GOLDER

REPORT

TOOLKIT #3 – EVALUATION OF REMEDIATION TECHNOLOGIES FOR PETROLEUM HYDROCARBON SITES

Remediation Toolkits Project

Submitted to:

Contaminated Sites Approved Professional Society of British Columbia & Shell Global Solutions

Submitted by:

Golder Associates Ltd.

Suite 200 - 2920 Virtual Way, Vancouver, British Columbia, V5M 0C4, Canada

+1 604 296 4200

1417511-009-R-Rev1

5 April 2021

Acknowledgement

The funding for this project was provided by the Contaminated Sites Approved Professional Society of British Columbia and Shell Global Solutions US Inc.

The primary authors of Toolkit #3 were Dr. Ian Hers of Hers Environmental Consulting, Inc. and Dr. Parisa Jourabchi of ARIS Environmental Ltd. Ms. Linda Kemp of Golder Associates Ltd. also contributed to the document.

The review and input provided by Dr. Matthew Lahvis, of Shell Global Solutions US Inc., and Mr. Guy Patrick, of Patrick Consulting, Inc. representing CSAP is gratefully acknowledged.

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Executive Summary

“Toolkit #3 – Evaluation of Remediation Technologies for Petroleum Hydrocarbon Sites” comprises the third of a four-volume set of toolkits developed to provide guidance and improved decision-making for practitioners who are involved with the investigation and remediation of petroleum hydrocarbon contaminated sites. The framework and tools in the toolkits are intended to lead to better, more technically-defensible decisions for evaluation of remedial options and sustainable remediation.

The four toolkits in the series are as follows[1]:

- Toolkit #1: Conceptual Site Model (CSM) and Case Studies (Golder 2016).
- Toolkit #2: Methods for Monitoring and Prediction of NSZD and MNA (Golder 2016).
- Toolkit #3: Evaluation of Remediation Technologies for Petroleum Hydrocarbon Sites (this report).
- Toolkit #4: Methods for Sustainable Remediation (Golder 2021).

Toolkit #3 describes a science-based approach for identification, screening and selection of remedial technologies based on the light non-aqueous phase liquid (LNAPL) conceptual site model, LNAPL concerns or risks, remedial goals, primary mechanisms and broad objectives, specific remedy criteria, performance metrics and transition thresholds. The guidance begins with a review of remedial options frameworks in other jurisdictions, followed by recommended site management process and step-wise approach to screening and selection of remedial technologies, and ends with a case study example. While the guidance does not address regulatory policy, the requirements of the BC Environmental Management Act (Section 56) and related protocols and guidance for selection of remediation options should be followed in British Columbia.

Toolkit #3 incorporates the emerging understanding of natural and enhanced attenuation of source zones and associated plumes in the identification of the site contamination concern and risk, selection of technologies and appropriate transition from active to natural remediation and ultimately site closure. The science, described in Toolkits #1 and #2, indicates that natural source zone depletion (NSZD) occurs through different mechanisms at relatively consistent rates for a broad cross-section of site types and results in depletion of bulk mass of hydrocarbons and contaminants of potential concern (COPCs)[2] over longer time frames. Empirical multi-site studies and modeling provide insight on the relative effectiveness of natural and enhanced attenuation and limits of different remedial strategies.

The overall framework is provided in Figure ES-1.

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[1] Remediation Toolkits 1 and 2 are available at https://csapsociety.bc.ca/members/professional-development/technical-studies/

[2] Depending on investigation stage may be contaminants of concern (COCs)

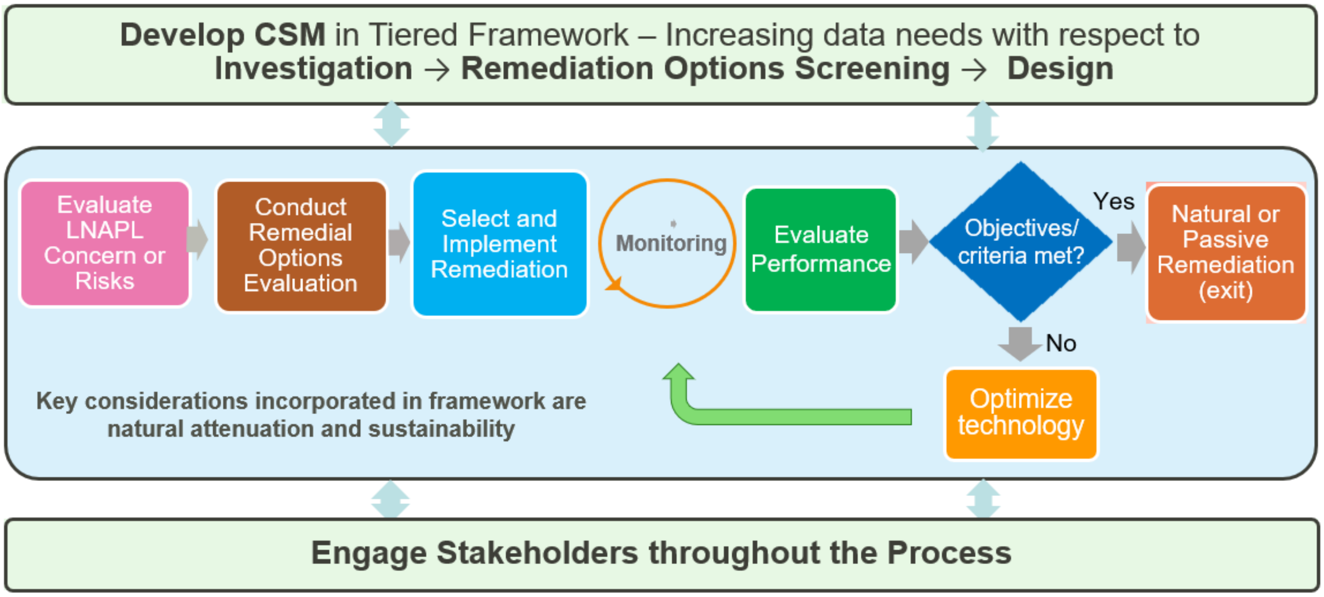

Figure ES-1. Remediation Framework

The site management process is divided into seven stages consisting of 1) identifying and verifying concerns; 2) establishing remedial goals; 3) identifying primary remediation mechanisms and broad remedial objectives; 4) identifying specific remedial criteria; 5) evaluating and selecting a remedy; 6) identifying performance metrics and transition thresholds; and 7) evaluating remedial performance and transition.

Following ITRC (2018), the LNAPL concerns or risks include:

- Migrating LNAPL, defined as a mobile LNAPL footprint that is expanding.
- Mobile LNAPL, defined as LNAPL above residual saturation, which exceeds an acceptable threshold.
- Subsurface concentrations (soil, groundwater, soil vapour) or mass flux or mass discharge associated with LNAPL sources that are above regulatory criteria or standards, and that typically are based on health risk concerns, and/or biogenic gas concentrations above a threshold that is based on safety risk (e.g., explosive soil gas concentrations).
- Aesthetic concerns (e.g., sheens or odours).

The staged remediation process incorporates potential concerns or risks to identify remedial goals, consisting of Saturation-, Composition-, Containment-, and Aesthetic-based goals. Saturation-based goals address migrating and mobile LNAPL concerns; Composition-based goals address concentration and mass flux or mass discharge concerns; Containment-based goals address migrating LNAPL and migrating plume concerns; and Aesthetic-based goals address aesthetic concerns. Flow-charts for the end-to-end remediation strategy for the Saturation- and Composition-based goals are provided in Figures ES-2 and ES-3.

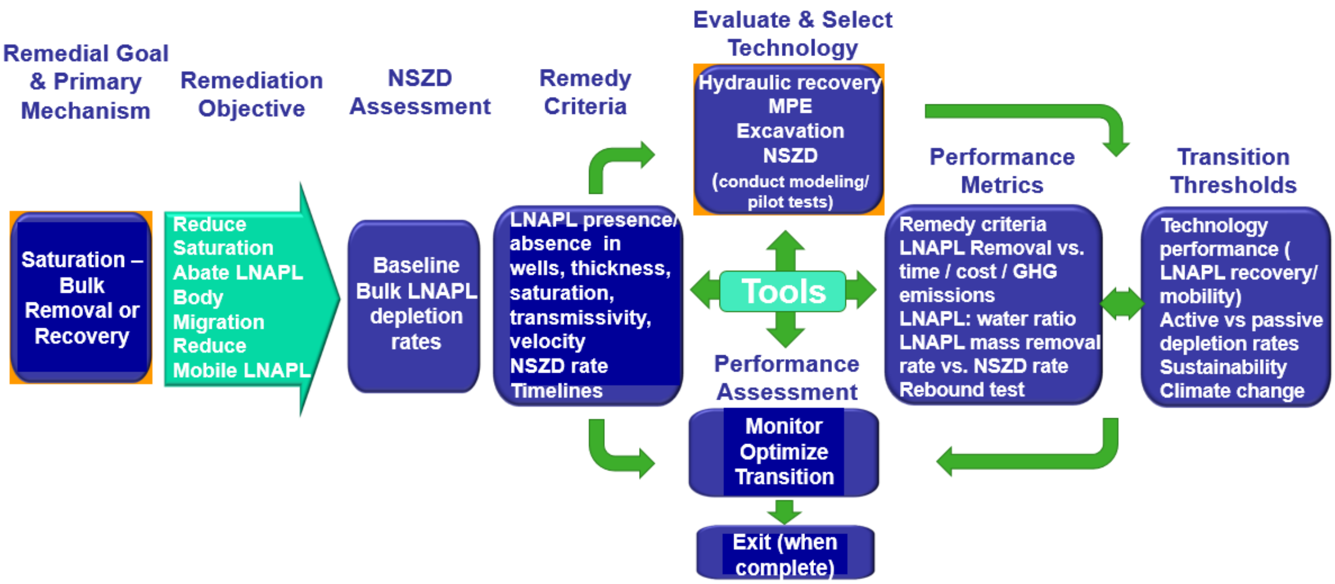

Figure ES-2: Remediation Options Evaluation Process for Where Concern is LNAPL Migration or Presence of Mobile LNAPL and there is a Saturation-based Remedial Goal

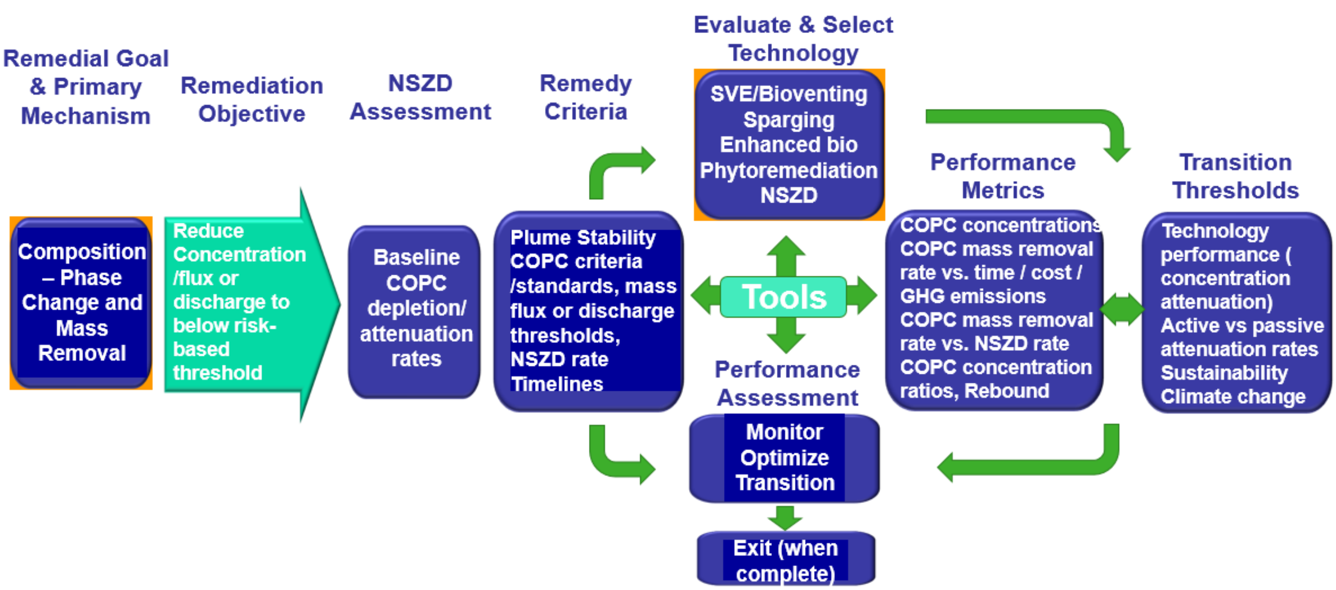

Figure ES-3: Remediation Options Evaluation Process for Where Concern is a Health Risk (above standard) and there is a Composition-based Remedial Goal

Following from the remedial goal, the remedial mechanism to achieve the goal is identified, consisting of Mass Recovery, Phase Change, and combination of Enhanced Phase Change and Mass Recovery. Remedy criteria depend on the remediation goal: when there is a Saturation-based goal, LNAPL stability is often the primary criteria to be met. In the context of a composition-based goal, there are often regulatory criteria or standards for different media; or mass flux, mass discharge and/or mass loading thresholds established from risk assessment. Remedy criteria may also include desired timelines for achieving criteria or standards.

Based on desired remedial mechanisms and objectives, a subset of applicable technologies is identified (Step 1), which are further screened according to technical feasibility and implementability (Step 2) and technology screening factors (Step 3). The technology screening factors include qualitative sustainability indicators, or a more detailed quantitative evaluation of sustainability can be conducted, as described in Toolkit #4. Approaches and models for estimation of natural attenuation rates and assessing longevity of petroleum hydrocarbon sources are addressed in Toolkits #1 and #2. An emerging consideration is incorporation of climate change and increasing likelihood of extreme weather events and wildfires into the remediation lifecycle.

Performance metrics are used to assess the performance of the remedy relative to defined objectives and remedy criteria and include: 1) subsurface metrics such as LNAPL recovery or transmissivity (Saturation), or measured subsurface concentrations, mass flux and/or mass discharge (Composition); and 2) system metrics, such as mass removal rates, concentration ratios or attenuation, or other system parameters. Evaluation of remedy performance will often require rebound tests to be conducted where an active system is turned off and subsurface and system metrics are monitored. Transition thresholds integrate remedy criteria and performance metrics, and are used for decision-making on when and how to support transitions from active to passive remedies. Transition thresholds should be established early in the remediation planning process. A new aspect of this framework is the incorporation of baseline NSZD measurements as a benchmark for comparison to active technologies.

A multiple lines of evidence framework for evaluating technology transitions from active to passive remedial technologies and site closure is presented, and consists of three main parts: 1) evaluate technology performance and limits; 2) compare relative performance of technologies including natural remediation, and 3) evaluate sustainability for project lifecycle. Based on these guiding principles, specific transitions thresholds may be identified depending on the concern, including for example, LNAPL recovery reaching an asymptote, LNAPL transmissivity below a defined threshold, progress to achieving concentration criteria, cross-over point between active and natured-based depletion rates (where active rates are less than nature-based rates), and greenhouse gas emissions (or other sustainability indicator) relative to mass removed or other endpoint. The guidance concludes with an example case study where the process is described for a hypothetical site where LNAPL recovery and soil vapour extraction (SVE) remediation is initially implemented, followed by transition to natural remediation approach.

The science-based and structured approach to identification of the LNAPL concern and risk, goals and objectives, remedy criteria, performance criteria and transition thresholds is expected to result in greater confidence in reaching remedy criteria, more informed decision-making and transitions from active to natural remediation, and increased overall sustainability of remediation and improved process for achieving site closure.

Glossary

ASTM	American Society for Testing and Materials
CL:AIRE	Contaminated Land: Applications in Real Environments (UK)
COPC	contaminant of potential concern
CSM	conceptual site model
DPE	dual-phase extraction
FCSAP	Federal Contaminated Sites Action Plan
FRTR	Federal Remediation Technologies Roundtable
GHG	greenhouse gas
GSR	green and sustainable remediation
GOST	Guidance and Orientation for Selection of Remediation Technologies (Canada)
ISCO	in situ chemical oxidation
ITRC	Interstate Technology and Regulatory Council
LCA	life cycle analysis
LNAPL	light non-aqueous phase liquid
MCA	multi-criteria analysis
MNA	monitored natural attenuation
MPE	multi-phase extraction
NSZD	natural source zone depletion
PRB	permeable reactive barrier
SVE	soil vapour extraction
SR	sustainable remediation
TPH	total petroleum hydrocarbons

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1.0 INTRODUCTION

"Toolkit #3 – Evaluation of Remediation Technologies for Petroleum Hydrocarbon Sites" comprises the third of a four-volume set of toolkits developed to provide guidance and improved decision-making for practitioners who are involved with the investigation and remediation of petroleum hydrocarbon contaminated sites (herein referred to as the "Remediation Toolkits"). The Remediation Toolkits have been developed to provide both technical background and a science-based practical means to evaluate natural source zone depletion (NSZD), monitored natural attenuation (MNA) and remediation of light non-aqueous phase liquid (LNAPL) source zones and associated plumes.

The four toolkits in the series are as follows:

- Toolkit #1: Conceptual Site Model and Case Studies (Golder, 2016)
- Toolkit #2: Methods for Monitoring and Prediction of NSZD and MNA (Golder, 2016)
- Toolkit #3: Evaluation of Remediation Technologies for Petroleum Hydrocarbon Sites (this report)
- Toolkit #4: Methods for Sustainable Remediation (Golder, 2021)

The framework and tools in this series of toolkits are intended to lead to better, more technically-defensible decisions for evaluation of remedial options and sustainable.

Toolkit #3 describes a science-based approach for identification, screening and selection of remedial technologies based on the LNAPL conceptual site model, LNAPL concerns or risks, remedial goals, primary mechanisms and broad objectives, remedial objectives, performance metrics and transition thresholds. An improved understanding of NSZD and MNA within the above framework for site contamination concern, risk and remediation can be used to make more informed decisions regarding the selection of technologies and appropriate transition from active remediation to implementation of natural remediation and ultimately site closure. Toolkit #3 does not provide details on how to evaluate site risk, including, developing a conceptual site model (CSM) and assessing contaminant mobility and recoverability. Such guidance is readily available elsewhere (e.g., ITRC 2018). These concepts are, however, summarized in this toolkit in the context of a framework for remedial decision making.

The organization of this toolkit is summarized as follows:

Section 2.0 is a summary of the BC regulatory framework with respect to remediation requirements.

Section 3.0 presents a review of select guidance on methods for evaluation of remedial options.

Section 4.0 describes the toolkit framework for site assessment focused on the LNAPL conceptual site model followed by the recommended approach for evaluation of remedial options.

Section 5.0 describes how to assess remediation technology performance and technical basis for transitions from active to passive remediation.

Section 6.0 presents a case study on implementation of the toolkit approach.

2.0 BC REGULATORY FRAMEWORK

In British Columbia, current protocols and technical guidance published by the BC Ministry of Environment and Climate Change Strategy (BC ENV) that address remediation requirements are:

- BC ENV Draft Technical Guidance (TG) 22 "Using Monitored Natural Attenuation (MNA) and Enhanced Attenuation (EA) for Groundwater Remediation" (November 2014) Requirements for demonstrating dissolved groundwater plume stability are described in BC ENV T8 “Groundwater Investigation and Characterization” (January 5, 2021).
- BC ENV TG 14, “Operation of Soil Treatment Facilities for the Bioremediation of Hydrocarbon Contaminated Soil” (April 2013) provides guidance and recommendations on operation of soil treatment facilities for the ex-situ bioremediation of hydrocarbon contaminated soil.
- BC ENV Protocol 15 “Soil Treatment Facility Design and Operation for Bioremediation of Hydrocarbon Contaminated Soil” (July 17, 2012) sets minimum requirements for the design, operation and management of soil treatment facilities. The protocol includes recommended levels of key environmental parameters for microbial populations, oxygen, pH, soil temperature, moisture content, and nutrient levels.

Draft BC ENV TG 22 indicates prerequisites for the application of MNA and EA include the use of these technologies resulting in concentration goals being met within 20 years. Sites applicable for implementation of MNA or EA remediation are sites with no unacceptable risks to human health or the environment and sites with stable or shrinking groundwater plumes. The effectiveness of MNA or EA must be demonstrated using a Multiple Lines of Evidence (MLE) approach including:

1) Observed reduction in contaminant mass (required), and
2) Use of geochemical and biochemical indicators (required); or
3) Microbiological laboratory data (only if the first and second lines of evidence are inconclusive).

BC ENV Protocol 13 and TG 8 provide information on technical methods for assessment of plume stability. Toolkit #1 provides an overview of case studies on remediation timelines for different technologies and Toolkit #2 provides detailed description of methods and tools for analysis of plume stability and longevity.

Additionally, the requirements of the BC Environmental Management Act (Section 56) for selection of remediation options must be followed in British Columbia.

3.0 REVIEW OF SELECT GUIDANCE ON EVALUATION OF REMEDIAL TECHNOLOGIES

Select existing guidance on evaluation of remediation technologies to support remedial decisions available through regulatory programs in Canada, US and United Kingdom, are summarized below.

- The Interstate Technology & Regulatory Council (ITRC) provides guidance for evaluating LNAPL remedial technologies (ITRC 2018). Overall, twenty-one technologies for LNAPL are systematically evaluated according to potential concern, remedial goals and objectives.
- The Contaminated Land: Applications in Real Environments (CL:AIRE) provides a series of remediation documents that are divided into three categories: 1) remediation options; 2) implementation of remediation strategy; and 3) management and evaluation of the remediation strategy.
- Several US federal agencies have collaborated to create a compendium of information for hazardous waste cleanup (Federal Remediation Technologies Roundtable (FRTR 2020).
- The Government of Canada, National Research Council (NRC 2020) has prepared a tool referred to as the “Guidance and Orientation for the Selection of Technologies,” or GOST tool, that contains practical information and factsheets for the implementation of various remedial technologies.
- The US National Research Council (US NRC 2004) report provides a basis for technology selection that is informed by site characterization data, remediation objectives and metrics. The report is the result of a study requested by the US Army Environmental Center to evaluate source remediation as a cleanup strategy with focus on dense non-aqueous phase liquids (DNAPLs) and chemical explosives.

The above guidance documents are further summarized in Appendix A.

4.0 FRAMEWORK FOR SITE ASSESSMENT AND EVALUATION OF REMEDIATION OPTIONS

The Toolkit #3 framework is a staged process for management of petroleum hydrocarbon impacted sites that consists of the following stages (Figure 1):

a) CSM development and evaluation of the LNAPL concern or risks.

b) Evaluation of remediation options.

c) Selection and implementation of remediation option(s).

d) Assessment of whether remediation performance is acceptable (with adjustments or transitions to alternative technologies when appropriate).

e) Assessment of whether remediation goals are met.

f) Confirmation of site closure when goals are met.

