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1. How to Use the Document

In 2009, ITRC published LNAPL-1: Evaluating Natural Source Zone Depletion at Sites with LNAPL (ITRC 2009b) and LNAPL-2: Evaluating LNAPL Remedial Technologies for Achieving Project Goals (ITRC 2009a) to aid in the understanding, cleanup, and management of LNAPL at thousands of sites with varied uses and complexities. These documents have been effective in assisting implementing agencies, responsible parties, and other practitioners to identify concerns, discriminate between LNAPL composition and saturation-based goals, to screen remedial technologies efficiently, to better define metrics and endpoints for removal of LNAPL to the "maximum extent practicable," and to move sites toward an acceptable resolution and eventual case closure.

This guidance, LNAPL-3: LNAPL Site Management: LCSM Evolution, Decision Process, and Remedial Technologies, builds upon and supersedes both previous ITRC LNAPL guidance documents in an updated, web-based format. LNAPL-1 and LNAPL-2 are still available for review; however, LNAPL-3 is inclusive of those materials with new topics presented and previous topics elaborated upon and further clarified.

Light Non-Aqueous Phase Liquid (LNAPL) Management is the process of LNAPL site assessment, monitoring, LNAPL Conceptual Site Model development, identification and validation of relevant LNAPL concerns, and the possible application of remediation technologies. The presence of LNAPL can create challenges at any site. In the subsurface, LNAPL can be difficult to assess or recover accurately and can lead to:

- human health, ecological risk, and exposure concerns (e.g., vapor, groundwater, and soil contamination)
- acute-risk concerns (e.g., explosive conditions)
- migration or occurrence concerns (e.g., regulations that require recovery of "free-product" regardless of thickness, recovery to prevent potential LNAPL migration, or recovery for aesthetic or non-technical reasons).

This guidance can be used for any LNAPL site regardless of size and site use and provides a systematic framework to:

- develop a comprehensive LNAPL Conceptual Site Model (LCSM) for the purpose of identifying specific LNAPL concerns;
- establish appropriate LNAPL remedial goals and specific, measurable, attainable, relevant, and timely (SMART) objectives for identified LNAPL concerns that may warrant remedial consideration;
- inform stakeholders of the applicability and capability of various LNAPL remedial technologies
- select remedial technologies that will best achieve the LNAPL remedial goals for a site, in the context of the identified LNAPL concerns and conditions;
- describe the process for transitioning between LNAPL strategies or technologies as the site moves through investigation, cleanup, and beyond; and
- evaluate the implemented remedial technologies to measure progress toward an identified technology specific endpoint.

Initial development and continued refinement of the LCSM is important to the identification and ultimate abatement of site-specific LNAPL concerns. Figure 1-1 identifies the stepwise evolution of the LCSM, the specific purpose of each LCSM phase, and the tools presented within this guidance to aid in the development of the LCSM. As depicted, the LCSM is the driving force for identifying actions to bring an LNAPL site to regulatory closure.

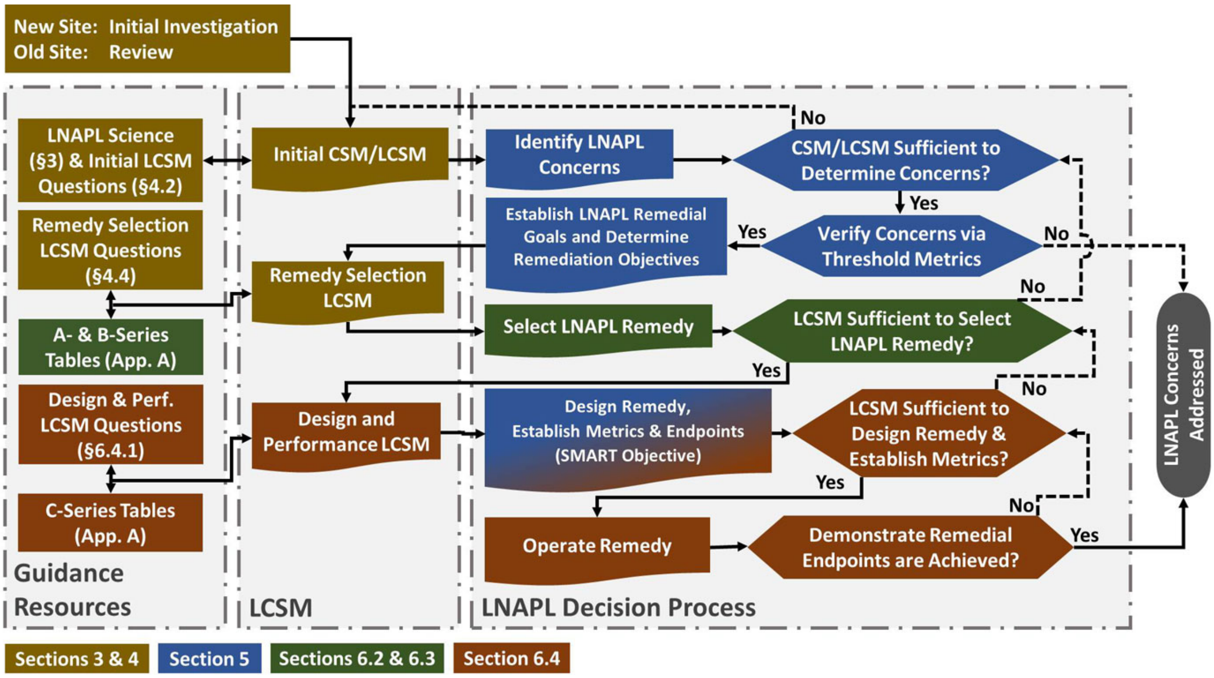

Figure 1-1. LNAPL remediation process and evolution of the LNAPL conceptual site model (LCSM).

This guidance document is organized into sections that lead you through the LNAPL site management process:

- **Section 2 – LNAPL Regulatory Context, Challenges, and Outreach**
  Section 2 identifies some of the challenges implementing agencies face when investigating, evaluating, or remediating LNAPL sites. These challenges include regulatory or guidance constraints, a lack of familiarity or understanding of LNAPL issues, and poorly or undefined objectives and strategies. This section also stresses the importance of identifying and communicating with stakeholders early in the process in order to address issues or concerns that can lead to delays or changes in strategy. Understanding and recognizing these challenges and concerns during development of a comprehensive LCSM can help reduce costs and lead to a more effective and efficient resolution at an LNAPL site.

- **Section 3 – Key LNAPL Concepts**
  Section 3 provides an overview of key LNAPL terminology and concepts including LNAPL behavior following a release to the subsurface (i.e., how LNAPL spreads away from the primary release point, its behavior above and below the water table, and how its migration eventually stops and naturally depletes). An understanding of these basic terms and concepts is crucial for developing a comprehensive LCSM and an effective LNAPL management plan.

- **Section 4 – LNAPL Conceptual Site Model (LCSM)**
  The LCSM is a component of the overall conceptual site model (CSM), and emphasizes the concern source (i.e., the LNAPL) of the CSM. The presence of LNAPL necessitates an additional level of site understanding. The unique elements of the LCSM are presented as a series of questions for the user to answer to help build their site-specific LCSM. Ultimately, a thoroughly-developed, initial LCSM provides the basis for identifying the LNAPL concerns associated with an LNAPL release.

- **Section 5 – LNAPL Concerns, Remedial Goals, Remediation Objectives, and Remedial Technology Groups**
  Section 5 describes the decision process for identifying LNAPL concerns, verifying concerns through the application of threshold metrics, establishing LNAPL remedial goals, and determining LNAPL remediation objectives. This section also introduces remedial technology groups, the concept of a treatment train approach, and how to transition between technologies to address the identified LNAPL concern(s) systematically and effectively. It is important to understand the content of this section prior to selecting and implementing an LNAPL remedial strategy.

- **Section 6 – LNAPL Remedial Technology Selection**

Section 6 describes the remedial technology screening, selection, and performance monitoring process. This section begins by identifying technologies recognized as effective for mitigating specific LNAPL concerns and achieving site-specific LNAPL remediation objectives based on the collective experience of the LNAPL Update Team. The **LNAPL Technologies Appendix** summarizes each of the technologies in detail and presents a systematic framework to aid the user in screening out technologies that are unlikely to be effective, ultimately leading to selection of the most appropriate technology(ies) to address the specific LNAPL concerns.

This guidance also includes relevant, state-of-the-science appendices for more detailed information on LNAPL specific topics:

- **LNAPL Technologies Appendix**
  This appendix describes in more detail each of the 21 LNAPL technologies introduced in the main document. The A-series tables describe information to evaluate the potential effectiveness of each technology for achieving LNAPL goals under site-specific conditions. Information includes the basic remediation process of each technology, the applicability of each technology to specific remedial goals, and technology-specific geologic screening factors. The B-series tables describe information to evaluate the potential implementability of each technology considering the most common site-specific factors. The C-series tables describe the minimum data requirements to make a final technology selection through bench-scale, pilot, and/or full-scale testing; they also describe metrics for tracking remedial technology performance and progress.
- **Natural Source Zone Depletion (NSZD) Appendix**
  This appendix provides a technical overview of NSZD for LNAPL and the methods by which rates can be estimated and measured. It also provides a discussion of long-term LNAPL site management and how NSZD can be applied as a remedy including decision charts to support integration of NSZD and case studies demonstrating its use. For this document, the original ITRC NSZD document (ITRC LNAPL-1) was updated and incorporated into the main body and appendix.
- **Transmissivity (T_n) Appendix**
  LNAPL transmissivity has application throughout the life cycle of a LNAPL project. This appendix provides an understanding of how transmissivity connects to the broader framework for LNAPL management including LNAPL recovery and mobility, and the potential for NSZD to decrease LNAPL transmissivity and mobility over time.
- **Fractured Rock Appendix**
  This appendix describes the behavior and differences of how LNAPL behaves in fractured bedrock formations. While some of the same physical principles apply for multiphase flow in fractured aquifers as in porous aquifers, unique characteristics of finite and restricted fluid flow paths can lead to unexpected results in fractured settings.
- **LNAPL Sheens Appendix**
  This appendix details how LNAPL sheens form, the concerns and challenges of sheens, and potential sheen mitigation technologies.

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2. LNAPL Regulatory Context, Challenges, and Outreach

The 2009 ITRC LNAPL guidance noted that implementing agencies have historically required removal of LNAPL (”free product” as used in the Code of Federal Regulations (CFR)) to the “maximum extent practicable” (MEP) at underground storage tank (UST) sites. This was largely due to a provision in the Code of Federal Regulations (40 CFR §280.64) pertaining to USTs, with the specific definition of MEP left to the “implementing agency.” At a minimum, LNAPL removal was intended to minimize the spread of contamination into previously uncontaminated zones. This regulation was intended to protect human health and the environment while giving program flexibility to the implementing agencies. Since MEP was not defined in the regulation, agency interpretations could range from no formal meaning to a specific maximum allowable LNAPL thickness in a monitoring well (e.g., sheen or 1/8-inch thickness). If these thickness interpretations were then incorporated into a state statute, LNAPL monitoring or recovery activities might continue long after the LNAPL body had stabilized.

In contrast, the Resource Conservation and Recovery Act (RCRA) Corrective Action regulations or guidance do not discuss removal of LNAPL to MEP, even though numerous RCRA Corrective Action sites (e.g., petroleum refineries and chemical plants) have LNAPL in monitoring wells. In RCRA Corrective Action, EPA guidance discusses “returning usable groundwater to its maximum beneficial use, where appropriate, within a timeframe that is reasonable given the particular circumstances of the facility” (EPA 1996) When restoration of groundwater is not practicable, EPA expects to prevent or minimize further migration of the plume, prevent exposure to contamination and evaluate further risk reduction (EPA 1996). The April 2004 guidance, “Handbook of Groundwater Protection and Cleanup Policies for RCRA Corrective Action for Facilities Subject to Corrective Action Under Subtitle C of the Resource Conservation and Recovery Act” indicates that “The term ‘restore’ or ‘restoration’ used in this context refers to achieving a certain cleanup level(s) developed to ensure protection based on maximum beneficial use of the groundwater at a particular facility. Restoring contaminated groundwater does not necessarily imply cleanup to pristine conditions” (EPA 2004).

LNAPL removal to MEP may leave LNAPL in the subsurface. As noted in the 2009 guidance, the EPA recognized that “…only a portion of the total volume of the LNAPL release will be recoverable. Even under ideal conditions a significant proportion of the free product will remain in the subsurface as immobile residue” (EPA 1996). Likewise with RCRA Corrective Action sites, since a significant proportion of immobile free product will remain in place, returning groundwater to its maximum beneficial use may simply not be feasible or realistic.

One of the goals of the original LNAPL guidance was to provide a framework for implementing agencies and stakeholders to evaluate and approve appropriate LNAPL remedial technologies within the confines of guidance interpretations or regulatory requirements (such as MEP). As with the original guidance, the ITRC LNAPL Team sent an updated survey in 2017 to implementing agencies in all 50 U.S. states, the District of Columbia, and Puerto Rico. The purpose was to gauge any change in how an implementing agency addresses LNAPL management issues, remedy selection, and site closures since the issuance of the 2009 ITRC LNAPL guidance. Multiple implementing agencies from 48 states responded, with the majority of responses from the programs directly involved with underground and aboveground petroleum storage tanks. Other responses were provided by the brownfields/voluntary remediation or waste programs. The recent survey indicated that 20 states had updated or changed their LNAPL management approach since the issuance of the original guidance.

2.1 Regulatory Challenges

Both the 2008 and 2017 surveys indicated that implementing agencies face regulatory challenges when managing, evaluating, or remediating LNAPL sites. If a requirement exists to remove LNAPL to a specified thickness, the implementing agency may assume that any selected removal strategy will be long and costly. This assumption could have a detrimental impact on the assessment and remediation decision. However, a more cost-effective or risk-appropriate decision, consistent within the regulatory constraints of the implementing agency, may be made if there is sufficient or increased understanding of the site and LNAPL concerns.

For RCRA Corrective Action sites, EPA outlines Technical Impracticability (TI), and believes that it is appropriate to recognize the limitations of current technologies to clean up groundwater to its maximum beneficial use. When discussing a TI, the presence of LNAPL is one of the factors to consider. Examples of a TI for LNAPL sites may be LNAPL distribution within low-permeability or highly heterogeneous soils, or complex fractures in bedrock. EPA guidance states a TI evaluation should be based on a comprehensive understanding of hydrogeological factors, chemical characteristics, as well as limitations of conventional and innovative technologies (EPA 2004). Section 6 of this guidance discusses these factors and characteristics as well as various conventional and innovative remedial technologies. Additional relevant discussion on TI can also be found in the ITRC Guidance Document "Remediation Management of Complex Sites" (ITRC 2017b).

The following subsections summarize six primary themes encountered in the 2017 regulator survey.

2.1.1 Lack of Familiarity and Understanding of LNAPL Subsurface Behavior

Sufficient understanding of LNAPL behavior in the subsurface is important in making appropriate site management decisions. Without a sufficient LCSM, the most appropriate remedies or endpoints may not be selected. This lack of understanding or familiarity of the site may be due to multiple reasons. Case managers may have minimal experience with LNAPL sites or funding for LNAPL site work may be limited or constrained. Additionally, site owners or consultants may not propose technologies or strategies outside of their experience or abilities. The 2017 updated LNAPL survey responses indicated that:

- Over half of the regulatory staff had less than 10 years of experience dealing with LNAPL sites.
- The majority of the responses indicated formal internal LNAPL training is not required.

Since issuance of the original guidance, over 2,000 participants have attended the multi-day LNAPL classroom training. These participants represented local/state/federal agencies, environmental consultants, site owners, academia, and other interested parties. Additionally, over 17,000 have participated in the three-part ITRC internet-based training (IBT). This suggests a real and tangible interest in understanding the complexities and issues associated with management and remedy selection of LNAPL sites. The 2017 regulator survey is a telling indicator that formal LNAPL training is useful. Seventy-seven percent of respondents indicated that their program uses the 2009 LNAPL guidance and 20 respondents indicated that there have been changes or updates in their program since the issuance of the 2009 ITRC guidance.

2.1.2 Undefined Strategies or Objective-Based LNAPL Characterization

Standard practice in many petroleum release investigations has been to include general remediation objectives in the CSM. These objectives, or the strategies to achieve them, may be defined by regulatory or guidance procedures utilized by the implementing agencies. However, as noted in the 2008 survey, risk-based approaches to define LNAPL remediation objectives were not considered within many regulatory agencies. The 2017 survey indicated that although 31 programs define when active recovery of LNAPL is no longer required, only half of the respondents indicated that their specific programs define when a site with remaining LNAPL can be issued a no further action/case closure/site completion letter. Many respondents commented that the site remedial goals and objectives were selected on a case-by-case basis. While this approach may promote flexibility, it can lead to cases being unresolved or inadequately defined.

It is important to develop and select realistic and SMART remediation objectives. Section 4 and Section 5 of this guidance describe the development of an LCSM and the factors affecting SMART remedial strategies and objectives. Additional discussion on the development and selection of SMART objectives can be found in the November 2011 ITRC Integrated DNAPL Site Strategy guidance (ITRC 2011).

2.1.3 Lack of Familiarity with Nontraditional LNAPL Characterization Methods

Many regulators are accustomed to traditional investigative methods such as borings to collect soil and soil gas samples and monitoring wells to collect groundwater. These traditional methods are sometimes incorporated into state regulations or reimbursement criteria for petroleum trust funds. Both the 2008 and 2017 regulator surveys indicated that some non-traditional methods, such as Laser Induced Fluorescence (LIF), coupled with Cone Penetrometer Testing (CPT), are utilized for investigative work. However, the recent survey did not indicate a clear increase or decrease in use of these methods over the years. Some of the comments indicated that non-traditional methods were used, but they were not "successful," or that new methods were not proposed by the consultant/owner. This may simply be a function of inexperience with the case managers within the implementing agency, or an insufficient LCSM.

As discussed in this guidance, the use of non-traditional methods can provide useful, higher resolution information that provides an improved understanding of LNAPL distribution. Although not included in this guidance, a discussion of non-traditional methods or tools can be found in Section 4 of the April 2015 ITRC Integrated DNAPL Site Characterization and Tools Selection guidance (ASTM 2015). Additionally, in 2017, ITRC approved the development of new guidance to address the selection, application, and integration of Advanced Site Characterization Tools (i.e., non-traditional methods) into the project life cycle of site characterization, remediation, monitoring, and closure. This guidance will be available in 2020.

2.1.4 Establishing Appropriate Remedial Goals and Determining Remediation Objectives

Establishing appropriate cleanup goals promotes consistency within the program and allows the regulated community to understand what is expected or required for LNAPL investigations. Most decisions regarding remedial goals and remediation objectives at LNAPL UST sites are driven by thickness and contaminant concentrations. The 2017 regulator survey responses indicated that:

- Twenty-four state programs define MEP.
- Nineteen programs use total petroleum hydrocarbon (TPH) toxicity or screening values as an indicator if LNAPL is not readily apparent in soil or groundwater.
- Twenty-three programs evaluate individual constituents for analytical compliance.

Thickness or concentration data alone may not provide a sound basis for defining the point at which a cleanup objective is achieved. These decisions can be improved by also considering contaminant mass discharge and mass flux. Mass discharge and flux estimates can help the implementing agency or regulated community understand the role or influence of natural attenuation and the risks to downgradient receptors. The estimates can also help prioritize which sites need further characterization and remediation, identify stratified aquifers, and evaluate performance data, all of which can promote more cost-effective cleanups. A discussion of mass discharge and flux can be found in the April 2010 ITRC Use and Measurement of Mass Flux and Mass Discharge guidance (ITRC 2010).

2.1.5 Differentiating Between Residual, Mobile, and Migrating LNAPL

In choosing an effective source remedy, it is important to differentiate between residual, mobile, and migrating LNAPL. The 2017 survey indicated that only 13 programs have defined these terms. In order for the implementing agencies to establish appropriate cleanup objectives, it is important to understand the differences between residual, mobile, and migrating LNAPL. Section 3 of this guidance discusses the differences and provides tools (e.g., LNAPL transmissivity) and suggestions in understanding the importance of establishing realistic and achievable objectives.

2.1.6 Transitioning between Technologies

One of the principal components of this guidance is to identify and select appropriate remediation strategies and technologies for LNAPL sites. Multiple technologies or “treatment trains” may be necessary in order to effectively control, recover, or conduct a phase change of the LNAPL mass. It is important to recognize and address this “transition” from one technology or strategy to the next in order to address the LNAPL and the identified risks and concerns effectively. Just as important, this should include the transition from an active technology driven strategy to the next, and perhaps final, less active strategy. The latter may include identification and measurement of NSZD rates, moving the site into Monitored Natural Attenuation (MNA), establishing institutional controls, or even approving case closure.

Describing the process and metrics for transitioning between LNAPL strategies or technologies can promote consistent remedial progress and navigation through the regulatory process as the site moves through investigation, cleanup, and beyond. This can allow the regulatory program to identify relevant permits, technical reviews, and approvals that may be required as the site transitions from one technology to the next. Describing the transition process and metrics can also provide financial efficiencies and assist with the budgeting process. Identifying relevant objectives and concerns during the transitions is just as important and can promote understanding and support from stakeholders that may be impacted or involved with the LNAPL case. A more detailed discussion of treatment trains and transitioning is located in Section 5 of this guidance.

2.2 Weather Vulnerabilities

In recent years, the EPA has identified possible additional LNAPL concerns associated with extreme weather events. There may be a need to increase engineering controls for contaminant migration at sites where a remedy is constructed in areas that are vulnerable to a greater incidence of flooding, hurricanes, drought, wildfires, or other consequences of extreme weather. The EPA’s Office of Underground Storage Tanks published the Underground Storage Tank Flood Guide (EPA 2010) to provide information about preparing for a flood, important actions to take after the flood, and information on financial assistance. In addition, the Institute for Sustainable Communities (ISC), partnering with the EPA, provides states and tribes with an increased understanding of specific vulnerabilities for sites under extreme weather conditions (EPA 2010).

2.3 Stakeholder Concerns, Community Outreach and Engagement

As noted in the 2017 regulator survey, multiple implementing agencies have made changes and improvements to project decision-making practices regarding LNAPL. However, it should be expected that changes in any implementing agencies' past actions regarding site assessment, remediation, or closure strategies (e.g., "What does "clean" mean?") can be met with skepticism in the stakeholder community. Presenting and explaining both the technical information and regulatory requirements to those who may be unfamiliar with the process can create difficulties and challenges for any case manager and implementing agency.

Identifying and recognizing potential stakeholders is of primary importance. Stakeholder types are listed and defined in several ITRC publications [(ITRC 2014) and (ITRC 2017b)] and can be generally defined as any person, group of persons, or organizations with some interest in a specific site, area or project. Stakeholders may include: local residents, tenants, and other potentially-impacted local parties or groups; local and other government agencies (as implementing agencies, land use officials, and safety professionals); local landowners; and/or land operators or tenants and their representatives. Impairments or impacts to these persons or groups can be physical (community health), mental (stress-related), financial (property values, loss of business activity, loss of property rights, etc.) and/or cultural (loss of resources).

Stakeholder issues for LNAPL are not dissimilar from other types of contaminants. Petroleum and potential LNAPL issues can be present in any industrial, commercial, or residential setting regardless of size or location. Petroleum and LNAPL can be associated with releases of short or long duration, from emergency responses to long-term maintenance and monitoring. Stakeholder issues for each of these situations will be dealt with in different ways, in accordance with a well-informed plan for dissemination of information, public education, and stakeholder outreach.

Recommended resources for public education and outreach involving public and tribal stakeholder issues include:

- stakeholders and stakeholder concerns (ITRC 2014),
- communication methods (ITRC 2014),
- community engagement plans and planning (ITRC 2014) that also include existing federal and state resources,
- risk communication (ITRC 2014), and
- regulatory processes for stakeholder involvement (ITRC 2017b).

Presenting technical data to the stakeholder community can be challenging. Presentations may need to include the science supporting the technology as well as the science-based conclusions that can be drawn from the data. Statistical representation of the confidence associated with the data can also be part of the presentation. It is recommended that explanations of the technology and how it contributes to the LCSM be presented in a manner that is understood easily by the stakeholders. Public acceptance and understanding of the difficulties with the site can be enhanced if the information is presented and explained in a way that defines the technical and regulatory steps in a clear and understandable format.

2.4 Streamlining the Corrective Action Process by Increased Communication

Inadequate or limited communication between the implementing agencies, the responsible party, and identified stakeholders can increase the amount of time to move a site through the investigation and corrective action process. In some cases, performance of initial emergency actions and abatement may be needed prior to communication with stakeholders. However, it is recommended that outreach and communication occur before corrective action is performed. Identifying and discussing difficult issues before any field work or report writing is done can often mitigate interruption, delay, and additional expense. RCRA FIRST (EPA 2015) is a streamlined process promoted by EPA for investigation and remediation at RCRA Corrective Action sites. This process can be applied at LNAPL corrective action sites.

Not every LNAPL site will require outreach or significant communication with stakeholders. The implementing agencies will determine the amount and effort based on their specific requirements and guidance. When appropriate, increased communication between the groups can facilitate better agreements on major issues at the beginning of the process, thereby reducing the amount of time to project completion.

3. Key LNAPL Concepts

The concepts presented in this section are integrated into the framework and tools presented in this guidance. They are fundamental to understanding the logic used in the development of the tools and key to appropriate application of this guidance. The remainder of this guidance assumes the reader is familiar with these key concepts and has a level of knowledge commensurate with the content of the ITRC's LNAPL Internet-Based Training (IBT) courses. The training courses are available online (www.clu-in.org/live/archive) at no cost.

3.1 Common Misconceptions

Understanding of LNAPL releases, the behavior of LNAPL in the subsurface, and the methods used to evaluate LNAPL releases have evolved significantly in recent years. Unfortunately, misconceptions derived from our early, less-informed understanding of LNAPL releases are frequently encountered. Table 3-1 outlines common misconceptions relating to LNAPL releases and the associated current understanding and key concepts which are discussed in detail in referenced sections of the document. A glossary of familiar LNAPL related terms is presented at the end of this document (Glossary).

Table 3-1. Common LNAPL misconceptions

Common Misconceptions	**Key Concepts**
LNAPL Distribution	
LNAPL enters soil pores just as easily as groundwater (Section 3.2). LNAPL floats on the water table or capillary fringe like a pancake and does not penetrate below the water table (Section 3.2).	• Typically, water is the wetting fluid in the saturated zone, in direct contact with the soil, and occupies the smaller pores. LNAPL must displace the water (and gases) within a pore space before it can migrate. For this to occur, it must have a driving head and overcome the capillary pressure exerted by the water in the pore. • LNAPL does not float on the water table in a uniform, high-saturation, "pancake"-like layer. The LNAPL is distributed above, at, and below the water table at saturations that vary vertically depending on past conditions such as LNAPL driving head and water table fluctuations.
LNAPL Occurrence	
If there is no LNAPL visible in a well, then there is no LNAPL present (Section 3.4).	• If LNAPL in soil adjacent to the well is below residual saturation, then LNAPL will not appear in the well, although the presence of a sheen is possible. • Persistent measurable dissolved- and/or vapor-phase petroleum hydrocarbon concentrations are indicative of the presence of LNAPL at or below residual saturation in the saturated and/or vadose zone.
Risk Assessment	
Risk assessment should not be conducted if LNAPL is present in a well (Section 3.5).	• Risks posed by mobile or residual LNAPL can be assessed using generally-accepted risk characterization and assessment practices (including Risk-Based Corrective Action). A mobile LNAPL that is migrating laterally may pose different risks than the same LNAPL at residual saturation within the same plume.
In-Well LNAPL Thickness	

Common Misconceptions	Key Concepts
LNAPL thicknesses in monitoring wells are exaggerated (compared to the formation) by factors of 2, 4, 10, etc. (Section 3.4) LNAPL thicknesses in monitoring wells are equal to the LNAPL thicknesses in the formation (Section 3.4).	• For unconfined LNAPL in a uniform geology at a location not significantly affected by water-table fluctuation, the thickness of LNAPL in the well will be similar to the thickness of the mobile LNAPL interval in the adjacent formation. • For LNAPL under confined or perched conditions, the LNAPL thickness in the adjacent well will likely be exaggerated. • For the same LNAPL in-well thickness, the volume of LNAPL per unit footprint area of the formation (LNAPL specific volume) can be different for different wells. The LNAPL specific volume is generally higher in coarse-grained soils than in fine-grained soils. • Due to the dependence of in-well LNAPL thickness on geology and variable groundwater hydraulics, it should not generally be used as a sole metric for recoverability and indication of migration.
LNAPL Saturation	
All soil pores in an LNAPL body are completely filled with LNAPL (Section 3.2). You can hydraulically recover all of the LNAPL from the subsurface (Section 3.6).	• The presence of LNAPL in a monitoring well indicates proximal presence of LNAPL above residual saturation. Soil pores are never 100% filled with LNAPL due to the concurrent presence of other fluids such as water and gases. The LNAPL saturation depends on the geology, LNAPL fluid properties, and release dynamics. • LNAPL cannot be completely removed from soil by hydraulic recovery due to mechanical limitations in subsurface soils. The lowest saturation theoretically attainable by hydraulic recovery is residual saturation, and that is rarely achieved.
Migrating LNAPL	
If you see LNAPL in a monitoring well, then it is migrating (Sections 3.2 and 3.4). LNAPL bodies spread due to groundwater flow (Section 3.2). LNAPL bodies continue to move long after the release is stopped (Section 3.5).	• The presence of LNAPL in a well is an indication that the LNAPL adjacent to the well exceeds residual saturation and is mobile. The LNAPL has the ability to flow into the “large” pore which is the well. However, mobility of the LNAPL into the well does not imply migration of the LNAPL body within the (much smaller) pore space of the adjacent soil. • LNAPL is considered migrating when it is observed to expand into previously unimpacted locations over time (i.e., in-well LNAPL appears in a monitoring well that had an initially clean borehole). • Migration of LNAPL cannot occur unless LNAPL is present above residual and within the mobile range of LNAPL saturations. • LNAPL bodies associated with a terminated or finite source (i.e., UST removal or a pipeline leak repaired) eventually stop migrating within a relatively short timeframe as the driving head dissipates. • Not all mobile LNAPL migrates, but LNAPL must be mobile in order to migrate. • Multiple lines of evidence may be needed to make the distinction between mobile and migrating LNAPL. • Reduction of LNAPL saturation to the residual range is not necessary to arrest LNAPL migration.
Mobile LNAPL	

Common Misconceptions	**Key Concepts**
If you see LNAPL in a monitoring well, then it is mobile and migrating (Section 3.5).	• LNAPL is considered mobile when it accumulates in a well (assuming the well is properly constructed and screened across the LNAPL smear zone). • LNAPL is mobile when it is present at a saturation greater than residual. • Mobile LNAPL is potentially hydraulically recoverable, but recoverability depends on various physical factors. • LNAPL presence in a well does not necessarily mean that the LNAPL body is migrating.
Residual LNAPL Saturation	
Residual saturation is easily determined (Section 3.5).	• Residual LNAPL saturation is different for the saturated and unsaturated zones due to the variable presence of other fluids such as water and gases. Typically, unsaturated (vadose) zone residual saturation is generally lower. • Water table fluctuations (e.g., seasonal or tidal) result in a dynamic change in the extent of the unsaturated and saturated zones, causing the LNAPL to continuously redistribute vertically. Consequently the amount of mobile LNAPL changes with time, while the total LNAPL volume remains unchanged. • Residual LNAPL saturation is not a single number, rather a range of saturations.
Concentrations in Groundwater and Vapor	
Hydraulic recovery of LNAPL reduces associated dissolved phase plume concentrations (Section 3.6).	• Most types of petroleum hydrocarbon LNAPL are a multi-constituent mixture (e.g., gasoline, diesel), the exception being single-constituent LNAPL (e.g., benzene). • Constituent concentrations in groundwater and/or vapor depend primarily on LNAPL composition (i.e., mole fractions of the individual constituents in the LNAPL and their pure phase solubility). They have limited dependence on LNAPL saturation. Therefore, rarely does hydraulic recovery reduce dissolved phase concentrations.
LNAPL Transmissivity	
There is no definition of evaluating “LNAPL removal to the maximum extent practicable” or recoverability (Section 3.6).	• LNAPL transmissivity is a reliable indicator of the ability of the formation to transmit LNAPL to a well. LNAPL transmissivity depends on soil type, LNAPL type, LNAPL saturation, and thickness of mobile LNAPL. • Since LNAPL transmissivity is related to all key variables (see above) that can affect recoverability, it is a better metric than the conventionally used metric of in-well LNAPL thickness. • The higher the LNAPL transmissivity, the higher the LNAPL recoverability.
Saturation vs. Composition	

Common Misconceptions	Key Concepts
Any LNAPL remediation technology can address all remediation objectives (Sections 3.2 and 3.6).	• Saturation reduction technologies (e.g., mass recovery) are best suited to abating LNAPL body migration and can shorten dissolved plume longevity. • Composition change technologies (e.g., phase change) are best suited to address remediation objectives of reducing constituent concentrations in groundwater and vapor. • Where mobile LNAPL is present, but LNAPL migration is not a concern, evaluate LNAPL saturation reduction in terms of added net benefit.

3.2 Life Cycle and Anatomy of an LNAPL Body

The following subsections discuss the key concepts associated with the initial formation of the LNAPL body from a release, its subsurface distribution, and changes that it undergoes over time.

3.2.1 LNAPL Body Formation and Initial Distribution

When an LNAPL release occurs, the LNAPL will move vertically downward under the influence of gravity through the permeable pathways (e.g., unconsolidated soil, fractures, and macropores) and, if sufficient LNAPL volume and head is generated by the release, the LNAPL will eventually encounter the water table. During the downward movement of LNAPL through the soil, the presence of confining layers, subsurface heterogeneities, or other preferential pathways may result in irregular and complex lateral spreading and/or perching of LNAPL before the water table is encountered. Once at the water table, the LNAPL will spread laterally in a radial fashion as well as penetrate vertically downward into the saturated zone, displacing water to some depth proportional to the driving force of the vertical LNAPL column (or LNAPL head). The vertical penetration of LNAPL into the saturated zone will continue to occur as long as the downward force produced by the LNAPL head or pressure from the LNAPL release exceeds the counteracting forces produced by the resistance of the soil matrix and the buoyancy resulting from the density difference between LNAPL and groundwater. Once the release of LNAPL is terminated, the areal extent of the LNAPL body will continue to expand for a relatively short time, and eventually stop once the resistive forces in the soil balance the driving force of the diminishing LNAPL head. When the LNAPL body reaches this state, the LNAPL body has stabilized in extent, and will not typically expand further unless additional releases or significant subsurface hydraulic changes occur. Conceptual depictions of an LNAPL release and the initial stabilization of an LNAPL body are provided in Figure 3-1. Section 4 of this document discusses the development of an LCSM that incorporates a release history and summary of processes that create the observed LNAPL distribution in the subsurface.

