency 2006).

Guidance on well design,3 the drillers’ classification system, and the administrative requirements and responsibilities for drilling in the various Australian jurisdictions are set out in the *Minimum construction requirements for water bores in Australia* (NWC 2012).

Groundwater monitoring wells should be constructed to appropriate standards, using suitable materials, typically screw-connecting well screens and casings that are chemically stable in an LNAPL impacted site setting (Environment Agency 2006).

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3 This guidance focuses on the installation of groundwater monitoring and production bores, and does not cover the investigation of contaminated sites. However, it sets out the licensing requirement for drillers working in single and multiple aquifer systems.
Attention should be paid to screening wells across the likely LNAPL bearing zone, and avoiding vertical interconnection with other groundwater-bearing units.

**Practitioner’s tip: How should I install an LNAPL monitoring well?**

Ensure that the well screen intersects the likely range of natural groundwater fluctuation. If well longevity is required or if it is envisaged that a monitoring well may serve as a future production well, durable materials like stainless steel should be considered. The well screen slot size and filter pack grain size should be suitable to promote the flow of LNAPL to the well. For multilayered systems, ensure discrete groundwater well installations in each zone, taking care not to cross-connect aquifers. Similarly, with fractured rock settings, care should be taken to ensure that the productive zones are targeted and screened correctly.

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**Field data acquisition**

The integrity of field data, which can be expensive to acquire, is of fundamental importance to LCSM development, LNAPL recovery modelling and ultimately the selection of remedial technology.

Accurate and complete soil and rock descriptions are required, which include moisture conditions, grain size, colour, heterogeneities, colour and, importantly, indications of LNAPL impact. Cores should be photographed and accompanied by continuous photo-ionisation detector (PID) measurements, if possible. CRC CARE (2006) provides a useful reference on the techniques and visual methods to characterise LNAPL in the field.

Laser induced fluorescence (LIF) data can be used to augment information gained from traditional boring methods and can provide invaluable information to support the delineation of the LNAPL plume. Kirkman (2011) provides an in-depth account of the limitations of LIF in LNAPL characterisation and notes that not all hydrocarbon sources fluoresce.

Geophysical techniques can also provide valuable information on the geology of the site, particularly local-scale heterogeneity, which can influence LNAPL behaviour. *Groundwater geophysics, a tool for hydrogeology* (Kirsch 2009) provides a wealth of reference on the use of geophysics in the characterisation of groundwater systems.

Following the installation of monitoring wells, baildown testing is likely to provide the most useful information on LNAPL distribution and recovery potential at a site. Baildown testing involves removing LNAPL accumulated in a well and observing LNAPL thickness recovery over time. Details on baildown testing, including estimation of LNAPL transmissivity, can be found in API (2012).
Laboratory analysis

For soil and groundwater samples collected in the field, diligent sample handling, storage and preservation protocols should be followed, backed by a rigorous program of quality assurance and quality control (QA/QC). VOCs require special sample containers, typically have short holding times, and should be chilled on collection and during transport to the laboratory to maximise the integrity of the data. Schedule B(2) of the ASC NEPM (NEPC 1999, amended 2013b) and the WA Contaminated sites management series of guidelines (DEP 2001) provide a comprehensive reference source on the collection of samples for laboratory analysis, sample management and QA/QC procedures.

In Australia, several analytical laboratories are accredited by the National Association of Testing Authorities (NATA) for standard soil, sediment and groundwater analytical determinands. Laboratory analysis provides some of the most important site characterisation data, and is vital for risk assessment and detailed remedial design. As in any contaminated site investigation, all laboratory results should be backed by a rigorous program of data validation to ensure the suitability of the data for interpretive purposes.

Key determinands that should be tested for include physicochemical properties of the LNAPL, concentrations of dissolved phase components in groundwater, and concentrations of LNAPL compounds in soil. Speciality core analysis can provide important information on soil or rock porosity, LNAPL saturation, relative permeability–capillary pressure relationships, moisture retention and residual saturation ratios. Johnston (2010) is a comprehensive reference on speciality core analysis to support LNAPL characterisation at a site.

It should be noted that petrophysical testing can be expensive, and not all laboratories in Australia are equipped to carry out such testing. Speciality oil field and environmental laboratories should be consulted on the services available, if this level of detail is required.

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4 Determinands (something determined or tested for in samples analysed) are sometimes called analytes, parameters, tests, properties, etc. Examples include pH, nutrients, hydrocarbons, heavy metals.
Step 2(c): Data collation, interpretation and visualisation

Following completion of DSI, a detailed interpretation of field and laboratory data should be undertaken to augment and refine the preliminary LCSM. The refined LCSM should include LNAPL volume estimates, predictions of likely recovery rates and estimates of SZNA, as well as detailed characterisation of the LNAPL source. Following the widely accepted practices for CSM development, and health and ecological risk assessment (HERA) (ASTM 2007; Johnston 2010), the LCSM should also address the risks associated with the presence of LNAPL in the subsurface, in accordance with guidance provided by each state or territory.

Risk assessment involves a tiered approach to identification of exposure pathways, linking sources to receptors via specific pathways. Receptor exposure assessment can be done qualitatively, or through fully quantitative modelling of contaminant fluxes and toxicological uptake of contaminants. For more information on risk assessment at contaminated sites, see the document produced by the WA DEC, *The use of risk assessment in contaminated site assessment and management: guidance on the overall approach* (DEC 2006).

Friebel and Nadebaum (2011a, 2011b, 2011c and 2011d), in CRC CARE Technical Report no. 10, provide detailed information on a screening-level risk assessment of petroleum hydrocarbons in soil and groundwater, with the derivation of HSLs for a
number of Australian land-use and soil-type scenarios. It should be noted that HSLs have limitations and are not applicable:

- to LNAPL
- to fractured rock settings
- where groundwater is present at a depth of less than 2 m
- to basements in buildings.

In these instances, alternative tiers of risk assessment are likely to be required.

The LCSM should be built up step by step, starting with the basic geometry of site conditions, geology and hydrogeology, and then layered with key information on the LNAPL source. This information should include the physical and chemical properties of the source, the potential for coexistence of multiple sources and, if applicable, the behaviour of multiphase systems and co-solvency effects.

The spatial extent of mobile ‘free phase' LNAPL versus residual LNAPL should be mapped with estimates of actual, as opposed to apparent, LNAPL thicknesses, as a preliminary indicator of LNAPL volume.

As the LCSM evolves, initial estimates of LNAPL transmissivity and recoverability can be added. The results of baildown testing are invaluable at this stage, to support the mapping of zones of LNAPL transmissivity. For further information on simulating the distribution and recovery of LNAPL in the environment, refer to:

- A methodology for estimating LNAPL conductivity and transmissivity from LNAPL baildown tests: the Lundy and Zimmerman approach (Lundy 2004)
- the API LNAPL distribution and recovery model (LDRM) (API LNAPL Resource Centre; www.api.org/environment-health-and-safety/clean-water/ground-water/lnapl/ldrm-form), and

Finally, the LCSM should be updated frequently as new information becomes available at every stage of the LNAPL remediation process. Following completion of a detailed LCSM (including the LNAPL recovery estimation), the user should then consider the sensitivity of the site in conjunction with the scale of the LNAPL problem to advance and inform the decision-making process of step 3.
Practitioner’s tip: What’s the best way to build an LCSM?

There is no single accepted way of developing an LCSM. Many experienced practitioners prefer to draw, by hand initially, a series of two-dimensional cross-sections ultimately expanded to a three-dimensional representation (see Figure 7). The intention is to demonstrate LNAPL occurrence in the subsurface, provenance and potential migration pathways. Key features of the subsurface should include stratigraphy, groundwater units, and levels and zones of LNAPL transmissivity. Key infrastructure and assets should also be depicted, including LNAPL migration pathways, sewer trenches, and buried pipelines and utilities. Receptors and the interconnecting pathways that link to the LNAPL source should also be included.

Further information


An excellent ESA reference for LNAPL contaminated sites is also provided by Clements, Palaia and Davis (2009) in CRC CARE Technical Report no. 11, Characterisation of sites impacted by petroleum hydrocarbons. This reference also provides a general LCSM Certainty Screening Tool, which supports analysis of the robustness of the LCSM and its suitability for remedial decision making.
Step 3: Set LNAPL remedial objectives, define LNAPL remediation end points and select LNAPL remedial technology

Step 3 constitutes the key decision-making stage in the LNAPL management process. It consists of four elements: a) derivation of LNAPL remedial objectives, b) establishment of LNAPL remediation end points, c) selection of remedial technology to meet these goals (if required) and d) analysis of the environmental, social sustainability and economic viability of possible remedial approaches across the project life cycle (where applicable). Stakeholder consultation and input are essential at this stage of the site management program.

Overview

One of the factors motivating the development of this guide was identification of the need to align the approach of stakeholders associated with LNAPL remediation with the need to set realistic LNAPL remediation end points for active treatment systems. The derivation of realistic LNAPL remediation end points – based on consideration of site sensitivity, the notion of technical impracticability, and the financial, social and environmental aspects of remediation – form the central premise of this guide.

When are remediation end points predetermined and technology selection made based on a preliminary LCSM?

In many site-specific circumstances, remediation is carried out to limit the damage that an LNAPL release could cause, or to address risks already apparent on discovery. For example:

- Direct exposure of people or the environment to LNAPL, causing unsafe conditions that threaten life. Remediation objectives in these circumstances are based on clear and present risks, and may start with a formal emergency response.

- A recent LNAPL release with high LNAPL heads in the source area and evidence of an expanding LNAPL plume. In this case, the priority remediation objective is LNAPL recovery to stop it from spreading. This requires LNAPL recovery technologies that can be readily and safely installed and operated in the LNAPL source area, based on a preliminary LCSM. Development of the detailed LCSM will commence during installation and operation of such systems.

