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At some complex sites, site-specific conditions make it difficult to fully remediate environmental contamination. Both technical and nontechnical challenges can impede remediation and may prevent a site from achieving federal- and state-mandated regulatory cleanup goals within a reasonable time frame. For example, technical challenges may include geologic, hydrogeologic, geochemical, and contaminant-related conditions as well as large-scale or surface conditions. In addition, nontechnical challenges may also play a role such as managing changes that occur over long time frames, overlapping regulatory and financial responsibilities between agencies, setting achievable site objectives, maintaining effective institutional controls, redevelopment and changes in land use, and funding considerations.

This ITRC guidance, Remediation Management of Complex Sites, provides a recommended, holistic process for managing complex sites, termed “adaptive site management”. This process is comprehensive, flexible, and iterative; it is well suited for sites where there is significant uncertainty in remedy performance predictions. Adaptive site management includes setting short-term interim objectives and long-term site objectives that reflect both technical and nontechnical challenges. The remedial approach may involve multiple technologies at any one time and changes in technologies over time. Comprehensive planning and scheduled evaluations of remedy performance help decision makers track remedy progress and adjust the remedy, if needed, to stay on track to achieving short-term interim objectives. Long-term planning can also improve the timeliness of remedy optimization, reevaluations, or transitions to other technologies or contingency actions.

This ITRC guidance document describes the following practical steps to manage the remediation process at complex sites:

- Identify and integrate technical and nontechnical challenges into a holistic approach to remediation.
- Use the Remediation Potential Assessment to identify whether adaptive site management is warranted due to site complexity.
- Understand and apply adaptive site management principles.
- Develop a performance-based long-term management plan.
- Apply well-demonstrated techniques for effective stakeholder engagement.
- Access additional resources, tools, and case studies most relevant for complex sites.
- Communicate the value of the guidance to regulators, practitioners, community members, and others.

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# Executive Summary

At some sites, complex site-specific conditions make it difficult to fully remediate environmental contamination using proven remediation approaches. This guidance presents a recommended process for remediation management at complex sites, termed "adaptive site management." The adaptive site management process is presented in a flow chart and each step is described in detail. Numerous case studies describe real-world applications of remediation and remediation management at complex sites. Stakeholder perspectives at complex sites are also summarized. This guidance incorporates and refers to best management practices, tools, and technologies described in previous publications by the U.S. Environmental Protection Agency (USEPA), ITRC, Department of Defense (DOD), and others.

**Complex Sites**

*The term "complex site" refers to sites where remediation progress is uncertain and remediation is not anticipated to achieve closure or even long-term management within a reasonable time frame.*

## Site Challenges

Both technical and nontechnical challenges can impede remediation and may prevent a site from achieving federal- and state-mandated regulatory cleanup goals within a reasonable time frame. Examples of technical challenges include geologic, hydrogeologic, geochemical, and contaminant-related conditions as well as large-scale or surface conditions. Examples of nontechnical challenges include managing changes that occur over long time frames, overlapping regulatory and financial responsibilities between agencies, setting achievable site objectives, maintaining effective institutional controls, redevelopment and changes in land use, and funding considerations. Nontechnical challenges may be exacerbated by technical challenges, long remediation time frames, and higher costs.

**Site Objectives**

*Site objectives are long-term remedial goals and objectives that are typically established based on federal and state environmental regulations. Examples include meeting applicable or relevant and appropriate requirements (ARARs), achieving target risk levels or contaminant concentrations, restoring impacted media to beneficial use, or protecting human health and the environment.*

This guidance offers tools and references for investigating complexities and improving the conceptual site model (CSM) at complex sites. Integrated site characterization (ITRC 2015b) can improve the CSM and maximize remedial effectiveness. This approach iteratively identifies key uncertainties or data gaps in the CSM and establishes objectives prior to data collection and interpretation (ITRC 2015b)**.**

## Remediation Potential Assessment

If substantial complexities are identified, a site-specific remediation potential assessment may be appropriate. The remediation potential assessment evaluates the likelihood of meeting site objectives within a reasonable time frame. Two different series of questions (pre- or postremedy implementation) are provided as examples. Site owners, regulators, and stakeholders can revise the questions and determine the relative importance or weighting of some questions to reflect site-specific concerns and address contaminated media other than groundwater. Many of the questions relate to effectiveness, feasibility, and cost. Each area of the site can be assessed separately (for example, source and plume, hydrogeologic unit, or operable unit).

