

Federal Contaminated Sites Action Plan (FCSAP)

Guidance Document on the Management
of Light Non-Aqueous Phase Liquids (LNAPL)
at Federal Contaminated Sites

Version 1.0



Environment and
Climate Change Canada

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Changement climatique Canada

Canada

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Abbreviations

AMA	Adaptive management approach
API	American Petroleum Institute
ASTM	ASTM International
CCME	Canadian Council of Ministers of the Environment
CO ₂	Carbon dioxide
CRC CARE	Cooperative Research Centre for Contamination Assessment and Remediation of the Environment (Australia)
CSM	Conceptual site model
CSMWG	Contaminated Sites Management Working Group
DMF	FCSAP decision making framework
DNAPL	Dense non-aqueous phase liquid
DND	Department of National Defence
FCSAP	Federal Contaminated Sites Action Plan
ITRC	Interstate Technology and Regulatory Council
LCSM	LNAPL conceptual site model
LDRM	LNAPL distribution and recovery model
LEL	Lower explosive limit
LIF	Laser induced fluorescence
LNAPL	Light non-aqueous phase liquid
LOE	Line of evidence
LTM	Long-term monitoring
MIP	Membrane interface probe
MNA	Monitored natural attenuation
NA	Natural attenuation
NCSCS	National Classification System for Contaminated Sites
NSZD	Natural source zone depletion
PAH	Polycyclic aromatic hydrocarbons
PHC	Petroleum hydrocarbons
PID	Photo ionization detector
PSPC	Public Services and Procurement Canada
R/RM	Remediation/risk management
RAP	Remedial action plan
RCRA	Resource Conservation and Recovery Act (United States of America)
RMP	Risk management plan
ROA	Remedial options analysis
SSTL	Site specific target level
SuRF-UK	United Kingdom's Sustainable Remediation Forum
TPH	Total petroleum hydrocarbons
US EPA	United States Environmental Protection Agency

1 Introduction

The Federal Contaminated Sites Action Plan (FCSAP) is a federal program established in 2005 with the goal of reducing environmental and human health risks from known federal contaminated sites in Canada and their associated federal financial liabilities. To achieve this objective, FCSAP provides guidance, tools and resources to federal departments, agencies and Consolidated Crown corporations (collectively referred to as “custodians”) to ensure that federal contaminated sites are managed in a scientifically sound and a nationally consistent manner. The FCSAP Decision-Making Framework (DMF) is a 10-step roadmap that outlines the specific activities, requirements and key decisions to effectively address federal contaminated sites in Canada. The DMF along with other FCSAP-related resources can be found on the [FCSAP website](#).

This guidance document addresses the management of light non-aqueous phase liquids (LNAPL) at federal contaminated sites throughout the 10 steps of the DMF. A number of federal contaminated sites have been identified as containing LNAPL petroleum hydrocarbon (PHC) contaminants, which cannot be readily remediated, and therefore require a more comprehensive analysis of appropriate remediation/risk management (R/RM) approaches. A LNAPL is a groundwater contaminant that is not soluble in water and has lower density than water, in contrast to a dense non-aqueous phase liquid (DNAPL) which has higher density than water. Once a LNAPL infiltrates the ground, it will stop at the height of the water table because the LNAPL is less dense than water.

The science and management of LNAPL sites has evolved over time. This guidance on the management of LNAPLs at federal contaminated sites seeks to provide custodians responsible for federal contaminated sites with an objective, simplified, risk-based approach to effective LNAPL site management. The objective of this LNAPL guidance document is to provide a consistent approach to dealing with LNAPL-impacted sites.

The tools and procedures outlined in this LNAPL guidance document are consistent with the risk-based philosophy on which the FCSAP program is based. This LNAPL guidance is also aligned with the federal management approach for contaminated sites set out in the FCSAP [Decision-Making Framework](#) (DMF) (FCSAP, 2018). The DMF provides guidance on key decisions at each step of the federal process. In addition to supporting the efforts of custodians and their consultants, the intention of this guidance is to improve national consistency in the management of federal contaminated sites. Indeed, the principles for managing LNAPL contaminated sites should be the same regardless of the size and complexity of the sites or where they are located in Canada. Nevertheless, this guidance document is not a prescriptive manual, nor is it a comprehensive discussion of all the technical details that may be relevant to a specific site. In all instances, managers of federal contaminated sites are responsible for making sure that management of the sites complies with the requirements set out in federal acts and their regulations, which include, but are not limited to:

- The *Fisheries Act* (FA);
- The *Canadian Environmental Protection Act* (CEPA);
- The *Impact Assessment Act* (IAA);

- The *Species at Risk Act* (SARA); and
- The *Migratory Birds Convention Act* (MBCA).

This document will assist custodians and other users with remediation/risk management (R/RM) planning tools for LNAPL site management, including decisions on whether to use active or passive approaches, data requirements in support of decision making, and risk management considerations. These tools are mostly aligned with Steps 7 through 9 of the DMF, but also include the preliminary data requirements that may be fulfilled during DMF Steps 3 or 5 (N.B. in this document, the terms "DMF Step" and "Step" are used interchangeably and refer specifically to the steps of the DMF). One of the primary goals is to assist in the evaluation of potential exposure pathways associated with the presence of LNAPL in a comprehensive LNAPL conceptual site model (LCSM), much of which is covered in Section 3 – Develop or Update an LNAPL Conceptual Site Model (DMF Steps 3 and 5). The LCSM documents and displays the essential elements of an LNAPL site and is essential whether the site is managed using active remediation or passive approaches. Section 3 provides direction on the lines of evidence (LOE) required to build or update a technically correct and reliable LCSM. More complex sites may require more in-depth LCSMs. The LOE used to create the LCSM are important building blocks upon which key decisions are made during the development and implementation of the R/RM strategy and implementation during DMF Steps 7 and 8 respectively.

This LNAPL guidance document makes no assumption about the highest step that a custodian has completed in the DMF. It is not uncommon for existing R/RM approaches to be revisited during the site management process if new information becomes available. For example, the discovery of other LNAPL bodies or an increased understanding of their behaviour may necessitate updating the LCSM, additional data collection, and possibly reconsideration of the R/RM strategy.

For the implementation of active (e.g., multi-phase vacuum extraction) and passive (e.g., natural source zone depletion [NSZD] or monitored natural attenuation [MNA] controls) LNAPL site management approaches, a range of technical and non-technical factors (refer to Section 4) should be considered. Custodians may also have to take into account site-specific (and often non-technical) considerations when formulating an R/RM strategy and action plan (e.g., demonstrate some effort at LNAPL recovery to facilitate property divestiture). Ultimately, custodians are responsible for all site management decisions.

This LNAPL guidance document focuses primarily on the behaviour of, and potential remedial drivers associated with, the LNAPL body. It also deals with the mechanisms by which the mass of the LNAPL body is reduced (i.e., NSZD). It should be read in conjunction with the following FCSAP resources, which provide more detailed information on dissolved phase natural attenuation (NA) and potential exposures associated with dissolved phase and vapour plumes:

- *Guidance Document on Monitored Natural Attenuation for Soil and Groundwater Remediation, Version 1.0* (FCSAP, 2021a);
- *Federal Contaminated Site Risk Assessment in Canada, Part VII: Guidance for Soil Vapour Intrusion Assessment at Contaminated Sites* (Health Canada, 2010d); and

- *Executive Summary of the FCSAP Long-Term Monitoring Planning Guidance* (FCSAP, 2013a).

Figure 1 sets out an abbreviated version of the 10-step process detailed in the DMF (FCSAP, 2018) with a focus on the details required for the design and implementation of an R/RM action plan for LNAPL sites (DMF Steps 7 and 8). The sections of this document, listed below, follow the sequence of steps depicted in Figure 1.

- Section 1 Introduction;
- Section 2 Site Assessment, Categorization and Classification (DMF Steps 1–6);
- Section 3 Develop or Update an LNAPL Conceptual Site Model (DMF Steps 3 and 5);
- Section 4 Develop a Remediation/Risk Management Strategy (DMF Step 7);
- Section 5 Implement a Remediation/Risk Management Strategy (DMF Step 8);
- Section 6 Confirmatory Sampling (DMF Step 9);
- Section 7 Long Term Monitoring (DMF Step 10), as appropriate; and
- Section 8 Site Closure (considerations).

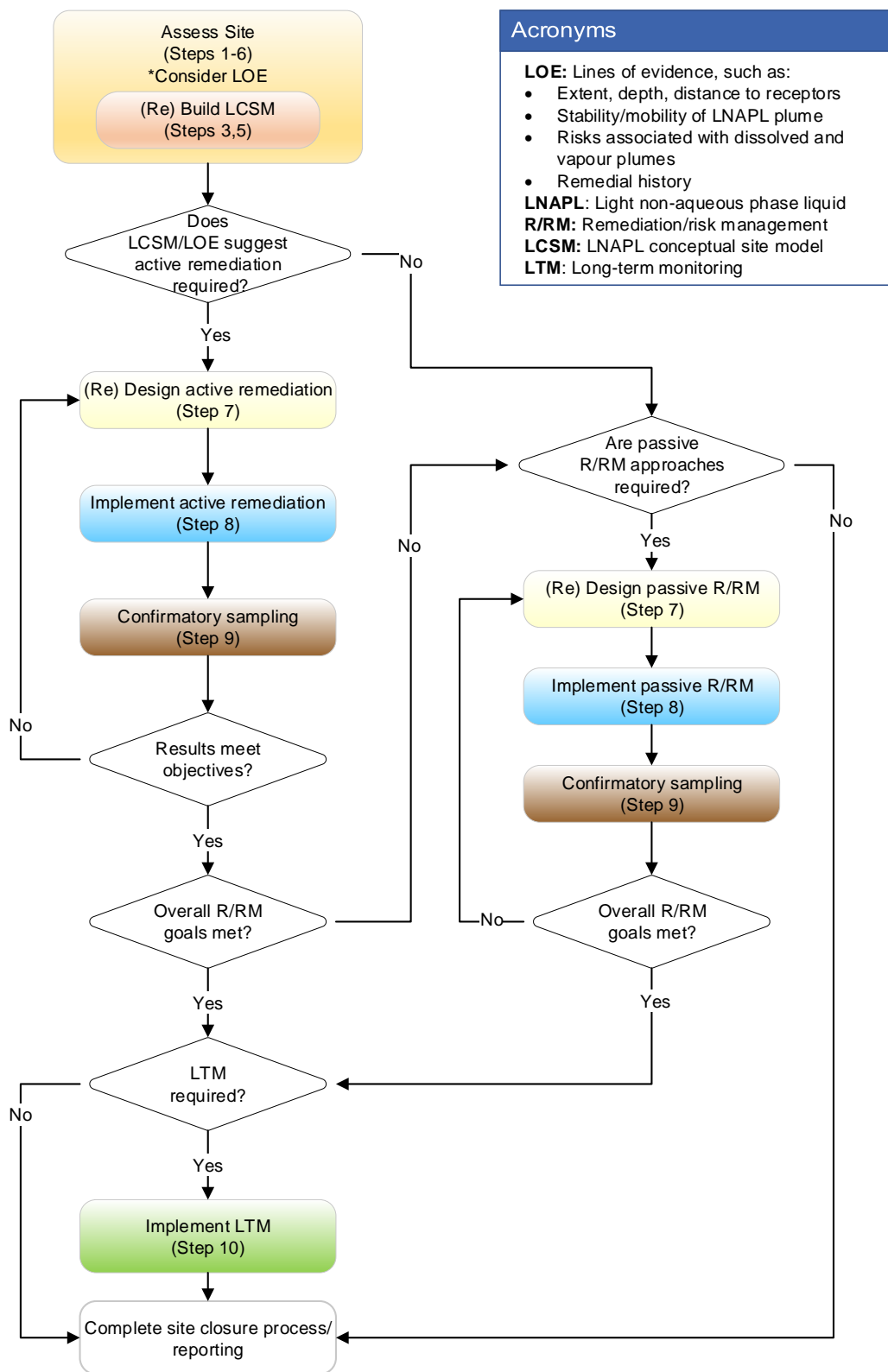


Figure 1 Steps for the design and implementation of an R/RM action plan for LNAPL sites

A brief overview of LNAPL behaviour basics is provided in Appendix A; it draws from available technical references including the following:

Evaluating LNAPL Remedial Technologies for Achieving Project Goals (ITRC, 2009a);

ASTM E2531-06, Standard Guide for Development of Conceptual Site Models and Remediation Strategies for Light Nonaqueous-Phase Liquids Released to the Subsurface (ASTM, 2006); and

A Practitioner's Guide for the Analysis, Management and Remediation of LNAPL (CRC CARE, 2015).

2 Site Assessment, Categorization and Classification (DMF Steps 1–6)

A preliminary understanding of site conditions and potential exposures based on existing information will aid in determining potential site investigation needs and provide an initial idea of possible remediation or risk management (R/RM) strategies or both. The potential data needs and exposure scenarios will be site-specific and highly variable, and largely dependent on such factors as the physical properties of the LNAPL and the subsurface, the length of time the LNAPL has been in the subsurface, and proximity to receptors. The various activities in this section are addressed in Steps 1 to 6 of the DMF.

Table 1 provides a generalized guide to LNAPL site categorization that can be used for initial planning purposes (for sites without significant investigation and/or remedial history) and can be revised as needed. This table provides a general guide only and professional judgment will be needed at every stage to confirm that potential data needs and exposure scenarios are fully understood. For this reason, a conservative approach to site categorization should be taken in assuming the highest risk¹ indicated by any of the categories until a sufficient body of evidence exists to indicate otherwise with a high degree of confidence. For example, it would be prudent to initially assume site risk is high in the presence of a potentially highly volatile LNAPL type or where receptors may reasonably be threatened even if the other considerations outlined in

¹ Risk refers both to the potential that LNAPL may be migrating/unstable and the potential that unacceptable exposures may exist due to the presence of LNAPL and/or any related dissolved or vapour phase impacts.

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Table 1 indicate a scenario with less risk. Site categorization is also supported by the National Contaminated Sites Classification System (NCSCS) implemented at Step 6 following detailed site assessment work.

Table 1 General Guide to LNAPL Site Categorization

Considerations	Tier I (low risk)	Tier II (medium risk)	Tier III (high risk)
LNAPL Type	Low volatility LNAPL (e.g., heavier oils, No. 6 fuel oil, Bunker C)	More volatile LNAPL (e.g., diesel fuel)	High volatility LNAPL (e.g., gasoline)
Extent of Impacts	Impacts on-site only	Impacts in vicinity of site boundaries	Impacts extend off-site
Subsurface Complexity	Simple stratigraphy	Significant heterogeneity	Highly complex subsurface (stratigraphy and infrastructure)
Proximity to Receptors	No receptors affected	Sensitive receptors may be affected in the future	Sensitive receptors are currently or may be affected in the future

Notes: This table provides a general guide only and professional judgment will be needed at every stage to ensure site-specific potential data needs and exposure scenarios are fully understood.

The Fisheries Act (more specifically, relevant sections related to habitat protection, pollution prevention provisions, and notification of deposits) is uniquely relevant to the proper R/RM of LNAPL sites based on the risk of transport of the contaminants to a surface water body through groundwater discharge. As the site management strategy undergoes an evaluation in accordance with section 82 of the *Impact Assessment Act*, other federal acts and regulations may also be considered, such as the *Migratory Birds Convention Act* and the *Species at Risk Act*. In addition, the following documents could be broadly applicable to LNAPL sites:

- *Federal Approach to Contaminated Sites* (CSMWG, 1999);
- *Federal Contaminated Sites Action Plan (FCSAP) Decision-Making Framework, Version 3.1* (FCSAP, 2018);
- *Framework for Addressing and Managing Aquatic Contaminated Sites under the Federal Contaminated Sites Action Plan (FCSAP), Version 2.1, 2021* (FCSAP, 2021b);
- *Federal Contaminated Site Risk Assessment in Canada* (Health Canada, 2010a, 2010b, 2010c, 2010d, 2021a and 2021b);
- *Ecological Risk Assessment Guidance* and associated modules (FCSAP, 2012);
- *Ecological Risk Assessment Guidance Document* (CCME, 2020);
- *Guidance Manual for Environmental Site Characterization in Support of Environmental and Human Health Risk Assessment, Volume 1 Guidance Manual* (CCME, 2016);
- *A Protocol for the Derivation of Soil Vapour Quality Guidelines for Protection of Human Exposures via Inhalation of Vapours* (CCME, 2014);
- *Guidance Document on Monitored Natural Attenuation for Soil and Groundwater Remediation. Version 1.0* (FCSAP, 2021a);
- *FCSAP Long-Term Monitoring Planning Guidance* (FCSAP, 2013b);
- *FCSAP Site Closure Report Template and Guidance, Version 2.0* (FCSAP, 2022a, b); and

- *Supplemental Guidance on Implementation of Canada-Wide Standard for Petroleum Hydrocarbons in Soil at Federal Contaminated Sites (FCSAP, 2022c).*

Additionally, multiple provincial guidance and regulations may apply in certain situations such as where contaminants have migrated (or potentially migrated) off-site, or when property divestiture is a site goal. Provincial jurisdictions may also have authority over the beneficial use of groundwater resources. Indigenous groups, community groups, and municipalities may also have a role to play in contaminated site management. Any of these considerations have the potential to shape the site assessment process and the ultimate R/RM strategy.

3 Develop or Update an LNAPL Conceptual Site Model (DMF Steps 3 and 5)

The LNAPL conceptual site model (LCSM) forms the basis for effective decision-making in the management of sites contaminated by LNAPLs, and has been described by various organizations such as ASTM (2006), ITRC (2009a) as well as CRC CARE (2015) more recently. The extent to which the LCSM needs to be developed will depend on the R/RM strategy goals, the complexity of the site and the magnitude of potential concerns. LNAPL sites with minimal migration potential that pose little threat to receptors may only require a relatively simple LCSM to adequately address site management concerns. In contrast, more complex LNAPL impacted sites may require much larger and more sophisticated data sets collected over longer time periods, in order to develop a higher level of confidence in the LCSM and any consequent site management strategy.