Step 3 constitutes the key decision-making step in the process. In consultation with stakeholders and following the integration of information derived from the completion of steps 1 and 2, this is intended to lead to the establishment of LNAPL remedial or management measures for the site. Step 3 consists of four key substeps that support and lead to the selection of remedial technology, if subsequently required (Figure 10):

- step 3(a) – setting LNAPL remedial objectives
• step 3(b) – establishing LNAPL remedial end points

• step 3(c) – technology selection (if required), and

• step 3(d) – economic and sustainability analysis of the remedial options and technology selection, across the project life cycle (where applicable).

Figure 10. Key stages in the LNAPL management decision-making process leading to technology selection

It should be emphasised that a site sensitivity classification of low – as demonstrated by an absence of receptor risk, plume stability, compatibility with the principles of ESD or stakeholder agreement – is likely to support a non-active approach to LNAPL remediation. Under these circumstances, continuing the process beyond step 3(b) may not be required. It may also be determined that SZNA is an appropriate management measure or that safe on-site retention of LNAPL (Fowler & Cole 2010) could be a sustainable management option.

Where the outcome of the site sensitivity classification prompts continuation of the sequential process, the boundary between steps 3(b) and 3(c) is, in practice, likely to be indistinct, and economic and sustainability analysis is likely to inform the establishment of the LNAPL remedial end points.

Where the outcome of steps 1, 2 and 3a triggers a requirement for an active LNAPL remediation approach and therefore the selection of a remedial technology, the derivation and establishment of the LNAPL remedial end point is likely to be influenced by the choice of technology and, if invoked, the results of economic and sustainability analysis. Moreover, subject to the subsequent performance of the full-scale LNAPL remediation system, desired end points may need to be re-evaluated or augmented during operation based on feedback and the principles of iterative design.

In practice therefore, step 3, which is illustrated sequentially in Figure 10, is likely to be an incremental process with a number of interdependencies. Moreover, where active remediation is determined to be necessary, desired LNAPL end points may need to be re-evaluated during operation, subject to performance of the full-scale LNAPL remediation system.

As noted by Clements, Palaia and Davis (2009), the key to effective LNAPL management and ultimately to LNAPL remediation system closeout is the development of a site end point strategy. Step 3, with the four substeps set out in Figure 10 and detailed in Figure 11, outlines the means by which the LNAPL remedial objectives and LNAPL remediation end points can be derived, and reviews the drivers that influence the decision-making process to meet these aims.
The Texas Commission on Environmental Quality (TCEQ) document *Regulatory guidance: risk-based NAPL management* (TCEQ 2008) describes the derivation of remedial goals and the establishment of LNAPL remediation end points.

The LNAPL remedial objective is defined as the aspirational target or condition to be achieved by the remedial strategy. The LNAPL remediation end point is defined as a practical target that may be achieved by the application of the remedial technology. This incorporates the notion of technical impracticability and acknowledges that a proportion of the LNAPL may not be recoverable, even under ideal ground conditions.

At this stage of the project, it is important to emphasise that attainment of the LNAPL remedial objective or the LNAPL remediation end point should only be considered as substeps of the overarching project objectives. Management of the adsorbed, dissolved or soil vapour phases is likely to continue and be addressed separately.

The substeps of step 3, combined with the analysis of performance in step 4, are likely to provide the basis for an iterative and incremental process with interdependencies, resulting in the need to redefine or reappraise LNAPL end points following system implementation. This is likely to be the subject of further stakeholder consultation and agreement.
Step 3: Set LNAPL remedial objectives, derive LNAPL remediation end points, select LNAPL remedial technology and conduct economic and sustainability assessment

**OVERVIEW**

Step 3 constitutes the key decision-making step in the process. In consultation with stakeholders and following the integration of information derived from the completion of step 1 and step 2, this leads to the agreement of remedial or management measures for the site.

### Step 3(a): Set remedial objectives

**i.** Develop long list of possible remedial objectives
   - Risk-based objectives
   - Non-risk-based objectives
   - Regulatory-driven objectives
   - Proceed based on site sensitivity (see figure 10)

**ii.** Low and moderate sensitivity sites: screen objectives
   - Clearly unacceptable remedial objectives
   - Yes > ELIMINATE
   - Mandated remedial objective
   - Yes > SELECT
   - Source reduction approaches and pathway intervention approaches
   - Yes > APPLY

**iii.** High sensitivity sites: screen objectives
   - Clearly unacceptable remedial objectives
   - Yes > ELIMINATE
   - Mandated remedial objective
   - Yes > SELECT
   - Temporal or physical constraints
   - Yes > APPLY

### Step 3(b): Define LNAPL remediation end points

For each remedial objective, one or more remediation end points can be defined. Remediation end points should be measurable characteristics that relate to the remedial progress of a technology towards the remedial objective (of eliminating, isolating or mitigating LNAPL at a site).

**Specific end points can include:**
- LNAPL water recovery ratio, with decreasing ratio potentially indicating decreasing recovery effectiveness
- LNAPL vapour recovery ratio
- Decline curve analysis — analysis of LNAPL recovery or recovery rate per unit time indicative of decreasing recovery effectiveness
- Dissolved phase stability or declining trend

### Step 3(c): Technology selection

Refer to Tables 4 and 5 and consider:
- Vadose zone and phreatic zone LNAPL impact
- Source elimination, pathway intervention or receptor protection methods
- Technical implementability of technology

**Perform secondary screen to assemble a short list of technologies that are effective for the conditions defined in the CSM and also cost-effective from the perspective of financial backers of the project**

**Select technology**
- Rank short list alternatives to make final selection
- Consider the widespread use of the technology versus innovative technologies
- Consider CAFEX versus OFEX costs and the predicted time scales of operation

### Step 3(d): Conduct economic and sustainability assessment

**i.** Option quantification
   - Short list of remedial objectives/approaches from step 3(a)
   - Estimate likely life-cycle planning horizon for remediation
   - Develop physical concept of each remedial approach
   - Model expected physical outcome of each approach

**ii.** Estimate costs and benefits
   - Develop level 1 cost estimate for each approach
   - Estimate life-cycle operation costs for each approach
   - Estimate life-cycle external costs for each approach
   - Value internal and external benefits of remediation
   - Refer to Hardisty (2008, 2010)

**iii.** Conduct economic sustainability assessment
   - Compare life-cycle costs and benefits for each approach
   - Conduct sensitivity analysis
   - Undertake stakeholder value analysis
   - Select remedial approach that optimises value for all
   - Refer to Hardisty (2008, 2010)

Figure 11. Setting LNAPL remedial objectives, defining end points and selecting LNAPL remedial technology
Step 3(a): Set LNAPL remedial objectives

When setting LNAPL remedial objectives, and considering the site sensitivity determinations of step 1, it is important to be clear whether any LNAPL remediation proposed is intended to address risk, as opposed to addressing LNAPL where an absence of risk has been demonstrated.

The overarching remedial objectives (non-risk or risk based) for the management of contaminated sites may include:

- protection of human health and environmental values
- mitigation of adverse community impacts
- consideration of intergenerational equity, and
- reduction or minimisation of liability associated with current or past industrial practices.

On a local level, LNAPL remedial objectives may be developed to reduce the hydrocarbon loading to water and air, to limit the expansion of an LNAPL plume, or for economic purposes – that is, reducing the longevity of a contaminated plume and the potential long-term monitoring requirements.

Contamination of groundwater by the release of LNAPL can pose a serious environmental and human health risk, which may continue for many years. The South Australian Environment Protection Authority states that the:

‘…ultimate goal of remediation of groundwater should be to select a socially and environmentally acceptable and cost-effective strategy that removes the threats to human health and the environment’. (SA EPA 2009)

Consideration of the current or potential groundwater ‘beneficial use’ is therefore vital in the assessment of site sensitivity and in the derivation of remedial objectives. The benefits of groundwater use can range from environmental and conservation benefits and values to exploitative benefits, including ecosystem protection, recreation and aesthetics, drinking water supply, agricultural water and industrial water (NHMRC & NRMMC 2011). Once the groundwater beneficial uses have been defined, specific LNAPL remedial objectives can be set in conjunction with remedial objectives for the dissolved phase plume.

Historically, poorly defined LNAPL remediation programs have resulted from ambiguous clean-up requirements. Thus, it is important to develop realistic LNAPL remedial objectives and end points that are consistent with the LCSM, and aligned with the requirements of the states and territories, and other stakeholders, including the financial backers of the remediation program.

It is also important that the behaviour of LNAPL in the subsurface is clearly explained to stakeholders, so that realistic remedial objectives are set and agreed. As discussed earlier, even under ideal subsurface conditions, a significant proportion of LNAPL is likely to remain in the ground as an immobile residue after remediation, potentially contributing to long-term dissolved phase groundwater contamination.
The setting of LNAPL remedial objectives will generally be based on one, or a combination, of the following three drivers, which will ultimately be used to define the remediation end point:

- a non–risk based approach to meet specific or arbitrary targets in reducing LNAPL presence
- a ‘tiered’ risk-based approach to reduce risk of exposure to LNAPL contamination, and
- a regulatory-driven approach, based on state or territory policies related to the management of LNAPL.

Examples of LNAPL remedial objectives that may be used to define the vision for site clean-up are shown in Figure 12.

![Figure 12. Examples of drivers for setting of LNAPL remedial objectives](image)

**Risk-based remedial objectives**

Over the past few decades, risk-based decision making has emerged as a powerful basis for deriving remediation objectives. This is particularly applicable in jurisdictions where LNAPL-specific guidelines are not available; risk-based objectives provide a valuable alternative.

The risk-based approach relies on the essential source–pathway–receptor components of the LCSM and the plausible interconnectedness between them. This forms the backbone to any risk assessment (Hardisty & Ozdemiroglu 2005).

A risk-based approach, backed by toxicity assessment, HERA, and fate and transport modelling, subject to the significance of exposure pathways, lends weight to argument in the derivation and establishment of remedial objectives. When it can be adequately
demonstrated that the risk of exposure of health or ecological receptors would be acceptable, within certain limits, then a firm basis for developing risk-based management measures (rather than a prescriptive approach to LNAPL recovery) may be applicable.