The remediation potential assessment has three possible outcomes: a high, moderate, or low likelihood of achieving site objectives. If remediation potential is high, the site area is not considered complex. If remediation potential is moderate, the assessment can be reevaluated (such as criteria used, questions that may dominate the assessment, and the weight of evidence balancing the categories). If remediation potential is low, the site will not likely achieve site objectives in a reasonable time frame and adaptive site management should be considered.

## Adaptive Site Management

Adaptive site management is a comprehensive, flexible, and iterative process of remediation management that is well-suited for complex sites, where there is significant uncertainty in remedy performance predictions. Adaptive site management includes periodically evaluating and adjusting the remedial approach, which may involve multiple technologies at any one time and changes in technologies over time. The CSM is refined using information gained from remedy performance. Note that complex sites may require more iterations of the adaptive site management process compared to simpler sites.

Regulatory agencies specify the criteria for evaluating and selecting a remedy—for example, Comprehensive Environmental Response Compensation and Liability Act (CERCLA) nine criteria per 40 Code of Federal Regulations (CFR) 300.430, Resource Conservation Recovery Act (RCRA) corrective measures criteria per 40 CFR 258.57, or analogous criteria under other state-led programs. At complex sites using adaptive site management, this evaluation may incorporate additional considerations. For example, is there flexibility to adjust or optimize the remedial approach based on performance data? Is the remedial approach synergistic with other technologies?

Site remediation managers adapt or adjust the selected remedy over time in response to remedy performance. These adjustments keep the remedy on track to meet interim objectives. Interim objectives and associated performance metrics may reflect a variety of goals such as removal rates/treatment efficiency or reduction in mass, mass flux, concentration, plume footprint, or volume of contaminated soil. Site managers develop time-bound interim objectives and performance metrics in parallel with remedial alternatives and document them in the decision document.

**Interim Objectives**

*Interim objectives are designed as steps or milestones to achieving the overall site objectives. Interim objectives can be specific to a technology or an area of the site (such as reducing mass flux from the source area, or containing an off-site plume). Achieving interim objectives leads to the next phase of remediation.*

If a site area is not sufficiently progressing towards interim objectives, despite remedy optimization and modifications, site objectives may be revisited. Applicable or relevant and appropriate requirements (ARAR) waivers may be considered at CERCLA sites. RCRA and other state cleanup programs have similar options – a state survey highlights approaches to consider under state cleanup programs.

## Long-Term Management

Adaptive site management continues during the long-term management phase of remediation. Recommended elements include the following:

1. Preparing a long-term management plan with a performance model and metrics. Project risks and uncertainties are also identified, mitigated and tracked.
2. Conducting periodic evaluations to compare actual progress with expected performance.
3. Following predefined decision logic to evaluate, adjust, optimize, modify or transition the remedial strategy if needed to stay on track to achieve interim objectives.

Comprehensive planning and scheduled periodic evaluations of remedy performance help decision makers track remedy progress and improve the timeliness of remedy optimization, reevaluations, or transition to other technologies/contingency actions. Note that optimization is not typically the focus of adaptive site management, but is often appropriate as part of the process.

Sites typically use institutional controls (ICs) and land use controls (such as deed restrictions and fencing) to prevent exposure over the long term. In *Long-Term Contaminant Management Using Institutional Controls*, ITRC (2016b) identified critical elements of effective IC management programs based on successes from established state and federal regulatory programs. These controls, however, are rarely used as stand-alone remediation strategies and are not drivers for changing site objectives or a substitute for remediation.

## Case Studies

Detailed case studies are included in this guidance. Each case study describes site conditions and complexities, the technical basis for remedial action, key decisions, remedial approach, monitoring and optimization activities, and regulatory and stakeholder involvement. Case studies describe any adaptive site management processes that were used for site evaluation and decision making.