In this framework, the primary concern is the LNAPL source and associated plumes. Essential to this process are an understanding of the CSM, stakeholder input, and regulatory requirements. The primary focus of Toolkit #3 is the process for identification, screening and selection of technologies, and establishing appropriate performance metrics. It is not intended as a design manual for remediation systems or as a guide for their operation and monitoring.

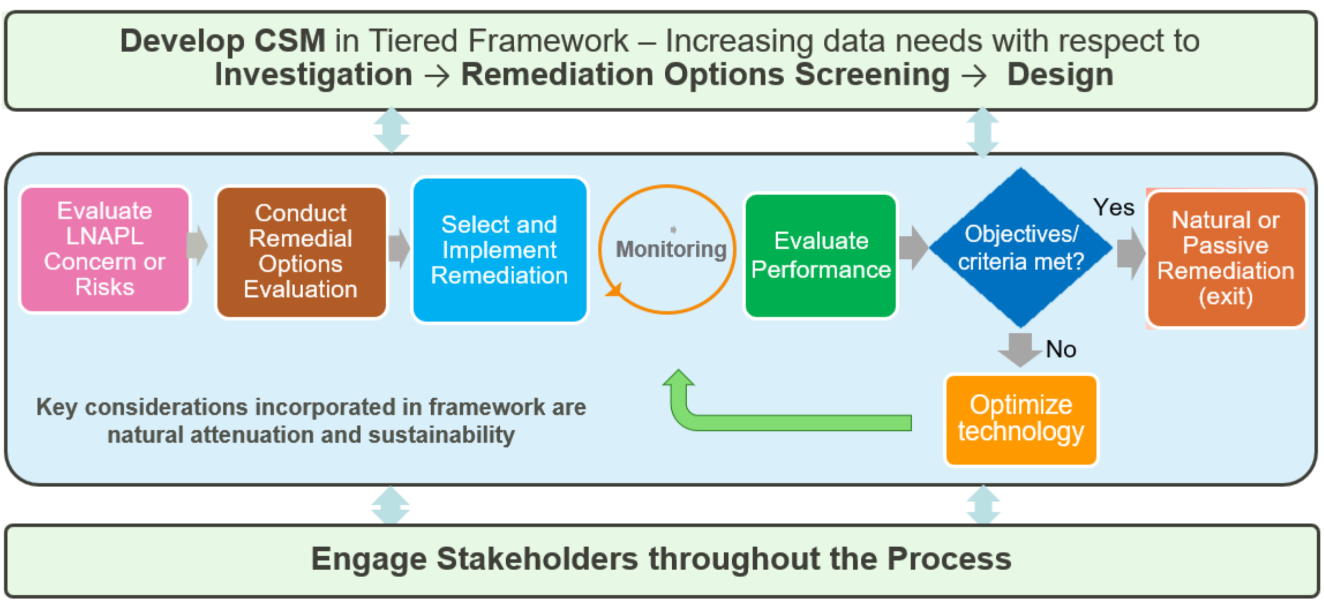


Figure 1: Remediation Framework

The site assessment and remedial options evaluation are divided into a seven-stage process consisting of 1) identifying and verifying concerns; 2) establishing remedial goals; 3) identifying primary remediation mechanisms and broad remedial objectives; 4) identifying specific remedial criteria; 5) evaluating and selecting a remedy; 6) identifying performance metrics and transition thresholds; and 7) evaluating remedial performance and transition (Figure 2).

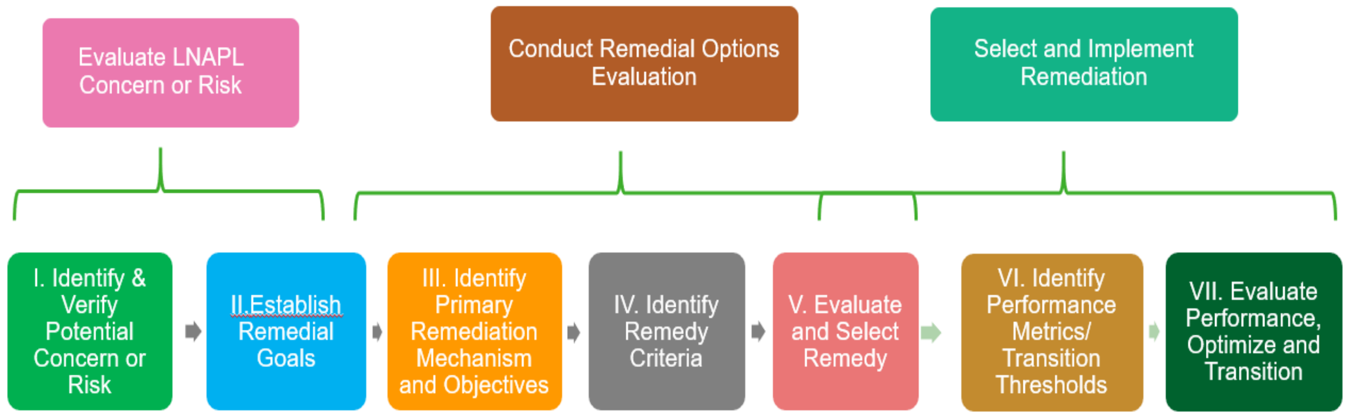


Figure 2: Site Assessment and Remediation Options Evaluation Process

4.1 LNAPL CSM

The development of a CSM is an essential component of providing information needed to identify LNAPL concerns, establish remediation goals and objectives and select remediation options. The CSM data objectives will vary depending on stage, but data needs and complexity will generally be a function of site heterogeneity and will increase as one progresses through the site investigation and remedial options evaluation and implementation phases. Importantly, the CSM should identify risks that require relatively rapid response (e.g., whether LNAPL or associated COPCs are migrating or expanding) and risks that require longer term management (e.g., the extent and magnitude of soil and groundwater contamination above numerical or risk-based standards).

A data checklist for CSM components is compiled in Table 1 and includes “basic” or lower tier data that would typically be obtained at all sites and “advanced” or higher tier data warranted at select sites. The distinction between basic and advanced data is based on best judgment and is intended as a general guide. The CSM checklist is not prescriptive and data requirements will depend on project- and site-specific conditions. Many data types will be required at both the site assessment and remediation stages, but the level of detail and specific data needs may vary. In general, the complexity of the CSM and associated data collection escalates with increasing site heterogeneity and site concern or risk.

The data components include: the site setting, the land use and receptors, information on the LNAPL type and release, the nature and extent of the LNAPL source, the associated dissolved groundwater and soil vapour plumes, the exposure pathways, and factors that affect the petroleum hydrocarbon distribution and fate and transport of associated plumes. These latter factors include geology, hydrogeology, geochemistry and LNAPL and component properties. Consideration should also be given to whether conceptual site model factors could be affected by potential climate change impacts and extreme weather events (Jourabchi and Muppidi 2019; Kumar and Reddy 2020; ITRC 2021). An example is the potential effect of increased precipitation or drought on water table elevations and LNAPL distribution.

Table 1: LNAPL Conceptual Site Model Component and Data Checklist

CSM Component	Basic or Lower Tier Data	Advanced or Higher Tier Data	References	✓
Site setting (risk framework)	Land use, source, pathways, receptors, distance from source to receptor	May include additional data on land use and receptors		
Geology	Stratigraphy, soil classification, index soil properties (soil moisture, grain size)	Specialized laboratory testing for capillary properties, porosity, density, soil permeability	API 4711	
Hydrogeology	Hydrostratigraphic units, hydraulic conductivity, hydraulic gradient, depth to groundwater, single-well response tests	Pumping testing, direct measurement of groundwater velocity, tracer studies, hydraulic profiling	BC ENV Technical Guidance #8 US EPA 2017[14] Verreydt et al. (2017)[15]	
LNAPL release	Evaluation of when release occurred and whether abated from records	Specialized forensics analyses, e.g., GC/FID[17] and/or GC/MS[17], PIANO[17], biomarkers	Stout and Wang (2017)[13]	
LNAPL type composition	Fuel type and additives from records	Detailed compositional (GC/FID and/or GC/MS), mole/mass fraction and weathering analyses	Simulated distillation by ASTM D2887	
LNAPL properties	Density, viscosity	Interfacial tension, vapour pressure	Empirical relations: API 4682, API 4731; Environment Canada Database[1]; Mercer & Cohen (1990); Specialized lab tests: ASTM D1481, ASTM D445, API 4711	
LNAPL distribution	Vertical and horizontal delineation from field tests (headspace vapour, observations of sheens) and TPH data	Specialized field tests through direct push probes and sensors; specialized laboratory testing of LNAPL saturation	Specialized field tests: LIF (ASTM D6187-97(2000), MIP (ASTM D7352-07 (2012); Specialized lab tests: UV light, pore fluids testing, lab centrifuge, water drive (API Bulletin 9[2], ITRC LNAPL Guidance (2018)[3])	
Mobile LNAPL (above residual saturation)	Evaluation of presence based on direct (LNAPL, sheen) and indirect indicators (concentration)	Specialized field and lab testing (see LNAPL distribution)	ITRC 2014 PVI Guidance[4]; see LNAPL distribution for additional references	
Mobile LNAPL behaviour	Confined, unconfined, perched from hydrostratigraphs[5] and/or Diagnostic Gauge Plots (DGPs)	LNAPL behaviour from LNAPL recovery tests	DGPs: ANSR articles[5]; ASTM E2856-13; Kirkman et al. (2013)[12]	
Potential for LNAPL migration or LNAPL body stability?	Line of Evidence (LOE's) include: presence of mobile LNAPL, observational data (in-well LNAPL thickness trends, dissolved plume trends at appropriately located wells, LNAPL transmissivity	LNAPL recovery or decline curve analysis, LNAPL velocity estimates, LNAPL dye tracer test, NSZD rates, modeling	BC Env Protocol 16; ITRC LNAPL Guidance (2018); ASTM E2856-13; API Transmissivity Guide[6]	

CSM Component	Basic or Lower Tier Data	Advanced or Higher Tier Data	References	✓
LNAPL recovery	LNAPL transmissivity, LNAPL recovery decline curves, LNAPL/water ratios	Specialized laboratory tests to support assessment of mobile LNAPL and recovery	ITRC LNAPL Guidance (2018), API Transmissivity Guide	
LNAPL NSZD	Focus on "bulk" TPH or LNAPL depletion rates from nomographs, simple measurements or literature values	NSZD rates of LNAPL or COPCs from CO_2 efflux, gradients in temperature or concentration, or LNAPL composition	Remediation Toolkits #2 and #3; API NSZD Guidance (2017)[7]; ITRC (2018); CRC CARE (2018); CRC CARE (2020)	
Associated groundwater and soil vapour plumes	Concentration data, comparison to applicable criteria and standards, field parameter data (pH, conductivity, redox, dissolved oxygen, etc.)	Mass flux or discharge, geochemistry data (e.g., electron acceptors), use of tracers	BC ENV TG #4, #8, #22; ITRC Mass Flux Guidance (2010)[8]; API 4730; GSI Mass Flux Toolkit[9]	
Preferential pathways	Anthropogenic (utilities) and natural (karst, fractured bedrock) from records and visual observations	Range of technologies including sampling pathways, use of tracers, geophysics techniques and video cameras	Select guidance for advanced methods[10,11]	
Safety concerns	Direct contact with LNAPL, hazardous gas concentrations, gas pressures	Gas flux or discharge measurements, continuous pressure and concentration monitoring	ASTM 2993-16	

Notes:

1) Environment Canada Database http://www.etc-cte.ec.gc.ca/databases/oilproperties/
2) http://www.api.org/~/media/Files/EHS/Clean_Water/Bulletins/09_Bull.pdf
3) ITRC LNAPL Guidance (2018).
4) ITRC PVI Guidance (2014) Table 5-3 http://www.itrcweb.org/PetroleumVI-Guidance/
5) http://www.h2altd.com/ansr
6) API Transmissivity Guide https://www.api.org/oil-and-natural-gas/environment/clean-water/ground-water/lnapl
7) API NSZD Guidance (2017) https://www.api.org/oil-and-natural-gas/environment/clean-water/ground-water/lnapl
8) http://www.itrcweb.org/GuidanceDocuments/MASSFLUX1.pdf
9) http://www.gsi-net.com/en/software/free-software/mass-flux-toolkit.html
10) https://www.serdp-estcp.org/ Program-Areas/Environmental-Restoration/Contaminated-Groundwater/Emerging-Issues/ER-201505/ER-201505
11) http://dnr.wi.gov/files/pdf/pubs/rr/rr649.pdf
12) Kirkman, A.J., M. Adamski and M. Hawthorne. 2013. Identification and Assessment of Confined and Perched LNAPL Conditions. GWMR. Summer.
13) Stout, S. and Z. Wang. 2017. Oil Spill Environmental Forensics Case Studies. Butterworth-Heinemann, Oct. 22 - Technology & Engineering - 860 pg.
14) US EPA. 2017. Best Practices for Environmental Site Management: A Practical Guide for Applying Environmental Sequence Stratigraphy to Improve Conceptual Site Models. https://clu-in.org/s.focus/c/pub/i/2723/
15) Verreydt, G. M. Razaei, P.Meire, I.V.Keer, J. Bronders and P. Seuntjens. 2017. Integrated passive flux measurement in groundwater: design and performance of iFLUX samplers. Geophysical Research Abstracts, Vol. 19, EGU2017-15460.
16) Potential geotechnical concerns associated with LNAPL are beyond scope of this guidance.

GC = gas chromatograph; FID = flame ionization detector; MS = mass spectroscopy; PIANO = paraffins, isoparaffins, aromatics, naphthenes (cycloalkanes), and olefins

Data requirements are site-, project- and technology-specific. For example, if excavation is chosen to remove a small volume of soil impacted with petroleum hydrocarbons, many of the types of data described in Table 1 would not be warranted. In contrast, a large LNAPL release with extensive mobile LNAPL located near a water body in a complex geologic setting may warrant extensive data collection and a detailed CSM.

As part of remedial design and depending on project requirements, bench-scale testing, pilot-scale testing and/or modeling may be conducted. The CSM is refined throughout the end-to-end process of managing contamination as new information becomes available, including before, during and after, the onset of remediation.

4.2 Evaluate LNAPL Concern or Risk

Evaluation of the LNAPL concern or risk is the first stage in the site management process (Figure 2). This section begins by defining commonly considered LNAPL concerns or risks and provides guidance on how to assess the concern. Next, the LNAPL science is summarized focusing on key definitions and lines of evidence for evaluating mobile and migrating LNAPL.

Following ITRC (2018), the LNAPL concerns or risks include the following (Table 2):

- Migrating LNAPL, defined as a mobile LNAPL footprint that is expanding.
- Mobile LNAPL that exceeds an acceptable threshold.
- Soil, groundwater and/or soil vapour concentrations associated with LNAPL sources that are above regulatory criteria or standards, and that typically are based on health risk concerns.
- Biogenic gas concentrations above a threshold that is based on safety risk (e.g., explosive soil gas concentrations).
- Other concerns such as aesthetics or sheens.

Table 2: Criteria, Guidance and Tools to Evaluate LNAPL Concerns or Risks

Potential Concern or Risks	Evaluation Criteria	Select Guidance and Tools
Migrating LNAPL	Multiple lines of evidence (MLE) evaluation	ITRC LNAPL Guidance (2018); ASTM E2856-13, API 4760 (LDRM Model); CL:AIRE LNAPL Handbook (2014); Remediation Toolkits #2 and 3, API NSZD Guidance (2017)
Presence of Mobile LNAPL	LNAPL thickness above a regulatory threshold (focus on thickness to exclusion of other metrics is not recommended)	Regulatory specific BC ENV Protocol 16 ITRC LNAPL Guidance (2018) CL:AIRE LNAPL Handbook (2014)
Health Risk or Safety Risk (soil, groundwater, soil vapour, biogenic gases)	Comparison to numerical or risk-based criteria or standard Risk assessment Safety assessment	Regulatory specific BC Contaminated Sites Regulation BC ENV Protocol 13 See Remediation Toolkit #2 for guidance on MNA ASTM E2993-1 (methane focus)
Aesthetics	Odour and staining Sheen in water	Regulatory specific Project specific

1 – Note geotechnical stability may be a potential additional concern associated with LNAPL presence

When evaluating the potential for migrating LNAPL or whether mobile LNAPL represents a concern, it is important that appropriate metrics be considered. This toolkit provides an overview of key concepts for LNAPL science that inform LNAPL mobility in sections below. For details, the reader is referred to ITRC LNAPL Guidance (2018) and other references provided.

In BC, an assessment of LNAPL mobility should be conducted in accordance with BC ENV Protocol 16. Mobile LNAPL, as defined in Protocol 16, is based on measured in-well LNAPL thicknesses for different soil types. The thicknesses represent theoretical thresholds for LNAPL movement that were predicted from a model. Mobile LNAPL may be demonstrated to be stable (i.e., not migrating), and therefore not mobile, based on the lines of evidence described in Protocol 16. In recent years, the LNAPL science has evolved in that definitions of LNAPL mobility have been refined and multiple lines of evidence are typically evaluated for decision-making. P16 describes two key lines of evidence beyond LNAPL thickness that should be considered when assessing LNAPL mobility. Toolkit #3 and ITRC LNAPL guidance identify additional lines of evidence that may be considered in an evaluation of LNAPL mobility or stability.

4.2.1 Definitions

Definitions for migrating and mobile LNAPL are:

- **Migrating LNAPL.** A LNAPL body that is observed to spread or expand laterally or vertically, or otherwise results in an increased volume of the LNAPL extent; usually indicated by time-series data. Migrating LNAPL does not include LNAPL that appears and disappears in a well due to a fluctuating water table.
- **Mobile LNAPL.** LNAPL that exceeds residual saturation and that is present as a continuous phase and consequently can enter a well but is not necessarily migrating. Residual saturation can be defined as the saturation at and below which LNAPL will no longer flow in an aquifer even under applied gradients (ITRC 2018). LNAPL saturation is the ratio of soil voids filled with LNAPL divided by the total volume of voids.

4.2.2 Key Mechanisms

Key factors that determine the potential for LNAPL migration include the LNAPL pressure head and gradient, and pore-scale forces including capillary pressures, gravity and buoyancy. In water-wet pores, the LNAPL pressure head must exceed the capillary pressure for LNAPL migration to occur, which is a function of the soil and LNAPL properties. As the LNAPL head dissipates, the potential for LNAPL migration is reduced, and therefore the potential for LNAPL migration generally decreases with increasing time after the release has ceased.

An additional factor that contributes to overall LNAPL body stability over longer time frames is LNAPL depletion through natural processes (e.g., dissolution, biodegradation, and volatilization). Where the LNAPL head exceeds the capillary pressure, the LNAPL may migrate (often slowly as controlled by the LNAPL saturation, LNAPL viscosity and soil permeability), but the overall LNAPL body may be stable if the rate of migration is matched or exceeded by the rate of natural LNAPL depletion.

4.2.3 Apparent LNAPL Thickness

The apparent LNAPL thickness in a monitoring well is a function of the mobile LNAPL interval in the soil formation under unconfined conditions and the location of the static water table. Under confined and perched conditions, the apparent LNAPL thickness may be exaggerated when compared to the mobile LNAPL interval. In either case, the apparent LNAPL thickness is poorly correlated to LNAPL recovery and potential for migration. Under certain conditions (static water table, homogeneous soil, unconfined conditions) the apparent LNAPL thickness in a well can be correlated to the mobile LNAPL in the formation; however, such correlations are often highly approximate because of non-ideal conditions and geologic variability.

Management decisions primarily on LNAPL thickness to the exclusion of other metrics are considered less useful based on current scientific knowledge. A remedial framework based on LNAPL clean-up to the extent practicable, while often historically adopted, is challenging to define and may be arbitrary when based primarily on LNAPL thickness.

4.2.4 Multiple Lines of Evidence Approach

Multiple lines of evidence that suggest reduced potential for LNAPL migration include:

- LNAPL absence in appropriately located sentinel wells.
- Stable or decreasing LNAPL thicknesses in wells screened across water table (groundwater elevation fluctuations should be considered when interpreting data).
- Dissolved-plume concentrations downgradient of the LNAPL body that are stable or decreasing (an expanding dissolved plume does not necessarily indicate an expanding LNAPL body).
- LNAPL transmissivity below a threshold, indicating that hydraulic recovery is no longer practical (see ASTM E2856-13, ITRC (2018)); this is primarily a metric for recovery but also an approximate indicator of mobility.
- LNAPL recovery data approaching asymptotic limits or approaching limits of recovery based on decline curve analysis.
- LNAPL seepage velocity that is less than a de-minimus value (BC ENV 2008).
- Laboratory testing and comparison of measured LNAPL saturation in cores to residual saturation.
- Comparison of measured LNAPL thicknesses to the theoretical thicknesses necessary for migration into pristine soil pores based on capillary entry pressure concepts.
- NSZD rates that are similar to or greater than the LNAPL volumetric flow rate estimated from transmissivity measurements and considerations of LNAPL geometry and flow direction (Mahler et al. 2012; ITRC 2018).

Science Based Approaches

Science-based approaches for LNAPL management are based on multiple metrics or lines of evidence. An important metric as part of this framework is the LNAPL transmissivity, defined as the volume of LNAPL that flows through a unit width of a porous medium under a unit pressure gradient in a unit time (ASTM E2856-13). LNAPL transmissivity is well correlated to LNAPL recovery and is an approximate indicator of mobility. The LNAPL transmissivity may be used as a leading (pre-remediation) and lagging (during remediation) metric throughout the site assessment and remediation process.

4.3 Remedial Options Evaluation

The staged remediation process incorporates potential concerns or risks to identify remedial goals, remedial mechanisms and objectives, remedial criteria, and performance metrics and transition thresholds. This forms the basis for selection of remedial technology groups subsequently described. The complete process, provided for four remedial goals (i.e., Saturation, Composition, Containment, and Aesthetic[3]) is presented in Table 3, and discussed in detail in the sections below. Example flow-charts for the end-to-end remediation strategy for the Saturation and Composition goals are provided in Figures 3 and 4. A new aspect of this framework is the incorporation of baseline NSZD measurements as a benchmark for comparison to active technologies. The staged process and flow-charts for the end-to-end strategy are further described in Sections 4.4 to 4.8.

3 The toolkit framework is similar to the ITRC (2018) framework. The primary differences are: 1) Four remediation goals and mechanisms are included rather than three; the added mechanism herein of Enhanced Phase Change and Recovery provides increased flexibility for including separately those technologies that are based on a combination of these mechanisms (e.g., enhancing soil vapour extraction through soil heating); and 2) The containment or control mechanism not only acts to control migrating LNAPL (which is the focus of the ITRC framework) but also can be used to address associated dissolved-phase plume or soil-vapour migration, which are also important remedial goals at many petroleum release sites.