**Setting an LNAPL remedial objective**

Remedial objective setting should follow a structured process, based on the findings of the step 1 site sensitivity determination and the LCSM refinement of step 2. Figure 12 provides a basic risk-based structure to help users identify a workable remedial objective for LNAPL contaminated sites. In all cases, it is good discipline to follow the same stakeholder-based approach used in step 1 to identify possible objectives. For low- and medium-sensitivity sites (which, in relative terms, will often pose lower risk overall), often either a remedial objective will be mandated by regulation, or a specific risk will clearly need management. For high-sensitivity (higher-risk) sites, a more detailed approach to remedial objective setting is worthwhile. This involves screening to a short list of possible objectives, and then comparing the implications of these possible objectives in terms of their performance in risk management, economics and sustainability. At more complex sites, several complementary remedial objectives may be selected for the best outcome. For a detailed discussion of remedial objective selection, refer to Hardisty and Ozdemiroglu (1995).

**Step 3(b): Define LNAPL remedial end points**

Johnston (2010) notes that LNAPL remediation and management guidance documents developed by the US EPA (2005), American Society for Testing Materials (ASTM 2007), TCEQ (2008) and ITRC (2009b) use a range of goals, objectives, metrics and end points that can be used for the assessment and management of LNAPL and remediation system performance.

LNAPL remediation end points in these documents are defined as targets that are used to evaluate whether remedial objectives have been achieved. Examples of LNAPL remediation end points are presented in Table 2 (ITRC 2009b; Johnston 2010; TCEQ 2008), providing some general perspectives on the different end points to be achieved in the management of LNAPL sites.

For each LNAPL remedial objective, one or more LNAPL remediation end points can be defined. LNAPL remediation end points should be realistic, achievable, measurable and agreed upon, and should reflect the technology-specific point at which active treatment can be terminated.

The LNAPL remediation end point is often based on declining recovery rates or asymptotic LNAPL recovery curves. The extent of practical LNAPL remediation is determined by the inherent limits of the system in progressing towards the remedial objective (eliminating, isolating or mitigating LNAPL at a site) and by the characteristics of the selected technology.

It is also important to note that consideration of remediation system ‘rebound’ (see step 5) is accommodated when deciding on the attainment of the LNAPL end point.
Practitioner’s tip: How do I choose an LNAPL end point that’s realistic?

It is important to avoid absolutes during the management of LNAPL. The behaviour of LNAPL in the subsurface is often unpredictable, especially from the onset of active remediation and with changing conditions. In practice, end points that commit to definitive metrics can be very difficult to meet. The selection of realistic LNAPL end points, which are linked to risk-based site-wide outcomes and agreed with the involvement of stakeholders, should be promoted, rather than arbitrary physical measurements at specific points.

Table 2. Examples of LNAPL remediation end points

<table>
<thead>
<tr>
<th>LNAPL remediation system performance metric</th>
<th>Description</th>
<th>Comments</th>
</tr>
</thead>
<tbody>
<tr>
<td>LNAPL/water recovery ratio</td>
<td>Ratio of unit volume of LNAPL recovered per unit volume of water</td>
<td>Decreasing ratio may indicate decreasing LNAPL recovery effectiveness</td>
</tr>
<tr>
<td>LNAPL/vapour recovery ratio</td>
<td>Ratio of unit volume of LNAPL recovered per unit volume of vapour</td>
<td>Decreasing ratio may indicate decreasing recovery effectiveness</td>
</tr>
<tr>
<td>Decline curve analysis</td>
<td>Analysis of LNAPL recovery or recovery rate per unit time</td>
<td>Declining curve indicates decreasing recovery effectiveness</td>
</tr>
<tr>
<td>Soil concentration</td>
<td>Concentrations reduced to specified limit</td>
<td>Soil vapour trends in the ground, in air spaces or from the exhaust of an soil vapour extraction system</td>
</tr>
<tr>
<td>LNAPL saturation profile</td>
<td>Comparison of saturations before and after treatment to demonstrate reduced saturations</td>
<td></td>
</tr>
<tr>
<td>Dissolved phase plume stabilised</td>
<td>Stabilisation of the dissolved phase plume geometry</td>
<td>Potentially an indication of a stable LNAPL body</td>
</tr>
<tr>
<td>No LNAPL occurrence in downgradient well</td>
<td>LNAPL is not measured in monitoring well installed outside of LNAPL body</td>
<td>Indicates stability of plume</td>
</tr>
<tr>
<td>Dissolved or vapour phase concentration</td>
<td>Concentrations reduced to regulatory standard at a compliance point</td>
<td></td>
</tr>
</tbody>
</table>

Sources: ITRC 2009b; Johnston 2010; TCEQ 2008

Provision should also be made for rebound monitoring, to demonstrate the efficacy of system performance and attainment of the LNAPL end point (see step 5).
Technical impracticability of LNAPL remediation

Answers to questions on the practical limits of LNAPL recovery from soil and groundwater are likely to be elusive, given the difficulties of comparing sites, LNAPL and hydrogeological properties, and remedial approaches adopted at sites.

The notion of ‘technical impracticability’ and arguments for invoking impracticability are discussed by Johnston (2010). They rely heavily on the integrity of the LCSM and demonstrable understanding of the LNAPL remedial options applicable to the environment.

Johnston (2010) argues that it is more likely that technical impracticability can be invoked following LNAPL remediation pilot studies or where full-scale implementation of the remediation system fails to deliver the remedial objectives. Information and factors supporting arguments for technical impracticability include:

- a detailed and robust LCSM
- LNAPL transmissivity
- demonstrable understanding of the environmental site setting and site sensitivity
- the results of pilot studies
- full-scale system performance results
- full-cost economics and sustainability analysis of the system life cycle and the net benefits of continued operation, and
- consideration of the principle of intergenerational equity.

It can also be argued that the technical impracticability of LNAPL remediation should only be considered in the absence of unacceptable risk.
Step 3(c): LNAPL technology selection

The screening and selection of remedial technology raise a number of considerations, including the applicability of the technology in the vadose and/or the phreatic zones; whether the technology is implementable at the site; and the likely effectiveness of the technology in low-permeability media, granular media or fractured rock media. Table 3 and Table 4 categorise available technologies for the vadose and phreatic zones, respectively, based on their mode of operation as acting on the source, isolating the pathway or protecting the receptor, following the risk-based approach to contaminated sites management. For each technology, the corresponding relative effectiveness and relative cost of implementation, where applicable, are provided.

Following the derivation of LNAPL remedial objectives and the establishment of LNAPL remediation end points, supported by full-cost economic and sustainability assessment, where applicable (see step 3(d)), the next step in the process of LNAPL remediation management is the screening and selection of remedial technology that will best achieve the LNAPL remedial objective.

CRC CARE Technical Report no. 18 (Johnston 2010) presents a detailed account of the in situ remediation technologies available for management of LNAPL. This section summarises some of the more widely used and readily available remedial technologies.
applicable to LNAPL, and provides a process for screening and selecting an appropriate technology (or technologies). The screening process used in this section focuses on the suitability of a particular technology for a range of ground conditions and provides an indication of relative cost to support decision making. Consideration of tried and proven technology in similar ground conditions on similar sites cannot be overemphasised.

**Available LNAPL remediation technologies**

Soil and groundwater remediation research is a field of rapid change, with new and innovative techniques becoming commercially available each year. Consequently, it is not the intention of this document to provide an all-encompassing guide to the available technology; instead, this document provides a guide to support technology screening and selection. There is no substitute for professional judgement and experience in selecting the optimum means of achieving the remediation objective.

Different LNAPL remedial technologies have different applicability and capabilities. The selection of a remedial technology primarily depends on the site sensitivity classification, the LCSM and the LNAPL remedial objectives defined for the site. Various guidance documents describe methods for classifying remediation types, such as presence within the vadose or phreatic zones, active or passive technologies, or ex situ or in situ treatment technologies.

Given the prominence of risk-based approaches to the management of contaminated sites in Australia, remedial technologies have been categorised based on their mode of operation, as follows:

- source reduction methods (removal or treatment of the LNAPL source)
- pathway intervention methods (containment by eliminating the LNAPL pathway), and
- receptor protection methods (engineered controls that control exposure potential).

**Source reduction methods**

Source reduction methods typically include LNAPL recovery methods, active treatment and/or removal technologies that are used to reduce the mass of LNAPL in the subsurface source area (US EPA 2005). Methods of LNAPL source reduction include, but are not limited to, those set out in Table 3. Table 3 also provides a brief description of the suitability of the application.

Further information on source reduction methods – including relative cost, suitability for a particular soil or rock matrix, and relative effectiveness – that may be considered during the planning and technology selection phase for LNAPL remediation is presented in Table 4 and Table 5.
Table 3. Source reduction methods

<table>
<thead>
<tr>
<th>Method</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Passive skimming</strong></td>
<td>• Manual bailing</td>
</tr>
<tr>
<td></td>
<td>• Sorbent well implant socks</td>
</tr>
<tr>
<td><strong>In-well skimmer pumps</strong></td>
<td>• Belt skimmer pumps – suitable for low transmissivity units</td>
</tr>
<tr>
<td></td>
<td>• Pneumatic skimmer pumps acting on the LNAPL–water-table interface, typically skimming the LNAPL through a hydrophobic filter – suitable for transmissive units</td>
</tr>
<tr>
<td><strong>Roving skimmer pumps/interceptor trenches</strong></td>
<td>• Suitable for deployment in recovery trenches</td>
</tr>
<tr>
<td><strong>Single-phase extraction</strong></td>
<td>• Typically used in conjunction with other techniques to suppress the water table and increase lateral migration of LNAPL into a recovery well</td>
</tr>
<tr>
<td><strong>Dual-phase extraction</strong></td>
<td>• Combines water and LNAPL recovery in a single pump unit, promoting the migration of LNAPL into a recovery well through enhancement of the hydraulic gradient</td>
</tr>
<tr>
<td><strong>Multiphase extraction (MPE)</strong></td>
<td>• Combines the recovery of soil vapour in addition to the dual-phase recovery of LNAPL and groundwater by the application of a vacuum to a sealed well, which acts on the response zone promoted by the depression of the water table. MPE is suitable for more viscous LNAPLs, such as lubricating oils</td>
</tr>
<tr>
<td><strong>Vacuum-enhanced recovery with bio-slurping</strong></td>
<td>• Application of a partial vacuum to a recovery well to promote air flow through the aquifer, and altered pressure gradients to increase LNAPL ingress. LNAPL extraction is achieved through a secondary vacuum drop tube – suitable for transmissive units</td>
</tr>
<tr>
<td><strong>Soil vapour extraction</strong></td>
<td>• Vadose zone only – suitable for granular soil profiles and most effective for volatile LNAPL constituents, with the flux of air increasing volatilisation and LNAPL mass reduction</td>
</tr>
<tr>
<td><strong>Enhanced oil recovery flooding and flushing techniques</strong></td>
<td>• LNAPL mobilisation through the use of hot water to modify LNAPL viscosities, or chemical flushing through the use of surfactants or co-solvents to promote the mobilisation and recovery of LNAPL</td>
</tr>
<tr>
<td><strong>In situ chemical treatments</strong></td>
<td>• Typically the injection or emplacement through infiltration galleries of oxidising compounds to enhance the oxidising process – likely to be more suitable for treatment of residual LNAPL following action on the mass by other technologies</td>
</tr>
<tr>
<td><strong>Thermal treatments</strong></td>
<td>• LNAPL mobilisation through the use of hot water to modify LNAPL</td>
</tr>
</tbody>
</table>
**Pathway intervention methods**