## Stakeholder Perspectives

Stakeholders are members of environmental organizations, community advocacy groups, or other citizens’ groups that address environmental issues. Stakeholders can actively participate in the decision-making process at complex sites. Unique circumstances that apply to tribal stakeholders are also discussed. This guidance also presents best practices for including stakeholders in the management of complex sites and communicating with stakeholders through a site-specific stakeholder communication plan or (at CERCLA sites) through the five-year review process.

## About ITRC

The Interstate Technology and Regulatory Council (ITRC) is a State-led public-private coalition working to reduce barriers to the use of innovative environmental technologies and approaches so that compliance costs are reduced and cleanup efficacy is maximized. ITRC produces documents and training that broaden and deepen technical knowledge and expedite quality regulatory decision making while protecting human health and the environment. With private and public sector members from all 50 states and the District of Columbia, ITRC truly provides a national perspective. More information on ITRC is available at www.itrcweb.org. ITRC is a program of the Environmental Research Institute of the States (ERIS), a 501(c)(3) organization incorporated in the District of Columbia and managed by the Environmental Council of the States (ECOS). ECOS is the national, nonprofit, nonpartisan association representing the state and territorial environmental commissioners. Its mission is to serve as a champion for states; to provide a clearinghouse of information for state environmental commissioners; to promote coordination in environmental management; and to articulate state positions on environmental issues to Congress, federal agencies, and the public.

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# Acronyms

| | |
|---|---|
| **ARAR** | applicable or relevant and appropriate requirement |
| **ACL** | alternate concentration limit |
| **BRAC** | Base Realignment and Closure Act |
| **BTEX** | benzene toluene ethylbenzene and xylene |
| **CEA** | Classification exception area |
| **CAS** | Corrective action study |
| **CERCLA** | Comprehensive Environmental Response, Compensation and Liability Act |
| **CEQA** | California Environmental Quality Act |
| **CFR** | Code of Federal Regulations |
| **COC** | contaminants of concern |
| **CSM** | conceptual site model |
| **DNAPL** | dense nonaqueous phase liquid |
| **DOD** | Department of Defense |
| **DOE** | Department of Energy |
| **DQO** | data quality objective |
| **ESTCP** | Environmental Security Technology Certification Program |
| **ESD** | Explanation of Significant Difference |
| **FAQ** | frequently asked questions |
| **FUDS** | Formerly Used Defense Sites |
| **FS** | feasibility study |
| **FFS** | focused feasibility study |
| **GAC** | granular activated carbon |
| **GAO** | Government Accountability Office |
| **GSR** | green and sustainable remediation |
| **HRSC** | high resolution site characterization |
| **ICs** | institutional controls |
| **IDSS** | Integrated DNAPL Site Strategy |
| **ISC** | integrated site characterization |
| **ISB** | in situ bioremediation |
| **ITRC** | Interstate Technology and Regulatory Council |
| **LLNL** | Lawrence Livermore National Laboratory |
| **LNAPL** | light nonaqueous phase liquid |
| **LTRA** | long term response actions |
| **LUCs** | land use controls |
| **MC** | munitions constituents |
| **MCL** | maximum contaminant level |
| **MDL** | method detection limit |