Effective management of an LNAPL site may involve a step-wise and iterative approach, which may need to be adjusted any time new information is collected that challenges previous conclusions or assumptions (e.g., R/RM action plan performance, land use changes, etc.). Depending on the site, the LCSM can continue to be developed and updated until it is deemed to contain all of the relevant information required to design a robust and implementable R/RM strategy and action plan. This iterative updating process is an inherent part of the design of the R/RM strategy in Step 7.

An LCSM is usually first developed in Step 3 (Initial Testing Program). It may be updated or further developed in Step 5, if some of the information needed to develop an appropriate R/RM strategy is missing. The LCSM may have to be updated if the R/RM strategy is called into question (for example, if the original strategy is deemed to be ineffective during DMF Step 8—Implement R/RM strategy, or during performance monitoring in the case of the LNAPL and associated plume management). The development of an LCSM for an LNAPL site in Step 3 or Step 5 involves looking at various data sets. The data sets may continue to expand in Step 7 as the R/RM strategy design is established, and as additional site information is collected from reports, such as site-specific ecological and human health risk assessments.

Note: This guidance document focuses on LNAPL in groundwater; however, sites with LNAPL may contain other contaminants which present their own potential risks. If other contaminants are present in soils and/or groundwater, a broader CSM including these other contaminants would be required.

A checklist is provided in

Table 2. It is organized around the gathering of LOE/data pertaining to the core elements of an LCSM. The checklist also facilitates the compilation of data/LOE that may already be available for a given LNAPL site, thus providing a tool for the quick assessment of potential data gaps in the LCSM. Table 3 provides more detail on evaluation methods and metrics associated with fundamental LNAPL site characterization and management considerations. In addition, the tools listed below can assist in the LCSM development process and provide a tiered approach that is consistent with the categorization of sites presented in

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Table 1:

- Table C-1 in *Evaluating LNAPL Remedial Technologies for Achieving Project Goals* (ITRC, 2009a);

Table 4.1 in *ASTM E2531-06, Standard Guide for Development of Conceptual Site Models and Remediation Strategies for Light Nonaqueous-Phase Liquids Released to the Subsurface* (ASTM, 2006).

Guidance/tools from other jurisdictions remain useful even where regulatory regimes differ since LNAPL science is not location- or jurisdiction-specific.

Table 2 LNAPL Site Management Checklist

	Question	Answer / Comment	
1	Site Goals and Regulatory Framework		
1.A	Are site goals well defined?	<input type="radio"/> Yes	
		<input type="radio"/> No	Engage stakeholders and establish goals.
1.B	Are regulatory requirements well understood?	<input type="radio"/> Yes	
		<input type="radio"/> No	Determine appropriate requirements/criteria.
2	LNAPL Release History ² and Properties		
2.A	Is the source of the LNAPL release known? (indicate if high volume and/or pressure release)	<input type="radio"/> Yes	
		<input type="radio"/> No	Determine whether the federal government is responsible. Consider a more comprehensive historical review (expanded Phase 1 ESA).
2.B	Is there any possibility of an ongoing release?	<input type="radio"/> Yes	Take immediate steps to halt release.
		<input type="radio"/> No	
2.C	Is there an imminent threat posed by the release that warrants immediate mitigation or emergency response?	<input type="radio"/> Yes	Activate emergency response or implement mitigation measures.
		<input type="radio"/> No	
2.D	Is the LNAPL type/types known?	<input type="radio"/> Yes	
		<input type="radio"/> No	See Table 3 for LCSM development options.
2.E	Is the date of the LNAPL release/approximate age of the LNAPL known?	<input type="radio"/> Yes	
		<input type="radio"/> No	See Table 3 for LCSM development options.
2.F	Are the density/specific gravity and viscosity of the LNAPL known?	<input type="radio"/> Yes	
		<input type="radio"/> No	See Table 3 for LCSM development options.

² Eligibility for FCSAP remediation funding may be influenced by release history, specifically whether contamination resulted from activities prior to or after April 1, 1998. The *FCSAP Directive on Phase IV Site and Costs Eligibility – Version 1.0* (FCSAP, 2021c) includes additional information on the basic eligibility criteria and relevant exceptions.

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	Question	Answer / Comment	
3	LNAPL Body		
3.A	Has the areal extent and vertical distribution of the LNAPL body been defined?	<input type="radio"/> Yes	
		<input type="radio"/> No	
		Indicate techniques used: <input type="radio"/> Visual/olfactory soil screening <input type="radio"/> Photo ionization detector (PID) soil screening <input type="radio"/> Hydrophobic dye soil screening <input type="radio"/> UV light soil screening <input type="radio"/> Traditional soil sampling and laboratory analysis <input type="radio"/> Soil core photography/petrophysical testing <input type="radio"/> Monitoring well data (gauging, sampling) <input type="radio"/> Electrical resistivity <input type="radio"/> Laser-induced fluorescence (LIF) * See Table 3 for more on LCSM development options.	
3.B	Is the LNAPL body stable in overall extent?	<input type="radio"/> Yes	
		<input type="radio"/> No	
		Lines of evidence: <input type="radio"/> Age of LNAPL <input type="radio"/> Sentry well monitoring <input type="radio"/> Dissolved phase trends <input type="radio"/> One or more LNAPL mobility lines of evidence along LNAPL body periphery <input type="radio"/> Natural attenuation indicators <input type="radio"/> LNAPL critical head estimates at LNAPL periphery * See Table 3 for more on LCSM development options.	
3.C		<input type="radio"/> Yes	

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	Question	Answer / Comment	
	Do areas with potentially mobile LNAPL exist within the LNAPL body?	<input type="radio"/> No	Indicate available lines of evidence: <input type="radio"/> Age of LNAPL <input type="radio"/> LNAPL saturation and/or residual saturation determinations (soil core petrophysical testing) <input type="radio"/> LNAPL transmissivity estimates <input type="radio"/> LNAPL recovery system performance <input type="radio"/> LNAPL saturation and/or residual saturation estimates (total petroleum hydrocarbons [TPH] conversions, analytical modelling) * See Table 3 for more on LCSM development options.
3.D	Has natural attenuation of the LNAPL body been assessed?	<input type="radio"/> Yes <input type="radio"/> No	Indicate available lines of evidence: <input type="radio"/> Soil data (petroleum degrading bacteria) <input type="radio"/> Soil gas data (soil gas concentration profiles, carbon dioxide, methane) <input type="radio"/> Dissolved phase natural attenuation indicators * See Table 3 for more on LCSM development options.
4	Dissolved and Vapour Phases		
4.A	Has any related dissolved phase plume been delineated?	<input type="radio"/> Yes <input type="radio"/> No	Indicate available lines of evidence: <input type="radio"/> Monitoring well sampling <input type="radio"/> Membrane interface probe (MIP) * See Table 3 for more on LCSM development options.
4.B	Has the stability of the dissolved phase plume been evaluated?	<input type="radio"/> Yes <input type="radio"/> No	

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	Question	Answer / Comment	
		Indicate available lines of evidence: <ul style="list-style-type: none"> <input type="radio"/> Trend analysis of groundwater monitoring data over time <input type="radio"/> Spatial distribution of groundwater monitoring data <input type="radio"/> Geochemical parameters (dissolved O₂, NO₃⁻, SO₄²⁻, ferrous iron (Fe²⁺), manganese (Mn²⁺), CO₂, and CH₄) * See Table 3 for more on LCSM development options.	
4.C	Has natural attenuation of the dissolved phase been assessed?	<input type="radio"/> Yes	
		<input type="radio"/> No	
		Indicate available lines of evidence: <ul style="list-style-type: none"> <input type="radio"/> Soil data (e.g., petroleum-degrading bacteria) <input type="radio"/> Trend analysis of groundwater monitoring data over time <input type="radio"/> Spatial distribution of groundwater monitoring data with respect to LNAPL body extent <input type="radio"/> Dissolved phase natural attenuation indicators (spatial/temporal reduction in constituent concentrations, terminal electron acceptors, geochemical parameters) * See Table 3 for more on LCSM development options.	
4.D	Has the potential for vapour phase impacts been evaluated (including methane)?	<input type="radio"/> Yes	
		<input type="radio"/> No	See Table 3 for LCSM development options.
5	Potential Exposures		
5.A	Identify potential receptors and detail any relevant land use information (e.g., potable water sources, age groups, site uses/activities)	<input type="radio"/> Human health:	
		<input type="radio"/> Ecological:	
		Indicate available lines of evidence: <ul style="list-style-type: none"> <input type="radio"/> Exposure and effects determination 	
5.B	Have any risk-based criteria been exceeded?	<input type="radio"/> Yes	Confirm relevance of pathways.
		<input type="radio"/> No	
5.C		<input type="radio"/> Yes	

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	Question	Answer / Comment	
	Are any of the respective pathways complete or potentially complete in the future?	<input type="radio"/> No	

Table 3 Potential LNAPL Site Characterization and Management Considerations

	Potential Parameters/Considerations	Potential Evaluation Methods	Discussion
LNAPL Body Delineation/Characterization	<ol style="list-style-type: none"> 1. LNAPL body geometry: horizontal/vertical extents, position relative to water table 2. Relative intensity of impacts (hot spots) 	<ol style="list-style-type: none"> 1. Installation of wells/borings, laser-induced fluorescence (LIF), resistivity 2. Soil sampling (TPH, LNAPL saturations), groundwater sampling, LIF, resistivity 	
Geology/Hydrogeology	<ol style="list-style-type: none"> 1. General Stratigraphy 2. Impacted Soil Types 3. Hydraulic Gradients 4. LNAPL Gradient 5. Hydraulic Conductivity 	<ol style="list-style-type: none"> 1,2. Field screening of soil borings, laboratory grain size analysis 3,4. Well gauging 5. Slug tests, pumping tests, laboratory testing 	
LNAPL Physical/Chemical Properties	<ol style="list-style-type: none"> 1. LNAPL viscosity 2. LNAPL relative density 3. LNAPL type/age 4. LNAPL chemical composition 	<ol style="list-style-type: none"> 1,2. Laboratory physical property testing 3. Laboratory forensic testing/fingerprinting 4. Laboratory chemical analytical testing 	

	Potential Parameters/Considerations	Potential Evaluation Methods	Discussion
Dissolved and Vapour Phase Impacts	<ol style="list-style-type: none"> 1. Groundwater concentrations of LNAPL constituents 2. Soil gas concentrations of LNAPL constituents and methane 3. Soil gas explosivity 	<ol style="list-style-type: none"> 1. Groundwater sampling/laboratory testing 2. Soil gas sampling/laboratory testing 3. Field screening of well headspace and/or soil gas samples using handheld lower explosive limit (LEL) meter 	<ol style="list-style-type: none"> 1. Focus on wells without LNAPL. The potential benefit of sampling groundwater under LNAPL should be weighed against the risk of obtaining LNAPL contaminated samples (LNAPL presence may not be readily apparent in a groundwater sample). 2. The need for soil gas sampling and the potential parameter list can be screened based on the volatility of the LNAPL and/or specific constituents (e.g., test for constituents with Henry's law constant $> 1\text{e}^{-5}$ atm-m³/mol and vapour pressure > 0.05 Torr) and/or separation distances between potential vapour sources and receptors.
LNAPL Mobility	<ol style="list-style-type: none"> 1. Age of LNAPL body 2. Soil TPH concentrations 3. LNAPL saturations and residual saturations 4. LNAPL transmissivity 5. Recovery system performance 6. Dissolved phase trends 	<ol style="list-style-type: none"> 1. Comparison against appropriate C_{res} value or conversion of TPH concentrations to saturations and comparison to typical residual saturation values (see ASTM E2531-06) 2/3. Soil core sampling and laboratory petrophysical testing (e.g., pore fluid saturation testing, water drive testing) 	<ol style="list-style-type: none"> 1. Older LNAPL is less likely to be mobile 2,3. LNAPL saturations exceeding residual levels provide a line of evidence of LNAPL mobility 4. LNAPL transmissivity > 0.1 m²/day provides a line of evidence of LNAPL mobility (ASTM, 2013c)

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	Potential Parameters/Considerations	Potential Evaluation Methods	Discussion
	NOTE: LNAPL mobility determination typically involves a weight-of-evidence approach where multiple lines of evidence are considered (due to the complexity of multi-phase flow in the subsurface and the technical limitations of the potential evaluation methods).	4. Field LNAPL baildown testing, pumping tests, field dye tracer testing (see ASTM E2856-11) 5. LNAPL recovery system cumulative recovery/recovery rate plots, decline curve analysis 6. Groundwater concentration trends of LNAPL parameters	5. Poor recovery system performance may provide strong evidence that remaining LNAPL is at residual levels/immobile (if the system has been effectively implemented and operated) 6. Dissolved phase trends provide an indication of the state of the LNAPL body (e.g., stable dissolved phase trends = stable LNAPL)
LNAPL Stability/Migration	1. LNAPL body expansion and migration NOTE: LNAPL migration differs from the LNAPL mobility consideration above in that it only considers the potential for LNAPL mobility around the periphery of an LNAPL body (i.e., its ability to migrate or expand into areas that are not already impacted).	1. One or more LNAPL mobility lines of evidence indicates potential mobility along LNAPL body perimeter 2. LNAPL observations in sentry wells installed in clean soil 3. Estimate critical LNAPL head (pore entry displacement pressure) at LNAPL periphery	1. Critical LNAPL head (pore entry displacement pressure) exceeded at LNAPL periphery represents potential for LNAPL body expansion/migration
Natural Attenuation	1. Groundwater concentration temporal trends (LNAPL constituents) 2. Groundwater concentration spatial distribution (LNAPL constituents) 3. Groundwater terminal electron acceptors, geochemical parameters 4. Soil gas analysis, profiles 5. Degree of LNAPL degradation	1. Statistical trend analysis to confirm stable or declining trends 2. Evaluate concentration gradient from source area 3. Soil gas sampling for oxygen, carbon dioxide, methane at different points laterally and vertically	1. Location-specific stable or declining trends over time provide evidence of natural attenuation 2. Decreasing concentrations with distance from source provide evidence of natural attenuation

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	Potential Parameters/Considerations	Potential Evaluation Methods	Discussion
		4. Near-surface carbon dioxide trap sampling with stable isotope analysis to confirm carbon origin, carbon dioxide flux chamber measurements 5. LNAPL forensic testing	3. Petrogenic carbon dioxide measurements can quantify natural losses in terms of volume of LNAPL degraded per unit area per unit time
Potential Remedial Drivers	1. Unacceptable human health or ecological exposures (compositional concerns) 2. LNAPL mobility/migration (saturation concerns) 3. Non-technical factors such as aesthetic (e.g., visual, olfactory), regulatory or other considerations (e.g., property transaction condition)	1. Will vary from comparison of existing site data to generic criteria, to quantitative human health and ecological risk assessment (depending on complexity of site and magnitude of potential risks) 2. See LNAPL mobility and LNAPL migration lines of evidence and approaches above 3. Review applicable non-technical factors to establish site R/RM objectives	

Notes:

- Table C-1 in *Evaluating LNAPL Remedial Technologies for Achieving Project Goals* (ITRC, 2009a) provides more detail on LCSM components and presents a three-tiered approach to LCSM development based on increasing levels of site complexity.
- Table 4.1 in *ASTM E2531-6* (ASTM, 2006) provides detailed information on LNAPL site data collection methods and their applicability.

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A brief discussion of factors to consider when evaluating the various elements of the LCSM, as well as details on data gathering are provided in the remainder of this section. The minimum data requirements that may be associated with each type of LNAPL site (low risk [Tier I], medium risk [Tier II], and high risk [Tier III], as outlined in

Table 1) are presented in Table 4. The selection and weighting of the LOE will be site-specific, and ultimately the responsibility of custodians.

The evaluation of each of the following LOE is a requirement to determine whether the R/RM strategy being considered in Step 7 anticipates active or passive solutions (or some combination thereof).

Table 4 Potential LNAPL Site Characterization Data Requirements

Item	Tier I (low risk)	Tier II (medium risk)	Tier III (high risk)
Delineation	Delineation using typical soil sampling, groundwater sampling and/or well gauging techniques	More sophisticated means may be required, with more emphasis on dissolved and vapour phases	More sophisticated means likely to be required, with detailed evaluation of dissolved and vapour phases
Risk Assessment	Comparison to generic criteria, basic pathway analysis	Quantitative site-specific evaluation of human health and ecological risks with more detailed evaluation of pathways may be required	Quantitative site-specific evaluation of human health and ecological risks with more detailed evaluation of pathways likely to be required
Mobility Evaluation	Estimation of LNAPL transmissivity	May require multiple lines of evidence at a representative number of locations	Will require more lines of evidence developed with greater data density (extensive areal coverage)
Evaluation/ Monitoring Period	At least 2 years of monitoring to confirm stability of contaminant concentration, plume extent, etc.	LCSM may require data spanning a 3-5 year period	LCSM may require 5-10 years of data

Notes:

- Error! Not a valid result for table.** and Table 3 provide more detail on potential evaluation techniques and metrics.
- LCSM development/site monitoring timelines are provided for example purposes only; professional judgment will play an important role in determining data needs and corresponding monitoring periods on a site-specific basis.

3.1 LNAPL Release/Remedial History

The LNAPL release and remedial history (if active remediation has been undertaken) can provide crucial information about the likely state of the LNAPL body and associated dissolved and vapour phase plumes. The following points can be useful in gauging site complexity, potential for LNAPL migration or unacceptable exposures, and potential R/RM strategies:

Newer releases are more likely to have a larger mobile fraction and therefore present a greater risk of LNAPL migration or expansion into unimpacted areas. Conversely, older LNAPL bodies are more likely to be stable with less migration potential. In addition, in older LNAPL bodies, the mobile fraction is expected to represent a small portion of the overall LNAPL body.

If an LNAPL body has been stable for some time (i.e., LNAPL is no longer migrating/expanding into unimpacted areas), it is also likely that the associated dissolved and/or vapour phase plume extent and concentration have reached an equilibrium and are stable. Likewise, the demonstration of a stable dissolved phase plume extent (i.e., no evidence of expansion of the plume(s) or increasing concentration trends) is typically interpreted as strong evidence that the same is true of the LNAPL body source (ITRC, 2018).