Pathway intervention technologies typically involve engineering controls that are used to provide containment of LNAPL to eliminate potential exposure pathways or prevent migration of contaminants. It is generally expected that such controls will be in place for long periods. They are often used when source reduction methods are unfeasible or impractical, or land-use or permitting restrictions apply. Examples of containment systems are:

- bentonite slurry walls
- sheet pile walls
- funnel-and-gate systems with in-gate treatment and collection systems
- permeable reactive barriers (for dissolved phase), and
- hydraulic containment systems.

**Receptor protection methods**

The use of receptor protection systems generally applies to human health receptors, but can extend to ecological receptors, where further LNAPL source removal is considered technically impractical but risk assessment indicates the potential for vapour exposure associated with a residual source. The underlying principle of the receptor protection method is that risk from residual LNAPL can be minimised through the use of ground or building engineering controls. Receptor protection methods can include:

- capping systems
- membrane systems
- underfloor ventilation systems, and
- positive air displacement systems.

In extreme cases, receptors can also be physically removed and relocated to prevent ongoing exposure. Administrative controls can also be implemented that impose restrictions on the use of groundwater.

**Review of existing remedial technology guidance**

The guidance documents that describe specific remedial technologies in more detail include:

- *Evaluating LNAPL remedial technologies for achieving project goals* (ITRC 2009b); and
**Technology options**

To support the identification and selection of LNAPL remediation technology, a matrix of available treatment technologies that should be considered for LNAPL remediation is presented in Table 4 and Table 5.

The tables, which are based on the work of Van Deuren et al. (2002), as set out in the Treatment Technologies Screening Matrix (version 4) of the United States Federal Remediation Technologies Roundtable, are presented in two parts:

- Table 4 – technologies applicable to the vadose or unsaturated zone, and
- Table 5 – technologies applicable to the phreatic or saturated zone.

For both the vadose zone and phreatic zone, the following information is provided:

- a classification of the remedial technology within the source–pathway–receptor risk assessment framework as a
  - source reduction method
  - pathway intervention method, or
  - receptor protection method
- an initial technology screen of the suitability of the method for LNAPL remediation
- a secondary technology screen focusing on the relative effectiveness (low, medium or high) of the various technologies for differing geological properties
  - low-permeability media
  - granular media, or
  - fractured rock media, and
- the likely relative (to each other) cost of the various technologies.

**Practitioner’s tip: Are the external costs of remediation significant?**

In addition to the direct capital expenditure for a remediation system, implementation external costs can represent a significant proportion of the overall cost of remediation. External costs of remediation include any damage to the environment and society that occurs as a result of remediation activities. Examples include stakeholder engagement, security, air emissions, liquid waste discharges, CO\(_2\) production from energy use, noise management, traffic management, accidents and emissions from heavy vehicle traffic, waste management and unplanned releases of contamination.
Table 4. Identification and screening of LNAPL remedial technologies – vadose zone

<table>
<thead>
<tr>
<th>LNAPL identification and screening</th>
<th>Initial technology screen</th>
<th>Secondary technology screen</th>
</tr>
</thead>
<tbody>
<tr>
<td>Treatment technology and process option</td>
<td>Technical comments</td>
<td>Effectiveness</td>
</tr>
<tr>
<td>In situ biological treatment</td>
<td></td>
<td>Low K media</td>
</tr>
<tr>
<td>Pneumatic/hydraulic fracturing</td>
<td>Technically implementable</td>
<td>L</td>
</tr>
<tr>
<td>Soil vapour extraction (SVE)</td>
<td>Technically implementable</td>
<td>L</td>
</tr>
<tr>
<td>Thermal/steam injection</td>
<td>Technically implementable</td>
<td>L</td>
</tr>
<tr>
<td>Chemical flushing</td>
<td>Technically implementable</td>
<td>L</td>
</tr>
<tr>
<td>Chemical oxidation</td>
<td>Technically implementable</td>
<td>L</td>
</tr>
<tr>
<td>Off-site disposal</td>
<td>Excavation and off-site disposal</td>
<td>Technically implementable</td>
</tr>
</tbody>
</table>

Ex situ biological treatment (assuming excavation)

| Landfarming | Technically implementable | H | H | N/A | Cost dependent on engineering design and location. Requires space and time. Not suitable for rock |
| Biopiles | Technically implementable | H | H | N/A | Cost dependent on engineering design and location. Requires space and time. Not suitable for rock |
| Slurry phase biological treatment | Technically implementable | H | H | N/A | Cost dependent on engineering design and location. Requires space and time. Not suitable for rock |

Ex situ physicochemical treatment (assuming excavation)

| Ex situ thermal treatment (assuming | Technically implementable | H | H | N/A | Cost dependent on project scale and location |

Receptor protection methods

| Capping | Technically implementable | H | H | | |
| Membranes systems | Technically implementable | H | H | | Cost dependent on engineering design |
| Underfloor ventilation systems | Technically implementable | H | H | | |
| Positive air displacement systems | Technically implementable | H | H | | |

Source: after Van Deuren et al. (2002)
Table 5. Identification and screening of LNAPL remedial technologies – phreatic zone
Part 1

<table>
<thead>
<tr>
<th>Phreatic zone</th>
<th>KEY</th>
<th>LOW - relative cost or level of technological effectiveness</th>
<th>MODERATE - relative cost or level of technological effectiveness</th>
<th>HIGH - relative cost or level of technological effectiveness</th>
<th>Refer to screening comments</th>
<th>K - Relative permeability</th>
</tr>
</thead>
<tbody>
<tr>
<td>LNAPL identification and screening</td>
<td>Initial technology screen</td>
<td>Secondary technology screen</td>
<td>Effectiveness</td>
<td>Likely relative cost</td>
<td>Screening comments</td>
<td></td>
</tr>
<tr>
<td>Treatment technology and process option</td>
<td>Technical comments</td>
<td>Low K</td>
<td>Granular media</td>
<td>Fractured rock</td>
<td>Generally not suitable for LNAPL</td>
<td></td>
</tr>
</tbody>
</table>

Source elimination methods

In situ biological treatment

<table>
<thead>
<tr>
<th>In situ biological treatments</th>
<th>Generally not suitable for LNAPL</th>
<th>Subject to HERA and stakeholder agreement</th>
<th>Generally requires stakeholder agreement backed by risk assessment</th>
</tr>
</thead>
<tbody>
<tr>
<td>In situ retention</td>
<td>Technically implementable</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Monitored natural attenuation (MNA)</td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

In situ physicochemical treatment

| Soil vapour extraction (SVE) | Technically implementable | | Generally not suitable in rock in the absence of fracturing |
| Air sparging (AS) | Technically implementable | | |
| Pneumatic/hydraulic fracturing | Technically implementable | | In conjunction with other technology |
| Chemical oxidation | Technically implementable | | In conjunction with other technology following bulk LNAPL recovery |
| Treatment walls (passive/reactive), funnel & gate (not applicable to rock) | Technically implementable | | Cost dependent on engineering design |

LNAPL recovery

| Sorbent socks (passive skimming) | | | |
| Hand bail | | | |
| Belt skimming systems | | | |
| Active skimming & pumping systems | | | |
| Vacuum trucks (total fluid pumping) | | | |
| Interceptor trenching | Technically implementable | | |
| Single and dual-pump recovery | | | |
| Vacuum enhanced recovery | | | |
| Dual-phase vapour extraction (DPVE) | | | |
| Multi-phase extraction (MPE) with biosurfing | | | |
| CO₂-supersaturated water injection & vapour extraction | | | |

Enhanced oil recovery:

| - Hot water flooding | | | |
| - Surfactant flushing | Technically implementable | | |
| - Co-solvent (ethanol) flooding | | | |

In situ thermal treatment

| Generally not suitable for LNAPL | |
| Ex situ biological treatment (assuming pumping) | Generally not suitable for LNAPL |
| Ex situ physicochemical treatment (assuming excavation) | Generally not suitable for LNAPL |
| Ex situ thermal treatment (assuming pumping) | Generally not suitable for LNAPL |
Remedial technology screening

ITRC (2009b) notes that, in the past few decades, LNAPL remedial technologies have evolved from conventional pumping or hydraulic recovery systems to a variety of innovative, active and experimental technologies that address the mobile and residual LNAPL fractions, as well as volatile and dissolved phase plumes.

The range of possible remedial technology options includes active technologies, passive technologies, institutional controls, engineering controls (i.e. containment) and combinations of these options. Thus, many different LNAPL remedial technologies with differing site and LNAPL applicabilities and capabilities are available to remediate LNAPL. This can add complexity to the selection of an appropriate remedial technology to address an LNAPL impact scenario. A systematic technology screening process that also ranks alternative technologies is recommended at this stage of the LNAPL management program.