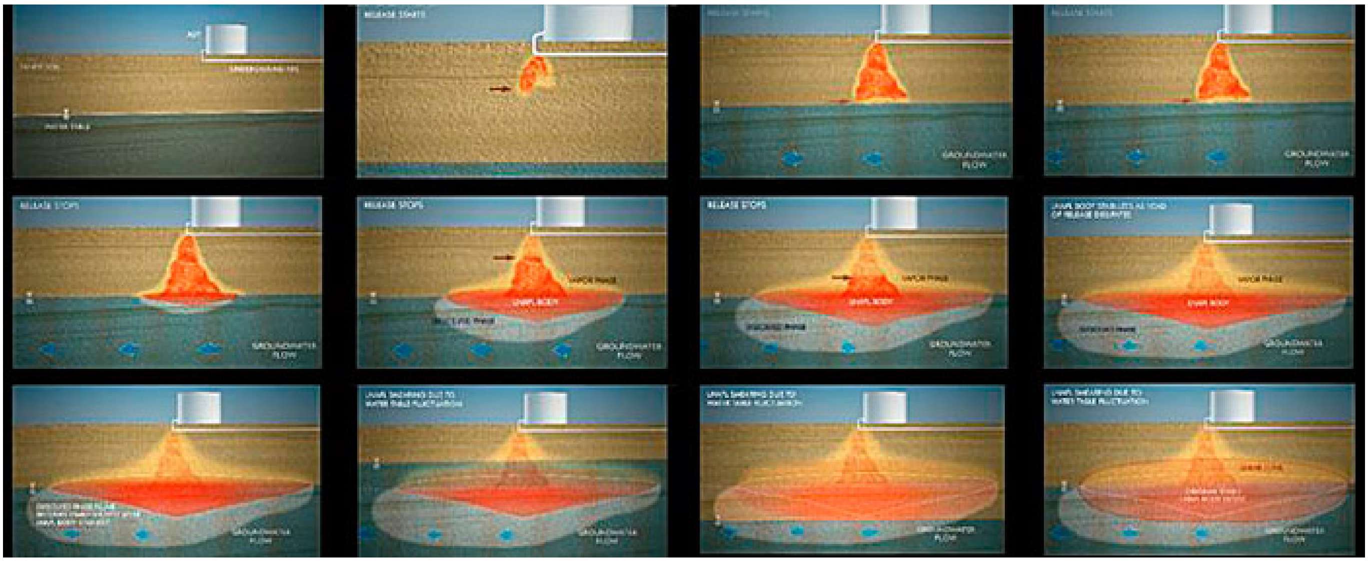


Figure 3-1. Time lapse conceptualization of LNAPL body formation (Courtesy of Matthew Rousseau/GHD).

A typical LNAPL body consists of LNAPL partially filling the soil pore space in a highly variable and often discontinuous distribution. The volume of aquifer occupied by an LNAPL body is not comprised of a single fluid phase, but rather of multiple fluids and soil in proportions that will vary throughout. An LNAPL body is therefore a multiphase system where the pore space contains varying quantities of LNAPL, groundwater, and/or gases both above and below the static water table elevation. Generally speaking, the spatial extent occupied by an LNAPL body is predominantly comprised of water, followed by a lesser amount of LNAPL, with the smallest fraction of the pore space occupied by gas. As shown in Figure 3-2, LNAPL saturations within an LNAPL body will typically be much less than 100%.

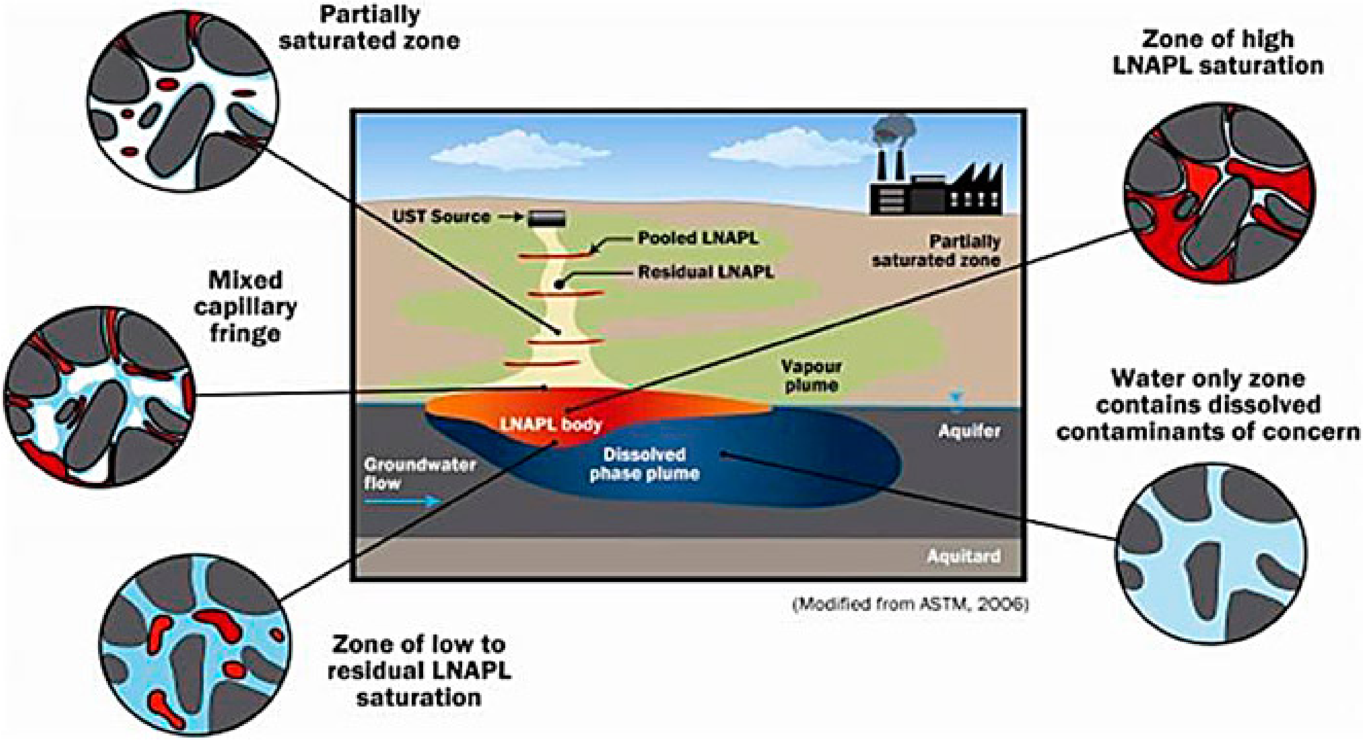


Figure 3-2. The multiphase system of a typical LNAPL body (CL:AIRE 2014).

In the simplest scenario of homogeneous sandy soil and unconfined conditions, the vertical distribution of LNAPL saturation will typically occur in a pattern commonly referred to as a ‘shark fin’ – visible on a plot of LNAPL saturation percent versus depth (Figure 3-3). The most highly saturated zone will generally be within the capillary fringe, coincident with and slightly above the water table, with diminishing saturations above and below. Considering this along with Figure 3-2, LNAPL saturations are continuously variable throughout an LNAPL body in three dimensions. Note that vertical equilibrium, a basis for the green lines on Figure 3-3, is a primary modeling assumption to satisfy the founding hydrostatic pressure equations.

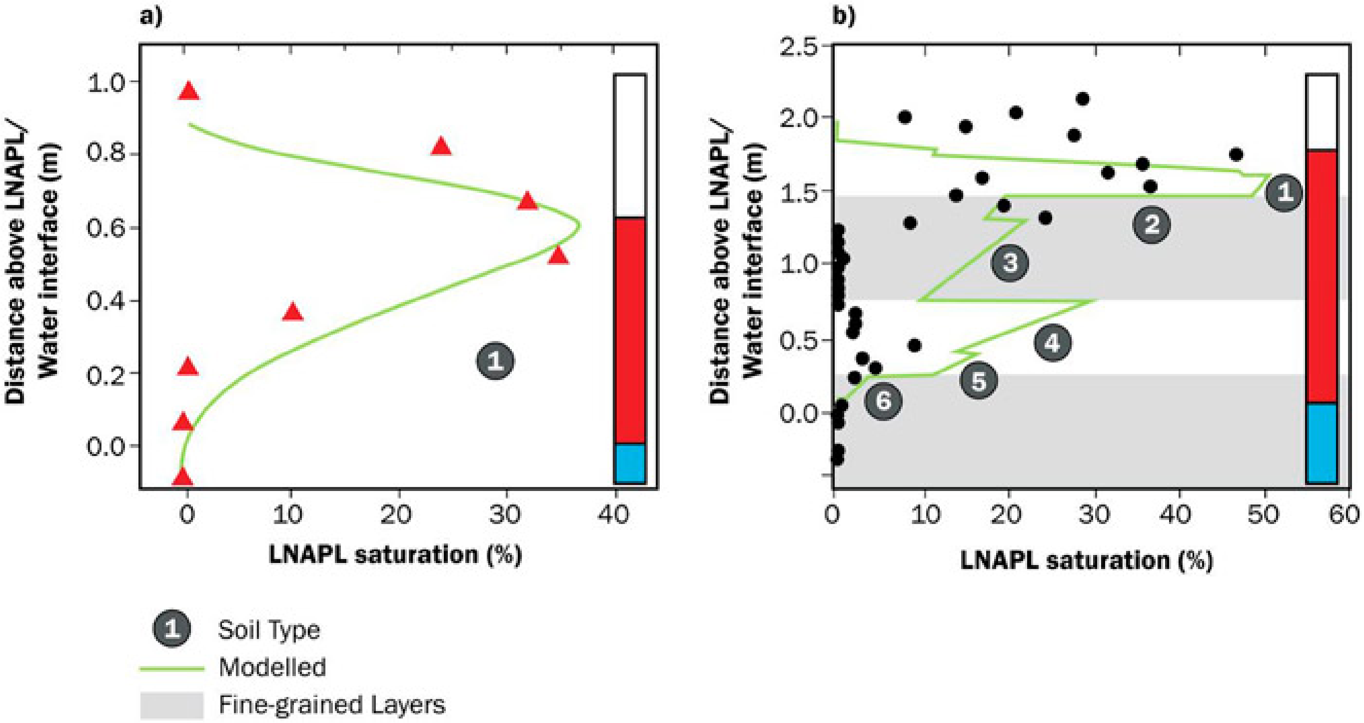
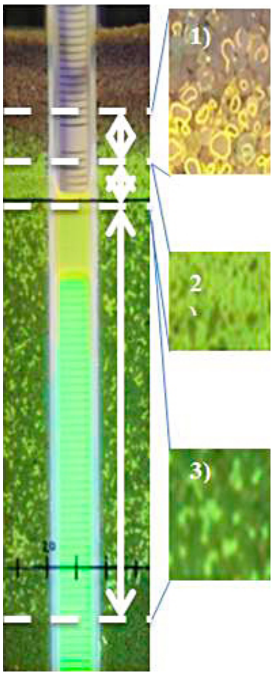


Figure 3-3. LNAPL saturation near the water table showing observed LNAPL saturation (a. red triangles; b. black dots) compared to vertical equilibrium model simulation predictions (green lines). The observed in-well LNAPL thickness is shown for: a) homogeneous soil (Beckett and Lundegard 1997); b) a heterogeneous case with finer grained layers (2, 3 and 6) and coarser grained layers (1, 4 and 5) (Huntley, Hawk, and Corley 1994) (Huntley, Wallace, and Hawk 1994).

On the pore-scale, LNAPL coexists with water and gases in different ways depending on where the LNAPL is located. LNAPL that occurs in the unsaturated zone will typically behave as a wetting phase with soil moisture. LNAPL becomes the non-wetting phase as moisture content increases toward the capillary fringe into the saturated zone (where water will be the wetting phase). This pore-scale distribution is illustrated in Figure 3-4.



1. **Unsaturated zone (Block 1) – LNAPL as a continuous intermediate wetting phase.** In the unsaturated zone of porous media, soil gas forms a continuous non-wetting phase, water is present as a continuous wetting phase on the solid media, and LNAPL is present as an intermediate wetting phase (Sale, Mahler, and Smith 2016). LNAPL in the unsaturated zone forms a film between the water (on the soil particles) and gas (in large pores). Volatile LNAPL constituents in the vadose zone partition directly into soil gas and soluble LNAPL constituents in the vadose zone partition directly into pore water surrounding soil particles.
2. **Saturated zone (Block 2) – LNAPL as continuous non-wetting phase.** In the saturated zone of porous media, gases are only present as a discontinuous non-wetting phase. A primary source of discontinuous gases is biologically-mediated degradation of LNAPL constituents (Amos et al. 2005). LNAPL is present as a continuous phase that is potentially mobile. Furthermore, following (Skinner and Sale 2013), depletion of LNAPL in the vadose zone via soil vapor extraction (SVE) or natural losses can draw continuous LNAPL in the saturated zone into the vadose zone via capillary processes (wicking).
3. **Saturated Zone (Block 3) – LNAPL as a discontinuous non-wetting phase.** Lastly, LNAPL can occur as a discontinuous phase in the saturated zone. Absent a continuous path, discontinuous LNAPL is immobile. The primary process that depletes discontinuous LNAPL in the saturated zones is dissolution into the aqueous phase, followed by degradation via biologically-mediated processes, if geochemical conditions are ideal for degradation.

Figure 3-4. Pore-scale LNAPL distribution (Hawkins 2012).

As with any fluid, LNAPL will take the path of least resistance in the subsurface, with preferential pathways (both natural and man-made) often controlling the ultimate LNAPL body geometry. Similarly, LNAPL is typically the non-wetting or intermediate wetting phase and will preferentially occupy larger pore spaces in the subsurface or macropores such as fractures in clays or bedrock. As a result, LNAPL may be found in all directions from a release point (i.e., not just downgradient) in highly irregular distributions. Conceptual distributions of LNAPL in different geologic settings are provided by Contaminated Land: Applications in Real Environments (CL:AIRE 2014).

3.2.2 Constituent Partitioning

Partitioning refers to the transfer of chemical mass from the LNAPL into other phases (gas, groundwater, and soil) adjacent to the LNAPL body. Partitioning results in LNAPL constituent presence in the vapor, dissolved, and/or adsorbed phases. Evaluation of the vapor phase is discussed in greater detail in the ITRC PVI document (ITRC 2014). Understanding constituent partitioning is important when investigating the occurrence of LNAPL, when evaluating the migration of LNAPL and its constituents, and when evaluating risk and safety concerns associated with LNAPL sites. Partitioning of petroleum constituents into other phases can result in additional risks (e.g., vapor intrusion into indoor air or migration of dissolved phase contaminants with groundwater). It is also important to account when appropriate remedial technologies are applied (e.g., soil vapor extraction [SVE] to remove vapors). Certain LNAPL remediation technologies rely upon constituent partitioning to remove mass (e.g., via a vapor phase using SVE) or to remove more volatile constituents and reduce risk (e.g., removal of benzene via air sparging). As such, a basic understanding of constituent partitioning is also important to develop and revise the conceptual site model, evaluate concerns, and select and implement a remedy.

As most commonly described, the tendency of a chemical constituent to partition from one phase to another is described by the following governing principles:

- Raoult’s Law – relates LNAPL constituent concentrations and the associated dissolved and vapor phase constituent concentrations;
- Henry’s Law – relates dissolved and vapor phase constituent concentrations; and
- Linear sorption isotherms – relate sorbed and dissolved phase constituent concentrations.

Data collected in the field (e.g., co-located LNAPL, soil, groundwater, and vapor samples) may also provide information relating to the partitioning of LNAPL constituents at a particular location. Further detail relating to chemical partitioning of LNAPL can be found in the ITRC TPH Risk document (ITRC 2018). Additional detail specifically with respect to partitioning within the vapor phase can be found in the January 2007 ITRC Vapor Intrusion Pathway: Investigative Approaches for Typical Scenarios (ITRC 2007).

One key phase partitioning relationship is LNAPL and groundwater. The dissolved concentration of an LNAPL constituent in groundwater, according to Raoult’s Law, is the product of its concentration in the LNAPL (mole fraction) and the aqueous solubility of the pure constituent; it is not based on the saturation of LNAPL in the pore space. For example, if benzene is present in gasoline at 0.5% by weight (0.6 mole %), it’s effective solubility (equilibrium groundwater concentration) is approximately 11 milligrams per liter (mg/L) (Scenario A, Figure 3-5). If the benzene concentration in gasoline is reduced to 0.25% by weight without any measurable reduction in LNAPL saturation (e.g., using SVE), the corresponding effective solubility would also be halved to about 5.5 mg/L (Scenario C, Figure 3-5). On the other hand, if the LNAPL saturation were halved with no change in LNAPL composition (e.g., by hydraulic recovery of LNAPL), the dissolved benzene concentration in groundwater would not change. In this case, however, the longevity of groundwater impacts (Scenario B, Figure 3-5) would decrease, as the total mass of benzene would be halved. Similar relationships exist for other constituents in different pairs of phases—for example, LNAPL and soil gas (vapor pressure and mole fraction), groundwater and soil gas (Henry’s Law). In summary, the composition of LNAPL and not its mass (or saturation level) is the primary control for concentrations in adjacent phases (groundwater and soil gas). It therefore follows that the effects of chemical weathering of LNAPL in the subsurface can have a significant effect on concentrations in adjacent phases.

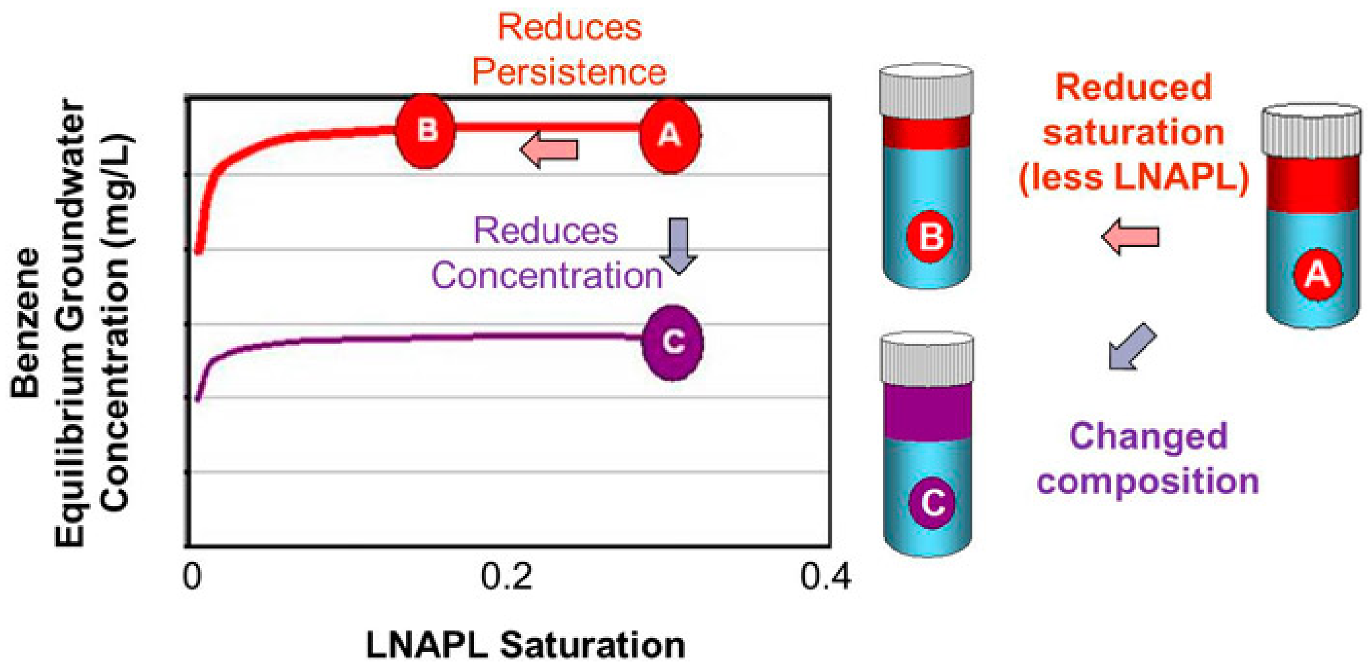


Figure 3-5. Comparison of LNAPL mass or saturation (S_o) reduction (A to B) and LNAPL composition reduction in constituent concentration in LNAPL (A to C) on dissolved phase benzene concentrations in groundwater *(Courtesy of S. Garg, Shell 2009)***.**

3.2.3 Longer-Term Changes in the LNAPL Body

Once a release has terminated and the LNAPL body has initially stabilized, longer-term changes in the LNAPL body will be dominated by NSZD processes (including dissolution, volatilization, and biodegradation) and smearing due to water table fluctuations.

NSZD processes progressively reduce LNAPL mass over time via direct biodegradation of LNAPL by microbes and by physical partitioning processes, into other phases (e.g., soil gas and groundwater), where biodegradation also occurs. This results in the depletion of constituents from the LNAPL and reduction in mass, and eventually, diminishing amounts of constituent dissolution and volatilization. NSZD processes therefore play an important role in risk mitigation and the long-term stability of LNAPL bodies (Mahler, Sale, and Lyverse 2012). NSZD processes are discussed in more detail later in this section and in the NSZD Appendix**.**

The smearing of LNAPL due to water table fluctuations will redistribute the LNAPL mass so that it becomes progressively less mobile and recoverable over time. For example, in a rising and subsequent falling water table in an unconfined condition: the mobile fraction of the LNAPL will move up with the water table during the rise (Figure 3-6), but some portion of this mobile fraction will become trapped in the pore space when the water table drops. Therefore, the vertical LNAPL distribution changes and the mobile fraction that remains afterwards are smaller. Seasonal fluctuations in the water table that redistribute the mobile LNAPL fraction, together with biodegradation, dissolution, and volatilization that deplete LNAPL mass, decrease the fraction of mobile LNAPL over time until all LNAPL exists as residual.

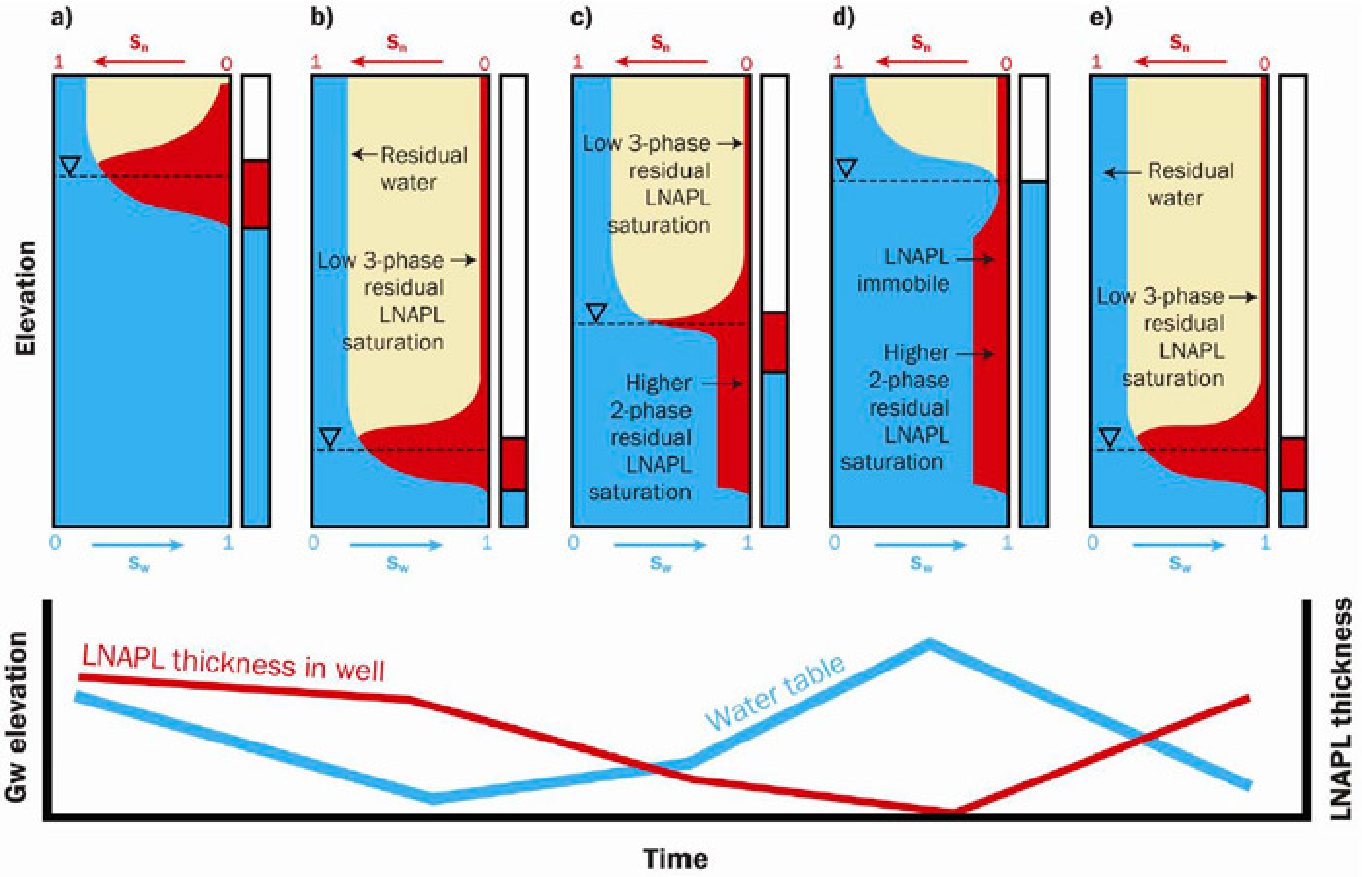


Figure 3-6. **Conceptual depiction of LNAPL observed within the formation and within monitoring wells (a – e) during a variable water table and LNAPL thickness shown on the bottom graph (after (ITRC 2009a); (CL:AIRE 2014)). S_n is saturation of the pore space of NAPL, and S_w is saturation of water.**

As described in Section 3.2, concentrations of dissolved and vapor phase constituents may gradually decline, but will typically decrease by less than an order of magnitude. Risks associated with phase changes (e.g., vapor phase, dissolved phase) are discussed further in Section 5 and Section 6. Specific factors affecting the mobility of the LNAPL such as soil type and saturation levels are discussed later in this section.

Typically, LNAPL will remain the non-wetting (saturated zone) or intermediate wetting (unsaturated zone) fluid. These sites exhibited high fractions of silt and clay content and weathered diesel.

3.3 Overview of Natural Source Zone Depletion

LNAPL NSZD encompasses a variety of processes that act to biologically degrade and physically redistribute LNAPL constituents to the aqueous or gaseous phases where they are also subsequently broken down biologically (ITRC 2009a). NSZD occurs primarily through direct contact oil biodegradation, biodegradation of solubilized hydrocarbons at the oil/water interface, LNAPL volatilization and biodegradation in the vadose / smear zone, and less significantly through dissolution into groundwater and biodegradation in the saturated zone [(Ng et al. 2014); (Ng et al. 2015); (Johnson, Lundegard, and Liu 2006); and (Molins et al. 2010)].

NSZD begins as soon as LNAPL is released to the subsurface, typically via volatilization and dissolution, and eventually most prominently through biodegradation as intrinsic microorganisms acclimate to the presence of the petroleum hydrocarbons and use it as a growth substrate.

Direct-contact biodegradation occurs in the immediate proximity to the LNAPL, within pores with oil where air-phase porosity is present (e.g., top of LNAPL body). By-product gases from this reaction are directly outgassed to the vadose zone and do not enter aqueous phase. At the Bemidji crude oil research site, greater than 80% of the observed carbon efflux was attributed to direct-contact biodegradation and outgassing (Ng et al. 2015).

Biodegradation of LNAPL constituents occurs across the entire smear zone (from unsaturated, to partially, to fully saturated) by naturally-occurring microorganisms. Biodegradation occurs via a multitude of mechanisms in both aerobic and anaerobic conditions. Aerobic biodegradation occurs where ample oxygen (O_2) is present. In a relatively short time (i.e., several months depending upon geochemistry), the often finite supply of electron acceptors within the LNAPL smear zone such as O_2, nitrate (NO_3^-), ferric iron (Fe^{3+}), and sulfate (SO_4^{2-}) are consumed and conditions become increasingly more favorable to anaerobic biodegrading organisms that produce methane (CH_4). Gaseous by-products of biodegradation processes, carbon dioxide (CO_2) and CH_4, are observable in the vadose zone soil gas above the LNAPL source zone. As the CH_4 diffuses upward, it encounters O_2 diffusing downward from the atmosphere which enables intrinsic methanotrophs and other microorganisms to consume the CH_4 and create CO_2 and water vapor. Vapor phase hydrocarbons (i.e., volatile organic compounds [VOCs]) are also degraded aerobically and anaerobically in the vadose zone, depending on the local (pore scale) conditions. CO_2 efflux, measurable at ground surface, provides evidence of these biodegradation processes.

In the saturated zone, dissolution losses are observed as dissolved phased hydrocarbons in analyzed groundwater samples collected from monitoring wells immediately adjacent to and downgradient from the LNAPL source. The effects of biodegradation of dissolved hydrocarbons can be observed in dissolved groundwater plumes by measuring changes in geochemical parameters: decreases in dissolved O_2, NO_3^-, and SO_4^{2-} and increases in dissolved ferrous iron (Fe^{2+}), manganese (Mn^{+2}), CO_2, and CH_4 (NRC 2000).

NSZD processes are observable at all LNAPL release sites. The rate that NSZD reduces the LNAPL mass (i.e., the bulk NSZD rate) can be estimated by measuring CO_2 efflux rates at the ground surface, CO_2 or O_2 gradients in vertically nested soil gas monitoring systems, and from temperature gradients measured with vertical thermocouple arrays placed in the ground (API 2017). The NSZD rates of individual compounds of interest (e.g., BTEX) are difficult to estimate with these approaches at this time, but can be assessed by observing the chemical changes in LNAPL composition over time.

NSZD rates at a given site are affected by a number of interrelated factors including: temperature, soil moisture, soil gas permeability, groundwater geochemistry, and microbiology. To date, most measurements have provided NSZD rates in a relatively narrow range. An analysis of rate information from 25 sites revealed the middle 50% of sites exhibited NSZD rates between 700 and 2,800 gallons/acre/year, with a median of approximately 1,700 gallons/acre/year (Garg et al. 2017).

The NSZD Appendix contains a more detailed discussion of NSZD processes.

3.4 LNAPL Thickness in Wells

Historically, thickness of LNAPL in a well was used to provide unit volume estimates of LNAPL, the mobile LNAPL interval, and as an indicator for the magnitude of recoverability. Today, it is better understood that higher resolution tools, such as LIF, provide a better resolution of LNAPL location, and in situ distribution and transmissivity provide a better indication of recoverability.

The apparent LNAPL thickness in a well relates to the hydrogeologic conditions and characteristics of the LNAPL and soil. Water table fluctuations can lead to the misconception that the LNAPL body is not stable. Water table fluctuations, due to seasonality or tidal fluctuations, influence the occurrence of LNAPL in the aquifer and wells [(ITRC 2009b); (Kemblowski and Chiang 1990)]. However, the changes in measurable thicknesses in a monitoring well are a result of changes in the vertical re-distribution of LNAPL saturation and do not typically indicate a change in the lateral extent of the LNAPL body.

The apparent thickness in the well is commonly exaggerated compared to the thickness of the mobile LNAPL interval in the formation as discussed below for unconfined, confined, perched, and fractured bedrock settings (Marinelli and Durnford 1996). For the reasons described below, assess the site-specific hydrogeologic conditions to interpret the data properly before using in-well LNAPL thickness in the LCSM.

3.4.1 Unconfined Conditions

Under unconfined conditions, LNAPL thickness in a monitoring well may increase as the water table falls and LNAPL flows into the well. As the water table rises, LNAPL becomes entrapped in the saturated soil and the apparent LNAPL thickness in the well decreases. When unconfined conditions are at equilibrium, the apparent LNAPL thickness in the well will closely match the equilibrium thickness of the mobile LNAPL interval intercepted by the well.

3.4.2 Confined Conditions

Under confined conditions, LNAPL thickness in a monitoring well typically increases as the potentiometric surface rises and decreases as the potentiometric surface falls. Often, the LNAPL thickness observed in the well may be exaggerated compared to the thickness of the mobile LNAPL interval within the formation.

Confined LNAPL is trapped in an aquifer beneath a layer that limits the upward movement of the LNAPL. The term ‘confined LNAPL’ is used because the mobile LNAPL is under pressure against the underside of a capillary confining layer (often fine-grained, lower permeability lithology). The LNAPL is under pressure within this zone, and a monitoring or recovery well screened across a mobile confined LNAPL interval acts as a “pressure release valve.” After installation, the LNAPL enters the well screen and rises in the well to equalize with atmospheric pressure. LNAPL accumulates as an exaggerated in-well LNAPL thickness (see Fractured Rock Appendix).

Monitoring the in-well LNAPL thickness response to water table (potentiometric) elevation changes is one way to assess whether LNAPL is confined. For confined LNAPL, the variability of the water table elevation with in-well LNAPL thickness will be the opposite of that described for the unconfined condition. For confined systems, the in-well LNAPL thickness will increase with an increase in potentiometric surface elevation, as shown in Figure 3-7. For a given site, both unconfined and confined LNAPL may exist. Further, a given location or well may be initially unconfined but may become confined through a rise in elevation of the water table. Additional, more specific information relating to changes in LNAPL thickness in confined conditions is available in (Kirkman 2013) and (ANSR 2012).

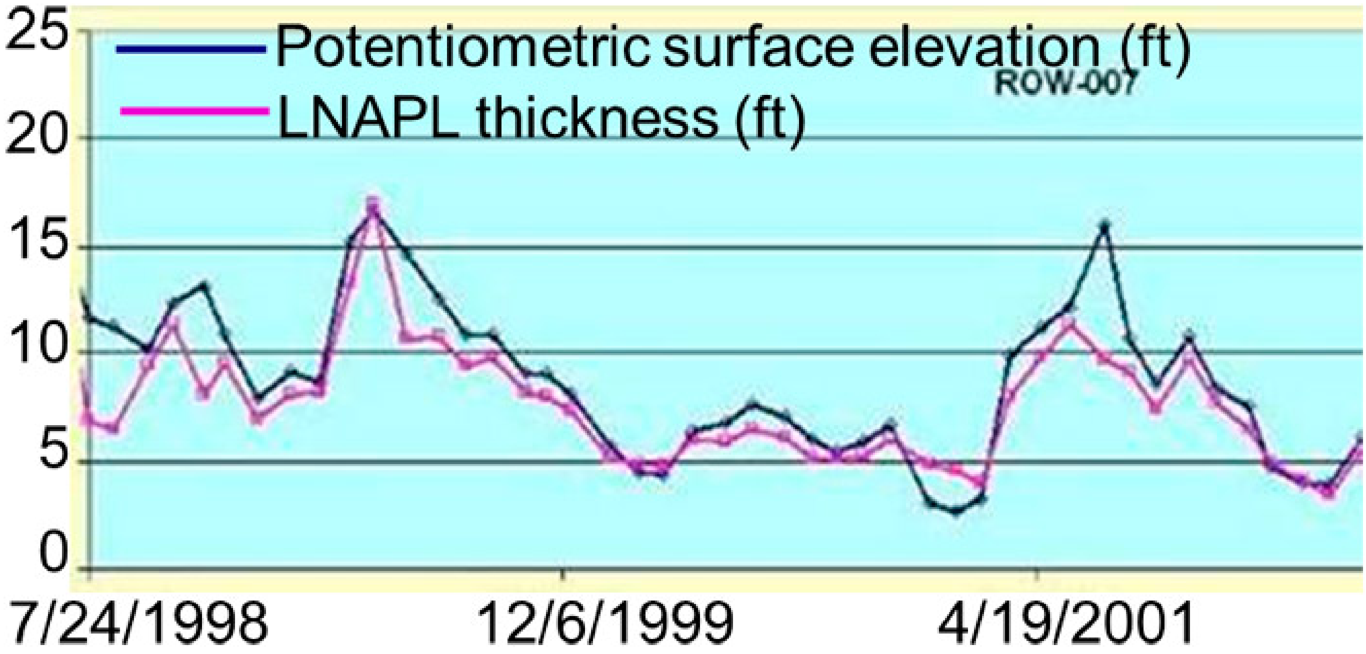


Figure 3-7. LNAPL thickness will mimic the potentiometric surface elevation for confined LNAPL conditions *(courtesy of BP)***.**

3.4.3 Perched Conditions

Under perched conditions, LNAPL thickness in a monitoring well may be exaggerated compared to the adjacent mobile LNAPL interval. If the well extends into the underlying confining layer, LNAPL will flow into the “sump” or reservoir created by drilling into the underlying confining layer.