Large volume and/or high-pressure releases (e.g., pipelines) can be expected to result in higher LNAPL saturations, higher mobility potential and more extensive migration/expansion (vertically and laterally). LNAPL remedial efforts that remove/dissipate the LNAPL head (excavation, extraction) can have a significant stabilizing effect on an LNAPL body. However, this is generally more applicable to newer releases where greater migration potential exists as opposed to older LNAPL bodies which may already have stabilized.

Hydraulic or more aggressive LNAPL recovery efforts that have been effectively implemented and operated, but are unable to recover LNAPL, can provide useful evidence of minimal mobility and migration potential.

These points are broadly applicable to LNAPL sites. However, it should be noted that with increased site complexity, less certainty is associated with the initial assumptions, and there is a greater need to develop multiple site specific LOE.

3.2 LNAPL Body Stability

The potential data needs listed in

Table 2 for the LNAPL body are focused on defining the vertical and areal extent of the LNAPL impacts, as well as evaluating the mobility and stability of the LNAPL. Defining the extent of an LNAPL body, particularly an older one, can be deceptively difficult and involves more than simply gauging and/or sampling monitoring wells for the presence of LNAPL. With any LNAPL body, what is observed in wells will only reflect the portion of the LNAPL body that exists above residual saturation levels at the water table (i.e., the potentially mobile/recoverable fraction). With older LNAPL bodies, this will most often represent a relatively small fraction of the overall LNAPL body, and a significant portion of the LNAPL can be expected to be found at low saturations and/or below the water table (see Appendix A for more details). As a result, additional methods may need to be employed, including those focusing on direct sensing of LNAPL in the subsurface such as laser-induced fluorescence (LIF)³, different types of soil sampling, and indirect methods such as screening groundwater constituent concentrations against the appropriate petroleum constituent effective solubility values.

LNAPL sites, especially the legacy sites of concern to federal custodians, often involve LNAPL that has been in the ground for many years and may have already stabilized and therefore may be unable to significantly migrate/expand in the future, unless new releases or other activities produce a sufficient LNAPL head to drive migration. LNAPL stability assessment will assist in verifying if these conditions exist.

³ The use of LIF technology is limited to certain fuel types and certain geological conditions.

Table 2 and Table 3 provide guidance on potential data needs and evaluation methods for the LNAPL body. Lahvis et al. (2013) provide useful screening criteria for detecting the presence of residual LNAPL, based on the types of data that already exist at many LNAPL sites. As previously noted, the sophistication and quantity of data required will increase with increasing site complexity and risk potential. This data gathering should be planned as part of the detailed testing program (Step 5), or subsequently when the need for additional data is identified in the gap analysis performed as part of the design process in Step 7.

3.3 Dissolved and Vapour Phase Plumes

This section discusses the key elements with respect to dissolved and vapour phases, which include delineation, evaluating potential exposures and assessing stability.

3.3.1 Dissolved Phase Impacts

Dissolved phase impacts are typically assessed using groundwater samples from monitoring wells and analyzing the petroleum product constituents based on LNAPL type and composition. It is important to properly delineate the dissolved phase impacts in order to determine the probability that the material will reach surface waters. Detailed information on the chemical composition of different LNAPL types can be found in *Volume 2: Composition of petroleum mixtures* (Potter and Simmons, 1998), which can aid in the development of analyte lists. This information can also be useful for assessing whether a given groundwater constituent detected at a site is likely to be related to the LNAPL. More complex sites may employ more sophisticated means of groundwater assessment/delineation (e.g., membrane interface probe, direct push in-situ groundwater sampling systems) or incorporate multi-level monitoring wells and/or monitoring wells with discrete sampling intervals. It is also crucial to understand groundwater flow patterns and identify preferential pathways in order to evaluate dissolved phase contaminant transport and potential exposures. More sophisticated techniques using hydraulic profile logging tools may be helpful in this regard.

3.3.2 Vapour Phase Impacts

The main concerns with vapour phase impacts are direct volatilization of LNAPL constituents or methane generation from anaerobic degradation (methanogenesis) which may lead to chronic exposure of receptors, or more acute issues associated with accumulation in structures (acute toxicity, flammability, explosion potential). Table 3 provides generalized screening values for constituent vapour pressure and Henry's Law constants that can aid in assessing the likelihood that a given LNAPL may result in vapour issues and/or in developing a list of potential soil gas analytes. Screening guidelines for potential LNAPL vapour intrusion issues and actual assessment of impacts are discussed in detail in many documents including:

Federal Contaminated Site Risk Assessment in Canada, Part VII: Guidance for Soil Vapour Intrusion Assessment at Contaminated Sites (Health Canada, 2010d);

A Protocol for the Derivation of Soil Vapour Quality Guidelines for Protection of Human Exposures via Inhalation of Vapours (CCME, 2014);

Guidance Manual for Environmental Site Characterization in Support of Environmental and Human Health Risk Assessment, Volumes 1-3 (CCME, 2016);

Technical Guide for Addressing Petroleum Vapor Intrusion at Leaking Underground Storage Tank Sites (US EPA, 2015);

Petroleum Vapor Intrusion: Fundamentals of Screening, Investigation, and Management (ITRC, 2014); and

Vapour Intrusion Screening at Petroleum UST Sites (Lahvis et al., 2013).

In the context of Canadian federal contaminated sites where the assessment of vapour intrusion is aimed at determining the potential risk to human health, it is necessary to use the Health Canada guidance document, *Federal Contaminated Site Risk Assessment in Canada, Part VII: Guidance for Soil Vapour Intrusion Assessment at Contaminated Sites* (Health Canada, 2010d).

3.3.3 Assessing Exposure Risk Associated with Dissolved and Vapour Phase Plumes

An important aspect of the LCSM development involves documenting exposure pathways that are expected to be active in various media and that reflect possible risk from the LNAPL body, dissolved phase plume and vapour phase plume. A thorough evaluation of applicable exposure pathways with respect to current and intended future land use is crucial to the effective implementation of an R/RM strategy. There are many sources of guidance on this topic that may be useful in developing this component of the LCSM, including the references already cited herein (e.g., CCME, 2016; Health Canada, 2010b and 2010d; ASTM, 2006; ITRC, 2009a; CRC CARE, 2015).

There has been significant change in the recommendations set out in the most recent petroleum vapour intrusion guidance from US EPA (2015) and ITRC (2014), particularly with respect to separation distances recommended for potential LNAPL and dissolved vapour sources. The historical norm has been to establish separation distances based on vapour transport modelling without accounting for biodegradation, which is notable given that petroleum vapours are readily biodegradable. The recommendations in the more recent guidance (US EPA, 2015; ITRC, 2014), which are based on the analysis of soil gas sampling data from hundreds of sites, translate into a reduction in the required separation distances relative to the historically used distances.

3.3.4 Assessing Stability of Dissolved Phase Plumes

Assessing whether a dissolved phase plume has reached a steady state and stabilized, both in terms of its extent, and concentrations of PHC constituents, is important for determining whether receptors may be impacted (see also Section 3.3.3) and evaluating the stability of the related LNAPL body (see also Section 3.2). The commonly accepted practice has been to conduct quarterly sampling over a two-year period (i.e., eight monitoring events) to assess the stability of dissolved phase plumes. More data and longer monitoring periods may be required at the more complex sites or where initial monitoring results do not indicate statistically significant stable or declining trends.

Statistical test methods are discussed in detail in US EPA's unified guidance, *Statistical Analysis of Groundwater Monitoring Data at RCRA Facilities* (US EPA, 2009). A comprehensive statistical software

package from US EPA, *Statistical Software ProUCL 5.0.00 for Environmental Applications for Data Sets with and without Nondetect Observations* (US EPA, 2013; see <https://www.epa.gov/land-research/proucl-software/>) can be used to perform the various statistical tests involved in trend analysis for the determination of stability. Most MNA guidance documents include a detailed discussion of statistical techniques. A few examples include:

Monitored Natural Attenuation Technical Guidance, Site Remediation Program (New Jersey Department of Environmental Protection, 2012);

Contaminated Sites Statistical Applications Guidance Document No. 12-4 – Distribution Models (British Columbia Ministry of Environment, 2001); and

Statistical Analysis of Groundwater Monitoring Data at RCRA Facilities, Unified Guidance. EPA 530-R-09-007. (US EPA, 2009).

The historical approach of analyzing groundwater data trends on a well-by-well basis may produce confounding results at many sites, where plume scale temporal changes in the location/extent of the dissolved or vapour phase petroleum mass is not adequately captured. Alternative approaches based on assessing the change in size or location of the centres of mass of dissolved phase constituents over time, such as the method proposed by Ricker (2008), may prove useful at many sites, especially those with more complex LNAPL impacts or settings.

3.4 Understanding the LNAPL Natural Source Zone Depletion and Natural Attenuation Potential

Petroleum hydrocarbons are readily biodegradable and some level of natural biodegradation will be occurring at most sites with LNAPL. LCSM development may therefore involve the evaluation of NSZD/NA mechanisms that reduce the mass of LNAPL in the subsurface. Dissolution and volatilization of contaminants from the LNAPL body are the primary mechanisms by which LNAPL bodies are naturally depleted and they represent the primary pathways that can lead to unacceptable risk of exposure over time (ITRC, 2009b).

If NSZD/NA is considered a potential R/RM approach for an LNAPL site, the custodian will need to gather supporting data for the NA early on to determine if this approach is feasible. Confirming that NSZD/NA processes are active and/or effective is a key part of risk based LNAPL management; it can provide valuable information since natural attenuation processes help to stabilize and limit the extent of LNAPL bodies and related dissolved and vapour phase plumes. Readers should refer to the *Guidance Document on Monitored Natural Attenuation for Soil and Groundwater Remediation, Version 1.0* (FCSAP, 2021a) for additional guidance on MNA.

Developing NSZD/NA rate estimates can also be useful when evaluating R/RM options that will allow passive approaches such as NSZD/MNA to be compared against expected outcomes from active remedial solutions (i.e., to realistically weigh the environmental risks/financial costs and benefits of the options being considered).

The assessment of natural losses from an LNAPL body is an especially important part of the overall assessment of NSZD/NA since the vast majority of LNAPL biodegradation will likely take place in the unsaturated zone. The dissolved phase degradation that may be quantifiable by traditional NA monitoring constitutes a very small fraction of the overall natural attenuation (ITRC, 2009b; Molins et al., 2010). Assessing the NSZD of LNAPL bodies in the vadose zone based on soil gas carbon dioxide (CO₂) levels is becoming a more widely used technique that allows direct quantification of natural biodegradation of LNAPL in terms of volume degraded per unit area over time. This can be accomplished via soil gas sampling or through the quantification of near-surface CO₂ flux/rates via passive traps or flux chamber (since CO₂ is the final by-product of petroleum hydrocarbon degradation). The different NSZD/NA measurement and estimation techniques are summarized below:

Gradient method: Involves the use of nested soil gas probes to measure petroleum hydrocarbon soil gas constituent concentrations at different depths to estimate attenuation rates (ITRC, 2009b).

Passive traps: Solid state sorbent media filled traps installed near the surface are used to passively sample for CO₂ over a period of time typically on the order of 2 to 4 weeks. Subsequent laboratory analysis allows for the quantification of NSZD rates. The trap method allows the estimated rates to be corrected for background CO₂ (naturally occurring non petroleum related) via stable isotope analysis (McCoy et al., 2014).

Flux chamber: A flux chamber (e.g., LI COR LI 8100) allows for the rapid direct measurement of CO₂ rates with background corrections accomplished via sampling at appropriate background/unimpacted locations, or through the use of traps (Sihota and Mayer, 2012).

Dissolved phase NA is a more established concept and many guidance documents (e.g., FCSAP, 2021a) deal with the different facets (i.e., NA indicators, LOE, monitoring plan development guidance) of NA evaluations. The evaluation of the dissolved phase portion of NA for LCSM development takes place during Step 5 and/or during adaptive management in Step 7. A consistent approach with respect to the following fundamental LOE for NA should be applied:

Primary LOE (direct): Decline in groundwater concentrations over time at specific groundwater wells and decline in concentrations with distance from source (reflects combination of dispersion, advection, dilution, and biodegradation);

Secondary LOE (indirect): Detection of and/or observed changes in terminal electron acceptors and geochemical parameters throughout the impacted zone (focus on biodegradation).

4 Develop a Remediation/Risk Management Strategy (DMF Step 7)

The development of an R/RM strategy starts with the selection of the R/RM objectives utilizing either generic guidelines (CCME Canada-Wide Standards for Petroleum Hydrocarbons [CWS for PHC]), referred to as Tier 1, or the development of site-specific target levels (SSTLs) normally developed through a risk assessment process (Tier 3). The CWS for PHC is grounded in the science of risk assessment and can be applied at any of three “Tiers”: Tier 1 – generic numerical levels; Tier 2 – adjustments to Tier 1 levels

based on site-specific information; Tier 3 – site-specific risk assessment. The same high level of environmental and human health protection is required at all three tiers (CCME, 2008).

R/RM objectives should be established as early as possible in order to engage stakeholders and to facilitate establishing both the scope of further investigative work on the site, and potential options for R/RM – which will rely heavily on the results of the risk assessment. R/RM objectives will typically be tied to specific media, land use, receptors, stakeholder considerations, and their associated generic or site-specific guidelines. The selected R/RM objectives will in turn lead to the consideration of specific technical R/RM strategies intended to achieve specific groundwater concentrations and mitigate direct contact exposure potential as the most significant risk driver for LNAPL sources. Once an R/RM strategy has been selected through this Remedial Options Analysis (ROA) process (refer to Appendix B of the DMF for additional guidance), an R/RM strategy is then developed (or otherwise referred to as the remedial action plan [RAP]).

Technical R/RM objectives typically fall into two general categories for any given LNAPL site: compositional and saturation-based (ITRC, 2018).

Compositional concerns relate to the “traditional” concentration-based risk associated with groundwater (dissolved phase), direct contact (LNAPL body) or soil gas-related (vapour phase) exposures. Compositional concerns therefore represent concerns where a change in LNAPL chemistry may be advantageous to limit the dissolution or volatilization of petroleum constituents, and subsequent exposure. The assessment of exposure risk in various media at an LNAPL site may often be based on comparisons against generic environmental quality guidelines but may also involve SSTLs generated from a quantitative risk assessment. Developing SSTLs is not discussed in detail herein as considerable guidance exists with respect to conducting human health and ecological risk assessments, including FCSAP guidance (refer to Section 2). In all instances though, it is important to consider the composition of the LNAPL body and its potential for direct or even indirect impacts to a surface body of water in accordance with the *Fisheries Act* (subsection 36(3)).

Saturation-based risk primarily relates to the potential for LNAPL migration into previously unimpacted areas and can be mitigated by reducing LNAPL saturations. Saturation-based R/RM techniques are therefore based on LNAPL mass recovery or control, and not on passive remediation. The mass recovery of LNAPL will most commonly involve hydraulic recovery (e.g., pumping, vacuum-enhanced pumping), while mass control will usually employ physical barriers (e.g., sheet piling, slurry walls) to prevent LNAPL expansion/migration into unimpacted areas. Mass recovery and/or control may be appropriate where LNAPL is migrating or has the realistic potential to migrate. These considerations will therefore be most applicable to new releases and much less relevant for older/legacy LNAPL bodies such as those normally found at FCSAP sites. Older LNAPL bodies will generally be stable with potentially mobile/recoverable fractions that are small (i.e., most of the LNAPL will be present as unrecoverable residual).

Non-technical site R/RM objectives, such as demonstrating LNAPL recovery effort to facilitate property divestiture or sustainability considerations (refer to Section 4.3), can be more complex to address. They will be constrained by what might be technically achievable at a given LNAPL site. Early engagement and working with stakeholders to explain the complexities (fate, transport, exposure) of LNAPL management

will produce the best outcome in terms of establishing R/RM objectives that are achievable and comply with the applicable acts and regulations (such as the *Fisheries Act*).

An adapted version of the 10-step process (Figure 1) illustrates the process for establishing a suitable R/RM strategy, which corresponds to Step 7. This Step starts with the establishment of R/RM objectives and an R/RM action plan based on a well-developed LCSM. Table 5 is an example of a matrix that may be used in conjunction with Figure 1 to determine the appropriate LNAPL R/RM strategy based on the range of situations that may be encountered at LNAPL sites.

At LNAPL sites, prior to developing the R/RM strategy, the focus should be on developing the LCSM and confirming the initial determinations of contaminant stability and potential risks. It is important to understand the distinction between migrating LNAPL, mobile LNAPL, and residual LNAPL (refer to the definitions in Appendix A) to establish appropriate R/RM objectives. For each of these three conditions, physical properties of the LNAPL, aquifer properties, LNAPL saturation (including LNAPL relative permeability), LNAPL hydraulic conditions (e.g., LNAPL head) and NSZD affect the ability of an LNAPL body to expand or for LNAPL to flow into a well (ITRC, 2018).

Table 5 LNAPL Site Management Strategy Matrix

Potential LNAPL Behaviour Scenarios				Potential Site Management Requirements	
Scenario	Compositional Risk ¹ ? (dissolved or vapour phase risk)	LNAPL Unstable/ Migrating? (mobile LNAPL at periphery of LNAPL body)	Mobile LNAPL? (within stable LNAPL body – non-migrating)	Compositional Change and/or Control Required?	Saturation Reduction ² (LNAPL Recovery) and/or Containment Required?
1	Yes	Yes	Yes	Yes	Yes
2	Yes	No	Yes	Yes	Assess net environmental benefit/non-technical drivers ³
3	Yes	No	No	Yes	No
4	No	Yes	Yes	No	Yes
5	No	No	Yes	No	Assess net environmental benefit/non-technical drivers ³
6	No	No	No	No	No

* Adapted from DND, 2013.

Potential LNAPL Behaviour Scenarios				Potential Site Management Requirements	
Scenario	Compositional Risk ¹ ? (dissolved or vapour phase risk)	LNAPL Unstable/Migrating? (mobile LNAPL at periphery of LNAPL body)	Mobile LNAPL? (within stable LNAPL body – non-migrating)	Compositional Change and/or Control Required?	Saturation Reduction ² (LNAPL Recovery) and/or Containment Required?

