Technology Overview

Using Remediation Risk Management to Address Groundwater Cleanup Challenges at Complex Sites

January 2012

Prepared by
The Interstate Technology & Regulatory Council
Remediation Risk Management Team

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RRM-2

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EXECUTIVE SUMMARY

Remediation programs for groundwater remediation share the ultimate goal of restoring groundwater to beneficial use. Based on past experience, groundwater remediation to final goals and objectives can be achieved successfully at most sites but remains challenging at highly complex sites. This document applies the framework of project risk management for site remediation to identify and manage such challenges. The term “remediation risk management” (RRM) is used to describe this approach of project risk management for site remediation.

The RRM process is a course of action through which project risks related to site remediation can be holistically addressed to better achieve secondary objectives of remediation (e.g., efficiency, timeliness, cost-effectiveness) while supporting the primary objective of remediation, namely protection of human health and the environment. The RRM process is described in more detail in *Project Risk Management for Site Remediation* (ITRC 2011). When applied to the issue of groundwater cleanup at highly complex sites, the RRM process can help project managers identify key technical challenges; evaluate the likelihood and impact of these challenges on the remedial strategy; and mitigate these challenges through better design, evaluation, and operation of groundwater treatment and management systems. This document identifies and evaluates several key technical challenges for groundwater remediation at highly complex sites. As part of the mitigation measures for project risks associated with those technical challenges, the document also describes several long-term management designations and approaches used at complex sites to maintain protectiveness of human health and the environment over long time frames. These long-term management designations and approaches are typically one part of an overall site-specific remedial strategy that complies with existing regulations. Examples include the use of technical impracticability waivers, greater risk waivers, state designations for groundwater management zones, and site management using phased approach. The use of these designations at other highly complex sites is demonstrated through case studies.

This document is intended to inform state regulators, practitioners, and other stakeholders who are evaluating technical cleanup challenges within their own programs. This document does not address policy questions associated with setting remedial goals and objectives, nor does it evaluate the acceptability of different project risk management strategies. Finally, the RRM process does not replace any existing regulations or process under the National Oil and Hazardous Waste Contingency Plan; Comprehensive Environmental Response, Compensation, and Liability Act; Resource Conservation and Recovery Act; or any other regulatory program.

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1. OVERVIEW

Over the past several decades, environmental remediation professionals in general and the U.S. Environmental Protection Agency (USEPA) as well as state regulatory programs in particular made significant strides in remediating groundwater and ensuring human health and environmental protection at contaminated sites. Groundwater resources are routinely restored to beneficial use under regulatory oversight provided by USEPA, other federal agencies, and state regulators. Remediation is typically accomplished through one or several of the following approaches: source removal and reduction, plume treatment to reduce the size and extent of contamination, plume containment to limit extent of contamination, monitoring, and institutional controls. Traditional and innovative remediation technologies are being used for groundwater cleanup. However, a small percentage of environmental remediation sites are highly complex, and it may not be practicable to restore the entire groundwater plume to beneficial uses at these sites within a reasonable time frame.

This document applies the framework of project risk management for site remediation provided by the Interstate Technology & Regulatory Council (ITRC) Remediation Risk Management (RRM) team to address groundwater remediation challenges at highly complex sites where remedial objectives may not be achieved within a reasonable time frame. RRM is a process through which key project risks related to remediation (termed “potential project risk events”) are identified, evaluated, and mitigated to minimize their probability of occurrence and/or consequences (ITRC 2011). Results are monitored over time and reported to stakeholders so that the analysis of key project risks can be adjusted if needed. The thought process outlined by RRM can be used by decision makers at various stages of the cleanup process, including remedy selection, design, implementation, and operation. The RRM process is described in more detail in the ITRC technical and regulatory guidance document titled *Project Risk Management for Site Remediation* (RRM-1, ITRC 2011).

Regulatory programs specify the process for selecting a remedy. For example, nine criteria for Comprehensive Environmental Response, Compensation, and Liability Act (CERCLA) sites or similar Resource Conservation and Recovery Act (RCRA) corrective measure evaluation criteria for RCRA sites are used to guide remedy selection. The RRM process (ITRC 2011) does not replace these criteria or any other program requirements for remedy selection. Rather RRM is meant to improve remedial decision making by identifying project risks and considering these during remedy selection and implementation. The RRM process aids the site management team in evaluating site characteristics and establishing decision points for evaluating groundwater restoration potential throughout a plume during the design and implementation of a selected groundwater restoration remedy. The characteristics and decision points identified in the RRM process should be continually evaluated and addressed as new information becomes available during the remediation process.

Following proper site characterization, remedy selection, remedy implementation and optimization, as shown on Figure 1-1 (Steps 1–3), remediation will result in achieving cleanup goals at many sites (Step 5 in Figure 1-1), for example, restoration of groundwater to drinking water standards within a reasonable period of time. However, there are sites where remediation goals cannot be achieved because of complex geological and hydrological conditions, technological limitations, contaminant physical properties, and chemical distribution; technology or remedial action objectives (RAOs) modification become necessary (Step 4 in Figure 1-1). This document discusses some approaches to understand, quantify, mitigate, and manage those specific project risks which may cause the remediation project to be placed into the technology and RAOs modification step (Step 4 of Figure 1-1) in a prudent and effective manner while protecting human health and the environment.

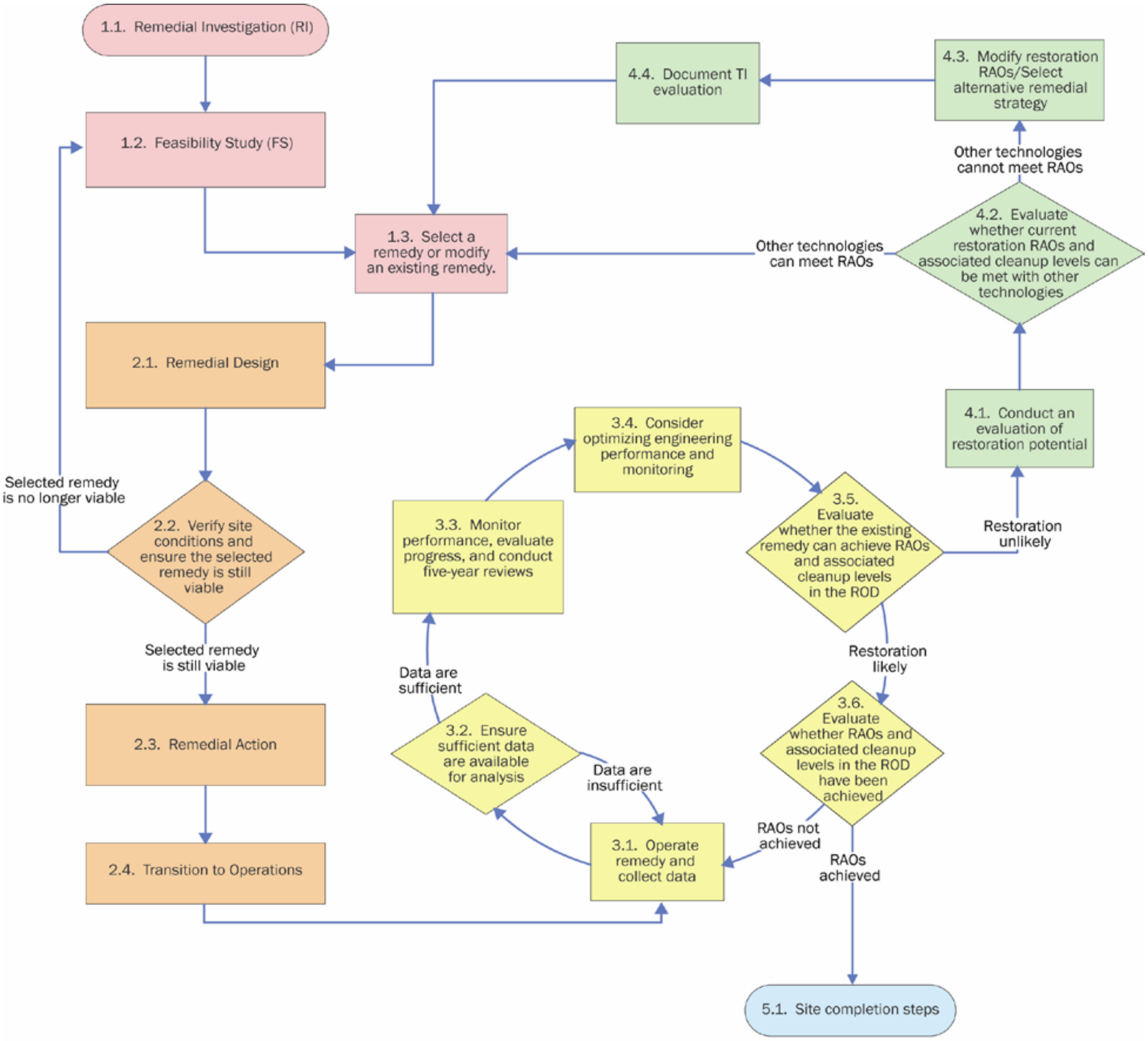

Figure 1-1. Recommended process for restoring contaminated groundwater at Superfund site. *Source*: USEPA 2011.

This document is intended to inform state environmental agencies who are evaluating the issue of long-term management and remediation at complex sites within their own programs and to illustrate how the RRM process can provide insights to the situation and aid in decision making. Section 2 describes tools and approaches for evaluating the complexity of site conditions. Section 3 provides examples of long-term management approaches used at other complex sites to acknowledge the long time frame to achieve remedial goals and maintain protectiveness of human health and the environment. Examples include modifying RAOs, technical impracticability (TI) waivers, greater risk waivers, groundwater management zones, site management using phased approach, alternative concentration limits (ACLs), and a variety of other state- and program-specific designations.

For more information about how to consistently and appropriately apply to these long-term management designations at complex sites, users of this document should consult the appropriate regulatory agency. This document does not address policy questions associated with setting remedial goals and objectives; nor does it evaluate the acceptability of different project risks.

1.1 The RRM Process

As defined in RRM-1, RRM is a course of action through which all project risks related to remediation (including site investigations, remedy selection, design, implementation, and completion) are holistically addressed to better achieve secondary objectives of remediation (i.e., efficiency, timeliness, cost-effectiveness) while supporting the primary objective of remediation, namely protection of human health and the environment.

The RRM process encompasses a broad set of project risk types which may affect the success of a project, including the following:

- remedy feasibility risks (project risks that limitations of a remedy are not properly evaluated or communicated)
- remedy selection risks (project risks that the selected remedy is not appropriate)
- remedy construction, operation, and monitoring risks (e.g., accident risks, uncontrollable environmental impact risks due to remedy construction or operation, cost and scheduling risks including funding and contracting issues)
- remedy performance risks (project risks that the remedy will not perform as intended, requiring optimization efforts and perhaps reevaluating the feasibility of the selected remedy)
- other unintended project risks of the remedial process, such as greenhouse gas emissions, energy consumption, and other green and sustainable impacts of the remedial decisions

The RRM process can reduce project risk and uncertainties, leading to more reliable protection of human health and environment, better project management, reduced time and cost associated with remediation decision making, and successful site closure (ITRC 2011).

