Sites contaminated by chlorinated solvents present a daunting environmental challenge. Chlorinated solvents are prevalent and persistent groundwater contaminants, found at tens of thousands of sites worldwide. They also are among the most difficult groundwater contaminants to remediate, especially at sites with dense, nonaqueous-phase liquid (DNAPL) still present in the source zone. Restoring sites contaminated by chlorinated solvents to typical regulatory criteria (low parts-per-billion concentrations) within a generation has proven exceptionally difficult, although there have been successes. Site managers must recognize that complete restoration of many of these sites will require prolonged treatment and involve several remediation technologies. To make as much progress as possible within a generation (approximately 20 years) requires a thorough understanding of the site, clear descriptions of achievable objectives, and use of more than one remedial technology. Making efficient progress requires an adaptive management strategy and may also require transitioning from one remedy to another as the optimum range of a technique is passed. Targeted monitoring should be used, and reevaluation should be done periodically. Managers must implement effective and adaptive treatments that integrate more than one remedy to address complex contamination scenarios.

The ITRC Integrated DNAPL Site Strategy (IDSS) Team intends this guidance document to assist site managers in developing an integrated DNAPL site management strategy containing five key features:

- a **conceptual site model** (CSM) based on reliable characterization methods and an understanding of the subsurface conditions that control contaminant transport, reactivity, and distribution
- **remedial objectives** and performance metrics that are clear, concise, and measureable
- **treatment technologies** applied in sequence or in parallel designed to optimize performance and take advantage of potential synergistic effects
- **monitoring strategies** based on interim and final cleanup objectives, the selected treatment technology and approach, and remedial performance goals
- **reevaluating the strategy** repeatedly and even modifying the approach when objectives are not being met or when alternative methods offer similar or better outcomes at lower cost

This document describes key concepts and recent developments in each of these areas to help managers develop successful integrated strategies for chlorinated-solvent sites. The following sections summarize these concepts.

This IDSS guidance is intended for regulators, remedial project managers, and remediation engineers responsible for sites contaminated by chlorinated solvents. Because the subject matter is complex, this guidance is targeted towards experienced users; however, novices to the field will benefit from a thorough review of the text and accompanying references. The user of this guidance should be, or become, familiar with and practiced in the latest evolution of site characterization challenges; realistic planning of site restoration; evolving treatment techniques; and evaluating, monitoring, and interpreting mass transport in the subsurface aqueous and vapor phases. While the primary focus of the document is chlorinated-solvent sites, other types of contaminated sites (e.g., petroleum, mixed contaminants, etc.) can use the same fundamental process described in this guidance.

The CSM is the initial tool in developing an IDSS. CSMs for chlorinated-solvent sites should reflect the importance of source architecture (i.e., three-dimensional distribution of the chlorinated solvents), subsurface heterogeneities, and constraints on dispersive processes.

The CSM is important for sites contaminated by chlorinated solvents where the contaminant mass is typically distributed across several geologic media and may exist in more than one physical phase in the subsurface. Movement of contaminant mass between the four phases (DNAPL, vapor, aqueous, sorbed) impacts overall contaminant transport at a site. The importance of both the separate phases and their distribution between more and less transmissive regions is illustrated in the 14-Compartment Model shown in Figure ES-1.

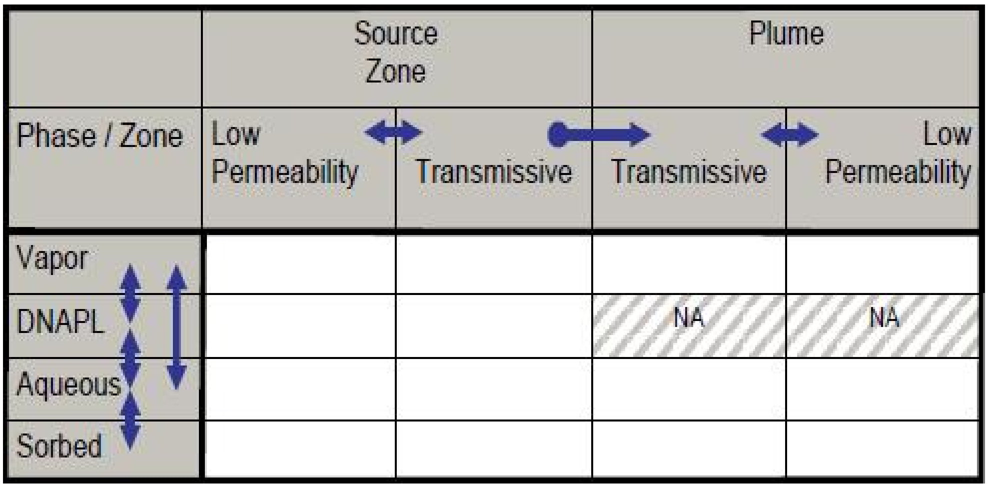

Figure ES-1. Mass transfer at a chlorinated-solvent site depicted by the 14-Compartment Model. *Source:* Sale and Newell 2011