LNAPL may be perched due to the pooling of LNAPL on top of a lower permeability feature within the unsaturated zone, or at the interface of the overburden and bedrock. Perched LNAPL is mobile LNAPL that accumulates in the vadose zone above less permeable layers, which exhibit a pore entry pressure greater than the available LNAPL head, and thus impedes the downward migration of LNAPL. If a sufficient volume of LNAPL collects above a less permeable (perching) layer, the resulting LNAPL thickness within a monitoring well screened into the perched LNAPL layer and into the underlying lower-permeability formation will result in a measured thickness that is greater than that in the surrounding formation. This condition results, in part, because the portion of the well screened below the interface and into the less permeable perching layer acts as a sump and allows LNAPL to accumulate. When the water table on the perched layer rises, the thickness of LNAPL in a well screened across the perching layer will decrease and again, will not be representative of the actual thickness of LNAPL within the formation at that location.

3.4.4 Fractured Preferential Pathway Conditions

In fractured and preferential pathway conditions (see the Fractured Rock Appendix), the relationship between the potentiometric surface and fractures intersected by the monitoring well may result in exaggerated LNAPL thickness compared to the mobile interval of LNAPL in the rock. Fractured and preferential pathway conditions represent LNAPL confined in a large pore network that is defined by capillary pressure contrasts, which may include open fractures in bedrock or desiccated soils, sand surrounded by clay, and macropores. For the same reasons as discussed for confined LNAPL above, the LNAPL thickness observed in a well is typically exaggerated compared to that within the formation. The LNAPL within the formation is limited to the secondary porosity features rather than being distributed within the primary porosity of the matrix. Indicators of LNAPL within a preferential pathway or fracture include:

- exaggerated LNAPL thicknesses in wells at equilibrium conditions;
- LNAPL observed at a considerable distance below the water table and laterally from the release location; and
- areas where the geology is known to have preferential pathways such as fractured clay and bedrock, or may have macropores or other secondary porosity features.

3.5 States of LNAPL Saturation

This section discusses the details of LNAPL occurrence in soil and how it relates to migrating, stable mobile, and residual LNAPL conditions. The terms migrating, mobile, and residual LNAPL saturation relate to LNAPL concerns, remedial technologies, and remedial metrics. This section explains the terminology and applies the understanding to LNAPL site management. For sites where LNAPL is not observed in-well, it also provides a summary of indicators in soil and groundwater that can be used to assess its presence.

Figure 3-8 illustrates the evolution of an LNAPL release. At the early stage of the release, the LNAPL head from the release develops a strong LNAPL gradient shown in the top figure; as the LNAPL continues to drain from the release—lowering the LNAPL head—the gradient dissipates and with time will mimic the water table gradient. The upper pane illustrates a situation before the LNAPL release is stopped. The LNAPL body is migrating due to the LNAPL head. LNAPL will continue to migrate laterally until the release is stopped and the LNAPL head dissipates. The middle pane illustrates a situation where the LNAPL release has been stopped and the LNAPL head had dissipated. LNAPL accumulates in a well installed in the LNAPL body, but the LNAPL is no longer migrating (spreading) laterally. The lower pane illustrates the situation where LNAPL is at residual saturation. LNAPL will not accumulate in a well installed in the LNAPL body unless the water table drops and LNAPL trapped below the water table can flow into the well.

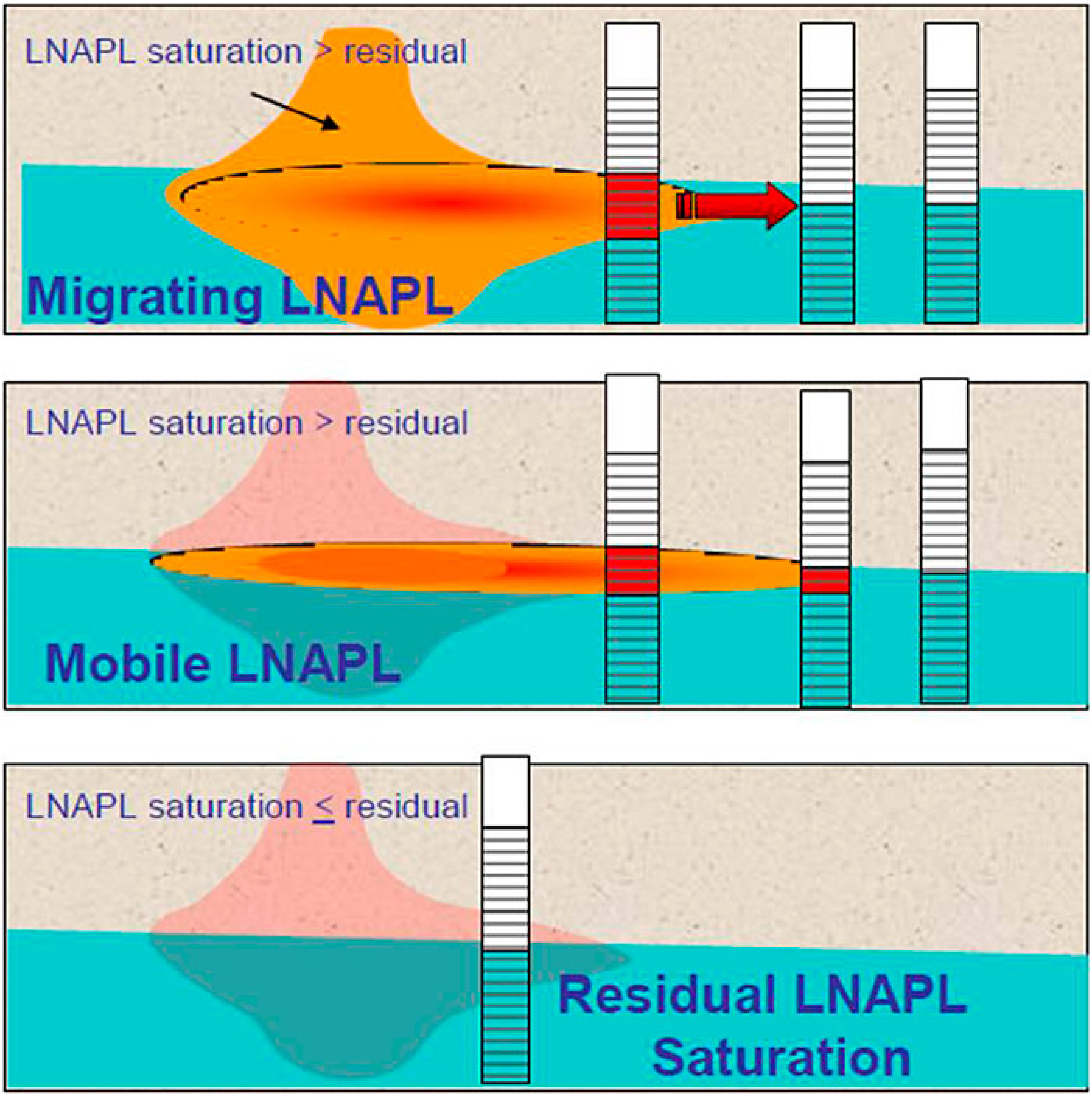


Figure 3-8. **Three LNAPL conditions (ITRC 2009a).**

LNAPL migration and mobility concerns have risk and non-risk implications at many LNAPL sites. It is important to understand the distinction between migrating LNAPL, mobile LNAPL, and residual LNAPL to establish appropriate remedial goals and determine remediation objectives. For each of these three conditions, physical properties of the LNAPL, aquifer properties, LNAPL saturation (including LNAPL relative permeability), LNAPL hydraulic conditions (e.g., LNAPL head) and NSZD affect the ability of an LNAPL body to expand or for LNAPL to flow into a well. Section 5 of this document describes the decision process for identifying LNAPL concerns, verifying concerns through the application of threshold metrics, establishing LNAPL remedial goals, and determining LNAPL remediation objectives. An understanding of whether the LNAPL at your site is residual, mobile, or migrating is key to evaluating concerns, establishing remedial goals, and determining remediation objectives.

3.5.1 Migrating LNAPL

Migrating LNAPL refers to plume-scale behavior; the overall body or a portion of the LNAPL body is expanding. The mechanisms that drive LNAPL migration are sufficient to overcome resistive forces. Conversely, stable LNAPL represents an LNAPL body that does not change over time and does not contain the driving forces to exceed the resistive forces. A stable

LNAPL body is comprised of residual LNAPL or a combination of mobile and residual LNAPL. LNAPL transmissivity is an indicator of the potential for migration, but by itself is insufficient to indicate the rate of migration. Assuming there are no resistive mechanisms, the rate of migration (or equivalently, the rate of LNAPL specific discharge) would be represented by LNAPL transmissivity times the LNAPL gradient. However, resistive mechanisms exist that render this calculation an overestimate of migration. These resistive mechanisms include water-table fluctuations, entry pressure head, and mass depletion via natural mechanisms (i.e., NSZD). Therefore, while mobile LNAPL and an LNAPL gradient may exist, migration may or may not occur because the resistive mechanisms may reduce the magnitude of migration, or counteract it completely.

LNAPL migration concern within an aquifer refers to lateral movement of the overall LNAPL body, whereby LNAPL enters aquifer pore spaces not previously containing LNAPL. This can occur only if the LNAPL possesses sufficient mobility potential (i.e., within the mobile range of LNAPL saturations) and sufficient LNAPL head (and capillary pressure) to drive the migration. Consequently, active LNAPL migration refers to spreading that occurs along the leading edge of the LNAPL body, where the LNAPL pressure head or driving force exceeds the capillary entry pressure (the resisting force) for the adjacent groundwater saturated aquifer. LNAPL migration tends to occur over the relatively early stages of a release, when the LNAPL head pressures and LNAPL saturations are greatest, except in the case of a change in hydraulic conditions (e.g., pumping on a nearby well). Following the termination of an active release, the LNAPL pressure head may decrease rapidly, which ultimately limits the overall volume of LNAPL available to migrate laterally. Afterwards, LNAPL typically is limited to vertical redistribution within the smear zone as new historical high or low water levels are attained. It is not necessary that the margin of the LNAPL body be at residual LNAPL saturation; equilibrium is typically established with the mobile (albeit diminished) LNAPL saturation still remaining. The water-filled pore spaces of the fully saturated aquifer simply act as a barrier to further LNAPL migration as capillary pressure decreases. Post release, as the plume spreads, the gradient decreases and the thickness decreases, which in turn decreases the transmissivity of the LNAPL, resulting in a self-limiting process.

Note that natural or manmade preferential pathways may exist at a given site that could allow migration to occur where it would not otherwise be expected. In such cases, the capillary entry pressure associated with the preferential pathway is less likely than that of the overall aquifer given the same LNAPL head pressure.

Care must be taken when using LNAPL thickness data from monitoring wells to assess LNAPL migration. Vertical re-distribution of LNAPL with a rising or falling water table can result in the appearance of an increased (i.e., growing) or decreased (i.e., shrinking) footprint, or apparent lateral migration of LNAPL that is not representative of actual conditions. LNAPL that “disappears” from a well may not be related to LNAPL migration, but rather to drainage. Likewise, increasing LNAPL thickness or appearance within a well is not necessarily a sign of increased or renewed migration. Rather, LNAPL thickness within a well is continually affected by drainage and imbibition effects within the near well bore formation and sand pack environment as water levels change. Figure 3-9 shows the apparent horizontal redistribution of LNAPL at a refinery over time resulting from vertical changes in LNAPL distribution. In actuality, there was very little change in horizontal or lateral footprint over the five-year duration depicted.

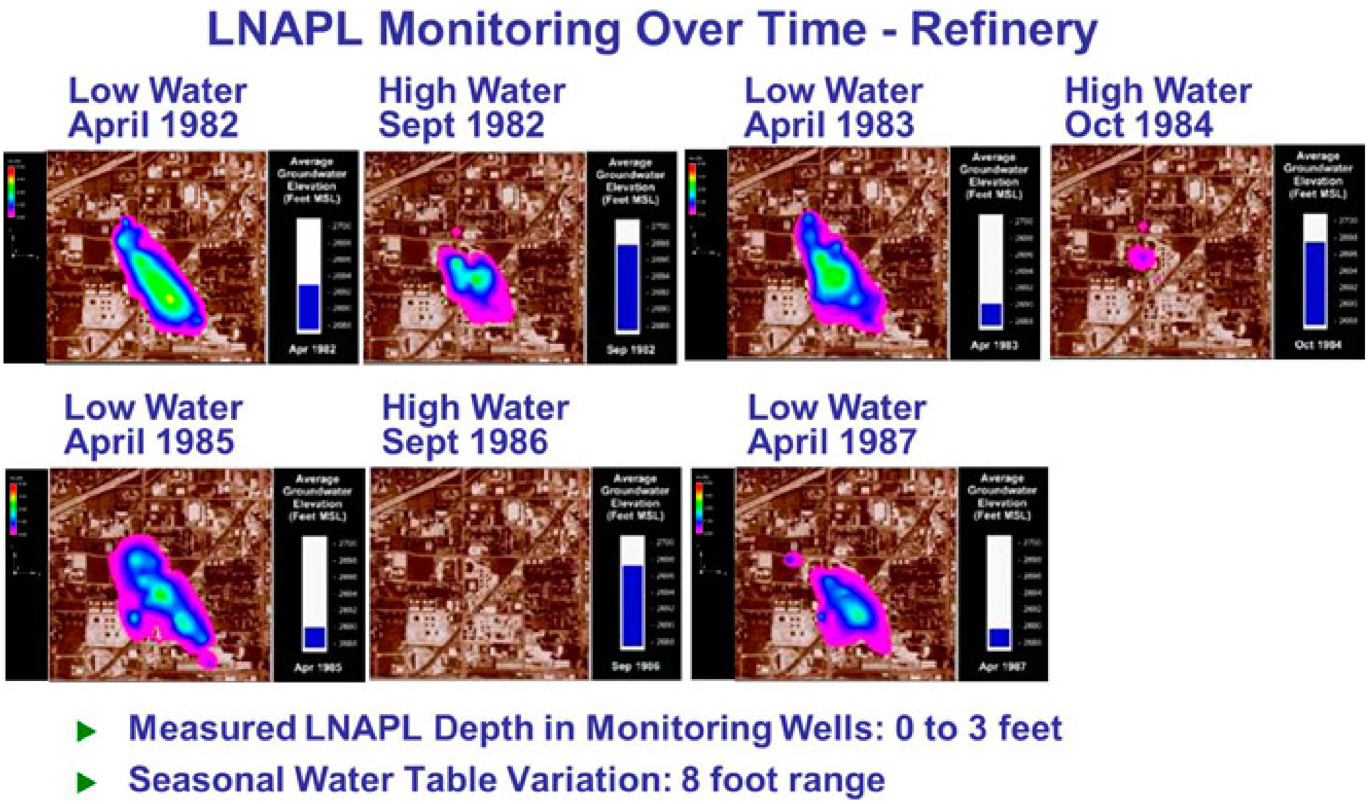


Figure 3-9. Examples of seasonal LNAPL redistribution (API 2006).

Multiple lines of evidence are recommended to fully assess the LNAPL migration for relatively recent releases (e.g., well gauging and dissolved phase plume behavior). LIF-based borings are a more technically sound means to define the leading edge of LNAPL accumulations, particularly in the early phases of an investigation. For late-stage release sites, it is often acceptable to assume lateral migration is at equilibrium, for the reasons discussed previously. Diagnostic gauge plots are a useful tool for evaluating whether or not the gauged thickness of LNAPL in a well is indicative of migration or rather more likely, the result of water table fluctuations.

Migration is also limited by NSZD processes (volatilization, dissolution, and biodegradation) resulting in mass loss and increased LNAPL viscosity (Mahler, Sale, and Lyverse 2012). NSZD losses can act to offset/balance the spreading effects caused by any local LNAPL pressure heads (Mahler, Sale, and Lyverse 2012). This is a dynamic relationship. When saturations are high, LNAPL mobility can cause LNAPL to migrate laterally toward the periphery of the body, while depletion processes act to remove LNAPL mass and diminish saturations, thereby balancing the movement. NSZD processes are discussed further in the NSZD Appendix of this document.

3.5.2 LNAPL Stability

Driving forces of a LNAPL release will penetrate below the water table. The LNAPL head gradient (i.e., the height of the LNAPL release above the water table) resulting from the LNAPL release principally determines the lateral spread of LNAPL near the water table, within the capillary fringe. Immediately following a release of sufficient volume, the LNAPL head is initially greater than the water table gradient. The LNAPL gradient will dissipate with time, eventually leading to LNAPL footprint stabilization (Figure 3-8). Stabilization depends on the type of LNAPL and the volume of the release. Commonly, low viscosity LNAPL (e.g., gasoline and diesel) takes weeks to months to stabilize, and high viscosity LNAPL (e.g., heating oil) requires months to years to eventually stabilize (CL:AIRE 2014). For distinct LNAPL releases, the LNAPL will eventually become stable and form a source of varying saturation levels within the pores of the formation. The LNAPL saturation at the leading edge will drop in saturation to below residual (i.e., fraction of the pore space occupied by LNAPL that cannot be mobilized under an applied gradient), and through balances of factors at the leading edge, will cease to migrate due to insufficient LNAPL head to exceed pore entry pressure, lower LNAPL saturations (i.e., residual), and NSZD processes (Tomlinson et al. 2017). Residual LNAPL is unlikely to become a problem if hydraulic conditions change, but mobile LNAPL may move with changes in hydraulic conditions (e.g., operation of a pumping well).

3.5.3 Mobile LNAPL

Mobile LNAPL represents a pore-scale concept. LNAPL occupies a sufficient fraction of the total porosity to form an interconnected network, but does not contain the driving forces on the LNAPL body to exceed the resistive forces. Mobile LNAPL can be detected via in-well fluid level gauging or through LNAPL transmissivity measurements. If an in-well thickness is measurable, then mobile LNAPL exists. The relative magnitude of LNAPL mobility can be assessed using LNAPL transmissivity.

Mobility refers to the ability of LNAPL to move or flow, vertically or horizontally, under a given gradient. LNAPL migration is the expansion of the LNAPL body footprint resulting from sufficient mobility and gradient, thus resulting in the expansion of the overall LNAPL body edge. LNAPL that accumulates in a well is considered mobile; however, its presence in a well is not a reliable indicator of potential recoverability nor the LNAPL body's migration potential.

The degree of mobility is dependent on both the proportion of movable LNAPL in the pore spaces (i.e., mobile LNAPL saturation) and the degree of interconnection between pore spaces (Figure 3-10). Residual LNAPL is not mobile. The proportion of the overall LNAPL body—associated with its residual LNAPL saturation—does not participate in its mobility (i.e., immobile fraction).

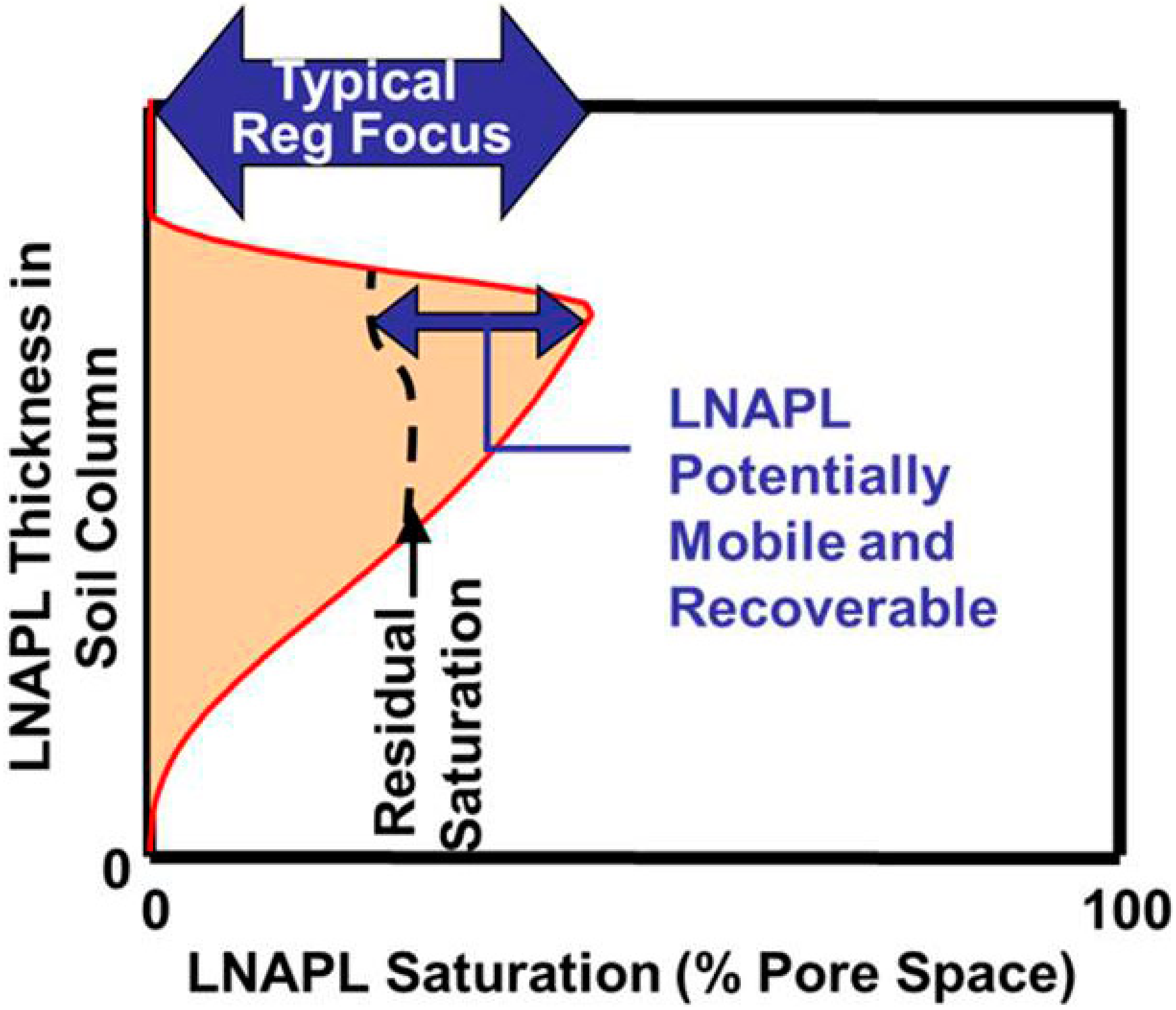


Figure 3-10. **LNAPL mobility is the additional consideration due to exceeding residual saturation** *(courtesy of S. Garg 2017)*.

3.5.4 Residual LNAPL

Residual LNAPL represents a pore-scale concept whereby LNAPL occupies a fraction of pore space that is discontinuous and too small for LNAPL flow to occur. Residual LNAPL has an insignificant transmissivity. As discussed above, residual spans a range of LNAPL saturation levels for a given soil and LNAPL type. An additional and significant factor for determining the residual saturation of a given soil is the maximum historical saturation [(Johnston and Adamski 2005); (Lenhard, Rayner, and

Davis 2017)]. Often the minimum and maximum historical saturation levels span a factor of 10 across a given LNAPL body.

Accepting residual saturation as a function of maximum saturation and applying it at plume scale can be useful to explain why quantifying residual saturation as a single value is not consistent with the current conceptual model of LNAPL occurrence and migration. The LNAPL head is greatest when a release occurs and LNAPL reaches the water table, resulting in the highest LNAPL saturations. After the release ceases and the LNAPL spreads out, LNAPL on the edges of the body is exposed to lower LNAPL heads resulting in lower LNAPL saturations. Thus, residual saturation is often higher in the center of the body than on the fringes. Similarly, the maximum historical LNAPL saturation will vary with depth at each location within the LNAPL footprint, resulting in vertically variable residual saturations. Water table fluctuations can help to reduce variability in residual saturation at some locations; however, variability still exists.

When considering site management options, determining whether LNAPL is mobile or residual is insufficient to identify the primary concerns (See Section 5). Most LNAPL concerns are driven by the migration of the LNAPL body, compositional risks, and abating LNAPL occurrence in wells to the maximum extent practicable. Migration can be evaluated using multiple lines of evidence.

If an LNAPL body is stable, then hydraulic recovery will have little impact on future management. Continued recovery will not reduce compositional-based risk, meaningfully reduce the source mass, nor significantly reduce source longevity. Conversely, if an LNAPL body is mobile, thus containing higher LNAPL transmissivity values, then hydraulic recovery may be beneficial to reduce LNAPL body mass. The efficacy of recovery indicated by LNAPL transmissivity is ultimately controlled by the ratio of residual to mobile LNAPL. High LNAPL transmissivity values with relatively thick smear zones will result in larger fractional source removal than thick residual smear zones exhibiting a similar LNAPL transmissivity value.

Residual saturation is discontinuous and immobile LNAPL under prevailing conditions and will not flow into a well (ASTM 2014b). The residual saturation within the unsaturated zone is the LNAPL saturation attained after an initially saturated soil is allowed to drain by gravity to equilibrium [(Hoag and Marley 1986); (Zytner, Biswas, and Bewtra 1993)], which is analogous to field moisture capacity as used in the agricultural engineering field. The residual LNAPL saturation in the saturated zone has been defined as the saturation at zero capillary pressure at the terminus of the spontaneous imbibition curve [(Pickell, Swanson, and Hickman 1966); (Bear 1972); (Dullien 1979); (Fetter Jr. 1992); and (Freeze and McWhorter 1997)]. Generally, the residual saturation will be lower within the unsaturated zone compared to the saturated zone. The unsaturated zone contains a more significant gas-filled porosity. Thus, the LNAPL becomes an intermediate wetting fluid which allows more of the fluid to drain from the soil as compared to the saturated zone where the gas phase is small and LNAPL is the non-wetting fluid.

It is notable that many literature values (particularly those developed based on petroleum exploration) of residual saturation typically overestimate residual saturation as they are frequently based on experimental data collected using sand or dry soils. This tends to result in a low threshold entry pressure and a higher initial LNAPL saturation resulting in a higher residual saturation. In all but well sorted sands, literature values of residual saturation are likely not applicable (becoming more so as soils get finer). Although some of the early references (e.g., (Mercer and Cohen 1990); (EPA 1995)) were based on state of the art science, our current understanding indicates that sites do not reach initial saturations of 100% at environmental sites. The user of literature values needs to understand their limitations.

Residual saturation is a fraction of the total saturation and is proportional to the maximum LNAPL saturation occurring in a given soil. As soil is successively flooded with and drained of LNAPL, such as occurs with repeated water table fluctuations as shown in Figure 3-6, the residual saturation tends to increase. Residual saturation is also inversely related to the grain size; it is typically larger in finer-grained soils.

Prior guidance attempted to define remediation endpoints based on residual saturation. However, the current state of the science supports that residual saturation is a conceptual limit; residual saturation cannot be easily measured and is not a value that is currently used as a remediation endpoint metric. It is recognized that the practical limits of recoverability are above the conceptual residual saturation value; this is discussed further in the Transmissivity Appendix.

Typically, a laboratory analysis can be performed to estimate the residual saturation. As discussed, these are estimates of the residual saturation for the given location and depth; residual saturation varies across any given site and typically, cannot be defined as a single number. To bind this range of variability, collect soil samples across a given boring and compare them to the mobile LNAPL interval. The samples outside of the mobile LNAPL interval represent residual LNAPL values.

3.5.5 LNAPL Indicators

At petroleum release sites where an LNAPL concern exists, but it has not been directly observed, a determination of LNAPL presence should rely on multiple lines of evidence to verify or eliminate the suspected LNAPL concern. Monitoring for the presence or absence of LNAPL in monitoring wells can be helpful; however, it should not be the only assessment tool. Where LNAPL is present in a properly constructed monitoring well, LNAPL can also be assumed present in the surrounding subsurface formation. However, it is a common misconception to assume that if no LNAPL is present in a monitoring well, then there is no LNAPL in the soil. Similarly, if in-well LNAPL thickness changes from measurable to not measurable following LNAPL remediation, it is a common misconception to assume that LNAPL is no longer present within the surrounding subsurface soil. In both of these scenarios, LNAPL may be present in discontinuous pores at saturations less than those needed to migrate laterally or to mobilize into a monitoring well.

Table 3-2 lists potential indicators of the presence of LNAPL in unconsolidated materials, and more importantly, also cautions the use of indicators that should be viewed as ‘lines of evidence’ rather than absolute indicators. Note also that Table 3-2 does not cover all situations (e.g., sediments nor fractured media). The use of soil or groundwater concentrations to assess whether LNAPL is present should be regarded as supporting evidence and not as absolute indicators. There is not a specific concentration in groundwater that indicates the presence of LNAPL, because varying product compositions and degrees of weathering affect concentrations of dissolved components. Similarly, the use of TPH concentrations in soil as an indicator of LNAPL presence should be exercised with caution as soil TPH concentrations may be affected by non-hydrocarbons (such as soil organic matter) and by the choice of analytical method. However, the closer a measured concentration in groundwater is to the effective solubility, the greater the likelihood that LNAPL is present. For more information, reference the ITRC TPH Risk Document (ITRC 2018).

A comparison of historic and current site-specific dissolved and vapor phase concentrations, and boring logs with notes about locations and depths of impacted soils, can provide additional lines of evidence pertaining to the presence or absence of an LNAPL body. For example, significant lateral migration and an increase in dissolved-phase concentrations, or the sudden appearance of vapor in buildings, may suggest that LNAPL is present.

Visual observations of the soil core combined with field screening tools such as a photoionization detector (PID) or flame ionization detector (FID) with CH_4 correction, or use of LIF tools as the boring is advanced, can confirm the presence or absence of LNAPL in the borings. Care should be taken to design a soil investigation that assesses the areas with the greatest potential for LNAPL. Inadequate distribution or placement of soil borings can lead to an incomplete investigation and the presumption of no LNAPL presence when it may indeed be present in the subsurface.

Table 3-2. Potential LNAPL indicators

Indicator^{1}	**Limitations**
Groundwater	
• **Effective solubility of a given constituent:** Greater than 1% to 10% (e.g., for gasoline) • **Benzene: > 1 – 5 mg/L**^{2,3} • **TPH**$_{(gasoline)}$**: > 30 mg/L**^{4} • **BTEX: > 20 mg/L**^{5} • **Current or historical presence of LNAPL (including sheens)** ^{2,3}	• There is not a specific petroleum hydrocarbon compound (PHC) concentration in groundwater that defines LNAPL because of varying product types and degrees of weathering.
Soil	

Indicator[1]	**Limitations**
• **Current or historical presence of LNAPL (including sheens, staining)**[2,3] • **Benzene > 10 mg/kg**[2] • **$\text{TPH}_{\text{(gasoline)}}$ > 250 – 500 mg/kg**[2,5] • **$\text{TPH}_{\text{(diesel)}}$: > 10 – 30 mg/kg**[6] • **Ultraviolet fluorescence (UV) or LIF response in LNAPL range**[7] • **PID or FID readings for a recent release > 500 ppm**[8]	• The use of TPH soil concentration data as LNAPL indicators should be exercised with caution. Note that the information in this table may not be applicable to media such as sediment or fractured media. • TPH soil concentrations can be affected by the presence of soil organic matter. • TPH soil concentrations are not well correlated with TPH or O_2 soil gas concentrations (Lahvis and Hers 2013). • Organic vapor readings are composition dependent. For older (weathered) releases, LNAPL may be present at much lower PID/FID readings.
Location Relative to Release Area	
• **Adjacent to (e.g., within 20 feet of) a known or suspected LNAPL release area or petroleum equipment**[2]	• The probability of encountering LNAPL increases closer to a known or suspected release.
Notes: Order of listing does not imply ranking. Indicators above are generalized and do not represent all possible situations. [1] One or more of these indicators may be used to define LNAPL. [2] Used in the derivation of PVI screening distances by (EPA 2013) and (Lahvis et al. 2013). [3] Used in the derivation of PVI screening distances by (Peargin and Kolhatkar 2011). [4] Used in the derivation of PVI screening distances by (EPA 2013). [5] Recommended by (Lahvis and Hers 2013). [6] From ITRC TPH Risk Document (ITRC 2018). [7] From ASTM E2531-06 (ASTM 2014b). [8] Recommended by (EPA 2013) and (Lahvis and Hers 2013).	

3.6 LNAPL Recoverability and Transmissivity

This section discusses the relation between mobile LNAPL and recoverability and introduces the key concept of LNAPL transmissivity.

3.6.1 LNAPL Recoverability

LNAPL recoverability refers to the ability to remove mobile LNAPL from the subsurface at a given location, as evaluated by comparing the measured LNAPL transmissivity to an agreed upon threshold. Understanding LNAPL recoverability is important, particularly for sites where one or more remediation endpoints are based on removal of LNAPL (e.g., to the maximum extent practicable). Although this discussion focuses on LNAPL recoverability under ambient site conditions, additional remedial technologies that rely on increasing the recoverability of LNAPL (e.g., water flooding, surfactant-enhanced remediation, and co-solvent flushing) are discussed in Section 6 of this document.

Reaching a recoverability limit does not necessarily mean that LNAPL saturations are reduced to residual, but it does typically represent an endpoint where the majority of remaining LNAPL is of limited mobility and/or residual. It may continue to accumulate in a monitoring well, for example. A critical factor in LNAPL recoverability is the decrease in LNAPL relative permeability over the operating time of the remediation technology. As removal progresses over time, LNAPL saturations are reduced, which causes the relative permeability of LNAPL to decrease (red line on Figure 3-11), and also results in declining recovery rates.

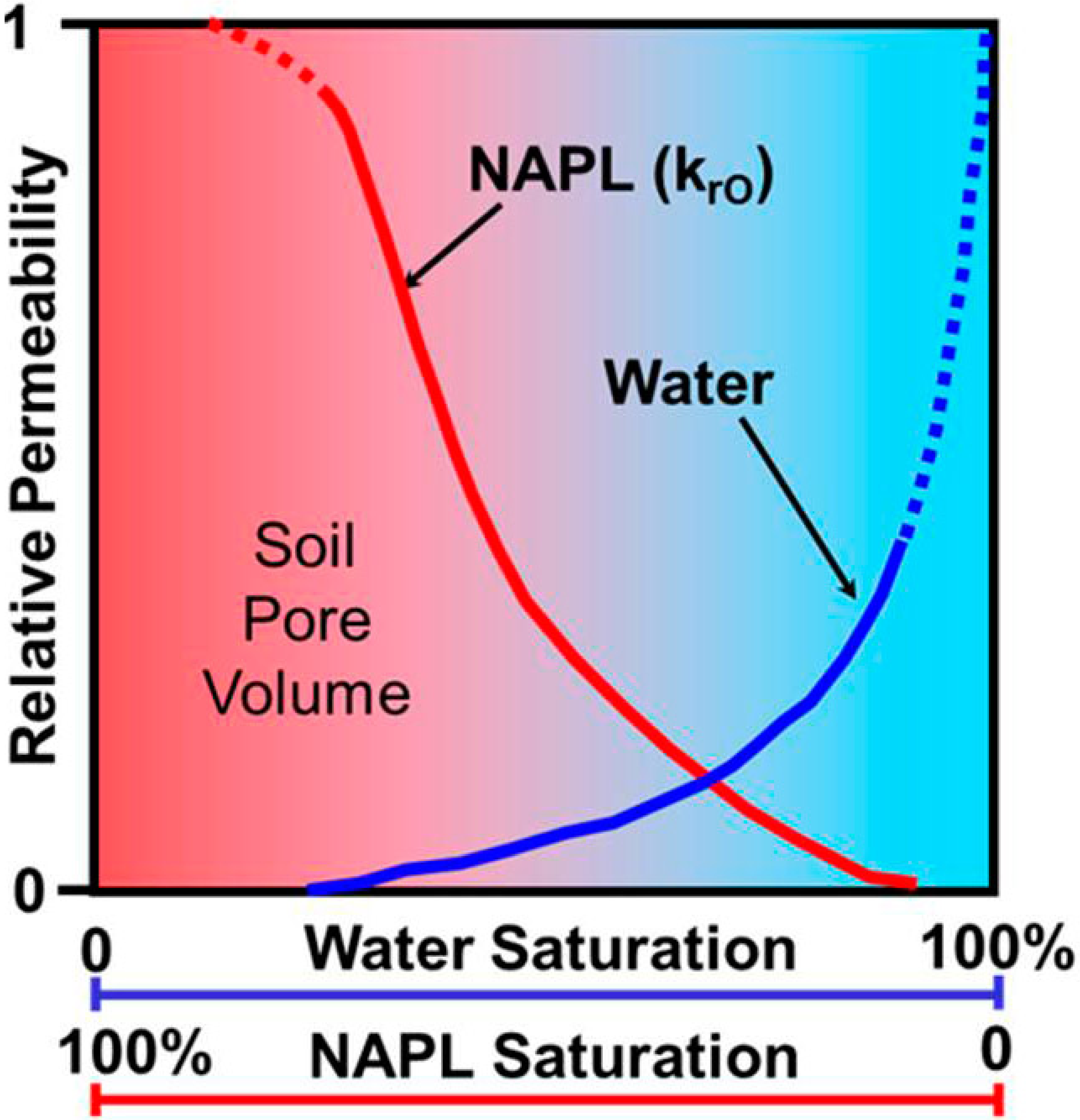


Figure 3-11. LNAPL relative permeability.