The RRM process has grown out of prior related efforts by ITRC and the environmental remediation community. ITRC's Remediation Process Optimization (RPO) Team produced a document titled *Remediation Process Optimization: Identifying Opportunities for Enhanced and More Efficient Site Remediation* (ITRC 2004a), which synthesized the various efforts into a coherent evaluation process. In 2007, the ITRC RPO Team published a technical and regulatory guidance document on performance-based environmental management (PBEM), a project management methodology intended to make use of several available tools in a life cycle–long project management program (ITRC 2007). The PBEM process evolved along with long-term monitoring optimization programs, such as the Monitoring and Remediation Optimization System (MAROS, AFCEE 2009), remediation system evaluation tools (USACE 2009), and most recently, ITRC's RRM-1 (ITRC 2011). Users of the above guidance documents need to ensure that the processes are applicable within the regulatory program under which cleanup is being conducted.

RRM collects a series of different tools and frames their use as part of a holistic examination of the site remediation process, with a focus on project risks. RRM considers and addresses project risks associated with site remediation from investigations and studies through remedy selection, implementation, and site closure. As recommended by the PBEM guidance (ITRC 2007), it is important to communicate the proposed RRM planning process to regulators and other stakeholders from the beginning of site investigation. Thus, by the time the RRM evaluation is considered, responsible parties, consultants, regulators, and the public are aware of each other's and other stakeholders' concerns and ready to identify and address key project risks.

1.2 Survey of State Needs and Interests

The RRM Team surveyed ITRC member states through the ITRC State Point of Contact network to capture how states are addressing remediation project risks and other remedial issues and to aid in the development of RRM-1 (ITRC 2011). A survey addendum was also issued to gain an understanding of states' interests in assessing the technical challenges to groundwater cleanup at all sites not specifically at complex sites. Combining responses to the initial survey and the survey addendum, a total of 30 states (65% of those contacted) responded to the survey. The majority of respondents worked for state environmental cleanup and hazardous waste management programs. Also represented were underground storage tank management, water quality, and Superfund programs. Key findings from the survey include the following:

- Several approaches are considered by states/state programs for long-term management, including monitored natural attenuation (MNA) (24)[1], land use controls (24), long-term monitoring (23), TI waivers (19), ACLs (13), combinations of alternatives (13), additional modeling (11), and mixing zones (6).
- These same alternatives are considered by states/state programs when progress towards remedial objectives is slow.
- States/state programs have a variety of existing protocols for technical assessment.
- States/state programs would benefit from knowing how to technically assess whether remedial objectives will be met using available technologies.

State representatives' responses to the ITRC survey indicated that states are currently using a variety of different management approaches to address contaminated groundwater remediation project risks but are also interested in a document that describes methods to evaluate whether

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[1] The number of responses is indicated in parentheses.

groundwater cleanup objectives will be met. This document provides context for determining (a) whether or not cleanup objectives can be met within a reasonable time frame at a variety of complex sites using the best available technologies and (b) how project risks associated with residual contamination can be mitigated through long-term management.

This document discusses the overarching concepts. There are numerous innovative treatment technologies and site characterization tools that should be considered to maximize the potential for groundwater restoration.

1.3 Using the RRM Process at Complex Sites

As described in RRM-1 (ITRC 2011), the RRM process includes the following steps:

1. <u>Project risk identification</u>. In general, this step involves identifying and describing in detail the potential project risk events that could affect groundwater remediation and protection of human health and the environment. Section 2 provides more details.

2. <u>Project risk evaluation</u>. This step addresses both the probability that the project risk event will occur and the adverse impacts that could result. This RRM element might focus on aspects of the conceptual site model (CSM), groundwater modeling predictions, or treatment system performance over time to evaluate how likely it is that the identified potential project risk events will occur. Section 2 provides more details.

3. <u>Project risk mitigation</u>. In this RRM element, strategies to prevent or mitigate the potential project risk event or position contingency response decision logic are developed. These would mitigate or streamline the process of optimizing or adapting remedies in the future, should the potential project risk event occur. Section 3 describes several ways to formally acknowledge and mitigate potential risks. Project risk mitigation may also involve identifying ways to reduce uncertainty in achieving the goal.

4. <u>Project risk monitoring</u>. This step specifies the way in which the project will be tracked over time to ensure that the project risk mitigation strategies have been successfully implemented and to identify and evaluate new project risks in a reasonable time frame.

5. <u>Project risk reporting</u>. This step summarizes the results from project risk monitoring and communicates results to stakeholders. For example, project risk results from different sites might be compiled and assessed at the program level.

Project risk planning is an iterative process that addresses each of the RRM elements. Each RRM element can be documented in a project risk management plan, which assigns responsibilities and establishes project risk reporting requirements. RRM planning should get under way as soon as site assessment and the remedy selection process begin (ITRC 2011).

2. IDENTIFYING AND EVALUATING GROUNDWATER REMEDIATION CHALLENGES AT COMPLEX SITES

The first steps of the RRM process are project risk identification and evaluation. The type of project risk event addressed in this overview document can be identified as not achieving remedial objectives for groundwater within a reasonable time frame due to underlying technical challenges. Project risk evaluation considers the probability that each identified project risk event will occur, as well as the significance of the resulting adverse effects. The following sections provide more detail on these steps. Assessment of these factors may identify a need to formally acknowledge the long time frame and to develop alternative remedial approaches to address groundwater contamination, as described in Section 3.

2.1 Source Removal, Source Control, and Restoration to Drinking Water Standards, Where Practicable

At all contaminated sites in a typical remediation process, source control and source remediation are not only considered but implemented as much as possible. At most remediation sites, effective remediation is possible to achieve restoration goals within reasonable time frames once the source removal or source control is achieved. Under the leadership of the federal agencies and state regulatory programs, the environmental industry made considerable progress in the last three decades in identifying, evaluating, and remediating sites to restore groundwater to drinking water standards. Thousands of sites have been restored to drinking water cleanup standards that are appropriate for their specific locations and applicable regulations. From the days of just controlling the plume movement or containing the extent of the plume using methods such as in situ treatment, pump and treat, etc., the remediation process has come a long way in completely eliminating the plumes at hundreds of sites. This goal was normally accomplished by source identification, control, and complete removal. Aggressively attacking the source regions and focusing on remediation aimed at source removal to the maximum extent possible, most of these sites have been completely restored groundwater to drinking water standards. *Groundwater Road Map* (USEPA 2011) clearly recommends an evaluation of restoration potential for groundwater contaminated sites as source control measures are critical to the success of aquifer restoration efforts. If sources are identified, they should be addressed. The emphasis should be on the "demonstration that contamination sources have been or will be identified and removed or treated to the extent practicable" during the evaluation of the restoration potential at a site (USEPA 2003). However, proper source delineation, removal, and control may have inherent uncertainties at complex sites; these sites may require approaches that go beyond source treatment and need additional approaches to address contaminants that potentially may not be completely remediated. The following sections further discuss challenges in understanding contamination and restoring the aquifers that complex sites may pose.

2.2 Identifying Technical Challenges to Groundwater Restoration

Gaining a better understanding of the underlying technical challenges to groundwater restoration is necessary to identify the nature and likelihood of the potential project risk events. At most sites the overall remedial goal is to restore groundwater to drinking water standards or other applicable standards (e.g., background water quality). However, at complex sites, groundwater restoration may take many decades, centuries, or even longer due to technical cleanup challenges. Technology-specific challenges are not described in this document. These would likely need to be addressed on a site-specific basis as part of a feasibility study or optimization effort. Several documents have been written in applying a comprehensive approach to remediation (ITRC 2007) for restoring groundwater to the required goals. Source removal (USEPA 2011, USEPA 2009b), groundwater source zone (MassDEP 2011, Utah DEQ 2011, NJDEP 1995), plume control (Keely 1989), and innovative technologies (USEPA n.d.) for remediation all will contribute to successful restoration of groundwater at contaminated sites. This section focuses on the underlying factors that may contribute to the technical challenges of meeting groundwater cleanup goals and objectives using any available technology. Some examples of technical challenges are the nature and extent of contamination, hydrogeologic setting, and other factors.

2.2.1 Contaminant-Related Challenges

Contaminant properties govern the behavior (fate and transport) of contaminants and mixtures in the environment. Chemical and physical properties may significantly influence the ability and time frame for groundwater remediation technologies to reach groundwater restoration goals such as drinking water standards. Factors relating to contaminant history may also limit groundwater cleanup and potentially reduce the effectiveness of many technologies. Examples include the nature and properties of the source, mass and extent of contamination, and overall volume and depth of contaminated media. In general, contaminant-related challenges may include one or more of the following:

- form of the contamination in the environment (e.g., dissolved, sorbed, present as a light or dense nonaqueous-phase liquid [NAPL])
- depth and lateral extent of contamination (e.g., regional contamination from acid mine drainage or from various sources discharging into receiving surface water body)
- transformation or degradability by biotic or abiotic processes
- partitioning properties, including NAPL dissolution rate, aqueous solubility, volatility, and adsorption affinity
- for NAPL, mobility factors such as interfacial surface tension, viscosity, and specific gravity
- presence of persistent and ubiquitous anthropogenic contaminants (such as DDT, polycyclic aromatic hydrocarbons)

The most common contaminant-related challenge for groundwater remedial efforts is the presence of the contaminant(s) as dense, nonaqueous-phase liquid (DNAPL) although the presence of DNAPL does not necessarily mean that remediation is infeasible (USEPA 1993). DNAPL characterization and remedial technologies have evolved to enable the detection and removal of substantial contaminant mass. Source material not addressed may affect restoration, and the presence of DNAPL in saturated, heterogeneous, and/or fractured geologic media continues to pose significant problems. USEPA summarized these cleanup challenges in a report titled *Recommendations from the USEPA Ground Water Task Force* (USEPA 2007) and published a discussion paper titled “Cleanup Goals Appropriate for DNAPL Source Zones” as Attachment A to that report. The publication of a recent USEPA report titled *DNAPL Remediation: Selected Projects Where Regulatory Closure Goals Have Been Achieved: Status Update* (USEPA 2009a) cited only a few examples of meeting drinking water quality standards for groundwater throughout the aquifer at DNAPL sites. At the Dry Clean USA #11502 site in Orlando, Florida, in situ chemical oxidation with hydrogen peroxide, pump and treat, and soil vapor extraction (SVE) were used to clean up tetrachloroethene (PCE) over a period of 3.5 years within a sandy area that was 800 × 300 feet to a depth of 68 feet (USEPA 2009a). The Pasley Solvents and Chemicals, Inc. site in Hempstead, New York relied on SVE and air sparging to remediate groundwater in sands and gravels within a 60 × 400 foot area containing *trans*-1,2-dichloroethene and other chlorinated solvents.