A CSM should integrate several features:

- the site geologic and hydrogeologic setting
- the physical and chemical properties of the contaminants
- geochemical conditions
- physical, chemical, and biological attenuation mechanisms (e.g., sorption-desorption, oxidation, microbial reductive dechlorination)
- the relevant transport processes within and between compartments

Also, the CSM should describe all media that are impacted by the contamination, including the unsaturated and saturated zones, and any geologically and anthropogenically controlled heterogeneities that may be present. The CSM should also address the aging of sources, as most sources have been in place for decades and aging causes important changes in contamination properties and phase distribution that can affect the selection and success of remedial actions.

The limited hydrodynamic dispersion that can occur within plumes and sources is often surprising. The lack of dispersion results in the frequently observed extreme spatial variability in concentrations and mass flux, for example along a plume transect. Two models have been advanced to deal with mass transfer limitations between zones of high- and low-permeability media:

- the dual-domain, multiporosity model, which acknowledges that most flow occurs through a small fraction of the total volume (through preferential flow regions) but that long-term cleanup often is dominated by contaminant release from less-conductive zones
- the streamtube model, with large numbers of streamtubes, each having different contaminant concentrations and flow velocities but with limited mixing between these streamtubes

In contrast to the lack of dispersion, diffusion (e.g., mass transfer) has become an important process to incorporate in the CSM. Diffusion into less-transmissive zones has been known for decades, but its importance to the goal of restoration and the subsequent back-diffusion of contaminants into the transmissive zones have become increasingly recognized. At many sites back-diffusion can sustain plumes long after source removal and result in very long time frames for complete restoration of chlorinated-solvent source zones and associated groundwater plumes.

Setting realistic objectives is critical when developing an IDSS. Objectives may be absolute (objectives based on broad social values, such as protection of public health) or functional (steps or activities taken to achieve absolute objectives, such as supplying bottled water to affected residents). Functional objectives are established to demonstrate attainment of absolute objectives and have often been missing, difficult to measure, or unattainable. A key concept of this guidance is that functional objectives should be specific, measurable, attainable, relevant, and time-bound (SMART).

Selecting objectives that reflect SMART attributes makes subsequent decisions more valid and remedial approaches more successful. It is often necessary to develop SMART functional objectives for different locations, phases, and alternative end points of an overall site cleanup. Given the unique perspectives of different stakeholders and the practical and economic limitations that exist, defining the SMART functional objectives appropriate for a given site requires cooperation, consensus, and often some compromises. An example site is used in this document to illustrate the potential functional objectives that may apply at a given site and how SMART criteria can be effectively applied when developing the final objectives.

Typical time frames involved in remediating chlorinated-solvent sites may be long (decades to centuries), but functional objectives should have relatively short time frames—years to less than one generation—to encourage accountability for specific actions and to make it easier to measure progress toward the objectives. The consensus of the IDSS Team is that functional objectives that extend beyond ~20 years are generally inappropriate, even though the absolute objectives may well require management and even subsequent active remediation well beyond such durations (see Chapter 3).

Many technologies have been developed for source and plume treatment, all with specific advantages and limitations. Selecting a treatment technology requires evaluating several factors, including technical site features (e.g., geology, hydrogeology, and contaminant levels), regulatory requirements, sustainability, and community stakeholder interests. Traditionally, treatment technologies are applied individually at a site, with the expectation that one technology can achieve all objectives. More comprehensive approaches have gained favor recently for chlorinated-solvent sites because complete restoration can be difficult. These comprehensive approaches involve integrating several technologies in time and space.

To assist in evaluating technologies, this guidance includes general summaries of most of the applicable remediation technologies, along with data from site performance studies. In most cases, performance is expressed as both the percent reduction in source zone concentration and the number of orders of magnitude reduction observed. This focus reflects the typical situation at chlorinated-solvent sites, where concentrations in and near a source zone may exceed the cleanup criteria by three to five orders of magnitude or more and complete cleanup with one technology is rarely achievable. The guidance also includes resources available for screening- level assessments of remediation technology performance. Finally, the guidance addresses the potential compatibilities and concerns when combining different technologies that are summarized in a technology-compatibility matrix.