Table 3: Remedial Evaluation Framework

Remedial Goal	Primary Mechanism	Remedial Objective and Criteria[12]	Example Technologies	Performance Metrics and Data		Guidance/Tools/Methods
				System (asymptote or threshold)	Media (attenuation rate or threshold)	
Saturation (S) Composition (CM) Containment (CN) Aesthetic (A)	Mass Recovery or Removal	Abate LNAPL migration Reduce saturation to acceptable threshold[2] Meet media criteria or standards[3] Meet timelines	Excavation Hydraulic recovery MPE NSZD	LNAPL recovery vs. time LNAPL recovery vs. cost LNAPL recovery vs. GHG emissions LNAPL/vapor ratio LNAPL/water ratio Can also establish metrics for TPH	Media concentrations[3] LNAPL thickness LNAPL presence/absence LNAPL transmissivity LNAPL saturation (mobile fraction remaining) LNAPL velocity NSZD (TPH) rate	General Framework ▪ ITRC LNAPL Guidance (2018) ▪ LNAPL Recovery ▪ ASTM E2856-13 ▪ API 4760 (LDRM) Model ▪ NSZD (TPH) rate – Remediation Toolkit #2 ▪ T1: Nomographs[11] ▪ T2: Measurements/ simple models (e.g., CO_2 efflux, gradient, VZBL, Control Volume) ▪ T3: Models: RemFUEL, API LNAST, MIN3P GHG Emissions - Remediation Toolkit #4
	Phase Change[1]	Reduce plume longevity Reduce concentrations Abate safety issues Reduce mass flux or discharge Meet criteria or standards[4] Meet timelines	NSZD/MNA Air sparging/biosparging SVE/bioventing In-situ bioremediation In-situ chemical oxidation Phytoremediation Activated carbon injection Chemically-enhanced electrokinetics	COPC recovery vs. time COPC recovery vs. cost COPC recovery vs. GHG emissions COPC/vapor ratio COPC/water ratio Can also establish metrics relative to TPH	COPC concentration of LNAPL, soil, groundwater, soil vapour COPC mass flux or discharge of groundwater, soil vapour NSZD (COPC) rate Biodegradation rate (respiration test) Transpiration rate (phytoremediation) MBT indicators	General Framework ▪ ITRC LNAPL Guidance (2018) ▪ Groundwater Models (Remediation Toolkit #2) ▪ BIOSCREEN, MAROS, GWSdat, GSI Mass Flux Toolkit (2012), Ricker Method, REGRESSION tool Soil Vapour Models ▪ BIOVAPOR, PVISCREEN ▪ NSZD (COPC or TPH) rate ▪ T1: Nomographs

Remedial Goal	Primary Mechanism	Remedial Objective and Criteria[12]	Example Technologies	Performance Metrics and Data		Guidance/Tools/Methods
				System (asymptote or threshold)	Media (attenuation rate or threshold)	
						▪ T2: Measurements/ simple models (e.g., CO_2 efflux, gradient, VZBL[13], Control Volume, BIOVAPOR) ▪ T3: Models: RemFUEL, API LNAST, MIN3P Biodegradation Rate: US EPA Bioventing Principles & Practices (1995), Hinchee and Leeson (1996)[10] GHG Emissions – Remediation Toolkit #4
	Containment or Control	Abate/control LNAPL migration Abate/control dissolved plume migration	Permeable reactive barriers (PRB) French drain or interception trench Barrier walls Hydraulic containment (groundwater pump-and-treat (P&T)) In-situ containment-capping Solidification/ Stabilization Ankeny moat[6]	Reaction rate (PRB) Pumping rate/drawdown Leaching of solidified mass (e.g., USEPA LEAF) Chemical compatibility of admixture with PHC Barrier permeability	Hydraulic capture zone (P&T) LNAPL presence/absence COPC concentration of soil, groundwater, soil vapour	General Framework ▪ ITRC LNAPL Guidance (2018) ▪ Select Guidance ▪ ITRC PRB Guidance (2011) ▪ USEPA 2005 Cost Effective Design P&T Systems. ▪ ITRC Solidification/Stabilization Guidance (2011)
	Enhanced Phase Change & Mass Recovery[13]	Abate LNAPL migration Abate safety issues Reduce saturation to acceptable threshold[5]	In-situ thermal Co-solvent flushing or surfactant enhanced LNAPL recovery Steam-enhanced recovery	Combination of Mass Recovery and Phase Change metrics with added metrics (e.g., temperature, surfactant/solvent loading, etc.)	Combination of Saturation and Composition metric	Select Guidance ▪ Los Angeles Light Non-Aqueous Phase Liquid (LNAPL) Recoverability Study[7] ▪ US EPA Surfactant Enhanced Aquifer Remediation (SEAR)[8]

Remedial Goal	Primary Mechanism	Remedial Objective and Criteria[12]	Example Technologies	Performance Metrics and Data		Guidance/Tools/Methods
				System (asymptote or threshold)	Media (attenuation rate or threshold)	
		Reduce concentrations Reduce volumetric flow rate Meet criteria or standards[4] Meet timelines	Water flooding			▪ US EPA In-situ Thermal Lessons Learned (2015)[9]

Notes:

1) While Phase Change is the primary goal depending on technology there can also be significant mass reduction.
2) A threshold for mobile LNAPL that is above residual saturation that is based on appropriate metrics.
3) Risk-based or numerical standard; ability to meet soil standards may depend on technology (i.e., excavation vs. LNAPL recovery from wells).
4) Risk-based or numerical standard.
5) The threshold for saturation may be based on achieving de-minimus mobile LNAPL conditions (i.e., residual saturation) or additional removal of residual LNAPL to meet concentration criteria (if feasible).
6) Direct groundwater flow around LNAPL source.
7) https://www.gsi-net.com/en/publications/la-lnapl-recoverability-study.html
8) https://nepis.epa.gov/Exe/ZyPDF.cgi/P1000NU0.PDF?Dockey=P1000NU0.PDF
9) https://www.epa.gov/sites/production/files/2015-06/documents/istt_ll_issue_paper.pdf
10) Hinchee, R. and A. Leeson. Soil Bioventing: Principles and Practices. CRC Press, December. 272 pg.
11) T1, T2, T3 = Tier 1 to 3.
12) Aesthetic concerns may also be considered depending on responsible party and regulatory requirements and input.
13) The technologies in this group are less common and are relatively aggressive. They are typically considered when there is a need for greater certainty and/or shorter timelines in achieving saturation-based goals.

MBT = molecular biological tools; VZBL = Vadose Zone Biological Loss model (see Remediation Toolkit #2)

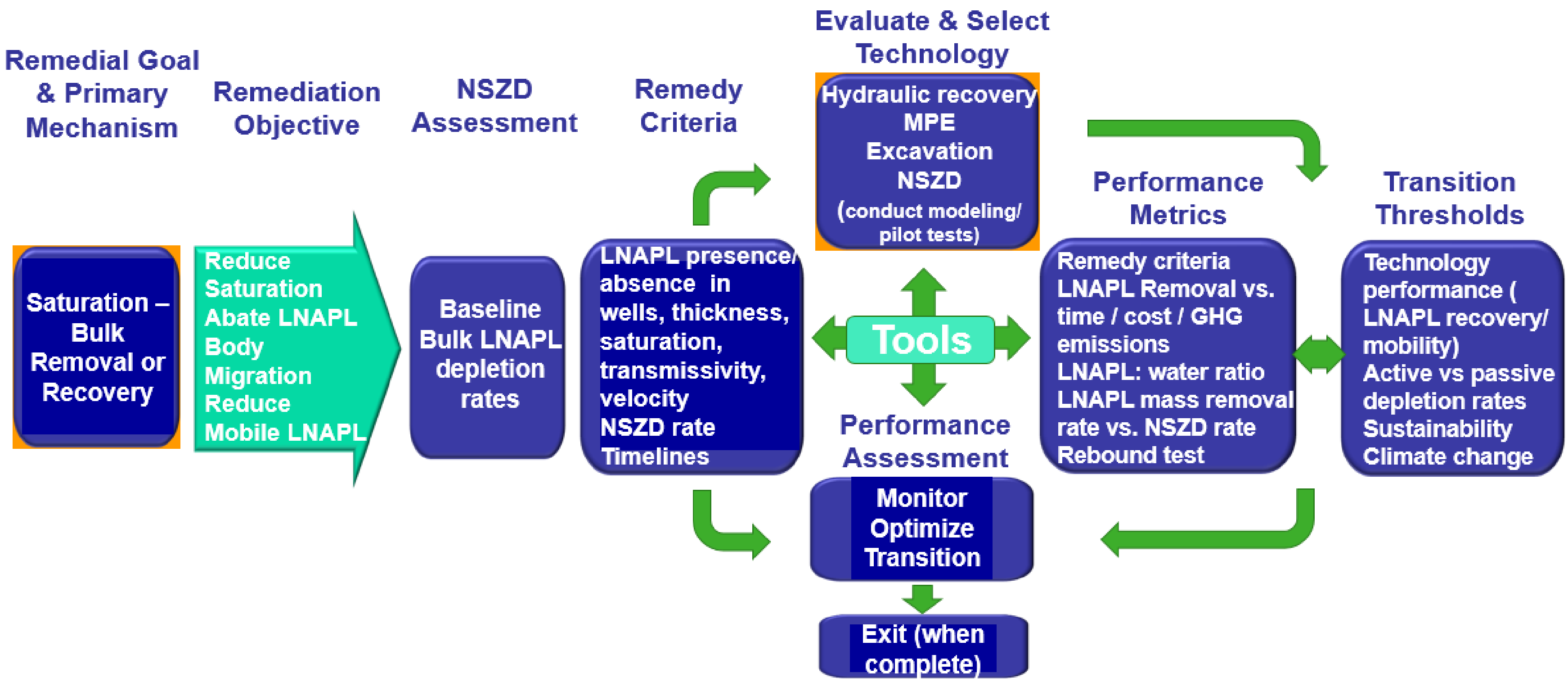


Figure 3: Remediation Options Evaluation Process for Where Concern is LNAPL Migration or Presence of Mobile LNAPL and there is a Saturation-based Goal

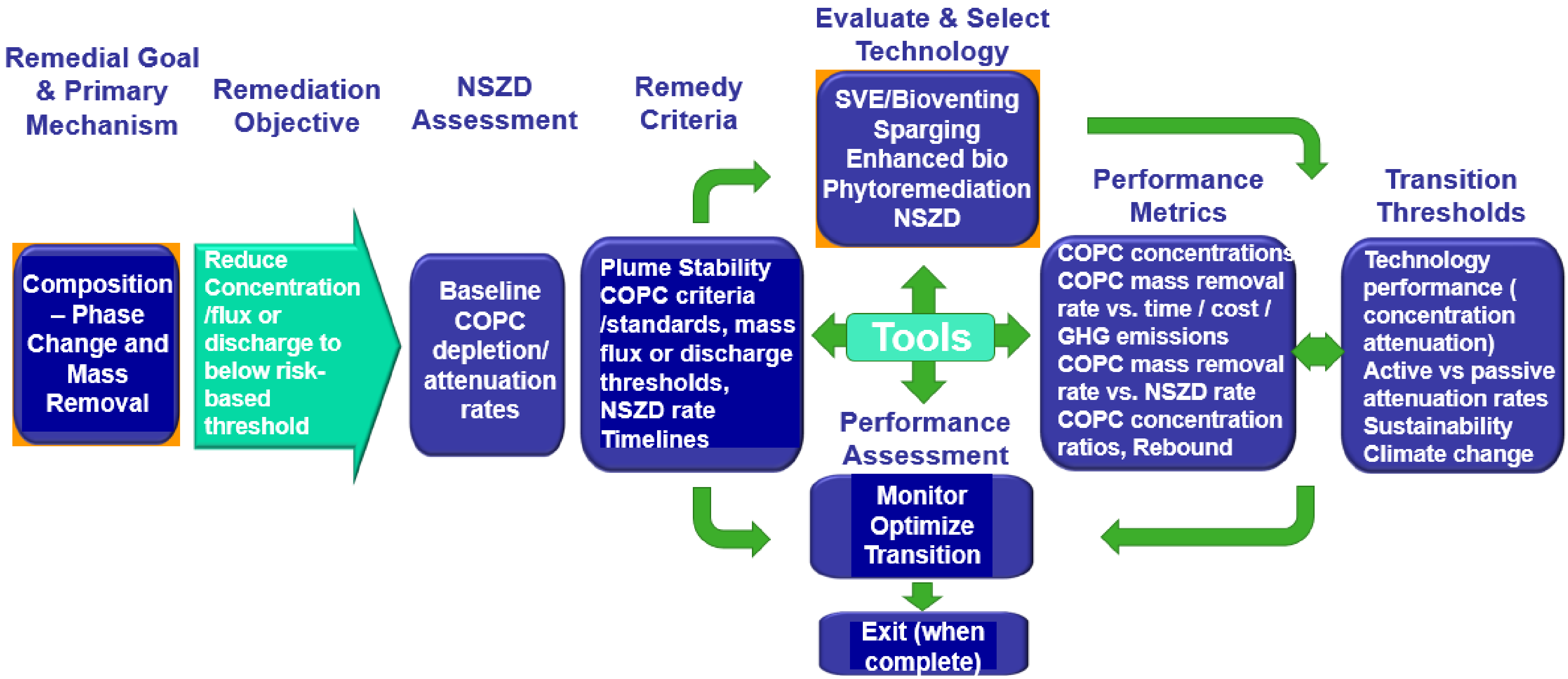


Figure 4: Remediation Options Evaluation Process for Where Concern is a Health Risk (above standard) and there is a Composition-based Remedial Goal

4.4 Remedial Goals

Setting remedial goals is the second stage in the site management process (Figure 2). Four broad remedial goals are defined as follows:

- Saturation
- Composition
- Containment
- Aesthetic

Goals broadly address the LNAPL concern, while objectives are the specific requirements of the remediation. The linkages between the concerns, goals and mechanisms are shown in Figure 5. Typically, the migrating LNAPL concern is addressed by the saturation or containment goal, while the mobile LNAPL concern is addressed by the saturation goal. The health risk and safety goal is addressed by the composition or containment goal. The aesthetic concern is addressed by the aesthetic goal.

Concern or Risk	Remedial Goal
Migrating LNAPL	Saturation or Containment
Presence of Mobile LNAPL	Saturation
Health Risk or Safety (soil, groundwater, soil vapour above risk-based criteria)	Composition or Containment
Aesthetics (sheens, taste, odour above thresholds)	Aesthetic

Remedial Goal	Primary Mechanism
Saturation	Mass Recovery - reduce LNAPL saturation
Composition	Phase Change - change LNAPL characteristics
Containment	Control Measures - stop LNAPL and associated plumes
Aesthetic	Phase Change - change LNAPL characteristics

Figure 5: Linkage between Concern, Remedial Goal and Primary Mechanism (an additional Primary Mechanism could include a combination of Enhanced Phase Change and Mass Recovery)

The remedial mechanisms are linked to the remedial goals as follows:

- The **saturation goal** is addressed through mass recovery or a combined approach involving mass recovery and phase change. The goal is commonly set at a conservative residual saturation value or may be based on observation of the absence of LNAPL migration or mobile LNAPL.
- The **composition goal** is addressed through phase change, or a combined approach involving mass recovery and phase change. Typically, compositional goals involve achieving concentration or mass flux or mass discharge criteria, and often targets substances that may be risk drivers (e.g., benzene). Mass recovery may be used to address a composition goal such as achieving a soil criterion when warranted.
- The **containment goal** is addressed through control measures such as hydraulic or pneumatic controls and/or barriers.

- The **aesthetic goal** is dependent on the concern. For example, if the concern is a sheen, remediation may require measures such as containment or an oleophilic barrier. Aesthetic goals should be carefully implemented as concerns may be subjective and difficult to define.

Mass-based estimates may represent a more accurate indication of risk than concentration criteria when evaluating remedy performance (ITRC 2012). Understanding how they are defined is important. They include: mass flux - mass per unit area per time; mass discharge - mass per time crossing plane of interest; and mass loading - mass per time at intersection of plume and receptor.

4.4.1 Remedial Mechanisms and Objectives

Identifying the primary remediation mechanism and remediation objectives are the third stage of the site management process (Figure 2). The objectives are the requirements of the remediation and should be aligned with technical, regulatory and business goals. They can incorporate future development plans, institutional goals, remediation and closure timelines, and probability of success. The four primary remediation mechanisms are described below.

4.4.2 Mass Recovery

Mass recovery technologies address primarily a saturation-based LNAPL remedial goal. Remedial objectives include abating LNAPL migration, reducing saturation to an acceptable threshold (e.g., to reduce mobile LNAPL concern), or total (bulk) mass recovery. The phase-change mechanism is typically chosen when the objective is to meet a risk-based or numerical concentration or mass discharge-based standard. However, in some cases, mass recovery may also be used to meet a concentration-based standard depending on the technology selected. For example, excavation of soil removes mass and if sufficiently complete may achieve a concentration-based standard.

Within this category are common technologies such as excavation[4] and hydraulic recovery of LNAPL using skimmers or single fluid pumps, or more aggressive technologies such as multi-phase extraction (MPE) where LNAPL, groundwater and soil gas are simultaneously removed. Except for excavation (where feasible), these technologies primarily address the mobile LNAPL fraction, although MPE may also promote mass reduction through phase change and biodegradation.

It is important to recognize the limits of hydraulic recovery technologies. Removal to the maximum extent practicable often results in a high fraction of mobile LNAPL remaining as it is typically not possible to fully achieve a condition of residual saturation. However, when other relevant performance metrics such as LNAPL transmissivity, LNAPL recovery decline curve, and NSZD rates are considered, the mobile LNAPL that remains may not be a concern as it is unlikely to migrate.

[4] We note that excavation is a mass removal technology as opposed to recovery but is included in this category as most appropriate fit given unique aspects

The NSZD rate is an appropriate metric for comparison to depletion rates from active in-situ remediation. It is also appropriate to consider NSZD itself as a saturation-based technology because depletion can reduce the potential for LNAPL migration and, in the longer-term, can result in significant mass reduction.

The key site considerations for mass recovery include factors such as properties of the LNAPL (viscosity, density), intrinsic geologic properties (e.g., fluid permeability and transmissivity), and LNAPL distribution (depth, source size, saturation). Key site considerations for excavation include factors such as contamination extent, depth to contamination, access restrictions and infrastructure.

4.4.3 Phase Change

Phase-change technologies address primarily composition-based remedial goals and do not directly remove LNAPL from the subsurface. These technologies exploit the characteristics of the petroleum hydrocarbon to partition or transfer chemicals in the LNAPL to aqueous or gas phases through dissolution or volatilization (e.g., preferential removal of more soluble or volatile substances). Alternatively, compounds are degraded or transformed through biodegradation or chemical oxidation reactions. Within this category, technologies that rely on bioremediation are an important group. These include both NSZD and technologies that enhance biodegradation in the subsurface, such as bioventing and biosparging.

Because many of these technologies also act to reduce mass, it is important to also recognize the mass reduction component and potential to reduce saturation, which can be significant depending on the technology. For example, soil vapour extraction (SVE) at a site with gasoline impacts can result in significant mass reduction. Over the longer-term, NSZD can also result in significant mass reduction. However, when saturation is a significant concern, it often is more appropriate to start with technologies that focus on reducing saturation until an appropriate endpoint is met that is based on achievable LNAPL thresholds and sustainability. Once met, then remediation can transition to technologies that promote phase-change as part of a treatment train approach.

The key site considerations for phase change include factors such as the properties of components within the LNAPL (e.g., solubility, biodegradability, and volatility), geology for some technologies (e.g., soil-air permeability, geologic complexity) and LNAPL distribution (depth, source size, above or below water table). Generation of wastes such as contaminated water or vapour may be significant and will vary depending on the technology.

4.4.4 Containment or Control

Containment or control technologies reduce or eliminate the migration of LNAPL and/or associated dissolved groundwater plumes. There are at least three approaches to achieving these objectives:

1) Change the configuration of the LNAPL itself within the soil matrix so that the contamination is bound or stabilized in the matrix and there is no longer a continuous-phase LNAPL that potentially could migrate, and by doing so, also reduce leaching of constituents into groundwater.

2) Create a physical barrier that prevents migration of LNAPL, groundwater and/or soil vapour.

3) Implement hydraulic or vapour containment, through pumping or other methods that affect hydraulic gradients or migration.

Within this framework, different technologies should be considered depending on whether there is primarily a LNAPL or dissolved groundwater plume concern. For example, a vertical barrier wall constructed of a low permeability material such as bentonite that is chemically compatible with petroleum degradation may be an appropriate technology for preventing LNAPL migration but may not be necessary if the objective is only to control a dissolved-phase or vapour plume. For this example, other technologies such as the Ankeny moat (see Table 5) (to divert groundwater around a source) or groundwater pump-and-treat may be a better option.

For technologies where the objective is to bind or stabilize LNAPL through use of amendments such as Portland cement and/or bentonite, a cautious approach should be followed including, for example, bench-scale testing of the technology. Compared to other technology groups, the long-term performance, monitoring and cost of remedies that manage rather than reduce mass may be an important consideration.

Key site considerations for mass control include factors such as contamination extent, depth to contamination, access restrictions and infrastructure. Further, it is important to recognize that typically a combined remedy is required when constructing barrier walls, in that groundwater control and pumping are usually also required.

4.4.5 Enhanced Phase Change and Mass Recovery

Enhanced phase change and mass recovery technologies address both composition- and saturation-based remedial goals by reducing LNAPL saturation to abate potentially migrating LNAPL and reduce mobile or residual LNAPL. The technologies can also address soil, groundwater and/or soil vapour concentrations above criteria or standards, potentially decreasing timelines for site closure.

Within this category are technologies that act to change the properties or nature of LNAPL to increase the rate of mass recovery through pumping or extraction of fluids (LNAPL, groundwater, soil vapour). Examples of technologies include solvent- or surfactant-enhanced recovery, thermal technologies and water-flooding. By increasing the volatilization rate and/or solubility, reducing the interfacial tension, or imposing hydraulic stresses (e.g., water flooding), the rate of mass recovery is increased. The technologies in this group are less common and typically considered relatively aggressive and may be considered when there is a need for greater certainty and/or shorter timelines in achieving saturation-based goals (e.g., removal of LNAPL to residual saturation) or numerical criteria or standards.

When selecting a technology, the feasibility and reliability of the technology, its environmental footprint (including GHG emissions) and cost should also be considered. Key site considerations include many of the factors applicable to phase change technologies discussed above in Section 4.4.4, with the additional understanding of relevant LNAPL and soil properties such as those determining the interaction between the LNAPL and surfactant or solvent. The intensity, energy requirements, wastes generated, and cost are relatively high for this group of technologies.

4.5 Remedy Criteria

Establishing specific remedy criteria is the fourth stage of the process (Figure 2). Remedy criteria depend on the remediation goal: when there is a Saturation-based goal, LNAPL stability is often the primary criteria to be met. In the context of a composition-based goal, there are often regulatory criteria or standards for soil, groundwater and/or soil vapour; or mass flux, mass discharge and/or mass loading thresholds established from risk assessment.