At the pore scale, LNAPL eventually becomes discontinuous by virtue of the decreasing saturations. While these isolated, discontinuous LNAPL occurrences may be above residual saturation locally, they are cut off from the overall, interconnected hydraulic flow field. Therefore, a practical limit for extraction (i.e., diminishing returns for LNAPL together with increasing groundwater extraction volumes and associated handling problems) typically is reached at a time when some proportion of mobile LNAPL remains within the zone of influence of the remedial system. LNAPL recovery is likely ineffective when the following conditions are reached:

- the plume is stable (not migrating, expanding, or inducing sheens), and
- recovery no longer reduces the source to the extent that conditions with respect to risk-based dissolved phase and/or vapor phase goals improve.

Practical limits can also be prepared in terms of economic return (e.g., cost per gallon) of LNAPL recovery, including the lifting and treatment cost of the produced groundwater), and/or physical restraints (e.g., gallon of LNAPL recovery/unit of time relative to the overall volume of in-place LNAPL, including the residual volumes or reduced LNAPL transmissivity values as recovery progresses). Again, some mobile LNAPL will remain after hydraulic recovery has ceased (in addition to the immobile, [residual] fraction of LNAPL that is unrecoverable due to inherent extraction inefficiencies).

3.6.2 LNAPL Transmissivity

LNAPL transmissivity is analogous to groundwater transmissivity; higher transmissivity values indicate higher production rates for a given drawdown induced. However, groundwater is typically expansive, and recharge by precipitation may sustain groundwater extraction for years at similar rates and drawdowns without exhibiting a decline in water production. In contrast, LNAPL bodies often have a limited extent of mobile LNAPL and transmissivity and recovery decline as LNAPL is removed.

LNAPL recovery is often termed “asymptotic” because the rate keeps decreasing, but never reaches zero. Decline curves have been used to illustrate this for optimized recovery systems with robust data sets. Figure 3-12 provides a chart of real site data where recovery started out at a high rate and declined over time.

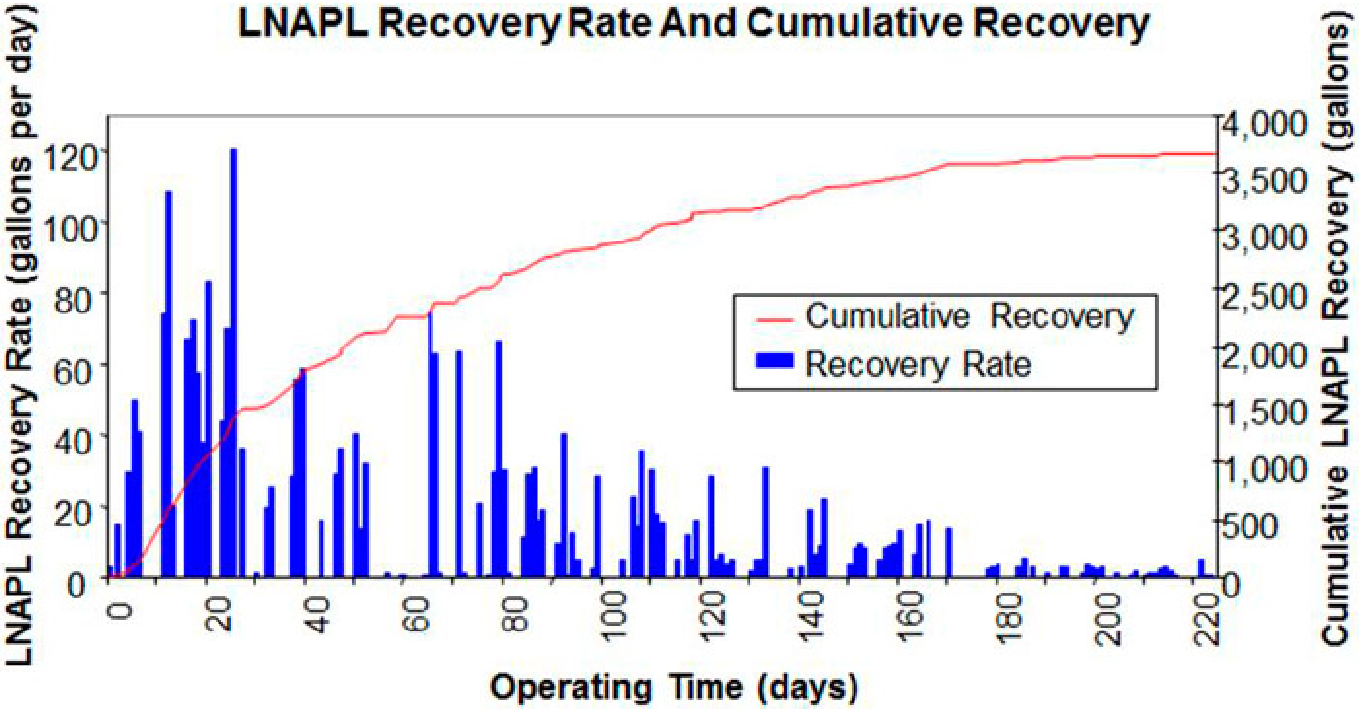


Figure 3-12. LNAPL recovery rate (blue columns) and recovered volume (red line) over time. *(courtesy of AECOM)*

The data in Figure 3-12 can also be plotted as recovery rate (y-axis) versus cumulative recovered volume (x-axis) to present a decline curve (Figure 3-13). The x-intercept of a best fit line through the data shows that the ultimate recovered volume is expected to be approximately 3,700 gallons. Although LNAPL may still occur in wells, it is understood from this analysis that continued LNAPL recovery will not perform as well as it had in the past. If additional remediation is warranted, this line of evidence indicates an alternative technology may be required, as the practicable limit of hydraulic recovery has been achieved.

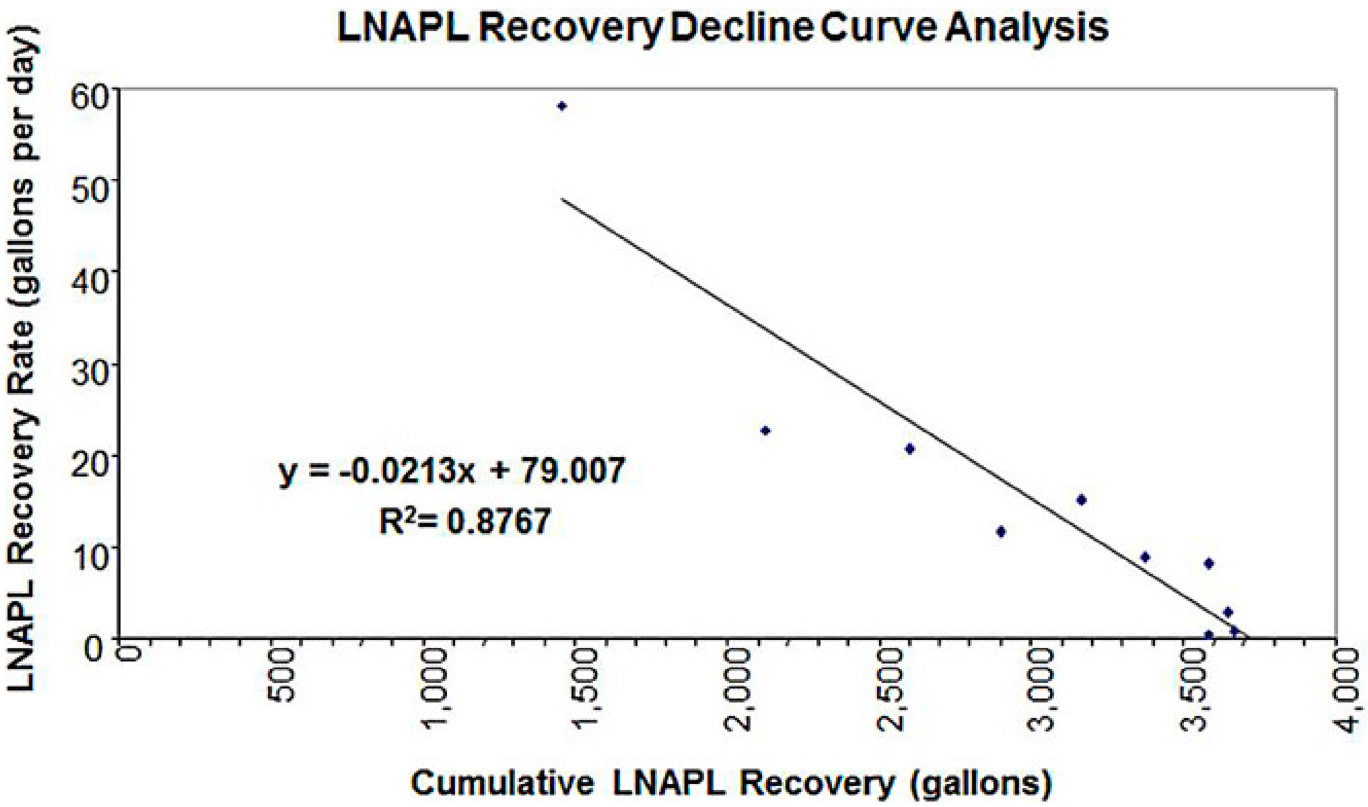


Figure 3-13. LNAPL recovery rate vs. cumulative volume recovered. *(courtesy of AECOM)*

Knowing of this practicable limit, LNAPL transmissivity can be used as a leading metric, in advance of system installation, to evaluate whether LNAPL recovery will be effective. Measurements of baseline LNAPL transmissivity, before system installation, can help provide a line of evidence to indicate if a site is already near its practicable limits for recovery.

Empirical data suggests that LNAPL transmissivity values below 0.1 to 0.8 ft^2/day indicate low recoverability and therefore, the majority of the LNAPL at a site is in a state of lesser mobile and residual saturation. ITRC (ITRC 2009a) proposed this empirical limit based on five sites in California, Kentucky, and Florida. The sites were closed or granted no further action after developing comprehensive LCSMs and operating LNAPL recovery systems. All sites demonstrated achievement of the impracticable limit (i.e., the lack of LNAPL recoverability) irrespective of in-well LNAPL thickness remaining. Since that time, data from four additional sites, with comprehensive LCSMs based on high-resolution data, were analyzed and affirmed the proposed limits. Refer to the LNAPL Transmissivity Appendix for additional discussion on the basis for the proposed range of recoverability limits.

3.7 Relation of LNAPL Saturation and Composition to Technology Selection

This section describes subsurface chemical partitioning processes and introduces the key concept of saturation- and composition-based remedial goals as they relate to technology selection.

Figure 3-14 provides a graphical representation of mobile, migrating, and residual LNAPL and illustrates where compositional, hydraulic recovery, and saturation reduction technologies are applicable within the spectrum. For example, a site with migration concerns and high LNAPL transmissivity, can be addressed with LNAPL recovery, where the remediation endpoint is 0.1 to 0.8 ft^2/day. However, if the remedial goal is to remove all LNAPL, then alternate technologies will be needed in addition to (or in lieu of) LNAPL recovery. Since the practicable limits of LNAPL recovery is represented by an LNAPL transmissivity of 0.1 to 0.8 ft^2/day, LNAPL recovery cannot meet a remedial goal of removing all LNAPL.

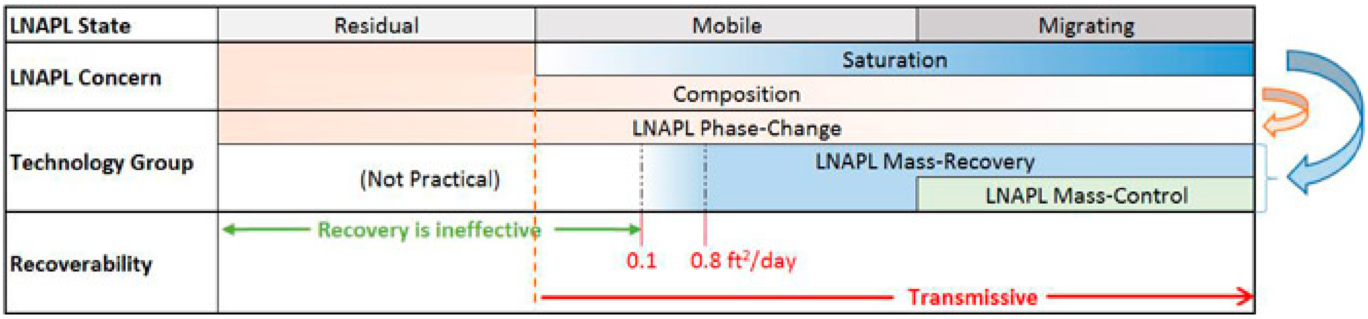


Figure 3-14. Relationship between LNAPL concern, LNAPL state, technology group and recoverability.

Where a compositional risk exists, consider phase-change technologies either in tandem with or in lieu of LNAPL recovery. While multi-phase extraction (MPE) would be worthwhile in a coarse sand with a dissolved phase concern and high transmissivity (e.g., mobile LNAPL) this technology may be less effective with a weathered diesel fuel and residual LNAPL. The weathered diesel fuel is unlikely to have a dissolved phase BTEX plume and will likely exhibit low or negligible LNAPL transmissivity. While excavation may target the total mass, depth limitations and cost may indicate that a bioremediation or NSZD alternative is more appropriate, as the majority of constituents within diesel are biodegradable.

4. LNAPL Conceptual Site Model (LCSM)

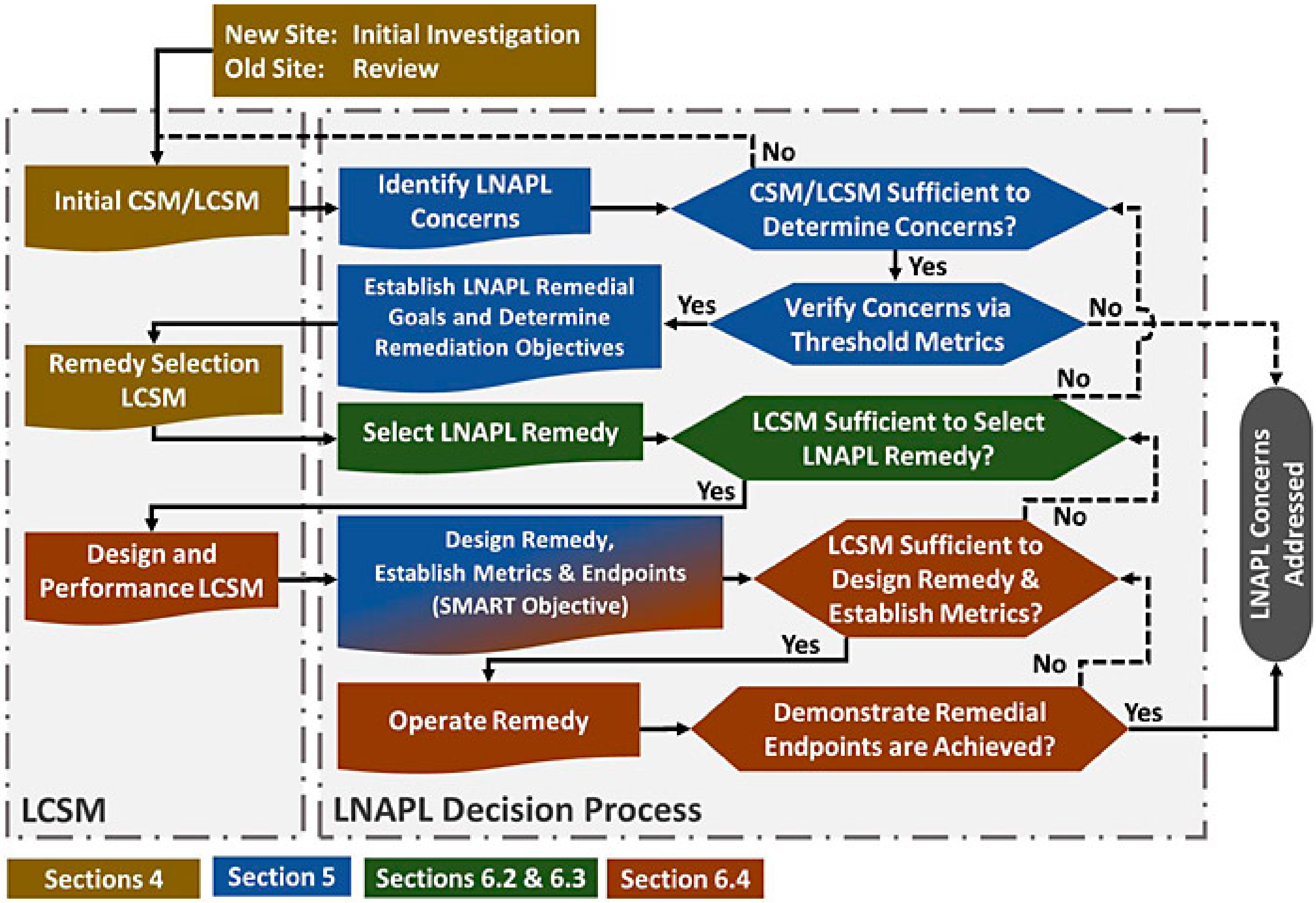


Figure 4-1. LNAPL conceptual site model (LCSM) stages and integration with LNAPL alternative evaluation.

The LCSM is the collection of information that incorporates key attributes of the LNAPL body with site setting and hydrogeology to support site assessment and corrective action decision-making. As with a conceptual site model for a non-LNAPL contaminated site, the LCSM integrates information and considerations specific to the LNAPL body relating to the risks of the contaminant source, exposure pathways, and receptors (for examples, see (ASTM 2014a)). The content of the LCSM will typically evolve over time as different phases of the corrective action process require different information. What remains consistent is the emphasis in the LCSM on characterizing and understanding the source component, the LNAPL (see (ASTM 2014b)).

From the moment of release and as a site matures, ongoing NSZD processes can affect significant changes to the LNAPL body such as stability, mobility, and recoverability and associated dissolved- and vapor-phase plumes. Ongoing remediation can also contribute to continuing changes or be ineffective. A complete and up-to-date LCSM allows the best possible management decisions about application and operation of remedial technologies (see (ASTM 2014b)). Further, remedial action data provides important feedback on the LCSM; for example, effective attainment of objectives provides validation, while non-attainment of objectives is often rooted in an incomplete LCSM and misdirected use of a given technology. The LCSM may comprise some or all of the following scientific and technological information (hereinafter referred to as the “science”):

- site setting (historical and current)—includes land use (as it informs potential sources), groundwater classification, presence and proximity of receptors, etc.
- geological and hydrogeological information/setting

- LNAPL physical properties (density, viscosity, interfacial tension, vapor pressure) and chemical properties (constituent solubilities and mole fractions)
- LNAPL body spatial distribution (vertical and horizontal delineation)
- LNAPL mobility and body stability information
- LNAPL recoverability information
- associated dissolved-phase and vapor-phase plume information (as it informs LNAPL distribution and pathways to receptor)
- LNAPL natural depletion processes (including rate measurements or estimates, if available)

These elements were introduced in ITRC's initial LNAPL guidance (LNAPL-1 and -2 documents), and for this update they have been grouped by the decisions that they support and transformed into the key questions in Section 4.2 and Section 4.4 that will help the investigator characterize, monitor, and understand LNAPL sources at their site. In answering the questions, the investigator will seek out the appropriate lines of evidence that bring the LNAPL concerns into sharper focus. This section is focused on what information is needed at what point for a given site. Section 3 provides insight to detailed LNAPL science. In addition, Section 4.3 includes a table summarizing LCSM data collection parameters, applicable tools, and educational references for investigation that may be useful in answering the key questions.

LNAPL source zones require utilizing lines of evidence which encompass microbiology, hydrogeology, petroleum chemistry, geochemistry, vapor transport. The reader must recognize the multifaceted aspects and utilize additional references provided throughout this document for detailed understanding of the LNAPL science.

The evolution of the LCSM during the corrective action is driven by the answers to questions shown in Figure 4-1 and by the three stages identified below:

1. The **Initial LCSM** identifies concerns by defining the nature and extent of LNAPL and how it relates to receptors and pathways. (see Section 4.2)
2. The **Remedy Selection LCSM** provides for **remedy evaluation** and selection of the most efficacious remedial technology or controls by characterizing aspects of the LNAPL and site subsurface relative to the potentially employed remedial mechanisms. (see Section 4.4)
3. The **Design and Performance LCSM** provides **remedy implementation** support and guides termination, remedy transition, or optimization through monitoring remedy performance metrics relative to the remediation objective. (see Section 6.4.1)

Over the life cycle of a typical LNAPL site investigation and remediation, the LCSM may include, but does not necessarily require, the three stages of evolution, each with a specific focus and a specific set of outcomes.

At the first stage, the focus of the Initial LCSM is the identification of one or more *LNAPL concerns*. An *LNAPL concern* is an LNAPL condition or potential condition that could:

- pose a risk to health or safety;
- result in additional LNAPL migration;
- address an LNAPL-specific regulatory requirement; or
- create some other physical or aesthetic impact or other specific regulatory or stakeholder requirement.

A well-developed Initial LCSM summarizes LNAPL and site conditions sufficiently to guide the identification and refinement of LNAPL concerns. Some LNAPL concerns may be readily identified in the early stages of site characterization, and others may be identified or further refined. It is recommended that the Initial LSCM includes sufficient information to *verify* LNAPL concerns using *threshold metrics* where available, and to establish *Remedial/Control Goals*. Section 5 provides further information on verifying initial LNAPL concerns, and translating verified LNAPL concerns into an LNAPL remedial strategy. This process is illustrated in Figure 4-1 in the blue steps and the initial green step.

At the second stage, the focus of the LCSM shifts to selecting potential remedial options. The outcome of the Remedy Selection LCSM is the identification of one or more *LNAPL remedies or controls* that address the verified LNAPL concerns. The Remedy Selection LSCM should include sufficient information to *select* appropriate remedies or control measures that are capable of abating the verified LNAPL concerns. These steps are illustrated by the green steps in Figure 4-1. Section 5 and Section 6 provide further information on selecting an LNAPL remedy/control strategy.

As illustrated by the red steps in Figure 4-1, in the third stage, the focus of the LCSM shifts to designing and implementing the selected remedial measures or controls, establishing technology-specific *remediation objectives*, and assessing progress and performance toward identified technology-specific *remediation endpoints*. The outcome of the Design and Performance LCSM is the implementation of one or more *LNAPL remedies or controls* that can achieve the established remediation objectives. The Design and Performance LCSM should include sufficient information to establish remediation objectives, design and implement remedies or control measures, and track progress toward defined remediation endpoints. Section 5 and Section 6 provide further information on establishing remediation objectives, implementing remedies, and identifying and tracking progress toward remediation endpoints.

The level of detail required in an LCSM for a specific site is a function of the complexity of environmental conditions, potential risk considerations, the regulatory framework, and overall LNAPL site management and remediation objectives (ASTM 2014b).

4.1 How Much Data is Enough?

ASTM International (ASTM 2014b) advocates development of an LCSM to evaluate LNAPL sites in a manner consistent with the Risk-Based Corrective Action (RBCA) process (see ASTM E1739–95 (ASTM 2015)) for more information about the RBCA process). ASTM identifies three tiers of LCSMs based on site complexity: Tier 1, Tier 2, and Tier 3 (with site complexity and LCSM requirements increasing with tier levels). Generally speaking, the LCSM for a given site is deemed adequate (in terms of level of detail) when the existing understanding is sufficient for the stakeholders to agree on a path forward. Ultimately, however, the judgment of the environmental professionals (e.g., environmental consultants, implementing agencies, responsible parties) is used to assess whether sufficient information has been gathered to make appropriate management decisions.

Figure 4-2 illustrates how as the level of risk or complexity of a site increases, a higher tier of LCSM is useful to provide sufficient information for decision making (after (ASTM 2014a)). This higher tier of information could be higher data density (spatial or temporal), or additional tools for a given line of evidence (e.g., geology or LNAPL composition). For example, in certain situations, where the size of the LNAPL body is relatively small and soil excavation is adequate to satisfy remediation objectives, the LCSM may be limited to spatial distribution, and further evaluation of LNAPL degradation or mobility are unnecessary. In other situations, where excavation is not feasible, the LCSM requires this additional detail.

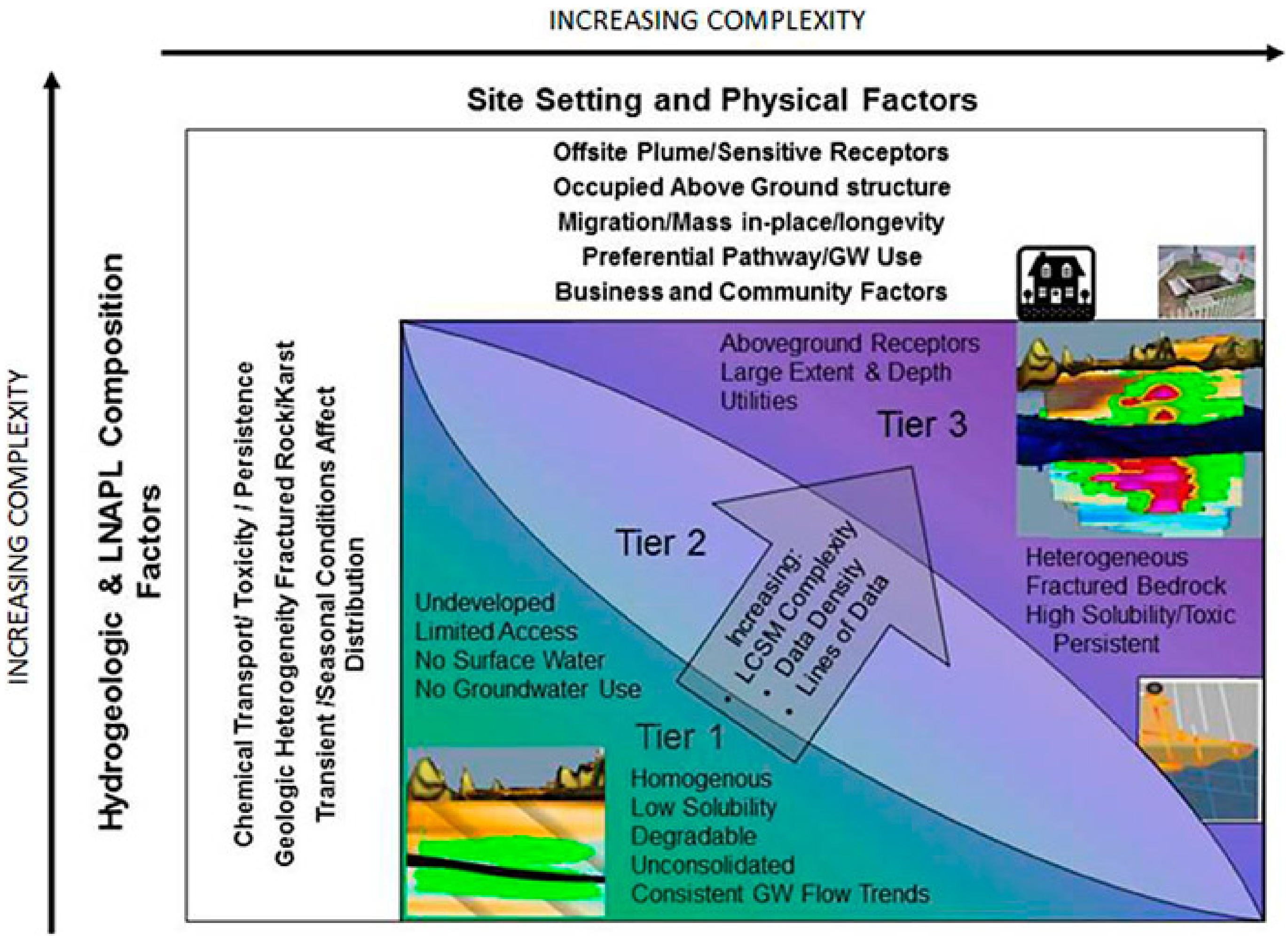


Figure 4-2. Factors governing 1) the potential to achieve a significant reduction in risk and 2) the cost of LNAPL depletion (arrows point in the direction of increase of the noted property). (adapted after (ASTM 2014a)).

It is important to note that a single factor may not increase the level of complexity by itself. Rather, if that factor results in challenges to remediation or confidence in the remedial decision, then the tier is increased. For example, a source zone in heterogeneous soil can either be a tier 3 or a tier 1. Where the source is shallow, the release history is known, and excavation can be performed, a tier 1 LCSM may be appropriate. In the event that excavation is not feasible or desirable due to cost, then additional information may be needed to characterize the distribution of impacts for alternate remedy evaluations. The additional data would identify cost and performance of alternate remedies for more informed decision making.

LNAPL sites are typically evaluated using various elements, including:

- historical data (e.g., LNAPL and dissolved phase footprint evolution, LNAPL occurrence versus potentiometric surface elevation, facility release record, and/or operational record);
- field data such as product recovery rates from interim measures, transmissivity values from baildown testing, and/or tracer dilution tests;
- site-specific laboratory data (e.g., TPH profiling and LNAPL saturations in soil cores);
- analytical and/or numerical modeling results;
- LNAPL risk assessment issues (including the consideration of both current and potential future site conditions);
- high resolution characterization data (e.g., DC resistivity, conductivity, LIF, and MIP); and
- combinations of the above.

The extent to which one particular line of evidence may be needed for the LCSM depends on other available lines of evidence. For example, at a site where there are little or no historical data or where the data sets are extremely sparse, there will be a stronger need for extensive sampling to obtain site-specific laboratory data, possibly supplemented with modeling that incorporates the new data to characterize LNAPL mobility and body stability issues. Conversely, at a site with an abundance of historical data covering the range of water table fluctuations, there will likely be less need to engage in a comprehensive laboratory program or modeling to develop the LCSM. Utilizing this thinking with the tiered concept in Figure 4-2 will support the overall litmus test for an LCSM – is there agreement by all stakeholders that sufficient information is available to make decisions to advance the site forward?

4.2 Initial LCSM

The Initial LCSM is utilized to support identification of concerns, verifying those with the threshold metrics (Section 5.1.1 and Table 5-1) and ultimately defining remedial goals (Section 5.2). Often data collected in the Initial LCSM will support additional portions of the LCSM and may be collected for efficiency of field mobilizations. However, it is not always plausible to understand the concerns, the remedial path forward, and the requirements for remedial design until an initial LCSM is created. A logical step is to collect sufficient information to understand the concerns and then verify them with threshold metrics. As discussed in Section 5.1, the primary categories of concerns include Risk and Safety, Migration, LNAPL Occurrence, and Other Concerns.

The questions described in this section were designed to guide an investigator through the key components of developing the concerns portion of the Initial LCSM. This represents the first steps shown in Figure 4-1.

While there are many questions that can be answered for a site, not all are necessarily relevant or required depending on the level of detail required for the LCSM. The questions in this section are widely applicable to LNAPL sites as they generally have to be answered to develop the LCSM for understanding concerns, risks, and LNAPL source distribution—from the most general (green) to more LNAPL specific concepts (brown).

🟩 **1. Is current and future land use known?** ▼*Read more*

The relevance of land use (both on-site and off-site) is of primary importance due to determination of exposure pathways (Question 8); the establishment of site cleanup goals; and any local, state, and federal requirements for institutional controls or other physical controls. Information regarding past and future land use and possible release(s) may dictate how aggressive a remedy needs to be to meet those cleanup goals, but may also limit the extent to which a remedy can be applied if the site is an active industrial facility or much of the site is covered by buildings or other structures that limit accessibility.

2. Does the potential for preferential pathways exist? ▼*Read more*

What will this tell me about the LNAPL body? Read More

The potential for preferential pathways for flow and transport can be identified based on local and regional geology, geomorphology, and site setting. These preferential pathways can create conveyances for LNAPL to migrate at a rapid rate relative to the surrounding matrix, over longer distances, and in directions that might not otherwise be expected.

How is the answer informed by the below categories: Read More

- **Site setting, current and future land use, potential receptors**

Site setting can help identify the existence and location of anthropogenic preferential pathways. These features can provide conduits for exposure inconsistent with what is expected in a typical soil matrix and can convey LNAPL vapor (ITRC 2011), and/or dissolved impacts over longer distances.

- **Site geology and hydrogeology**

Understanding the distribution of preferential pathways in different geologic and hydrogeologic settings (e.g., heterogeneous unconsolidated soil, karst, and fractured rock) and the degree of anisotropy will better enable the investigator to understand the LNAPL migration potential relative to receptors. Preferential pathways should be evaluated and understood in both the vadose and saturated zones.

Varied stratigraphy can result in anisotropic LNAPL occurrences. Void spaces can also create collection points for LNAPL that can serve as persistent source areas for dissolution to groundwater and for LNAPL sources to the surrounding matrix. Characterization should account for soil variability influencing the anisotropy. This can be done with a simple increased boring and well density, but often improved approaches utilize the stratigraphy to strategically locate the same number of borings and wells and/or couple with tools such as geophysical or high resolution borings to provide an improved understanding with fewer wells for increased confidence in the LCSM. Preferential pathways for flow and transport may also exist in fractured rock, which is further discussed in the Fractured Rock Appendix.

- **LNAPL body spatial distribution/extent**

Permeable soil layers may intersect a utility corridor or other preferential pathway, which results in anisotropic distribution and transport of LNAPL, vapor, and/or dissolved phase impacts. LNAPL can more easily flow through more permeable units as well as achieve a higher degree of impact within the matrix for a given release. Cross-sections and/or illustrations of the LNAPL body extent that include utilities and stratigraphic information are useful in illustrating the spatial relationship of the LNAPL impacts to site geology and anthropogenic subsurface features.

- **Dissolved and vapor phase plume characterization**

Dissolved and vapor impacts at greater distances or different locations than expected may be an indicator of an LNAPL intersecting a preferential pathway.

What information might already exist about a site that would help answer this question? Read More

Information included in the Phase I environmental site assessment (ESA), including local and regional geology, is often sufficient to provide a reasonable understanding of any anthropogenic preferential pathways. When combined with initial delineation activities (e.g., Phase II investigations or initial site characterization), Phase I ESA information can then be used to screen for the preferential pathways as a receptor or migration pathway.

What is the minimum information that might answer this question and what would that simple LCSM look like? Read More

Where no pathways exist, the pathways do not lead to receptors, or the LNAPL body does not intersect pathways, the information above is sufficient; where the potential exists, then additional investigation using a systematic elimination approach is often needed. This can include sampling alternate pathways to confirm they are not a complete pathway if a receptor is known to be impacted. Reporting includes a narrative, maps, cross-sections, site setting information, and soil borings.