The screening of remedial technologies or the implementation of engineering controls (or a combination of solutions) is typically supported by reviewing the LCSM, the results of product recovery analysis (baildown tests) and LNAPL recovery modelling, where applicable. The integration of this information informs the ground conditions, the three-dimensional distribution of LNAPL and likely recovery rates, enabling an initial
technology screen to be performed. Subject to the above factors, a number of the technologies set out in Table 4 and Table 5, or technologies not discussed here (such as steam-stripping) may be considered for further appraisal.

During the process of technology selection, remediation technologies should be screened for their ability to meet the agreed remedial objectives, and for compatibility with the site conditions and LNAPL properties. It is also important at this stage that sight is not lost of the site sensitivity classification developed during step 1, and that this is considered in the decision-making process.

Minimum data requirements are associated with each remedial technology to fully evaluate the technology and its suitability to meet the remedial objectives. In general, most data requirements relate to site-specific hydrogeological or LNAPL characterisation, which will be developed on completion of the detailed LCSM. The importance of characterising transmissivity and likely LNAPL recovery rates cannot be overstated.

To begin the process of technology screening, site-specific factors, such as those shown as Table 6, should be reviewed, in conjunction with the remedial objectives and derived end points for the site.

Table 6. Factors that should be taken into consideration during technology screening

<table>
<thead>
<tr>
<th>Overall consideration</th>
<th>Specific factors</th>
</tr>
</thead>
<tbody>
<tr>
<td>Technical input</td>
<td>• Risk profile&lt;br&gt;• Suitability to media&lt;br&gt;• Previous successes and feasibility rating&lt;br&gt;• System performance specifications&lt;br&gt;• LNAPL distribution and characteristics&lt;br&gt;• Likely recovery rates&lt;br&gt;• Emissions control&lt;br&gt;• Carbon footprint&lt;br&gt;• Energy requirements&lt;br&gt;• Waste stream and disposal options&lt;br&gt;• Regulations or guidelines</td>
</tr>
<tr>
<td>Logistical requirements</td>
<td>• Community or stakeholder concerns&lt;br&gt;• Site restrictions, including hours of operation&lt;br&gt;• Safety concerns</td>
</tr>
<tr>
<td>Financial issues</td>
<td>• Costs, including capital expenditure (CAPEX) and operational expenditure (OPEX)&lt;br&gt;• Cost–benefit analysis&lt;br&gt;• Sustainability and economic assessment</td>
</tr>
<tr>
<td>Timing and schedule</td>
<td>• Remedial timeframe</td>
</tr>
</tbody>
</table>
**Technology combinations**

In developing an LNAPL remedial strategy, the application of multiple technologies and engineering controls, either as a system or as a sequentially applied treatment train, should be considered during the screening process. Multiple technologies and controls are sometimes necessary to address exposure pathways – for example, pumping of LNAPL to reduce LNAPL mobility, along with soil vapour extraction (SVE) to control the potential intrusion of vapours into buildings.

**Remedial technology selection**

Following the initial technology screen and the assembly of a 'short list' of suitable LNAPL remedial technologies, the next step in the process is to identify the optimum solution for the site that will achieve the remedial objectives and end points.

To make the final technology selection, we recommend that, in addition to the factors that are considered in Table 4 and Table 5, alternatives are further ranked, as shown in Figure 13. This final element of the technology selection process focuses on the applicability of the technology to the site, the technology's track record of success in similar ground conditions, and whether the technology is widely used or is innovative.

**Practitioner's tip: How important is it that technology be 'proven'?**

The use of a technology that has a proven track record of success in LNAPL remediation in Australia or success on sites with similar ground conditions will lower costs, reduce the risk of failure and improve the likelihood that remedial objectives will be met.

The financial cost of the various technologies on the short list should also be considered at this stage, along with the predicted timescales of operation, to enable a comparison of capital expenditure (CAPEX) versus operational expenditure (OPEX) costs.
Flexibility should be retained in the remedial technology selection process, in case it becomes apparent that remedial objectives may not be attained within practical constraints of budget or time. Therefore, following detailed screening and economics analysis, and even in the pilot study stage, it may be necessary to select another technology to meet the remedial objectives.
Practitioner's tip: What about fractured rock?

Technology selection for LNAPL remediation in fractured rock is not straightforward. There is a lot less experience globally, and much less practical guidance in the literature. Porous medium models do not necessarily apply, and many of the conventional remediation technologies are ineffective. The geometry of the fracture network is a key factor in LNAPL behaviour and therefore remedial success. Some practitioners have used angled or horizontal wells to intercept the vertical fractures that seem to dominate LNAPL movement. The use of physical barriers, constructed by grouting up fracture networks to allow LNAPL to pool up-gradient, has also met with some success. High-vacuum extraction systems have also been used. Many of the technical impracticability determinations in the United States, for instance, have involved fractured rock site. More research is needed, especially into demonstration of practical remediation.

Step 3(d): Conduct an economics and sustainability assessment

One aspect of remediation that is often overlooked is whether the cost of reaching the proposed objective is justified, in terms of the environmental, social and economic benefits that would be delivered. Cost alone is rarely a good indicator of the economic viability or the sustainability of remediation. For sites with low or moderate sensitivity, where remediation is likely to be difficult or costly, a full life-cycle analysis of the environmental, social and economic costs and benefits of remediation can provide important insight for decision makers, and quantitatively describe how sustainable the planned remediation is.

For high-sensitivity (higher-risk or higher-profile) sites, quantitative economic comparison of a short list of possible remedial objectives (with the accompanying risk-based remedial approach used to reach them) can be useful. Such an analysis should consider the full life cycle of the project, comparing environmental, social and financial costs of remediation with the benefits that would result if various remedial objectives were met. Many different methods are available to undertake such assessments, including qualitative and semi-quantitative, multi-criteria-based, sustainability assessments.

More sophisticated approaches, such as the environmental and economic sustainability assessment (Hardisty 2010), involve complete monetisation of all costs (including the external or social costs of remediation [Hardisty, Ozdemiroglu & Arch 2008]) and all benefits of remediation. Understanding the value that remediation brings helps to put remedial cost estimates into perspective and to quantify the sometimes vague notion of ‘sustainability’. Least-cost approaches do not necessarily generate higher overall net benefit, and remediation that delivers more overall benefit across the life cycle than cost is sustainable, regardless of cost. For more information on applying integrated quantitative economic and sustainability assessment to remediation decision making, consult Hardisty and Ozdemiroglu (2005) and Hardisty (2010).
Practitioner’s tip: What are the implications of applying full-cost economics and sustainability assessment to the derivation of LNAPL remediation end points? How do we manage change when an LNAPL remediation system does not perform as expected?

The derivation of LNAPL remediation end points is likely to be an iterative and incremental process. Full-cost economics and sustainability analyses are likely to inform the establishment of the LNAPL remedial end points.

Effective management of change is critical during detailed performance monitoring of the full-scale LNAPL remediation system. Subject to stakeholder consultation, desired end points may need to be re-evaluated and communicated during operation.
Step 4: Undertake pilot testing and technology implementation

Steps 1, 2 and 3 have led to site sensitivity classification, development or refinement of an LSCM, identification of an LNAPL remedial objective, and selection of technologies that are best suited to reaching that objective. Pilot testing, at an appropriate cost and scale, is vital before moving to full-scale remediation. For small, low-sensitivity, low-risk sites that will involve use of basic low-cost remediation technology, pilot testing may be dispensed with. However, for any remediation that involves considerable cost, or where site sensitivity is moderate or high, pilot testing is highly recommended. Pilot testing helps prove the applicability of the chosen technology, provides data that are vital in full-scale design, and helps ensure that objectives will be met at full scale. Installation and operation of the full-scale system requires careful planning and management, and a fully integrated site health and safety plan that protects workers, neighbours and the environment.

Pilot testing

Subject to site sensitivity classification, the magnitude of the LNAPL impact, the technology selection and the projected CAPEX remedial budget, it is prudent to conduct pilot testing in advance of installation of the main system (Figure 14). For small, low-sensitivity, low-risk sites that will involve use of basic low-cost remediation technology, pilot testing may be dispensed with. However, for any remediation that involves considerable cost, or where site sensitivity is moderate or high, pilot testing is highly recommended.

Pilot studies, which can include small-scale bench testing on site-specific material or preliminary small-scale field trials, are typically conducted to evaluate the effectiveness of technology selection and to provide valuable data for the design of the full-scale system.

Findings from pilot testing often lead to modification or adjustment of the final remedial technology design, or possibly even rejection of the initial selection of remedial technology in favour of an alternative. Hardisty and Ozdemiroglu (2005), in The economics of groundwater remediation and protection, suggest that pilot test scaling and expenditure should range between approximately 5% and 10% of the size and CAPEX budget of the anticipated full-scale system.

During pilot testing, monitoring is conducted to assess the performance of the technology against expected outcomes (ITRC 2006; Johnston 2010). Johnston (2010) notes that the nature of pilot testing may mean that methods for evaluating some of the performance metrics may need to be varied or intensified because of the limited duration and spatial scale of pilot testing.

The results of pilot testing are typically integrated with the data acquired during steps 1–4, to confirm the suitability of the technology selection, and the design and installation requirements.

A remediation system that is actively working will, in many situations, change subsurface conditions. As LNAPL is removed by pumping, for instance, saturations and thus relative permeability will decrease, lowering flow rates and changing flow
As LNAPL is vaporised, high vapour pressure components will be removed preferentially, changing the physical and chemical properties of the LNAPL that remains in the ground; this may alter the way the LNAPL behaves.

**Step 4: Pilot testing and LNAPL technology implementation**

**OVERVIEW**

Steps 1, 2 and 3 have led to development of an LSCM, identification of a remedial objective, and selection of technologies that are best suited to reaching that objective. Pilot testing, at an appropriate cost and scale, is vital before moving to full-scale remediation. For small, low-sensitivity, low-risk sites that will involve use of basic low-cost remediation technology, pilot testing may be dispensed with. But for any remediation that involves considerable cost, or where site sensitivity is moderate or high, pilot testing is highly recommended.