Remedy criteria may also be defined with respect to the rate at which concentrations or mass are decreasing, or the rate at which concentrations are approaching guidelines or standards through statistical analysis of plume concentration trends (Remediation Toolkit #2). Criteria may also include mass depletion rates of total petroleum hydrocarbons (TPH) or individual contaminants of potential concern (COPCs) established with respect to LNAPL source zones where depletion is expected to achieve composition goals. In the context of a saturation-based goal, remedy criteria may include presence/absence of LNAPL in wells and LNAPL transmissivity. Remedy criteria also may include desired timelines for achieving criteria or standards.

4.6 Screening and Selection of Remedial Technologies

Screening and selection of remedial technologies is the fifth stage of the site management process (Figure 2). Building on the framework described above, Toolkit #3 provides for a practical step-wise approach to screen and select technologies to achieve remediation goals and objectives (Figure 6). Following a similar approach to ITRC (2009) and ITRC (2018), Step 1 of the remedial selection process is to identify the desired primary remediation mechanism based on the project goals from which the applicable technologies are identified (Table 5). To further refine the list of identified technologies in Step 1, Step 2 of the remedial selection process considers key parts related to technical feasibility and implementability (or constructability) (Table A, attached). Step 3 is to further evaluate technology factors.

Technical feasibility and implementability are considered as "stoppers" in that if a technology is not considered feasible and/or implementable due to site-specific factors then it should not be carried forward for further evaluation. Technical feasibility refers to the likelihood of achieving the intended objectives of the technology given scientific and technical knowledge. A technology with significant uncertainty or likelihood of failure is undesirable. The potential for failure should be within reasonable or acceptable bounds and as applicable considering extreme events such as earthquakes, extreme temperatures and precipitation (including increased threats associated with climate change), flooding, etc. Implementability in this context refers to consideration of significant constraints or impediments that challenge the implementation and/or service reliability of the technology. Neither Step 2a nor Step 2b address the sustainability of the technology, which may be addressed in Step 3 through consideration of select indicators, and in greater detail in Remediation Toolkit #4.

Climate Change Impacts

An emerging consideration is incorporation of climate change and increasing extreme weather events and wildfires in the remediation life cycle (US EPA 2015, Washington Department of Ecology 2017, BC ENV 2019). The time scales and future magnitude of climate change are increasingly become clearer and in context of this toolkit would be of greatest importance for long-term risk management. Examples of weather events with potential implications for site remediation projects in Canada include increased temperature, which could affect ecosystems, and in northern areas permafrost; increased precipitation and/or drought (depending on region), which could affect groundwater systems and water table elevations; declining snowpack, which may affect surface water and groundwater systems; sea level rise, which could affect remediation in low-lying areas; and increased flooding, which could affect remediation in flood-prone areas. Where vulnerabilities are identified, resiliency and adaptation measures can be developed and incorporated in the remedial design to maintain the long-term integrity of the remedy over time. Additional guidance on this topic is provided in Remediation Toolkit #4.

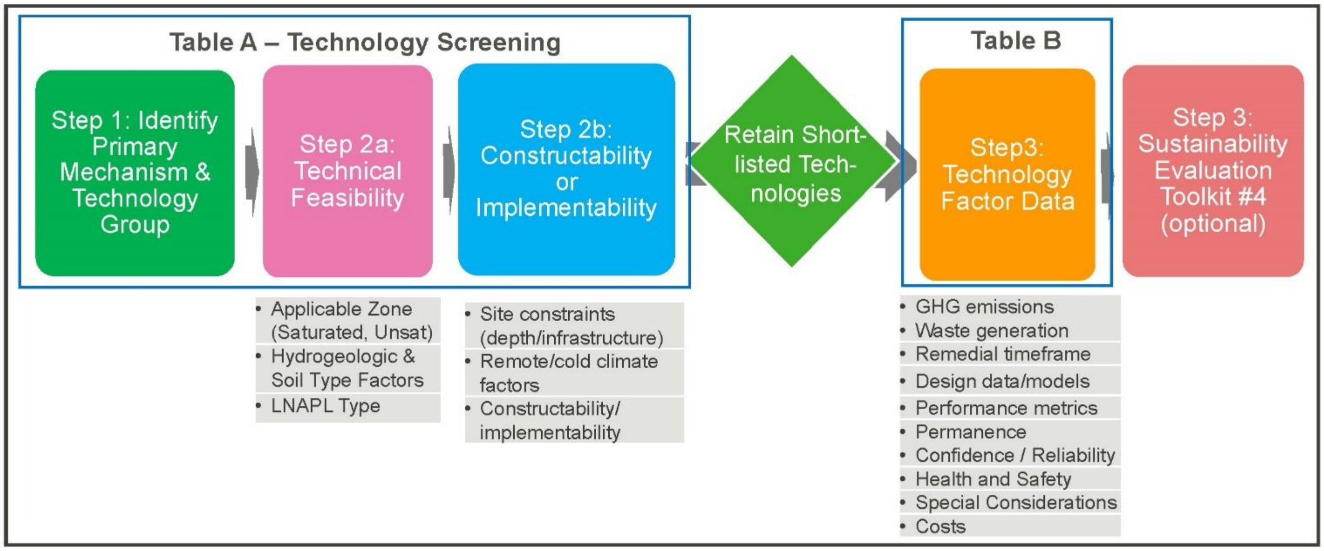


Figure 6: Technology Screening Process

4.6.1 Table A: Technology Screening

Factors identified for evaluating technical feasibility are grouped into site-specific data according to: applicable zone (saturated / unsaturated), hydrogeological conditions, soil type, and LNAPL type. For each remediation technology listed, Table A (appended) provides brief information on how these factors affect the remedial technology. Site-specific information and the identified factors help the user to rank applicable technologies as high, medium, or low with respect to feasibility and implementability. This qualitative ranking by the user can be directly input in Table A under the Step 2: Technical Feasibility column.

Likewise, additional information is provided for each technology with respect to implementability in terms of the potential effect of a) depth to source, b) the presence of infrastructure, c) whether the site is remote, and d) cold climate conditions. In consideration of these site-specific factors related to the location of the site and source zone, qualitative ranking of high, medium, or low can be assigned by the user in Table A under the Step 2: Implementability / Constructability. And finally, based on rankings of technical feasibility and implementability / constructability, the user can input an overall ranking with respect to technologies that are retained or not retained, to develop a short list of technologies with which to move forward to Remediation Toolkit #4.

Table 4: Overview of Remedial Technologies

Primary Mechanism	Technologies Available
LNAPL Mass Recovery	▪ Excavation ▪ Multi-phase extraction (MPE), dual-phase extraction (DPE), dual-phase liquid extraction (DPLE) ▪ LNAPL skimming or vacuum-enhanced skimming ▪ NSZD

Primary Mechanism	Technologies Available
Phase Change	*In-situ* ▪ NSZD and MNA ▪ Air Sparging ▪ Soil vapour extraction (SVE) ▪ Bioventing ▪ Biosparging ▪ In-situ chemical oxidation (ISCO) ▪ In-situ bioremediation ▪ Activated carbon injection ▪ Phytoremediation ▪ Chemically enhanced electrokinetics
Mass Control and Containment	▪ Permeable reactive barrier (PRB) ▪ Drains ▪ Impermeable/slurry walls ▪ In-Situ Containment-Capping and Solidification-Stabilization (including vitrification) ▪ Ankeny moat (hybrid mass containment method) ▪ Groundwater pump & treat
Enhanced Phase Change & Mass Recovery	▪ In-situ thermal (radio frequency heating, electrical resistance heating, thermal conductive heating) and enhanced recovery ▪ Solvent or surfactant treatment for enhanced recovery ▪ Steam treatment for enhanced recovery ▪ Water flooding or hot water flooding for enhanced recovery

MPE = multi-phase extraction
DPE = dual-phase extraction
DPLE = dual-phase liquid extraction
SVE = soil vapour extraction
ISCO = in-situ chemical oxidation
PRB = permeable reactive barrier

With the development of new methods, refinement of existing methods, or combined or sequential treatments, there are numerous possible technologies for the management of petroleum hydrocarbon sites, all of which cannot be practically covered in this Toolkit #3. A total of 24 remedial technologies are provided in Table 4 and Table A. The approach and framework provides a basis for the user to consider and analyse alternatives or combinations of remedial technologies that can be evaluated in terms of technical feasibility and implementability / constructability.

Key factors related to implementability / constructability that are relevant to many sites in northern latitudes are remoteness and cold climate. While green and sustainable remediation and environmental footprint analysis is covered in Remediation Toolkit #4, aspects of the cold-climate studies that inform the qualitative ranking for implementability / constructability in Table A are additionally summarized through case studies in Appendix B.

4.6.2 Table B: Technology Factor Data

To assist in the remedial technology evaluation process, select technology factors that are related to technology characteristics, design requirements, or performance metrics (Table B, appended) are identified. For each of the 24 remedial technologies identified in Table 4, considerations related to these key factors are summarized as follows:

- **Greenhouse Gas Emissions** – the main greenhouse gases are carbon dioxide, methane and nitrous oxide. Passive technologies such as NSZD or phytoremediation will tend to have lower GHG emissions than energy intensive technologies; however, a lifecycle type analysis (LCA) should be conducted to facilitate appropriate comparisons. It is recommended that the methodology described in Remediation Toolkit #4 be used for assessment of GHC emissions.
- **Waste Generation** – the different waste streams such as water, air and NAPL and residual by-products associated with different technologies.
- **Remedial Timeframe** – how long will it take to achieve site closure classified as short duration (months), medium duration (years) and long duration (decades).
- **Design Data and Models** – data needed for design of technologies and models that can assist in the evaluation and design process.
- **Performance Metrics** – system and subsurface metrics that may be used to evaluate performance of technologies.
- **Health and Safety** – worker and community health and safety issues associated with implementation of the technology both on-site and near-site, for example, equipment use, hazardous materials use, hazardous atmospheres, potential for accidents and off-site safety concerns, for example, associated with transport of people and materials.
- **Permanence** – the attributes of the technology with respect to reducing to volume, mass and/or toxicity of the contamination.
- **Confidence in Remediation Effectiveness and Reliability** – the confidence and reliability in the remediation technology in meeting remediation objectives based on site-specific considerations.
- **Climate Change Considerations** – the vulnerability of technology to increased extreme weather, sea-level rise, and other potential climate change related impacts and measures to increase resiliency may be considered (see Remediation Toolkit #4).
- **Special Considerations** - regulatory considerations, for example, approvals or authorizations that may be required for technologies including injected substrates or re-injection of treated water, or potential unintended consequences that could arise from technology implementation.
- **Cost** – relative capital costs (low, medium, high) and operating and maintenance costs (low, medium, high).

The technology factors may be used to conduct further technology evaluations and screening. However, we note that the above technology factors do not fully consider project- or site-specific considerations. Therefore, we recommend that the above factors together with other environmental, societal and financial indicators be considered in a more in-depth sustainability assessment as described in Remediation Toolkit #4.

4.7 Performance Metrics and Transition Thresholds

Defining performance metrics and transition thresholds is the sixth stage in the site management process (Figure 2). There are two categories of performance metrics: system and subsurface media. These metrics are used to assess performance of the remedy and include: 1) subsurface metrics such as LNAPL recovery or transmissivity, or measured subsurface concentrations, mass flux and/or mass discharge; and 2) system metrics, such as mass removal rates, concentration ratios or attenuation, or other system parameters. Performance metrics may also include the calculated mass flux and/or mass discharge. Certain data should be agreed upon as either or both a leading metric (before remediation) or a lagging metric (during or after remediation) to compare against baseline performance. For example, most subsurface metrics in the text box could be considered both a leading and lagging metric and obtained before, during and after remediation, where warranted.

SMART Performance Metrics

Establishing SMART performance metrics, i.e., that are Specific, Measurable, Achievable, Realistic, and Timely, are a key aspect of the remediation framework (Table 3). Example system metrics include:

- *LNAPL recovery vs. time, cost or GHG emissions*
- *LNAPL/vapour ratio or LNAPL/water ratio*
- TPH/COPC mass recovery vs. time, cost or GHG emissions
- TPH/COPC concentration attenuation
- COPC/vapour ratio or COPC/water ratio

Example subsurface metrics include:

- *LNAPL presence/absence in wells*
- *LNAPL transmissivity*
- *LNAPL saturation (mobile fraction remaining)*
- *LNAPL velocity*
- *NSZD (TPH or COPC) rate*
- *Concentration and/or mass flux or mass discharge*
- *Concentration and/or mass flux or mass discharge attenuation*
- *Biodegradation rate*

An example transition or endpoint threshold could be to achieve 95% recovery of LNAPL based on decline curve analysis.

Rebound tests and concentration data are often required to evaluate system performance. Composition and flux data and analysis to predict longevity of plumes may be relevant performance metrics after initial LNAPL migration concerns are addressed.

Transition thresholds integrate remedy criteria and performance metrics, and are used for decision-making on when and how to support transitions from active to passive remedies. Transition thresholds should be established and agreed upon with stakeholders early in the remediation planning process.

A library of performance metrics is summarized in Table 5.

Table 5: Library of Performance Metrics and Data

Performance Metric/Data	RG	Description	References
LNAPL transmissivity	S	Hydraulic recovery becomes ineffective for LNAPL bodies exhibiting low LNAPL transmissivity. ITRC (2018) suggests the practical limit of hydraulic recovery corresponds to a transmissivity range of 0.1 to 0.8 ft^2/day (3 to 24 cm^2/day). Transmissivity below this threshold can be an indirect line of evidence for a stable LNAPL body. Further work is needed to establish correlation between transmissivity and mobility.	ITRC LNAPL Guidance (2018), ASTM E2856-13, API Transmissivity Guide
LNAPL recovery approaching an asymptotic limit	S	Analysis of cumulative LNAPL recovery or recovery rate per unit time. A curve reaching an asymptotic limit indicates diminishing effectiveness of recovery. This is an indirect line of evidence for a stable LNAPL body.	API 4760, ITRC LNAPL Guidance (2018), MADEP LNAPL Guidance (2016)
LNAPL recovery: Decline curve analysis	S	Analysis of unit volume of LNAPL recovery or recovery rate per unit time plotted on log-scale. A decline curve may be used to predict potential additional recoverable LNAPL and timeline for recovery. Such estimates can be compared to NSZD depletion rates.	API 4711, ITRC LNAPL Guidance (2018)
LNAPL body footprint (presence/absence)	S	Time-series evaluation of the LNAPL body footprint to evaluate whether the footprint is increasing, stable or decreasing in size. The body footprint can also be compared before and after remediation.	ITRC LNAPL Guidance (2018), BC MoE (2008)
LNAPL saturation profile	S	Comparison of vertical LNAPL saturation profiles before and after treatment to demonstrate reduced saturations.	ITRC LNAPL Guidance (2018)
Comparison of NSZD rate to LNAPL discharge rate for migrating LNAPL body	S	Using estimates of the LNAPL transmissivity, thickness and width of the mobile LNAPL interval and LNAPL gradient, the LNAPL discharge may be estimated. The LNAPL discharge can be compared to the depletion rate from NSZD or active recovery calculated for the equivalent zone. If the discharge is similar to or less than the depletion rate, this is a line of evidence for LNAPL body stability.	ITRC (2018), Mahler et al. (2012), Hers et al. (2016)
LNAPL mass depletion rate	S	Rates under natural and/or enhanced conditions can be used to evaluate remedial progress to saturation end-point	API NSZD Guidance (2017), Remediation Toolkit #2
LNAPL seepage velocity	S	Using estimates of the LNAPL fluid conductivity in soil and LNAPL gradient, the LNAPL seepage velocity can be estimated. The velocity can be compared to a de-minimus LNAPL velocity of concern. We caution that a theoretical seepage velocity is not typically a robust metric because it does not incorporate processes that reduce mobility such as degradation and capillary pressures.	BC ENV (2006); API 4760 (LDRM Model)
LNAPL composition	CM	Reduced mole fraction of volatile or soluble LNAPL constituents can indicate reduced potential for risk drivers that exceed standards.	ASTM D2887
In-well LNAPL thickness	S	Apparent LNAPL thickness is often not well correlated to formation mobile LNAPL thickness and LNAPL recovery rate. LNAPL thickness may not be an accurate indicator of the LNAPL concern. Seasonal data should be obtained to evaluate LNAPL thickness under a range	BC ENV (2006); ITRC LNAPL Guidance (2018)

Performance Metric/Data	RG	Description	References
		of conditions and should be interpreted based on whether LNAPL exhibits unconfined, confined and perched behavior. Limited LNAPL thickness or ephemeral LNAPL may indicate conditions close to residual saturation.	
Stable or shrinking dissolved-phase plume	S, CM	This is a line of evidence for a stable LNAPL body. This metric may be important if there is a compositional concern.	BC ENV (2006); ITRC LNAPL Guidance (2018)
Concentration attenuation rate	CM	Analysis of trends can be conducted to assess likelihood of achieving concentrations within certain timeframes.	Remediation Toolkit #2 (MAROS, Ricker, REGRESSION Tool)
Biodegradation rate	CM	An in-situ respiration test can be used to assess TPH biodegradation rate. Soil gas COPC and fixed gas data can be used to assess COPC biodegradation rate.	Remediation Toolkit #2, BIOVAPOR model US EPA (1995); Hinchee and Leeson (1996)
Tonne CO2-e/LNAPL mass treated	S	GHG or other impacts per mass treated can be evaluated as part of a sustainability assessment.	Remediation Toolkit #4
Unit cost of mass recovery or reduction	S, CM	Increasing cost per unit mass of LNAPL recovered or COPC change indicates decreasing cost- effectiveness. When unit costs increase ways to optimize the remediation should be evaluated.	ITRC LNAPL Guidance (2018)

Notes:

RG = Remedial Goal; S = saturation, CM = composition

Hinchee, R. and A. Leeson. 1996. Soil Bioventing: Principles and Practices. CRC Press, December. 272 pg.

5.0 TECHNOLOGY PERFORMANCE ASSESSMENT AND TRANSITION

Technology performance assessment and transition is the seventh stage in the site management process (Figure 2). A framework for evaluating technology transitions from active to passive remedial technologies and site closure is presented in Figure 7. This framework is intended to promote sustainable management of petroleum hydrocarbon sites. As described below, it is recommended that a structured approach that considers multiple factors or lines of evidence be followed.

The framework begins with a review of remedial objectives relative to regulatory requirements. Key considerations are the stability of the LNAPL body and associated groundwater and soil vapour plumes. The implications of potential transition to MNA and passive (NSZD) remediation should be considered relative to risk-based standards or criteria. For example, if SVE is being used to contain a vapour plume and prevent potential exposure to vapours, continued operation is warranted until it can be shown that alternative measures are similarly protective. Groundwater protection goals may also warrant active remediation unless time-based or area-based waivers or exclusions are an acceptable strategy as informed by practicability or sustainability considerations.

The factors or lines of evidence that should be considered when evaluating transitions are:

1) Evaluate technology progress, performance and limits.

2) Compare relative performance of technologies (system and media measurements).

3) Evaluate sustainability for project lifecycle.

Based on the above framework, transition thresholds should be established. Lines of evidence that may be considered in evaluation of transitions are described below and example thresholds are illustrated in Figure 8.

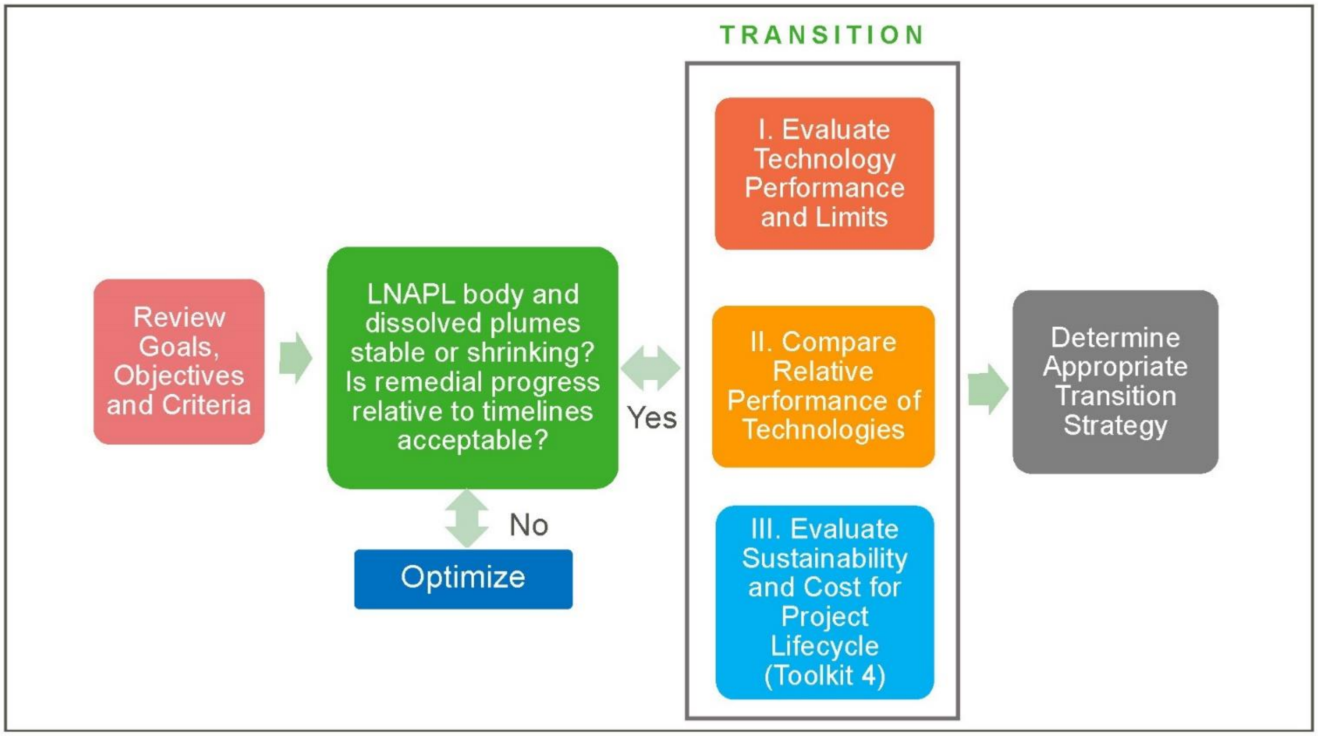


Figure 7: Technology Transition Framework

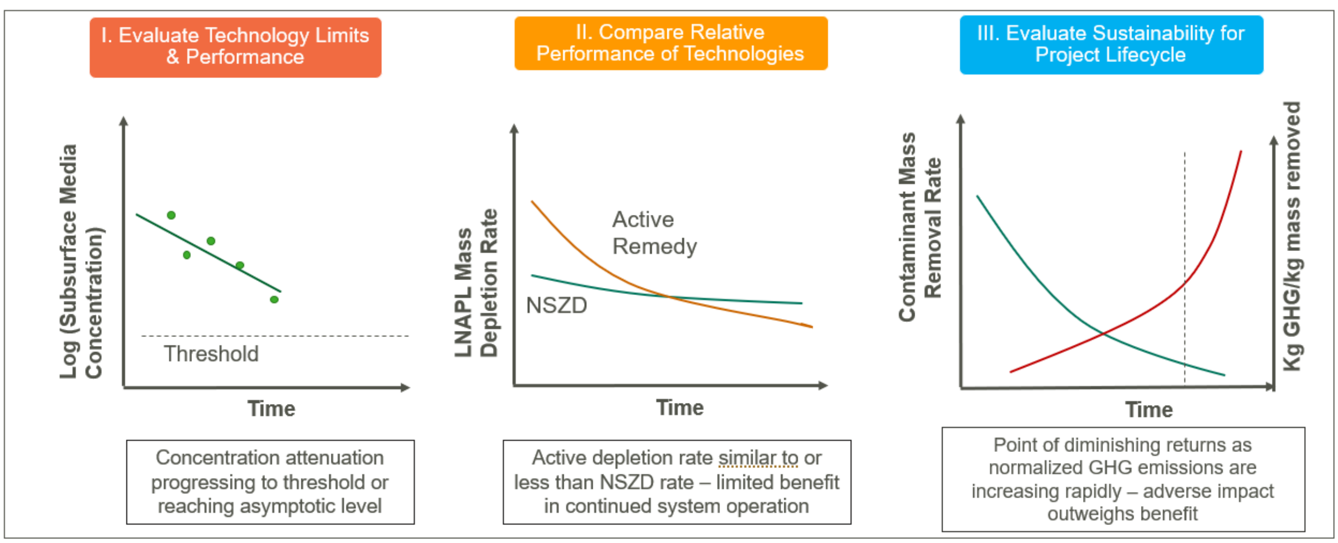


Figure 8: Example Transition Thresholds

5.1 Technology Progress, Performance and Limits

The broad technology performance and limits are addressed through evaluation of multi-site studies summarized in Remediation Toolkit #1. In some studies of active technologies, there was a relatively small increase in the rate of attenuation of COPCs in source zone or near source zone wells for sites undergoing active in-situ remediation compared to sites managed only using a NSZD and MNA approach.