1. Compositional risks are concentration-based risks associated with groundwater (dissolved phase), direct contact (LNAPL body) or soil gas related (vapour phase) exposures
2. Saturation-based risk primarily relates to the potential for migration of LNAPL into previously unimpacted areas and can be mitigated by reducing LNAPL saturations
3. Net benefit is based on factors such as the ability to cost effectively recover non-migrating free product (i.e., product easily recoverable in term of volumes vs. cost/effort). Non-technical drivers include factors such as departmental risk tolerance, regulations, and stakeholder concerns.

4.1 Remediation/Risk Management Drivers

R/RM drivers are technical, non-technical, and regulatory factors or site-specific conditions that play critical roles in deciding the R/RM strategy, and additionally, approaches that are not suitable for use in the R/RM strategy. The success of any LNAPL R/RM strategy development process hinges on an evidence-based determination of what technical, non-technical, and regulatory R/RM drivers may exist, and their relative importance. R/RM objectives should be directly linked to R/RM drivers. Additional information on the selection of R/RM objectives is included in Section 4.4. As previously noted, technical R/RM drivers relate to two general categories for any given LNAPL site: compositional and saturation-based (ITRC, 2009b; DND, 2013).

Beyond the technical considerations, non-technical factors such as property transaction conditions or regulatory requirements may be primary drivers, and may necessitate the development of an R/RM strategy that would not otherwise be suitable from a strictly technical standpoint (e.g., excavation or active LNAPL recovery where LNAPL is stable/not migrating). In these cases, it is advisable to consider the potential environmental footprint and the risk associated with remedial activities during the development of the R/RM strategy in order to assess the potential impacts of the R/RM activities; which would not otherwise be required from a technical standpoint.

4.2 Remediation/Risk Management Options Analysis and Selection

An analysis of the potential R/RM options should be completed by undertaking a remedial options analysis (ROA), which can consider both active and passive techniques. R/RM options need to consider the LNAPL compositional and saturation concerns described above, and could consist of active remediation (e.g., excavation, LNAPL recovery and in-situ chemical oxidation), passive remediation (e.g.,

NSZD/MNA), controls (engineered and/or institutional, such as land use restrictions), or some combination thereof. Various technologies and strategies can be employed to achieve a given R/RM objective at an LNAPL site.

The development of a ROA is outlined in the DMF at Step 7 and in Appendix A (FCSAP, 2018). The applicability, advantages, and disadvantages of typical remedial options specific to LNAPL sites are discussed in detail in the following documents:

ITRC (2009a);
CRC CARE (2015); and
FCSAP (2013b).

4.3 Sustainability Considerations

Alternative criteria such as sustainability considerations may be useful in cases where :

The costs and benefits of two or more equally attractive R/RM options are under consideration;
The R/RM strategy involves both passive R/RM options such as NSZD/MNA and active R/RM options, which would both equally allow for the achievement of R/RM objectives;
Reducing the environmental footprint of active R/RM techniques is also an objective; and
The R/RM strategy is driven by non-technical factors and therefore small carbon/environmental footprint activities would be more desirable.

When evaluating potential R/RM options, use a net environmental benefit approach. For each option, consider both positive and negative impacts associated with a variety of factors (e.g., resource usage, environmental emissions, and remediation risk) and document these findings in an objective, unbiased manner. Activities involving large carbon/environmental footprints and/or significant remedial risk to local ecology, remedial workers, and/or surrounding communities should generally be considered less desirable, particularly where the R/RM strategy is being driven by non-technical factors.

The following documents offer guidance on incorporating green and sustainable remediation concepts into R/RM planning and assessing the environmental footprints of remedial systems:

- 1) Appendix A in the Decision-Making Framework (FCSAP, 2018)
- 2) E2893-13: Standard Guide for Greener Cleanups (ASTM, 2013a)
- 3) E2876-13: Standard Guide for Integrating Sustainable Objectives into Cleanup (ASTM, 2013b)
- 4) Methodology for Understanding and Reducing a Project's Environmental Footprint, EPA 542-R-12-002 (US EPA, 2012)
- 5) Green and Sustainable Remediation: A Practical Framework, GSR-2 (ITRC, 2011)

- 6) A Framework for Assessing the Sustainability of Soil and Groundwater Remediation (SuRF -UK, 2010)
- 7) Sustainable development analysis tool, version 1.2 (PSPC, no date; <https://oadd-uat.tpsgc.gc.ca/index.aspx?lang=eng>)
- 8) Guidance and Orientation for the Selection of Technologies [GOST], version 1.1 (PSPC, no date; <https://gost.tpsgc-pwgsc.gc.ca/index.aspx?lang=eng>).

4.4 Remediation/Risk Management Objectives

R/RM objectives relate to measurable conditions where the risks to human health and the environment are deemed acceptable. They are discussed in detail by ITRC (2009a), US EPA (2005), CRC CARE (2015) and Johnston (2010).

R/RM objectives for compositional change techniques usually involve satisfying one or more media-specific risk-based criteria. Saturation-based objectives will likely only be applicable at FCSAP sites with older legacy LNAPL bodies for which there is a non-technical driver. In cases where custodians wish to proceed with LNAPL recovery for non-technical reasons, they are encouraged to seek out practical science based objectives which may include:

- Reduction of LNAPL saturations to field residual levels⁴ and

LNAPL recovery performance data exhibiting an asymptotic trend and/or achievement of a pre-determined *de minimis* recovery rate.

Prior to implementing the R/RM strategy, an R/RM monitoring plan should be developed. The monitoring plan should be detailed and include clear objectives so that it is easy to track site progress against the plan, keeping in mind that adjustments to the LCSM and/or R/RM action plan may be required if unexpected results are observed in Step 8. In other words, an adaptive management approach (AMA) should be employed.

5 Implement a Remediation/Risk Management Strategy (DMF Step 8)

The implementation of the LNAPL R/RM strategy developed in Step 7, whether it involves active or passive approaches (or a combination of the two), is founded on the LCSM and built upon the decisions made in response to R/RM drivers to meet R/RM objectives. This strategy takes into account the physical constraints of the site (i.e., proximity of the contaminants to the surface and to potential receptors) and other risk drivers.

Groundwater monitoring results obtained from the implementation of the R/RM monitoring plan should be clearly documented. A comprehensive monitoring plan can be developed by drawing from the FCSAP

⁴ Can be inferred from LNAPL transmissivity estimates and remedial system performance and/or directly measured via soil sampling and subsequent TPH or soil core petrophysical laboratory analysis.

Long-Term Monitoring Planning Guidance (FCSAP, 2013b) as part of a scientifically-defendable approach to the development of a monitoring program.

6 Confirmatory Sampling (DMF Step 9)

Confirmatory sampling is carried out at step 9 of the DMF and involves confirming the achievement of the R/RM objectives following the implementation of the R/RM strategy. The LCSM should also be reviewed at this point to confirm that it remains representative. The design of the confirmatory sampling plan, including parameters to be monitored, frequency of sampling and duration of sampling, is dependent upon the R/RM strategy that was implemented and the R/RM objectives. Confirmatory sampling should be designed to verify that the LOE indicate that the LNAPL body is stable. As stated previously, as a minimum the confirmatory sampling program usually consists of quarterly monitoring for a period of two years.

Confirmatory sampling could reveal that the objectives of the R/RM strategy have not been met. This would require going back to DMF Step 7 to revise the R/RM strategy. However, if the confirmatory sampling confirms that the R/RM objectives have been met, development of a long-term monitoring program may be required.

7 Long Term Monitoring (DMF Step 10)

Once confirmatory sampling (Step 9) has demonstrated the achievement of the R/RM objectives, long term monitoring (LTM; Step 10) may follow. This monitoring may be required to verify that assumptions surrounding site conditions and the overall LCSM have not changed. Long-term monitoring is typically required at sites where R/RM involves approaches – other than direct remedial actions – that reduce the probability, intensity, frequency, or duration of the exposure to contamination. Sites can be closed when LTM demonstrates that engineered controls functioned properly, no action response was triggered, and there is no expectation that this will change. Specific guidance on the need for and potential components of a long term monitoring plan is provided in FCSAP's *Long Term Monitoring Planning Guidance* (FCSAP, 2013b).

It is expected that LTM will occur for a scientifically established length of time, as specified in the remedial action plan (RAP) or risk management plan (RMP), based on professional judgement. LTM costs should be included in the remediation liability for that scientifically established length of time, but should not be included in the liability on a long-term basis. Any additional monitoring, beyond the scientifically established LTM period, would typically be part of the custodian's regular environmental program for managing the site, and ineligible for FCSAP funding (FCSAP, 2021c).

8 Site Closure

According to the Treasury Board, a site can be considered for closure when no future action is required and no further liability exists. This may occur after successful achievement of R/RM objectives at Step 9, or possibly at the successful completion of an LTM plan (Step 10) where appropriate. The custodian is therefore responsible for determining that the contamination at the site does not present an unacceptable risk to human health and the environment. Specific guidance on achieving site closure is provided in FCSAP's updated *Site Closure Report Template and Guidance* (FCSAP, 2022a, b) and *Long-Term Monitoring Planning Guidance* (FCSAP, 2013b).

Below are some considerations related to the closure of an LNAPL site:

- R/RM objectives involving the implementation of active R/RM techniques have been achieved;
- Multiple LOE indicate that the LNAPL body is stable and/or appropriate passive R/RM (engineering controls) are in place to prevent further migration and/or exposure;
- At least two years of quarterly data indicate that dissolved and/or vapour phase plumes are stable or diminishing (post remediation, if active remedial actions used); and
- As appropriate, add a covenant or other legal instruments to flag residual contamination and any restrictions for future use of the property within the real property management framework of the department responsible for the site.

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If the conditions set out in the first three bulleted items above are met, sufficient evidence may be available for the long-term risk management decision that needs to be taken with regard to the site. The continued presence of the LNAPL body will nonetheless remain an operational concern for the department with regard to management of the real property. Although LTM may not be required, some form of due diligence monitoring/management oversight will likely remain a requirement during the life of the property. A known change in conditions would trigger the need to reassess the active and/or passive R/RM strategies as per Figure 1.

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10 Appendices

Appendix A LNAPL Basics

GLOSSARY

Capillary Pressure: The pressure difference between the non-wetting phase (i.e., LNAPL) and the wetting phase (i.e., groundwater) in a multi-phase system such as an LNAPL-groundwater system. Typically, water is the wetting fluid in the saturated zone, in direct contact with the soil, and occupies the smaller pores. LNAPL must displace the water (and gases) within a pore space before it can migrate. For this to occur, it must have a driving head and overcome the capillary pressure exerted by the water in the pore space. LNAPL migration can occur only when sufficient LNAPL head (and capillary pressure) is present to drive the migration

Confined Condition: A subsurface condition where pore fluids are under pressure at all reference points or elevations. In a confined condition, in-well LNAPL thickness varies directly with potentiometric surface elevation. Hence, an increase in the potentiometric surface elevation leads to an increase in in-well LNAPL thickness, and vice versa. LNAPL within the secondary porosity (fractures, fissures, seams) of fine textured soils (silts and clays) and in fractured rock settings is often present in a confined condition. Confined conditions can produce in-well LNAPL thicknesses that over-represent the quantity of LNAPL in the formation.

C_{sat} : The theoretical limit of a soil's ability to effectively hold or contain a chemical constituent (or mixture) in the adsorbed, dissolved and vapour phases. Total soil concentrations in excess of a chemical constituent's (or mixture's) corresponding C_{sat} value will typically be assumed to indicate the presence of LNAPL. Published C_{sat} values will have limited use at LNAPL sites due to the site-specific nature of LNAPL composition and the difficulty in determining appropriate C_{sat} values for complex petroleum mixtures consisting of hundreds of individual chemical constituents.

Effective Solubility: Unlike pure-phase solubility, effective solubility describes the ability of a chemical constituent in a mixture to dissolve in water in the presence of other constituents in the mixture. It is a particularly important consideration for LNAPLs that are complex petroleum mixtures. Effective solubility is a function of the mole fraction of the constituent in the mixture, and is commonly orders of magnitude less than the constituent's corresponding pure-phase solubility. Groundwater concentrations in excess of a petroleum constituent's effective solubility may indicate the presence of LNAPL in the vicinity of a monitoring well.

Interfacial Tension: The tension or attractive forces between two fluids along the interface of contact between the two. The interfacial tension between LNAPL and water in the subsurface tends to limit the ability of LNAPL to move.

Laser-induced Fluorescence (LIF): A real-time LNAPL delineation technology that uses ultraviolet wavelengths of light to cause polycyclic aromatic hydrocarbons (PAHs) present in LNAPLs to fluoresce. LIF is employed in the field using direct-push techniques to delineate LNAPL impacts in the subsurface laterally and vertically (both above and below the water table). LIF also provides an indication of the intensity of impacts across an LNAPL body and the type(s) of LNAPL encountered.

LNAPL: Light non-aqueous phase liquid. LNAPLs are immiscible fluids that are less dense than water, and may be composed of a pure chemical or solvent, or a complex mixture of chemicals, such as petroleum-based fuels. The term “LNAPL” most often refers to immiscible petroleum mixtures/fuels (i.e., gasoline, kerosene, diesel, and crude oil).

LNAPL Body: The multi-phase fluid zone of LNAPL impacts in the subsurface. An LNAPL body is composed of three fluids: air, LNAPL and water. Generally speaking, an LNAPL body is composed predominantly of water, with a lesser amount of LNAPL, and even smaller amount of air.

LNAPL Conductivity: A hydrogeological term that helps describe the ability of LNAPL to move through the subsurface. LNAPL conductivity accounts for LNAPL relative permeability, hydraulic conductivity, and the densities and viscosities of the fluids (water and LNAPL). LNAPL conductivity is a function of and varies directly with LNAPL relative permeability. Hence, an increase in LNAPL relative permeability results in an increase in LNAPL conductivity, and vice versa.

LNAPL Head: The LNAPL pressure conditions at any point within an LNAPL body created by the release conditions. The pressure head can result from the vertical column of LNAPL due to accumulation at or in the vicinity of the water table from a surface or near-surface source (e.g., tank), or from other pressure conditions at the time of the release (e.g., pressure conditions of a subsurface pipeline release). The greater the pressure head, the more the LNAPL will penetrate into the water table (both vertically and laterally) and spread. Once the pressure head dissipates (i.e., source of release is terminated), the LNAPL will soon after cease to migrate and become stable.

LNAPL Migration: A description of the expansion of the perimeter of an unstable LNAPL body in some or all directions (i.e., the footprint of the overall LNAPL body or body periphery is continuing to grow). All migrating LNAPL is mobile; not all mobile LNAPL is migrating. Mobile LNAPL can be present within the interior of an LNAPL body that is not migrating. An LNAPL body that is not migrating is also referred to as being “stable”; conversely, an LNAPL body that is migrating is “unstable”.

LNAPL Mobility: A description of the potential for LNAPL to move at any point within an LNAPL body. LNAPL may be mobile in a case where the LNAPL is continuous at saturations above residual saturation. Because LNAPL residual saturation within an LNAPL body varies from the vadose zone to the saturated zone, LNAPL mobility will also vary temporally due to natural fluctuations in water table elevation. The presence of mobile LNAPL within an LNAPL body does not necessarily mean that the LNAPL body as a whole is unstable or migrating.

LNAPL Relative Permeability: A measure of the porous medium’s (soil’s) ability to enable movement of LNAPL in the subsurface in the presence of water. LNAPL relative permeability is a function of and varies directly with LNAPL saturation. An increase in LNAPL saturation therefore results in an increase in LNAPL

relative permeability, and vice versa. For example, the residual LNAPL concentration in the vadose zone is higher in fine-grained soils than in coarse grained soils.

LNAPL Residual Saturation: The LNAPL saturation level or threshold below which LNAPL will not flow under normal hydraulic conditions. LNAPL present at saturations that are less than or equal to residual saturation levels (i.e., within the residual range) will generally be considered to be immobile. Conceptually speaking, LNAPL residual saturation represents the LNAPL saturation threshold where the LNAPL, due to its relatively low saturation, starts to break up or become discontinuous in the form of droplets, stringers, ganglia, etc. As LNAPL saturation approaches or decreases to residual, the relative permeability of the LNAPL approaches zero, and the conductivity of the LNAPL approaches zero. The greater the amount of LNAPL that initially saturates the soil pore space during a release, the higher the residual saturation will be (up to a theoretical maximum). Consequently, LNAPL residual saturation also varies continuously within an LNAPL body.

LNAPL Saturation: The percent of the soil pore space that is occupied by LNAPL. LNAPL saturation at a given point in the subsurface will be proportional to the capillary pressure at that point (i.e., the greater the capillary pressure, the greater the resulting LNAPL saturation). Because the capillary pressure varies throughout the impacted zone, LNAPL saturation also varies accordingly. The larger the soil pore space, the greater the ability for the soil to hold LNAPL, the greater the LNAPL saturation, and vice versa.

LNAPL Stability: A description of the potential for the perimeter or footprint of an LNAPL body to move or expand over time. An LNAPL body that is moving or expanding (i.e., footprint of LNAPL body is growing) is deemed to be unstable or migrating. Conversely, an LNAPL body that is not moving or expanding with time is deemed to be stable and non-migrating. Stable LNAPL bodies will often contain localized areas of mobile LNAPL with the overall footprint remaining unchanged over time.

LNAPL Velocity: The speed and direction in which the LNAPL can travel, based on Darcy flow principles. LNAPL velocity is based on the properties of the porous medium and fluids (water and LNAPL), pore fluid saturations, and the LNAPL gradient. LNAPL velocity only applies within the LNAPL body where there is continuous LNAPL at saturations above residual. There is no LNAPL velocity or movement within an LNAPL body where the LNAPL is not continuous and saturations are below residual. In addition, there is no LNAPL velocity or movement outside of a stable LNAPL body.

Non-Wetting Fluid: The fluid that does not preferentially coat the soil grains or particles in a multi-phase fluid system, but rather occupies the middle of the larger soil pores. In an air-water-LNAPL system (i.e., an LNAPL body), both air (primarily in the unsaturated portion of the smear zone) and LNAPL (primarily in the saturated portion of the smear zone) tend to be the non-wetting fluids.