USEPA also recognizes that there are other contaminant-specific challenges to groundwater remediation technologies, such as the slow rate of contaminant desorption from aquifer materials (USEPA 1993). In recent years, mass storage in hydraulically stagnant zones within the plume and subsequent slow diffusion into transmissive zones have been recognized as a challenge to aquifer restoration beyond the source zone (Sale et al. 2007).

2.2.2 Hydrogeologic Challenges

Complex geological and hydrological conditions at a site can impose enormous challenges to understand, evaluate, and address contaminated sites. Factors such as the subtle variations in geology within a limited vertical and horizontal distances, anisotropy, preferential geological formations, fractures and fault zones, physical properties of aquifers, hydraulic properties of contaminants and interaction with the groundwater, ability to identify these subtle changes and appropriately monitor using targeted wells, etc. can all affect the ability to define the nature and extent of contamination in subsurface and appropriately address with remediation technology that can be effective at the site.

In highly heterogeneous or otherwise complex hydrogeologic settings, the characterization and removal of contaminants may be difficult. Complex hydrogeologic conditions, as they pertain to aquifer restoration, arise from local variations in porosity, hydraulic conductivity, and other parameters that originate during the natural development of geological systems. High-resolution, next-generation characterization tools have been developed to delineate contaminant distribution in the subsurface. However, these tools are generally not adequate in the most complex hydrogeologic settings such as deep alluvial basins, karst aquifers, and fractured bedrock aquifers. A report prepared for the U.S. Army Environmental Center (Malcolm Pirnie 2002) discusses the unique challenges presented at karst sites. Ultimately, a combination of complex geology and contaminant-related factors may combine to pose remedial challenges, despite advances in characterization and remediation technologies.

2.2.3 Other Challenges

Other challenges in groundwater remediation may include barriers to accessing contaminated media, such as buildings and other structures, surface activities, wetlands, and endangered species habitats. There may be subsurface hydrogeologic difficulties in accessing contaminated media, such as low-yield aquifers or hydraulic connections to rivers. Neighboring sites, if their contaminations have not been addressed before remediation, may contribute contamination to the groundwater plume, potentially recontaminating an area after it is treated. These factors, as well as potential legal issues associated with commingled plumes, such as litigation between responsible parties, can pose obstacles to implementing effective treatment or hydraulic containment systems.

Another challenge in groundwater remediation is "inordinate cost," defined in relative rather than absolute terms. This can be a factor in determining impracticability but is subordinate to technical or engineering constraints (USEPA 1993). Compliance with cleanup requirements is not subject to a cost-benefit analysis, and cost is not as important as protectiveness (see Section 3.1, USEPA 1993). The preamble to Section 300.430(f)(1)(ii)(C)(3) of the National Oil and Hazardous Substance Pollution Contingency Plan (NCP) states the following:

> EPA believes that cost should generally play a subordinate role in determining practicability from an engineering perspective. Engineering practice is in reality ultimately limited by costs; hence cost may legitimately be considered in determining what is ultimately practicable. On the other hand, if cost were a key criterion in determining the practicability of an ARAR [applicable or relevant and appropriate requirement], ARARs would likely be subjected to a cost-benefit analysis rather than a test of true practicability.

Cost is one of the nine CERCLA criteria and one of the RCRA corrective measures factors considered during the remedy selection process. Although this document focuses primarily on technical challenges to remediation, some complex sites have expressed these challenges in terms of inordinate cost. Operation and maintenance are also considerations for containment remedies.

2.3 Evaluating the Likelihood of Technical Cleanup Challenges

At a typical remediation site, following the source control and completion of source remediation, the rest of the contamination at the site is evaluated for complete restoration. Applying an existing technology or an alternative technology, including innovative approaches, the restoration of the groundwater across the entire contaminated portions of a site is desired and often achieved. At groundwater remediation sites, technologies must be appropriate for site-specific conditions. Successful remediation is often a result of adequate characterization, accurate identification of sources, and aggressive approach to remove sources and treat portions of contaminated area using a treatment train or combination of appropriate technologies. However, at many complex sites, it may still take long time to achieve remediation goals. Long-term management may be needed to protect human health and the environment. Understanding the appropriate cleanup time frame may help decision makers determine the best approach to remediation and long-term management.

The goal of this step in the RRM process is to assess the likelihood that intrinsic technical challenges will prevent groundwater cleanup goals and objectives from being achieved within a "reasonable time frame," a duration that is not defined in absolute terms but is assessed on a site-specific basis (USEPA 1993). Remedial goals and objectives vary with the cleanup program and may be site specific. At most sites, goals are risk-based concentrations, drinking water standards, or health advisory levels for contaminants of concern either throughout the aquifer or at designated compliance locations. The assessment's focus and level of detail depend on site conditions, the type of available data, and the cleanup program requirements.

Simple assessments to illustrate technical challenges and/or predict remediation time frames can be performed at any stage in the cleanup process using available site characterization data. Example assessments include the following:

- mass estimates in support of the CSM
- groundwater trends, extrapolated to predict remedial performance over time
- DNAPL dissolution, which can limit remedy effectiveness and prolong cleanup time frames
- likelihood of uncontrolled contaminant mobilization during remedial activities
- matrix back-diffusion, which can limit remedy effectiveness and lengthen cleanup time frames in hydrogeologic settings with significant matrix porosity (e.g., clay, fractured rock)
- cost estimates to illustrate inordinate costs, if applicable

If site-specific treatability data are available from pilot- or full-scale treatment, a detailed assessment could also include an evaluation of the system's performance and limitations. Such data can be further analyzed using modeling to predict remedial performance, cleanup time frames, and plume stability under a variety of natural and treatment scenarios.

These predictive modeling tools and analyses have been described in previous publications by ITRC, USEPA, and others (for example, ITRC 2004b, USEPA 2003, NRC 2005). Although the assessment methods are fairly straightforward in principle, their practical application at specific sites requires resources (e.g., collection of field data and professional assessment).

State cleanup programs may choose to integrate these assessments into future guidance as appropriate. As noted by one commenter in the ITRC state survey (Section 1.3), state regulators do not typically specify the type of data collection and analyses that will be conducted by responsible parties and their consultants. Rather, responsible parties are asked to meet certain regulatory requirements, and they choose how to go about it. Still, USEPA and some states publish guidance and other protocols to help responsible parties anticipate and address regulator concerns before conducting field work and submitting technical assessments for regulatory review. Issuing guidance can also facilitate a state's own review process and encourage procedures that are consistent among sites in the same cleanup programs.

2.3.1 Conceptual Assessments of Cleanup Challenges

The following assessments can be used to evaluate the intrinsic technical challenges and predict time frames that would be required to completely remediate contaminated groundwater. These assessments may assist in remedy decision making but not replace regulatory remedy decision framework and requirements.

Mass estimates

Subsurface mass estimates form the basis for assessment of remedy performances, remedial time frames, and cost. Mass estimates can be expressed as a rough approximation or as a range of values. Mass estimates can be expressed as a rough approximation or as a range of values. Typically, contaminant mass is quantified using an approach that illustrates the amount of mass present in different forms (DNAPL, aqueous, gaseous, sorbed, diffused into solid pore spaces) and at different depths (e.g., saturated vs. unsaturated zone, in different aquifers and aquitards). The mass estimate therefore illustrates the overall magnitude of the contamination problem in each contamination zone and identifies the type of mass storage reservoirs (e.g., soil, rock fractures and rock matrix) where contaminants are expected to be present. General mass balance equations and estimates of DNAPL residual saturation have been previously published (for example, Mayer and Hassanizadeh 2005).

A wide range of estimated mass indicates a high level of uncertainty that may make it difficult to design treatment systems and increases the project risk of remedial performance. At some sites, particularly if they are early along in the site cleanup process, this uncertainty can be reduced through more site characterization. At other sites, extensive characterization data have already been collected, yet a high degree of uncertainty remains because of the nature of the hydrogeologic setting, magnitude of the contaminated area, and/or inability of current technology to effectively characterize the site. Natural heterogeneity may occur over a small scale so that two samples collected in close proximity to each other nevertheless yield different results. A high degree of uncertainty in subsurface conditions to derive the mass estimate, despite best efforts at site characterization, may indicate that there is a significant project risk of remedial performance.

Groundwater concentration trends

Trends in contaminant concentrations can be extrapolated to predict remedial time frames. When interpreted spatially, trends in groundwater concentrations can also be used to assess plume stability over time, a key question if preventing migration is one of the remedial objectives or if natural attenuation is being evaluated as a treatment option. A comparison of actual contaminant trends with the reduction needed to achieve remedial goals can help determine the effectiveness of the treatment technology being employed.

DNAPL dissolution

Many technologies such as pump and treat primarily address aqueous-phase contamination. If DNAPL is present, the rate of DNAPL dissolution can be used to predict the minimum remediation time frame using pump-and-treat technology. One method for predicting DNAPL dissolution rates is to measure mass discharge coming from the source area per unit time (pounds per day) while dissolved-phase contaminant concentrations remain fairly steady (ITRC 2010). Based on the projected rates of removal, the total mass in the source area can be divided by the projected mass removal rates to estimate the remedial time frame. This approach assumes that DNAPL is completely accessible to dissolve into the flowing groundwater and that the dissolution rate is constant until the entire mass of DNAPL has dissolved. In reality, DNAPL in high- and low-flow zones may dissolve at different rates. A method that does not take this variability into account will likely underestimate the actual required time frame.

DNAPL dissolution rates can be enhanced through biological treatment. For example, anaerobic enhanced bioremediation has been demonstrated to enhance PCE DNAPL dissolution (Carr, Garg, and Hughes 2000; Yang and McCarty 2002; Ward et al. 2009). In the field, demonstrations of enhanced DNAPL dissolution rates may be confounded by associated changes in subsurface permeability and groundwater flow (ESTCP 2008b). DNAPL dissolution rates can be used to estimate the impact of aggressive remediation on remedial time frames.

DNAPL mobilization

Remedial activity in source areas has the potential to mobilize DNAPL pools and ganglia. Without a containment system or an underlying confining layer, DNAPL can move downward, spreading contamination to deeper aquifers. DNAPL mobilization can be calculated as a function of entry pressure and pore size/fracture aperture. The ability to prevent DNAPL mobilization is a function of uncertainty in DNAPL extent and the feasibility of hydraulically controlling the area where in situ remedial technologies are applied. The project risk of DNAPL mobilization may preclude the use of a number of remedial technologies without proper containment or in situ strategy in source areas.

Matrix back-diffusion

Matrix diffusion refers to the process of contaminant dissolution into groundwater and diffusion under a concentration gradient from matrix material into matrix pore water in open fractures until aqueous concentrations in the fractures and the matrix equilibrate (see, e.g., Parker, Gillham, and Cherry 1994). In the presence of DNAPL, this process eventually decreases the DNAPL mass held in the pore space, slowing the migration of the concentration front in the matrix. In fractured rock settings, the storage capacity of the matrix can be significant compared to the storage capacity of the fractures, and matrix diffusion can account for the complete disappearance of DNAPL from fractures (Parker, Gillham, and Cherry 1994). For example, in rock with fracture apertures <1 mm and matrix porosity >5%, the total void space in the matrix of fractured media is orders of magnitude larger than the void space provided by the fracture network. Matrix diffusion can also be significant in low-permeability zones (silts and clays). An implication of matrix diffusion is that the bulk of dissolved- and sorbed-phase contamination may be located in the matrix and not in the interconnected fractures when the void space of the matrix is larger than the void space of the fractures. This is also true in nonfractured environments with high heterogeneity, where high-permeability zones may be coarse-grained sands and gravels interbedded with low-permeability silts and clays with significant storage capacity.