**Step 4(a): Pilot testing**

- **i. Design and plan pilot test**
  - Choose representative location
  - Ensure site is clear of utilities
  - Scale down selected technology (10% of full scale)
  - Develop data collection and monitoring system
  - Inform stakeholders as needed
  - Estimate test timing and duration
  - Develop cost estimate
  - Develop health and safety plan
  - Acquire necessary internal and external approvals
  - Establish baseline pre-test ground conditions

- **ii. Install and operate pilot test**
  - Install all equipment and monitoring systems
  - Establish pre-installation ground conditions
  - Conduct phase 1 pilot test
  - Monitor and record all operational parameters, continue testing
  - Shut down system
  - Complete post-test monitoring

- **iii. Collate and analyse pilot test data**
  - Assess system performance
  - Model predicted attainment of remedial end points
  - Recommend system design or operation changes
  - Consider technology changes or upgrades as needed
  - Evaluate safety performance
  - Consider integrating pilot into full-scale design

**Step 4(b): Full-scale system design and implementation**

- **i. Design and plan full-scale system installation**
  - Determine remediation system physical boundaries
  - Ensure site is clear of utilities and services infrastructure
  - Scale up selected technology(s)
  - Develop data collection and monitoring system
  - Inform and involve stakeholders as needed
  - Estimate remedial duration
  - Develop cost estimate
  - Develop health and safety plan
  - Acquire necessary internal and external approvals
  - Establish baseline pre-remediation ground conditions

- **ii. Install and operate system**
  - Install all equipment and monitoring systems
  - Establish post-installation pre-start ground conditions
  - Commission system
  - Execute start up and initial operation period
  - Execute phase 1 shut down and evaluation
  - Execute main operation period

**Figure 14. Pilot testing and technology implementation**

Most remediation systems are dynamic in nature and will need augmenting or rebalancing during the LNAPL remediation phase to optimise performance. Performance metrics established during pilot testing are suited to track remedial progress in real time. If system performance falls below expectations, early action is required to understand the cause and determine what action is needed to improve results. Action could involve adjusting or phasing operation of the system, expanding coverage, increasing area of influence, adding components to the system, or modifying system design to cope with changing conditions.

Full-scale system design needs to take into consideration not only the physical installation of the technology but also the longer-term issues of operation, monitoring
and maintenance. Some of those key considerations are presented in Figure 13. The overview of pilot testing and technology implementation is presented in Figure 15.

### Figure 15. Remediation system installation considerations

#### Health and safety

LNAPL remediation works have the potential to cause harm to people and the environment. Possible hazards include exposure of site workers to LNAPL compounds through inhalation of vapours, dermal contact with pure liquid or dissolved phase components, or accidental ingestion. The risk of fire and explosion is always present where volatile hydrocarbon compounds are present. Design of the remediation system should be undertaken to eliminate exposure pathways, wherever possible and practical, and all on-site activities (from installation to operations and eventual decommissioning) should be conducted under a detailed and rigorous health and safety plan.

Potential hazards extend beyond the site to neighbours, passers-by and the wider natural environment. Remedial design should consider managing and reducing off-site impacts that result from remediation activities, including release of vapours, dust and other airborne pollutants, noise, odour, accidental releases of liquids, heavy vehicle movement and other traffic, vibration and other ground disturbance, effects on wildlife, and site security.
Practitioner’s tip: What are the most common remediation mistakes?

Perhaps the most common mistake in LNAPL remediation is a failure to set a clear LNAPL remedial objective, end points for remediation, and performance criteria by which the given technology will be assessed during operation for effectiveness (in reaching the end points). Advancing to technology selection as soon as basic site investigation is complete remains common practice. Remediation is not only about how, but also about what (what are we trying to protect, improve and ameliorate, and why). Another common difficulty is underestimating the effects of heterogeneity on system performance. The importance of involving stakeholders in decision making cannot be overemphasised.

One of the most significant mistakes made in LNAPL remediation (after a lack of clearly defined end points and performance criteria) is failing to interpret remediation system performance data. Once a remediation system reaches its end point (based on set performance criteria) or it becomes clear that these end points cannot be met (e.g. recovery rates decrease and asymptote, or slow to negligible, before end points are reached), it should be switched off and the remediation strategy reviewed. The latter could, in fact, be the point of technical impracticability for the technology.

Invariably system performance is overestimated while remediation budgets are underestimated. Any remediation system should be considered a short-term action to achieve specific end points. Meeting all the objectives for an LNAPL remediation project will likely require application of more than one remediation approach. Remediation budgets should be estimated based on all anticipated approaches required to meet the required objectives. The further ahead in time these costs need to be estimated, the less their certainty. There is no single rule of thumb that enables accurate estimation of all project costs for LNAPL remediation. Practitioners are advised to map out the total project costs to meet all the remediation objectives and the anticipated strategies to meet them. Such estimates will need to include descriptions of the variables causing uncertainty, and their likely impact on project costs and timing.
Step 5: System operation, performance monitoring and LNAPL closeout reporting

The final stage in the process of managing LNAPL on a site comprises ongoing system operation, maintenance and performance monitoring, leading to attainment of remedial end points. This is followed by stakeholder-endorsed cessation of LNAPL remediation, and LNAPL closeout reporting.

Reaching the LNAPL end point

For the purposes of this guidance, the attainment of the LNAPL remedial end point should be regarded as realised when the limit of practical LNAPL remediation of the selected technology can be demonstrated. Identification of the limits of practical LNAPL remediation, and therefore the LNAPL end point, should be supported by analysis of key indicators, such as declining recovery rates or asymptotic LNAPL recovery curves, backed by statistics, where applicable. The inherent limits of the remediation system should also be considered in this process.

The technical impracticability of further remediation for LNAPL impacted soils and aquifers is discussed by Johnston (2010) in CRC CARE Technical Report no.18. Technical impracticability as an argued LNAPL end point should be endorsed by stakeholders through the acceptance of an LNAPL closeout report. This should be done before the transfer of focus from immobile or residual LNAPL to the management of dissolved and vapour phases, where applicable.

Figure 16 illustrates the process of completion of LNAPL remedial action, from monitoring of the implemented remediation system to LNAPL stage closeout reporting.

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**Figure 16. The stages of LNAPL remediation management, monitoring and closeout**
System management and performance monitoring

Performance monitoring, associated trend analysis and reporting provide the necessary feedback to enable the remediation system to be augmented with, for example, additional recovery wells, balanced or adjusted to optimise system efficiency and the duration of operation.

Monitoring and trend analysis will comprise the field gauging of LNAPL distribution, and measurement and recording of total fluids recovered. System performance should tend towards the LNAPL volume predictions developed in the LCSM, less natural losses and the proportion of LNAPL that will remain in the subsurface as immobile residue (the ganglia discussed above). An asymptotic trend usually indicates that practical LNAPL recovery limits are being approached.

Where assessment and reporting of the system performance indicates a significant departure from modelled or predicted recovery rates, provision to respond to changing or adverse conditions needs to be retained.

Waste management is an integral component of system operation, performance monitoring and reporting. Documentation of LNAPL recovery and the route of disposal is an essential element of closeout reporting.

If SVE is incorporated into the remedial strategy and emissions treatment is instigated, off-gas measurements should be performed to support the calculation of losses from the system and trend analysis.

Seasonal effects, including recharge and fluctuating groundwater levels, also need to be considered during the assessment of system performance. The phenomenon of 'rebound', which is commonly reported following the temporary shut-down of in situ groundwater pump and treat, and SVE, systems (Switzer et al. 2004), should also be considered during the LNAPL remediation monitoring phase.

Provision should be made for several phases of rebound monitoring, to demonstrate the efficacy of system performance and attainment of LNAPL remedial end points. This should occur before advancing to cessation of the LNAPL remediation system, and transferring remedial focus from source removal to management of the dissolved and vapour phases, where applicable.

The OPEX is subject to the technology selection and the complexity of the approach to LNAPL remediation. Provision for OPEX should allow for system maintenance, management of wastes, control of emissions, performance monitoring and periodic reporting.

ITRC (2009b) provides an example of a performance metric that gives an indication of the remedial technology's performance. An LNAPL skimming system is given a performance metric of in-well LNAPL thickness at the down-gradient edge of the LNAPL body. If sufficient reduction in the LNAPL body's migration is not observed at the down-gradient edge, additional skimming wells may be warranted in that area.

Cessation of operation

LNAPL remediation can cease when the LNAPL remedial objectives and technology end points have been attained. Further remediation or management may be required to meet additional remedial objectives relating to adsorbed, dissolved and vapour
petroleum hydrocarbon phases. Engagement with stakeholders to obtain agreement that LNAPL objectives and end points have been met is critical, as is acceptance of the final condition of the land (particularly if any LNAPL remains in place), and relevant and agreed management controls.

Stakeholder-endorsed termination of the LNAPL remediation program should be documented through a closeout report. This should include provision to address and respond to any adverse data trends following the transfer of focus from the LNAPL source remediation to management and monitoring of the secondary phases of soil and groundwater impact.

**LNAPL stage closeout**

Following attainment of the LNAPL remedial objectives and LNAPL remediation end points set out in step 3, in conjunction with stakeholder endorsement of the proposal to terminate the LNAPL remediation system, closeout reporting is the final LNAPL management element. It is likely that management of dissolved and vapour phase hydrocarbons, treated concurrently with the LNAPL phase, will be ongoing and subject to separate closeout reporting.

The aim of LNAPL closeout reporting should be documentation of the five-step process from the summary of site conditions, through the development of the LCSM and subsequent decision making, to the attainment of the remedial objectives and LNAPL remediation end points.

The US EPA (2011) provides guidance for the development of closeout reports in the document *Close out procedures for national priorities list sites*. A suggested structure for preliminary and final LNAPL closeout reports, developed from this document, is set out in Table 7.