What are more detailed data that might answer this question and what would that more complex LCSM look like? Read More

While the minimum consists of site setting review, LNAPL body, and dissolved and vapor phase extents, any remaining uncertainty related to risk and preferential pathways could be addressed with additional lines of evidence that provide confidence and utilize the existing sampling network (e.g., a period of resampling of wells and receptor points). Additional borings utilizing standard or high resolution tools, or a sampling frequency based on seasonal or other expected changes in transport potential, may be required.

What additional data is appropriate for the next steps in the evolution of the LCSM (i.e., remedy selection LCSM, remedy performance LCSM)? Read More

A higher density of data points that characterize the site’s heterogeneity in addition to modeling, pilot studies, or bench scale studies may be required due to the added complexity of a site where preferential pathways dominate.

3. How does stratigraphy relate to affecting impacts and potential migration? ▼*Read more*

What will this tell me about the LNAPL body? Read More

Soil type variations can influence the distribution of LNAPL as well as contaminant migration pathways. The depositional environment may result in natural anisotropy that can be inferred from existing geomorphology and regional geologic literature. Many physical soil properties can be estimated via visual logging, cone penetrometer, hydraulic profiling, and/or grain size analysis.

How is the answer informed by the below categories? Read More

- **Site geology and hydrogeology**

Site geology and hydrogeology provide a framework for understanding the preferred distribution of LNAPL upon being released to the subsurface. Typically, coarser materials are preferred over finer-grained. In addition, the confined/unconfined state of the impacted aquifer unit(s) stratigraphy should be understood. Areas of perched groundwater that are impacted with LNAPL can also serve as sources to underlying aquifer units.

- **LNAPL body spatial distribution/extent**

The extent of LNAPL compared to geology/hydrogeology and other site features will highlight the pathways of highest migration potential. Areas of higher permeability soils typically allow for a larger spatial extent of an LNAPL body than low permeability zones. In addition, the confined/unconfined state of the impacted aquifer unit(s) stratigraphy are important to understand as increases in gauged LNAPL thickness may be correlated to water table fluctuations rather than migration. Water table fluctuations can result in intermittent and non-uniform LNAPL occurrences for unconfined, perched, and confined conditions; in such instances, mobile LNAPL distribution will not be uniform and may be intermittent.

- **LNAPL mobility**

Evaluation of LNAPL mobility alone does not give a direct indication of LNAPL migration. Migration is the result of LNAPL being transmissive, exposed to a gradient such that the overall flux is greater than the total losses. The assessment of LNAPL mobility needs to be combined with other quantified factors.

Monitoring the magnitude of LNAPL mobility over time and accounting for seasonal water table fluctuations can be useful in monitoring plume stability. LNAPL mobility can be quantified using field transmissivity tests (Transmissivity Appendix). Quantification of mobility using gauged LNAPL thickness and soil capillary and permeability properties, combined with LNAPL physical fluid properties and LNAPL saturation soil samples, can support field transmissivity testing, but are difficult to utilize alone for quantifying LNAPL mobility.

Quantification of LNAPL mobility requires an understanding whether the LNAPL is confined, unconfined, or perched no matter the methodology.

What information might already exist about a site that would help answer this question? Read More

For a new release with no prior investigation, the only information that may be available is a regional geologic map, aerial photography, and possibly some state well reports for water wells located adjacent to the site. The EPA Hydrocarbon Spill Screening Model is also available to screen the vertical migration rates for a given spill (EPA 1997).

Existing boring logs, monitoring well logs, and fluid gauging measurements can be used to evaluate LNAPL body stability (see Section 3.5.2) for previously investigated sites. The boring logs should encompass the aerial and vertical extent of an LNAPL body and dissolved and vapor impacts.

What is the minimum information that might answer this question and what would that simple LCSM look like? Read More

Visual observations from soil borings delineating source areas and dissolved and/or vapor phase can be utilized to confirm and refine the depositional setting suggested from regional soil geology reports. This information would be sufficient to develop cross-sections and a general written description to support answering each of the other questions described in this document.

What are more detailed data that might answer this question and what would that more complex LCSM look like? Read More

As complexity increases or if the project requires a remedy, additional definition of the soil profile using high resolution tools or quantification of soil parameters such as hydraulic conductivity (see Section 4.3) for additional parameters) would be expected.

What additional data is appropriate for the next steps in the evolution of the LCSM (i.e., remedy selection LCSM, remedy performance LCSM)? Read More

Collecting soil, groundwater, and vapor samples from fringes and within source plumes can support improved understanding of dissolved and vapor phase fate and transport and biodegradation processes. A variety of tools exist to develop proper characterization and are further described in Section 4.3.

4. Is the source and extent of the LNAPL known? ▼*Read more*

What will this tell me about the LNAPL body? Read More

Understanding the extent of LNAPL is required to understand the concerns posed by the LNAPL, including potential dissolved, vapor, and surface water concerns. The extent to which LNAPL delineation occurs (i.e., applicability of vertical, up-gradient, downgradient, and side-gradient directions) will be based upon the ultimate remedial endpoints and the scale and potential complexity of the site, subsurface, and LNAPL extent. The source can extend above and below the water table and occur as mobile or residual LNAPL. Residual LNAPL identification requires visual soil logging, shake tests, soil samples, LIF, or alternate forms of delineation.

How is the answer informed by the below categories? Read More

- **Site setting, current and future land use, potential receptors**

The locations of petroleum storage and processing can identify potential release source areas. Building foundations could be barriers to LNAPL migration, building drainage systems may provide preferential migration pathways, locations of operations or buildings can prevent or influence investigations in certain locations, and migration across property boundaries can either prevent investigations in certain locations or make access agreements necessary.

- **LNAPL release details (location, timing, volume)**

Potential release locations are useful starting points to understand where LNAPL could migrate and inform where to focus delineation activities. Where known, the volume and timing of a release can identify if the plume is expected to be stable or migrating. Experience by ITRC LNAPL Update team members indicates that the majority of plumes stabilize within six months to a few years post-release. Ultimately, the time for any release to stabilize is dependent on LNAPL type, loss rate, release rate, and subsurface characteristics.

- **Site geology and hydrogeology**

Site geology and hydrogeology provide clues on the lateral and vertical extent of the LNAPL body because they provide constraints on its migration. For example, fine-grained soil could constrain vertical extent causing perched or confined LNAPL conditions (reference basic concepts). Lateral extent is influenced by locations of more permeable soils and/or pathways.

The LNAPL extent should be considered in context with historical water table elevations, particularly where there have been extreme fluctuations in water level. Additionally, while LNAPL migration is influenced by the groundwater gradient, LNAPL heads during the early stages of release can be sufficient when combined with more permeable soils to allow up-gradient migration during the release.

- **Dissolved and vapor phase plume characterization**

Information on vapor phase characterization can be found in the ITRC PVI guidance document (ITRC 2014). Vapor phase concentrations represent indirect evidence of the presence of LNAPL. Decreasing dissolved phase concentrations or a consistent center of dissolved mass can indicate stability of an LNAPL source body. Increasing concentrations indicate the need to further evaluate stability of the LNAPL source body unless attributable to other factors such as seasonal changes in groundwater flow conditions.

What information might already exist about a site that would help answer this question? Read More

In addition to the LNAPL release details, there may be state records from drinking water well installation, previous environmental investigations, and previous geotechnical investigations at the site or neighboring sites that can be used to show presence or absence of LNAPL.

What is the minimum information that might answer this question and what would that simple LCSM look like? Read More

At a minimum, it is recommended that enough data be collected to understand the spatial extent and critical data gaps be filled. Field screening observations from a tank removal or soil borings are examples of information that could support a simple LCSM. It is suggested that a narrative with plan view and cross-sectional maps that depict the lateral and vertical extent of the LNAPL be developed.

What are more detailed data that might answer this question and what would that more complex LCSM look like? Read More

A more complex LCSM could include three-dimensional representation of the LNAPL body relative to heterogeneous subsurface, key site aspects such as utility corridors, surface water features, and other receptors. A variety of delineation tools and techniques are presented in the LCSM table in Section 4.3.

Because several of these tools are indirect indicators, practical experience in their application may be helpful to properly apply and interpret them.

Are the detailed data more appropriate for the next steps in the evolution of the LCSM (i.e., remedy selection LCSM, remedy performance LCSM)? Read More

Further delineation may include LNAPL body stability evaluations, identification of residual LNAPL areas, and internal delineation of LNAPL components, or potential exposure pathways.

5. Are dissolved or vapor issues expected based on LNAPL composition?▼*Read more*

What will this tell me about the LNAPL body? Read More

Understanding the LNAPL composition and chemical properties, and its effect on dissolved and vapor phase plume concentrations provides data to help interpret and support the assessment of the LNAPL body extent and related risks. When an LNAPL release potentially poses an unacceptable human health or ecological risk, it is often a result of specific components in the LNAPL rather than the magnitude of TPH in soil, the LNAPL saturation, or mobility of the LNAPL (see (ITRC 2018)). Understanding if the LNAPL composition has the potential to or is likely to cause dissolved or vapor issues, helps the practitioner plan site investigation work, collect data to document the dissolved and vapor phase concentrations, and/or collect data to assess remedial technologies that result in composition changes.

How is the answer informed by the below categories? Read More

- **Site setting, current and future land use, potential receptors**

Information on the current and future land use and receptors allows assessment of whether the dissolved and vapor plumes present potential current or future risks, which may influence the need for and prioritization of remedial actions.

- **LNAPL type, composition, physical properties**

Knowledge of the fuel type and composition can be used to estimate the constituents of concern and resulting vapor and dissolved phase concentrations in equilibrium with the LNAPL.

What information might already exist about a site that would help answer this question? Read More

Knowledge of the release details such as the LNAPL type (e.g., gasoline, diesel, heating oil, JP4, crude oil), age (recent release vs. decades-old release), release location, volume, and depth to groundwater can provide general information on the likelihood of dissolved phase and vapor phase issues.

What is the minimum information that might answer this question and what would that simple LCSM look like? Read More

The type and composition of the LNAPL is needed to understand the risk of dissolved and vapor phases that can be expected at a release site. Dissolved phase plumes emanating from LNAPL may be expected:

- in and downgradient from smear zone and saturated zone LNAPL bodies of lighter and more soluble hydrocarbons;
- below vadose zone LNAPL bodies of lighter and more soluble hydrocarbons; and
- in and immediately downgradient from smear zone and saturated zone LNAPL bodies of less soluble hydrocarbon mixtures.

Vapor phase plumes emanating from LNAPL that have the potential to cause issues if receptors are present may be expected:

- to overlie the LNAPL body where the LNAPL body is within approximately 15 feet of an occupied structure. If the LNAPL body is more than approximately 15 feet below grade then the vapors are likely mitigated (ITRC 2014).
- to overlie dissolved phase hydrocarbon plumes where the water table is within approximately 5 feet of the bottom of building. If the dissolved phase plume is more than approximately 5 feet below grade, then the vapors are likely attenuated.
- where basements or elevator shafts exist below grade; these features should be considered when comparing to the screening distances provided above.

What are more detailed data that might answer this question and what would that more complex LCSM look like? Read More

Detailed estimates of the dissolved phase and vapor phase concentrations can be made based on laboratory analysis of LNAPL samples or soil samples containing residual or mobile LNAPL. The laboratory analysis may characterize the VOC, PAH and bulk hydrocarbon concentrations in aromatic and aliphatic equivalent carbon groups (as recommended by (TPHCWG 1997) and (ITRC 2018)). The calculation of equilibrium LNAPL-water and equilibrium LNAPL-vapor concentrations is based on four-phase partitioning using Raoult's Law.

The results of the vapor phase concentration estimates can be used as input to vapor intrusion models such as BioVapor (API 2010). The results of the LNAPL-water dissolved phase calculations can be used:

- to help interpret groundwater sample data (e.g., assess whether groundwater samples contain LNAPL or polar biodegradation metabolites);
- along with dilution-attenuation factors to calculate groundwater concentrations at specific points of interest; and
- as input for dissolved phase transport models to assess the potential extent of and risk associated with the dissolved phase plumes.

The results of the dissolved and vapor phase concentration calculations can also be used to assess the degree of compositional change required for remedial options relying on compositional changes. In practice, it is likely that the dissolved phase plume delineation would be based on or supported by groundwater sampling.

What additional data are appropriate for the next steps in the evolution of the LCSM (i.e., remedy selection LCSM, remedy performance LCSM)? Read More

Tracking of LNAPL composition over time may assist remedy performance evaluation during the implementation phase.

6. Are dissolved or vapor plumes characterized?▼*Read more*

What will this tell me about the LNAPL body? Read More

The extent and nature of dissolved and vapor plumes may be required to assess the concerns related to the site, and can help inform the practitioner on the presence and location of LNAPL.

How is the answer informed by the below categories? Read More

- **Site setting, current and future land use, potential receptors**

Both current and future land use need to be considered in assessing the appropriate extent of dissolved or vapor plume characterization to identify current and future potential receptors.

- **Site geology and hydrogeology**

Geology and hydrogeology are critical considerations in exposure pathway assessment, particularly with respect to transport mechanisms from a contamination source to a receptor exposure point. Additional discussion is provided under the site geology/hydrogeology and preferential pathways discussion.

- **LNAPL mobility**

If LNAPL is migrating, then the delineation of ultimate dissolved and vapor phase plume extents will not be complete until LNAPL migration ceases or its ultimate extent can be confidently projected.

- **Natural degradation processes**

Natural degradation processes are important to understanding the transport of petroleum contaminants from the source to an exposure point for LNAPL, dissolved phase, and petroleum vapor impacts. Natural degradation is further discussed in the NSZD Appendix.

What information might already exist about a site that would help answer this question? Read More

An existing monitoring well network and historical dissolved phase data can provide insights to dissolved delineation as well as LNAPL body delineation. Concentrations that approach the effective solubility or vapor pressure for a given constituent can be a screening level indicator of LNAPL being present near the sample location.

What is the minimum information that might answer this question and what would that simple LCSM look like? Read More

Delineation of affected groundwater to the specified or agreed-upon screening criteria is necessary to develop an LCSM. Screening assessment of potential vapor plumes can be based on depth to LNAPL and LNAPL composition, and depth to water and constituents of concern (COC) concentrations in groundwater.

What are more detailed data that might answer this question and what would that more complex LCSM look like? Read More

If distance-based screening of LNAPL and/or groundwater data indicates a potential vapor intrusion concern, the LCSM may require soil gas, sub-slab gas, or indoor air data to fully evaluate vapor intrusion potential. As site geology complexity increases, additional delineation points may be required (e.g., membrane interface probes, wells, etc.). Multiple sources could create the need for specialized sampling techniques such as forensic compositional analyses or compound specific isotope analyses.

What additional data is more appropriate for the next steps in the evolution of the LCSM (i.e., remedy selection LCSM, remedy performance LCSM)? Read More

Dissolved gases and higher vertical resolution COC sampling may be utilized for enhanced understanding of biodegradation mechanisms and remedy performance.

7. Do soil or groundwater concentrations exceed criteria? ▼*Read more*

What will this tell me about the LNAPL body? Read More

The presence of COCs in soil, groundwater, or soil vapor at concentrations exceeding applicable criteria at compliance points identifies the need for remediation or alternate protection of receptors, in addition to remediation or control of the LNAPL source.

How is the answer informed by the below categories? Read More

- **Site setting, current and future land use, potential receptors**

Soil concerns apply primarily to the original LNAPL release point or when the LNAPL smear zone is shallow enough for potential receptor contact (e.g., future construction workers). Soil vapor should be assessed in consideration of existing or future planned buildings. Groundwater can be assessed in consideration of groundwater usage and ecological concerns.

- **LNAPL release details (location, timing, volume)**

Understanding the location, timing, and volume of an LNAPL release will help the investigator understand the potential for soil and dissolved phase impacts. If the release duration was short and/or volume was small, the extent of lateral and vertical delineation of soil or groundwater impact may be reduced. However, as the duration and size of the release grows, the extent of impact may increase. If the release is older than one year, then NSZD processes require consideration to assess plume stability (NSZD Appendix). Areas of perched LNAPL or groundwater may serve as sources to underlying aquifer units.

- **Natural degradation processes**

Understanding the occurrence and impact of natural degradation processes under site-specific circumstances is useful for assessing long-term plume behavior and risk. At any given location, natural degradation processes can result in significant reductions in dissolved or vapor phase COC concentrations over periods of time that are relevant to risk-based site management. While natural processes may effectively restore aquifer conditions, if receptors are currently exposed to unacceptable risks, it is not advised to solely rely on natural degradation processes for protection.

What information might already exist about a site that would help answer this question? Read More

Existing dissolved phase data provide direct evidence of groundwater concentrations. Depths to soil or groundwater impacts can be compared to screening distances for PVI. LNAPL compositional data can help estimate the likelihood of environmental media having COC concentrations above applicable criteria. For more information on this aspect, refer to Question 5: Are dissolved or vapor issues expected based on LNAPL composition?

What is the minimum information that might answer this question and what would that simple LCSM look like? Read More

Soil and groundwater concentrations require comparison to applicable screening criteria. The groundwater and LNAPL source depths relative to existing buildings are needed to screen PVI concerns. Note that some regulatory agencies may also require vapor assessment data.

What are more detailed data that might answer this question and what would that more complex LCSM look like? Read More

Exceeding applicable criteria may trigger the need for more refined delineation of the extent of impact. Quantification of remedy performance is beneficial when a remedy is implemented to address exceeded values at compliance points. The LCSM can be further developed to provide quantitative and qualitative indicators of the potential performance of various remedial mechanisms to support remedial selection. Section 6 and the LNAPL Technologies Appendix can provide more information on data needs for a more complex LCSM as a site moves toward a remedy.

What additional data are appropriate for the next steps in the evolution of the LCSM (i.e., remedy selection LCSM, remedy performance LCSM)? Read More

Tracking changes in soil or groundwater concentrations over time can be useful for assessing remedy performance.

8. Are exposure pathways complete or incomplete? ▼*Read more*

What will this tell me about the LNAPL body? Read More

Assessing the completeness of an exposure pathway will help the investigator prioritize actions related to LNAPL characterization and corrective action.

How is the answer informed by the below categories? Read More

- **Site setting, current and future land use, potential receptors**

Receptors may be broadly defined as persons, structures, utilities, surface waters, water supply wells, and sensitive environments that are adversely affected by a release under current conditions, or that could be adversely affected under future conditions (ASTM 2015). It is recommended that long-term land use within the area of actual or potential impact be considered in assessing exposure pathways under future conditions.

- **LNAPL release details (location, timing, volume)**

Details about the timing and extent of the LNAPL release can be useful for understanding the LNAPL body stability. Read More

- **Site geology and hydrogeology**

An understanding of the maximum extent of dissolved and vapor phase plumes is important for analyzing the exposure pathway. If LNAPL is present at mobile saturations, the potential exists for further LNAPL migration. If NSZD rates are not greater than the LNAPL mass flux from the source, then migration may occur.

- **Natural degradation processes**

Natural degradation processes are often central to understanding whether contaminants can migrate from the source to an exposure point. For example, sufficient dissolved phase plume characterization will often demonstrate the plumes are at a steady-state or declining status by virtue of natural attenuation processes, and therefore will not migrate to distal exposure points. Analysis of soil gas samples and/or comparison with screening distances can demonstrate whether bioattenuation will prevent sources of soil vapor from impacting overlying structures.

What information might already exist about a site that would help answer this question? Read More

Some LNAPL release sites come into the corrective action process because of concerns such as impacts to private water wells or sheen discharge to surface water. In these cases, it is important to focus the initial site assessment on the confirmation or refutation of complete exposure pathways because of specific LNAPL sources.

What is the minimum information that might answer this question and what would that simple LCSM look like? Read More

For an exposure pathway to be complete, the following five exposure elements must be in place: 1) contaminant source or release, 2) migration through an environmental medium, 3) contaminant presence at an exposure point, 4) route of receptor exposure, and 5) potentially exposed receptor population (ATSDR 2005). These are the minimum aspects of the LCSM that must be understood to identify concerns and develop corrective action objectives.

What are more detailed data that might answer this question and what would that more complex LCSM look like? Read More

The existence of a complete exposure pathway does not necessarily equate to an unacceptable risk that requires corrective action. In these cases, additional data may be required to understand the significance of the exposure and the resulting health risks.

What additional data is appropriate for the next steps in the evolution of the LCSM (i.e., remedy selection LCSM, remedy performance LCSM)? Read More

If receptor assumptions should change during the course of the remedy or after remedy completion, the LCSM and remedy protectiveness may need reevaluation.

🟧 9. Is the LNAPL body stable? ▼Read more

What will this tell me about the LNAPL body? Read More

An evaluation of LNAPL stability can provide key information for understanding potential risks and assessing LNAPL management alternatives. Demonstrating that an LNAPL body is stable and no longer expanding ensures that new risks will not occur in the future as the result of LNAPL migration into new areas. Determining whether there is potential for future expansion of the LNAPL body may be critical when assessing the need for a mass control remedy, or evaluating the potential effects of turning off an existing recovery or mass control system.

LNAPL stability is typically evaluated using multiple, complimentary lines of evidence, where agreement between multiple methods builds confidence in the conclusion. Examples of LNAPL stability lines of evidence highlighting key data requirements, relative weighting, and a brief summary of cautions for each line of evidence are presented in Table 4-1.

How is the answer informed by the below categories? Read More

- **Site setting, current and future land use, potential receptors**

Facility operational history can give an indication of stability. Sites that have been inactive for several years with complete petroleum storage removal are less likely to exhibit migration because any release would be historical in nature. Assessing LNAPL stability provides a basis for evaluating potential exposure pathways under current and future land use conditions. If LNAPL and associated vapor and/or dissolved phase plumes are stable and do not present unacceptable risks under current conditions, then unacceptable risks in the future are unlikely under current hydrogeologic conditions.

- **LNAPL release details (location, timing, volume)**

Knowledge of LNAPL release location, type, volume, age, and duration often provides useful information to support interpretation of LNAPL distribution and stability. The release point location relative to the position of the leading edge or the LNAPL body's center of mass, along with the release duration, can be utilized to place reasonable bounds on LNAPL migration history. Additionally, the time elapsed since the release provides a useful, qualitative line of evidence when assessing LNAPL stability, as LNAPL bodies originating from older releases are more likely to be stable than more recent releases because of dissipation of LNAPL head over time, smearing of LNAPL to residual levels, and mass depletion through remediation and/or NSZD processes.

- **Site geology and hydrogeology**

Site geology and hydrogeology influence how LNAPL and other fluids behave upon being released to the subsurface.

- **LNAPL body spatial distribution/extent**

Mapping of the current and historical distribution of LNAPL, permeable zones, and stratigraphy can provide direct evidence of recent and/or historical LNAPL body expansion. The distribution of LNAPL can be evaluated using multiple data types, including visual observations from current and historical soil borings, fluid level gauging data, laser-induced fluorescence results, and laboratory analytical soil data.

- **Dissolved phase plume characterization**

Temporal trends in dissolved phase concentrations of LNAPL constituents can be evaluated to infer LNAPL body extent over time when compared to effective solubility values. Additionally, dissolved phase trends can be evaluated statistically to infer LNAPL body stability. A stable or contracting dissolved phase plume suggests a stable or contracting LNAPL body. Table 4-1 provides additional detail on the use of dissolved phase plume stability data as a line of evidence for inferring LNAPL body stability.

- **LNAPL type, composition, physical properties**

LNAPL composition and weathering patterns over time can be used to verify release sources. LNAPL density and viscosity are fundamental to calculations involving LNAPL conductivity/velocity potential, while knowledge of fluid interfacial tensions provide data that can be used to evaluate LNAPL pore entry pressures.

- **LNAPL mobility**

The lack of mobile LNAPL (i.e., accumulations in wells) or LNAPL at low transmissivity values are indications that the majority of the LNAPL is at or close to residual saturation. This is a qualitative measure of plume stability. LNAPL transmissivity is best applied towards plume stability when combined with NSZD loss rates and gradient (see below).

- **Natural degradation processes**

LNAPL losses through NSZD processes act to limit LNAPL flux from the interior of an LNAPL body. At some threshold, NSZD rates will match or exceed rates of lateral expansion and the LNAPL body will stabilize and/or contract. Quantification of LNAPL loss rates through NSZD processes can be evaluated in conjunction with LNAPL flux toward the leading edge of the LNAPL body using a mass balance approach to evaluate LNAPL stability (Mahler, Sale, and Lyverse 2012). Table 4-1 provides additional detail on the use of NSZD results as a line of evidence for inferring LNAPL stability.

What information might already exist about a site that would help answer this question? Read More

Data collected during routine monitoring activities near the leading edge of an LNAPL body, (e.g., well gauging and dissolved phase concentration data) are often available at existing sites. These data, assuming adequate spatial coverage and sufficient temporal data density, provide direct field observations of LNAPL migration/stability. Table 4-1 provides examples of the use of temporal trends in well gauging and dissolved phase concentration data as lines of evidence for assessing LNAPL stability. Additionally, a boring log from an existing monitoring wells (MW) that indicates past LNAPL presence (e.g., soil staining), but currently contains no in-well LNAPL is useful evidence of NSZD.

What is the minimum information that might answer this question and what would that simple LCSM look like? Read More

Table 4-1 presents common lines of evidence used to assess LNAPL stability. Typically three or more of these lines provide sufficient evidence to demonstrate stability (or instability). A minimal LCSM may only include well gauging data, dissolved phase plume data, and age of release.

What are more detailed data that might answer this question and what would that more complex LCSM look like? Read More

A more detailed LCSM may include several of the lines of evidence presented in Table 4-1. Depending on the proximity of potential receptors and the significance or consequences of LNAPL migration, a more detailed assessment may include data collection at higher spatial and or temporal resolution to demonstrate stability at a scale that is commensurate with the level of detail required to support informed LNAPL management decisions.

Table 4-1. LNAPL migration lines of evidence.

View Table 4-1 in Adobe PDF format.

10. Is the mobile LNAPL hydrogeologic condition known? ▼Read more

What will this tell me about the LNAPL body? Read More
Understanding hydrogeologic conditions that influence LNAPL mobility are important to developing a comprehensive LCSM. This includes determining whether the LNAPL is present under confined, unconfined, or perched condition as it affects the interpretation of site data (e.g., what does the in-well LNAPL thickness represent?), mobility/recoverability, and site management/remedial strategy.
How is the answer informed by the below categories? Read More

- **Site setting, current and future land use, potential receptors**

Certain site conditions may have impact on flow conditions and changes to these conditions may alter LNAPL mobility. These conditions include the presence of a surface impoundment or pond, climatic influences, or even the presence of treatment systems that can alter groundwater flow patterns.

- **Site geology and hydrogeology**

Question 3 discusses the importance of site geology and hydrogeology to LNAPL mobility.
What information might already exist about a site that would help answer this question? Read More
Soil boring data will provide initial information on the site lithology. If the site investigation is older, there may also be years of fluid level gauging data. In addition, release data, if available, can provide the LNAPL properties important to assessing the mobility.
What is the minimum information that might answer this question and what would that simple LCSM look like? Read More
Understanding hydrogeologic conditions that influence LNAPL mobility are important to developing an LCSM. At a minimum, this would include fluid levels over multiple years and/or seasons, lithology, and aquifer type (perched, confined, unconfined). Some basic estimated LNAPL properties may be known, either through direct measurement (e.g., viscosity and specific gravity), or based on composition of the release.
What are more detailed data that might answer this question and what would that more complex LCSM look like? Read More
More detailed data on the physical properties of the matrix such as hydraulic conductivity, grain size, residual water saturation, and capillary properties (i.e., van Genuchten, or Brooks-Corey models) representative of variations at the site may help refine understanding of the LNAPL saturation, transmissivity, velocity, and associated plume migration/dissolution. It may also be important to characterize LNAPL properties such as specific gravity, viscosity, and interfacial tension. Sufficient core and LNAPL samples may be collected and analyzed to characterize these physical properties. LNAPL baildown tests can also be a useful tool in determining matrix and LNAPL properties as well as LNAPL transmissivity (Transmissivity Appendix).
What additional data are more appropriate for the next steps in the evolution of the LCSM (i.e., remedy selection LCSM, remedy performance LCSM)? Read More
Over the course of remedy implementation, changes in groundwater elevations may impact plume migration by exposing mobile LNAPL to different stratigraphic units, and can impact groundwater flow and LNAPL flow patterns and directions. Seasonal impacts of rainfall and evaporation can induce these changes. Variations in groundwater elevations can change the extents of exposed and submerged LNAPL along the capillary fringe and impact NSZD processes. Variations in groundwater elevations may also impact groundwater velocities and LNAPL migration rates. Therefore, it is important to continue to collect and review seasonal/historical groundwater data and associated flow patterns. Time series plan view maps should be constructed to assist with this understanding.
It is also important to understand the presence of any groundwater sources and sinks. Areas of discharge to surface water bodies should be identified along with groundwater withdrawn from pumping for domestic and agricultural purposes. These features may influence LNAPL migration patterns and present receptor exposure pathways. If an area impacted by LNAPL fluctuates between unconfined, semi-confined, and/or confined, it may present unique challenges for LNAPL remediation. It is recommended that these situations be identified in the LCSM.

4.3 LNAPL Tools

Table 4.2 provides additional tools available to characterize a given component of the LCSM. Within the table, each tool typically includes a reference for the method and a brief description. The notes provide insights regarding recently improved best practices for tool selection at sites. It is the intent of this guide to identify available tools and provide an improved understanding of their use where existing standards or literature is not available or an update is needed.

Table 4-2. LNAPL tools for characterizing LCSM components.

View Table 4-2 in Adobe PDF format.

4.4 Remedy Selection LCSM

The Remedy Selection LCSM is utilized to support selection of a remedial technology(ies) and/or controls by characterizing aspects of the LNAPL and site subsurface relative to the potentially employed remedial mechanisms. Update the Initial LCSM (e.g., by pilot testing or detailed/spot assessment) to confirm the site is adequately characterized to screen technologies to address concerns.

The questions described in this section were designed to guide an investigator through the key components of developing the technology evaluation portion of the LCSM. This represents the middle steps shown in Figure 4-1 which seek to review the Initial LCSM and remediation objectives and select the most appropriate means for LNAPL remediation or control. While there are many questions that can be answered for a site, not all are necessarily relevant or required depending on the level of detail required for the LCSM. The questions in this section are widely applicable to LNAPL sites as they generally have to be answered to develop the LCSM for understanding concerns, risks, and LNAPL source distribution—from the most general (green) to more LNAPL specific concepts (brown). Note that the discussion of the questions below are applicable to unconsolidated, bedrock and karst; however, further detail on LNAPL occurrence in fractured rock is provided in the Fractured Rock Appendix.

🟩 **1. Where is the source mass?** ▼*Read more*

The goal of this question is to understand how the water table, subsurface geology, preferential pathways, and the LNAPL distribution (mobile vs. residual) will affect the application of a technology.

🟩 **A. Homogeneous Permeable Soil** ▼*Read more*

Multiple technologies are effective in homogeneous higher permeability soils. The primary improved LCSM would rely on further understanding the residual versus mobile fractions and distribution relative to the water table to ensure optimal remedial technology selection. The use of high resolution approaches—core photography, cone penetrometer tool, hydraulic profiling tool, or detailed visual soil boring logs—have revised several conceptual models where prior soil boring data did not give sufficient credit to variability that was significant for LNAPL source zone behavior. Thin seams of fine-grained layers that separate sand layers that can also behave as competent confining layers may be missed in less detailed visual soil boring logs and electrical conductivity logs.

🟩 **B. Interbedded Soil** ▼*Read more*

In the event of concerns that require remediation and careful evaluation of the source distribution relative to the finer grained layers and more permeable layers, it is important to recognize that most technologies will be focused on the more permeable zones and have less influence on the finer grained layers. Note that sand layers and gravel layers can exhibit permeability values varying over three orders of magnitude. Understanding the distribution of more permeable layers relative to LNAPL impacts and connectivity will ensure that the remedial design will target the correct intervals. High-resolution approaches for both the LNAPL and soil profile are critical to identifying heterogeneity in the source area.

🟩 **C. Within low permeability media, secondary porosity, fractures** ▼*Read more*

The lower the permeability, the more difficult it is to reduce the LNAPL source mass. LNAPL in fine-grained media often occurs in macro pores or secondary porosity when considering unconsolidated sites. The small pore spaces of the primary pore matrix, combined with sufficient moisture content, result in a large barrier to LNAPL migration; however, secondary porosity features can transport LNAPL vertically or horizontally more easily. The presence of confined or perched conditions should also be considered. High-resolution approaches may be worthwhile, but in many cases cannot substitute for detailed visual logging and core photography because secondary porosity in unconsolidated materials is not necessarily detectable by a cone penetrometer tool, a hydraulic profiling tool, or electrical conductivity.

D. Is the LNAPL source distributed above or below the water table? ▼*Read more*

Characterizing the distribution of LNAPL sources relative to the water table ensures that the source of vapor and/or dissolved phase risks is properly identified.

Combining the hydraulic profiling tool or cone penetrometer tool with LIF can give a good overall picture of LNAPL distribution or a detailed look at a single boring with respect to the water table (see Figures 4-3 and 4-6). This is particularly important in confined LNAPL situations, where a remedy (e.g., SVE) may erroneously be applied opposite the confining layer (correlated to the top of the gauged thickness interval) instead of targeting the lower sand that is the actual source of LNAPL.

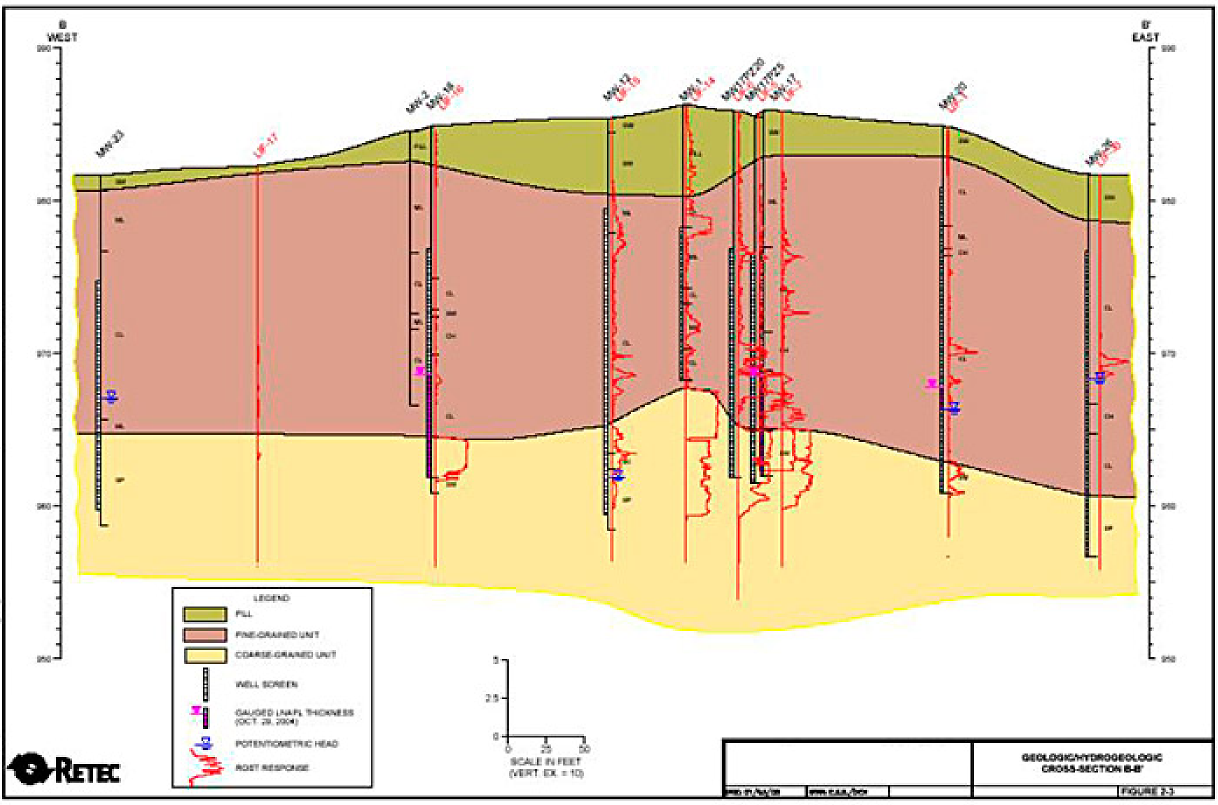


Figure 4-3. Cross-section using soil profiles with LIF.