After DNAPL has been depleted, dissolved concentrations in the fractures decline below solubility. The concentration gradient between the fracture and the rock matrix then reverses, causing mass to diffuse back out from the matrix into the fracture. This process, known as “back-diffusion,” is limited by the diffusion rate and is often slower than forward diffusion because the concentration gradient is not as high. The mass flux coming from the matrix will continue to feed contaminant mass into groundwater over this time period (Reynolds and Kueper 2002).

At sites with significant matrix storage capacity and high contaminant concentrations (e.g., historical presence of DNAPL in contact with clays or fractured rock), the back-diffusion of stored contaminants into the pore space from the matrix can significantly prolong elevated groundwater concentrations, contribute to rebound after treatment system operation, and lengthen cleanup time frames.

Cost estimates

Rough cost estimates, using unit costs, can illustrate the impact of remedial complexities and technical challenges on cost. Under most cleanup programs, remediation is not subject to a cost-benefit analysis (see Section 2.2.3). "Inordinate cost" is language used in the NCP and defined in relative than absolute terms. Quantitative cost estimates of treatment scenarios must be compared based on other equally effective terms, such as remedial efficiency and time frame, community acceptance, etc. to assess cost-effectiveness. There are several published examples of CERCLA sites where remediation costs were described as inordinate (Malcolm Pirnie 2004). Inordinate cost can be a way of expressing cleanup challenges and communicating site complexities.

2.3.2 Integration into the CSM

Conceptual assessments can be integrated into the CSM so that it not only describes site conditions but also illustrates the underlying reasons for groundwater cleanup challenges, such as heterogeneous subsurface conditions, the likely presence of DNAPL, mass removal rates, etc. CSMs typically describe the following:

- contaminant types, characteristics, sources, and release mechanisms
- fate and transport processes in the environment, including transport pathways, phase transfer processes and rates, degradation processes and rates, dilution, and other natural attenuation mechanisms
- contaminant distribution in the subsurface, including the hydrogeologic setting and locations and form of subsurface contaminant mass
- current and/or potential future receptors, their locations relative to the site, and any existing or potential future exposure pathways

The CSM serves as a primary framework for evaluating the site's restoration potential. Thus, the accuracy, robustness, and completeness of the CSM are critical to assessing groundwater cleanup challenges and selecting an alternative remedy. The CSM is meant to guide the identification of data gaps, collection of additional data if needed, and the subsequent continual improvement, testing, and necessary updates of the CSM using the newly collected site data.

The conceptual assessments described previously can help communicate the underlying challenges to restoration and help decision makers assess the project risks. Several sources of information and guidance on preparing CSMs have been previously published, including a publication by USEPA (1988), a guidance document specifically addressing CSMs by ASTM International (1995), and an engineering manual produced by the U.S. Army Corps of Engineers (USACE 2003). In addition, USEPA guidance (USEPA 1993) depicts several elements of a CSM and describes the evolution of a CSM that may occur at sites over time as more information is collected.

It may be helpful to evaluate some aspects of the CSM using published literature, case studies, and site-specific treatability studies. Based on contaminant properties and hydrogeologic setting in the CSM, a site scoring system can be used to rank the difficulty of groundwater cleanup (NRC 2005).

2.3.3 Use of Groundwater Models

After evaluation and incorporation of existing site characterization data into the CSM, additional questions may remain that are relevant to assessing the challenges of groundwater remediation. Additional site investigation or more detailed assessments such as groundwater modeling and/or technology testing may be needed. A discussion of risks related to groundwater modeling and verification process is provided in Appendix F of RRM-1 (ITRC 2011). That document emphasizes that models are tools to reasonably project flow and chemical behavior and require calibration and field verification as essential elements of the modeling process. Groundwater models typically address one or both of the following:

- hydraulic modeling/containment over space and time
- contaminant fate and transport modeling/plume stability over space and time

The objectives of these modeling exercises vary. A typical objective is to predict the impact of different active treatment technologies over time, compare this with the baseline conditions, predict remedial time frames, assess plume stability, and assess the overall protectiveness of different remedial options. Modeling may also help to evaluate the benefits of alternative remedial approaches, such as partial mass removal, and answer questions regarding the necessary level of treatment that would be required to meet remedial goals within a given time frame.

Different modeling software packages are available for different purposes. For example, the Naval Facilities Engineering Command (NAVFAC), U.S. Geological Survey, and Virginia Tech recently developed the Natural Attenuation Software (NAS) to use as a screening tool to predict remedial time frames for MNA with varying degrees of source area remediation (ESTCP 2008b). Other multidimensional numerical simulators such as the University of Texas Chemical Simulator (UTCHEM) have also been used (SERDP 2008).

2.3.4 Technology Performance Assessments

At some sites, pilot- or full-scale remediation technologies have already been implemented, and technology test data can be included in the assessment of various technologies and estimating time frame to meet cleanup goals. From the perspective of streamlining the site remediation process, it is better to address technology performance risks early in the cleanup process, prior to conducting pilot- or full-scale technology demonstrations. However, from the perspective of data needed to assess the likelihood and significance of poor technology performance, sites that are farther along in the cleanup process have an advantage. These sites are more likely to reach stakeholder consensus on the need for an alternative approach. Below is a discussion of the types of questions that can be answered using treatability study and full-scale remediation data to assess remedial technology performance.

Treatability testing (bench or pilot tests)

When evaluating treatability test plans or existing data from complex sites facing groundwater restoration challenges, it is important to consider a number of questions, such as the following.

Documentation of these questions may be required by regulatory programs or kept for internal planning purposes only.

- What were the study objectives? Were they clearly defined? If so, were the objectives helpful in evaluating intrinsic and/or technology-specific challenges of groundwater restoration? Did the objectives relate only to the feasibility of the technology or also to technology performance?

- What was the rationale for selecting this technology for testing? Was the technology considered “best available technology” for the site? Does the CSM suggest that other technologies could yield more promising results? Was the technology innovative, with the potential to overcome or lessen groundwater cleanup challenges? Could the results of the study be extrapolated to evaluate other technologies?

- How was the study designed? What metrics and measurement methods were used to evaluate the technology’s performance? Were the benefits/drawbacks of the technology appropriately captured by these metrics and measurement methods?

- What level of technology performance would be needed to meet groundwater cleanup goals? Can this question be addressed quantitatively or just qualitatively?

- What scale-up issues and other uncertainties might exist when extrapolating the study results and challenges to full-scale remedial systems? A discussion of key uncertainties of extrapolating study results to full-scale systems is critical to ensuring that pilot-study results can be evaluated. Is the scale of a full-scale remedial system cost-prohibitive or subject to other limitations?

- Were comments solicited from stakeholders (i.e., stakeholders agreed with the study’s objectives, design, and performance matrices), and were they satisfactorily addressed?

Data evaluation and interpretation may be enhanced by referencing lessons learned from technology applications at other sites. A review of technology performance at similar sites could be used to supplement site-specific treatability test results.

Full-scale remedy

An existing remedy may not be making sufficient progress towards cleanup goals despite optimization. Decision makers may have reached the point of evaluating the next steps to meet cleanup goals. Next steps may involve reopening the record of decision (ROD), conducting additional technology evaluations/feasibility studies, and perhaps issuing a new decision document (e.g., ROD amendment or explanation of significant differences [ESD] at CERCLA sites).

It is important to evaluate the reasons that a treatment system did not perform as expected. The improper selection, design, or operation of a technology must be ruled out as the cause of poor performance (USEPA 1993). The following questions should be considered to clarify whether the remediation system is limited by improper technology design and construction:

- Are the operations data sufficient to evaluate treatment system performance? Demonstrate that the monitoring program is of sufficient quality and detail to evaluate remedial action performance (e.g., analyze plume stability, containment, and concentration trends).

- Are there any additional sources of contamination identified following the initial design of the system? If so, document these sources and consider additional requirements that need to be addressed to modify and update the treatment system to improve performance.

- What is the evidence indicating that groundwater cleanup levels will not likely be achieved within a reasonable time frame using the selected technology(ies)? Describe relevant trends in subsurface contaminant concentrations, types and quantities of contaminant mass removed, removal rates, whether the plume is shrinking or stable, and the extent to which these trends are occurring naturally or as a result of treatment conditions. Include other relevant information regarding underlying cleanup challenges, such as whether aqueous-phase concentrations rebounded when the system was shut down or whether contaminated soils on site are contaminating the groundwater.

- Did the remedy function as intended? How did actual system performance compare with the predicted performance? If there were discrepancies between predicted and actual performance, what were the likely reasons for these discrepancies? Were there opportunities to modify operations based on lessons learned or optimization efforts?

- How was the remedy designed and operated? Describe the design and as-built construction information, design basis, operating parameters, system downtime, and any operation and maintenance problems. Demonstrate that the existing remedy was effectively operated and adequately maintained.

- Were enhancements to the original design considered or implemented? Describe and evaluate the effectiveness of any modifications or enhancements to the physical treatment system or operational parameters. Present monitoring data and analyses that illustrate the impact of these enhancements on system performance.

- How was the remedy selected? Would any other remediation technologies likely be more successful? Were these technologies ever evaluated at the site previously? Have new data become available since that time that would change the analysis?

- Is the underperformed remedy more appropriately viewed as the first remedy in a treatment train where, after achieving an interim milestone appropriate for the technology used, another technology is then applied to achieve further remediation? Can this information lead into site management using phased approach?

These are examples of questions that could be considered to rigorously demonstrate that the observed underperformance is not due to inadequate technology selection, design, implementation, operation, and/or maintenance. Such an evaluation may also provide insights into potential effective remedy modifications.

Contingency language (stating that Plan B will be evaluated in the future if Plan A does not meet performance expectations) may be included in the original decision document in an attempt to mitigate the potential project risk of not meeting groundwater cleanup goals. The use of contingency language may reduce some of the administrative decision document amendment requirements and may facilitate the transition to a long-term management approach, perhaps using metrics that were previously agreed upon. If no contingency was considered in the original decision, significant effort may be needed to demonstrate or justify selecting a new approach.

2.4 Evaluating the Adverse Impacts of Technical Cleanup Challenges

Adverse impacts of technical cleanup challenges are identified during this step of the RRM process. Adverse impacts vary based on the cleanup program and site-specific circumstances. Based on experiences at other sites, the following adverse impacts may be associated with technical cleanup challenges:

- <u>Noncompliance with regulations</u>. For example, at CERCLA sites, achieving ARARs is one of two threshold criteria for a final remedy. Remedies that do not achieve ARARs and do not invoke one of the six types of ARAR waivers are not in compliance with regulations. RODs can therefore be reopened on the basis that the remedy is not meeting cleanup objectives. State cleanup programs have similar regulatory requirements.