Pore Entry Displacement Pressure: The threshold pressure necessary for one fluid to enter into a porous medium occupied by another fluid, thereby displacing the fluid originally present. Pore entry displacement pressures may account for air displacing groundwater, LNAPL displacing groundwater, air displacing LNAPL, etc. In a water-saturated soil, the capillary pressure must equal or exceed the pore entry displacement pressure in order for the LNAPL to move and displace water.

Soil Resistive Forces: The forces that act to prevent the movement of LNAPL in a water-saturated porous medium. These forces, which are based on pore entry displacement pressure principles, account for the contact angle or wettability of the fluids (LNAPL and water), the interfacial tension between the fluids, and the soil pore size. LNAPL movement will only occur if the displacement pressure is sufficient to overcome the soil resistive forces.

Unconfined Condition: A subsurface condition with identical or similar pressure-related fluid characteristics to an unconfined aquifer or water table condition. LNAPL within the primary porosity of granular soils (sands and gravels) in a water table/phreatic surface setting is deemed to be in an unconfined condition. In an unconfined condition, in-well LNAPL thickness typically varies inversely with water table elevation. Hence, an increase in the water table elevation can often lead to a decrease in in-well LNAPL thickness, and vice versa.

van Genuchten Parameters: Curve fitting parameters that describe how water drains from a given soil in response to increasing pressure conditions. These parameters serve as critical inputs for LNAPL modelling simulations.

Wetting Fluid: The fluid that preferentially coats the soil grains or particles in a multi-phase fluid system. In an air-water-LNAPL system (i.e., an LNAPL body), water typically acts as the wetting fluid while air and LNAPL act as non-wetting fluids. The wetting fluid is typically the predominant fluid present in a multi-phase fluid system.

FUNDAMENTALS OF LNAPL BEHAVIOUR

This section addresses LNAPL behaviour at the water table (i.e., unconfined condition) and includes the vertically impacted soil zone typically referred to as the smear zone. The smear zone is where potentially mobile LNAPL may be found in locations where the source(s) of the LNAPL impacts have ceased for some time (i.e., no active sources). The behaviour of LNAPL in the vadose or unsaturated zone (above the smear zone) is not addressed here since LNAPL in these zones (particularly at older release sites) is often present at low saturations, and typically does not pose a risk in terms of additional LNAPL at the water table.

LNAPL Release Dynamics and the Creation of a Multi-Phase Fluid System

When an LNAPL release occurs, the LNAPL will move vertically downward under the influence of gravity through the soil and, if sufficient LNAPL head is generated, it will encounter the water table. As LNAPL moves downward toward the water table, any confining layers and/or other subsurface heterogeneities it encounters may cause exaggerated and uneven lateral spreading and/or perching of LNAPL above the water table. Once it reaches the water table, the LNAPL will penetrate vertically downward as well as laterally (including in the up-gradient direction) into the water table, displacing an amount of water proportional to the driving force of the vertical LNAPL column (or LNAPL head) created by the release. Groundwater displacement will continue to occur as long as the downward force produced by the LNAPL head or pressure from the LNAPL release exceeds the upward force produced by the resistance of the

soil matrix and the buoyancy force resulting from the density difference between LNAPL and groundwater. After the release of LNAPL is terminated, the LNAPL footprint at the water table will continue to expand for a relatively short time and will eventually stop once the LNAPL head dissipates. The LNAPL eventually ceases to expand because the driving force (pressure or head) responsible for LNAPL migration is no longer sufficient to overcome the resistive forces necessary to displace groundwater from unimpacted soil pores. When the LNAPL body reaches this state, the LNAPL body is referred to as stable or non-migrating. A conceptual schematic of a stable LNAPL body is provided in Figure A.1.

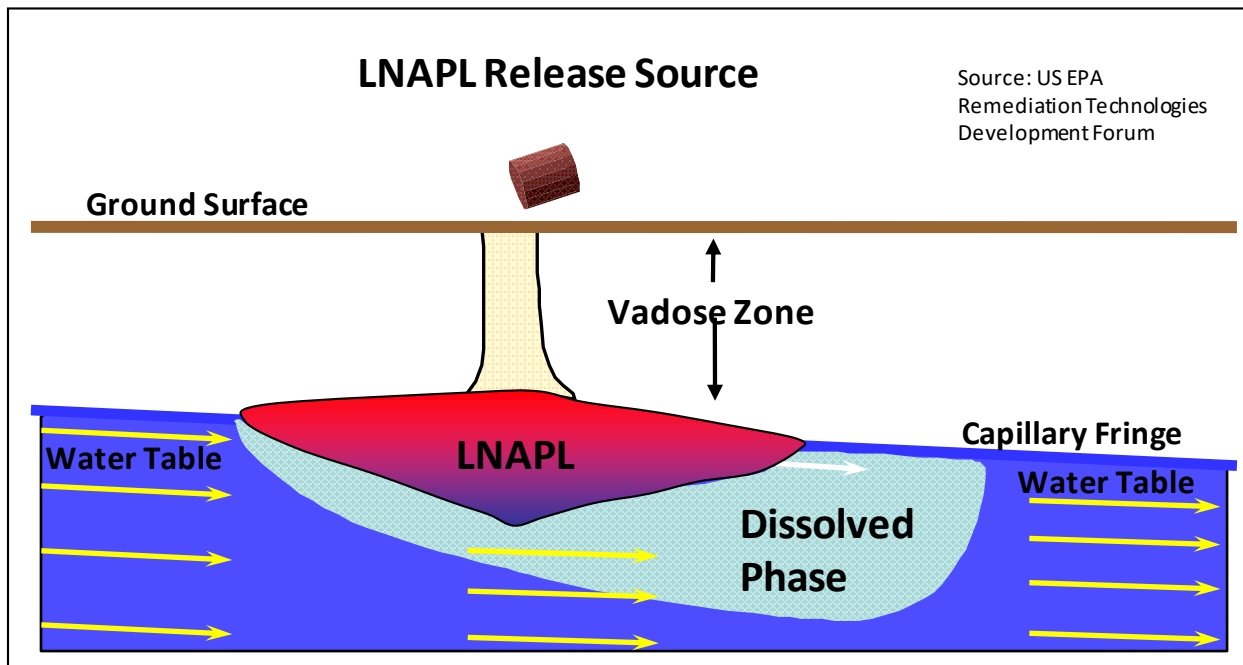


Figure A.1 Typical LNAPL release scenario with resulting LNAPL body at water table

The concept of LNAPL penetrating vertically into the saturated zone (i.e., below the water table) during a release contradicts earlier beliefs that LNAPL “floats” like a pancake (filling 100% of the soil pore space within the LNAPL impacted zone on top of the water table) because it is less dense than water, with no portion of the LNAPL penetrating into the saturated zone. Recent LNAPL science and significant empirical evidence have consistently demonstrated that some LNAPL (and oftentimes the majority of LNAPL at a given site) is commonly submerged beneath the theoretical water table surface. Further, LNAPL does not displace all groundwater from the soil pore space, but rather a portion of the groundwater that occupies the “largest” soil pore space only. Consequently, a typical LNAPL body consists of LNAPL that has filled much less of the soil pore space and resulted in a more highly variable and discontinuous distribution than that indicated by the historical assumption based on the “pancake” conceptualization. The LNAPL body at the water table does not consist of a single fluid phase (LNAPL) but rather multiple fluids, both LNAPL and water. The top portion of the LNAPL body often includes a third fluid phase: air. Therefore, the term “LNAPL body” represents the spatial limits of LNAPL impacts, within which exists a multi-phase fluid system composed of LNAPL, water and/or air in proportions that will vary throughout. Furthermore, because of the multi-phase nature of the LNAPL occurrence in the subsurface, it is

generally incorrect to refer to LNAPL as floating on the water table. It is more appropriate to think of an LNAPL body as a zone of LNAPL impacts where the pore space contains variable quantities of LNAPL, groundwater and/or air both above and below the static water table elevation. Generally speaking, the spatial extent occupied by an LNAPL body is predominantly composed of water, followed by a lesser amount of LNAPL, with the smallest fraction of the pore space occupied by air. Figure A.2 presents a pore-scale depiction of LNAPL and water co-existing in the soil pore space.

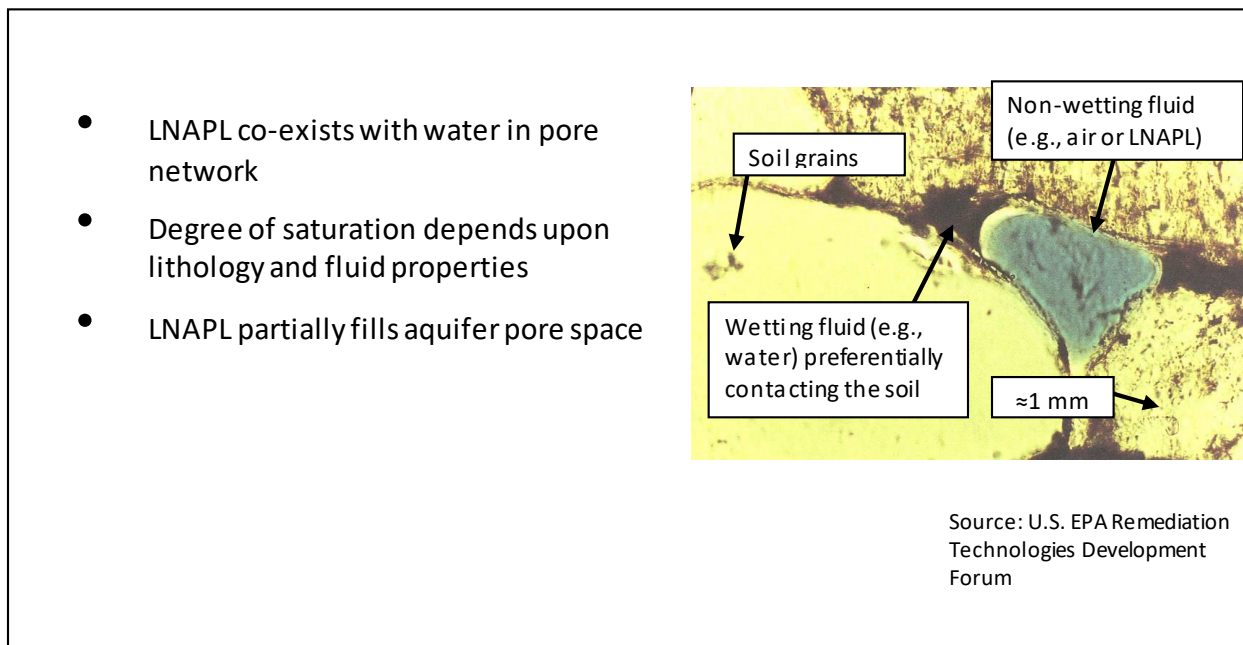


Figure A.2 Photomicrograph of LNAPL and water distribution in soil pore space

LNAPL at the water table requires pressure in order to move. Unlike groundwater (including dissolved phase constituents), which typically forms a continuous system with flow velocity based on hydraulic gradients, LNAPL, being a non-wetting fluid, requires pressure to force it through the soil pores and displace the existing pore water. More specifically, LNAPL needs sufficient displacement pressure to overcome the resistive forces in the soil to enable the continued displacement of groundwater. In a multi-phase (LNAPL/water) fluid system, capillary pressure (also referred to as excess pressure), is the difference between the pressure in the non-wetting phase (LNAPL) and the pressure in the wetting phase (groundwater). The pressure necessary to overcome the resistive forces and allow a non-wetting LNAPL to enter water-saturated media is called the pore entry displacement pressure (Mercer and Cohen, 1990). In other words, if sufficient pressure is acting on the LNAPL, it will be able to enter a given pore space by forcing some portion of the groundwater out. Once the pore entry displacement pressure is achieved or exceeded, the LNAPL will continue to expand in a vertical and radial direction until there is insufficient LNAPL head or pressure to continue to displace water. The LNAPL head will usually become insufficient to displace water and enter non-impacted pore space shortly after the LNAPL release is terminated. Hence, soon after the LNAPL release is terminated, the LNAPL body becomes stable (i.e., spatial extent no longer moving or expanding).

Because the main mechanism for LNAPL spreading is the pressure/head of the release (during the release and until the LNAPL body stabilizes), the groundwater gradient will only influence the direction of LNAPL spreading but will not typically induce additional LNAPL spreading or migration once stabilization has been achieved. In short, LNAPL movement is not typically caused by horizontal hydraulic gradients (ASTM, 2006). It is also important to note that the radial component that is typical of LNAPL spreading can result in significant up-gradient and cross-gradient LNAPL spreading.

The porous media flow concepts that apply to groundwater systems (Darcy flow equations, etc.) also apply to LNAPL bodies, with two distinct differences. First, LNAPL conductivity (as opposed to water or hydraulic conductivity) includes a relative permeability term, which accounts for the negative influence of groundwater on the ability of LNAPL to flow and for the differences in density and viscosity between LNAPL and groundwater. Second, Darcy flow in an LNAPL body only applies where there is continuous LNAPL within the body. Hence, in any areas of discontinuous LNAPL within an LNAPL body or outside of a stable LNAPL body, there is no LNAPL flow or movement.

LNAPL Saturation

LNAPL saturation is defined as the percent of the soil pore space that is occupied by LNAPL. As previously discussed, LNAPL does not float on the water table like a pancake, but rather co-exists with air and groundwater at varying saturations within the impacted soil zone, both above and below the water table. This is because the saturation level of a given LNAPL body at a given point in the subsurface will be proportional to the capillary pressure at that point (i.e., the greater the displacement pressure, the greater the resulting LNAPL saturation). Because the displacement pressure will vary throughout the impacted zone, LNAPL saturation will also vary accordingly.

Geology plays an extremely important role with respect to LNAPL saturation (and mobility). The larger the soil pores making up the primary porosity of the soil matrix, the greater the soil's capacity to hold LNAPL, the greater the ease with which LNAPL can move, and the less pressure that is required for LNAPL to displace water and enter the pore space. Granular soils, such as sands and gravels, have large soil pores relative to silts and clays, and can hold LNAPL at saturations upwards of 40–60% (although typical maximum saturations encountered in the field are usually in the 20–30% range). Conversely, silts and clays, which have extremely small soil pores compared to sands and gravels, typically only allow LNAPL saturations on the order of 5–15%. The smaller soil pores not only limit the amount of LNAPL saturation, but also limit the flow or movement of LNAPL.

Soil porosity principles for LNAPL saturation and movement in overburden soil may also be applied to certain types of competent bedrock (i.e., bedrock that does not have secondary porosity in the form of fractures). For example, competent sandstone will enable LNAPL to behave in a similar manner as in a similar grain/pore sized sandy soil.

Secondary porosity also plays an extremely important role at LNAPL sites. Fine-textured soils, such as silts and clays, are often characterized by secondary porosity which may include macropores such as fractures, fissures and sand seams. The same holds true for fractured bedrock. Many sites also contain subsurface infrastructure usually associated with utilities that will constitute artificial macropores.

LNAPL movement through secondary porosity may occur at rates several orders of magnitude greater than the movement through primary porosity. This is primarily due to the fact that macropores generally have much larger pore sizes than primary porosity, with a corresponding pore entry displacement pressure that is much lower. In other words, LNAPL can displace water and move through macropores much more easily and to a greater extent than it can in the primary porosity of a fine-grained soil or rock matrix. Hence, the potential for LNAPL movement through secondary porosity must be considered when LNAPL impacts are present in fine-textured soil and fractured bedrock, or where subsurface infrastructure coincides with the location of an LNAPL body.

Idealized LNAPL saturation profiles (in the vertical profile) can be generated using LNAPL analytical models such as the American Petroleum Institute's (API) LNAPL Distribution and Recovery Model (LDRM) which are based on in-well LNAPL thicknesses and capillary pressure principles. Figure A.3 shows an idealized saturation profile illustrating the typical variation in LNAPL saturation above and below the theoretical water table in a homogenous granular soil with pore fluids at vertical equilibrium.

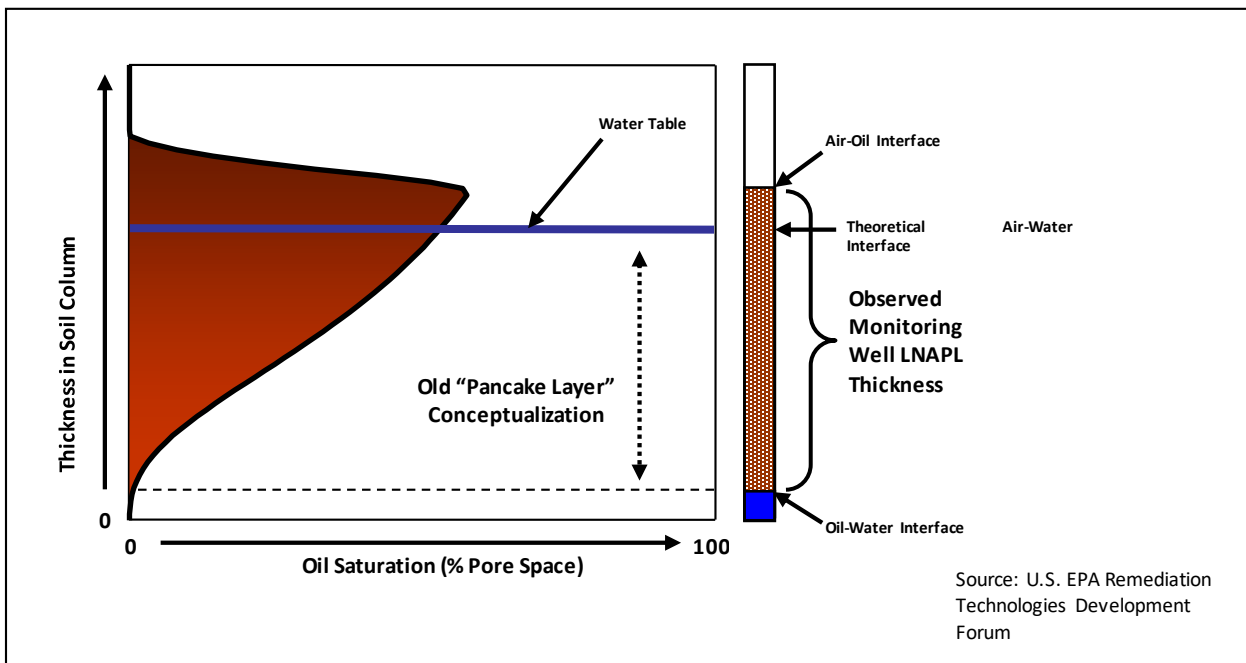


Figure A.3 Idealized LNAPL saturation profile using capillary pressure principles

The idealized LNAPL saturation profile in Figure A.3 is based on the in-well LNAPL thickness identified in the monitoring well adjacent to the profile. Note that the saturation profile commences in the capillary fringe, above the corresponding air/LNAPL interface in the well, and continues down to the LNAPL/water interface in a non-linear manner. Note also that the highest degree of LNAPL saturation occurs in the formation at the approximate location of the air/LNAPL interface in the adjacent well. This type of saturation profile is also referred to as a capillary pressure prediction curve, and is based on the following critical assumptions: (1) the fluids (water and LNAPL) are in vertical equilibrium (i.e., not fluctuating up and down); and (2) the soil formation is homogeneous. These assumptions are required in order for the LNAPL saturation profile to accurately represent and correspond to the in-well LNAPL thickness.