The site-specific limits of remediation should be evaluated relative to performance metrics and data (Tables 1 and 4). For example, measurements of LNAPL transmissivity from bail-down tests, skimming tests or other methods can be used to evaluate whether hydraulic recovery is practically feasible. If LNAPL recovery is occurring, decline curve analysis can be performed to predict future rates. Rebound tests should be conducted where appropriate to assess remedial performance (Brusseau et al. 2010). While early on the focus is often on a LNAPL saturation objective and mass recovery, during latter stages of a project achieving compositional objectives related to constituent concentrations (e.g., maximum contaminant levels in soil or groundwater) and/or mass flux or mass discharge may become more important. Thresholds such as dollar cost or kg of GHG emissions per kg of LNAPL removed may also be appropriate thresholds.

LNAPL Transmissivity

Models may be used to predict LNAPL recovery rates for different systems using LNAPL transmissivity data for comparison to NSZD rates. For example, using Equation 16 in the ASTM E2856-13, the recovery rate for skimming can be estimated for a range of remediation design parameters. Koons et al. (2017) present an example assuming a LNAPL transmissivity of 0.3 ft^2/day (9.1 cm^2/day), 0.1 ft (3 cm) of LNAPL drawdown and 16 skimming wells per acre (approximately 60 ft (18 m) spacing). For these values, the estimated recovery rate was 2,700 gallons/acre/yr (25,500 L/hectare/yr).

The LNAPL recovery rate and mobile LNAPL remaining in the formation may also be estimated from the API LNAPL Distribution and Recovery Model (LDRM) (API 2007) or similar models. Using the vertical equilibrium model, the specific volume of LNAPL and LNAPL recovery rate may be estimated from the measured in-well LNAPL thickness and soil and LNAPL properties.

The rate of mass recovery for biodegradation and for each fluid (LNAPL, groundwater, soil vapour) removed should be quantified. While the system is operating it may be possible to estimate biodegradation rates from fixed gas data (oxygen, carbon dioxide, methane) in exhaust (if extraction system) or soil gas probes. For SVE and bioventing systems, it is also recommended that an in-situ respiration test be performed by turning the system off and monitoring the consumption of oxygen and increase in hydrocarbon concentrations. Respiration test protocols for estimation of biodegradation rates are provided in US EPA (1995) and Hinchee and Leeson (1996).

When remediation performance metrics begin to approach asymptotic levels, the need for and merits of transition to other technologies should be considered.

5.2 Comparison of Petroleum Hydrocarbon Mass Loss Rates

The measured mass loss rates versus time for active remediation technologies implemented at a site should be compiled based on both system and media parameters (see case studies in Appendix C). Because active air-phase remediation technologies enhance biodegradation rates, estimates of mass loss should include biodegradation, in addition to mass recovered in extracted fluids (LNAPL, vapour, water). The NSZD rates can be estimated using the methods described in Remediation Toolkit #2. It is recommended that seasonal NSZD rates be measured to enable more accurate estimates to be obtained. Comparisons should be made recognizing that the level of accuracy in the estimates is typically an order of magnitude. Conceptually similar comparisons can be made based on compositional change although further method development and case studies are required.

Comparison of Mass Loss Rates

An emerging approach for site management is the comparison of petroleum hydrocarbon mass loss rates through NSZD to loss rates through active remediation technologies. Such evaluations can be performed at various stages of the project lifecycle including during remedial evaluation and implementation stages. NSZD rate comparisons can inform technology transitions and site closure. These comparisons indicate that NSZD rates are similar or in some cases greater than active mass removal rates (excluding natural depletion) particularly during later stages of active remediation. Typically, comparisons of active remediation and NSZD rates should be conducted for the "site" or LNAPL body. Case studies are summarized in Appendix C.

5.3 Evaluate Sustainability for Project Lifecycle

A roadmap for conducting sustainability evaluations is provided in Remediation Toolkit #4. The level of complexity and indicators or metrics used in evaluation of sustainability, referred to as sustainable remediation (SR) in Remediation Toolkit #4, varies widely and depends on project-specific requirements. For comparing different remedial alternatives, consideration of environmental, social and economic impacts is generally recommended. Key environmental indicators include greenhouse gas emissions, air pollutants, energy use, raw material use and waste generation. Tools such as multi-criteria analysis (MCA) can be used to conduct qualitative or quantitative comparisons. Key considerations include that similar boundaries for the project lifecycle (time) and geography (e.g., on-site and off-site) should be assumed when comparing alternatives.

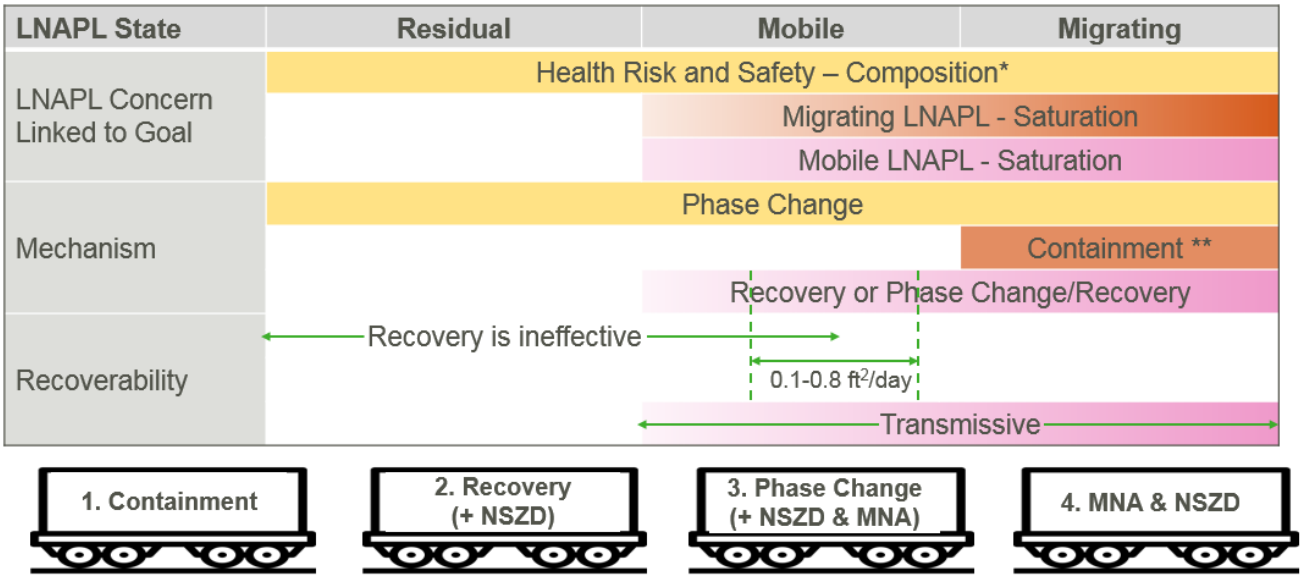
5.4 Sequenced Deployment of Technologies (Treatment Trains)

Sequenced deployment of technologies (a "treatment train") is an appropriate strategy at many sites. A framework for sequenced technology deployment that incorporates the linkage between LNAPL concern and saturation and composition goals is shown in Figure 9. The integration of LNAPL transmissivity in this framework helps guide when LNAPL recovery may be warranted (ITRC 2018).

Examples of specific ways technologies could be sequenced are:

- LNAPL recovery using skimming systems to meet the objective of reducing LNAPL mobility (saturation goal), followed by NSZD and MNA to achieve long-term compositional (and potentially saturation) goals.
- Bioventing to meet primary compositional goals, but also potentially to address saturation concerns and mobile LNAPL reduction objectives (saturation goal), followed by MNA and NSZD to achieve long-term compositional (and potentially saturation) goals.
- LNAPL recovery using dual-pump systems (i.e., separate LNAPL and water recovery) to meet saturation goals followed by soil vapour extraction (SVE) to address soil vapour intrusion concerns.

We note that biodegradation typically occurs throughout the entire project lifecycle.



* In some cases a saturation goal is needed to address a health risk or safety concern

** Containment includes controls to addressed associated plumes (groundwater, soil vapour).

Figure 9: Framework for Sequenced Deployment of Technologies (adapted from ITRC 2018)

6.0 CASE STUDY EXAMPLE

A hypothetical case study is described to illustrate the use of this toolkit. It is intended to illustrate principles and possible decision points for addressing concerns, risks and ultimately reaching site closure. All applicable regulatory requirements in British Columbia (or in other jurisdictions where this toolkit is used) should be followed when applying this toolkit to sites.

6.1 Site Description and Results of Field Investigation

A release of a combination of light- and middle-distillate petroleum products at a 5-hectare former tank farm (infrastructure decommissioned) resulted in residual and free LNAPL impacts over an approximate 1-hectare area. The depths to the water table were 7 to 8 m and soils consisted of sand to silty sand. The ground surface at the site was mostly uncovered. There was a surface water body close to the site (few ten's of meters from site boundary).

Sixteen 50 mm (two inch) diameter monitoring wells were initially installed at the site. Eight of the wells were within the LNAPL-impacted area (both mobile and residual LNAPL impacts) and were situated at approximately 20 m to 30 m spacing. There were variable thicknesses of LNAPL in wells. An assessment of LNAPL mobility was conducted consisting of monitoring of LNAPL thicknesses and groundwater elevations and data analysis using diagnostic gauge plots, observations of LNAPL presence/absence in wells, dissolved-phase concentrations in wells downgradient of the LNAPL body and transmissivity testing. Soil cores were obtained to enable testing of LNAPL saturation (through distillation extraction procedure) and residual saturation (through centrifuge or other applicable laboratory tests) (see ITRC 2018 and BCE 2008 for methods). Residual saturation may also be estimated from soil texture and empirical data. The LNAPL transmissivity in wells ranged from 0.5 to 2 ft^2/day (15 to 60 cm^2/day). Mobile LNAPL was identified based on LNAPL saturations in soil cores that were as high as 18%, compared to a residual saturation of 10%. Although the observational data of LNAPL presence in wells did not indicate LNAPL body expansion, the other lines of evidence indicated the potential for LNAPL migration, and consequently, active remediation was deemed warranted.

6.2 Remediation to Saturation Goal

The remedial goal was to address saturation and the primary mechanism was mass recovery. The remedial objective was to abate potential LNAPL migration through reduction in LNAPL saturation. The remedial options in Table A under the saturation option were considered, consisting of

- Excavation
- Hydraulic recovery
- MPE
- NSZD

Excavation was deemed infeasible because of site constraints. Hydraulic recovery through LNAPL skimming was selected as the remedial technology. Eight additional 50 mm diameter wells were installed to improve LNAPL skimming effectiveness. MPE was also considered but was eliminated as being significantly more costly than hydraulic recovery but likely not much more effective based on modeling conducted. MNA and NSZD as stand-alone options were considered not sufficiently effective with respect to the remedial objective but NSZD was identified as an important metric to evaluate remedial progress.

The primary objectives and performance metrics were to

- Reduce LNAPL transmissivity to less than 0.8 ft^2/day at all wells (24 cm^2/day) and to less than 0.5 ft^2/day (15 cm^2/day) on average (mid-point of the ITRC transmissivity range indicating hydraulic recovery is generally no longer feasible).
- Reduce mobile LNAPL such that LNAPL saturation is within 1% of the residual saturation in soil cores.
- LNAPL recovery approaching asymptotic limits based on decline curve analysis (i.e., minimum of 95% recovery relative to maximum predicted LNAPL recovery).
- Continued absence of LNAPL in sentinel wells.
- Stable or shrinking dissolved plume at wells downgradient of the LNAPL body.

In addition, the LNAPL recovery versus cost and LNAPL recovery versus GHG emissions (using methods in Remediation Toolkit #4) were tracked.

While not a primary metric, the LNAPL velocity was estimated from the measured transmissivity and thickness of mobile LNAPL estimated from TPH measurements in soil cores and the LNAPL gradient. The LNAPL velocity was estimated as 1 m/yr. This is a theoretical rate based on properties in the core of the LNAPL body in an area with highest LNAPL transmissivity and doesn’t account for capillary forces that constrain LNAPL movement. The NSZD rate was also measured using CO_2 efflux measurements by the dynamic closed chamber (DCC) method. Two monitoring events were conducted to obtain seasonal data, with site NSZD rates ranging from 250 to 1,000 US gal/acre/yr (2,360 to 9,430 L/hectare/yr) and a seasonal average of approximately 625 US gal/acre/yr (5,900 L/hectare/yr).

The LNAPL discharge in the direction of LNAPL gradient was estimated from the width of the LNAPL body perpendicular to the direction of the LNAPL gradient (50 m), LNAPL thickness (0.3 m), LNAPL velocity (1 m/yr) and LNAPL saturation (0.08). The LNAPL saturation was estimated by subtracting the residual (0.1) from total saturation (0.18). The estimated LNAPL discharge was:

$$\text{LNAPL discharge} = 50\text{ m} \times 0.3\text{ m} \times 1\text{ m/yr} \times 0.08 = 1.2\text{ m}^3\text{/yr} = 1{,}200\text{ L/yr}$$

The areal extent of mobile LNAPL was estimated to be 50 m by 50 m or 2,500 m^2. The NSZD rate over this area was estimated as

$$\text{NSZD rate} = 5{,}900\text{ L/hectare/yr} \times 2{,}500\text{ m}^2/10{,}000\text{ m}^2\text{/hectare} = 1{,}425\text{ L/yr} \sim 1{,}400\text{ L/yr}$$

Although the calculations are approximate, the NSZD rate was on the same order as the LNAPL discharge.

After five years of skimming, the LNAPL transmissivity, on average, decreased to less than 0.5 ft^2/day (15 cm^2/day). Analysis of LNAPL recovery data indicated approximately 5,000 L of LNAPL had been recovered through skimming. The LNAPL recovery approached asymptotic conditions and during the fifth year of operation, only 15 L of LNAPL was recovered. There were variable thicknesses of LNAPL remaining in wells that fluctuated inversely with water table elevation (unconfined LNAPL behaviour was observed). Testing of a soil core indicated that the LNAPL saturation was within 1% of the residual saturation.

6.3 Remediation to Address Composition Goal

The dissolved plume monitoring initially consisted of quarterly monitoring over one year and then annual monitoring thereafter. These data indicated that the dissolved petroleum hydrocarbon plume was likely stable although the data analysis was inconclusive with respect to benzene. Given the proximity to a receiving water body and aquatic receptors, it was determined that active remediation to reduce dissolved plume concentrations was warranted at the site (note that at some sites NZSD and MNA is an appropriate strategy to address dissolved plume migration). Both the composition and containment goals were considered, but in this case, the composition goal was selected. The remedial objectives were to reduce dissolved benzene concentrations and dissolved benzene flux downgradient of the LNAPL body.

The remedial options in Table A under the composition option were considered, consisting of

- NSZD (MNA and/or institutional controls)
- Air Sparging
- SVE
- Bioventing
- Biosparging
- ISCO
- In-situ bioremediation (active or enhanced: biostimulation or bioaugmentation; aerobic or anaerobic; thermally enhanced (e.g., solarization))
- Activated carbon injection
- Phytoremediation
- Chemically-enhanced electrokinetics

Technologies that were retained based on feasibility, effectiveness and implementability were NSZD (MNA), biosparging (injection of air or oxygen), ISCO, in-situ bioremediation (biostimulation through injecting compounds that add terminal electron acceptors to the subsurface) and activated carbon injection. Given the uncertainty in plume stability and proximity to aquatic receptors, NSZD (MNA) was eliminated. ISCO was eliminated because the mass of hydrocarbon, in combination with native organic matter present would result in inefficiencies in the use of this technology. The remainder of the technologies (biosparging, in-situ bioremediation and activated carbon injection) were identified as potentially feasible. An option at this point would be to use the Roadmap in Remediation Toolkit #4 to conduct a sustainability evaluation and to select a technology using multi-criteria analysis (MCA).

For purposes of this case study, biosparging/bioventing technology was chosen. The technology was implemented using existing wells supplemented with five additional multi-depth wells installed at the site. An advantage of biosparging/bioventing at this site was that air treatment was not required.

To monitor system performance and the expected increase in the biodegradation rate, the CO_2 efflux was monitored. Soil gas concentrations were measured at probes to determine if petroleum hydrocarbon vapours were oxidized as they approached ground surface. Because all infrastructure had been removed from the site, indoor vapour intrusion was not a concern; however, it was important to demonstrate that petroleum hydrocarbons were biodegraded in the subsurface. As described in Remediation Toolkit #2, there is technology available to conduct continuous measurements of CO_2 efflux to enable improved analysis of remediation effectiveness.

The primary performance metrics for the compositional objective of remediation were to:

- Through chemical analysis, demonstrate a decrease in the concentration and mass discharge of benzene in groundwater and soil vapour.
- Through geochemical testing, evaluate effectiveness of biostimulation (e.g., dissolved oxygen and other terminal electron acceptors in groundwater; soil gas oxygen, carbon dioxide and methane).
- Demonstrate an increase in the biodegradation rate, based on in-situ respiration tests and CO_2 efflux monitoring.

There are also molecular biological testing (MBT) approaches that, in some cases, may be warranted to assess the progress of remediation.

The biosparging/bioventing system was operated for two years. Based on geochemical and soil gas monitoring it was estimated that approximately 2,000 L of petroleum hydrocarbons were biodegraded. The benzene concentrations decreased by over 60% at wells not used for treatment purposes. A rebound test conducted over a six-month period after the system was turned off indicated minimal rebound and acceptable performance. The rebound test monitoring involved measuring soil gas oxygen concentrations, which indicated a minimal decrease in oxygen concentrations and an inferred increase in hydrocarbon concentrations and oxygen demand.

6.4 Remedy Transition

The framework in Figure 7 was followed to assess technology transition. The following factors supported a transition from active to natural remediation consisting of NSZD and MNA:

- acceptable risk conditions
- stable or shrinking plumes (acceptable MNA conditions)
- decrease in LNAPL transmissivity to below practical limits for hydraulic recovery
- LNAPL recovery reaching asymptotic limits
- enhanced biodegradation resulting in reduced concentrations of risk driver (COPCs such as benzene)
- reduced sustainability associated with the active remedy based on GHG emissions per mass of hydrocarbon treated (and other sustainability factors)

For the final phase of remediation, a staged monitoring program was implemented where the monitoring frequency and scope were reduced based on the data. The main concerns and focus of remediation efforts at the site, acceptable risk conditions and attenuation and reduced concentrations of COPCs that are risk drivers, have been met. In addition, the estimates of the mass of LNAPL remaining, combined with the predicted NSZD rates, were used to estimate the approximate time for continued depletion of the bulk petroleum hydrocarbon mass at the site.

Analysis of soil cores previously indicated an approximate 1 m thick hydrocarbon smear zone and residual LNAPL saturation of 10% (or 0.1 as a fraction). The LNAPL volume per acre is estimated from the thickness of the smear zone (1 m), residual saturation (0.1), total porosity (0.35) and area in m^2 per acre (4,047 m^2), and conversion factor for m^3 to US Gal (264.2)

$$\text{LNAPL volume} = 1\text{ m} \times 0.1 \times 0.35 \times 4{,}047\text{ m}^2 \times 264.2\text{ US Gal/m}^3 = 37{,}423\text{ US Gal} \sim 37{,}000\text{ US Gal}$$

As indicated above, the seasonal average vadose zone NSZD rate was approximately 625 US gal/acre/yr (5,900 L/hectare/yr). A saturated zone biodegradation rate of 75 US gal/acre/yr was estimated using the control volume method described in Remediation Toolkit #2 and saturated zone data on dissolved hydrocarbon concentrations and biogeochemical data. The total NSZD rate was estimated as 700 US gal/acre/yr. An order of magnitude estimate of the time for hydrocarbon mass depletion to occur, assuming rates remain constant in time, is roughly 53 years.

There is uncertainty in longer term rates because mass depletion is affected by the relative proportion of petroleum hydrocarbon mass in the unsaturated versus saturated soil zones, and processes and depletion rates in each zone. Further, the rate of mass depletion is dependent on the composition of the petroleum hydrocarbon because rates vary depending on hydrocarbon class or type. There is on-going research on longer-term hydrocarbon depletion rates. In addition, there are approaches and methods being developed to better understand compositional change and depletion or attenuation rates of key risk drivers such as BTEX compounds, including analysis using soil gas data as proposed by Lahvis (2019).

7.0 SUMMARY

Toolkit #3 describes a science-based approach for identification, screening and selection of remedial technologies based on the LNAPL conceptual site model, LNAPL concerns or risks, remedial goals, primary mechanisms and objectives, remedy criteria, performance metrics and transition thresholds. Remediation technologies are broadly selected based on the remediation goal and primary mechanisms with goals relating to saturation, composition, containment and aesthetics.

Building on the framework, a practical step-wise approach to screen and select technologies to achieve remediation goals and objectives is provided. Step 1 of the remedial selection process is to identify the desired primary remediation mechanism based on the project goals from which the applicable technologies are identified. To further refine the list of identified technologies in Step 1, Step 2 of the remedial selection process considers key parts related to technical feasibility and implementability. Additional factors including those relating to remediation permanence, reliability and resiliency (including to climate change) should be considered. Information on 24 remedial technologies is provided.