A monitoring approach that relates remedy performance to site-specific SMART functional objectives is a critical element of an integrated strategy. The monitoring approach must include a spatially and temporally sufficient and reliable data set of the remedy performance. An appropriate monitoring program should be dynamic and adjusted to accommodate new data and changing conditions as remediation progresses. Monitoring programs should be routinely reviewed and adjusted to ensure that data being collected continue to be useful. The monitoring program should be designed to assist in making decisions about transitioning between technologies or implementing contingency actions.

Three types of monitoring are needed: **compliance monitoring** used throughout the remediation lifetime to document the nature and extent of impacts and to ensure that potential exposure pathways are controlled, **process monitoring** to assess whether the system is functioning as intended, and **performance monitoring** to assess effectiveness of the remedial approach in meeting SMART functional objectives. Typically, multiple lines of evidence are monitored to evaluate remediation performance. An effective performance monitoring approach enables decision makers to assess the value of the existing remediation program, identify required alterations of the existing remedial approach, and evaluate the progress toward meeting the functional objectives. The metrics most useful for this type of monitoring may not be typical monitoring data. For example, mass discharge and flux data may be more valuable for deciding when to convert from one technology to another than would concentration data alone. Similarly, relatively high-resolution monitoring data collected along transects may be valuable in determining where to target treatments and in measuring performance. Transect-based data can also form a robust basis for measuring contaminant flux.

In developing a monitoring program, modeling is often helpful. Models can be valuable tools for assessing monitoring data, and useful models have been developed to assist managers of chlorinated-solvent sites. This guidance summarizes the features of several of the most widely used analytical and numerical models and describes their advantages and limitations. Regardless of the type of model, sensitivity analyses should be used to assess the potential impact of parameter values on simulation results and to develop a range of possible outcomes.

Given the technical difficulties and need for several phases of remediation, it is normally necessary to reevaluate the overall strategy and its components at intervals. Such reevaluations are valuable in efficiently managing complex problems. The reevaluation involves answering a series of questions: (1) whether functional objectives are being met or whether the progress is acceptable; (2) whether the objectives can be achieved with greater efficiency (e.g., shorter time frames, lower costs); and (3) if the objectives are not being achieved, whether the remedy can be optimized or combined with another technology.

The first question is generally addressed under scheduled (e.g., 5-year) comprehensive site reviews but may be addressed to evaluate one particular remedial action or functional objective (e.g., whether source treatment reduced contaminant mass discharge within the first 5 years of a 20-year plume remedy). Such reviews should identify any changes that have occurred, rate of progress, any new potential risks, and any opportunities for improvement (i.e., optimization).

The second question should be raised at intervals because of the long time frames involved, the dynamic nature of environmental regulations and remedial technologies, and the ever-increasing understanding of the impacts of remedial actions (including green and sustainable practices). Even when a site is progressing satisfactorily toward its objectives, there is value in periodically evaluating options for cost reductions, changes in resource use (e.g., property transfer), incorporation of new technologies, and enhancement of existing systems.

The third question involves cases where the objectives are not being met. It is important to start by revisiting the functional objectives and the CSM because there can be many inaccuracies in a CSM that impact technology performance and it is common that the original objectives may need revision given new information. Assuming the objectives and CSM are still appropriate, the next step is to revisit the basis for the original technology selection because the actual performance of a technology is very site-specific and the database of information on technology performance at different types of sites is constantly growing. An iterative approach to troubleshooting technology performance is often required, and typical approaches include analysis of data trends, evaluation of whether the remedial action has reached a point of diminishing returns or even no recognizable benefit, and assessment of best practices involving determinations of whether the original technology has been improved or whether other more suitable and effective technologies are available.

The difficulties in remediating many chlorinated-solvent sites often make an integrated strategy necessary. The concept of an integrated strategy is not new although it has often proven difficult to implement. Developing an integrated strategy emphasizes the usefulness of a CSM that is based on a sound understanding of contaminant fate and transport, clear and achievable remedial objectives, a systematic treatment approach of two or more treatment technologies, a well- designed performance monitoring system, a defined process and time period for reevaluating progress, and an adaptive treatment approach. This IDSS does not suggest ignoring the regulatory requirements for site restoration, but it may mean leaving some contamination to be managed by longer-term treatment while using aggressive treatment technologies to reduce the site’s risks. This IDSS guidance, including the examples presented as case studies, is intended to help site managers develop more efficient and effective integrated site management strategies through a collaborative process.

Integrated strategies should reflect our current understanding of chlorinated solvents in the subsurface where dispersion is often very limited and diffusion into and back from lower- permeability zones can be very important. An IDSS should define a series of SMART functional objectives and use treatment technologies where and when they are most appropriate to achieve those objectives. Functional objectives should be achievable within 20 years at most, even though site management and liabilities may continue for much longer.