- <u>Reopening the decision document</u>. Once a decision document has been reopened, additional site characterization may need to be performed and treatability/pilot-scale studies may need to be conducted. Additional time and cost will be needed to select, design, and construct another final remedy.

- <u>Long-term property restrictions</u>. If remedial objectives are not likely to be met within a reasonable time frame, deed restrictions, water-use restrictions, easements, and other property restrictions may be needed to maintain protectiveness. Unplanned property restrictions can delay or disrupt property transactions, discourage prospective buyers, and create conflict with other long-term use plans. Negotiations regarding cost-sharing or legal issues may result at sites where property transactions have already occurred. Some of these project risks can be mitigated through environmental insurance.

- <u>Public perception</u>. Failing to achieve remedial objectives may result in negative perceptions and reduce trust from the public and other stakeholders, particularly if the responsible parties and/or regulators did not communicate the underlying technical challenges to remediation or communicated key messages to other stakeholders that did not match the realities of treatment system performance.

- <u>Litigation</u>. Litigation may result if remedial objectives are not met within a reasonable time frame due to one or more of the complications described previously or to similar claims. The importance of legal project risks should generally be considered on a site-specific basis.

The severity of potential adverse effects can be assessed through the RRM process to determine whether or not project risk mitigation efforts are warranted. Section 3 discusses considering long-term management approaches at complex sites as the project risk mitigation measure.

2.5 Documenting, Monitoring, and Reporting of Project Risk Management for Remedial Actions Not Meeting Remedial Objectives

The RRM process (ITRC 2011) clearly identifies potential risk events associated with remediation projects and requires a plan of action to address those risk events if they are realized. Normally, a project risk management plan details such preplanned risk mitigation measures (as discussed in the following sections). By addressing the project risks at appropriate time during the remedy implementation, the progress toward meeting remediation goals moves forward. A well-planned project risk monitoring and reporting process helps to identify such risks ahead of time and to make course corrections to remediation approaches. Monitoring and reporting such risks as part of the site remediation management process can result in taking appropriate actions for ensuring protection of human health and the environment.

3. CONSIDERING LONG-TERM MANAGEMENT AT COMPLEX SITES

At some sites, the potential project risk of not meeting final groundwater cleanup goals in a reasonable time frame is determined to be significant. A variety of long-term management approaches may be considered to mitigate this project risk. Long-term management strategies provide an option to modify groundwater cleanup goals and proceed with a remedial strategy that will maintain protectiveness of human health and the environment.

Several of these long-term management approaches must waive the final groundwater cleanup standard, replacing it with other remedial action goals and objectives to maintain protectiveness of human health and the environment. For example, if technical challenges prevent statutory cleanup requirements from being achieved at CERCLA sites, a waiver of those requirements may be invoked based on technical impracticability (USEPA 1993). Nearer-term remedial goals or objectives may be established to guide other aspects of remediation. Phased approaches to remediation may be appropriate to meet nearer-term goals, e.g., iteratively conduct remediation, collect performance data, and dynamically adjust the remedial system within the specifications of the final remedy.

This section describes important considerations to mitigate project risks that are common to all remedial approaches that involve long-term management, including remedy performance, the value and purpose of various long-term management designations in the overall site remediation strategy, and stakeholder perceptions. Types of long-term management designations that have been used to address technical challenges of groundwater cleanup, as described in this document, include the following:

- modifying RAOs
- ARARs waiver based on TI, also known as a TI waiver
- ARARs waiver based on greater risk to human health and the environment
- ACLs
- groundwater management zone
- site management using phased approach

3.1 Maintaining Protectiveness

Protecting human health and the environment is one of the threshold criteria for any remedial approach, and it is one of the fundamental objectives of any federal or state cleanup program. Any long-term management approach must be protective of human health and the environment. This point was emphasized by USEPA in its guidance document on TI waivers (USEPA 1993), which states that ARAR waivers must not and do not waive protection of human health and the environment. In fact, if a remedy is not likely to be protective in the future, it is not considered in compliance as a final remedy. This is one of two USEPA criteria for determining TI from an engineering perspective, along with engineering infeasibility (where current engineering methods and best available technologies designed to meet ARARs cannot reasonably be implemented) (USEPA 1993).

3.2 Modifying RAOs

Under state cleanup authority, in conjunction with groundwater management zone, containment zone, or groundwater classification, as discussed in Section 3.5, many state remediation programs accommodate designation of alternative RAOs. These are managed based on site-specific conditions, such as source zone control, stable/declining dissolved-phase concentrations, and no potential receptors and pathways connecting the sources to receptors. For example, when groundwater contamination is contained on the property of a facility, states such as Colorado (CDPHE n.d.) and South Carolina (SCDHEC 1997) use a tiered approach to establish alternative designations (standard, site-specific, and applying covenants or deed restrictions, as appropriate) to manage contaminated sites. Certain states will consider that the level of protection is adequate for closure with provisions for enforceable covenants combined with site-specific alternative designation of RAOs.

Certain concentration limits could be set based on the fact that there is no potential for future migration of contamination off site over the maximum contaminant levels (MCLs), while the institutional controls are in place to ensure the on-site use of groundwater and exposure to potential receptors is eliminated. This approach allows an alternative designation of RAO "to ensure no contamination moves off site above MCLs."

Other state designations take into account cleanup costs and benefits as well as underlying technical challenges. For example, the Ohio Voluntary Cleanup Program has an urban setting designation that recognizes cleanup to drinking water standards may not necessary at many urban sites (Ohio EPA 2009).

Under CERCLA, for drinking water aquifers, restoration objectives may generally be modified if ARARs have been waived (see Section 3.3).

3.3 Waiver

At CERCLA sites, the TI waiver process is an example of a formal approach. This decision is documented in the ROD or ROD amendment.

A determination of TI can also be issued at RCRA corrective action sites. Such waivers are consistent with the May 1, 1996 Advance Notice of Proposed Rulemaking (ANPR) for RCRA sites. This proposed rule was never issued by USEPA because most states were becoming authorized to implement RCRA corrective action in place of USEPA. To avoid conflicting regulations, USEPA announced the ANPR as guidance. As with CERCLA sites, at RCRA sites USEPA requires that a determination of TI be accompanied by a remedial strategy that limits human and environmental exposures and is consistent with the overall remedial action objectives. Parallels between the RCRA and CERCLA programs are encouraged under the ANPR, which states, "…as a general philosophy, USEPA believes that RCRA and CERCLA remedial programs should operate consistently and result in similar environmental solutions when faced with similar circumstances." Therefore, the RCRA determination of TI process may reference USEPA guidance for CERCLA sites.

State cleanup programs have a number of formal designations that are similar to CERCLA TI waivers. For example, the California State Water Resources Control Board (SWRCB) has a containment zone policy, which is documented in SWRCB Resolution 92-49. At least nine other states (Connecticut, Georgia, Illinois, Missouri, Mississippi, New Jersey, North Carolina, Texas, and Wyoming) and the District of Columbia consider TI in their corrective action policies within at least one of their cleanup programs. Formal state approaches to TI may take the form of a groundwater management zone or local reclassification of the beneficial uses of the impacted groundwater.

3.3.1 ARAR Waiver Based on Technical Impracticability

"Technical impracticability," a term used to describe technical/engineering challenges to the complete restoration of contaminated groundwater within a reasonable time frame, is listed in the NCP as one of six reasons to waive ARARs. USEPA's primary guidance illustrating the TI evaluation process (USEPA 1993), issued in 1993 and still used, outlines a consistent, site-specific approach for evaluating the TI of groundwater cleanup and establishing protective alternative remedial strategies if restoration is determined to be technically impracticable within a reasonable time frame.

Per USEPA (1993) guidance, a TI waiver relates to certain contaminant(s) for which chemical-specific ARARs cannot be achieved within a reasonable time frame due to technical challenges. The TI waiver defines the volume of the aquifer within which the waiver applies. The document also described the process for evaluating whether a TI waiver was appropriate at a given site. Although this analysis must be site specific, the document describes site characteristics that can lead to a determination of TI. It also identifies the necessary components of a TI evaluation and stipulates that a protective remedial strategy must be developed in place of achieving ARARs within the TI zone. As stated previously, TI waivers are just one component of the final remedy, which may include source zone and/or plume treatment, containment, monitoring, institutional controls, and engineering controls to protect human health and the environment (USEPA 1993). The decision is documented in the ROD or ROD amendment.

USEPA subsequently issued *Memorandum: Consistent Implementation of the FY 1993 Guidance on Technical Impracticability of Groundwater Restoration at Superfund Sites* (USEPA 1995).

This implementation memorandum attempted to standardize the decision-making process and implementation of TI waivers in different USEPA regions. Other regulatory agencies have since provided guidance on TI waivers or other approaches to these issues. A TI waiver may be considered during any stage of the remedial process. For CERCLA sites, USEPA believes that in many cases TI decisions should be made only after interim or full-scale remediation systems are implemented. This step, referred to as a "post-implementation TI waiver," is based on data from the remediation system and is documented in a ROD amendment. In some cases, TI decisions may be made prior to remedy implementation. Referred to as "front-end TI waivers," these decisions must be supported adequately by detailed site characterization and data analysis, and the evaluations should focus on those data and analyses that define the most critical limitations to groundwater restoration (USEPA 1993).

3.3.2 ARAR Waiver Based on Greater Risk to Human Health and the Environment

This ARAR waiver applies if compliance with the ARAR would result in greater risk to human health and the environment compared with another alternative that does not comply with the ARAR (NCP Preamble, Section 300.430 (f)(1)(ii)(C)(2)). The determination of what constitutes a greater risk is made by assessing the magnitude, duration, and reversibility of adverse impacts resulting from compliance with the ARAR compared to the impacts resulting from a remedy that does not comply with that ARAR (53 FR 51439). The nature of the potential greater risk varies with site circumstances. Some examples taken from real case studies include the following (ESTCP 2010):

- greater risk to drinking water aquifer(s) due to potential contaminant mobilization during remedial activity

- greater risk to nearby wetlands, agriculture, and/or ecosystems of implementing pump-and-treat remedies that cause dewatering or land subsidence

- greater risk to sensitive ecosystems in areas where remediation activities would be a disturbance, including sediment disturbance in aquatic ecosystems during dredging or excavation

- greater risk posed by explosive hazards or other health and safety issues associated with particular remedial technologies

- liner or capping requirements that reduce the amount of natural recharge potentially affecting groundwater's fate and transport and extending cleanup time frames for groundwater (original 1990 ROD for Moss-American site but was withdrawn by the 1998 ROD amendment)

The key component for a greater risk waiver is that it must be justified based on the fact that the remedy will pose a greater risk to human health and the environment. Although greater risk waivers are not meant to address TI, both waivers may potentially apply at a complex site. For example, at the E.I. du Pont de Nemours and Co. CERCLA site, an ARAR waiver for groundwater was granted based on greater risk associated with contaminant mobilization because attempts to remediate the lower drinking water aquifer would draw more contamination into it from the more contaminated upper aquifer. Remedial attempts in the upper aquifer would adversely affect wetland areas. This problem could have been viewed as TI, i.e., the shortcoming of technology to address widespread contamination in a multilayered hydrogeologic setting. Incidentally, a TI waiver was also granted at this site for surface water. At the Onondaga Lake site, elemental mercury DNAPL was present in groundwater. A time frame of 30,000 years to reach ARARs was estimated, indicating that complete restoration of groundwater was technically impracticable. However, groundwater ARARs were waived on the basis of greater risk, citing losses of nearby wetlands from dewatering if a more aggressive pump-and-treat system were installed. The greater risk to human health and the environment waiver allows selecting an alternative remedy that addresses those concerns.