The framework incorporates recent science and improved understanding of NSZD and MNA and performance and transition thresholds that consider remedy criteria, timelines and sustainability. Guidance on NSZD and MNA is provided in Remediation Toolkit #2 and BC ENV Technical Guidance 8. The intended outcome is a more structured approach to remedial options evaluation, a framework and metrics to guide and inform transitions from active to natural remediation and an improved process for achieving site closure.

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Table A: Steps 1 2 of the Technology Screening Process

Step 1			Step 2							
Primary Mechanism	Technologies Available	Brief Technology Description	Applicable Zone (Saturated, Unsaturated)	Hydrogeologic & Soil Type Factors	LNAPL Type / chemical types (refers to petroleum hydrocarbons)	Technical Feasibility[1]	Effect of Depth to Source & Infrastructure on Technology	Effect of Remoteness and Cold Climate on Technology	Constructability / Implementability[1]	Overall Ranking [1]
						* Based on Step 1 factors and general knowledge rank technology (High = 3, Medium = 2, Low = 1)			* Based on Step 2 factors and general knowledge of Constructivity (3 = High, 2 = Medium, 1 = Low)	Retained / Not Retained
Mass Recovery	Excavation	LNAPL source is physically removed and impacted soil and product is properly treated or disposed.	Both	Potential geotechnical stability concerns; easier to excavate unconsolidated soil and less practical for bedrock	All types		May be impracticable for deep sources and where access is limited by infrastructure	Disposal options potentially limited; relatively short window for implementation		
	Multi-phase extraction (MPE), dual-phase extraction (DPE), dual-phase liquid extraction (DPLE)	MPE consists of the removal of LNAPL, water and vapor, either using a single pump or dual pumps for liquid extraction. The drawdown of LNAPL, drawdown of groundwater and vacuum creates an LNAPL gradient toward a recovery point. The drawdown of groundwater may expose LNAPL thereby increasing the rate of recovery. DPE or DPLE is the removal of LNAPL and water, either implemented using a single pump or dual pumps. The drawdown of groundwater and LNAPL creates an LNAPL gradient toward a recovery point.	Saturated	Effective and applicable for range of soil types; MPE can be used to target silty and sandy soils with mid-range hydraulic conductivity values of 10^{-5} to 10^{-3} cm/s (GOST); drawdown is enhanced in lower permeability soils although excessive smearing should be avoided; can be highly effective for confined LNAPL because smearing is limited; in clay soils, high vacuums and closely spaced wells may be needed	All types, more efficient for lower viscosity LNAPL (0.5–1.5 cP) than higher viscosity LNAPL (>6 cP) (ITRC 2018).		Generally not impacted by presence of infrastructure, at greater depths, bioslurping mode of extraction may become challenging, although dual pump system could be used	Potential limitations in access to utilities or local operations & maintenance labour; water freezing; deep frost or permafrost; potentially long periods without collected product removal		
	LNAPL skimming or vacuum-enhanced LNAPL skimming	Active skimming is the removal of LNAPL under natural gradients at the air/LNAPL interface air using a pump or similar continuous mechanical device (e.g., belt skimmer) in either a well or trench. Vacuum-enhanced skimming involves removal of LNAPL and vapour. LNAPL drawdown via skimming and vacuum induce an LNAPL gradient toward a recovery point to enhance recovery (also referred to as bioslurping or vacuum enhanced fluid recovery (VEFR)). Passive skimming is use of a bailer or collection device with oleophilic screen to collect LNAPL.	Saturated	Greater effectiveness for higher permeability (i.e., coarse-grained) soils and lower residual LNAPL saturation in coarser grained soils (i.e., lower capillary pressure); hydraulic conductivity should be > 10-4 cm/sec to ensure a sufficient influx of LNAPL to the skimmer (CRC Care 2018)	All types, more efficient for lower viscosity LNAPL (0.5–1.5 cP) than higher viscosity LNAPL (>6 cP) (ITRC 2018).		Generally not impacted by presence of infrastructure or depth to source	Potential limitations in access to utilities or local operations & maintenance labour; water freezing (if removed); deep frost or permafrost; potentially long periods without collected product removal; may be possible operate skimming system using solar power (at least part of the year)		
	NSZD ("bulk" or "mass" removal)	LNAPL mass is depleted or lost through naturally occurring weathering processes consisting of biodegradation, dissolution and volatilization.	Both	Effective for range of hydrogeologic and soil type factors; may be higher depletion and degradation rates in coarser-grained deposits where oxygen is able to more readily migrate to contamination zones	Natural depletion has been demonstrated for broad range of petroleum hydrocarbon types; depletion rates in heavy oils or products with less soluble or biodegradable compounds may be slower than for light or medium distillate products.		Remediation effectiveness generally not impacted, except where infrastructure significantly affects oxygen transport to the subsurface; potential reduction in effectiveness and challenges for monitoring of very deep sources	Potential lower biodegradation rates in extreme cold conditions; however, research shows biodegradation takes place even at temperatures approaching freezing; shallow soils may be potentially affected to greater extent by cold temperatures		
Phase Change[2]	NSZD and MNA	LNAPL constituents are naturally depleted from the LNAPL body over time by volatilization, dissolution, absorption and degradation.	Both	Effective for range of hydrogeologic and soil type factors; may be higher depletion and degradation rates in coarser-grained deposits where oxygen is able to more readily migrate to contamination zones	Natural depletion has been demonstrated for broad range of petroleum hydrocarbon types; depletion rates in heavy oils or products with less soluble or biodegradable compounds may be slower than for light or medium distillate products.		Remediation effectiveness generally not impacted, except where infrastructure (e.g., paved surfaces) significantly affects oxygen transport to the subsurface; potential reduction in effectiveness and challenges for monitoring of very deep sources	Potential lower biodegradation rates in extreme cold conditions; however, research shows biodegradation takes place even at temperatures approaching freezing; shallow soils may be potentially affected to greater extent by cold temperatures		
	Air Sparging	Air sparging involves injection of air into the saturated zone within the area of LNAPL impacts or dissolved plume body to volatilize residual LNAPL and dissolved phase constituents. Often is used in conjunction with SVE. Generally not suited for treatment of free or mobile LNAPL because of the potential to cause lateral migration and spreading of LNAPL.	Saturated	Greater effectiveness for higher permeability (i.e., coarse-grained soils) that are relatively homogeneous over treatment zone (i.e., without significant layering)	All types, more efficient for LNAPL with higher volatility components		Generally not impacted by presence of infrastructure or depth to source	Potential limitations in access to utilities or local operations & maintenance labour; may be less impacted by cold weather than technologies that pump groundwater and product		
	Soil vapour extraction (SVE)	SVE is a technology where vacuum is applied to unsaturated soil to induce controlled air flow, which enhances volatilization and removal of volatile constituents in residual LNAPL and petroleum hydrocarbon contamination in the unsaturated zone. It is primarily suited to meet a compositional objective, but can also be used to meet a mass removal objective.	Unsaturated	Greater effectiveness for higher permeability (i.e., coarse-grained) soils although with appropriate design can be effective for moderate permeability fine-grained soils	Volatile petroleum hydrocarbons such as gasoline and Jet fuel B. The volatile fraction of diesel is also amenable to SVE.		Generally not impacted by presence of infrastructure or depth to source; less effective when source is within the capillary fringe although some wicking of LNAPL may occur and steep diffusion gradients will promote treatment	Potential limitations in access to utilities or local operations & maintenance labour; may be less impacted by cold weather than technologies that pump groundwater and product. Extreme cold can reduce volatilization of shallow contamination.		
	Bioventing	Similar process to SVE except air/oxygen is either injected or extracted to enhance aerobic biodegradation of residual LNAPL and petroleum hydrocarbon contamination in the unsaturated zone. Typically, lower air flow rates are used compared to SVE.	Unsaturated	Greater effectiveness for higher permeability (i.e., coarse-grained) soils although with appropriate design can be effective for moderate permeability fine-grained soils	All biodegradable petroleum hydrocarbons; higher biodegradation rates are expected for light to middle distillate petroleum hydrocarbons such as gasoline and diesel compared to heavier molecular weight hydrocarbons.		Generally not impacted by presence of infrastructure or depth to source; less effective when source is within the capillary fringe although some wicking of LNAPL may occur and steep diffusion gradients will promote treatment	Potential limitations in access to utilities or local operations & maintenance labour; may be less impacted by cold weather than technologies that pump groundwater and product. Extreme cold can reduce biodegradation rates of shallow contamination.		
	Biosparging	Similar process to air sparging except air/oxygen is injected to stimulate aerobic biodegradation of petroleum hydrocarbons in the saturated zone either residual LNAPL or dissolved phase constituents. Typically, lower air flow rates are used compared to air sparging.	Saturated	Greater effectiveness for higher permeability (i.e., coarse-grained soils)	Most types of petroleum hydrocarbons (all that are biodegradable)		Generally not impacted by presence of infrastructure or depth to source	Potential limitations in access to utilities or local operations & maintenance labour; may be less impacted by cold weather than technologies that pump groundwater and product.		
	ISCO	ISCO involves injecting an oxidant to react with and destroy organic compounds. Either or both LNAPL source zones and dissolved plumes may be treated although high quantities of oxidant may be required to treat LNAPL, which may become uneconomic. Oxidation reactions occur in the dissolved phase. A key success factor is delivery of oxidant to contamination zones. Injection of oxidant under pressure using direct push technology is preferred over injection in wells. The oxidant must be matched to site conditions and correct dose must be used relative to stoichiometric results. Multiple injections are typically required. Increased groundwater concentrations of LNAPL constituents in groundwater after initial ISCO application is not uncommon.	Saturated	More effective in higher permeability coarse-grained soil compared to finer-grained soil, more effective in relatively homogeneous compared to heterogeneous soils. May require closely spaced injection points. While primarily a technology for treatment of residual LNAPL and/or dissolved plume in saturated soil zone, certain oxidants (ozone) and injection strategies may enable use in unsaturated zone.	All types		Potential access and integrity issues for oxidant delivery where source zone located below or near infrastructure	Potential limitations in access to utilities or local operations & maintenance labour; may be less impacted by cold weather than technologies that pump groundwater and product.		
	In-situ bioremediation	In-situ bioremediation involves the use of amendments to either increase aerobic or anaerobic biodegradation rates of petroleum hydrocarbons; the technology may involve either biostimulation of indigenous microorganism or bioaugmentation through addition of external microbial cultures, which is less common for petroleum hydrocarbons as there are usually indigenous microorganisms that can be sufficiently stimulated; bioremediation involves the addition of electron acceptors (e.g., oxygen, nitrate, sulphate, etc) and, in some cases, nutrients (trace elements) to the subsurface through injection during drilling or direct push, injection in wells, placement on excavation surfaces, or via infiltration gallery; use of soluble electron acceptors such as nitrate and sulphate can be advantageous because of higher rates of loading compared to for example oxygen; as heating of soil can increase biodegradation rates, solarization, which is heating of soil using surface plastic cover, or addition of hot water or air to soil has recently been used.	Both	Greater effectiveness for higher permeability (i.e., coarse-grained) soils although with appropriate design (closely-spaced injection points) can be effective for moderate to lower permeability fine-grained soils	All biodegradable petroleum hydrocarbons; higher biodegradation rates are expected for light to middle distillate petroleum hydrocarbons such as gasoline and diesel compared to heavier molecular weight hydrocarbons.		Potential issues in delivery of amendments to source zones directly below infrastructure	Potential limitations in access to utilities or local operations & maintenance labour; may be less impacted by cold weather and remoteness than technologies that require continuous operation.		
	Activated carbon (usually with other amendments)	Activated carbon with or without bio-nutrients, oxidants or reactive materials (zero-valent iron) is injected into aquifer or placed into excavation. The activated carbon sorb dissolved phase chemicals and through binding of chemical provides time for reaction processes to occur. Different types of activated carbon include granular, powdered (slurry) and nano(colloidal)-scale (liquid) form. Direct contact with contaminants is necessary for sorption to occur, therefore effective distribution of carbon to contamination zones is required. Activated carbon injection is typically used to reduce dissolved phase mass flux or discharge emanating from source zones. While it may be appropriate to use in low LNAPL saturation or concentration source zones in some cases, caution should be used when addressing this objective.	Saturated	Greater effectiveness for higher permeability (i.e., coarse-grained) soils although with appropriate design (closely-spaced injection points) can be effective for moderate permeability fine-grained soils	All types, when bio-nutrients are added to enhance degradation consideration of redox and electron acceptors is required		Generally not impacted by presence of infrastructure or depth to source	Potential limitations in access to utilities or local operations & maintenance labour; may be less impacted by cold weather and remoteness than technologies that require continuous operation.		
	Phytoremediation	Use of plants to degrade, extract, contain, or immobilize chemicals in soil and groundwater. Phytohydraulics generally use phreatophytic trees and plants that have the capacity to evapotranspire large volumes of water resulting in hydraulic containment and removal of contaminated groundwater. Rhizodegradation is the breakdown of contaminants within the plant root zone, or rhizosphere. Phytodegradation is the update and metabolism of contaminants in the plant tissues. Phytovolatilization is the uptake and release to atmosphere of volatile contaminants. Technology is limited to depths within the root zone. While primarily mechanism is concentration reduction and hydraulic control, has been proposed to also control LNAPL through mass reduction.	Both	Applicable to a wide range of soil types where plants can be grown, may be limited effectiveness for very wet or dry soils, soils that are dense or compact and where root penetration is limited. While primarily a technology that addresses unsaturated soil zone, where groundwater is shallow, phytohydraulic methods may target the saturated zone	All types, although more amenable to more soluble and volatile fractions of petroleum hydrocarbons. May not be effective for higher LNAPL saturations or petroleum hydrocarbon concentrations where plant growth is reduced.		Limited to depth of plant roots and potentially impacted by presence of infrastructure	Cold climate make limit the types of species or effectiveness of plants for phytoremediation. Because plants must be maintained, remote sites are at a disadvantage with regards to access to local operations & maintenance labour. Plant species should be compatible with local fauna and site uses.		
	Chemically enhanced electrokinetics	Electrokinetics is a technology that extracts or immobilizes contaminants from soil or groundwater, the technology involves the application of a low-intensity electric current between pairs of electrodes (anodes and cathodes) located in and around a zone of contamination or installed perpendicular to the direction of groundwater flow to create a barrier, movement of ions to toward an anode is induced, because petroleum hydrocarbons have low polarity, a chemical compound with strong polarity (e.g. carboxymethyl-ß-cyclodextrin) is added to the contaminated matrix to enhance the solubility of the hydrophobic organic compounds and migration toward an electrode facilitated by polarity of the mixture, electrokinetic technology can be combined with the extraction of contaminants through precipitation near the electrodes, electro-deposition (formation of a deposit on the surface of a conductive extractor), pumping of water near the electrodes, use of heating element to volatilize contaminants combined with extraction, or formation of a complex with ion-exchanging resins.	Both	More effective in fine grained soils such as clay or silt	All types		Potential issues in chemical delivery and installation of electrodes near to infrastructure	Potential limitations in access to utilities or local operations & maintenance labour; may be less impacted by cold weather and remoteness than technologies that require continuous operation.		

Table A: Steps 1 2 of the Technology Screening Process

Step 1			Step 2							
Primary Mechanism	Technologies Available	Brief Technology Description	Applicable Zone (Saturated, Unsaturated)	Hydrogeologic & Soil Type Factors	LNAPL Type / chemical types (refers to petroleum hydrocarbons)	Technical Feasibility[1] * Based on Step 1 factors and general knowledge rank technology (High = 3, Medium = 2, Low = 1)	Effect of Depth to Source & Infrastructure on Technology	Effect of Remoteness and Cold Climate on Technology	Constructability / Implementability[1] * Based on Step 2 factors and general knowledge of Constructivity (3 = High, 2 = Medium, 1 = Low)	Overall Ranking [1] Retained / Not Retained
Mass Control and Containment	Permeable reactive barriers (PRBs)	PRBs are in situ treatment systems that consist of media that result in passive chemical reactions combined structures for groundwater flow management to treat dissolved phase contaminants in groundwater. The reactions can consist of degradation or mass destruction through reactions of petroleum hydrocarbons with zero-valent iron or oxygen release compounds (often magnesium oxide type compounds) or immobilization through precipitation-type reactions (through organic amendments that create reducing conditions and, e.g., sulphur complexes) or adsorption reactions (e.g., activated carbon). The reactive media depending on design life and other factors may require replacement. Groundwater flow management can be provided through walls constructed of sheet piles, low permeability materials (e.g., slurry walls) or other means. PRBs are not designed to be barriers for LNAPL migration.	Saturated	Effective for wide range of hydrogeologic conditions and soil types; the potential for a sinking plume, groundwater mounding or groundwater "diving" due to presence of barrier should be evaluated	All types of dissolved PHCs		Becomes impracticable and uneconomic for deep sources and where access is limited by infrastructure; potential for fouling and precipitation that can reduces performance over time; potential requirement to replenish reagent	Potential high cost of mobilization for large equipment, limited access to utilities and labour for construction and operation and maintenance; cold climate design considerations include protection against frost heave, spring thaw and deep freezing		
	Drains	Hydraulic containment is provided by closed or buried French drains that consist of gravel-filled trench and perforated pipe or open water trench; installed below water table; typically there is a sump where water is pumped from to create a hydraulic gradient to the drain. French drains generally are ineffective for containing migrating LNAPL but can be used to contain a dissolved petroleum hydrocarbon plume. Open drains can be used to contain and collect LNAPL when combined with appropriate means to recover product, water and product must be appropriately treated and disposed of.	Saturated	Effective for wide range of hydrogeologic conditions and soil types; the potential for a sinking plume should be evaluated (i.e., as plume could migrate below drain)	All types		Becomes impracticable and uneconomic for deep sources and where access is limited by infrastructure	Potential high cost of mobilization for large equipment, limited access to utilities and labour for construction and operation and maintenance; cold climate design considerations include protection against frost heave, spring thaw and deep freezing		
	Impermeable/slurry walls	Physical containment is provided through impermeable barriers (or slurry walls) to contain migration of dissolved plume and/or mobile LNAPL, slurry walls consist of vertically excavated trenches that are filled with slurry, walls may also be constructed through jet grouting, walls are typically comprised of soil, bentonite and water mixtures, other mixtures included cement/bentonite, pozzolanic materials/bentonite or organically modified bentonite, the type of amendments or materials used will depend on requirements for permeability, strength, durability and chemical compatibility with contamination, when LNAPL is in contact with wall materials, special attention to compatibility and possible effects of chemicals in LNAPL on permeability are required, typically, there are groundwater extraction wells upgradient of the impermeable/slurry wall.	Both	Effective for wide range of hydrogeologic conditions and soil types, the soil gradation and permeability affects the amount of amendments needed to achieve design permeability for the wall, there may be cases where walls are impracticable, where there are fill soils with debris or very coarse soils (e.g., cobbles, boulders) pre-excavation and removal may be required.	All types		Becomes impracticable and uneconomic for deep sources and where access is limited by infrastructure	Potential high cost of mobilization for large equipment, limited access to utilities and labour for construction and operation and maintenance; cold climate design considerations include protection against frost heave, spring thaw and deep freezing		
	In-Situ Containment-Capping and Solidification-Stabilization (including vitrification)	Physical containment or control of dissolved plumes, vapour plumes or mobile LNAPL is provided through use of chemical amendments to bind contaminants in soil to reduce leaching and/or volatilization of chemicals and their impacts and to immobilize LNAPL, soil is mixed with stabilizers and/or binding agents such as Portland cement, pozzolanic materials, ash, lime and/or bentonite clay, consideration must be made with respect to the compatibility of the contaminants and the materials used.	Both	Effective for wide range of hydrogeologic conditions and soil types; the soil gradation and permeability affects the amount of amendments needed to achieve design permeability, leaching and strength for the wall, there may be cases where stabilization/solidification is impracticable (e.g., high LNAPL saturations), where there are fill soils with debris or very coarse soil pre-excavation and removal may be required.	All types		Becomes impracticable and uneconomic for deep sources and where access is limited by infrastructure	Potential high cost of mobilization for large equipment, limited access to utilities and labour for construction and operation and maintenance; cold climate design considerations include protection against frost heave, spring thaw and deep freezing		
	Ankeny Moat	A system of interconnected lateral drains is placed within a highly conductive backfill in a trench to create a moat. The moat isolates the source zone from the flowing groundwater by providing a preferred pathway for groundwater flow upgradient of the source zone. This is a hybrid technology in the it incorporates hydraulic control. However, hydraulic control acts to reduce contact of groundwater with contamination and through lower mass flux also provides opportunity for natural biodegradation processes to additionally reduce concentrations.	Saturated	Effective where it is possible to create hydraulic barrier. May not be effective for highly permeable soils.	All types, more applicable to smaller, shallower sources because requires a "ring" construction of moat around contamination		More suitable to shallower sources	Potential limitations in access to utilities or local operations & maintenance labour; passive technology so may be less affected by cold weather and remoteness than technologies that require continuous operation.		
	Groundwater Pump & Treat	Hydraulic containment of dissolved plume is provided through pumping wells that extract groundwater. By modifying gradients, hydraulic control is provided, with intended goal of plume capture. The pumped groundwater is either treated or disposed-of in an appropriate manner.	Saturated	Effective for wide range of hydrogeologic conditions and soil types, may be less effective for very high permeable soil because of very large pumping rates that may be required, and for very low permeable soil because capture zone may be limited	All types		Generally not impacted by presence of infrastructure or depth to source	Potential limitations in access to utilities or local operations & maintenance labour; water freezing; deep frost or permafrost		
Enhanced Phase Change and Mass Recovery	In-situ thermal (radio frequency heating (RFH), electrical resistance heating (ERH), thermal conductive heating (TCH)	Thermal technologies are used to heat soil and groundwater to increase volatilization rate and mass recovery, and/or reduce the viscosity and interfacial tension of LNAPL for enhanced hydraulic recovery, technology requires extraction wells to remove vapour or product, thermal technologies have potential to address both phase change (composition) and mass recovery (saturation) objectives, thermal technologies heat soil through electromagnetic energy (RFH), electrical energy (ERH) and heating element (TCH)	Both	Effective for range of soil types, can be particularly effective for finer-grained soil as silts and clays tend to be more electrically conductive than sands and gravels, and therefore can be efficiently heated. Treatment rates depend on water content and porosity. Heterogeneity is less of a factor than other remediation approaches because soil thermal properties typically vary over relatively small ranges. In saturated zone, heating is less effective for higher groundwater flow rates because thermal specific heat capacity of water is about 4X higher than for soil or rock matrix. ITRC (2018) suggests TCH is effective in saturated soils with groundwater seepage velocities that are less than 1 foot/day.	All types; lower viscosity and/or higher volatility LNAPL components are more effectively treated		Potential access and integrity issues for heating where source zone located below or near infrastructure.	Potential limitations in access to utilities or local operations & maintenance labour; increased energy due to deep frost or permafrost; potentially long periods without collected product removal		
	Co-solvent flushing or surfactant enhanced LNAPL recovery	A surfactant or solvent is injected in soil to change LNAPL properties and increase rate of mass recovery. Surfactants composed of hydrophilic and hydrophobic groups increase the solubility of LNAPL and thus increase the mass recovery when pumping groundwater. Cosolvent flushing involves the injection and subsequent extraction of a cosolvent (e.g., an alcohol) to solubilize LNAPL. These technologies have potential to address both phase change (composition) and mass recovery (saturation) objectives.	Saturated	More effective for higher permeability soils, less effective for heterogeneous soils with layering as this will cause greater variability in solvent or surfactant distribution in soil	All types, higher solubility and lower viscosity LNAPL components are more effectively treated		Potential access and integrity issues for surfactant/solvent delivery where source zone located below or near infrastructure. Surfactants may be relatively benign.	Potential limitations in access to utilities or local operations & maintenance labour; water freezing; deep frost or permafrost; potentially long periods without collected product removal		
	Steam enhanced LNAPL recovery	Steam is injected into wells to heat the surrounding soil and LNAPL, steam injection induces a pressure gradient that pushes ahead of it, in sequence, from the distal point, an ambient temperature water front, a hot water front, and a steam front that targets the LNAPL zone. In the unsaturated zone, a steam and condensation front develops. The mobilized LNAPL and groundwater are recovered from extraction wells, and volatilized LNAPL components are collected at vapor extraction wells. By modifying or cycling the steam pressure, it may be possible to optimize the vapourization of volatile chemicals. This technology has the potential to address both phase change (composition) and mass recovery (saturation) objectives.	Unsaturated and Saturated	Effective only when there are relative permeable soils ((hydraulic conductivity >10-5 cm/sec, ITRC 2018), where there is less resistance to flow for steam and water. If there are lower permeable layers, some treatment will occur through heat conduction	All types, lower viscosity and high volatility LNAPL components are more effectively treated		Potential access and integrity issues for steam delivery where source zone located below or near infrastructure	Potential limitations in access to utilities or local operations & maintenance labour; increased energy due to deep frost or permafrost; potentially long periods without collected product removal		
	Water flooding	Water flooding involves groundwater recirculation in a combined injection/ extraction well configuration with the objective of displacing LNAPL and increasing the LNAPL gradient and LNAPL flow toward recovery wells. Hot water may be used to reduce interfacial tension and viscosity of the LNAPL and further enhance LNAPL removal by hydraulic recovery. The technology must be carefully implemented because raising and lowering the water table may cause smearing and reduction of saturation without the benefit of increased recovery. This technology has the potential to address both phase change (composition) and mass recovery (saturation) objectives. Phase change (composition) objective is only possible for hot water where significant mass removal occurs.	Saturated	Potentially more effective for higher permeability soils with lower LNAPL capillary pressures; however, as hydraulic conductivity increases, pumping rates also increase making this technology infeasible.	All types		Potential access and integrity issues for water delivery where source zone located below or near infrastructure	Potential limitations in access to utilities or local operations & maintenance labour; increased energy due to deep frost or permafrost; potentially long periods without collected product removal		