Figure A.4 is a conceptual depiction of pore-scale fluid saturations through an LNAPL body, based on capillary pressure principles. Figure A.5 shows how LNAPL saturation profiles can be depicted across an LNAPL body. It should be noted that in-well LNAPL thicknesses are often not representative of the LNAPL saturation profile in the adjacent soil.

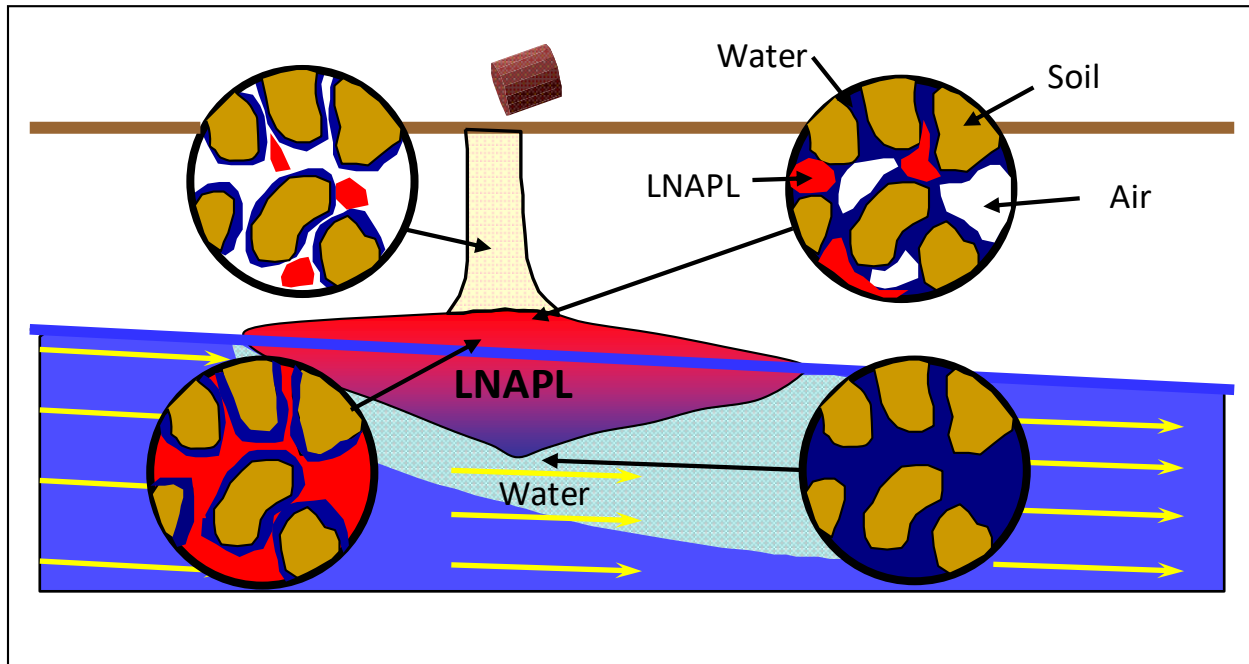


Figure A.4 Distribution of different fluid phases in a typical LNAPL body

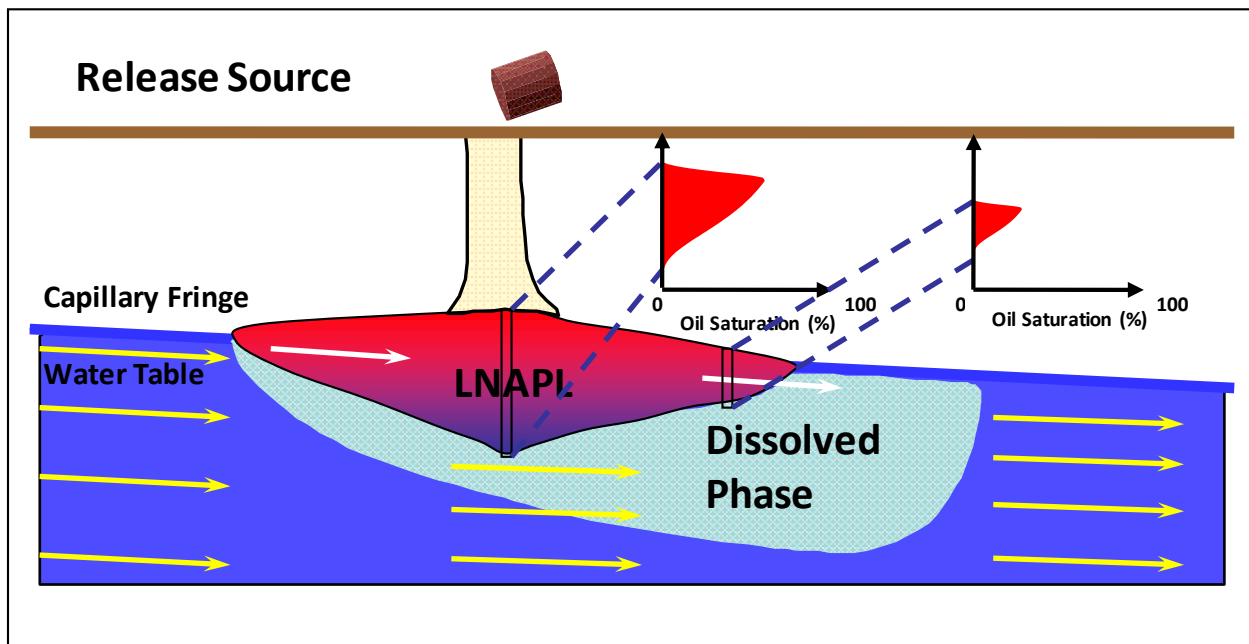


Figure A.5 LNAPL saturation profile changes with respect to location within LNAPL body

As previously discussed, geology plays an extremely important role with respect to LNAPL saturation. Figure A.6 illustrates how LNAPL saturation profiles differ for various types of soil (due to differences in soil pore size). Figure A.7 illustrates how saturation profiles differ for a given soil with varying in-well LNAPL thicknesses.

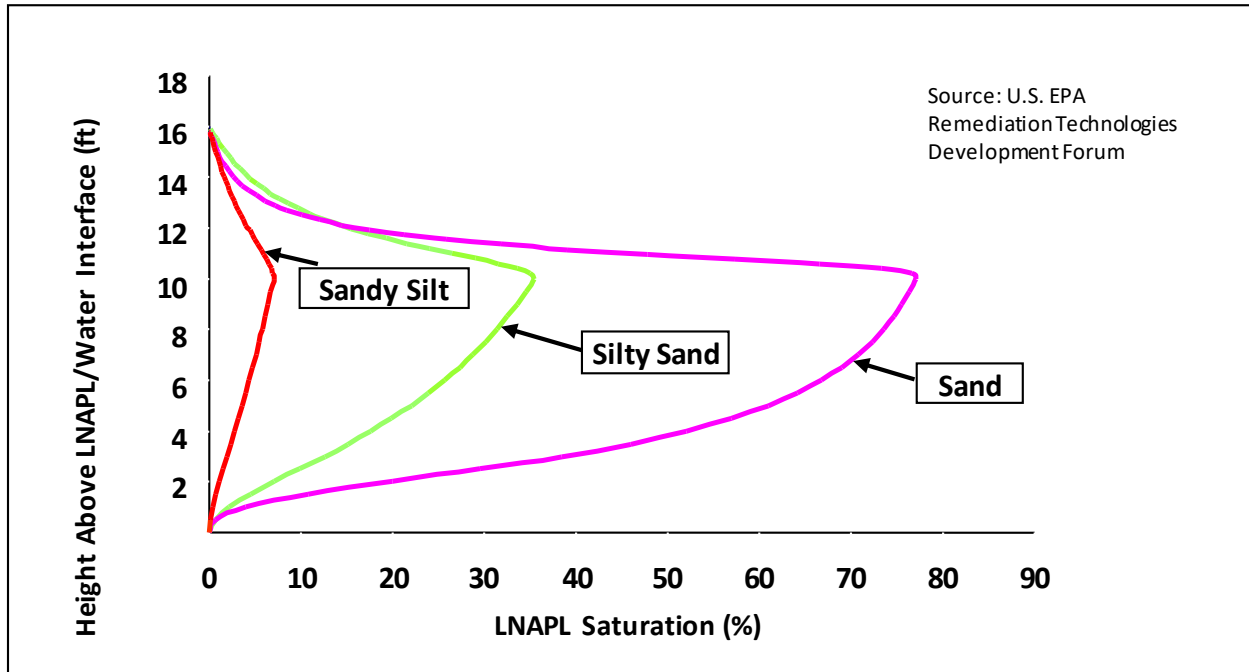


Figure A.6 LNAPL saturation profiles in different soil types for a given in-well LNAPL thickness

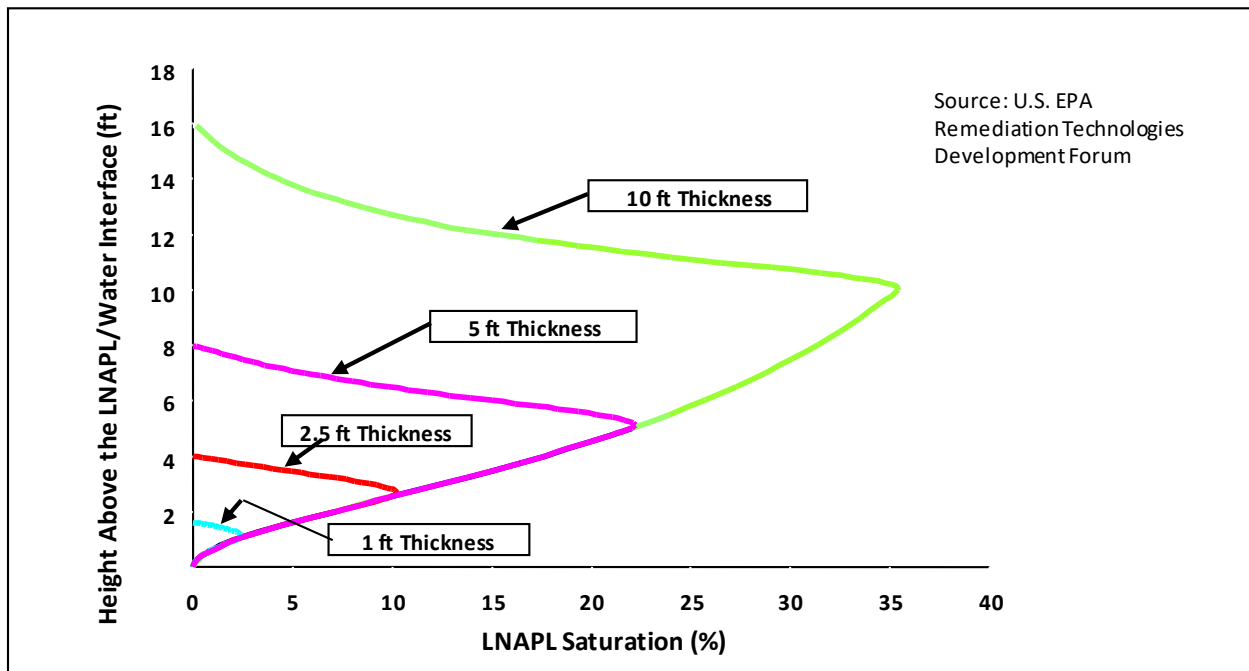


Figure A.7 LNAPL saturation profiles for a given soil with varying in-well LNAPL thicknesses

Again, capillary pressure predictions for LNAPL saturation profiles are based on idealized assumptions, which are useful from a theoretical standpoint to illustrate the multi-phase model of LNAPL occurrence and behaviour. However, these assumptions will not be met at many environmental sites, and in-well LNAPL thickness data will not typically provide an accurate depiction of the vertical extent of the LNAPL body in the adjacent soil. Where preferential pathways and/or other subsurface heterogeneities exist, LNAPL saturations can vary dramatically throughout an impacted zone and will be difficult or impossible to predict.

LNAPL saturations can be determined and/or measured by several methods:

1. Total petroleum hydrocarbon (TPH) soil concentrations can be converted to LNAPL saturations using the following equation (ASTM, 2006):

$$S_o = \frac{[TPH]}{10^6} \cdot \frac{\rho_{fb}}{\rho_o} \cdot \Theta^{-1}$$

Where:

S_o = LNAPL saturation (fraction of pore space filled with LNAPL)

$[TPH]$ = total petroleum hydrocarbon soil concentration (mg/kg)

ρ_{fb} = soil bulk density

ρ_o = LNAPL/oil density

Θ^{-1} = total soil porosity

2. LNAPL-saturated soil core samples can be collected and tested at certain specialized petrophysical laboratories to directly determine LNAPL saturations (e.g., Dean-Stark extraction method); and/or
3. Various tools are available from the API that can be used to estimate LNAPL saturations based on in-well LNAPL thickness observations and soil and LNAPL physical properties (e.g., API's LDRM).

Method 3 is widely used but generally less reliable than Methods 1 and 2 as it is primarily dependent upon in-well LNAPL thickness observations. As previously discussed, conditions at most environmental sites (i.e., water table fluctuations, subsurface heterogeneities, etc.) make it difficult or impossible to obtain an accurate correlation between in-well LNAPL thicknesses and the actual impacted interval in the adjacent soil formation.

LNAPL saturations are dynamic and will change over time as LNAPL initially displaces water (during vertical and lateral migration following a release), and is subsequently displaced as water flows back into a portion of the pore space when water table elevation increases (API, 2004). This process of vertical redistribution of LNAPL in response to water table fluctuations is commonly referred to as “smearing”. LNAPL saturations can be expected to continue to change until such time as the LNAPL becomes sufficiently discontinuous, such that all saturations are at or below LNAPL residual saturation levels. A discussion of LNAPL residual saturation follows.

LNAPL Residual Saturation

LNAPL residual saturation is defined as the LNAPL saturation level or threshold below which LNAPL will not flow under normal hydraulic conditions. Consequently, LNAPL that is present at saturations that are less than or equal to residual saturation levels will generally be considered to be immobile and unrecoverable. Conceptually, LNAPL residual saturation represents the LNAPL saturation threshold where the LNAPL, due to its relatively low saturation, starts to break up or become discontinuous in the form of droplets, stringers, ganglia, etc. It can also be said that LNAPL residual saturation represents the amount of LNAPL trapped by capillary forces within the pore network that is hydraulically unable to move (Beckett, 2005). As LNAPL in the vadose zone is subject to greater capillary forces in fine-textured soils, the LNAPL residual saturation in this zone will be greater than in coarse-grained soils which are more drainable. As LNAPL saturation approaches or decreases to the residual level, the relative permeability of the LNAPL approaches zero, and the conductivity of the LNAPL approaches zero. Figure A.8 provides both a conceptual and pore-scale illustration of LNAPL at residual saturation on the periphery of an LNAPL body.

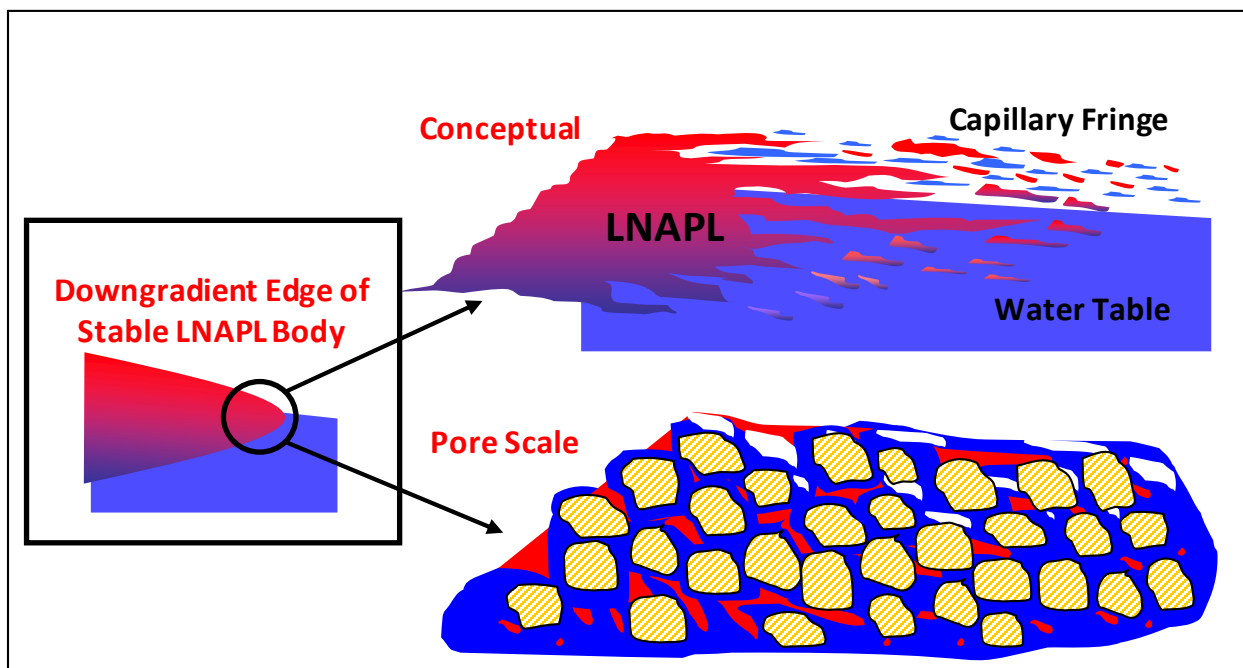


Figure A.8 Conceptualization of discontinuous residual LNAPL at LNAPL body periphery

The greater the initial saturation at any point in an LNAPL body, the greater the residual saturation at that point (Johnston and Adamski, 2005). In other words, the more LNAPL that initially enters a pore space, the more that will become trapped and unable to move out of the pore space. Hence, an entire LNAPL body will be comprised of a variety of initial saturation and corresponding residual saturation values depending on the reference point or location within the body (refer to Figure A.9).