| | |
|---|---|
| **MNA** | monitored natural attenuation |
| **MMRP** | Military Munitions Response Program |
| **MT** | magnetotellurics |
| **MTBE** | methyl tertiary butyl ether |
| **NAPL** | nonaqueous phase liquid |
| **NAS** | National Academy of Science |
| **NACEPT** | National Advisory Council for Environmental Policy and Technology |
| **NCP** | National Contingency Plan |
| **ND** | nondetect |
| **NDMA** | N-nitrosodimethylamine |
| **NEPA** | National Environmental Policy Act |
| **NFA** | no further action |
| **NJDEP** | New Jersey Department of Environmental Protection |
| **NPL** | National Priority List |
| **NRC** | National Research Council |
| **O&M** | operation and maintenance |
| **OOM** | order of magnitude |
| **OSWER** | Office of Solid Waste and Emergency Response |
| **OPS** | Oil and Public Safety |
| **ORP** | oxidation reduction potential |
| **OU** | operable unit |
| **PAH** | polyaromatic hydrocarbon |
| **PCB** | polychlorinated biphenyl |
| **POC** | points of contact |
| **PRP** | potentially responsible party |
| **PRB** | permeable reactive barrier |
| **RAB** | Restoration Advisory Board |
| **RAO** | remedial action objective |
| **RECAP** | Risk evaluation/Corrective action program |
| **RI** | remedial investigation |
| **RCRA** | Resource Conservation and Recovery Act |
| **RMCS** | remediation management of complex sites |
| **RA** | remedial action |
| **RPO** | remedial performance optimization |
| **RSE** | remediation system evaluation |
| **ROD** | Record of Decision |
| **SERDP** | Strategic Environmental Research and Development Program |
| **SMART** | specific, measurable, attainable, relevant and time bound |
| **SVE** | soil vapor extraction |
| **SWMU** | solid waste management unit |
| **TAPP** | Technical Assistance for Public Participation |
| **TCE** | trichloroethylene |
| **TEM** | Time domain electromagnetic induction |

| | |
|---|---|
| **TI** | technical impracticability |
| **UCL** | upper confidence limit |
| **USEPA** | United States Environmental Protection Agency |
| **USACE** | United States Army Corps of Engineers |
| **UST** | underground storage tank |
| **UU/UE** | unrestricted use/unrestricted exposure |
| **VE** | value engineering |
| **VI** | vapor intrusion |
| **VOC** | volatile organic compounds |

# 1. Introduction

It is difficult to achieve remediation objectives at some contaminated sites because of complex, site-specific conditions. Remedial success at these complex sites may ultimately depend on integrating multiple remediation and risk management approaches and on long-term management. This section describes the need for additional guidance for remediation management of complex sites, what makes a site complex, and the significance of complex sites. Because remedial success partly depends on remediation objectives and the acceptable time frame for achieving them, this section provides a brief background on site objectives and interpretations of reasonable time frames for achieving them. Adaptive site management is a comprehensive process for managing remediation at complex sites and is presented as a framework for decision making.

Despite previous relevant guidance on aspects of remediation at complex sites, no comprehensive guidance document describes the elements, tools, and options for successful remediation at complex sites.

### A Clear Need for Guidance

*One representative for a site owner summarized the difficulties with complex sites as follows:*

*". . . It is a major frustration that various alternative endpoints and adaptive management strategies are permitted by regulations but are seldom practiced. The lack of detailed guidance and clear precedent leads to indecisiveness and continuing with the status quo."*

*A state regulator noted the need for a cooperative approach:*

*"Complex sites that are transferred under Long Term Response Actions place substantial strain on states' financial resources. States and USEPA should work together to fully understand site challenges when evaluating and selecting a remedy and creating and aligning remediation objectives that are protective and can be met in mutually agreed upon time frames that are respectful of states' resource limitations."*

This guidance presents a process for managing remediation at complex sites and describes each step of the adaptive site management process. This guidance does not offer short cuts or the means to avoid site remediation, but rather describes how complex sites can be managed effectively to ensure protection of human health and the environment and progress towards site objectives. Effective management can streamline decision making, decrease remediation costs, and potentially reduce remediation time frames.

▼*Read more*

Other potential benefits of using this guidance include the following:

- identification of site complexities early in the remediation process, thereby maximizing the potential benefits of effective management
- reduction in potential technical, regulatory, and procedural barriers to using various remediation management approaches that exist but are infrequently practiced (including continued remediation, monitoring, institutional controls (ICs), alternate concentration limits (ACLs), or technical impracticability (TI) waivers)
- demonstration of precedent for implementing site management approaches in sixteen case studies
- return of all or part of the site to beneficial reuse earlier in the remediation life cycle as remediation milestones are reached, while recognizing that additional time will be needed to achieve overall site objectives
- reduction in environmental footprint and other benefits to society, while complying with environmental regulations that protect human health and the environment
- familiarity with existing guidance on a variety of tools, technologies, and approaches to use at different steps of remediation and postremedy management, which can rule out ineffective remedial technologies and minimize the gathering of unnecessary data
- references to existing federal and state guidance and stakeholder engagement practices that are relevant for complex sites
- assistance with long-term management at sites that may require decades to reach site objectives, including development of site-specific long-term management plans for remediation systems, ICs, maintenance, and monitoring