When an IDSS in implemented, dynamic monitoring plans should be developed to measure progress towards achieving functional objectives and to determine when to transition to another more cost-effective technology. The monitoring plans should consider nontraditional metrics such as mass discharge and nontraditional approaches such as high-resolution transect monitoring. Any integrated strategy should be flexible, be adaptive, and identify contingency actions if results do not meet the expectations regarding performance. The strategy should also include deliberate reevaluations of the CSM and subsequence changes in the remedial objectives and remedial approach.

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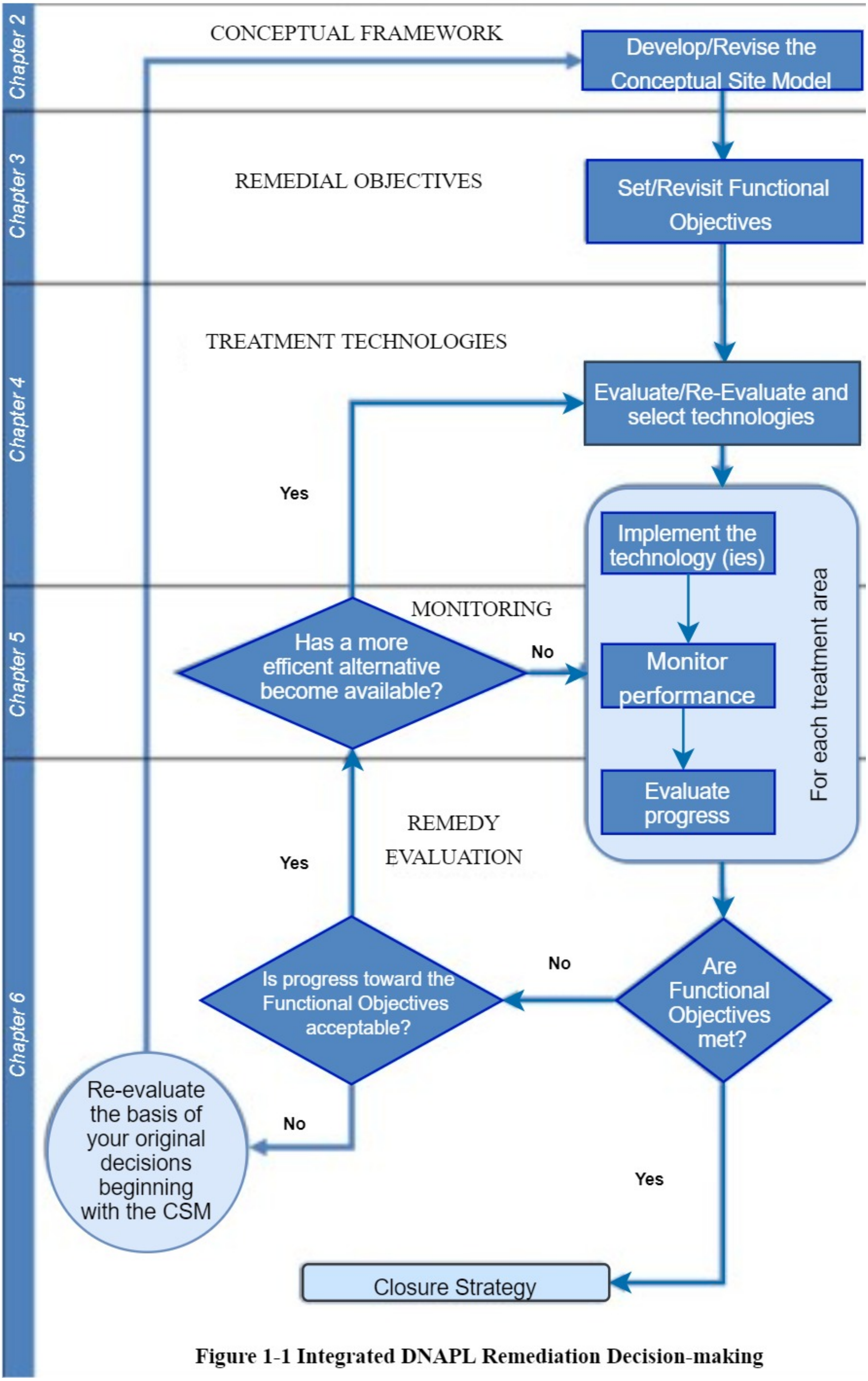

Figure 1-1 Integrated DNAPL Remediation Decision-making