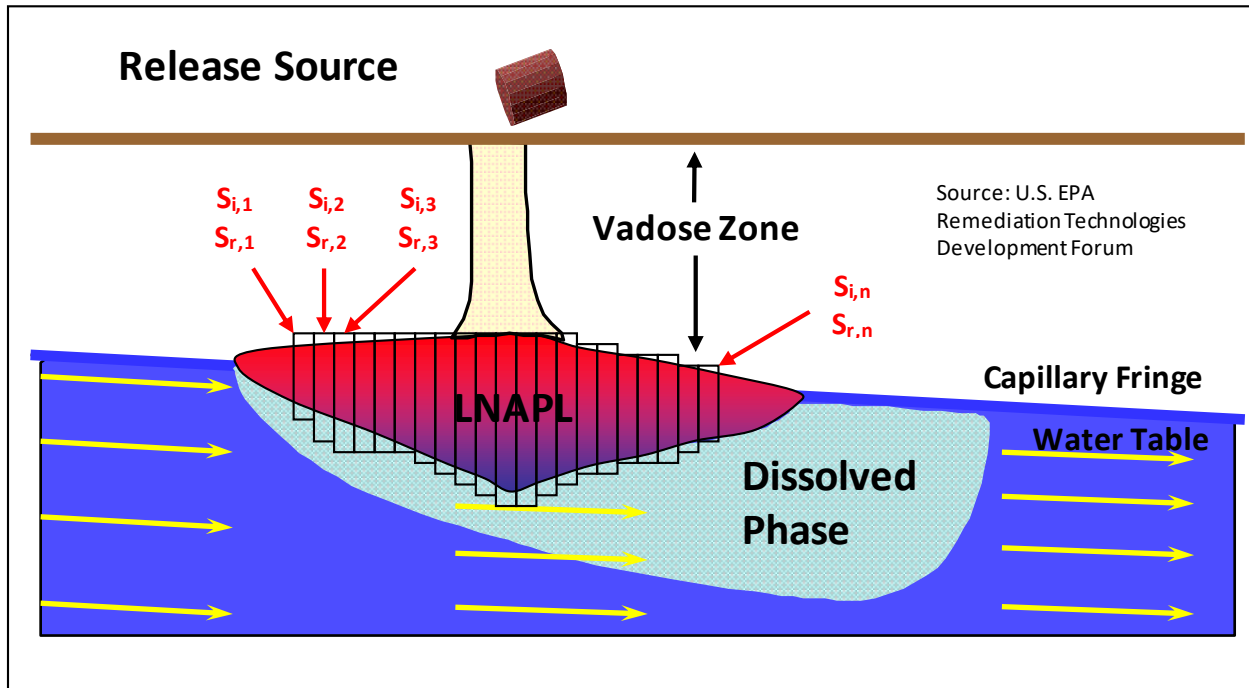


Figure A.9 LNAPL residual saturation as a function of initial saturation

Residual LNAPL saturations can be determined by obtaining undisturbed soil core samples from a site (maintained in a frozen state to prevent pore fluid drainage) and subjecting them to one of several different laboratory methods:

1. Oil/water drainage/imbibition capillary pressure testing: Involves spiking (via centrifuge) a sub-sample from the soil core with LNAPL up to its maximum saturation, then forcing water through under pressure to drain as much LNAPL as possible. Whatever LNAPL is left constitutes the residual LNAPL saturation.
2. Free product mobility testing via centrifuge at 1,000 times the force of gravity (Brady and Kunkel, 2005): Performed by taking a sub-sample from a soil core as-received (no pre-spiking with LNAPL) and spinning it in a centrifuge at 1,000 times the force of gravity (approximately equal to 40-50 psi applied to sample) for 1 hour. LNAPL remaining in the sample following the centrifuge represents the residual LNAPL saturation.
3. Water drive/flood testing: Involves forcing multiple (typically 10-15) pore volumes of water through a sub-sample from a soil core under 25 psi pressure. The LNAPL residual saturation is represented by the LNAPL that remains in the sample following the water drive.

Methods 1 and 2 both have aspects about the way the test is run that may result in residual saturation results that are unduly biased. For Method 1, recall that residual LNAPL saturation is a function of initial LNAPL saturation (i.e., the more LNAPL that occupies the pore space initially, the higher the residual saturation). The initial spiking of the sample with LNAPL in Method 1 may therefore produce a residual saturation result that is biased high compared with what would be representative of an unspiked sample. With Method 2, the pressure applied during the test is so exceedingly high that it is far beyond the pressure conditions produced by typical hydraulic conditions at most sites. Furthermore, the elevated pressure utilized with Method 2 more often leads to the compression or collapse of the soil matrix during the test. When this occurs, one may not be able to conclude whether any LNAPL released from the sample during the test was the result of the applied gradient or the compression of the soil matrix “squeezing” LNAPL out of the sample. In either case, the results of Method 2 are likely to produce a residual saturation result that will be biased low and non-representative of actual site conditions, which may result in the conclusion that much more LNAPL may be mobile or recoverable at a given site than actually is. Method 3 also involves an applied pressure that is likely to be higher than conditions at a typical environmental site; however, because the pressure is much lower than Method 2 and the method does not involve any pre-spiking of LNAPL as in Method 1, it is the method that is likely to produce the most representative results.

It is important to note that LNAPL residual saturation for a given LNAPL and soil type at a given location within the LNAPL body varies greatly between the unsaturated (vadose) and saturated zones. Generally speaking, LNAPL residual saturations in the vadose zone are much lower than corresponding residual saturations in the saturated zone. This is true because of the difference in densities and interfacial tensions between an air/LNAPL pair versus an LNAPL/water pair. LNAPL in the vadose zone has a much greater ability to drain under the force of gravity and flow into a monitoring well, as opposed to LNAPL that is submerged beneath the water table. Put simply, much less pressure is required for LNAPL to push air out of the way to enter a pore than would be required for LNAPL to do the same to groundwater. This also plays a role in the appearance and disappearance of LNAPL in wells resulting from fluctuations of the water table elevation. Typical LNAPL residual saturations in the vadose and saturated zones for given soil types are shown in Table A.1 below (ITRC, 2009b):

Table A.1 Representative LNAPL residual saturation values for the vadose and saturated zones

Soil Type	Residual Saturation (Vadose)	Residual Saturation (Saturated)
Sand	3%	25%
Sandy Loam	5%	22%
Loam	7%	18%
Silty Loam	7%	16%
Sandy Clay	7%	10%

Silty Clay	4%	6%
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Note that the “saturated” residual saturation of LNAPL in a coarse-grained material (sand) is much higher than the corresponding “saturated” residual saturation in a silt or clay. As previously discussed, this is because a coarse-grained soil has a much greater capacity to hold LNAPL (due to larger soil pores) than a fine textured soil. Hence, the LNAPL saturations and corresponding residual saturations in a coarse-grained soil in the saturated zone are typically much higher than the LNAPL saturations and residual saturations in a fine textured soil. As previously noted, secondary porosity may control LNAPL flow in finer grained soils. Consequently, these typical values may or may not apply where this condition is present. Note: Residual saturation in the vadose zone is greater in fine soils than coarse soils due to the capillary pressure.

LNAPL Mobility

The mobility of LNAPL generally relates to its ability to move in a localized sense at any point within an LNAPL body. LNAPL mobility can be highly influenced by a fluctuating water table and is dependent on a variety of LNAPL properties (density, viscosity, interfacial tension) and soil properties (soil type(s) and drainage characteristics) and is often characterized in terms of LNAPL saturations (at any point within an LNAPL body) and the corresponding residual saturations. LNAPL saturations that exceed residual saturation levels indicate a potential for mobility; however, this does not necessarily indicate that the LNAPL body as a whole is unstable or migrating (ASTM, 2006; ITRC, 2009b).

Seasonal water table fluctuations have a direct impact on the mobility of LNAPL. A rising and falling water table creates a “smear zone” where mobile, continuous LNAPL becomes spread vertically and becomes discontinuous as water and LNAPL compete for pore space. Assuming a continuous source is not present, this interaction between water and LNAPL will progressively trap LNAPL as discontinuous, immobile droplets within the soil matrix over time (API 2004). Consequently, during seasonal high water tables, some or all of the LNAPL in the smear zone (in an unconfined setting) can become submerged or trapped beneath the water table. This results in the submerged LNAPL losing much of its ability to flow through the soil matrix and/or into a monitoring well (due to a higher residual saturation in the saturated zone). In some situations, all LNAPL in a well can “disappear” with an increase in water table elevation.

The disappearance and reappearance of LNAPL in monitoring wells in response to fluctuating water table elevations is a common occurrence. During a rising water table condition, there is a delay in the response or rising of the LNAPL in the formation as buoyancy forces attempt to move the LNAPL upward through the resistance presented by the soil formation (Oostrom et al., 2006). This delay is due to the resistance to LNAPL movement provided by the soil matrix and the fact that groundwater is less viscous than LNAPL and is able to move more easily through the soil than LNAPL. The LNAPL in a well, however, does not encounter this resistance to upward movement that the LNAPL in the formation does, and will rise on top of the water in the well more quickly than the LNAPL in the formation is able to rise through the soil matrix. This creates an LNAPL gradient from the well toward the formation, resulting in LNAPL flow out of the well and, in some situations, results in all LNAPL disappearing from the well. Conversely, during

seasonal low water tables, more of the LNAPL in the smear zone becomes exposed, gaining the ability to drain from the newly unsaturated soil under gravity and flow in the soil and/or into a monitoring well (due to a lower residual saturation in the unsaturated zone). This explains the reappearance of LNAPL or increases in LNAPL thickness in wells during seasonal low water tables.

The rising and lowering of the water table has a direct influence on the inherent mobility of LNAPL within an LNAPL body, but a localized increase in LNAPL mobility signified by increasing in-well LNAPL thickness does not necessarily indicate that an LNAPL body is unstable or migrating. Furthermore, at sites that do not have ongoing sources, changes in in-well LNAPL thickness that correlate with fluctuations in the water table elevation are more likely to be a result of localized vertical redistribution of LNAPL in and out of the well (as described above) as opposed to being representative of any significant lateral mobility (ITRC, 2009a).

As suggested above, LNAPL thickness in a monitoring well varies inversely with water table elevation in an unconfined setting or condition. Hence, an increase in water table elevation results in a decrease in in-well LNAPL thickness. Conversely, a decrease in water table elevation results in an increase in in-well LNAPL thickness. In a confined setting (including LNAPL present in the secondary porosity of silts, clays and possible fractured rock), in-well LNAPL thickness tends to vary directly with potentiometric surface elevation. Hence, an increase in potentiometric surface elevation results in an increase in in-well LNAPL thickness, and vice versa.

LNAPL STABILITY AND POTENTIAL EXPOSURES

LNAPL Stability

LNAPL stability relates to the ability or inability of an LNAPL body to migrate (i.e., whether or not the periphery or extent of an LNAPL body is expanding/advancing over time). If the periphery of an LNAPL body is growing or moving over time, the body is typically referred to as migrating or unstable. If the LNAPL body remains essentially the same size and in the same location over time (i.e., same overall footprint over time), the body is referred to as stable or non-migrating. Generally speaking, most historical LNAPL bodies where the release has terminated will be found to be stable. LNAPL bodies are spatially self-limiting, unless continually supplied from an ongoing release, which sets them apart from dissolved and vapour plumes, which can migrate significant distances (API 2004). Typically, once the release stops, the LNAPL will eventually cease to move as the resistive forces in the saturated soils balance the dissipating LNAPL head (API, 2002; Huntley and Beckett, 2001). Often times, the following factors combine to produce a stable plume that is not spreading or migrating (US EPA, 2005):

- LNAPL fluid properties
- LNAPL relative permeability
- Conductivity of the porous media
- Hydraulic gradient
- Pore throat displacement entry pressure
- Fluctuating water table

With regard to an LNAPL body as a whole, LNAPL will often be found to possess some localized mobility within interior portions of the body where LNAPL saturations are highest (and in-well LNAPL thicknesses can be significant), and to be immobile at the outer edges of the body where saturation decreases to a residual level. Hence, the overall body will remain stable despite the presence of localized areas where LNAPL may be sufficiently mobile to be observed in wells and recovered. In the case of LNAPL that has been stable for some time, the potentially mobile fraction represented by the LNAPL observed in wells will most likely represent a very small fraction of the overall LNAPL body.

Figure A.10 provides a conceptual drawing of an LNAPL body that is continuing to expand or migrate. The expanding body is represented at the periphery by thick “force” arrows, which indicate that the LNAPL has sufficient pressure or head to continue displacing groundwater. Conversely, Figure A.11 shows a stable LNAPL body with “force” arrows that are in equilibrium with the counteracting force produced by the resistance of the soil and groundwater.

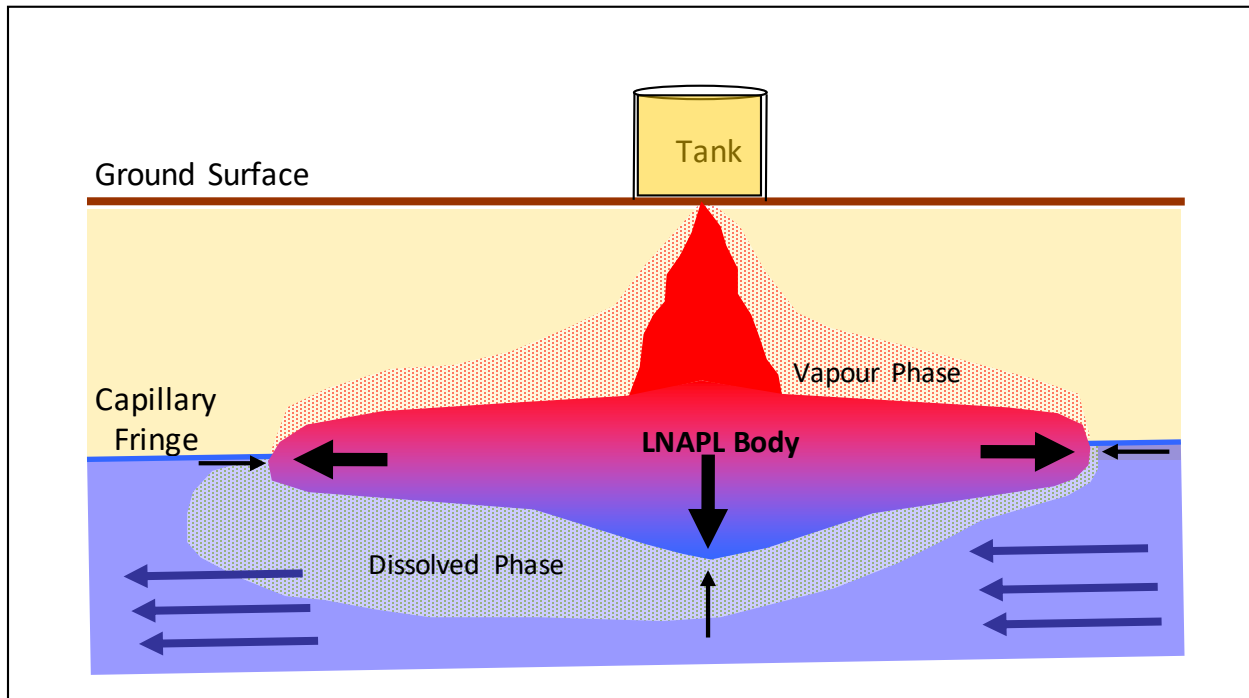


Figure A.10 Expanding/migrating LNAPL body (thick force/pressure arrows within body indicate continued migration in all directions)

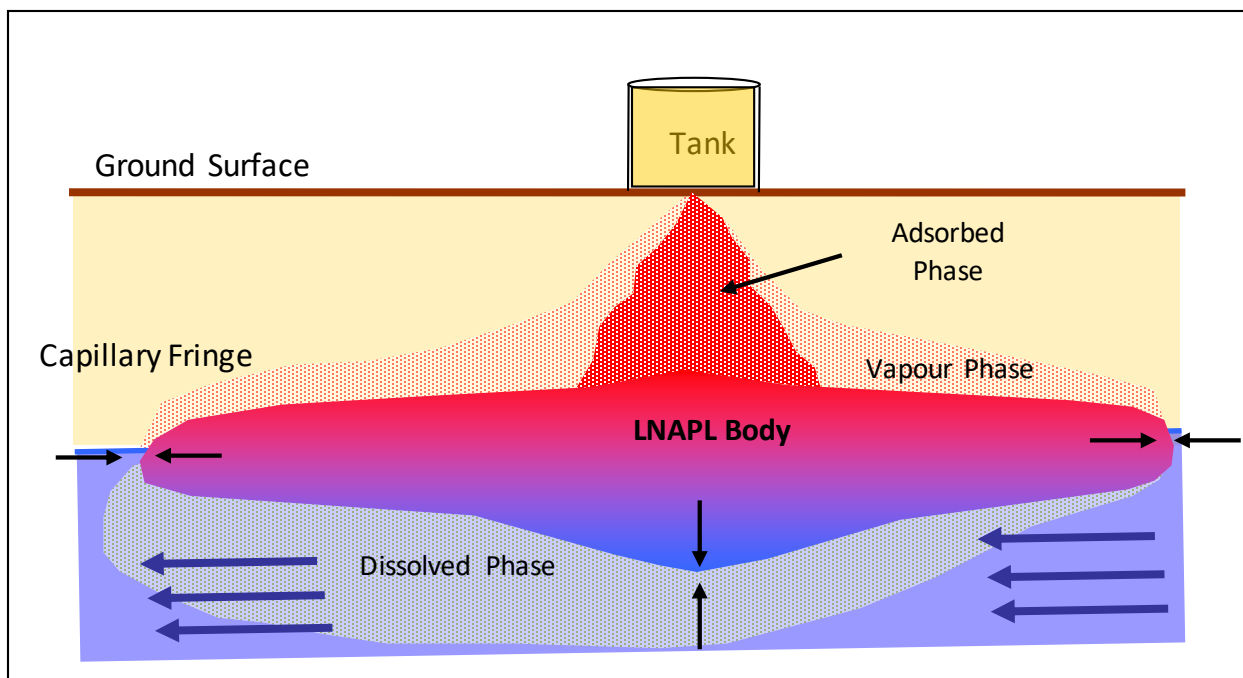


Figure A.11 Stable/non-migrating LNAPL body (arrows within and outside of LNAPL body indicate that opposing forces/pressures are in equilibrium)

Water table fluctuations in a stable LNAPL body may cause immobile LNAPL to migrate in a very localized area and flow or drain into an immediately adjacent monitoring well. However, although some limited LNAPL drainage and vertical redistribution or smearing may occur, the LNAPL body is likely to remain stable and immobile. Hence, at a site with a stable LNAPL body (i.e., release of LNAPL has ceased), the disappearance of LNAPL from a monitoring well for months or even years and its subsequent reappearance, does not necessarily mean that the LNAPL is migrating.