<table>
<thead>
<tr>
<th>Table 7. Outline for preliminary and final LNAPL remediation closeout reporting</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Report section</strong></td>
</tr>
<tr>
<td>Introduction</td>
</tr>
</tbody>
</table>
| Site identification and background | • Provide site identification in accordance with state or territory reporting requirements (if applicable)  
• Provide background information on site history pertaining to the release of LNAPL |
| Summary of site conditions | • Document the results of environmental site assessments leading to the establishment of the robust LCSM that formed the basis of decision making  
• Document the appraisal of site sensitivity  
• Document the basis and process for the derivation of remedial objectives and establishment of end points  
• Document stakeholder acceptance of proposed remedial end points |
<p>| System design and implementation | • Document the screening and selection of remedial technologies, including, where applicable, the incorporation of full-cost economics and sustainability into the decision-making process |</p>
<table>
<thead>
<tr>
<th>Report section</th>
<th>Contents</th>
</tr>
</thead>
</table>
| Monitoring results                                | • Provide the results of pilot testing, where applicable  
• Document the installation and implementation of the LNAPL remediation system                                                               |
| Monitoring results                                | • Present the results of LNAPL distribution in the source areas over time  
• Present the volumes of recovered LNAPL versus predicted levels in ground before the commencement of remediation  
• Document quality assurance/quality control processes  
• Document waste management, including waste transfer  
• Document emissions control  
• Document trend analysis, augmented by statistics, where applicable, and rebound monitoring |
| Attainment of LNAPL remedial objective and end point| • Provide a summary of monitoring data and a regression analysis to demonstrate attainment of stakeholder-endorsed LNAPL remedial end points |
| Stakeholder consultation                         | • Provide details of stakeholders consulted during all phases of the project  
• Provide a comparison of stakeholder-endorsed remedial end points with the conditions at which cessation of LNAPL remediation has been agreed as acceptable |
| Conclusion and recommendations                    | • Summarise the LNAPL remediation program  
• Provide a strategy for the ongoing management of dissolved or vapour phase impacts, where applicable  
• Provide a response strategy in the event that adverse data trends are subsequently reported  
• Provide a statement of LNAPL remedial action completion |
Step 5: System operation, performance monitoring and LNAPL closeout reporting

OVERVIEW
The final stage in the process of managing LNAPL on a site comprises ongoing system operation, maintenance and performance monitoring, leading to attainment of remedial end points. This is followed by stakeholder-endorsed cessation of LNAPL remediation and closeout reporting. For the purposes of this guidance, attainment of the LNAPL remedial end point is realised when further LNAPL source removal, backed by statistics where applicable, appears to be impractical.

The operational and monitoring phase of the remediation system consists of a number of elements, including maintenance, power and waste management.

- Operational phase considerations:
  - Power requirements
  - Waste liquids management
  - Emissions control
  - Hours of operation
  - Telemetry/remote operation
  - Other site users
  - Safety and site security

- Monitoring phase considerations:
  - Maintenance and shutdown
  - Emergency response
  - Performance monitoring
  - Emissions monitoring
  - Telemetry/remote monitoring
  - Rebound monitoring
  - Safety
  - Stakeholder communication

LNAPL closeout — the point at which LNAPL recovery can cease, which should be stakeholder endorsed, supported by robust and defensible monitoring data.

- Cessation of operation:
  - Stakeholder consultation
  - Review of the LNAPL end point(s)
  - Review of the DOOs
  - Statistical analysis and presentation of monitoring data
  - Termination of LNAPL recovery system

- LNAPL stage closeout:
  - Preliminary closeout report
  - Final LNAPL closeout report

LNAPL remedial action completed
Transfer focus to the management of dissolved or vapour phase impacts

Figure 17. System operation, performance monitoring and LNAPL closeout reporting
Summary and conclusion

No two LNAPL impact scenarios are likely to be the same, and the regulatory approach to the management of LNAPL in the subsurface in the different jurisdictions of Australia will, in all likelihood, continue to differ in the future. Therefore, recognising the variation in policy and hydrogeochemical conditions, this guide has been developed to provide a risk-based framework for remediation of LNAPL in Australia.

Rather than restate the wealth of technical literature that exists on the subject of LNAPL remediation, this guidance focuses on a step-by-step framework to help users move through what can be a complex and bewildering process. LNAPL remediation should be approached in much the same way as all remediation: logically, scientifically, cooperatively and rationally. In its most basic form, this guidance suggests that users:

- prioritise sites, particularly where an emergency response to a pollution incident and associated statutory reporting are concerned (step 1)
- define site sensitivity, based on the principles of risk assessment and, where applicable, the full-cost economic value of the land (step 1)
- understand the problem – engage LNAPL experienced field engineers to conduct site investigation and develop a detailed LCSM (step 2)
- set the LNAPL remedial objectives and LNAPL remediation end points, based on integration of the LCSM with an assessment of site sensitivity and risk; importantly, consult with stakeholders at this step (step 3)
- select the LNAPL remediation technology, considering technical and full-cost economic factors, and incorporating the social and environmental aspects of the project life cycle in addition to the financial cost (step 3)
- where applicable, pilot test the selected technology at small scale; adjust the full-scale design as needed (step 4)
- implement the system at full scale – design, install and commission the system safely (step 4)
- manage and monitor performance – realise that remediation is dynamic and prepare for change (step 5), and
- undertake LNAPL closeout once the LNAPL remediation end points are met, potential rebound has been addressed and stakeholders are satisfied; acknowledge that other phases of contaminated sites management and remediation may be ongoing (step 5).

Finally, a sense of proportionality should be maintained in the use of this guide and in the management of LNAPL impacted sites. It is important to develop realistic LNAPL remedial objectives and establish LNAPL remediation end points that are consistent with the LCSM, and aligned with the requirements of the states and territories, and other stakeholders, including the financial backers of the remediation program. The success of an LNAPL remediation program ultimately relies heavily on the quality of the LCSM and the professional judgement of the remediation practitioners.
References


API (American Petroleum Institute) 2012, *API transmissivity workbook: Calculation of LNAPL transmissivity from baildown test data*, API publication 36, API Regulatory and Scientific Affairs Department, Washington, DC.


CRC CARE (Cooperative Research Centre for Contamination Assessment and Remediation of the Environment) 2009, *Acid sulfate soils (ASS)*, fact sheet 6, CRC CARE, Adelaide.


DEC (Department of Environment and Conservation, Western Australia) 2013, Identification and investigation of acid sulfate soils and acidic landscapes, DEC, Perth.

DEP (Department of Environmental Protection, Western Australia) 2001, Development of sampling and analysis programs, contaminated sites management series, DEP, Perth.


ITRC (Interstate Technology and Regulatory Council) 2009a, *Evaluating natural source zone depletion at sites with LNAPL*, prepared by the ITRC LNAPLs Team, ITRC, Washington, DC.

ITRC (Interstate Technology and Regulatory Council) 2009b, *Evaluating LNAPL remedial technologies for achieving project goals*, prepared by the ITRC LNAPLs Team, ITRC, Washington, DC.


APPENDIX A: Worked examples
The worked example 1 shows a decommissioned service station with LNAPL discovered during environmental due diligence. The service station was closed 10 years ago, and all underground petroleum storage systems (UPSS) and buildings were removed. The site is now vacant and to be sold for redevelopment. A detailed site investigation (DSI) done as part of environmental due diligence before sale identified LNAPL under the former UPSS and a portion of the site, extending under the adjacent road. The site is predominantly clay soil with groundwater at 8 m below ground. Soil contamination was not observed during drilling, but LNAPL accumulated in several wells over a period of weeks. Background groundwater quality was identified as suitable for domestic use using TDS measurements, but the aquifer yield was very low (wells bailed dry during sampling). There are no registered bores within a 1 km radius of the site, and publicly available data indicate that this water table aquifer is unsuitable for extractive use as a result of low yield in this region of the state. There are no surface water bodies within 2 km of the site.

While this example does not map out the stakeholders or the points of engagement, it should be read on the basis that community, regulators, and all land and utility owners in the affected area were engaged as per the ASC NEPM community engagement guidelines. This example should be considered on the understanding that all statutory requirements for engagement with regulators were an integral part of the sequence of events; these requirements vary by jurisdiction.

### Table: LNAPL project prioritisation, site sensitivity and risk screening

<table>
<thead>
<tr>
<th>Sensitivity</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>MODERATE</td>
<td>LNAPL plume likely stable but extending beyond site boundaries under the adjacent road</td>
</tr>
<tr>
<td></td>
<td>Presence of dissolved hydrocarbon in groundwater</td>
</tr>
<tr>
<td></td>
<td>Historical LNAPL release (10 years or more)</td>
</tr>
<tr>
<td></td>
<td>Low-permeability aquifer</td>
</tr>
</tbody>
</table>

To ensure compliance with local environmental legislation AND transparent disclosure of land condition before sale and redevelopment, the site is notified to the environmental regulator and planning authority per a negotiated agreement (step 3).

### Diagram: Quantity LCSM

**Detailed site investigation confirms the nature and extent of the LNAPL, and associated soil vapour and dissolved hydrocarbons in groundwater. The LNAPL and related dissolved phase hydrocarbon impact is limited in extent, and naturally contained by the inherent properties of the soil and naturally occurring biological degradation processes in the aquifer. These processes are also shown to have the capacity to mineralise the LNAPL in time.**

The work completed in step 2 has identified the following:

- **The site is safe, and the land is suitable for redevelopment with the LNAPL in place**
- **Groundwater environmental values are not precluded by the presence of LNAPL**
- **LNAPL and related groundwater contamination is of limited extent, and the potential for future migration is low as a result of natural conditions and natural attenuation processes**

Consultation with environmental regulator and the local development authority (responsible for approving any redevelopment) resulted in agreement that no remediation was required, but that conditions should be documented on the public record for the property. These should identify the condition of the land and restrictions on future development that could result in the LNAPL contamination becoming a risk to users of the land.

**Engagement with environmental regulators can include both statutory obligations (mandatory) and expectations (responsible and transparent communication). This engagement should be agreed between the party responsible for the LNAPL and the regulator when initial notification of the LNAPL contamination occurs.**

### Diagram: LNAPL closeout reporting

- **No risk to people on- and off-site (including vapour intrusion, as long as future development basements are not deeper than 4 metres below grade)***
- **No risk to environment (LNAPL and contaminated groundwater impact is limited as a result of soil properties and natural attenuation)***

Risk assessment confirms site is suitable for zoned land uses without need for remediation or management controls due to LNAPL.