The cross-section in Figure 4-3 illustrates that the gauged LNAPL thickness in MW-2 rises into the overlying clay is misleading due to confined conditions. The LIF more accurately identifies that the majority of impacts are in the sandy confined aquifer. Similarly, the LNAPL near well MW-1 in the center, while near a topographic high in the sand, is likely confined although shallow impacts within the finer grained layers will likely remain post-treatment of the sand. The data shown in Figure 4-3 identifies the distribution of LNAPL more accurately and demonstrates why gauged LNAPL thicknesses are misleading where confining conditions are present. Any required remediation at this site would need to consider multiple soil types and saturated zone treatment. This site was granted closure with no further action based on exhibited low LNAPL transmissivity values, gauged LNAPL thicknesses that were indicative of confining conditions, non-recoverability of LNAPL, and a stable dissolved phase plume with no receptors.

Evaluating LNAPL distribution goes beyond determining a bulk TPH concentration or LNAPL measurements since a historical release may have exhibited different natural weathering/biodegradation rates above and below the water table. More complex sites may benefit from more detailed soil analysis to identify specific zones that are higher in COC concern, such as BTEX.

Gauged LNAPL thickness in monitoring wells has often been a prioritized piece of data for LNAPL sources zone identification and remedial decision making. Gauged LNAPL thickness is easy to conceptualize and can be frequently monitored. As a result, technologies have often been focused on the mobile LNAPL via hydraulic recovery. Mobile LNAPL can generally be well characterized as utilizing gauging data representative of equilibrium conditions combined with subsurface geologic characterization. A comprehensive approach to identifying residual and mobile source areas allows a practitioner to better target remediation to achieve remedial goals and provide context on the effectiveness of LNAPL recovery. Characterization techniques for both the mobile and residual source zone have improved. Mobile LNAPL is now understood to exist in unconfined, confined, and perched states, as well as in secondary porosity. Residual smear zones are difficult or costly to routinely monitor over time although there are screening approaches (See Table 3-2, e.g., PID, visual observations, temporal evaluation, or vapor and/or dissolved phase indicators) as well as more definitive approaches (e.g., LIF, shake tests, TPH analysis) for soil borings that can be used for characterization and delineation.

2. What is the nature of the source? ▼*Read more*

This question considers the chemical nature of the source LNAPL relative to the available remedial mechanism. The prior question primarily addressed the physical nature of the LNAPL and source removal via extraction. An alternate aspect of LNAPL remedial technologies relates to the chemical nature of the LNAPL and its mobility where the highest potential removal rates may be through a hydraulic gradient, a vapor removal mechanism, solubilization, or biodegradation, and taking into account the limits of these mechanisms. These questions may be too detailed if excavation is the presumptive remedy and alternate details may be required if surfactant flushing or steam is the recommended approach.

A. Volatile and/or Soluble ▼Read more

Is the LNAPL source volatile and/or soluble?

Where a remedial technology encourages in situ destruction or removal of a hydrocarbon constituent via induced partitioning, the chemical nature of the LNAPL affects remedial performance. As discussed in Section 3.2, the concentration of a constituent in LNAPL is directly related to its vapor or dissolved concentration as described by Raoult’s Law. Therefore, if soil vapor extraction is being used, its efficacy can be forecasted using the LNAPL composition. Figure 4-4 provides an example composition of regular grade gasoline as it evaporates. The data illustrate that after 95% of the mass has evaporated, primarily 1,2,4 trimethylbenzene through naphthalene remain. The textbook vapor pressure of 1,2,4 trimethylbenzene and naphthalene at 37 degrees Celsius is near or less than 0.12 pounds per square inch (psi). In contrast, the vapor pressure of gasoline is typically 7.8 to 13.5 psi at similar temperature and pressure. Thus, the efficacy of volatilization to remove 1,2,4 trimethylbenzene and naphthalene is reduced by two orders of magnitude. Naphthalene and trimethylbenzene compounds are biodegradable, which may make it worthwhile to also evaluate the biodegradation potential in order to estimate a technology like biosparging or bioventing to achieve further degradation of the gasoline.

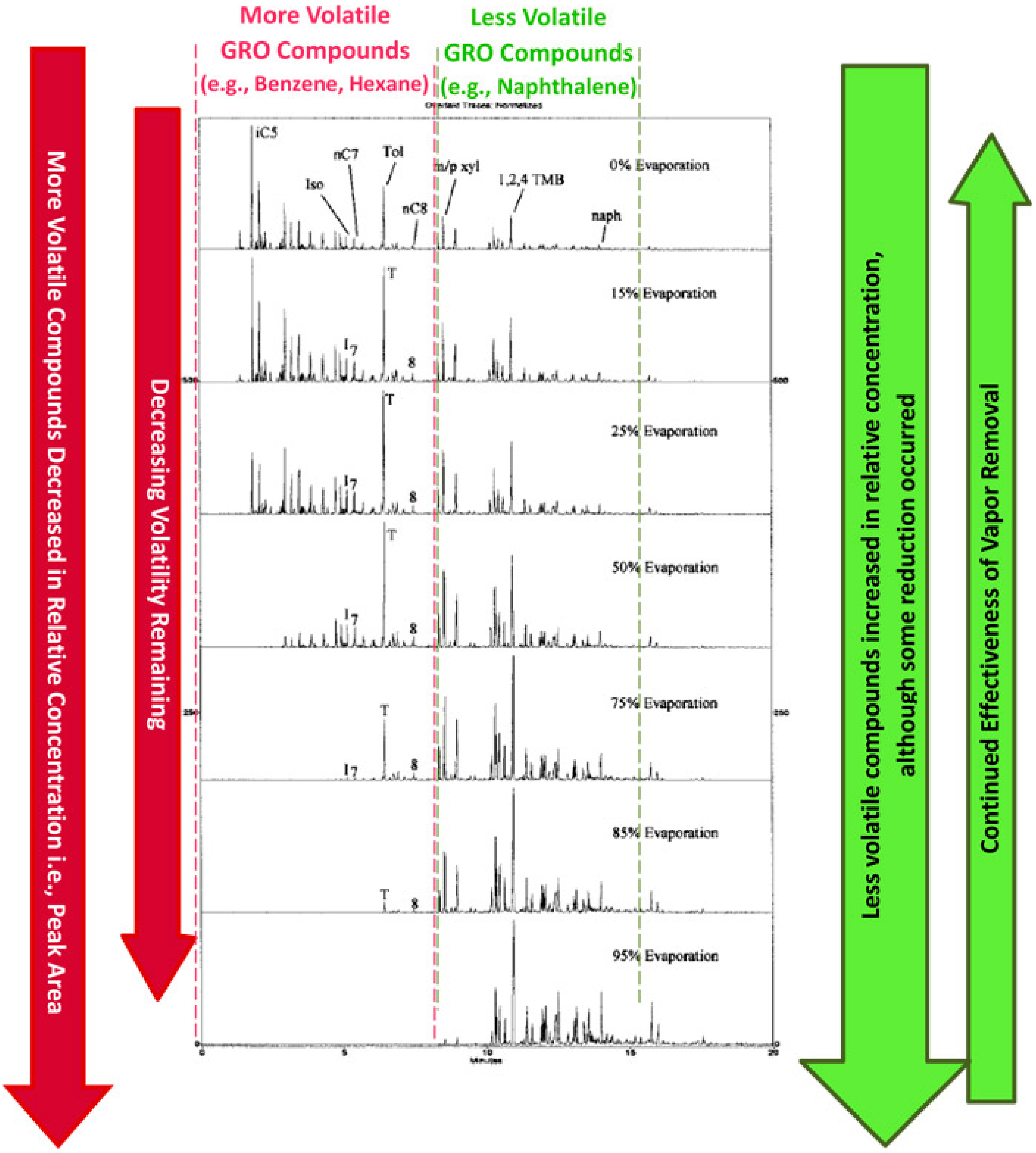


Figure 4-4. Gas chromatogram data chart (left) and simplified LNAPL composition bar chart (Right) illustrate change in LNAPL composition with increasing evaporation (Figure from (Schmidt, Beckmann, and Torkelson 2003)).

B. Biodegradable ▼*Read more*

What is the efficacy of biodegradation?

Figure 4-5 represents the remedial performance of LNAPL recovery, vapor recovery, and biodegradation from a multi-phase extraction system. Overall biodegradation was the dominant component. LNAPL recovery was the least efficient, although initially LNAPL appeared to be the most promising.

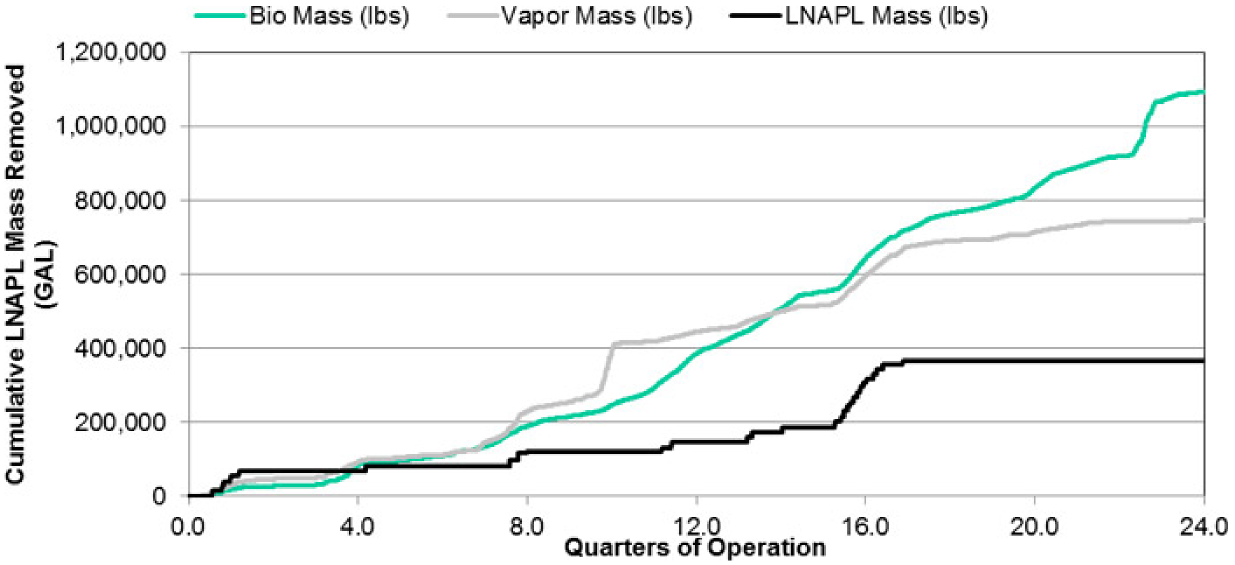


Figure 4-5. Remedial rate data from a multi-phase extraction system operating at a site with gasoline range LNAPL (unrefined product).

Characterizing the extent of LNAPL transmissivity, biodegradation rate, and vapor removal rates spatially, as well as at individual points, can help forecast longevity of a given mechanism. In this case, LNAPL recovery may not have been required and more resources could have been applied towards the biodegradation mechanism if additional up-gradient investigation had been performed. The LNAPL recovery decision here was based on mobile LNAPL in the recovery wells with no up-gradient testing of LNAPL transmissivity.

For sites with LNAPL occurrence and risk-based concerns, there are technologies that can potentially address both types of concerns.

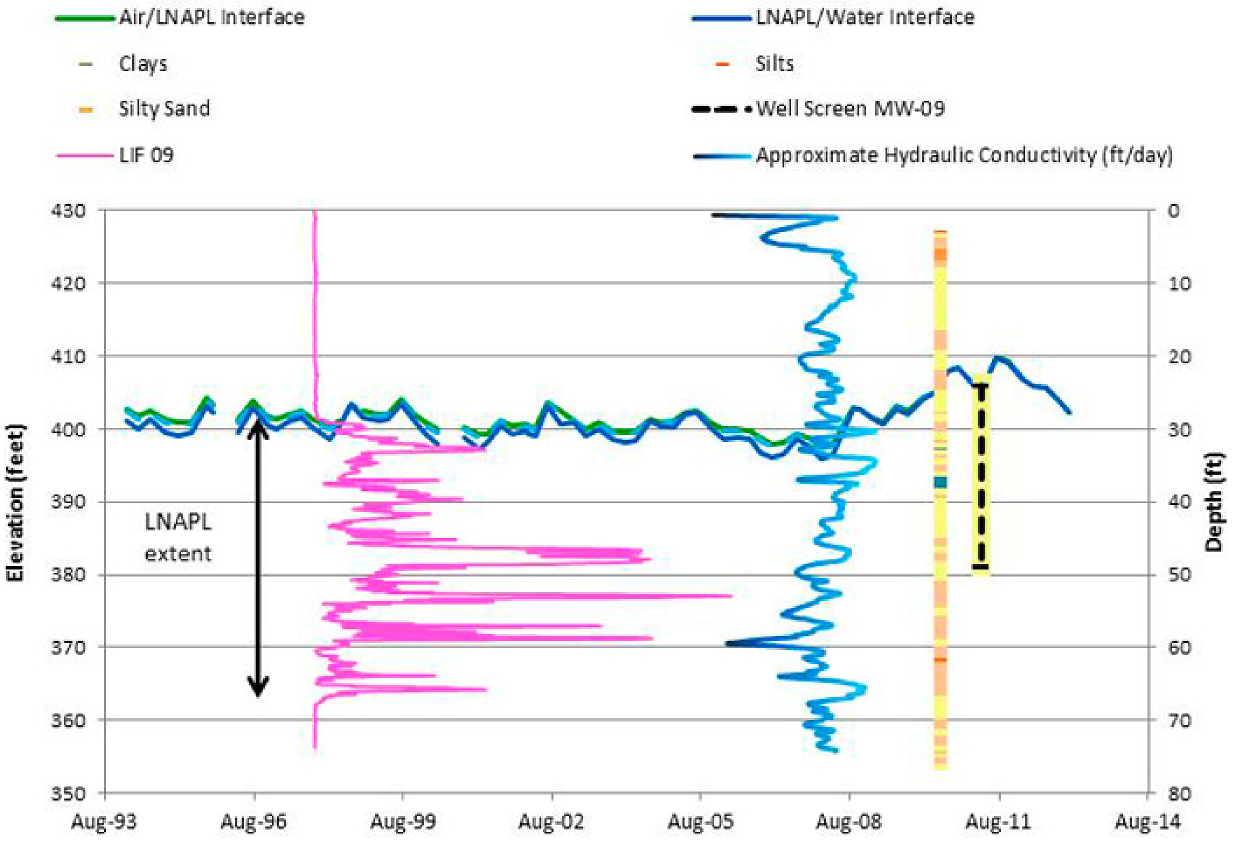


Figure 4-6. Hydrograph with well screen, LIF, hydraulic conductivity log, and soil profile (from cone penetrometer tool).

C. Mobile vs. Residual Fractions ▼*Read more*

What are the fractions of mobile and residual LNAPL?

Due to heterogeneity in the subsurface, it can be difficult to quantify the residual and mobile fractions within 10 percent of the actual value. However, improved investigation tools do allow for more gross estimates, which are often sufficient to identify when residual dominates the source area, and when it is worthwhile to reduce the mobile fraction. Understanding these fractions improves the technology selection and allows the practitioner to evaluate the value of generating additional groundwater waste during mobile LNAPL recovery or if vapor enhanced recovery is preferred. Where residual LNAPL dominates, it may be preferable to focus resources towards the residual or both the mobile and residual fractions.

The data in Figure 4-6 illustrates that measurable LNAPL thickness can exist for potentiometric surface elevations below approximately 403 feet. If only this fact is considered for LNAPL source removal (i.e., skimming), the 35 feet of LNAPL identified below the water table by the LIF would be missed by the remedy, resulting in continued risk and an increased time to achieve remediation objectives.

When considering how to estimate the mobile and residual fractions shown in Figure 4-6, a variety of methods exist. While analytical soil TPH results above, at, and below the water table will give a good indication of relative fractions, this method can be costly.

Another line of evidence utilizes LNAPL transmissivity. LNAPL transmissivity values at this site are in the range of 0.1 to 0.8 ft^2/day indicating that the majority of mass at the site is residual.

Seasonal fluctuations can affect the mobility of the LNAPL as well as distribution relative to the water table. Seasonal low water tables for unconfined sandy settings can result in submerged LNAPL becoming mobile. Quantification of this seasonality will help understand if recovering in low water level periods is beneficial to achieve remedial goals. Additionally, vapor removal and biodegradation rates for soil vapor extraction and bioventing have been observed to increase during seasonal water table lows. Understanding the period of improved availability and magnitude of improved LNAPL remediation rates is important to evaluating if a change in remedial approach due to seasonal differences is needed. The API NSZD Guidance (API 2017) encourages seasonal measurement of passive biodegradation mechanisms via NSZD rate measurement to understand this mechanism more fully and the benefits to site remedial goals.

3. What is achievable for a given technology? ▼*Read more*

Knowing the limitations of a technology and what LNAPL fractions will remain when that limit is reached helps to set expectations for remedial outcomes and whether additional technologies are needed.

A. Mobility Based Limit ▼*Read more*

What is the mobility based limit?

LNAPL recovery theoretically can remove the entire mobile fraction of LNAPL, which results in a limit at residual LNAPL saturation or zero LNAPL transmissivity. However, the asymptotic nature of LNAPL recovery results in a higher limit of LNAPL recovery, representing 0.1 to 0.8 ft^2/day LNAPL transmissivity. At this point, the majority of LNAPL is residual and LNAPL recovery will not continue to meaningfully reduce the source mass.

B. Volatility Based Limit ▼*Read more*

What is the volatilization based limit?

Volatilization remedial mechanisms typically address compounds with lower carbon numbers than C$_{10}$ (i.e., the gasoline range lighter than and including naphthalene). However, data in Figure 4-4, combined with vapor pressure data, indicate that a reduction in mass reduces the volatilization rate of the weathered fraction compared to fresh gasoline. Additional reductions through volatilization may require extended timeframes with little improvement. While volatilization does address both mobile and residual LNAPL above and below the water table, an alternate limit on the application may be the background biodegradation rate or other removal mechanisms.

C. Solubility Based Limit ▼*Read more*

What is the solubilization based limit?

ISCO and co-solvent flushing would have limited effect when used alone on less soluble hydrocarbons. LNAPL analytical data, combined with the distribution of LNAPL, are often sufficient to illustrate that while these technologies may remove mass or further mobilize it for recovery, the costs limits and/or waste management for surfactants often result in these technologies not being selected.

D. Biodegradability Based Limit ▼*Read more*

What is the biodegradation based limit?

Biodegradation is not limited to the light end of the carbon range like solubility or volatility. Biodegradation occurs regardless of carbon number and is more targeted towards molecular structure. Alkanes across a wide range of carbon numbers (i.e., light ends to longer chain alkanes in the C^{40} range) are biodegradable. However, branched alkanes or isoprenoids, asphaltenes, are less easily biodegraded. Variability also occurs due to aerobic and anaerobic degradation processes. Enhanced biodegradation limits are often defined by the magnitude of enhancement versus background degradation rates, as well as comparison to other remedial mechanisms.

Whether the technology focuses on liquid recovery, removal of volatiles, or biodegradation, there are limitations; performance will be dependent on the nature of the hydrocarbon and other physical site characteristics. Technology endpoints are often defined while considering site-specific physical obstructions, background degradation rates, and the nature of the LNAPL impacts. Qualitative methods available to help indicate relative performance rates are outlined in Table 4-3.

Table 4-3. Qualitative methods to indicate relative performance rates

Remedial Mechanism	**Method**
LNAPL Recovery	• 3D source and soil characterization • LNAPL transmissivity values as compared to 0.1 to 0.8 ft^2/day range • Mobile vs. Residual fraction estimates
Vapor Removal Potential	• Site setting knowledge • 3D source and soil characterization • Field headspace screening • LNAPL analytical characterization • Pilot testing
Biodegradation	• NSZD rates represent lower bound for biodegradation • Single well in field respiration testing to represent aerobic potential • LNAPL analytical characterization
Thermal (resistive, radio wave, etc.)	• 3D source and soil characterization • LNAPL analytical characterization
ISCO, Surfactant	• 3D source and soil characterization • LNAPL analytical characterization

Quantified estimates of remedial performance can be completed via pilot testing, additional field characterization and/or modeling. Table 4-4 provides a list of models or analytical methods for evaluating various technology aspects. The accuracy of these estimates is often dependent on the input accuracy and site variability.

Table 4-4. Analytical methods for evaluating technologies

Mechanism or Technology to Estimate	**Applicable Technologies**	**Reference Document(s)**
Diffusive vapor flux	NSZD, background rate for sparging or vapor extraction	• API 4784 (API 2017)
Advective vapor flux	SVE, Bioventing	• ASTM E2531 – Appendix X (ASTM 2014b) • USACE (USAEC 2002)
Respiration Rates	Bioventing, Soil Vapor Extraction, Air Sparging, NSZD	• AFCEE (AFCEE 2004) • USACE (USAEC 2002) • EPA (EPA 1995)
Natural Source Zone Depletion Rates	NSZD, potential lower bound for aerobic technologies (SVE, Air Sparging, Bioventing)	• API 4784 (API 2017) • Vadose Zone Biodegradation Loss model, VZBL (Wilson, Hers, and Jourabchi 2016)
LNAPL Transmissivity	LNAPL Recovery Technologies	• API 4729 (API 2003) • API 4762 (API 2016) • ASTM E2856-13 (ASTM 2013)
Hydraulic control and injection	Mass Control	• Modflow – USGS • Visual AEM University of Waterloo
Vapor Model	See ITRC PVI guidance	• (ITRC 2014)

Printed from: Interstate Technology & Regulatory Council (ITRC). 2018. *Light Non-Aqueous Phase Liquid (LNAPL) Site Management: LCSM Evolution, Decision Process, and Remedial Technologies.* LNAPL-3. Washington, D.C. https://lnapl-3.itrcweb.org.

5. LNAPL Concerns, Remedial Goals, Remediation Objectives, and Remedial Technology Groups

This section describes the decision process for identifying LNAPL concerns, verifying concerns through the application of threshold metrics, selecting LNAPL remedial goals, and determining LNAPL remediation objectives. These steps necessarily precede the selection of LNAPL remedial technologies, and the establishment of associated remedial performance metrics and remediation endpoints. This section also introduces remedial technology groups and the concept of a combined technologies approach.

Figure 5-1 shows the process of identification and verification of LNAPL concerns, and the subsequent selection of remedial goals, remediation objectives, remedial technologies, remediation performance metrics, and remediation endpoints. The following subsections describes each of these steps.

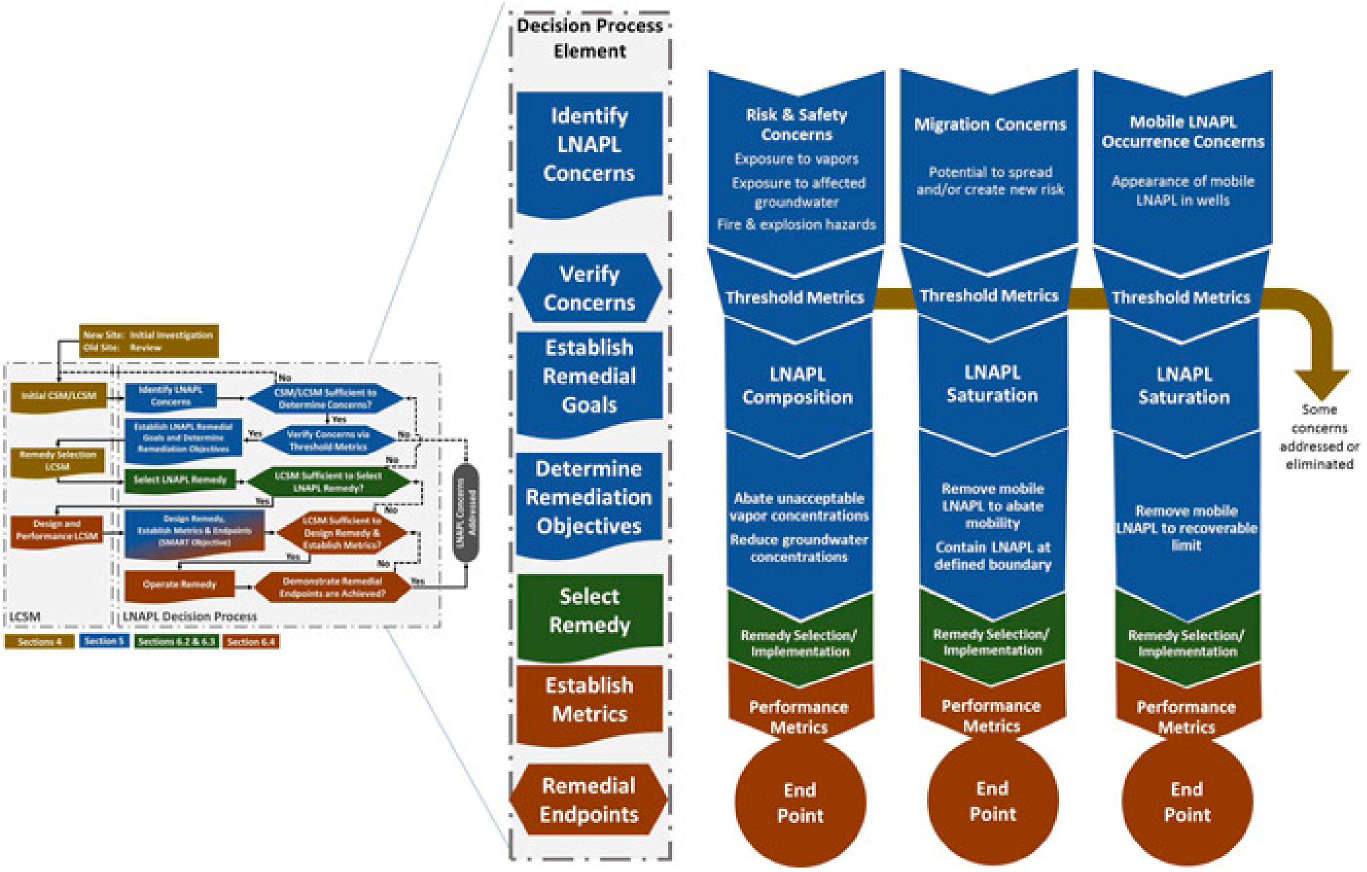


Figure 5-1. Decision process to identify/verify LNAPL concerns and establish remedial goals, objectives, technologies, performance metrics, and endpoints.

5.1 Identifying LNAPL Concerns

An LNAPL Concern is an LNAPL condition or potential condition that could:

- pose a risk to health or safety (composition-based),
- result in additional LNAPL migration (saturation-based),
- address an LNAPL-specific regulatory requirement (regulatory-based), or
- create some other physical or aesthetic impact or other specific regulatory or stakeholder requirements.

A well-developed Initial LCSM should summarize LNAPL conditions and guide the identification and refinement of LNAPL concerns. Some LNAPL concerns may be readily identified in the early stages of site characterization, and others may be identified or further refined following further development of the LCSM.

When LNAPL is present at a site, potential LNAPL concerns tend to fall into four categories:

1. Risk and Safety Concerns –

- Are there human or ecological exposures and risk concerns arising from the presence of the LNAPL?
- Are there potential fire or explosivity concerns associated with the LNAPL?

2. Migration Concerns –

- Is there an ongoing LNAPL release?
- Is there potential for further LNAPL migration, which may create new exposures and risks?

3. Mobile LNAPL Occurrence Concerns –

- Are there LNAPL-specific regulatory requirements, such as removal of mobile LNAPL from existing wells to a defined threshold?

4. Other LNAPL Concerns –

- Are non-risk odors or surficial stains from the LNAPL a potential nuisance?
- Are there geotechnical concerns due to the presence of LNAPL in soil?
- Is stakeholder perception of the occurrence of LNAPL a concern?

The first three categories of concern are shown in Figure 5-1. “Other” LNAPL concerns are not explicitly shown in Figure 5-1, and are covered in less detail in the decision steps discussed below.

5.1.1 Using LNAPL Threshold Metrics to Verify LNAPL Concerns

Once identified, potential LNAPL concerns should be verified, because some concerns may be eliminated or managed without the need for remediation. As part of the verification process, LNAPL concerns may be compared to threshold metrics. A threshold metric can indicate whether an LNAPL concern may be eliminated, or whether it may be appropriate for carrying forward to establish remedial goals, complete a remedial technology selection process, establish remediation objectives, and lastly establish remedial performance metrics and remediation endpoints.

In contrast to performance metrics, which indicate whether a remediation technology is progressing toward its remediation endpoint, threshold metrics are used to indicate whether remediation is warranted or if it can be managed without remediation.

Not all LNAPL concerns will necessitate remediation; therefore, not all LNAPL concerns will generate LNAPL remedial goals and objectives. Verification of LNAPL concerns is a necessary step toward establishing LNAPL remedial goals and determining remediation objectives.

1. The appearance of measurable LNAPL in a monitoring well may be identified as a possible mobile LNAPL occurrence concern, potentially triggering a regulatory requirement to recover LNAPL to the extent practicable. An appropriate verification action would be to compare the measured LNAPL transmissivity in that well to a threshold metric, such as the ITRC-recommended LNAPL transmissivity endpoint range for LNAPL recoverability. If the measured LNAPL transmissivity exceeds the recommended endpoint range, the mobile LNAPL concern would be considered verified, and carried forward for remedial goal and objective development.
2. Buildings overlying an LNAPL body may be identified as a potential petroleum vapor intrusion (PVI) concern. This concern may be verified by comparing the vertical separation distance to the applicable risk-based screening distance (ITRC 2014) or other risk-based screening criterion[1]. If the screening indicates that there is a potentially complete exposure pathway (current or future) that could result in an unacceptable risk, then the LNAPL PVI concern is verified, and the concern would be carried forward to select remedial goals.
3. A potential LNAPL migration concern has been identified at a large LNAPL body. One threshold metric that could be applied to verify this concern is an assessment of LNAPL body stability using existing site monitoring data. If the LNAPL body can be demonstrated to be stable or receding, the concern for LNAPL migration can be eliminated. Conversely, a site with a documented expanding LNAPL body and/or visible LNAPL seep(s) would be carried forward to remedial goal selection.

4. A potential concern about near-surface occurrence of LNAPL has been identified at a site with historical surface releases. The state has numerical limits for TPH in shallow soil based on a theoretical threshold for the occurrence of a separate phase (C_{sat}). Comparison of soil sampling data for TPH in soil to state numerical TPH standards can be used to validate or eliminate this concern.

Once LNAPL concerns have been evaluated, those that have not been eliminated or managed without remediation are considered in the selection of LNAPL remedial goals (Figure 5-1).

5.2 Establishing LNAPL Remedial Goals

Once LNAPL concerns have been verified, appropriate LNAPL remedial goals are established to address those concerns. LNAPL remedial goals are the desired LNAPL condition to be achieved by the remedial strategy or action that constitutes the end of LNAPL management for a specific LNAPL concern. The elimination of the LNAPL concern necessitating LNAPL management occurs when the goal is achieved.. Because more than one LNAPL concern may need to be addressed to render the site protected, multiple goals may be established so that the different concerns are eliminated. For example, if there are three LNAPL concerns at the site, then three LNAPL remedial goals may be selected – one to address each concern.

LNAPL remedial goals are generally expressed through three LNAPL conditions: LNAPL Composition, LNAPL Saturation, and LNAPL Aesthetics. Each LNAPL concern is linked closely to a corresponding LNAPL goal:

- LNAPL risk concerns typically generate LNAPL composition-based goals.
- LNAPL migration concerns typically generate LNAPL saturation-based goals.
- Mobile LNAPL occurrence concerns typically generate LNAPL saturation-based goals.
- “Other” LNAPL concerns typically generate LNAPL aesthetic goals.

A compilation of example concerns, potential threshold metrics, and remedial goals is shown in Table 5-1.

Table 5-1. Connecting LNAPL concerns and objectives with remedial goals and technology groups

LNAPL Concern	Potential Threshold Metrics	LNAPL Remediation Goal	LNAPL Remediation Objective	Technology Group	Performance Metrics	Remediation Technology Selection
LNAPL saturation-based goals						

LNAPL Concern	**Potential Threshold Metrics**	**LNAPL Remediation Goal**	**LNAPL Remediation Objective**	**Technology Group**	**Performance Metrics**	**Remediation Technology Selection**
LNAPL occurrence in wells	LNAPL transmissivity to assess recoverability	Reduce mobile LNAPL saturation	Recover LNAPL to a practicable limit	LNAPL mass recovery	**See Tables 5-2 and 6-3**	**See Table 6-2**
LNAPL occurrence in soil	Soil TPH regulatory standards	Abate unacceptable soil concentrations even if/when LNAPL is within residual saturation range	Reduce soil concentrations (e.g., TPH) to below soil regulatory limits	LNAPL mass recovery and LNAPL phase change		
Potential LNAPL migration	LNAPL body footprint stability	Terminate LNAPL body migration and reduce potential for LNAPL migration	Abate LNAPL body migration by sufficient physical removal of mobile LNAPL mass	LNAPL mass recovery		
			Stop LNAPL migration by physical barrier	LNAPL mass control		
LNAPL composition-based goals						
Groundwater impacts from an LNAPL source	Dissolved-phase regulatory standards	Abate unacceptable constituent concentrations in dissolved phase from an LNAPL source	Control or treat soluble plume to abate dissolved-phase concentrations. Contain LNAPL body and affected groundwater to prevent groundwater impacts at compliance point(s)	LNAPL mass control and LNAPL phase change		
	Dissolved-phase plume stability	Abate unacceptable constituent concentrations in dissolved phase from LNAPL source	Control or treat soluble plume to abate dissolved-phase concentrations	LNAPL mass control and LNAPL phase change		
Petroleum vapor intrusion overlying dissolved plume aside from the LNAPL source	Vapor intrusion screening distances	Abate unacceptable constituent concentrations in soil vapor from groundwater source	Reduction of groundwater and vapor concentrations beyond acceptable levels	LNAPL phase change and LNAPL mass control		
Petroleum vapor intrusion overlying LNAPL source	Vapor intrusion screening distances	Reduce constituent concentrations in soil vapor and/or LNAPL source	Abate unacceptable vapor accumulations by sufficient depletion of volatile constituents in LNAPL	LNAPL phase change and LNAPL mass control		
LNAPL occurrence in soil	Soil regulatory standards	Abate unacceptable soil concentrations even if/when LNAPL is within residual saturation range (e.g., TPH concentration)	Reduction of risk from specific components	LNAPL phase change		
LNAPL aesthetic-based goals						
Geotechnical instability of LNAPL-affected soil	Geotechnical structural tests	Restore soil stability (saturation-based goal)	Abate geotechnical soil instability	LNAPL mass recovery and LNAPL mass control		
Stains and odors	Field inspection	Remove aesthetic concerns (composition-based goal)	Abate offensive odors	LNAPL mass control and LNAPL phase change (vapor)		
	Odor-based screening levels					

5.3 Determining LNAPL Remediation Objectives

An LNAPL Remediation Objective describes how the remedial goal will be accomplished and must be linked to the technology(ies) to be used. Combined with performance metrics and a remediation endpoint (Section 5.5), the LNAPL remediation objective becomes a “SMART” objective (Specific, Measurable, Attainable, Relevant and Timely).