Although in many cases the fate of and risk associated with contaminants within the dissolved phase plume are of primary regulatory importance, the evaluation of metrics that measure the stability (and recoverability) of the LNAPL body is also critical as this stability is directly related to the stability of the dissolved phase plume. A portion of an LNAPL body will always exist as immobile and unrecoverable residual (excluding consideration of excavation options), thereby providing a fundamental limit to the fraction of an LNAPL body that may contribute to instability. Upper-bound estimates of LNAPL fractions that are recoverable at LNAPL sites without the use of excavation fall in the 40-60% range (API 2004). However, this level of recovery is only likely to be achieved with relatively recent releases characterized by high LNAPL saturations and recovery potential.

Potential Exposures

Figure A.12 presents a conceptual drawing of an LNAPL release with potential exposure scenarios. The extent to which an LNAPL body may pose a risk to human health and/or the environment will depend greatly on the type of LNAPL involved, the amount of time the LNAPL has been in the ground, and the

proximity and sensitivity of the receiving environments. The potential level of risk posed by the dissolved phase plume resulting from the presence of an LNAPL body will be a major factor in a site owner’s decision on whether to use active or passive remedial approaches.

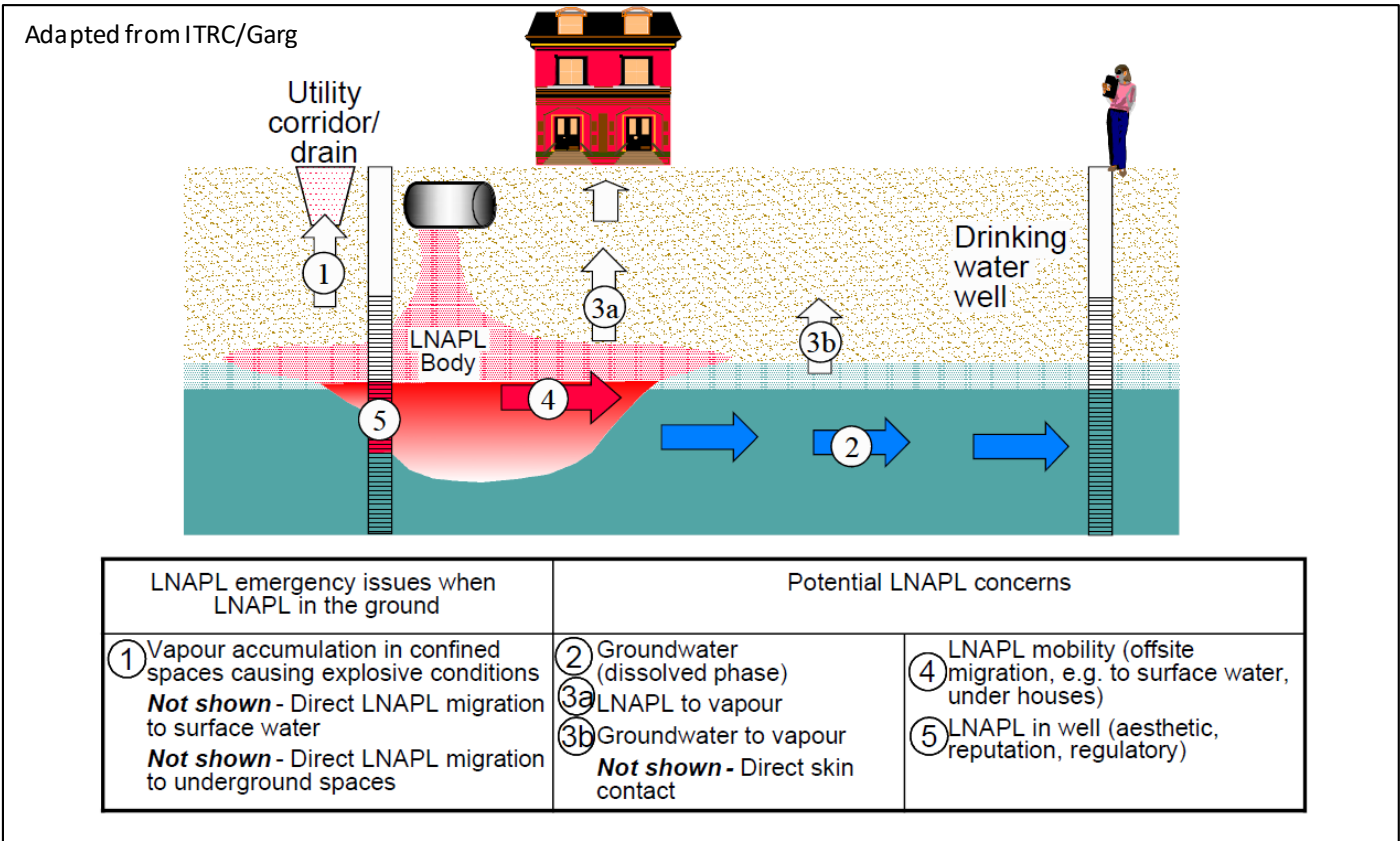


Figure A.12 Conceptual release and potential exposures

The risk of potential exposures varies significantly with LNAPL type, with heavier LNAPL types such as oils typically representing much less potential risk than lighter fuels such as gasoline which contain more volatile and soluble constituents. The potential risk associated with a given LNAPL will also decrease over time as (natural source zone depletion) NSZD processes progressively reduce volatility and constituent dissolution rates. Consequently, older degraded LNAPL typically represents less potential risk than newer releases. For this reason, older degraded and/or heavier LNAPL bodies can be often found to produce levels of dissolved and/or vapour phase impacts that are well within typical risk-based screening levels. It is also noted that gasoline LNAPLs may contain additives that will be of significance in the evaluation of potential exposures (e.g., oxygenates, methyl tert-butyl ether/MTBE). Figure A.13 provides an overview of the properties of different LNAPL types.

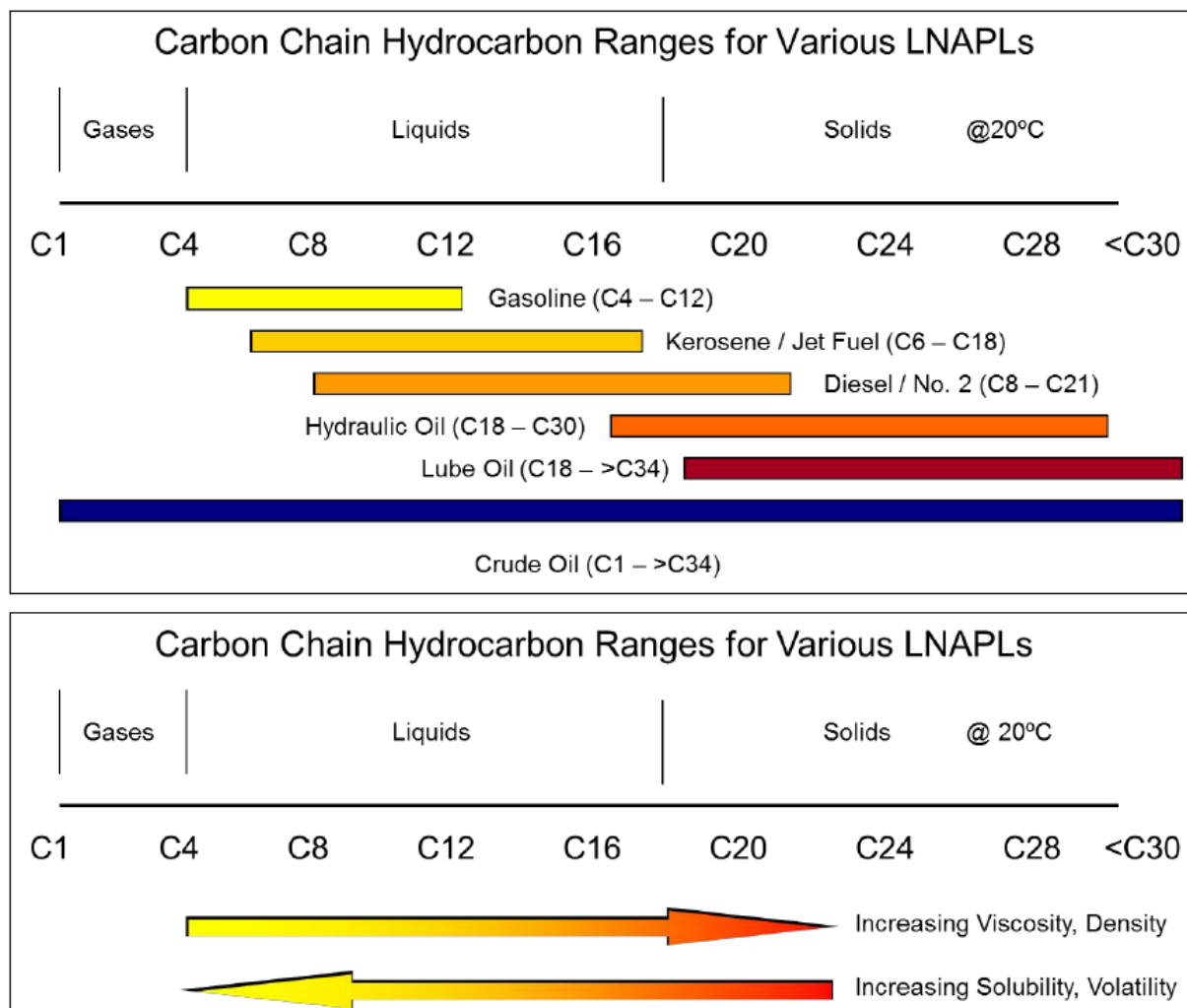


Figure A.13 Properties of different LNAPL types

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Appendix A – LNAPL Basics

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Appendix B LNAPL Site Management Checklist

Table B.1 LNAPL Site Management Checklist

	Question	Answer / Comment	
1	Site Goals and Regulatory Framework		
1.A	Are site goals well defined?	<input type="radio"/> Yes	
		<input type="radio"/> No	Engage stakeholders and establish goals.
1.B	Are regulatory requirements well understood?	<input type="radio"/> Yes	
		<input type="radio"/> No	Determine appropriate requirements/criteria.
2	LNAPL Release History ⁵ and Properties		
2.A	Is the source of the LNAPL release known? (indicate if high volume and/or pressure release)	<input type="radio"/> Yes	
		<input type="radio"/> No	Determine whether the federal government is responsible. Consider a more comprehensive historical review (expanded Phase 1 ESA).
2.B	Is there any possibility of an ongoing release?	<input type="radio"/> Yes	Take immediate steps to halt release.
		<input type="radio"/> No	
2.C	Is there an imminent threat posed by the release that warrants immediate mitigation or emergency response?	<input type="radio"/> Yes	Activate emergency response or implement mitigation measures.
		<input type="radio"/> No	
2.D	Is the LNAPL type/types known?	<input type="radio"/> Yes	
		<input type="radio"/> No	See Table 3 for LCSM development options.
2.E		<input type="radio"/> Yes	

⁵ Eligibility for FCSAP remediation funding may be influenced by release history, specifically whether contamination resulted from activities prior to or after April 1, 1998. The *FCSAP Directive on Phase IV Site and Costs Eligibility – Version 1.0* (FCSAP, 2021c) includes additional information on the basic eligibility criteria and relevant exceptions.

Appendix B – Checklist

	Question	Answer / Comment	
	Is the date of the LNAPL release/approximate age of the LNAPL known?	<input type="radio"/> No	See Table 3 for LCSM development options.
2.F	Are the relative density/specific gravity and viscosity of the LNAPL known?	<input type="radio"/> Yes	
		<input type="radio"/> No	See Table 3 for LCSM development options.
3	LNAPL Body		
3.A	Has the areal extent and vertical distribution of the LNAPL body been defined?	<input type="radio"/> Yes	
		<input type="radio"/> No	
		Indicate techniques used: <input type="radio"/> Visual/olfactory soil screening <input type="radio"/> Photo ionization detector (PID) soil screening <input type="radio"/> Hydrophobic dye soil screening <input type="radio"/> UV light soil screening <input type="radio"/> Traditional soil sampling and laboratory analysis <input type="radio"/> Soil core photography/petrophysical testing <input type="radio"/> Monitoring well data (gauging, sampling) <input type="radio"/> Electrical resistivity <input type="radio"/> Laser-induced fluorescence (LIF) * See Table 3 for more on LCSM development options.	
3.B	Is the LNAPL body stable in overall extent?	<input type="radio"/> Yes	
		<input type="radio"/> No	
		Lines of evidence: <input type="radio"/> Age of LNAPL <input type="radio"/> Sentry well monitoring <input type="radio"/> Dissolved phase trends <input type="radio"/> One or more LNAPL mobility lines of evidence along LNAPL body periphery	

Appendix B – Checklist

	Question	Answer / Comment	
		<input type="radio"/> Natural attenuation indicators <input type="radio"/> LNAPL critical head estimates at LNAPL periphery * See Table 3 for more on LCSM development options.	
3.C	Do areas with potentially mobile LNAPL exist within the LNAPL body?	<input type="radio"/> Yes <input type="radio"/> No	Indicate available lines of evidence: <input type="radio"/> Age of LNAPL <input type="radio"/> LNAPL saturation and/or residual saturation determinations (soil core petrophysical testing) <input type="radio"/> LNAPL transmissivity estimates <input type="radio"/> LNAPL recovery system performance <input type="radio"/> LNAPL saturation and/or residual saturation estimates (total petroleum hydrocarbons [TPH] conversions, analytical modelling) * See Table 3 for more on LCSM development options.
3.D	Has natural attenuation of the LNAPL body been assessed?	<input type="radio"/> Yes <input type="radio"/> No	Indicate available lines of evidence: <input type="radio"/> Soil data (petroleum degrading bacteria) <input type="radio"/> Soil gas data (soil gas concentration profiles, carbon dioxide, methane) <input type="radio"/> Dissolved phase natural attenuation indicators * See Table 3 for more on LCSM development options.
4	Dissolved and Vapour Phases		
4.A	Has any related dissolved phase plume been delineated?	<input type="radio"/> Yes <input type="radio"/> No	Indicate available lines of evidence: <input type="radio"/> Monitoring well sampling

Appendix B – Checklist

	Question	Answer / Comment	
		<input type="radio"/> Membrane interface probe (MIP) * See Table 3 for more on LCSM development options.	
4.B	Has the stability of the dissolved phase plume been evaluated?	<input type="radio"/> Yes	
		<input type="radio"/> No	
		Indicate available lines of evidence: <input type="radio"/> Trend analysis of groundwater monitoring data over time <input type="radio"/> Spatial distribution of groundwater monitoring data <input type="radio"/> Geochemical parameters (dissolved O ₂ , NO ₃ ⁻ , SO ₄ ²⁻ , ferrous iron (Fe ²⁺), manganese (Mn ²⁺), CO ₂ , and CH ₄) * See Table 3 for more on LCSM development options.	
4.C	Has natural attenuation of the dissolved phase been assessed?	<input type="radio"/> Yes	
		<input type="radio"/> No	
		Indicate available lines of evidence: <input type="radio"/> Soil data (e.g., petroleum-degrading bacteria) <input type="radio"/> Trend analysis of groundwater monitoring data over time <input type="radio"/> Spatial distribution of groundwater monitoring data with respect to LNAPL body extent <input type="radio"/> Dissolved phase natural attenuation indicators (spatial/temporal reduction in constituent concentrations, terminal electron acceptors, geochemical parameters) * See Table 3 for more on LCSM development options.	
4.D	Has the potential for vapour phase impacts been evaluated (including methane)?	<input type="radio"/> Yes	
		<input type="radio"/> No	See Table 3 for LCSM development options.
5	Potential Exposures		
5.A	Identify potential receptors and detail any relevant land use	<input type="radio"/> Human health:	
		<input type="radio"/> Ecological:	

Appendix B – Checklist

	Question	Answer / Comment	
	information (e.g., potable water sources, age groups, site uses/activities)	Indicate available lines of evidence: <input type="radio"/> Exposure and effects determination	
5.B	Have any risk-based criteria been exceeded?	<input type="radio"/> Yes	Confirm relevance of pathways.
		<input type="radio"/> No	
5.C	Are any of the respective pathways complete or potentially complete in the future?	<input type="radio"/> Yes	
		<input type="radio"/> No	

Additional information can be obtained at:

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