**MODERATE sensitivity**

- LNAPL plume likely stable but extending beyond site boundaries under the adjacent road
- Presence of dissolved hydrocarbon in groundwater
- Historical LNAPL release (10 years or more)
- Low-permeability aquifer

**LOW sensitivity**

- No unacceptable risk to people and environment
- LNAPL stable
- No unacceptable risk to people and environment
- LNAPL does not preclude environmental values or abstractive beneficial uses

**Lateral extent of LNAPL plume**

- Historical LNAPL release (10 years or more)

**Site stability**

- Groundwater environmental values are not precluded by the presence of LNAPL
- LNAPL and related groundwater contamination is of limited extent, and the potential for future migration is low as a result of natural conditions and natural attenuation processes

**Risk assessment**

- Risk assessment confirms site is suitable for zoned land uses without need for remediation or management controls due to LNAPL.

**Environmental regulator**

- Engagement with environmental regulators can include both statutory obligations (mandatory) and expectations (responsible and transparent communication). This engagement should be agreed between the party responsible for the LNAPL and the regulator when initial notification of the LNAPL contamination occurs.

**Step 1: LNAPL project prioritisation, site sensitivity and risk screening**

1. LNAPL project prioritisation, site sensitivity and risk screening
2. Quantitative LNAPL analysis and LCSM development/refinement
3. (a) Set LNAPL remedial objectives
   (b) Derive LNAPL remediation end points
3. (c) Remedial options appraisal and technology selection
4. (a) Pilot testing
   (b) Main system design and implementation
5. (a) System operation and performance monitoring
   (b) LNAPL doseout reporting

**Step 2: Quantitative LCSM**

- Detailed site investigation confirms the nature and extent of the LNAPL, and associated soil vapour and dissolved hydrocarbons in groundwater.
- The LNAPL and related dissolved phase hydrocarbon impact is limited in extent, and naturally contained by the inherent properties of the soil and naturally occurring biological degradation processes in the aquifer. These processes are also shown to have the capacity to mineralise the LNAPL in time.

The work completed in step 2 has identified the following:

- The site is safe, and the land is suitable for redevelopment with the LNAPL in place
- Groundwater environmental values are not precluded by the presence of LNAPL
- LNAPL and related groundwater contamination is of limited extent, and the potential for future migration is low as a result of natural conditions and natural attenuation processes

Consultation with environmental regulator and the local development authority (responsible for approving any redevelopment) resulted in agreement that no remediation was required, but that conditions should be documented on the public record for the property. These should identify the condition of the land and restrictions on future development that could result in the LNAPL contamination becoming a risk to users of the land.

**Step 3:**

3(a). Set LNAPL remedial objectives
3(b). Derive LNAPL remediation end points
3(c). Remedial options appraisal and technology selection
3(d). Economic and sustainability assessment

**Step 4:**

4(a). Pilot testing
4(b). Main system design and implementation

**Step 5:**

5(a). System operation and performance monitoring
5(b). LNAPL doseout reporting

**Step 6:**

5(b). A closeout report documenting the condition of the land (LNAPL), restrictions affecting future developments on the land, the case for no further monitoring, and abandonment of all groundwater monitoring wells is prepared and submitted to the environmental regulator and planning authority per a negotiated agreement (step 3).
Worked example 2: Failure of an on-ground 5 ML diesel tank, resulting in 60,000 L of diesel leaking into the ground over a weekend. The loss was noted when the operator compared the tank volume on Monday morning with that measured the previous Friday.

NOTE: This example represents one possible negotiated outcome for this scenario.

Groundwater data gathered during installation of boundary groundwater monitoring wells and subsequent regular compliance monitoring provided initial site conceptual model, including sand soil with groundwater at ~4 m (±0.5 m) below ground level and flowing west towards a mixed-residential and commercial area, and then a surf beach. Groundwater quality (e.g. total dissolved solids—TDS) indicates no extractive beneficial use and no registered bores in the area of the fuel storage facility.

While this example does not map out the stakeholders or the points of engagement, it should be read on the basis that community, regulators, and all land and utility owners in the affected area were engaged as per the ASC NEPM community engagement guidelines. This example should be considered on the understanding that all statutory requirements for engagement with regulators were an integral part of the sequence of events; these requirements vary by jurisdiction.

1. LNAPL project prioritisation, site sensitivity and risk screening
   - HIGH sensitivity
     - 60,000 L diesel lost to ground with no surface expression
     - Shallow groundwater and high-permeability aquifer
     - Emergency services and environmental regulator notified
     - Emergency response initiated to ensure safety of people and property

   - QUALITATIVE LCSM
     - LNAPL plume spreading vertically and radially from failed tank (source area) through vadose zone and into saturated zone due to driving head
     - Install LNAPL recovery wells, starting around source area

   - QUANTITATIVE LCSM
     - 1. Detailed investigations to determine the nature and extent of LNAPL and consequential impact (vapour and dissolved hydrocarbons) and quantify risks (including consequential soil vapour and dissolved hydrocarbon plumes)
     - 2. Quantify LNAPL mobility end points

   - MODERATE sensitivity
     - LNAPL plume stable but extending under road
     - No unacceptable risk to people or environment
     - Groundwater monitoring continues per original environmental licence requirements, with some addition for monitoring the remaining LNAPL plume

2. Quantitative LNAPL analysis and LCSM development/refinement
   - 3(a). Set LNAPL remedial objectives
     - 1. Stop LNAPL spreading and start pollution incident cleanup
     - 2. Identify and mitigate risks to people and the environment

   - 3(b). Derive LNAPL remediation end points
     - 1. No LNAPL driving head
     - 2. LNAPL transmissivity < threshold
     - 3. LNAPL extent (plume) stable

   - 3(c). Remedial options appraisal and technology selection
   - 3(d). Economic and sustainability assessment

3. LNAPL remedial objectives
   - 3a. LNAPL remedial objectives
     - 1. Stop LNAPL spreading and start pollution incident cleanup
     - 2. Identify and mitigate risks to people and the environment

4. LNAPL recovery
   - 4(a). Pilot testing
   - 4(b). Commence LNAPL recovery
     - Design and install recovery system using information at hand, qualitative LCSM and data collected during well installation
     - Priority is LNAPL recovery in the source area while other investigations continue

5. LNAPL closeout reporting
   - 5(a). Monitoring of LNAPL recovery rates and plume extent (spreading)
   - 5(b). Stop LNAPL recovery and write closeout report for regulatory review/approval

Engagement with environmental regulators can include both statutory obligations (mandatory) and expectations (responsible and transparent communication). This engagement should be agreed between the party responsible for the LNAPL and the regulator when initial notification of the LNAPL contamination occurs.
**Worked example 3:** Metropolitan service station where unleaded petrol (ULP) inventory reconciliation monitoring identifies a loss of ULP from one of the underground petroleum storage systems (UPSS)

**NOTE:** This example represents one possible negotiated outcome for this scenario.

The service station is located in a suburban residential neighbourhood, with houses either side and behind. Groundwater is at approximately 3 m depth and of a quality suitable for domestic use. There are registered and unregistered bores in the area, with the nearest 300 m down-gradient of the site boundary (in the direction of groundwater flow). Groundwater flow direction is north from the site towards the house behind the service station. Soil in the area is sand. The nearest surface water is 2 km north. The quantity of fuel lost is unknown, but the detailed review of the inventory records suggests that the losses started one month ago and have progressively increased. The loss rate when the loss was identified by the review and the UPSS was taken out of service was in the order of 50 L/day. This process could take many years to get to LOW sensitivity.

While this example does not map out the stakeholders or the points of engagement, it should be read on the basis that community, regulators, and all land and utility owners in the affected area were engaged as per the ASC NEPM community engagement guidelines. This example should be considered on the understanding that all statutory requirements for engagement with regulators were an integral part of the sequence of events; these requirements vary by jurisdiction.

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**1. LNA(P) project prioritisation, site sensitivity and risk screening**

- Exact quantity of ULP entering the ground unknown but may be >1000 L
- Shallow groundwater and high-permeability aquifer
- ULP has potential for harm to people through direct contact or vapours creating dangerous atmospheres
- Environmental regulator notified, and immediate survey of site and surrounding area for evidence of vapours or LNA(P) (includes door-knock to identify unregistered groundwater bores)

**2. Quantitative LNA(P) analysis and LCSM development/refinement**

- Sensitive site
- Environmental regulator notified, and immediate survey of site and surrounding area for evidence of vapours or LNA(P) (includes door-knock to identify unregistered groundwater bores)

**3(a). Set LNA(P) remedial objectives**

- Identify nature and extent of LNA(P)
- Benzene concentrations in soil gas
- Benzene concentrations in LNA(P)
- No acute risks to health or safety but potential chronic risk to residents from LNA(P)-sourced vapour intrusion (benzene)

**3(b). Derive LNAPL remedial end points**

- No LNAPL or vapours in underground utilities
- Local government and utility owners informed of potential for deep excavations in the area to encounter petrol, and special controls required to manage health and safety risks

**3(c). Remedial options appraisal and technology selection**

- No unacceptable risks to people or the environment
- Groundwater beneficial (extractive) uses precluded

**3(d). Economic and sustainability assessment**

- No unacceptable risks to people or the environment
- Groundwater beneficial uses precluded

**4(a). Pilot testing**

- SVE system installed across end of plume extent
- Soil vapour extraction (SVE)

**4(b). Main system design and implementation**

- System is capable of meeting objective
- No acute risks and no chronic risks from vapour intrusion. Dissolved plume will stabilise (natural attenuation) and not reach surface water

**5(a). System operation and performance monitoring**

- Implementation of environmental management plan
- Monitoring of SVE performance

**5(b). LNA(P) closeout reporting**

- Monitoring of LNAPL recovery rates and plume extent (spreading)
- Stop LNAPL recovery and write closeout report

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**NOTE: This example represents one possible negotiated outcome for this scenario.**