1 User input field.
2 There may also be significant mass reduction associated with these technologies

Table B: Key Factors and Data Requirements

Primary Mechanism	Technologies Available	Waste Generation	Relative Remedial Timeframe[1]	Data Requirements (all technologies require basic information on LNAPL release (age, volume, duration, area), LNAPL distribution and soil and groundwater concentrations)	Special Considerations	Performance Metrics	Applicable Models	Relative Safety Concerns[2]	Relative Cost[3]	BC Context
Mass Recovery	Excavation	Soil and seepage water; characterization and treatment/disposal required; additional requirements for hazardous waste	Short (weeks to months)	Soil concentrations, extent of contamination zone to be excavated, soil type; hydrogeological data, groundwater concentrations, dewatering, geotechnical and slope stabilization data (i.e., to design excavation, shoring, cut-off walls, etc.)	Potential dust generation and air quality concerns; potential for mobilizing contamination through pumping for groundwater dewatering, neighbour/stakeholder concerns frequently with respect to dust, noise, odour, lights (at night) and traffic.	Soil; groundwater; and possibly soil vapour concentrations; LNAPL presence	Geotechnical models for slope stability and design of excavation works	Moderate to high, construction related safety concerns for excavation and dewatering, generation of potentially hazardous dust and vapour, transportation related concerns, excavation has safety concerns typical of heavy construction.	Low to high	Remote sites often have high mobilization and monitoring costs; northern locations may have short work windows, challenges with mobilization to remote sites may be necessitate reliance on field screening, expedited programs and/or risk management
	Multi-phase extraction (MPE), dual-phase extraction (DPE), dual-phase liquid extraction (DPLE)	Soil, water, LNAPL, and vapour requires treatment/disposal and/or recycling; use of dual pumps to separately remove LNAPL and water may be desirable to avoid emulsification and more costly treatment	Short (weeks to months)	Soil properties (porosity, moisture content, grain size, gas permeability, interfacial tension with product), hydrogeological properties (depth to groundwater, hydraulic conductivity, hydraulic gradient, groundwater flow direction), LNAPL properties (density, transmissivity, viscosity, solubility, vapour pressure); explosivity of LNAPL and potential safety precautions; pilot scale test often conducted	Product recovered may need to be disposed of as a hazardous waste; technology has relatively high energy requirements; LNAPL recovery rates typically decline relatively quickly (weeks to months). When further LNAPL recovery becomes un-economic, the MPE system is often replaced with an alternative strategy (such as MNA) to manage residual impacts.	Groundwater, soil gas and product recovery rates; concentrations in groundwater and soil gas; mass removal rates (product, groundwater, soil vapour); ratio of product to water recovered (if goal is product recovery); pressure data; cost and/or GHG emission per unit volume of LNAPL recovered	Use of decline curve analysis, semi-log plots, etc. to predict future LNAPL recoveries and help determine when LNAPL recovery is approaching asymptotic limits.	Moderate, potential concerns with equipment, process equipment under pressure or vapour, explosivity or asphyxiation from vapours, exposures to LNAPL	Moderate to high	Cold climate may pose challenges for operation. Process equipment should be protected from freezing; automation and remote data monitoring may improve operation
	LNAPL skimming or vacuum-enhanced LNAPL skimming	LNAPL recovered requires disposal, treatment, and/or recycling	Moderate to long (years)	Soil properties (porosity, moisture content, grain size, interfacial tension with product), hydrogeological properties (depth to groundwater, hydraulic conductivity, hydraulic gradient, groundwater flow direction), LNAPL properties (density, transmissivity, viscosity); explosivity of LNAPL and potential safety precautions; pilot scale test may be conducted	Product recovered may need to be disposed of as a hazardous waste; may be possible to implement solar-powered skimming systems as more sustainable approach	LNAPL recovery rate and total volume; ratio of recovered LNAPL to incidental groundwater recovered; cost and/or GHG emission per unit volume of LNAPL recovered	Use of decline curve analysis, semi-log plots, etc. to predict future LNAPL recoveries and help determine when LNAPL recovery is approaching asymptotic limits.	Low to moderate, potential concerns with equipment, explosivity or asphyxiation from vapours, exposures to LNAPL	Low to moderate	Cold climate may pose challenges for operation. Process equipment should be protected from freezing; automation and remote data monitoring may improve operation
	NSZD ("bulk" or "mass" removal)	None	Long (years to decades)	Soil type; LNAPL properties (vapour pressure, density, solubility); hydrogeological properties (depth to groundwater, hydraulic conductivity, hydraulic gradient, groundwater flow direction), biodegradation indicators	Often implemented in conjunction with active technologies as treatment train approach. Essential to appropriately define performance metrics and transition thresholds or points where active technology is transitioned to NSZD	Soil gas profiles (fixed gases); CO_2 efflux; dissolved phase geochemical data, temperature data	Soil gas gradient method, temperature method models, control volume calculations for saturated zone, BIOSCREEN	Low	Low to moderate: depends on remediation time frame and monitoring	Cold climate or very wet conditions may result in reduced biodegradation rates compared to warmer and drier climates, however, biodegradation has been shown to occur at even low temperatures approaching freezing; seasonal monitoring should typically be conducted to assess rates
Phase Change[4]	NSZD and MNA	None	Long (years to decades)	Soil type; LNAPL properties (vapour pressure, density, solubility); hydrogeological properties (depth to groundwater, hydraulic conductivity, hydraulic gradient, groundwater flow direction), biodegradation indicators, groundwater geochemical data	Often implemented in conjunction with active technologies as treatment train approach. Essential to appropriately define performance metrics and transition thresholds or points where active technology is transitioned to NSZD	Soil gas profiles (fixed gases); CO_2 efflux; dissolved phase geochemical data, temperature data	Soil gas gradient method, temperature method models, control volume calculations for saturated zone, BIOSCREEN	Low	Low to moderate: depends on remediation time frame and monitoring	Cold climate or very wet conditions may result in reduced biodegradation rates compared to warmer and drier climates, however, biodegradation has been shown to occur at even low tempera Turing approaching freezing; seasonal monitoring should typically be conducted to assess rates
	Air Sparging	Typically implemented in conjunction with SVE, see below	Moderate (years)	Soil permeability and aquifer heterogeneities (e.g., layering), depth to groundwater, LNAPL chemistry and volatile fraction; expected air flow rate, pressure and radius of influence, often a pilot test is conducted	Aquifer heterogeneities and soil layers should be well understood because of potential for unintended lateral migration; is not an appropriate technology when there is free or mobile LNAPL present (unless limited to very thin layers) because of the potential to cause LNAPL migration and spreading	Pressure, air flow rate, radius of influence, water table mounding, DO concentrations, mass recovered (see SVE), groundwater concentrations, mass flux and discharge, may include tracer test (e.g., helium) and/or neutron probe to assess soil air content/distribution, rebound		Moderate, a potential safety concern is uncontrolled migration of vapours that volatilize from sparging, safety concern include those associated with equipment and piping under pressure or vacuum	Moderate	Cold climate may pose challenges for operation; process equipment should be protected from freezing; automation and remote data monitoring may improve operation
	Soil vapour extraction (SVE)	Generated vapours typically require treatment	Moderate (months to years)	Soil permeability and vadose zone heterogeneities (e.g., layering), depth to groundwater, surface cover, LNAPL chemistry and volatile fraction, expected air flow rate, pressure and radius of influence; often a pilot test is conducted	There is often tailing in performance of SVE systems over time in concentration reduction or mass removal rates; in some cases, concentration rebound may occur after system is turned off due to back diffusion from lower permeability zones	Air flow rate, pressure, soil gas concentrations in exhaust, mass removal rate, water level mounding, groundwater and soil gas concentrations, mass flux or discharge, cost and/or GHG emission per unit concentration reduction or mass recovery; rebound	BIoSVE, VIETUS	Low to moderate (for gasoline), a potential safety concern is uncontrolled migration of vapours that volatize from venting; safety concerns include those associated with equipment and piping under pressure	Moderate	Cold climate may pose challenges for operation; process equipment should be protected from freezing; automation and remote data monitoring may improve operation
	Bioventing	None if air is injected as opposed to extracted	Moderate (months to years)	Soil permeability and vadose zone heterogeneities (e.g., layering), depth to groundwater, surface cover, LNAPL chemistry, volatile and biodegradable fraction, soil gas concentrations, pH, nutrients, terminal electron acceptors, native fraction organic carbon, in-situ respiration rate; expected air flow rate, pressure and radius of influence; often a pilot test is conducted	Addition of nutrients may potentially increase degradation rates	Air flow rate, CO_2 efflux, CO_2 concentrations in exhaust (if extraction system), in-situ respiration test, soil gas O_2, CO_2 and CH_4, soil concentrations, GHG emissions and/or cost per unit mass degraded	BIoSVE	Low to moderate (for gasoline), a potential safety concern is uncontrolled migration of vapours that volatize from venting; safety concerns include those associated with equipment and piping under pressure	Low to moderate	Cold climate may pose challenges for operation, process equipment should be protected from freezing, automation and remote data monitoring may improve operation, biodegradation rates may be slower in cold climates in shallow soil, although research indicates biodegradation does occur even at temperatures approaching freezing
	Biosparging	None if air is injected as opposed to extracted	Moderate (years)	Soil permeability and aquifer heterogeneities (e.g., layering), depth to groundwater, LNAPL chemistry, volatile and biodegradable fraction; dissolved gas concentrations, pH, redox, nutrients, terminal electron acceptors, native fraction organic carbon, expected air flow rate, pressure and radius of influence; often a pilot test is conducted	Addition of nutrients may potentially increase degradation rates, generally is not an appropriate technology when there is free or mobile LNAPL present because of the potential to cause LNAPL migration and spreading, sparging will change the pH and redox and may cause secondary effects such as mobilization of metals	Air flow rate, pressure, dissolved gas concentrations (O_2, CO_2, CH_4), geochemical parameters (e.g., nutrients, terminal electron acceptors), groundwater concentrations, mass flux and discharge, GHG emissions and/or cost per unit mass degraded		Low to moderate (for gasoline), a potential safety concern is uncontrolled migration of vapours that volatize from sparging; safety concerns include those associated with equipment and piping under pressure	Low to moderate	Cold climate may pose challenges for operation, process equipment should be protected from freezing, automation and remote data monitoring may improve operation.
	In-situ chemical oxidation (ISCO)	Recirculation delivery generates wastes. Certain oxidants such as sodium or potassium permanganate leaves elevated sodium or potassium levels and precipitated manganese dioxide in soil.	Short to moderate (weeks to months); "rebound" frequently necessitates multiple treatment events.	Groundwater geochemistry, total organic carbon, depth to groundwater, hydraulic conductivity, hydraulic gradient, LNAPL volume/mass, LNAPL composition, soil density, soil grain size, expected radius of influence and distribution for injection; often bench scale and pilot scale tests are performed	Naturally-occurring organics may represent a significant oxidant demand; oxidants may result in significant changes to pH and redox, and inadvertently mobilize inorganic and organic chemicals in soil; sodium or potassium permanganate leaves elevated sodium or potassium levels and precipitated manganese dioxide; because of oxidation state, dissolved manganese is typically not an issue, but should be confirmed through monitoring; sodium persulphate will leave elevated levels of both sodium and sulphate; composition of raw materials should be determined as chemicals may contain impurities, including, for example, metals; concentration rebound due to back diffusion from lower permeability units is a relatively common occurrence.	ORP, pH, alkalinity, chloride, injected oxidant, contaminant, daughter products, groundwater elevations, oxidant amount delivered; oxidant distribution; groundwater concentrations, mass flux and discharge, rebound		High, the reaction of oxidants with aquifer materials can be very rapid and exothermic; oxidant handling requires personal protective equipment (PPE); oxidant may affect subsurface infrastructure; piping and values for injection must be compatible with the oxidant	Moderate to high	Cold climate may pose challenges for injection. Because of absence of continually operated equipment less concern than with some other in situ technologies
	In-situ bioremediation	None	Moderate to long (months to years)	Soil permeability and aquifer heterogeneities (e.g., layering), depth to groundwater, LNAPL chemistry, volatile and biodegradable fractions; dissolved gas concentrations, pH, redox, nutrients, terminal electron acceptors, native fraction organic carbon, expected radius of influence for injection; often a pilot test is conducted	In Canada micro-organisms must be registered on the Domestic Substances List (DSL) in order to be considered for bioaugmentation, there may also be provincial requirements for bioaugmentation, bioremediation may change pH and redox and cause secondary effects such as mobilization of metals	Groundwater concentrations, geochemical data, mass flux and discharge, potentially CO_2 concentrations or efflux	Bioscreen can be used to calculate assimilative capacity, BioPlume III	Low to moderate, increased concern with systems where amendments are injected under pressure	Low to moderate	Cold climate may pose challenges for injection. Because of absence of continually operated equipment less concern than with some other in situ technologies
	Activated carbon (usually with other amendments)	Limited although activated carbon may surface during injection	Moderate to long (months to years)	Groundwater geochemistry, total organic carbon, depth to groundwater, hydraulic conductivity, hydraulic gradient, LNAPL volume/mass, LNAPL composition, soil density, soil grain size, expected radius of influence and distribution for injection; often bench scale and pilot scale tests are performed	Can be effective in addressing persistent plumes and containing or capturing chemicals that back diffuse from low permeability sources, can be rebound, also can result in higher concentrations in some wells because of injection process. Mass estimates are important	Groundwater concentrations, mass flux and discharge, injection pressure, radius of influence, activated carbon concentrations in cores; care must be taken to ensure that monitoring wells, and samples from them, are not impacted by activated carbon that may negatively bias sample results.	None	Low to moderate, higher safety concern potentially if added to excavation	Moderate	Cold climate may pose challenges for injection. Because of absence of continually operated equipment less concern than with some other in situ technologies
	Phytoremediation	Plant residues after harvesting require proper handling, storage, and disposal. Treatment of petroleum hydrocarbons is not expected to generate hazardous plant residues.	Long (years)	Soil physical properties (grain size, density, water retention), soil chemistry (pH, native organic carbon, nutrients, metals, salt), climate data; LNAPL solubility and biodegradability of components, often involves bench or pilot tests to evaluate plant and root growth	Higher LNAPL saturation or concentrations of petroleum hydrocarbons may be toxic to plants. Risk assessment may be necessary before disposal of any contaminated plant material. Contamination depth must be taken into consideration as phytoremediation is limited to shallow depths. There may be food chain impacts if potential for uptake by wildlife.	Plant growth, transpiration rate, soil and groundwater concentrations, groundwater levels	None	Low	Low to moderate	Cold climate may pose challenges for plant growth
	Chemically enhanced electrokinetics	Significant changes in pH around the electrodes may cause the formation and mobilisation of secondary products, reactions may result in gas generation requiring a gas recovery system	Moderate (months to years)	Soil physical and chemical properties, soil gradation, hydrogeologic properties (possibly tracer testing and evaluation of radius of influence), LNAPL characteristics including viscosity, density, solubility, and vapour pressure	Significant changes in pH and redox around the electrodes can induce the formation and mobilisation of secondary products, the technology is complex and there may be electrode corrosion issues and moisture content may affect treatment effectiveness. Technology requires a relatively high amount of electricity.	Groundwater concentrations, mass flux and discharge, injection pressure, radius of influence, activated carbon concentrations in cores; care must be taken to ensure that monitoring wells, and samples from them, are not impacted by activated carbon that may negatively bias sample results.	None	Moderate, electricity use, chemical use, potential gas generation	Moderate to high	Cold climate may pose challenges for injection, because of absence of continually operated process equipment less concern than with some other in situ technologies