LNAPL remedial goals are grouped in Table 5-1 by those that address LNAPL Saturation, LNAPL Composition, and LNAPL Aesthetics. LNAPL remediation objectives are closely linked to goals within those groups. Specifically, the remediation objective articulates the action required to address specific LNAPL remedial goals.

When stating an LNAPL remediation objective to accomplish a specific LNAPL remedial goal, the objective typically includes one of the phrases: “stop,” “abate,” “control,” “change,” “reduce,” “remove,” or “recover.” Articulating objectives with these words help connect the remedial goals to one of the technology groups described in Section 5.4.

Therefore, for specific, agreed-upon LNAPL concerns and LNAPL remedial goals, remediation objectives can be defined. Example remediation objectives are included in Figure 5-1 in association with the concerns and goals to which they relate. Figure 5-2 illustrates the LNAPL decision process with specific examples.

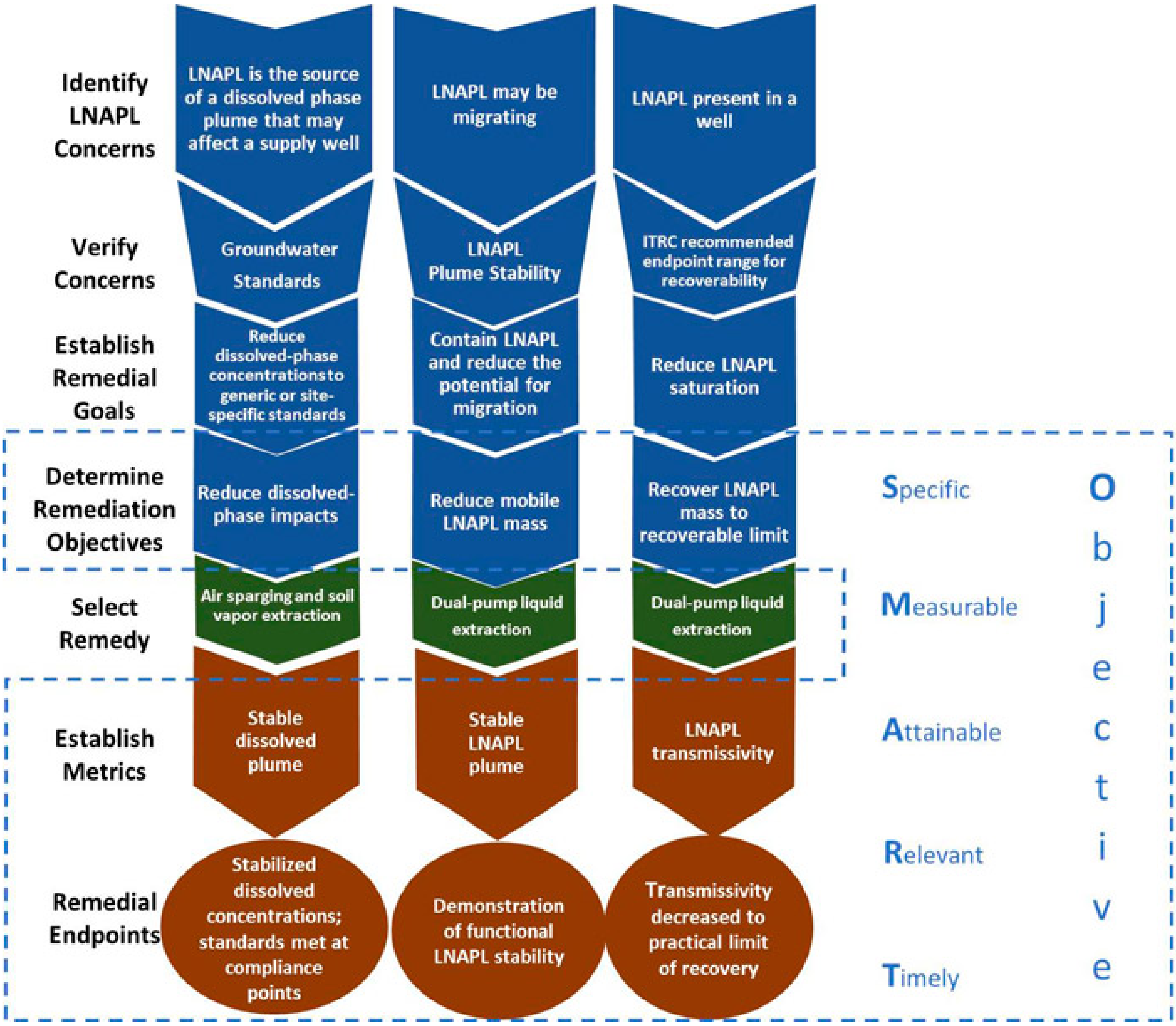


Figure 5-2. Example LNAPL decisions for verified LNAPL concerns.

Careful consideration and linkage of LNAPL concerns, goals, and remediation objectives is essential. For example, if the concern is “LNAPL is the source of the dissolved plume” and the goal is “to reduce the dissolved phase COCs from the LNAPL source” (a composition goal), then an objective of “removal of LNAPL with hydraulic recovery” would not address the concern or meet the goal, because LNAPL mass recovery addresses saturation, and not composition (see Figure 5-3).

5.4 LNAPL Remedial Technology Groups

LNAPL concerns can also be mitigated by implementing institutional controls (ICs) or engineering controls (ECs). It is a site-specific decision to choose between IC, EC, or remediation technologies. This guidance focuses on remediation technologies.

Section 6.1 describes the LNAPL remedial technology selection process with technology specific descriptions and information presented in Table 6-1 and Table 6-2, respectively. Each technology identified has unique applicability and capability, particularly with consideration to the LNAPL concerns, goals, and objectives. A selected LNAPL remedial technology should align with the particular LNAPL concern, remedial goal, and remediation objective. To aid in this alignment, this guidance identifies three basic groups to associate a technology with the primary mechanism by which it manages the LNAPL:

- Mass-recovery
- Phase-change
- Mass-control

A specific technology may not necessarily be a pure end member of any particular technology group. For this reason, a ternary graph is included in Table 6-1 for each technology to represent visually how the technology associates with the technology groups, which are described below.

5.4.1 LNAPL Mass-Recovery Technology

LNAPL mass-recovery technologies address saturation-based LNAPL remedial goals and are the technologies most frequently used exclusively for LNAPL remediation. These technologies recover LNAPL via physical removal, such as with excavation of LNAPL-saturated soil or hydraulic recovery (e.g., LNAPL pumping or skimming). Hydraulic recovery may be pursued with or without flow augmentation using remedial techniques that reduce LNAPL viscosity or interfacial tension (e.g., surfactants or solvents), thereby enhancing LNAPL mobility flow characteristics. Subject to logistical and practical limits, LNAPL mass recovery using pumping or skimming technologies is limited to reducing LNAPL saturation to residual saturation. One exception is excavation, which can achieve complete LNAPL removal. At residual saturation, LNAPL will not flow and, therefore, hydraulic recovery is no longer possible (see Section 3.6 for more details on the limit of hydraulic recovery).

5.4.2 LNAPL Phase-Change Technology

LNAPL phase-change technologies do not directly remove LNAPL from the environment as is the case for LNAPL mass-recovery technologies. Instead, LNAPL phase-change technologies rely on the physical properties (e.g., vapor pressures, Henry’s Constant, solubility) of LNAPL to partition from a multi-constituent liquid to other phases by increasing the rates of volatilization, dissolution, or degradation of the LNAPL constituents. Those LNAPL constituents are either degraded in situ or captured and treated in the vapor or dissolved phases as they are removed from the subsurface. The composition of LNAPL changes through the removal of LNAPL constituents that readily degrade, volatilize, or dissolve. LNAPL phase-change technologies are thus primarily applicable to composition-based LNAPL remedial goals. LNAPL phase change results in some saturation reduction (e.g., SVE for gasoline LNAPL can reduce overall LNAPL saturation), therefore these technologies may have some secondary application for saturation-based LNAPL remedial goals.

LNAPL phase-change technologies are not limited by residual LNAPL saturation because they do not depend on the presence of mobile LNAPL. Some LNAPL phase-change technologies are more elaborate to design and implement than LNAPL mass-recovery technologies, and their practicable limits may not be as well established as those of LNAPL mass-recovery technologies. Thus, LNAPL phase-change technologies may be costlier to design and/or deploy, but use of strategic/targeted applications may minimize such limitations and possibly shorten the LNAPL phase-change remediation life cycle. For example, to achieve a remedial goal of LNAPL recovery to saturations less than residual, it might be more appropriate to hold off deployment of the LNAPL phase-change remedial technology until after an LNAPL mass-recovery technology has reached its recovery limit, or an LNAPL remediation objective is reached that is set to transition between the two technologies.

5.4.3 LNAPL Mass-Control Technology

LNAPL mass-control technologies are primarily suited for saturation-based LNAPL remedial goals because they limit mobility or eliminate migration. LNAPL mass-control technologies may stabilize a migrating LNAPL by reducing the LNAPL saturation via blending a binding agent with the LNAPL zone (mixing technologies) or by physically blocking LNAPL migration (containment technologies). Such technologies alone may satisfactorily meet the remedial goal or can be used in combination with LNAPL mass-recovery or LNAPL phase-change technologies. Additional long-term operation and maintenance and stewardship requirements may also be warranted, depending on site conditions and property use. The containment technologies are limited in applicability to LNAPL saturations in excess of residual saturation, since at residual saturations the LNAPL body is, by definition, immobile. In some instances, mixing technologies may also reduce cross-media impacts (e.g., recharge infiltration and leaching through the LNAPL zone) since some binding agents (e.g., Portland cement, bentonite) can reduce the soil permeability of the LNAPL zone or degrade the volatile or soluble LNAPL constituents.

5.4.4 Combination of Technologies

An effective remedial strategy depends on the optimum use of technologies to maximize LNAPL removal at the lowest cost and effort while achieving remedial goals. Formerly, LNAPL remedial designs used a single technology to remediate an LNAPL source or plume or both, with the expectation that the technology would achieve the remedial goal over the course of the design life cycle. Experience has shown this has not always been the case as remedial systems were found to be ineffective and costly while regulatory closures were not achieved. Based on lessons learned from this practice, a single technology approach may not be the most practical or cost effective for LNAPL management and remediation. A more practical and cost-effective strategy may be to sequence and/or combine technologies at different stages of the remediation life cycle based on the specific LNAPL remedial goals and targeted areas. It is of critical note that careful planning should be employed with regard to use of multiple technologies. Technologies should be chosen with consideration to their ability to progress toward the remedial goals. The use of multiple technologies should be thoughtful and deliberate, rather than a reaction to a failed technology.

The selection, sequencing, or combining of technologies for LNAPL management should be determined after LNAPL concerns have been verified, remedial goals have been stated, and a Remedy Selection LCSM has been developed and understood by all stakeholders (see Section 4.4). The sequencing or synergy of combining technologies may be either temporal, where the technologies are applied one after the other as treatment trains, or spatially at the same time in different parts of the source area and plume. Typically, the more aggressive technology is applied first to remove or contain LNAPL above residual saturation, followed by phase-change technologies. Examples of remediation technology combinations include:

- Targeted use of dual-pump liquid extraction (mass recovery technology) to reduce LNAPL saturation, followed by air sparging and soil vapor extraction (phase change and mass recovery technology) to change LNAPL composition (thus addressing risk concerns) and further reduce LNAPL mass. A final remedy might include natural source zone depletion, with adequate data collection to assess its efficacy and progress.
- Utilization of a barrier wall (mass control technology) to halt migration toward a receptor, followed by in situ smoldering (mass removal technology) to reduce LNAPL mass.

Figure 5-3 summarizes a sequenced technology deployment treatment train that shows remedial actions from aggressive controls or removals to passive technologies (e.g., NSZD).

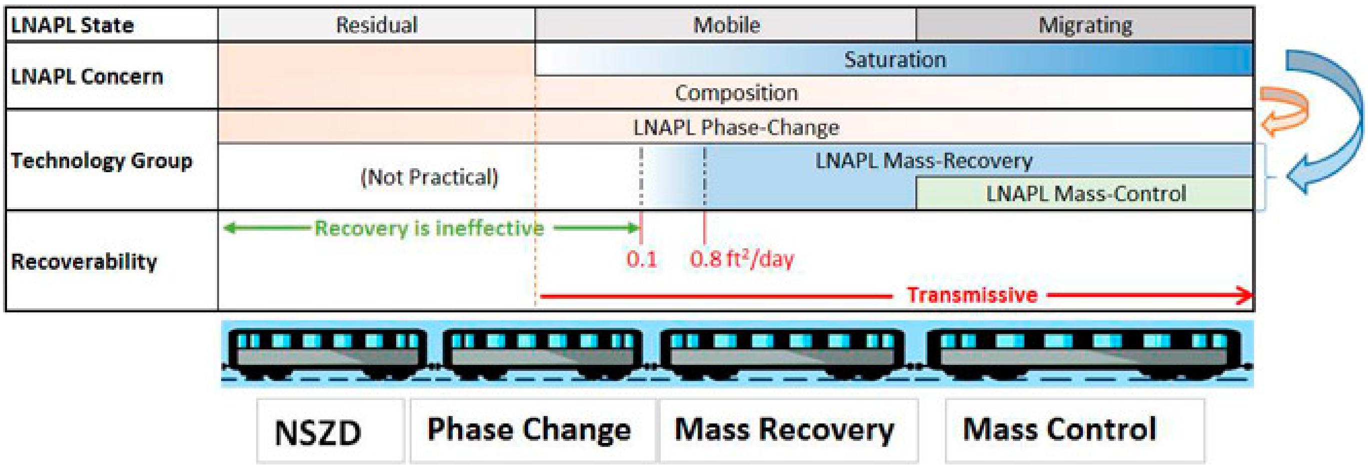


Figure 5-3. Relationship between LNAPL State, LNAPL Concern, Technology Group, and Recoverability.

5.4.5 Transitioning Remedial Technologies

As described in Section 5.4.4, the implementation of one sole remedial technology is often not practical for a timely cleanup, nor feasible for situations where there is more than one LNAPL concern. LNAPL bodies with both migration and risk concerns are common, and those differing concerns often lead to different technology selections. Many sites will require an adaptive remedial strategy that includes deliberate and timely transitioning of technologies spatially or temporally to make satisfactory progress toward, or to achieve, the remedial goals. Technology transitions are intended to compliment remedial actions that have already taken place, and should be in consideration of changing site conditions. Transitioning from one technology to another (or a combination of technologies) should not be a reaction to a failed technology. “Failed technologies” are more typically ‘failed technology selections’ due to a gap in the site understanding or a lack of complete understanding of the LNAPL concerns and the types of technologies appropriate for those concerns. To prevent failed technology selections and assess the timing for a technology transition, the LSCM should be updated regularly to improve site understanding as active and/or natural processes affect site conditions. An updated Design and Performance LCSM may be utilized to identify successes and support system shutdown, and where applicable, identify areas where there has been a shift in concern, supporting technology transition.

Remedial technologies should be selected only after considering the technologies appropriate to the identified LNAPL concerns. After careful pairing of LNAPL concerns and remedial goals with appropriate technologies, the selected technology is implemented. Performance metrics for the implemented technology are evaluated during operations, which is critical to making a technology transition. The performance metrics may indicate the need for system optimization, or indicate that further progress toward achieving remedial goals is likely to be limited through continued use of the current technology. If the performance metrics indicate the practical endpoint for a technology has been met, then continued use of the technology is unlikely to move the site further toward achieving the remedial goals, and a technology transition is warranted.

5.5 Establishing Remedial Performance Metrics and Remediation Endpoints

For each LNAPL remediation objective, one or more “performance metrics” are defined. Performance metrics are measurable characteristics that relate to the remedial progress of a technology in abating the concern. LNAPL remediation technologies address LNAPL concerns differently (e.g., excavation vs. co-solvent flushing), and therefore, the performance metrics used to demonstrate progress toward the LNAPL remediation objective depend on the technology used. Table 5-2 lists example performance metrics and remediation objectives.

Table 5-2. Example performance metrics and remediation endpoints

Example performance metrics and remediation endpoints	Description
Asymptotic performance of optimized recovery system	Analysis of unit volume of LNAPL recovery or recovery rate per unit of time, after considering optimization. Endpoint reached when asymptotic curve indicates the limit of recovery effectiveness (e.g., analysis indicates that further recovery of remaining LNAPL is impracticable).
Decline curve analysis	Analysis of unit volume of LNAPL recovery or recovery rate per unit of time. Endpoint reached when decline curve analysis indicates that the remaining LNAPL volume is below threshold of concern, or the time and effort to recover the remaining volume is impracticable.
Dissolved-phase concentration	Concentrations stable or decreasing; endpoint reached when reduced to regulatory standards at a compliance point.
Dissolved-phase plume stabilized	If exhibited, then it is also an indication of a stable LNAPL body.
Limited/infrequent in-well LNAPL thickness	Stated LNAPL thickness objective or LNAPL thickness typically not observed in monitoring well under average site conditions. Indicative that LNAPL is not consistently recoverable and the majority of remaining impacts are residual.
LNAPL body footprint stabilized	Assesses whether technology effectively counters existing LNAPL driving gradient and/or captures migrating LNAPL. Comparison of LNAPL body footprint before and after treatment to demonstrate stable or shrinking footprint.

Example performance metrics and remediation endpoints	**Description**
LNAPL composition	Reduce mole fraction of volatile or soluble LNAPL constituents. Endpoint reached when volatile or soluble constituents of concern reduced to risk-based regulatory standards in media of concern.
Enhanced biodegradation rate	Assure remedial performance by maintaining threshold oxygen concentration in zone targeted by air sparging, soil vapor extraction, or bioventing. Endpoint reached when soil respiration rate or CO_2 production declines below established threshold.
LNAPL recovery rate vs. estimated LNAPL flux	The recovery system either diminishes the driving LNAPL gradient and/or achieves a higher recovery rate than the estimated LNAPL flux across the width of the LNAPL body front. Endpoint reached when LNAPL flux diminishes to zero, or another target threshold.
LNAPL saturation profile	Comparison of saturations before and after treatment to demonstrate reduced saturations. Endpoint reached when saturation-based concerns have been abated.
LNAPL transmissivity	Use reduction of transmissivity over time to assess technology performance. Endpoint reached when LNAPL transmissivity indicates recovery has reached its practicable limit, or concern has been abated.
LNAPL/vapor recovery ratio	Ratio of unit volume of LNAPL recovered per unit volume of vapor. Decreasing ratio indicates decreasing recovery effectiveness. Endpoint reached when further reduction of this ratio is impracticable, or concern has been abated.
LNAPL/water recovery ratio	Ratio of unit volume of LNAPL recovered per unit volume of water. Decreasing ratio indicates decreasing recovery effectiveness. Endpoint reached when further reduction of this ratio is impracticable, or concern has been abated.
No first LNAPL occurrence in downgradient well	Performance metric to address/limit LNAPL migration. LNAPL never enters a monitoring well installed outside of LNAPL body.
Soil saturation for soil stability	LNAPL saturation reduced to yield acceptable soil bearing capacity.
Soil concentrations	Concentrations stable or decreasing; endpoint reached when reduced to regulatory limits.
Vapor-phase concentration	Concentrations reduced until regulatory standards are met at a compliance point.
Unit cost of incremental mass removal	Increasing cost per unit LNAPL recovered indicates decreasing cost- effectiveness (cost may not always be in line with regulatory requirements; however, in certain circumstances this metric can be useful for assessing practicable limits).

Ideally, each performance metric has a measurable predetermined value that describes when the technology has reached its limits of beneficial application. That is the remediation endpoint for the technology chosen. It is important to note that the remediation endpoint is technology specific, and may not fully eliminate the LNAPL concern or achieve the LNAPL remedial goal. For example, air sparging and soil vapor extraction may be applied with the objective of changing the LNAPL composition to address risk concerns. The remediation endpoint may be a practicable mass removal rate, or a target soil respiration rate, or some other measure(s) of the beneficial limits of the technology. If risk concerns still exist when these beneficial limits have been reached, then another remedial technology is needed. A transition to another technology such as NSZD is then implemented, with the intent of fully addressing the remaining risk concerns by further reducing the concentrations of risk-driving LNAPL components in soil vapor or groundwater to levels that no longer pose a risk.

5.6 Integration of the LCSM and LNAPL Remedial Technology Selection

The development of an Initial LCSM (Section 4) aids in the effective identification of potential LNAPL concerns. Once potential LNAPL concerns have been identified, threshold metrics, such as comparison to generic numerical screening levels, can be applied to confirm whether a potential concern can be screened out from further evaluation or consideration. SMART remediation objectives can be developed specific to the identified LNAPL concerns by establishing remedial goals, selecting one or more appropriate remedial technologies, and identifying remedial technology-specific endpoints and performance metrics. Section 6 of this document provides more detailed information to aid in the selection of an appropriate remedial technology, or combination of technologies, to meet the defined remedial goals.

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[1] More detailed verification of risk concerns can be made via risk assessment, which evaluates potential exposure and toxicity concerns associated with the presence of LNAPL, considers LNAPL composition, and accounts for the attenuation of mobile LNAPL constituents. Evaluation of risk is not dependent on the abatement of mobile LNAPL, and may be initiated at any point in the project life cycle.

6. LNAPL Remedial Technology Selection

6.1 Process Overview

This section provides a summary of the remedial technology selection process. *This process is NOT appropriate for emergency response situations*.

Figure 6-1 illustrates the technology selection process and how it relates to coincidental, ongoing LCSM development. Note that Figure 6-1 assumes the LCSM was developed sufficiently in Section 4 and that all LNAPL concerns were identified in Section 5 prior to beginning remedial technology screening in this chapter.

Technology selection is a stepwise and linear process for addressing each LNAPL concern; however, remedy selection is seldom linear. The initial focus in technology selection, therefore, should not be when (i.e., in what sequence) each concern is addressed or step is performed, but rather that each is addressed/performed sufficiently. If all concerns are addressed, then the regulating authority can be confident that a complete remedial strategy is being proposed, and the proposing entity can be confident that the proposal is likely to be effective and acceptable to regulators and stakeholders alike. However, some concerns ultimately may take precedence over others and thus dictate the order of technology implementation.

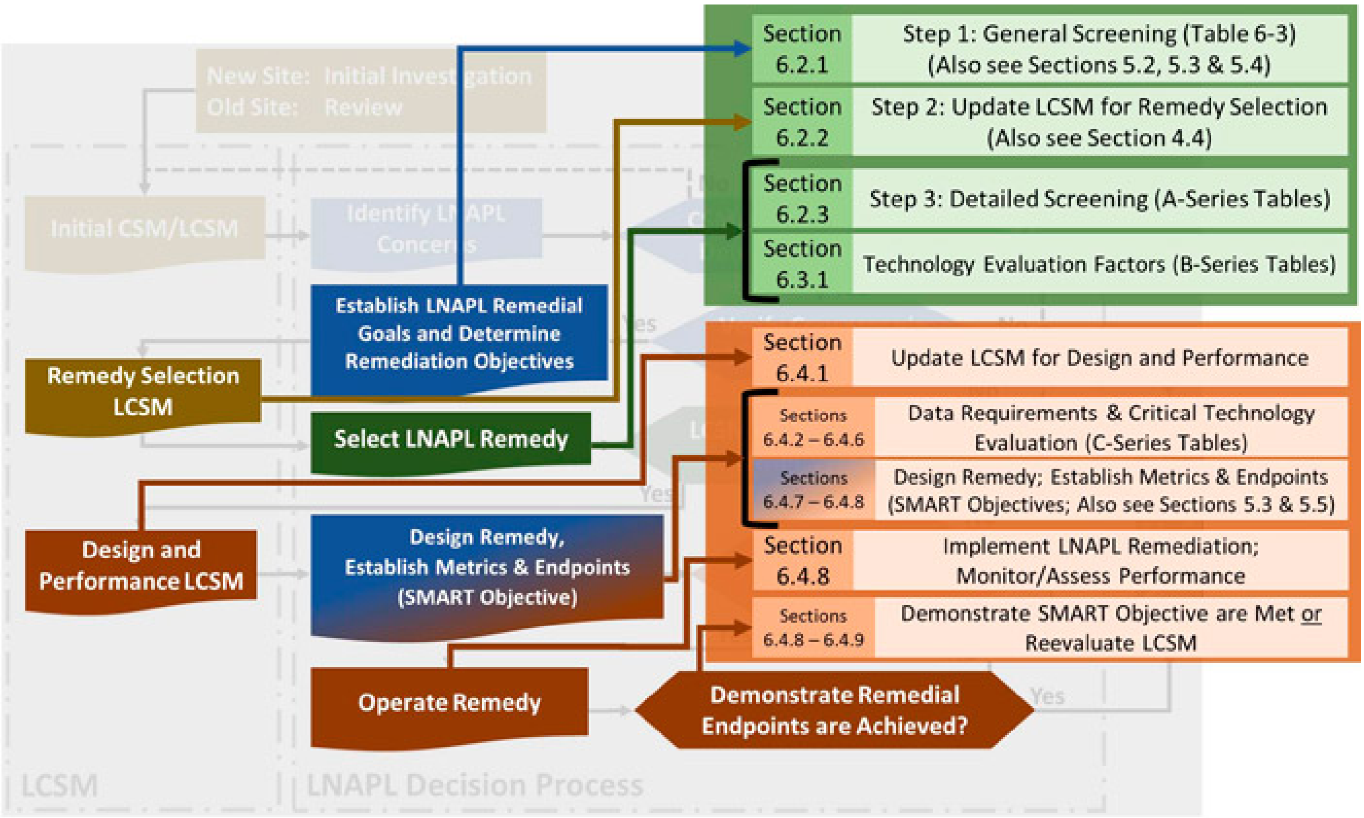


Figure 6-1. LNAPL technology screening and selection coincident with LCSM development.

Before screening and selecting LNAPL technologies, the user should be familiar with the variety of LNAPL remediation technologies currently available as described in this document and elsewhere (e.g., Enviro Wiki, http://erwiki.net/index.php?title=Main_Page). Familiarity with technologies will assist in screening. Useful elements of this document for remedial technology screening include:

- Table 6-1 provides a brief description of each of the technologies addressed in this guidance. The technologies listed are based upon a survey of the LNAPL team's experience and knowledge; some are more innovative or

have a better record of accomplishment than others.
Please note that less intensive LNAPL recovery technologies such as the use of adsorbent socks, manual bailing, passive skimmers, or (periodic, short-term) vacuum trucks are not included in the technology tables. These methods generally are not very effective to recover significant LNAPL. However, depending on the expected or measured yield of recoverable LNAPL, these technologies may be appropriate when dictated by local regulations, aesthetic concerns, or emergency response actions not included in this process.

- Table 6-2 provides categorical information about each technology, including assignation to a technology group (refer to Section 5), applicable site conditions, relative rate of cleanup, and a quick reference to specific Appendix A
- Appendix A provides detailed information on each of the technologies presented in this guidance through a series of three tables (A-, B-, and C-series tables) that correlate to the screening process in Section 6.2 through Section 6.4, respectively.

Because of the number of potential technology candidates and the wide array of applicability of the technologies, selection of an appropriate technology is multifaceted. The selection process must consider the LNAPL remedial goals in light of the overall site use (current and future), LNAPL remediation objectives, site conditions, LNAPL type, and non-technical factors.

Table 6-1. Overview of LNAPL remedial technologies

LNAPL Technology	**Description of Technology**
Excavation	LNAPL body is physically removed and properly treated or disposed. Accomplishes removal and/or reduction of all phases including LNAPL, adsorbed, dissolved, and vapor.
Fluid recovery (4 variations; excludes SVE or groundwater-only recovery)	• **Skimming:** LNAPL is the only fluid removed using a pump or similar continuous mechanical device. There may be incidental, small volume water recovery.
	• **Vacuum Enhanced Skimming:** LNAPL and vapor are the fluids removed. LNAPL drawdown via skimming and vacuum induce an LNAPL gradient toward the recovery point. Also referred to as bioslurping or vacuum enhanced fluid recovery (VEFR).
	• **Total Liquid Extraction:** LNAPL and water are the fluids removed. Drawdown of LNAPL and groundwater induce an LNAPL gradient toward the recovery point. Groundwater drawdown may expose submerged LNAPL thereby increasing LNAPL mobility and recovery rate. Groundwater extraction may also provide hydraulic containment of potentially migrating LNAPL. Also referred to as dual pump liquid extraction (DPLE) (ITRC 2009a).
	• **Multi-Phase Extraction (MPE):** LNAPL, water, and vapor are the fluids removed. LNAPL drawdown, groundwater drawdown, and vacuum induce an LNAPL gradient toward the recovery point. Groundwater drawdown may expose submerged LNAPL thereby increasing LNAPL recovery rate. Groundwater extraction may also provide hydraulic containment of potentially migrating LNAPL. Also referred to as dual-phase extraction (DPE) or two-phase extraction (TPE) (USACE 1999). MPE is also often used as a phase-change technology to expose submerged LNAPL (as well as LNAPL in the vadose zone) to volatilization and enhanced aerobic biodegradation with hydraulic LNAPL removal as a secondary remediation objective.
Enhanced LNAPL recovery (3 variations)	• **Water flooding (incl. hot water flooding):** Water is injected to enhance the LNAPL gradient toward recovery wells. Hot water may be injected to reduce LNAPL viscosity and interfacial tension and further enhance LNAPL removal by hydraulic recovery.
	• **Surfactant-enhanced subsurface remediation (SESR):** A surfactant is injected to decrease interfacial tension and increase solubility. LNAPL and water are recovered hydraulically.
	• **Cosolvent flushing:** A solvent is injected to increase LNAPL solubility and mobility. LNAPL and water are recovered hydraulically.

LNAPL Technology	**Description of Technology**
In situ thermal remediation (4 variations)	• **Steam injection:** LNAPL is removed by forcing steam into the aquifer to vaporize and solubilize LNAPL, increase LNAPL recovery by reducing the viscosity and interfacial tension of LNAPL, and enhance LNAPL gradient. Vapors, impacted groundwater, and LNAPL are recovered via vapor extraction and hydraulic recovery.
	• **Thermal conduction heating:** Soil is heated using heating elements to vaporize and solubilize LNAPL and increase LNAPL recovery by reducing the viscosity and interfacial tension of LNAPL. Vapors, impacted groundwater, and LNAPL are recovered via vapor extraction and hydraulic recovery.
	• **Electrical resistance heating:** Electrical current is used to heat soil and groundwater through subsurface electrodes to vaporize and solubilize LNAPL and increase LNAPL recovery by reducing the viscosity and interfacial tension of LNAPL. Vapors, impacted groundwater, and LNAPL are recovered via vapor extraction and hydraulic recovery.
	• **In situ smoldering:** Initiated through a short duration, low energy “ignition event.” Combustion is sustained by the addition of air through a well to the target treatment zone. The energy of the reacting contaminants is used to pre-heat and initiate combustion of contaminants in adjacent areas, propagating a combustion front through the LNAPL-impacted zone in a self-sustaining manner, provided a sufficient flux of oxygen is supplied.
Air sparging/ soil vapor extraction (AS/SVE)	AS injects air into the saturated zone to solubilize (turbulence), biodegrade (aerobic), and volatilize LNAPL constituents from the submerged and overlying portions of the LNAPL body where airflow occurs. SVE also enhances aerobic biodegradation and volatilization of the LNAPL constituents from the vadose zone and collects vapors created by AS. AS or SVE can also be used individually if conditions are appropriate. A significant portion of the LNAPL depletion accomplished by AS/SVE is due to enhancement of aerobic biodegradation. Depletion of LNAPL in the vadose zone is enhanced by SVE because it can draw continuous LNAPL from the saturated zone into the vadose zone via capillary processes (wicking).
Biosparging/ bioventing	Similar processes to AS/SVE, except air/oxygen is injected more slowly with the main goal being stimulation of aerobic biological degradation of LNAPL in the saturated and unsaturated zones. Various configurations are possible including inducing airflow into the unsaturated zone by extraction of soil vapors.
In situ chemical oxidation	LNAPL is depleted by enhanced solubilization and chemical destruction through the addition of a chemical oxidant into the LNAPL zone (e.g., hydrogen peroxide and persulfate). Chemical oxidation typically requires the addition of catalysts, stabilizers, and/or activators to control the rates of oxidation. Oxidation reactions with LNAPL can be vigorous and require controls for off-gas, for example.
Enhanced anaerobic biodegradation	Enhanced anaerobic biodegradation involves supplying electron acceptors other than oxygen (e.g., nitrate and sulfate). Anaerobic biodegradation can also be achieved by increasing the subsurface temperature to increase natural biodegradation rates.
Natural source zone depletion (NSZD)	LNAPL is degraded via naturally occurring processes of biodegradation, volatilization, and dissolution. The predominant process is biodegradation, including direct LNAPL-contact biodegradation. LNAPL constituents dissolve, biodegrade, volatilize, solubilize in soil moisture, and also subsequently biodegrade in the vadose zone. Biodegradation produces gaseous products, such as methane and carbon dioxide and ultimately completely mineralize the LNAPL.
Activated carbon	Activated carbon with electron acceptors or chemical oxidants is injected or placed into excavations to enhance biodegradation or destruction processes. The activated carbon adsorbs organic compounds and provides a substrate for biomass growth. The added reagents support enhanced (aerobic or anaerobic) bioremediation or destruction by chemical oxidation.

LNAPL Technology	Description of Technology
Phytotechnology	Phytotechnologies use plants to remediate or contain contaminants in the soil, groundwater, surface water, or sediments. Phytoremediation is generally considered a phase-change technology, enhancing subsurface biodegradation, but, to a lesser extent, can also be considered mass control technology if designed for hydraulic control.
Physical or hydraulic containment	Subsurface barriers (e.g., sheet piles, French drain, slurry wall, groundwater extraction, trenches, and permeable absorptive barrier) are constructed to prevent, impede, or divert LNAPL migration. It is generally a mass control technology and does not significantly reduce LNAPL mass.
In situ soil mixing (stabilization)	LNAPL is immobilized by reducing the permeability of the LNAPL zone through in situ mixing of amendments (e.g., addition of bentonite clay or cement). In addition to reducing LNAPL mobility, it also reduces the leachability and volatility of the LNAPL constituents.
Notes: *1 – Enhanced aerobic biodegradation is not listed in this table separately because aerobic biodegradation occurs during many of the other technologies including all aeration methods and ISCO.*	

Table 6-2. Summary information for LNAPL remediation technologies

View Table 6-2 in Adobe PDF format.

As shown on the upper right side of Figure 6-1 (modified from Figure 4-1), the technology selection process begins with a preliminary screening of LNAPL and site conditions as described in Section 6.2. The user will first screen the technologies based on their potential to achieve the LNAPL remedial goals and objectives given the general site and LNAPL conditions. Table 6-3 rearranges the technologies by applicability to LNAPL goals and objectives. Leaving Section 6.2, the user will have a shortened (screened) list of technologies that have the potential to achieve the LNAPL remediation objectives, given the geologic conditions at the site.

Further evaluation of screened technologies is performed using Section 6.3. Table 6-4 and the B-series tables in Appendix A list miscellaneous technology evaluation factors (including remedial timeframe, public concern, carbon footprint, and site use) that carry varying degrees of significance with respect to the site and to stakeholders in choosing a final technology to implement.

The final evaluation step is to select a technology based on engineering data requirements. Section 6.4 and the C-series tables in Appendix A will assist the user in recognizing the critical site-specific requirements that must be evaluated, along with the Design and Performance LCSM, for selecting the final technology(ies) and establishing LNAPL remediation milestones and performance metrics.

Although it is beyond the scope of this document, technology implementation (i.e., construction and execution/operation) is important. First, even if the proper technology is selected, poor implementation will guarantee non-optimum performance and increase the likelihood of technology failure. It may not become apparent to stakeholders until later that implementation, not technology selection, was the reason for failure. Second, there is often more than one way to implement a technology (e.g., horizontal vs. vertical wells; constant vs. pulsed system operation). When dictated by site-specific needs, creativity and innovation by the environmental professional, contractors, and vendors are critical to remedial success.