3.4 Alternative Concentration Limits

ACLs are another type of management approach that has been used at complex sites with long cleanup time frames. Unlike the other designations described in this document, ACLs can provide substitute cleanup goals under specific circumstances. ACLs specify an alternative numeric cleanup goal, which is typically derived from an analysis of groundwater discharging into surface water. An ACL can be established at CERCLA sites in accordance with CERCLA Section 121(d)(2)(B)(ii). ACLs are risk-based concentrations that do not pose a substantial hazard to human health or environmental receptors (given exposure pathways and other factors). Under CERCLA, ACLs may not be used to replace MCLs or other standards that are relevant and appropriate. An ACL establishes the new, regulatory-approved target cleanup concentration, as opposed to waiving the ARAR entirely. In general, ACLs may be adopted provided that the following three conditions are met:

- Groundwater discharges into surface water (there are “known and projected points of entry” to surface water).
- Groundwater discharge does not lead to a “statistically significant increase” of contaminants in the surface water or any “accumulation” of contaminants downstream.
- Institutional controls prevent human exposure to contaminated groundwater between the facility boundary and the discharge point(s) of groundwater into surface water.

A recent USEPA policy memorandum (USEPA 2005) specified several additional factors to consider prior to establishing ACLs, including the following:

- whether all plumes of contaminated groundwater are discharging to surface water (e.g., are contaminants present in a deeper aquifer that does not discharge to surface water?)
- whether significant degradation of the aquifer might occur prior to discharge to surface water (e.g., could the plume spread to uncontaminated portions of the aquifer?)
- whether “known and projected” points of entry of the plume(s) into surface water have been, or can be, specifically identified

- consideration of accumulation of contaminants in sediments or below points of entry into surface waters
- whether groundwater can be restored
- the potential for degradation by-products within the zone between the source and point(s) of entry to surface waters and the potential for a “statistically significant” increase in degradation products in surface water and corresponding risks
- whether institutional controls and other enforceable measures can preclude human exposure to groundwater contaminants above health-based levels
- whether total maximum daily loads (TMDLs) have been established for surface waters, and whether the ACL could result in a TMDL exceedance

The 2005 USEPA memorandum appears to make the use of ACLs more difficult at CERCLA sites. For example, the Waterloo Coal Gasification Plant is a CERCLA site in Iowa that recently rescinded ACLs and approved a TI waiver instead. The decision was documented in an ESD for Operable Unit (OU) 1, dated August 11, 2006. Although a 2004 ROD had approved ACLs, the actual ACL values had not been approved at the time of the ROD. According to the ESD, USEPA (the lead agency) decided as a policy matter not to use the ACL approach to address groundwater at the site. This decision is consistent with the timing of the USEPA memorandum (USEPA 2005). No examples of CERCLA sites that approved ACLs after 2005 were found.

In contrast, the criteria for determining whether ACLs are appropriate at RCRA sites are not as prescriptive. Per RCRA regulations (40 CFR 264.94), ACLs can be established as long as the concentration does not pose a substantial risk to human health or environment. This determination is made after considering the potential adverse effects on the quality of groundwater and hydraulically connected surface water and taking into account several factors, including waste characteristics and mobility, hydrogeologic setting, groundwater flow, groundwater and surface water usage (current and future), surface water quality standards, existing groundwater and surface water quality and quantity, rainfall patterns, proximity of source zone to surface waters, potential for human exposure and related health risks, potential for other risks, and the permanence of potential adverse effects (40 CFR 264.94).

Sites in RCRA and state cleanup programs may use an approach similar to ACLs. Mixing zones were considered by several states (e.g., SCDHEC 1997) responding to the ITRC survey. The Jacksonville Naval Air Station OU 3 site is in the process of conducting fate and transport modeling and a mixing zone analysis to develop ACLs for groundwater that discharges into the St. Johns River (NAVFAC 2008).

3.5 Groundwater Management Zone

Summary of Key Existing EPA CERCLA Policy for Groundwater Restoration (USEPA 2009b) states that EPA will defer to formal state programs to establish an approved comprehensive state ground water protection program to determine current and future groundwater uses. If such a program is not available, USEPA will evaluate groundwater classification under 1986 USEPA groundwater classification guidelines. This groundwater classification typically drives the remedy selection and, as needed, implementation. For state cleanup programs, groundwater management zones, containment zones, or groundwater classification exemption areas can be established as portions of the zones the constituents are technically determined to be impracticable to meet the specific groundwater classification, while defining the points of compliance within these zones. Groundwater management zones can also be applied at sites during implementation of an interim remedy.

The purpose of zones may vary by state with some designations implying technical and economic infeasibility of cleanup with the zone. Other zones are established primarily as a way to keep track of areas with groundwater contamination above permissible levels and related institutional controls. Different states use different nomenclature to describe this concept. The idea of a containment or management zone is inherent in RCRA corrective action regulations and in the RCRA approach to managing landfills and other solid waste management units (SWMUs).

Similarly, some state cleanup programs have site-specific variations or exceptions for groundwater classification (e.g., urban brownfields sites, voluntary cleanup programs, or underground storage tank programs). These zones are designated by states to indicate that groundwater contamination is present above permissible levels. A preliminary review of available information (Malcolm Pirnie 2002) along with current inputs from the survey indicates that a minimum of 14 states (California, Connecticut, Delaware, Georgia, Illinois, Michigan, Missouri, Nebraska, New Hampshire, New Jersey, Ohio, Tennessee, Texas, and Wyoming) consider some form of groundwater containment zones in their corrective action policies. Table 3-1 shows several examples of formal state designations. For example, Connecticut has a groundwater quality classification for areas (a) where groundwater is known or presumed to be polluted and (b) that have an alternative to using groundwater as a supply of potable water. Connecticut's cleanup standards for sites within these groundwater classification areas are different from areas of the state where the groundwater quality goal is based on drinking water standards. States may also grant variances or alternate criteria on a case-by-case basis. Connecticut considers establishment of groundwater management zones as a part of a TI variance.

Table 3-1. Examples of state designations for groundwater

State, program	Designation	Reference
California, State Water Resources Control Board	Containment zone	State Water Resources Control Board Resolution No. 92-49
California, Regional Water Quality Control Board (RWQCB), San Francisco Bay Region	Low-threat closures	California RWQCB, 2009
California Department of Public Health (formerly Department of Health Services)	Extremely impaired sources	State of California Department of Health Services Policy Memorandum 97-005
Delaware Department of Natural Resources and Environmental Control	Groundwater management zones	Remediation Standards Guidance under the Delaware Hazardous Substance Cleanup Act

State, program	Designation	Reference
Georgia Voluntary Remediation Program Act	TI	SB78 (Amended Article 3 of Chapter 8 of Title 12 of the Official Code of Georgia Annotated)
Illinois Environmental Protection Agency RCRA Facilities	Groundwater management zone	35 Illinois Administrative Code Part 620.250
Illinois Environmental Protection Agency	Consideration of TI through risk-based corrective action programs, tiered remedial objectives	35 Illinois Administrative Code Part 742
Michigan Department of Environmental Quality Waste Management Division	Groundwater not in an aquifer determinations	Michigan Natural Resources and Environmental Protection Act, 1994 PA 451; Part 31, Water Resources Protection; Part 111, Hazardous Waste Management and Part 115, Solid Waste Management
Missouri Department of Natural Resources Voluntary Cleanup Program	Tiered cleanup levels	Missouri Department of Natural Resources, Cleanup Levels for Missouri Fact Sheet
Nebraska Department of Environmental Quality (DEQ)	Procedures for changing a groundwater classification	Nebraska DEQ Title 118 Chapter 8
New Hampshire Department of Environmental Services	Groundwater management zone	New Hampshire Code of Administrative Rules, Chapter Env-Or 600
New Jersey Department of Environmental Protection	Classification exemption areas	New Jersey Administrative Code 7:9-6:6
Ohio Environmental Protection Agency Voluntary Action Program	Urban setting designation	Ohio Administrative Code Rule 3745-300-10
Tennessee Department of Environment and Conservation, Tennessee Water Quality Control Board, Division of Water Pollution Control	Site-specific impaired groundwater	Rule 1200-04-03
Texas Commission on Environmental Quality	Groundwater plume management zone	30 Texas Administrative Code Sections 350.33(f)(3)(A)-(E) and 350.37(1)(4)
Wyoming Department of Environmental Quality Voluntary Remediation Program	TI determination and establishment of alternative cleanup levels	Wyoming Statutes Section 35-11-1605(d)

Within these zones, soil and groundwater are managed to protect human health and the environment. Exposure is often prevented through capping, groundwater use restrictions, and other controls. Contamination is prevented from spreading beyond the groundwater management zone through the use of hydraulic and/or barrier containment and/or attenuation verified by monitoring. Groundwater within these zones may or may not be expected to meet MCLs or other final cleanup goals; in some cases, the zone designation provides context for specifying alternative cleanup levels. Groundwater management zones may also make it easier for states to designate and track institutional controls and area/property use restrictions.

3.6 Site Management Using Phased Approach

The *Groundwater Road Map* (USEPA 2011) and *Presumptive Response Strategy and Ex Situ Treatment Technologies for Contaminated Ground Water at CERCLA Sites* (USEPA 1996) discuss a phased approach for groundwater remediation (www.epa.gov/superfund/health/conmedia/gwdocs/pha_app.htm). In a phased response approach, site response activities are implemented in a sequence of steps, or phases, such that information gained from earlier phases is used to refine subsequent investigations, objectives, or actions. Phased remedy approaches may include the implementation of early and interim actions. These actions generally may address exposure to contaminated groundwater, prevent further migration of groundwater, or prevent further migration of contaminants from sources. Similar to the phased approach, the National Research Council (NRC 2003) uses the term "adaptive site management" to contrast the typical CERCLA process, which is a "highly linear, unidirectional march from site investigation to remedial action and eventually to site closure."

Adaptive site management incorporates a more iterative and dynamic approach to effectively generate knowledge (through site investigation, remedy design, and analysis of remedy performance). This knowledge is used as feedback to guide site decision making and adjust the remedial approach if necessary (NRC 2003). The Navy, Air Force, ITRC, and other organizations have published approaches for site characterization, remedy selection, and optimization that are adaptive, recognizing that the pathway to site closure often changes as remediation progresses. For example, at Hanscom Field/Hanscom Air Force Base, data were periodically evaluated to determine the frequency and locations of permanganate injections into the fractured rock subsurface and the pump-and-treat extraction rate from various wells. Other optimization options such as reuse of pumped-and-treated groundwater for nonpotable water purposes is another way of managing valuable resources for quicker remediation with less treatment rather than treating water to the costly higher standards just for discharging. Site managers were open to making treatment system modifications and optimizations and accommodating changes to the remedy through a dynamic approach.