- streamlined process for stakeholder engagement with owners and regulators of complex sites, which studies show reduces the cost of remediation and long-term management

Ultimately, this guidance describes adaptive management principles that can lead to better decision making and remediation management at complex sites. ITRC guidance is intended to benefit a variety of site decision makers, including regulators, responsible parties and their consultants, and public and tribal stakeholders.

## 1.1 What is a Complex Site?

For the purposes of this guidance, ITRC defines a complex site as a “site where remedial approaches are not anticipated to bring the site to closure or facilitate transitioning to sustainable long-term management within a reasonable time frame”. Complex sites typically have multiple attributes that present remediation challenges and therefore take much longer to reach site objectives compared with typical sites. ITRC uses the term “complex site” because this guidance focuses on the technical challenges and additional nontechnical factors, similar to the focus of the National Research Council (NRC 2013).

**Terminology**

*Terms and definitions vary among different environmental remediation programs. To avoid confusion, this guidance consistently uses a narrow set of terms defined in the Glossary. When possible, this guidance uses common terms that are not associated with a narrow, legal or policy definition. Acronyms are defined in Appendix E.*

▼*Read more*

The USEPA began developing policy regarding complex sites (also termed “mega-sites”) in the early 2000s (Means 2001). Although USEPA initially used the terms “mega” and “complex” sites somewhat interchangeably; for example, see National Advisory Council for Environmental Policy and Technology Superfund Subcommittee 2003 (USEPA 2003), USEPA eventually preferred the term “mega-site” and did not use the term “complex site” in regulations or guidance. Only one state uses the term “complex sites” in its environmental programs (Washington Department of Ecology 2017). Europe recognized the concept around the same time (Darmendrail et al. 2004). Problems with these sites were soon recognized at the highest levels of USEPA management (Horinko 2002):

> *The remaining number of Superfund sites that have not reached the completion stage includes area-wide groundwater sites, mining sites, sediment sites, and federal facility sites. The size and complexity of these remaining sites generally indicate longer project durations and increased costs required to complete cleanup construction. There is now a greater number of federal facilities and very large and complex sites (sites exceeding $50 million in cleanup costs) as a percentage of National Priority List (NPL) sites not yet completed than ever before. Of the remaining 675 final NPL sites that have not reached construction complete, 138 are federal facilities and an additional 93 sites are very large and complex sites.*

The National Research Council has also described complex sites as sites that require long-term remediation based on site-specific technical or regulatory complexities. Both USEPA and European definitions of “mega-site” include an economic criterion that NRC’s does not. NRC describes complex sites as follows (NRC 2013):

> *Although progress has been made in remediating many hazardous waste sites, there remains a sizeable population of complex sites, where restoration is likely not achievable in the next 50-100 years. Although there is no formal definition of complexity, most remediation professionals agree that attributes include areally extensive groundwater contamination, heterogeneous geology, large releases and/or source zones, multiple and/or recalcitrant contaminants, heterogeneous contaminant distribution in the subsurface, and long time frames since releases occurred. Additional factors that contribute to complexity include restrictions on the physical placement or operation of remedial technologies and challenging expectations (such as regulatory requirements, cleanup goals, and community expectations). The complexity of a site increases with the number of these characteristics present.*

## 1.2 Significance of Complex Sites

A site with substantial technical and nontechnical challenges typically has a longer remediation time frame, higher remediation cost, and larger environmental footprint (such as energy use or carbon emissions), particularly if site challenges are not adequately understood and addressed early on. Conversely, complex sites have a greater potential for cost savings, environmental footprint reductions, beneficial land reuse, and other societal benefits.