6.2 Preliminary Technology Screening

This section describes a preliminary site-evaluation process to narrow the list of LNAPL remedial technologies (introduced in Tables 6-1 and 6-2). As illustrated in Figure 6-2, the screening process uses three steps to evaluate site-specific input parameters:

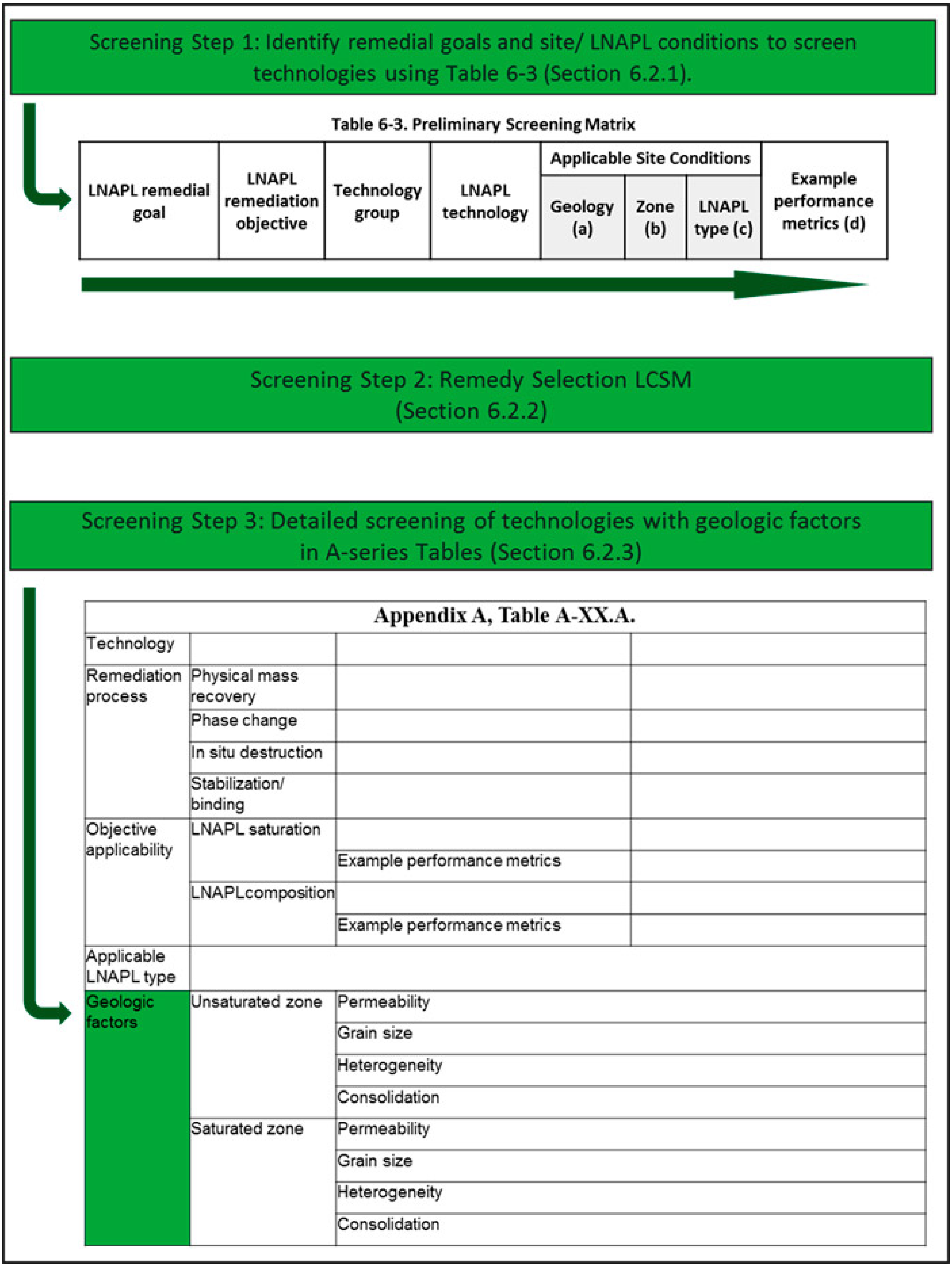
1. Consider LNAPL remedial goals and LNAPL remediation objectives to generate a reduced list of feasible LNAPL remedial technologies (see Table 6-3). Table 6-3 is a restatement of technologies from Table 6-2 in relation to remediation objectives and goals. This table has the advantage of providing the user with technology choices or alternatives to address specific concerns and is critical to screening technologies. Examples of possible

performance metrics are also provided.

> ***The potentially applicable technologies listed in Table 6-3 are limited to those most likely to be selected from, in the opinion of the ITRC LNAPL Team. Other technologies may be conceptually applicable; however, they are considerably less likely to pass screening and are not listed.***

2. Revisit the LCSM to collate data and, as necessary, collect additional site characterization data that will be used in Step 3 to screen out technologies that are not likely to be effective for the geologic and LNAPL conditions specific to the site being evaluated—and, in Section 6.3, to further screen out technologies that are likely to be more difficult to implement due to other site-specific factors.
3. Take the results from Steps 1 and 2 and, using Appendix A tables, apply site-specific geologic and hydrogeologic characteristics to focus the list of applicable remedial technologies.

Each of these steps is described in more detail below.



Screening Step 1: Identify remedial goals and site/ LNAPL conditions to screen technologies using Table 6-3 (Section 6.2.1).

Table 6-3. Preliminary Screening Matrix

LNAPL remedial goal	LNAPL remediation objective	Technology group	LNAPL technology	Applicable Site Conditions			Example performance metrics (d)
				Geology (a)	Zone (b)	LNAPL type (c)	

Screening Step 2: Remedy Selection LCSM (Section 6.2.2)

Screening Step 3: Detailed screening of technologies with geologic factors in A-series Tables (Section 6.2.3)

Appendix A, Table A-XX.A.			
Technology			
Remediation process	Physical mass recovery		
	Phase change		
	In situ destruction		
	Stabilization/ binding		
Objective applicability	LNAPL saturation		
		Example performance metrics	
	LNAPLcomposition		
		Example performance metrics	
Applicable LNAPL type			
Geologic factors	Unsaturated zone	Permeability	
		Grain size	
		Heterogeneity	
		Consolidation	
	Saturated zone	Permeability	
		Grain size	
		Heterogeneity	
		Consolidation	

Figure 6-2. Process overview of Steps 1 through 3.

Table 6-3. Preliminary screening matrix

View Table 6-3 in Adobe PDF format.

6.2.1 Step 1: General Screening ▼*Read more*

The screening process begins with the first (left) column of Table 6-3, which lists LNAPL remedial goals covering the typical spectrum of site-specific LNAPL concerns. The user should note that some remedial goals might have more than one LNAPL remediation objective (column 2), which means more than one technology can be utilized to achieve the identified remedial goal. The remediation objective is basically a restatement of the remedial goal in the context of remediation technology. The Technology group (column 3) describes the general method by which the remediation objective can be achieved. A suite of potentially applicable technologies (column 4) is associated with each LNAPL remediation objective. Applicable site conditions (columns 5, 6, and 7) assist in choosing a technology.

Repeat the procedures above for each applicable LNAPL remedial goal. You may find that some technologies already identified are capable of addressing more than one LNAPL objective. The LNAPL technologies that pass Step 1 will be further evaluated in Step 3.

6.2.2 Step 2: Refinement of the Remedy Selection LCSM ▼*Read more*

The Initial LCSM that was developed through the application of questions in Section 4 was sufficient for identification of LNAPL concerns developed in Section 5. However, at this point, the user may find there is not enough information available from the assessment phase to continue the technology selection process. For example, it may be that the lateral extent of LNAPL is defined, but the vertical distribution is not. This is where the Remedy Selection LCSM becomes important, and the questions in Section 4.4 should be answered. The key aspect of this step is to assess additional site-specific parameters to further screen technologies.

6.2.3 Step 3: Detailed Screening ▼*Read more*

Screening Step 3 uses the A-series tables provided in Appendix A to further screen and eliminate technologies that fail after a more detailed assessment of technology-specific factors. For some technologies (e.g., excavation, some heating technologies), geologic factors do not affect the suitability of the technology; however, success for other technologies may depend significantly on certain geologic conditions being present at the site. For example, ISCO and enhanced anaerobic biodegradation may not be a primary technology choice when soils are impermeable or highly heterogeneous.

Technologies carried forward from Step 3 will be evaluated as explained in Section 6.3 and Section 6.4. If no remedial technology passes by this point, repeat the process for Step 1, but select a different LNAPL remedial goal. If no technology can be identified to achieve the required objective, consider discussing this outcome with the regulatory authority (see Section 6.3.2).

6.3 Technology Evaluation

After the user has completed Section 6.2 and identified a list of technologies (at least two) that are applicable to the site, these technologies are further evaluated to identify which might be successfully implemented at the site. Preferences for specific remediation objectives may be apparent upon reviewing the list of applicable technologies. Alternatively, if the most suitable remediation objective is not apparent from Section 6.2, then review of additional evaluation factors may clarify which remediation objective is best suited. Then the user can return to Section 6.2 and complete the initial technology screening process.

6.3.1 Technology Evaluation Factors

Table 6-4 provides nine factors specific to LNAPL remediation to consider when selecting key evaluation factors for the project. Based on the LCSM and remediation objectives, identify a short list of factors (typically four to six) that are likely to be most relevant for technology selection. To ensure acceptance of the technology selection process, this set of factors should be selected in consultation with all of the site stakeholders.

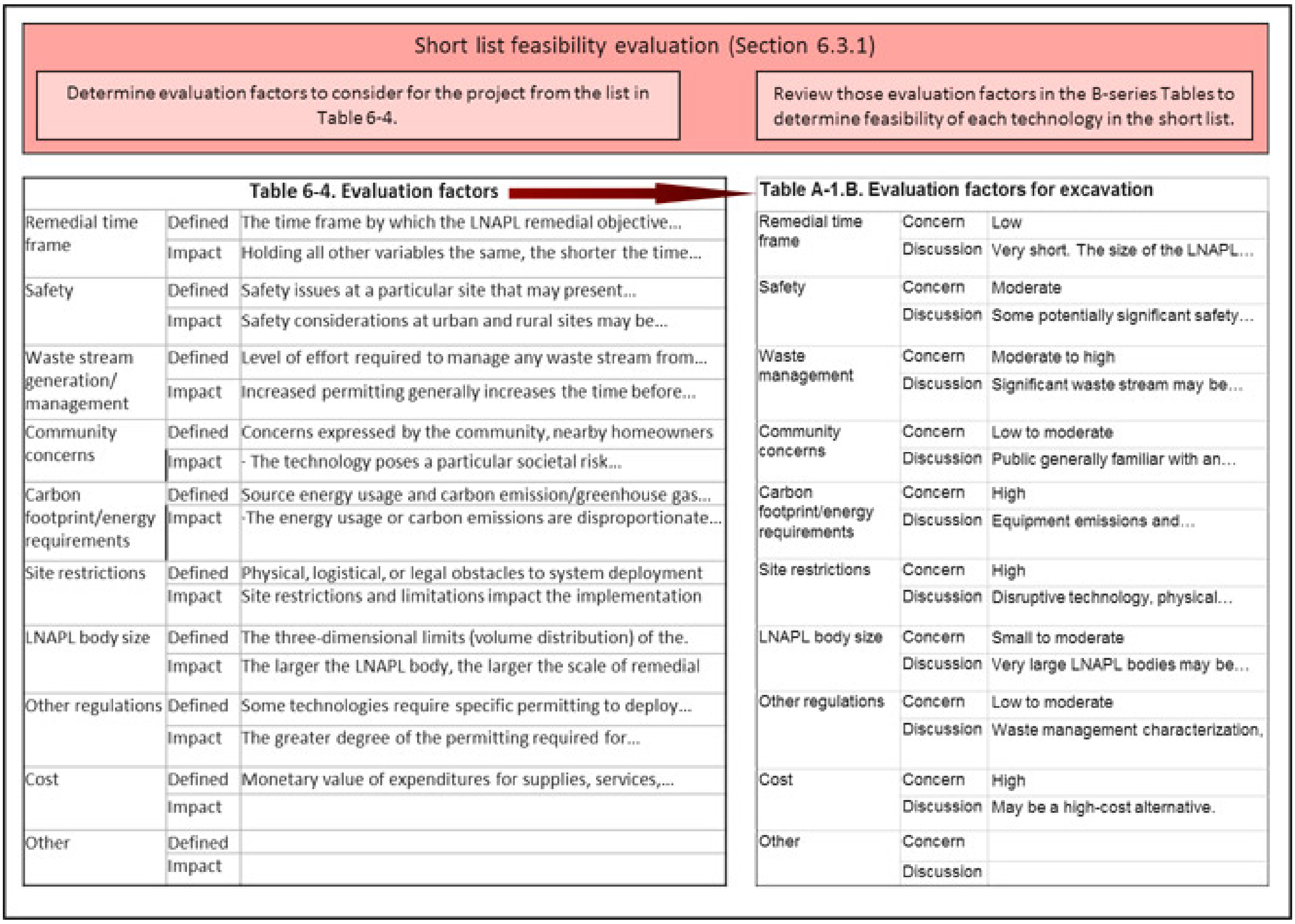
Once a set of factors has been determined for the project, the B-series tables in Appendix A should be reviewed for the screened technologies from Section 6.2. These factors should be considered for each technology in the short list to confirm that the technology is feasible for the project. Figure 6-3 provides an example of this evaluation process for excavation.

Table 6-4. Evaluation factors(a).

Remedial timeframe	Defined	The timeframe by which the LNAPL remediation objective is to be met. The timeframe may be a regulatory or non-regulatory evaluation factor. Any one LNAPL remediation project may have different timeframes to meet different LNAPL remedial goals or remedial objectives.
	Impact	Holding all other variables the same, the shorter the timeframe, the more aggressive the effort required, which often increases costs. For a given technology, the time required to meet an end point increases with the size of the LNAPL body unless the remediation system scale increases. Increased permitting requirements for one technology over another increases the time that lapses before technology implementation. Increased infrastructure/site barriers commonly slow technology implementation because of the need to avoid infrastructure impacts and compensate for barriers.
Safety	Defined	Safety issues at a particular site that may present a particular challenge to a technology, and safety considerations unique or particular to a technology. This guidance presumes that all construction activities will be in compliance with Occupational Safety and Health Administration (OSHA) health and safety requirements, and that system operation will be within applicable regulations. In addition, it is presumed that any engineered technology has inherent basic safety issues, but the technology may involve the addition of electricity, heat, or chemicals that may pose a particular operational risk if applied at large field scale or in close proximity to workers or the public. Published accident rates for the construction or operational activities may suffice for screening.
	Impact	Safety considerations at urban and rural sites may be different or more intensive. At public access, non-restricted access facilities, it may be more difficult to reliably manage safety issues. Infrastructure issues may be more critical for certain technologies than others. Some technologies may produce waste streams or conditions that are particularly difficult to manage at a particular site or that potentially escalate quickly to a critical state.
Waste stream generation and management	Defined	Level of effort required to manage any waste stream from the remediation.
	Impact	Increased permitting generally increases the time before a technology can be deployed. Waste streams may be more toxic or more difficult to control than the parent LNAPL. Larger waste streams present more of a challenge for disposal or treatment and on-site management pending disposal or treatment.
Community concerns	Defined	Concerns expressed by the community, nearby homeowners, civic organizations, elected officials, or concerns that are likely to be expressed as the LNAPL remediation progresses.
	Impact	• The technology poses a particular societal risk. • The completion of the remediation causes more harm than good or renders a site less fit for active and productive use or reduces the existing level of ecological use. • The LNAPL remediation is applied to public lands possibly controlling the degree or timing of public participation or requiring additional permits (National Environmental Policy Act). • The remedy is not, or is not perceived to be, consistent with current and future planned land use, reducing property value or use. • LNAPL site is in close proximity to sensitive receptors. • LNAPL technology is particularly vulnerable to environmental justice considerations.
Environmental factors (carbon footprint/ energy requirements/ waste generation)	Defined	Resource (e.g. energy and water) usage and availability, and waste generation (amount, toxicity and treatment/disposal) options.
	Impact	• The energy usage or waste generated is disproportionate to other technologies. • An energy source is not reliably or amply available to power the technology as required. • Natural passive energy sources (solar, wind) can power the technology adequately.

Site restrictions	Defined	Physical, logistical, or legal obstacles to system deployment at the site (e.g., building locations, high-traffic areas, small property size, noise ordinances, site geology [e.g., depth to bedrock, presence of bedrock, depth to groundwater], or nearby sensitive receptors, such as schools, day cares, hospitals, etc.)
	Impact	Site restrictions and limitations impact the implementation of some technologies more than others, due to equipment size, degree of surface disruption, etc. At sites with more potential physical, logistical, or legal site restrictions, the physically larger, more “disruptive” technologies may be less feasible to implement.
LNAPL body size	Defined	The three-dimensional limits (volume distribution) of the LNAPL body.
	Impact	The larger the LNAPL body, the larger the scale of remedial effort required. The feasibility of some technologies may be limited to small-scale application, while others are more feasible for small- and large-scale application. Treatment of larger sites may be complicated by access limitations, physical barriers, cost constraints, or technology limitations.
Regulations and permits	Defined	Some technologies require specific permitting to deploy (e.g., underground injection control [UIC], air, waste management, remediation, maximum available air control technology [air emissions], or OSHA compliance).
	Impact	The greater degree of the permitting required for technology deployment, the higher the costs and more likely the delays to system deployment.
Cost	Defined	Monetary value of expenditures for supplies, services, labor, products, equipment, and other items purchased for both implementation and operational phases.
	Impact	Each technology has different costs, and those costs vary widely depending on the site conditions, inflation, and time it takes to remediate. Reasonably accurate planning-level cost estimates (+100%/–50%) would be required for each technology based on knowledge of the treatment area, key physical constraints, and unit cost rates. Design level costs (i.e., +30%) typically are not available at the screening stage. Consider capital costs vs. life cycle costs, even at the screening level. (AACE Cost Estimate classification system, https://web.aacei.org/resources/publications)
Other	Defined	(user defined)
	Impact	(user defined)

(a) These factors are used in the B-series tables in Appendix A. Some factors are weighted High, Moderate, or Low. “High” means the technology has high sensitivity or contribution to the factor. “Low” means the technology has low sensitivity or contribution to the factor.



Short list feasibility evaluation (Section 6.3.1)

Determine evaluation factors to consider for the project from the list in Table 6-4.

Review those evaluation factors in the B-series Tables to determine feasibility of each technology in the short list.

Table 6-4. Evaluation factors

Remedial time frame	Defined	The time frame by which the LNAPL remedial objective...
	Impact	Holding all other variables the same, the shorter the time...
Safety	Defined	Safety issues at a particular site that may present...
	Impact	Safety considerations at urban and rural sites may be...
Waste stream generation/ management	Defined	Level of effort required to manage any waste stream from...
	Impact	Increased permitting generally increases the time before...
Community concerns	Defined	Concerns expressed by the community, nearby homeowners
	Impact	- The technology poses a particular societal risk...
Carbon footprint/energy requirements	Defined	Source energy usage and carbon emission/greenhouse gas...
	Impact	-The energy usage or carbon emissions are disproportionate...
Site restrictions	Defined	Physical, logistical, or legal obstacles to system deployment
	Impact	Site restrictions and limitations impact the implementation
LNAPL body size	Defined	The three-dimensional limits (volume distribution) of the.
	Impact	The larger the LNAPL body, the larger the scale of remedial
Other regulations	Defined	Some technologies require specific permitting to deploy...
	Impact	The greater degree of the permitting required for...
Cost	Defined	Monetary value of expenditures for supplies, services,...
	Impact	
Other	Defined	
	Impact	

Table A-1.B. Evaluation factors for excavation

Remedial time frame	Concern	Low
	Discussion	Very short. The size of the LNAPL...
Safety	Concern	Moderate
	Discussion	Some potentially significant safety...
Waste management	Concern	Moderate to high
	Discussion	Significant waste stream may be...
Community concerns	Concern	Low to moderate
	Discussion	Public generally familiar with an...
Carbon footprint/energy requirements	Concern	High
	Discussion	Equipment emissions and...
Site restrictions	Concern	High
	Discussion	Disruptive technology, physical...
LNAPL body size	Concern	Small to moderate
	Discussion	Very large LNAPL bodies may be...
Other regulations	Concern	Low to moderate
	Discussion	Waste management characterization,
Cost	Concern	High
	Discussion	May be a high-cost alternative.
Other	Concern	
	Discussion	

Figure 6-3. Evaluation factors for determining feasibility of technologies: example for excavation.

6.3.2 Scenarios with No Feasible Remedial Options

At some sites, evaluation using the available remediation objectives and the selected key factors may result in elimination of all retained technologies. In these cases, the user either identifies additional technologies for evaluation, modifies the remedial goals so that one or more technologies are retained through the evaluation process, reconsiders the evaluation factors, and/or seeks guidance from the regulatory authority. For example, if no active LNAPL remediation technologies can achieve all of the remedial goals, then risk mitigation may need to be addressed through the use of controls (i.e., administrative, engineering, and/or institutional) in addition to or as an alternative to active remediation. Alternatively, one might consider a combination of technologies that might collectively achieve the goal.

6.4 Technology Selection, Implementation, and Evaluation

After one or more technologies have been evaluated through the processes described in Section 6.3, minimum data requirements need to be defined to support the following:

- selecting the final technology,
- engineering the technology to meet remedial goals / remediation objectives, and
- evaluating remedial progress toward those goals.

This section describes these minimum data requirements. The C-series tables in Appendix A describe the data requirements for each technology in more detail, to the extent information is available. Coincidentally, the LCSM should again be reviewed to identify data gaps and the need for additional site data to further technology selection.

Information provided in this section does not replace the services of qualified professionals in the technology selection, engineering, and evaluation process. The information provided in this section is designed to support review of site-specific plans and indicate the types of data that are typically used for the required evaluations. Federal, state, and local requirements should be researched and understood by those individuals

implementing the technology selection and design.

When developing the minimum data requirements and critical considerations for a technology, the mode(s) of action should be considered. For example, multi-phase extraction can function as an LNAPL mass-recovery technology or a phase-change technology. Testing, design, and remedial performance and progress metrics should be developed to assess the mode(s) of action to be relied upon to reach remediation objectives and, ultimately, the remedial goals.

6.4.1 Design and Performance LCSM

Example performance metrics for the different objectives to identify what type of data are needed to evaluate performance for the chosen technology(ies) are provided in Table 6-3 (far right column). Together, the technology group and performance metrics columns (columns 3 and 8, Table 6-3) explain how the LNAPL can be addressed in the context of that objective and how achievement of the objective can be demonstrated. The performance metrics are different for the different LNAPL remediation objectives, but all measure progress toward the LNAPL remedial goal.

1. What are the conditions to be created by the selected technology(s) that will accelerate LNAPL depletion? ▼*Read more*

The goal of implementing a technology is to change subsurface conditions to accelerate depletion of LNAPL beyond the natural rate of depletion (i.e., the rate of NSZD). As technology selection enters the design and performance phase, a detailed understanding of whether and how the remaining screened technology(ies) can maintain intended changes to subsurface conditions is the final check that the technology will be effective and implementable before full-scale installation and operation is undertaken.

For a remedial goal requiring a LNAPL mass recovery technology, one of the most important conditions to change is the LNAPL gradient toward the extraction point (e.g., well, trench, etc.). Using the LCSM already developed, consider where in the hydrostratigraphy (position relative to formation layering and the water table) it will be most effective to induce an LNAPL gradient. Inducing gradients in other fluid phases present in the same interval as the mobile LNAPL can enhance the LNAPL gradient. For example, when implementing vacuum-enhanced fluid recovery for a perched LNAPL body, it is most effective to focus the vacuum and soil vapor flow on the permeable layer containing the mobile LNAPL on top of the perching layer. Applying vacuum to and inducing soil vapor flow from layers underlying and/or overlying the mobile LNAPL will not directly enhance the LNAPL gradient.

For a remedial goal requiring a phase-change technology, conditions for which the technology is intended may include one or more of the following:

- increased air flow through the LNAPL zone to enhance depletion of volatile LNAPL constituents;
- increased oxygen concentration (in soil vapor and/or groundwater) in the LNAPL zone to enhance aerobic biodegradation of the LNAPL;
- groundwater flow through the LNAPL zone to enhance depletion of soluble LNAPL constituents;
- increased non-oxygen electron acceptor concentrations (e.g., nitrate or sulfate) in the LNAPL zone to enhance anaerobic biodegradation of the LNAPL; or
- increased temperature in the LNAPL zone to enhance volatility and solubility of LNAPL constituents as well as, up to moderate temperatures, microbial activity, and biodegradation rates.

The technology(ies) undergoing final screening (i.e., laboratory and/or pilot-scale testing) and design must be able to maintain the conditions intended to accelerate LNAPL depletion and should focus those conditions on the LNAPL zone or at least the target portion of the LNAPL zone. These conditions should be:

- the focus of laboratory and/or pilot-scale testing (this is also known as the primary failure criteria for technology testing);
- the main criteria for remedial design (for example, the criteria that determine well spacing); and
- the primary metric(s) of operational performance.

Using the existing LCSM to understand how geological heterogeneity and LNAPL distribution will complicate or simplify establishing and maintaining the intended conditions throughout the target zone is integral to this LCSM question.

2. What conditions will demonstrate the desired LNAPL changes? ▼*Read more*

As the LNAPL is depleted, the LNAPL condition(s) in the subsurface will change. The conditions in the aqueous and vapor phases in and around the LNAPL may change too. Some of these changes will directly relate to the LNAPL remediation objectives and the LNAPL remediation endpoints. Some will relate indirectly. For example, when the remediation objective is reduction of LNAPL mobility, LNAPL transmissivity can provide a direct measure, and LNAPL saturation (soil concentration) may provide an indirect measure, of the mobility changes (which are also likely to be subject to a high degree of uncertainty).

The ability to measure changes in the LNAPL conditions targeted by remediation is central to demonstrating that:

1. remediation is changing the LNAPL as intended (e.g., reducing mobility or depleting a constituent of concern from the LNAPL);
2. the spatial extent of those changes is as intended;
3. the rate of those changes is as intended; and
4. remediation objectives are met and remediation endpoints achieved.

The changing LNAPL condition(s) are the performance metrics by which remedial progress is measured. During remediation, these performance metrics will confirm that the remedial technology selected is appropriate, given its site-specific effectiveness and implementability for the remediation objective. Further, these metrics will provide insight into whether the remedial design is sufficient to reach the intended remediation endpoints. If they indicate that the implemented technology is not likely to be sufficient to meet the remediation endpoints, then reevaluation of the LCSM and remedial technology selection decision may be warranted. However, the first step should be updating the LCSM with the operation and progress information gained from full-scale operation of the remedial technology. Reevaluation of the design using this updated LCSM may reveal that with design, installation, and/or operation modifications, the selected technology can accomplish the remediation objectives and meet the remediation endpoints.

The performance metrics of remedial progress will also be used to demonstrate that the remediation endpoints have been achieved. For some remedial technologies, “rebound” may occur after termination of activity. For example, groundwater concentrations may initially be reduced by ISCO and then increase again after all the oxidant is depleted. Similarly, while SVE is running, hydrocarbon concentrations in soil vapor may be low and then increase again after SVE is shut down. Remediation objectives and endpoints should be compared to these rebounded conditions to evaluate true progress and update the LCSM. Understanding the site-specific processes that will cause rebound and a remedial technology’s ability to mitigate those site-specific processes provides additional final technology screening, design, and performance information. Note also that those metrics typically subject to rebound, while simpler to measure, may be the most robust metrics available. In the preceding examples, a more robust metric might be leachability or volatility of LNAPL in soil samples. These would provide a more direct measure of the potential for the LNAPL zone to continue to act as a source for elevated concentrations of hydrocarbon in groundwater and/or soil vapor.

6.4.2 Minimum Data for Final Evaluation of Technology Suitability

The technology(ies) that are selected through the processes in Sections 6.2 and 6.3 require final screening and site-specific testing to confirm the suitability of the technology to the site, the remediation objectives, and the remediation endpoints. It is important to conduct this screening and testing with several purposes in mind, including data collection for full-scale engineering design and site-specific technology testing. Even though considerable effort may have been exerted to get to the point of conducting a site-specific test, it is important to allow negative test results (if any) to prompt reconsideration of the LCSM, the technology, and/or the LNAPL remedial goals. That is, if a test result is unfavorable to the selected technology, then it may be necessary to conclude that the selected technology will not be able to achieve the LNAPL remediation objectives and reach the remediation endpoints.

The data collection and testing recommended should allow a 90% design cost estimate to be developed, which is an important step in evaluating the feasibility of a selected technology. Accurate costing for application of the selected remedial technology(ies) may provide a final discriminating factor between technologies or as a go/no-go point for a single selected technology.

6.4.3 Site-Specific Data for Technology Evaluation

These basic data are likely to have been collected already as part of the technology selection process. For the most part, these are measurements of site-specific hydrogeological or LNAPL characteristics. The representativeness of the measured characteristics is a factor that should be carefully considered. For example, for the results of a pumping test to be relevant to the design of an MPE system, it should have been conducted in the area where the system will be implemented or in an area where the LCSM indicates that hydrogeologic conditions are similar. Similarly, the coincident effects of two technologies (e.g., air sparging and SVE) on each other need to be assessed; pilot testing each separately may not reveal their interaction. Use of non-representative data may lead to erroneous design calculations.

6.4.4 Bench-Scale Testing

Bench-scale testing of a remedial technology can be an important step toward evaluating feasibility. It can provide initial estimates of important data and parameters for engineering a remedial technology. In general, bench-scale tests are most useful when applied to investigate the feasibility of technologies in which reagent injection or biodegradation is a key element. For example, bench-scale testing of a chemical oxidant provides information about its effectiveness in destroying the target LNAPL constituents, allows estimates of the portion of the chemical oxidant required just to overcome the natural oxidant demand of the soil, and produces information regarding potential occurrence of unfavorable by-products. In this example, if the natural soil oxidant demand is very high, then feasibility of ISCO may be called into question because of cost and deliverability factors (while it may be hydraulically feasible to deliver the oxidant, the oxidant demand may be such that the oxidant is depleted before it reaches all the target LNAPL constituents).

6.4.5 Pilot Testing

Pilot testing a remedial technology provides data to evaluate field-scale application and remedial technology design. In many cases, a pilot test involves collecting more data (spatially and temporally) than during full-scale remediation. For example, SVE system pilot testing includes pressure and soil-vapor concentration observations at varying distances and directions to determine the ROI, which is then used to estimate the SVE well spacing. This expanded data set provides both a final feasibility step and important information for successful engineering, design, and operation of the selected technology. As mentioned in Section 6.4.3, if two technologies will be implemented simultaneously in the same area, pilot testing of the combined remedy as it will be implemented is recommended.

Pilot testing is recommended for almost all technologies and can often be implemented as a portion of the full-scale design. It is important to gather data that allow evaluation of whether the technology will perform as expected and is capable of achieving the LNAPL remediation objectives. It is also important to consider what data are needed if computer models (Section 6.4.6) will be utilized later. If it does not perform as expected, the technology and its selection process should be carefully reevaluated, including updating the LCSM and acknowledging the infeasibility of the technology as warranted. While much effort and capital may have been invested in a selected technology to get it through pilot testing, one of the main reasons for pilot testing is to provide a final confirmation of the remedial approach before investing “full-scale” effort and capital. Ideally, the equipment installed for the pilot test (e.g., monitoring wells, injection wells) can be used as part of the full-scale system.

6.4.6 Applicable Models

In some cases, semi-analytical and/or numerical models are a useful technology evaluation tool. They may be used to assist in a feasibility study for a selected technology, engineering design of a remedial system, remedial progress evaluation, and/or development of metrics for technology application to the extent practicable. Models can be very powerful tools and give relevant insights into the application of a technology. They also have uncertainty, however, that is inherent in the simplifications necessary to implement modeling, such as simplification of the heterogeneity of the actual hydrogeologic system or simplification of LNAPL behavior. Recognition of this uncertainty and appropriate quantification, such as sensitivity studies, allows model results to be used to their fullest extent and, just as importantly, limit their use to what is reasonable. Care should be taken to calibrate the model against known site conditions and site data. Implementation of models, and in particular, implementation of numerical models for simulation of multiphase flow and behavior, is another area where relevant professional skills and experience are considered particularly important.

6.4.7 Engineering for Full-Scale Design

Full-scale design of the selected technology should consider the data and parameters developed during site investigation and bench- and pilot-scale technology testing. The data and parameters in this section of the C-series tables in Appendix A are crucial to a successful full-scale design. Professional expertise (skill and experience) is particularly critical at this stage.

As mentioned in Section 6.1, technology implementation (i.e., construction and execution/operation) considerations become important at this point in the process. Practitioners should work with competent and trustworthy contractors and vendors.

6.4.8 Performance Metrics for Monitoring Operation and Remediation Progress

During full-scale operation of the selected remedial technology, monitoring both the operational performance of the technology and the progress of remedial efforts is necessary to determine the effectiveness of remediation. Thus, it is crucial to establish performance metrics for operations and remediation progress for each given technology prior to full-scale implementation. These metrics are necessary for demonstrating when a technology has been applied successfully, and/or to the extent practicable, evaluating progress toward remedial goals. See ASTM (ASTM 2014b) for additional performance metric examples.

Operational performance monitoring allows for efficient and optimized operation of the remedial system/technology. Careful monitoring of specific data (referred to here as operational performance metrics) during technology implementation is important for gauging whether the technology continues to perform as expected. For example, operational performance monitoring for a multi-phase extraction system would include monitoring parameters such as the flow rate, differential pressure and static pressure to verify that these parameters are within acceptable ranges previously determined during previous projects and pilot testing.

Performance metrics for remediation progress allow interpretation of the progress toward a remediation objective. If progress appears to be too slow, the design and operation of the remedial technology should be reevaluated, either throughout the site or in the portion of the site where performance is inadequate. For example, if the performance metric of LNAPL transmissivity at the downgradient edge of an LNAPL body does not demonstrate sufficient reduction in the LNAPL body’s migration potential in one particular segment of the body front for an LNAPL skimming system, then additional skimming wells in that segment may be warranted. It is also possible that the segment contains a previously unrecognized preferential flow channel and that skimming will not work in that particular location. Performance metrics for remediation progress may also be useful in determining if and when the remediation objectives and remedial goals have been met. This skimmer example also highlights the importance of reevaluating the LCSM throughout the life of the remedial operations, particularly whenever unexpected data are observed (and results confirmed). A complete and up-to-date LCSM allows the best possible decisions about application and operation of remedial technology(ies) to be made. See ASTM (ASTM 2014b) for additional insights in updating the LCSM.

6.4.9 Evaluating the LCSM During Remediation

It is important to note that after implementation of a selected technology(ies), the LCSM should continue to be evaluated, particularly if the selected technology is not performing as anticipated and there are no mechanical or execution issues. The effects of remedial efforts on the subsurface (in general) and LNAPL concentrations (more specifically) should be monitored and recorded to confirm efforts are effective. For example, if ISCO fails to meet intended remediation objectives, it may be that unidentified geological conditions (e.g., lithology changes or fractures) or pockets of LNAPL are responsible. Additionally, data gathered from operations should be reviewed for abnormalities if the selected technology is not performing as anticipated, for example, if vacuum from SVE operations is not affecting a targeted area. If these types of situations develop and there is no apparent cause, it should be considered that the LCSM is incomplete or inaccurate and may need to be corrected before continuing.

6.4.10 References and Further Information

The technologies briefly described in this document have been more fully documented in other sources; some of these sources are listed in a later section of this document. After initial technology selection, it is strongly recommended that these additional sources, as well as others that are available (or become available after this document is published), be consulted. This process will allow the practitioner and regulator to develop a good, working understanding of the technology so that the most appropriate decisions for application of the LNAPL remedial technology can be made.