Note that this approach does not avoid setting cleanup objectives; it simply makes the process more flexible. Adaptive site management, in some instances, may be consistent with the CERCLA process (NRC 2003). Some adjustments to the remedy can be incorporated into the original ROD using contingency logic. Significant changes to remedies are documented through ROD amendments and ESDs. The five-year review process provides a mechanism to evaluate the need for changes to the remedy (NRC 2003).

Adaptive site management is often used at complex sites where it is difficult to quantitatively predict the outcome of remediation. For example, many state cleanup programs have specific regulatory requirements to remove NAPL to the extent practicable. In such cases, treatment could be a precursor to a TI variance or to establishing MNA and preventing exposure to residual contamination over the long-term. Presenting a final remedy in terms of an adaptive site management strategy helps manage stakeholder expectations of source treatment. Other benefits of this approach may include a strong focus on remedial progress at the site, documentation of remedial progress towards metrics, adaptability/innovation, and furthering of technology.

One of NRC's recommendations for some complex sites is to leave absolute objectives unchanged and establish functional objectives and metrics to measure short-term remedial progress. Examples of functional objectives include meeting specific, short-term numerical remediation goals; containing the plume; reducing groundwater concentrations, mass flux, or mass; managing risk; and decreasing plume longevity (Sale et al. 2008). These can be reflected in the wording of RAOs. Sites can acknowledge that the time frame for meeting final cleanup goals (absolute objectives) is likely long and focus instead on defining remedial progress in the interim. Decision documents written using this approach use agreed-upon language that clearly states the positive progress of the selected remedy without waiving final cleanup goals.

3.7 Role of Various Long-Term Management Designations in the Final Remedy

One of the common misconceptions about long-term management designations is that they provide an opportunity to walk away from a site, or "do nothing." Depending on the approach, numeric cleanup goals for contaminant concentrations may remain unchanged, may be waived for specific contaminants within a defined volume, or may be replaced with alternative concentration goals. When facing technological challenges to groundwater cleanup, a combination of partial source and/or plume treatment, containment, long-term monitoring, periodic reviews, institutional controls, and/or engineering controls, as well as financial assurance, will likely be required to protect human health and the environment. Thus, the components of a final remedy may be similar at complex sites that formally implement long-term management designation and those that do not. Long-term remedial expectations will be different for each site. Also, as an iterative approach of the RRM process, using the long-term management designation to mitigate the project risk associated with the technical challenge in groundwater remediation at complex site should be evaluated periodically based on the new site conditions. For example, if a new technology is developed and proven to be effective to alleviate the uncertainties to achieve the cleanup goals, a TI waiver may no longer be needed and may potentially be reconsidered.

Source zone treatment can be used in conjunction with long-term management. The benefits of source zone treatment, though well documented at many simple sites, are uncertain at complex sites where there are technical challenges to groundwater cleanup (see, e.g., USEPA 2003, SERDP 2008). Source zone treatment benefits at complex sites may be difficult to quantify due to uncertainties in the mass of contamination present and the distribution of mass or architecture of the source zone. More research and experience are needed to reliably quantify the impact of mass removal from source areas on cleanup time frames, volume of aquifer restored, or reduction of concentrations at potential points of exposure. Research on this topic has recently been published by ESTCP (2008b). Source mass removal, though important at many sites, may have uncertain or immeasurable benefit at complex sites. Nevertheless, source mass removal may be required by regulators and other stakeholders since containing the source material is generally not considered reliable over time.

In addition, selection of MNA needs to be based on lines of evidence that show that the plume has ceased to expand or is contracting and that there is evidence that MNA will achieve the cleanup levels. Demonstrating source control greatly aides in this evaluation.

3.8 Stakeholder Considerations

The ease of the process to evaluate and implement appropriate long-term management strategy depends in part on the expectations of remedial decision makers, including site owner(s), USEPA and other federal lead agencies, state regulators, and others. If stakeholders understand and agree on the underlying technical challenges for cleanup using any technology, they are more likely to support the use of a long-term management approach at complex sites. Formal evaluation processes (e.g., preparing a TI evaluation report) are then used to confirm and document stakeholder decisions rather than convince others in the group.

3.9 Case Studies of Long-Term Management Approaches at Complex Sites

A number of case studies of various designations for long-term management at complex sites have been identified through previous research efforts. In 2004, on behalf of the U.S. Army Environmental Center, Malcolm Pirnie conducted a systematic evaluation of TI waivers granted at CERCLA sites as of 2002, identified 48 sites, prepared detailed site summaries, and interviewed USEPA and state personnel who were familiar with the TI evaluation process (Malcolm Pirnie 2004). USEPA headquarters personnel reviewed the draft document and provided comments that were incorporated into the final report. The final report highlighted key statistics about the population of CERCLA sites with TI waivers for groundwater, including the following:

- reason(s) that restoration was technically impracticable
- timing of TI waiver (i.e., front-end, post-implementation)
- type of supporting data and level of documentation of TI arguments
- effective management for integrating TI considerations into the site cleanup approach
- reasons why TI waivers have been infrequently evaluated by site owners
- estimated cost savings and other benefits of a TI waiver approach

Malcolm Pirnie recently prepared an updated analysis of CERCLA sites with TI waivers for groundwater for ESTCP (ESTCP 2010). The report, *Assessing Alternative Endpoints for Groundwater Remediation at Contaminated Sites*, identified 77 CERCLA sites that have received TI waivers for groundwater as of November 2010 (see Table 3-2). This list of CERCLA sites with TI waivers has been confirmed by USEPA in an internal USEPA memorandum (personal communication of Dr. Matt Charsky, USEPA, to Dr. Rula A. Deeb, Malcolm Pirnie, August 2009). The ESTCP report also provided summary statistics about TI waivers for groundwater and described TI waivers in the context of similar state approaches. Key findings from this report regarding TI waivers included the following (ESTCP 2010):

- Most TI waivers are granted because of contaminant-specific and/or hydrogeologic complexities limiting the progress of groundwater restoration. This is the primary reason given at 75%–80% of sites. NAPL was thought to be present at more than half of the sites.

- TI waivers have been implemented in almost every USEPA region (except Region 4) and approximately half of all states (1–16 waivers per region). Regions and states and that have led or concurred with the TI waiver process most frequently include Regions 1 and 3, Pennsylvania, California, Texas, Maine, New York, New Jersey, and Montana. Regions least likely to be using the process include Regions 4 and 10.

- Integration of TI waivers into final remedies is limited. Based on the research presented in this report, TI waivers have been included in an average of 2% of CERCLA decision documents issued from 1989 through mid-2009.

- The majority of CERCLA sites (65% of all sites to 73% of post-1993 sites) received TI waivers for groundwater based on front-end evaluations, rather than after a full-scale treatment system had been installed, operated, and optimized (post-implementation TI waivers).

- Federal MCLs are the most common ARAR waived, accounting for 94% of all TI waivers issued in the time period from 1994 to mid-2009 (all TI waivers issued after 1993 USEPA guidance as of the writing of this report).

- For waivers issued after 1993, the most common designation of the TI zone includes both the source area and the plume. This designation was not frequently used prior to 1993, when TI waivers were more commonly applied to the entire property or to the source area. The difference may reflect the growing understanding of matrix diffusion on cleanup time frames for plumes as well as the difficulty of characterizing and treating plumes in fractured rock.

- Contingency language has been used in RODs to identify that a TI waiver may be needed in the future. However, a TI evaluation will still need to be written in accordance with the USEPA guidance (and a TI decision made by USEPA) regardless of contingency language in the original decision document. Such language merely serves to communicate stakeholder expectations and does not simplify the TI waiver process, subsequent public participation process, and ROD amendment.

Table 3-2. List of 77 CERCLA sites that have received TI waivers for groundwater contamination as of November 2010 (*Source*: ESTCP 2010)

#	Site name	St.	USEPA ID	Document date	USEPA region
1	Aberdeen Proving Ground (Edgewood Area), Canal Creek Beach Point	MD	MD2210020036	9/24/1997	3
2	Aberdeen Proving Ground (Edgewood Area), J-Field	MD	MD2210020036	9/28/2001	3
3	Aladdin Plating	PA	PAD075993378	12/30/1993	3
4	Aluminum Co. of America–Davenport	IA	IAD005270160	9/28/2004	7
5	Anaconda Co. Smelter	MT	MTD093291656	9/29/1998	8
6	Broderick Wood Products	CO	COD000110254	3/24/1992	8
7	Brodhead Creek	PA	PAD981033285	6/30/1995	3
8	Caldwell Trucking Co.	NJ	NJD048798953	9/28/1989	2
9	California Gulch	CO	COD980717938	9/22/2009	8
10	Charles-George Reclamation Trust Landfill	MA	MAD003809266	9/29/1988	3
11	Chemical Insecticide Corp.	NJ	NJD980484653	12/22/2003	2
12	Cherokee County (Galena)	KS	KSD980741862	9/18/1989	7