Table B: Key Factors and Data Requirements

Primary Mechanism	Technologies Available	Waste Generation	Relative Remedial Timeframe[1]	Data Requirements (all technologies require basic information on LNAPL release (age, volume, duration, area), LNAPL distribution and soil and groundwater concentrations)	Special Considerations	Performance Metrics	Applicable Models	Relative Safety Concerns[2]	Relative Cost[3]	BC Context
Mass Control and Containment	Permeable reactive barriers (PRBs)	Soils excavated for construction. Dewatering for construction if required. If PRBs are excavated at the end of their design lifetime, PRB-related residuals. Systems may be designed, however, with the intent of leaving materials in place indefinitely.	Long (years): will depend on design life of reactive material used	Soil physical properties, depth to groundwater, hydraulic gradient, hydraulic conductivity and LNAPL distribution; Site access and location of infrastructure and utilities. PRBs are generally not designed to be barrier for mobile LNAPL. Bench scale column tests may be conducted	Subsurface conditions are difficult to predict perfectly; defects in characterization or barrier construction can allow contaminants to bypass treatment or breakthrough wall. Individual "bypass" or "breakthrough" areas may be difficult to detect using conventional monitoring well arrays. Changes in system hydraulics (for example, groundwater "mounding" behind a barrier with diminished permeability) may create new areas of bypass or breakthrough over time.	Monitoring downgradient of the barrier consisting of groundwater concentration, mass flux and mass discharge, possible sampling of wall materials to assess reactivity and fouling, redox and pH to monitor geochemical conditions as reagents are consumed, as fouling occurs, as precipitation occurs, etc., the performance of the barrier may diminish over time	FEFLOW, MODFLOW or other groundwater models	Moderate to high, construction related safety concerns for excavation and construction; generation of potentially hazardous dust and vapour, transportation related concerns	Moderate to high	Remote sites often have high mobilization and monitoring costs, northern locations may have shorter work windows for construction projects
	Drains	Soils excavated for construction. Dewatering for construction, if required, may generate wastes that require treatment.	Long or indefinite; will be required for as long as the source remains	Soil physical properties, LNAPL distribution, depth to groundwater, hydraulic gradient, hydraulic conductivity, site access and location of infrastructure and utilities, if drain is to address containment of mobile LNAPL, appropriate features for collection, storage and disposal should be incorporated in the design.	Potential for bypass, clogging of drains over time	Monitoring downgradient of drain; groundwater concentrations, mass flux and mass discharge, presence of LNAPL	FEFLOW, MODFLOW or other groundwater models	Moderate to high: construction related safety concerns for excavation and construction; generation of potentially hazardous dust and vapour, transportation related concerns	Moderate	Remote sites often have high mobilization and monitoring costs; northern locations may have shorter work windows for construction projects
	Impermeable/slurry walls	Significant liquid waste stream may be generated during construction. Soils visibly saturated with LNAPL cannot be used in the slurry mix and are segregated. Excess slurry and soils not included in the slurry mix are waste materials. Dewatering and treatment may generate wastes.	Long or indefinite; will be required for as long as the source remains	Geotechnical parameters including soil permeability, soil density, soil compaction, grain size, porosity, which are all factors when determining the wall design including the amount of amendments (e.g., bentonite or cement) needed to achieve the desired wall permeability. Debris and cobbles and boulders can have significant impact on construction and may require pre-excavation or appropriate handling. Bench scales tests may be warranted.	Potential for groundwater mounding (typically groundwater pump and treat is also required); potential for contaminant breakthrough, appropriate geotechnical design is critical	Monitoring downgradient of barrier; groundwater concentrations, mass flux and mass discharge, presence of LNAPL	FEFLOW, MODFLOW or other groundwater models	Moderate to high, construction related safety concerns for excavation and construction; generation of potentially hazardous dust and vapour, transportation related concerns	Moderate to high	Remote sites often have high mobilization and monitoring costs; northern locations may have shorter work windows for construction projects
	In-Situ Containment-Capping and Solidification-Stabilization (including vitrification)	Minimal, may include excess slurry.	Long or indefinite; will be required for as long as the source remains	Geotechnical parameters including soil permeability, soil density, soil compaction, grain size, porosity, which are all factors when determining the mix design including the amount of amendments (e.g., bentonite or cement) needed to achieve the desired properties with respect to immobilization and prevention of leaching. Debris and cobbles and boulders can have significant impact on construction and mixing and may require pre-excavation or appropriate handling. Bench scale tests may be warranted.	Site use restrictions may be required (e.g., to prevent planting deep rooted trees), on-going monitoring may be required to assess effectiveness.	Monitoring downgradient of solidified soil mass; groundwater concentrations, mass flux and mass discharge, presence of LNAPL, soil vapour	FEFLOW, MODFLOW or other groundwater models	Moderate to high, construction related safety concerns for excavation and construction; generation of potentially hazardous dust and vapour, transportation related concerns, mixing under pressure, possible soil instability	Moderate to high	Remote sites often have high mobilization and monitoring costs; northern locations may have shorter work windows for construction projects
	Ankeny Moat	Soil excavated for trench	Long (years) (risk management control)	Groundwater geochemistry, depth to groundwater, hydraulic conductivity, hydraulic gradient, source zone extent, soil density, soil grain size	More suited to shallow sources near water table.	Groundwater concentrations, geochemical data, mass flux and discharge, hydraulic heads	None	Moderate	Low to moderate	Remote sites often have high mobilization and monitoring costs; northern locations may have shorter work windows for construction projects
	Groundwater Pump & Treat	Extracted groundwater typically requires treatment; there may be solid and vapour phase residuals associated with treatment	Long or indefinite; will be required for as long as the source remains, although will depend on whether groundwater pump and treat over long term results in significant contaminant reduction (typically not)	Soil and hydrogeologic properties, site access and location of infrastructure and utilities	Large pumping rates and significant drawdown may cause ground subsidence, hydraulic gradients may induce inadvertent LNAPL flow to well, which requires collection and special handling, fouling of well screens may occur over time, groundwater capture may be optimized through dipole (or multiple) wells with injection and extraction, groundwater injection typically requires permitting.	Groundwater concentrations, mass flux and discharge, hydraulic heads, capture zone	FEFLOW, MODFLOW or other groundwater models	Low to moderate, potential concerns with equipment, process equipment under pressure, additional concerns if groundwater that is extracted is contaminated	Moderate (potentially high cost of installation and operation and maintenance)	Cold climate may pose challenges for operation. Process equipment should be protected from freezing; automation and remote data monitoring may improve operation
Enhanced Phase Change and Mass Recovery	In-situ thermal (radio frequency heating (RFH), electrical resistance heating (ERH), thermal conductive heating (TCH))	LNAPL recovered requires disposal, treatment, and/or recycling; can have an LNAPL/water/air emulsion that is difficult to break. Vapour emissions required treatment	Short	Soil thermal properties (conductivity, heat capacity), soil density, moisture content, grain size, clay and silt content, depth to groundwater; anticipated radius of influence or zone of heating, often pilot test is conducted	Subsurface infrastructure and subsurface debris can interfere with treatment; soil that is tight with low permeability may be difficult to treat as there is reduced permeability to air and extraction of vapours may be challenging; very low or high moisture may affect efficiency of treatment; dry soils may require moisture addition	Temperature, soil moisture, mass removal rates and concentrations in extracted vapours, soil concentrations, groundwater concentrations, mass flux, mass discharge, LNAPL saturation, LNAPL mobility, cost and/or GHG emissions per unit of mass recovered or energy use, rebound	COMPFLOW	Moderate to high depending on operating temperatures and potential for steam generation	Moderate to high	Cold climate may pose challenges for operation. Process equipment should be protected from freezing; automation and remote data monitoring may improve operation; equipment is complex, which may be disadvantage for remote sites
	Co-solvent flushing or surfactant enhanced LNAPL recovery	Recovered surfactant or co-solvent and LNAPL require appropriate characterization and disposal; water may contain very high dissolved concentrations, concentrations of LNAPL constituents and can pose challenges for aqueous-phase treatment systems	Short	Soil permeability, soil gradation, soil density, soil heterogeneity, depth to groundwater, hydraulic conductivity, hydraulic gradient, anticipated radius of influence for injection, LNAPL composition and physical properties (solubility, viscosity, interfacial tension, density), often pilot bench scale (selection of surfactant) and pilot scale tests are conducted (extracted mixture characterization, treatment, recycling)	Product may need to be disposed of as hazardous waste, significant care must be exercised with respect to possible mobilization of subsurface LNAPL and controls should be in place to address this	Groundwater concentrations, mass flux and discharge, hydraulic heads, capture zone, LNAPL saturation, LNAPL mobility, LNAPL recovery, surfactant properties, cost and/or GHG emissions per unit of mass recovered or energy use, rebound		Moderate to high: potential concerns with equipment, use of potentially harmful and flammable chemicals if alcohols are used, generation of wastes with high concentrations and consequently potential for higher volatilization rates and explosivity concerns	Moderate to high	Cold climate may pose challenges for operation; process equipment should be protected from freezing; automation and remote data monitoring may improve operation; equipment is complex, which may be disadvantage for remote sites
	Steam enhanced LNAPL recovery	LNAPL recovered requires disposal, treatment, and/or recycling; vapours and groundwater require treatment, may be high concentrations in effluent	Short	Soil permeability, soil gradation, soil density, soil heterogeneity, depth to groundwater, hydraulic conductivity, hydraulic gradient, temperature, anticipated radius of influence for injection, LNAPL composition and physical properties (vapour pressure, solubility, viscosity, interfacial tension, density), often bench scale (column studies for evaluation of steam transport) and pilot scale test are conducted (heating in soil and steam front movement)	Product may need to be disposed of as hazardous waste, significant care must be exercised with respect to possible mobilization of LNAPL and controls should be in place to address this; possible effect of steam on infrastructure, soil drying, geotechnical concerns	Groundwater concentrations, mass flux and discharge, hydraulic heads, capture zone, LNAPL saturation, LNAPL recovery, temperature, cost and/or GHG emissions per unit of mass recovered or energy use, rebound		High, concern with steam under pressure and hot water and LNAPL extracted, release of steam at wells	Moderate to high	Cold climate may pose challenges for operation, process equipment should be protected from freezing, automation and remote data monitoring may improve operation, equipment is complex, which may be a disadvantage for remote sites
	Water flooding	LNAPL must be removed from extracted water and appropriately treated and disposed of; groundwater may also require treatment	Short	Hydraulic conductivity, hydraulic gradient, temperature, heterogeneity, anticipated radius of influence for injection and extraction, LNAPL composition and physical properties (solubility, viscosity, interfacial tension, density), often bench scale and pilot scale test are conducted	Product may need to be disposed of as hazardous waste, significant care must be exercised with respect to possible mobilization of LNAPL and controls should be in place to address this	Groundwater concentrations, mass flux and discharge, hydraulic heads, capture zone, LNAPL saturation, LNAPL mobility, LNAPL recovery, temperature, cost and/or GHG emissions per unit of mass recovered or energy use, rebound		Moderate to high, concern with use of hot-water in process, and handling of LNAPL	Moderate to high	Cold climate may pose challenges for operation, process equipment should be protected from freezing, automation and remote data monitoring may improve operation, equipment is complex, which may be a disadvantage for remote sites

Notes:
1. Relative remedial timeframe is subject to remedial objectives and criteria and site and technology factors and thus can vary widely
2. Relative safety concern is highly dependent on project, site and technology specific conditions and may vary from what is provided; in all cases, a site-specific health and safety plan should be developed and hazard and operability study should be conducted
3. Relative cost is highly dependent on project, site and technology specific conditions and can vary from what is provided
4. There may also be significant mass reduction associated with these technologies

APPENDIX A

Review of Select Guidance on Evaluation of Remedial Technologies

This appendix summarizes available resources and guidance on remedial technology selection.

1.0 ITRC (2018)

The Interstate Technology & Regulatory Council (ITRC) provides guidance for evaluating LNAPL remedial technologies (ITRC, 2018). Overall, twenty-one technologies for LNAPL are systematically evaluated according to potential concern, remedial goals and objectives. The framework includes guidance on remedy selection based on defined remedial goals and objectives. Remedy performance is evaluated using relevant metrics and end-points that are based on LNAPL science and the CSM. NSZD is integrated in the framework as both a technology and metric.

There are three goals and associated objectives provided in the guidance:

- "Saturation Goal" – LNAPL Mass Recovery or Control Objective
  - Reduce LNAPL saturation by recovering LNAPL
  - Stop LNAPL migration by containing LNAPL
- "Composition Goal" – LNAPL Phase Change Objective
  - Change LNAPL characteristics by phase change
- "Aesthetic Goal" – LNAPL Saturation or Composition Goals

Technology groups are divided into three objectives: Mass Control (saturation), Mass Recovery (saturation) and Phase Change (composition).

To guide technology evaluation, selection and performance monitoring, three sets of tables are utilized: Series A (screening step factors), series B (evaluation factors for short list), and series C (technical implementation considerations) (Appendix A, ITRC 2018).

2.0 CL:AIRE (UK ORGANIZATION)

The Contaminated Land: Applications in Real Environments (CL:AIRE) provides a series of remediation documents that are divided into three categories: 1) remediation options; 2) implementation of remediation strategy; and 3) management and evaluation of the remediation strategy. The outline of available resources provided on the CL:AIRE web site (CL:AIRE 2020) is as follows:

1) Options Appraisal
   a) Identification of feasible remediation options (INFO-OA1)
   b) Detailed evaluation of remediation options (INFO-OA2)
   c) Developing the remediation strategy (INFO-OA3)

2) Implementation of the Remediation Strategy

   a) Planning (INFO-IMP1)

   b) Implementation, verification and monitoring (INFO-IMP2)

   c) Long term monitoring and maintenance (INFO-IMP3)

3) Project Management

   a) Guidance specific to particular industrial or commercial sectors (INFO-PM1)

   b) Health and safety and quality management (INFO-PM2)

   c) Communication (INFO-PM3)

The available resources are a series of generally technology-specific guidance documents and fact sheets that have been published over the past 25-years. The Options Appraisal component of the guidance is likely the most useful reference for the Toolkits.

3.0 CANADA NATIONAL RESEARCH COUNCIL (NRC)

The Government of Canada, National Research Council (NRC) has prepared a tool referred to as the “Guidance and Orientation for the Selection of Technologies,” or GOST tool, that contains practical information for the implementation of various remedial technologies (NRC 2020). The tool aids the user in selecting potential technologies based on site-specific parameters gathered through site characterization. A list of technologies considered by the tool is presented below in Table 1, which summarizes the technologies based on the treatment type and on in-situ and ex-situ treatments. The online resource provides Technology Fact Sheets, as well as a table that allows the user to compare and contrast technologies based on the following key information (selected fields):

- Treatment time
- State of technology
- Target contaminants
- Treatment type
- Recommended analyses for detailed characterization;
- Recommended trials for detailed characterization
- Other information for detailed characterization

Table 1: Canada NRC Summary of Remediation Treatment Technologies

Treatment Type	In-Situ	Ex-Situ
Biological	Anaerobic Biostimulation Bioaugmentation Biopile Biosparging Bioventing Enhanced Aerobic Bioremediation Methanotrophic Biodegradation Monitored Natural Attenuation Mycoremediation: white rot fungus Phytoremediation Reductive dechlorination	Aerobic Biopile Aerobic Composting Bioreactor Constructed Wetlands Land Farming
Chemical	Catalytic Reductive Dehalogenation Chemical Oxidation with Ozone, Permanganate, or Peroxide Soil Mixing Soil Washing, Leaching, or Chemical Extraction	Chemical Oxidation with Ozone, Permanganate, or Peroxide Dehalogenation Soil Washing and Solvent Extraction
NAPL	Drawdown Pumping System Multi-phase Extraction System Pump & Treat Skimming	-
Physical	Solidification / Stabilization Adsorption Air Sparging Electrokinetics Frozen Walls Hydraulic Containment Impermeable / Slurry Walls Permeable Reactive / Passive Walls Pump & Treat Soil Vapour Extraction	Adsorption Air Stripping Excavation & Treatment Separation Solidification / Stabilization Ultraviolet Treatment
Sediment	Biodegradation Capping Chemical Oxidation Monitored Natural Recovery Sequestration	-
Thermal	Electrical Resistance Heating Electromagnetic Heating Hot Air Injection Hot Water Injection Steam Injection Vitrification	High Temperature Thermal Desorption Hot Gas Decontamination Incineration Low Temperature Thermal Desorption Pyrolysis Vitrification

4.0 US FEDERAL REMEDIATION TECHNOLOGIES ROUNDTABLE (FRTR)

Several US federal agencies have collaborated to create a compendium of information for hazardous waste cleanup (FRTR 2020). The member agencies are US Department of Defence, US Environmental Protection Agency, US Department of Energy, US Department of the Interior, and National Aeronautics and Space Administration. This online resource includes a Remediation Technologies Screening Matrix and Reference Guide (4th Edition), which serves as a user-friendly tool for screening applicable technologies for site remediation. This resource has a dedicated section on fuels that expands on properties and behaviours of fuels and the common treatment technologies and treatment trains for fuels. Twelve categories of technologies are described by development status, use rating, applicability, reliability, cleanup time and technology function (destruct, extract, immobilize). The twelve categories are classified below in Table 2 into either in-situ and ex-situ technologies that target solids (soil, sediment or sludge) or water (groundwater, surface water leachate). The table indicates the number of technologies of each treatment type applicable to each medium.

Table 2: Remediation categories and number of technologies in the FRTR Screening Matrix by treatment type

Target Media:	Soil, Sediment, Sludge	Groundwater, Surface Water, and Leachate
In-Situ	Biological (3); Physical/chemical (6); Thermal (1)	Biological (3); Physical/chemical (8); Thermal (1); Containment (2)
Ex-Situ	Biological (4); Physical/chemical (6); Thermal (5) + excavation and off-site disposal	Biological (2); Physical/chemical (9)

5.0 US NRC (2004)

The US National Research Council (US NRC 2004) report provides a basis for technology selection that is informed by site characterization data, remediation objectives and metrics. The report is the result of a study requested by the US Army Environmental Center to evaluate source remediation as a cleanup strategy with focus on dense non-aqueous phase liquids (DNAPLs) and chemical explosives. An emphasis is placed on site characterization data in terms of source zone and hydrogeologic conditions that are key in the selection and evaluation of a remediation technology.

As one of the study tasks, the report defines source zones as:

"A source zone is a saturated or unsaturated subsurface zone containing hazardous substances, pollutants, or contaminants that acts as a reservoir that sustains a contaminant plume in groundwater, surface water, or air, or acts as a source for direct exposure. This volume is or has been in contact with separate phase contaminant (NAPL or solid). Source zone mass can include sorbed and aqueous phase contaminants as well as contamination that exists as a solid or NAPL."

Five types of hydrogeologic settings are defined:

- Type I granular media with low heterogeneity and moderate to high permeability
- Type II granular media with low heterogeneity and low permeability
- Type III granular media with moderate to high heterogeneity
- Type IV fractured media with low matrix porosity
- Type V fractured media with high matrix porosity

The study also provides four steps for source zone characterization as follows:

1) Understanding source presence and nature.

2) Characterizing hydrogeology.

3) Determining source zone geometry, distribution, migration, and dissolution rate.

4) Understanding the biogeochemistry.

The study summarizes characterization methods and tools and recommends that source characterization be conducted iteratively throughout the remediation process. The remedial objectives are described as “absolute” or “functional”. For example, meeting regulatory criteria for groundwater at a specific location and time would be an absolute objective, whereas meeting the same criteria for reducing risk to human health (i.e., as a means to an end) is described as a functional objective. Objectives are also characterized as a) physical relating to mass removal, concentration reduction, mass flux reduction, reduction of source migration potential, plume size reduction, and changes in toxicity or mobility of residuals, or b) those relating to risk reduction, cost minimization, and scheduling.

A list of technologies and comparison tables are provided in the report, as well as a six-step process for source remediation (Figure ES-1 in US NRC 2004). The document provides useful concepts with respect to the development of a CSM, and on the effects of hydrogeologic complexity on selection of remedial technologies.

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APPENDIX B

Cold Climate Case Studies

This appendix summarizes two case studies where unique aspects of cold climate remediation were considered.

Diesel-Contaminated Site – Northern Canada (Sanscartier et al. 2010)

This study of diesel contaminated site in Northern Canada considers the environmental benefits of remediation by taking into account the impact of remedial activities at remote sites, where transport over long distances may be required. Environmental life cycle assessment (LCA) combined with risk assessment was conducted to quantify the overall impact of remediation systems on the environment. The three options assessed were:

- Option A: On-site ex-situ bioremediation (biopile) in a temporary facility, followed by disposal in an unlined landfill
- Option B: Off-site bioremediation at permanent treatment facility (mechanical mixing and collection of leachate in a holding pond)
- Option C: Containment through paving with asphalt (portion of area to eliminate exposure pathway) & in-situ treatment through bioventing

The study concluded that transportation was the main contributor to overall pollution, with the off-site treatment (Option B) having the greater environmental impact.

Petroleum Hydrocarbon Sites – Antarctic and Arctic (Camenzuli and Freidman 2015)

This study reviews six on-site or in-situ technologies for remediation of petroleum hydrocarbon contaminated sites in the Antarctic and Arctic. The review includes a comparative analysis of the six technologies with reference to example case studies where available: bioremediation, landfarming, biopiles, phytoremediation, electrokinetic remediation, and permeable reactive barriers. Coupling of technologies is also discussed to address the presence of co-contaminated sites with heavy metals and also sites that are “highly heterogeneous” with respect to soil type and contaminant distribution.

The site-specific factors considered are similar to those presented in Table A of this Toolkit; however, the authors emphasize the importance of detailed site investigation and data requirements for effective implementation of the technologies due fewer field-based studies in these cold and remote regions. They also identify a gap in field trials that couple technologies as either a simultaneous application or technologies in a treatment train.

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APPENDIX C

Literature Review of Case Studies Comparing NSZD Rates to Active Remediation Mass Depletion Rates

An emerging approach for site management is the comparison of petroleum hydrocarbon mass loss rates through NSZD to loss rates through active remediation technologies. Such evaluations can be performed at various stages of the project lifecycle including during remedial evaluation and implementation stages. NSZD rate comparisons can inform technology transitions and site closure. These comparisons indicate that often NSZD rates are similar to or in some cases greater than active mass removal particularly during later stages of active remediation. The following case studies illustrate estimates of depletion rates for active and NSZD remediation technologies.

- **McDonald et al. (2015)**

  This study compared the measured NSZD depletion rates from CO_2 efflux measurements to enhanced depletion through SVE and air sparging (Site 1), and multi-phase extraction (MPE) (Site 2). The study results showed that for Site 1, the NSZD depletion rates were similar to those estimated for active remediation. For Site 2, there was significant variability in the mass depletion rate for MPE between monitoring events. The rates in the short-term events ranged from comparable to NSZD to about one order of magnitude greater than NSZD. However, MPE was noted in the study as being an energy and cost intensive process.

- **Mahler et al. (2015)**

  This study compared the measured NSZD depletion rates from 43 sites to a median mass loss measured from CO_2 efflux measurements at eight diverse sites (e.g., pipeline, terminal railyard, gas plant, etc.). The active remedial technologies reviewed were LNAPL skimming, groundwater drawdown-enhanced skimming, bioventing/biosparging, soil vapour extraction, air sparging/soil vapour extraction and multi-phase extraction. The median NSZD mass loss rate (700 US gal/acre/yr) (6,600 L/hectare/yr) was greater or similar to median rates for skimming, soil vapour extraction, air sparging/soil vapour extraction, but less than that for remaining technologies. The rates for active remediation were shown to decrease at the approximate midway point and later stages of remediation, when the rates dropped below the NSZD rate, or remained higher but comparable to NSZD (i.e., within a factor of three).

- **Fernández et al. (2016)**

  This study assessed three treatment technologies implemented individually and as combinations at a diesel impacted site: phytoremediation, bioremediation and chemical oxidation. The early responses to CO_2 efflux were used as performance metrics, where early response referred to measurements approximately one year following the implementation of the treatment technology. A total of eight different scenarios were evaluated: phytobarrier, phytoremediation, bioremediation, ISCO, phytoremediation + bioremediation, phytoremediation + ISCO, phytoremediation + bioremediation + ISCO and no treatment in a low-polluted area.

  The early response to soil CO_2 efflux was shown to be statistically significant for the biological treatments including bioremediation that consisted of mechanical ploughing, and addition of surfactant and fertilizer. The method, although insightful, does not take into account the effect of the treatments on natural soil respiration and its contribution to the total CO_2 efflux. In addition, the effect of chemical remediation such as ISCO using hydrogen peroxide may be short-lived and was not captured in assessment one year following the treatment.

  This study found a correlation between CO_2 efflux measurements in the low-polluted area and soil temperature (measured at 10 cm depth); however, there was no significant relationship with temperature in the high-polluted soils, which the authors attribute to the slow growth and activity of the diesel degrading microorganisms.

  Although there were limitations in the study, it demonstrated the concept of using CO_2 efflux measurements as a performance metric to evaluate enhanced bioremediation.

- **The LA LNAPL Workgroup. (2015)**

  This study compared the measured NSZD depletion rates from CO_2 efflux measurements to enhanced depletion through pulsed oxygen biosparging (POBs) and surfactant enhanced aquifer remediation (SEAR) at two sites in the Los Angeles (LA) Basin. The application of POBs at the Shell Carson facility resulted in a statistically significant decrease in the benzene and BTEX mass fraction (i.e., a compositional change in the LNAPL), while the SEAR technology applied to the Tesoro Hynes facility resulted in removal of only 1% of the LNAPL in the treatment zone.

  NSZD assessments were conducted with average site-wide rates estimated at 1,700 US gal/acre/yr (16,000 L/hectare/yr) at the Shell Carson facility and 1,100 US gal/acre/yr (10,400 L/hectare/r) at the Tesoro Hynes facility. The assessments were conducted using carbon traps in collaboration with the Colorado State University.

- **Pennington et al. (2018)**

  This study describes the site remediation process and transition from active to passive (NSZD) remedies for a diesel-contaminated site. There were sandy soils and petroleum hydrocarbon smear zone from 6 to 12 ft. (1.9 to 3.7 m) below ground surface. The active LNAPL recovery at the site is summarized as follows:

  - Manual/periodic removal from wells (2010 – present): 250 US gallons (955 L) of LNAPL
  - High-vacuum extraction (2011 – 2012): 1,550 US gallons (5,920 L)
  - Skimming from wells (2012 – 2014): 206 US gallons (787 L)
  - Bioventing/vacuum-enhanced biodegradation (2013 – present): 1,800 US gallons (6,880 L)
  - Excavation/Soil Removal in Fueling Area (2015): 8,220 US gallons (31,400 L)

  Monitoring indicated that the LNAPL footprint and dissolved-phase plume were stable. The dissolved-phase plume "halo" beyond the LNAPL source was relatively small. In 2017, two rounds of transmissivity testing indicated that the transmissivity was between 0.1 to 0.8 ft^2/day (3 to 24 cm^2/day), the range where LNAPL recovery becomes impracticable (ITRC, 2018). In 2016, the NSZD rate was estimated at 1,500 US gal/acre-yr (14,400 L/hectare/yr) (or 3,000 to 4,000 US gal/yr for the entire site) based on CO_2 efflux measurements. In comparison, approximately 640 US gallons per year was removed from other remedies in 2016. Transitioning to NSZD was recommended based on the comparison between active and passive recovery rates and other lines of evidence considered.

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