▼*Read more*

Complex sites constitute a small percentage of all sites, but consume a large proportion of cleanup costs. USEPA recognized in 2006 that a few complex sites consume much of the agency's cleanup budget (Bodine 2006):

> *The largest and most complex Superfund sites must be managed as multi-year construction projects. This is particularly true of the "mega-sites" with estimated costs over $50 million. USEPA-funded mega-sites consume the majority of resources. In fiscal year 2005, approximately 50% of the Superfund obligations for long-term, ongoing cleanup work were committed to just eleven sites. The Agency expects to have a similar situation this year.*

In 2011, the Strategic Environmental Research and Development Program and the Environmental Security Technology Certification Program (SERDP/ESTCP) compiled data from 588 Army, Navy, Air Force, and Defense Logistics Agency sites where groundwater remediation will not be completed until at least 2022. The greatest costs for cleanup of these sites were associated with source zones, groundwater, landfills, underground storage tanks, and surface disposal areas. Among these sites, 90% had cost-to-completion estimates of less than $14.3 million, and 10% of the sites had cost-to-completion estimates ranging from $14.3 to $122.2 million. Thus, 31% of the sites accounted for 80% of the total cost-to-completion (Vogel 2015).

Sites with a high cost of remediation also tend to have a high environmental footprint, including consumption of large amounts of energy and other resources, emission of greenhouse gases and criteria pollutants, and waste generation. Promoting more efficient approaches to managing complex sites improves the sustainability of remediation programs and is consistent with the objectives of green and sustainable remediation (GSR).

Complex sites may have a greater potential for land reuse and other societal benefits. Economic benefits can also accrue from remediating complex sites. One study found that brownfield site assessment or remediation can increase nearby residential property values by 5 to 15% and (based on anecdotal surveys) reduce crime (USEPA 2016b). Site remediation can mitigate damage to public resources and improve resource availability, restoring clean drinking water, hunting, fishing, and recreational land uses. Site remediation can also decrease public health risks, reduce stigma, improve commerce, and avoid the loss of cultural practices. Site remediation can mitigate these effects even when sites are not restored to a condition that allows for unlimited use and unrestricted exposure (for instance, at Brownfields sites). Restoring the beneficial use of land, surface water, groundwater, and other natural resources can benefit municipalities, rural residents, tribes, and others.

### Green and Sustainable Remediation

*Green remediation is the practice of considering all environmental effects of a remedy and incorporating options to maximize net environmental benefit of cleanup actions (USEPA 2011b). This practice uses natural resources and energy efficiently, reduces negative effects on the environment, minimizes or eliminates pollution at its source, and reduces waste. GSR is similar to green remediation but also considers community goals and economic effects, as well as environmental effects (ITRC 2011a). The approaches discussed in this guidance are key tools in achieving the goals of GSR for complex sites.*

## 1.3 Site Objectives and Interim Objectives

Remediation at complex sites is guided by the site objectives. This guidance uses the term "site objectives" to describe the overall expectations for site remediation. Site objectives are typically established based on regulatory requirements, regardless of the technical ability to meet them. Examples include applicable or relevant and appropriate requirements (ARARs), other federal and state standards, and target risk levels that are protective of human health and the environment. Factors that are considered in establishing site objectives at Comprehensive Environmental Response, Compensation and Liability Act (CERCLA) sites are outlined in 40 CFR 300.430(e)(2)(i). These factors include meeting identified ARARs or justifying a waiver of specific ARARs, while still reducing risks to human health and environment and returning the site to beneficial use (ITRC 2012).

> ***Site objectives*** *are the overall expectations for a site, which include protecting public health and the environment. If site objectives are not achievable within a time frame that is agreed upon as reasonable, then revisit the site objectives may be necessary.*
>
> ***Interim objectives*** *are intermediary goals that guide progress towards achieving site objectives.*

At complex sites where regulators agree it is impracticable to achieve default expectations (such as drinking water standards), regulators may require alternative site objectives, such as restoring affected media to beneficial use while protecting human health and the environment. At complex sites where it is not technically or economically practicable to restore affected media to beneficial uses, regulators may establish site objectives for source removal, containment, and exposure prevention. At these complex sites, community engagement will likely be an ongoing component of the remedy. When establishing site objectives, a thorough conceptual site model (CSM) can best represent site complexities, define remediation potential based on site complexities, and may inform the identification of ARARs or the development of site-specific target risk levels and exposure pathways of potential concern.