#	Site name	St.	USEPA ID	Document date	USEPA region
13	Cherokee County (Treece/Baxter)	KS	KSD980741862	8/20/1997	7
14	Conrail Rail Yard (Elkhart)	IN	IND000715490	9/27/2000	5
15	Continental Steel Corp.	IN	IND001213503	9/30/1998	5
16	Crystal Chemical Co.	TX	TXD990707010	3/19/1997	6
17	Del Norte Pesticide Storage	CA	CAD000626176	8/29/2000	9
18	Dorney Road	PA	PAD980508832	9/30/1991	3
19	DuPont/Necco Park	NY	NYD980532162	9/18/1998	2
20	Durham Meadows	CT	CTD001452093	9/30/2005	1
21	Edwards Air Force Base (AFB), South Air Force Research Laboratory	CA	CA1570024504	9/24/2007	9
22	Eielson AFB, OU 2	AK	AK1570028646	9/29/1998	10
23	Eielson AFB ST58, OU 4	AK	AK1570028646	9/29/1998	10
24	Elizabeth Mine Superfund Site	VT	VTD988366621	9/28/2006	1
25	Federal Creosote	NJ	NJ0001900281	9/30/2002	2
26	Garland Creosoting	TX	TXD007330053	9/15/2006	6
27	GE Moreau	NY	NYD980528335	10/4/1994	2
28	Hardage/Criner	OK	OKD000400093	11/22/1989	6
29	Hart Creosoting Co.	TX	TXD050299577	9/21/2006	6
30	Heleva Landfill	PA	PAD980537716	9/30/1991	3
31	Highway 71/72 Refinery	LA	LAD981054075	9/28/2000	6
32	Hocomonco Pond	MA	MAD980732341	9/21/1999	1
33	Horseshoe Road/Atlantic Resources	NJ	NJD980663678	9/30/2004	2
34	Hunterstown Road	PA	PAD980830897	8/2/1993	3
35	Iowa City Former Manufactured Gas Plant	IA	IAD984591172	9/26/2006	7
36	J. H. Baxter & Co.	CA	CAD000625731	3/27/1998	9
37	Jasper Creosoting Co., Inc.	TX	TXD008096240	9/20/2006	6
38	Keystone Sanitation Landfill	PA	PAD054142781	6/25/1999	3
39	Koppers Co., Inc. (Oroville Plant)	CA	CAD009112087	9/23/1999	9
40	Libby Groundwater Contamination	MT	MTD980502736	9/14/1993	8
41	Lindane Dump	PA	PAD980712798	3/31/1992	3
42	Loring AFB Entomology Shop/Jet Engine Build-Up Shop	ME	ME9570024522	9/19/1999	1
43	Loring AFB Quarry Site	ME	ME9570024522	9/19/1999	1
44	Love Canal	NY	NYD000606947	5/15/1991	2
45	McKin Co.	ME	MED980524078	3/30/2001	1
46	Middletown Air Field	PA	PAD980538763	12/17/1990	3
47	Midland Products	AR	ARD980745665	6/9/2006	6
48	Missouri Electric Works	MO	MOD980965982	9/28/2005	7
49	Montrose/Del Amo	CA	CAD029544731 CAD008242711	3/30/1999	9
50	Naval Air Development Center (8 waste areas)	PA	PA6170024545	9/27/2000	3
51	Niagara Mohawk Power Corp. (Saratoga Springs Plant)	NY	NYD980664361	9/29/1995	2
52	O’Connor Co.	ME	MED980731475	9/26/2002	1
53	Old Springfield Landfill	VT	VTD000860239	9/28/1990	1
54	Oronogo-Duenweg Mining Belt	MO	MOD980686281	7/29/1998	7
55	Pease AFB	NH	NH7570024847	9/26/1995	1

#	Site name	St.	USEPA ID	Document date	USEPA region
56	Petro-Chemical Systems, Inc. (Turtle Bayou)	TX	TXD980873350	9/22/2006	6
57	Pinette's Salvage Yard	ME	MED980732291	5/30/1989	1
58	Popile, Inc.	AR	ARD008052508	9/28/2001	6
59	Revere Chemical Corp.	PA	PAD981033285	9/30/1999	3
60	Riverfront	MO	MOD981720246	3/26/2009	7
61	Rodale Manufacturing Site	PA	PAD981033285	9/30/1999	3
62	Roebling Steel Co.	NJ	NJD07372257	9/1/2003	2
63	Schofield Barracks	HI	HI7210090026	2/7/1997	9
64	Silver Bow Creek/Butte Area	MT	MTD980502777	9/29/1994	8
65	South Municipal Water Supply Well Site	NH	NHD980671069	2/3/1997	1
66	Sullivan's Ledge	MA	MAD9807343	6/28/1989	1
67	Tansitor Electronics, Inc.	VT	VTD000509174	9/29/1995	1
68	Tucson International Airport Area	AZ	AZD980737530	9/30/1997	9
69	UGI Columbia Gas Plant	PA	PAD980539126	9/24/2007	3
70	Vertac, Inc.	AR	ARD000023440	9/17/1996	6
71	Waterloo Coal Gasification Plant	IA	IAD984566356	8/11/2006	7
72	West Site/Hows Corners	ME	MED985466168	9/28/2006	1
73	Westinghouse Electric Corp. (Sharon Plant)	PA	PAD005000575	2/20/2003	3
74	Westinghouse Electric Corp. (Sunnyvale Plant)	CA	CAD001864081	10/16/1991	9
75	Westinghouse Elevator Co. Plant	PA	PAD043882281	6/30/1992	3
76	Whitewood Creek	SD	SDD980717136	3/30/1990	8
77	Whitmoyer Laboratories	PA	PAD003005014	12/31/1990	3

The ESTCP (2010) report also described case studies of sites that have implemented other types of long-term management. Table 3-3 summarizes a list of case studies described in that report. Additional case studies of state sites can be identified through research efforts referencing the state-specific, long-term management strategy designations listed in Table 3-1.

Table 3-3. Case studies of sites implementing long-term management designations

Long-term management designations	Case study site name	Regulatory program	Reference
ARAR waiver based on TI	Various CERCLA sites, listed in Table 3-2 of this document	CERCLA	Malcolm Pirnie 2004, ESTCP 2010
ARAR waiver based on greater risk	E.I. Du Pont de Nemours & Co., Inc. (Newport Pigment Plant Landfill), OU 1, Delaware	CERCLA	ROD dated 9/29/93
	Moss-American Co., Inc. (Kerr-McGee Oil Co.), OU 1, Milwaukee, Wisconsin	CERCLA	ROD dated 9/27/90 (later withdrawn by 1998 ROD amendment)
	Onondaga Lake, OU 5, New York	CERCLA	ROD dated 9/29/00
Other ARAR waivers	None	--	--
ACLs	Waterloo Coal Gasification Plant, OU 1, Iowa	CERCLA	ROD dated 9/24/2004 (later replaced with TI waiver, per 8/11/06 ESD)

Long-term management designations	**Case study site name**	**Regulatory program**	**Reference**
	Naval Surface Warfare Center Crane, SWMU 3, Indiana	RCRA	NAVFAC 2008
Mixing zone analysis (in progress)	Jacksonville Naval Air Station OU 3, Florida	CERCLA	NAVFAC 2008
Groundwater management zone	Halby Chemical Co., OU 2, Delaware	CERCLA	ROD dated 3/31/98, five-year review dated 9/28/07
	Dover AFB, OU 24, Delaware	CERCLA	ROD dated 11/22/05
	Joliet Army Ammunition Plant, OU 1 and 2, Illinois	CERCLA	ROD dated 10/30/98, five-year review dated 2004
Plume management zone	Spector Salvage Yard, Texas	State Superfund	32 Texas Register 966-967 dated 2/23/07
	State Highway 123 PCE plume, Texas	State Superfund	Proposed remedial action document dated 12/9/04
	Hardy Street Rail Yard site, Texas	State voluntary cleanup program	City of Houston Municipal Setting Designation Application, May 2009
Site-specific impaired groundwater	Porter Cable/Rockwell site, Tennessee	State cleanup program	Tennessee Department of Environmental Conservation (TDEC) Chapter 1200-4-3
	Isabella/Eureka Mine, Tennessee		TDEC Chapter 1200-4-3
Containment zone rescinded/low-threat site closure	Intel Fab 1 facility, California	State cleanup program	RWQCB San Francisco Bay Region Order No. 99-044
	Norge Cleaners, Napa, California		RWQCB San Francisco Bay Region Executive Officer's Report dated 9/21/05
Containment zone (being considered from the five-year review)	Fairchild Semiconductor Corp., California	CERCLA	ROD dated 3/20/89, RWQCB five-year review dated 7/14/99
Alternative designations of remedial action objectives (removal of DNAPL to the extent practicable)	Union Pacific Railroad Co. Tie-Treating Plant, OU 1, Oregon	CERCLA	ROD dated 3/27/96, five-year review dated 12/07
Site management using phased approach	Hanscom AFB/Hanscom Field, OU 1, Massachusetts	CERCLA	ROD dated 9/28/07

As indicated by these prior studies, case studies provide examples of how long-term management has been used to address technical challenges to complex restoration. Case studies can stimulate thought and more careful consideration of alternative, beneficial, and cost-effective cleanup goals and metrics that are appropriate and can be achieved over the short term while eventually meeting long-term cleanup objectives. Long-term management approaches are applicable under a variety of cleanup programs, including CERCLA, RCRA, state Superfund programs, and state voluntary cleanup programs. These approaches provide a way to adopt RRM principles to manage groundwater remediation challenges.

4. SUMMARY AND CONCLUSIONS

Based on the past experience, remediation of groundwater to its final goals and objectives is always challenging at complex sites. This document applies the framework of RRM process to manage remediation project risks that may affect achieving the groundwater cleanup goals and/or objectives due to technical challenges.

The methods to evaluating the remediation project risks associated with technical challenges and remedial time frames include mass estimates, groundwater concentration trends, DNAPL dissolution and mobilization, matrix back-diffusion, cost estimates, modeling, technology assessment, etc. Long-term management approaches, including ARAR waivers, groundwater management zone designations, ACLs designation, and site management using phased approach, can be used to maintain protectiveness and mitigate the project risk from technical challenges associated with remediation at complex sites. Selecting an appropriate long-term management strategy to address groundwater remediation challenges requires site-specific and program-specific consultation with regulators. Long-term management designations are not a way to "do nothing" or walk away from a site. Instead, any approach must be protective of human health and the environment. As an iterative approach of the RRM process, using the long-term management designation to mitigate the project risk associated with the technical challenge in groundwater remediation at complex site should be evaluated periodically as remediation progresses.

This document is intended to inform, in the context of the RRM process, the state regulators, stakeholders, and practitioners who are evaluating these issues within their own programs. This document does not address policy questions associated with setting remedial goals and objectives, nor evaluate the acceptability of different project risk management strategies.

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Appendix B

Acronyms

ACRONYMS

ACL	alternative concentration limit
AFB	Air Force Base
AFCEE	Air Force Center for Engineering and the Environment
ANPR	Advance Notice of Proposed Rulemaking
ARAR	applicable or relevant and appropriate requirement
ASTM	ASTM International, formerly American Society for Testing and Materials
CERCLA	Comprehensive Environmental Response, Compensation, and Liability Act
CFR	Code of Federal Regulations
CSM	conceptual site model
DNAPL	dense, nonaqueous-phase liquid
ESD	explanation of significant differences
ESTCP	Environmental Security Technology Certification Program
FR	Federal Register
ITRC	Interstate Technology & Regulatory Council
MAROS	Monitoring and Remediation Optimization System
MCL	maximum contaminant level
MNA	monitored natural attenuation
NAPL	nonaqueous-phase liquid
NAS	Natural Attenuation Software
NAVFAC	Naval Facilities Engineering Command
NCP	National Oil and Hazardous Substance Pollution Contingency Plan
NRC	National Research Council
OSWER	(U.S. Department of Energy) Office of Solid Waste and Emergency Response
OU	operable unit
PBEM	performance-based environmental management
PCE	tetrachloroethene (perchloroethene)
PMZ	plume management zone
RAO	remedial action objective
RCRA	Resource Conservation and Recovery Act
ROD	record of decision
RPO	remediation process optimization
RRM	remediation risk management
RWQCB	Regional Water Quality Control Board
SERDP	Strategic Environmental Research and Development Program
SVE	soil vapor extraction
SWMU	solid waste management unit
SWRCB	State Water Resources Control Board
TDEC	Tennessee Department of Environmental Conservation
TI	technical impracticability
TMDL	total maximum daily load
USACE	U.S. Army Corps of Engineers
USEPA	U.S. Environmental Protection Agency
UTCHEM	University of Texas Chemical Simulator