The term "interim objectives" is used in this guidance to describe intermediary goals that guide progress towards achieving site objectives. Interim objectives are sometimes termed "functional objectives" (ITRC 2011b). They may reflect technology-specific goals and nearer-term remediation goals. Setting interim objectives and associated performance metrics helps to keep the remedy on track to ultimately achieve site objectives. Interim objectives can be developed in parallel with remedial alternatives for each affected media or site area.

### Example: Site and Interim Objectives

***Scenario***: *Chlorinated solvents are present in a residential water supply well in a fractured bedrock aquifer.*

***Complexities***: *Fracture-controlled aqueous phase solvent distribution, propensity for solvent components to diffuse into and out of the aquifer matrix, and solvent degradation to vinyl chloride*

***Possible site objectives***:

- *Contain impaired groundwater within well head buffer area.*
- *Achieve drinking water criteria outside well head buffer area.*

***Possible interim objectives***:

- *Achieve hydraulic control in fractured bedrock aquifer within six months to isolate impaired groundwater from the well intake.*
- *Achieve hydraulic source control within one year.*
- *Reduce mass flux off site by 50% within five years so that hydraulic control at the well is no longer needed.*
- *Begin groundwater restoration at the source area within three years, and continue O&M until asymptotic performance is reached*

- *Execute on site groundwater use prohibition within one year, and continue long-term management until off site groundwater meets drinking water criteria under natural flow conditions.*

## 1.4 Remediation and a Reasonable Remediation Time Frame

State and federal regulations often require remediation within a reasonable time frame. For example, USEPA expects to return usable ground waters "…to their beneficial uses wherever practicable, within a time frame that is reasonable given the particular circumstances of the site"; see 40 CFR 300.430(1)(a)(iii)(F). USEPA does not, however, offer a specific numerical criterion for a reasonable time frame for remediation within its guidance or regulations.

Determining a reasonable time frame for achieving and maintaining site objectives is a complex and site-specific decision. A generic period applied to all sites and facilities is not appropriate (ITRC 2010a). There are typically multiple remedy components at complex groundwater sites (see Table 10); each component may require many years to achieve interim objectives. For example, when monitored natural attenuation (MNA) is a remedy component, its implementation will run "for some time agreed upon by site owners, regulators, and stakeholders" (ITRC 2010a).

▼*Read more*

It is sometimes difficult for site owners, regulators, and stakeholders to agree on a reasonable time frame for remediation for a complex site, as well as the degree of site complexity. For example, the ITRC authoring team for this guidance includes federal agency and private party site owners, state and federal regulators, stakeholders, remediation contractors, and academics. At the beginning of the team's process, these participants were surveyed about complex sites and time frames for remediation. Results, shown in Table 1, indicate a wide disparity in opinions:

**Table 1. ITRC team survey results: time frames and complex sites (Appendix A)**

| **Survey Question: A remediation/restoration time frame greater than the following usually makes for a complex site:** | | |
|---|---|---|
| **Time Frame** | **Survey Response** | **Response Count** |
| **10 years or longer** | 11% | 12 |
| **30 years or longer** | 28% | 30 |
| **60 years or longer** | 6% | 6 |
| **100 years or longer** | 14% | 15 |
| **Remediation time frame does not determine whether a site is complex** | 47% | 50 |
| **TOTAL** | | 107 |

*Note: survey responses total more than 100% because 5 survey respondents selected multiple answers.

### Example Criteria for Assessing Reasonable Restoration Timeframe

*Washington state regulations use qualitative factors to determine whether a cleanup action provides for a reasonable restoration time frame. Washington Administrative Code 173-340-360(4)(b) includes the following considerations:*

*"(i) Potential risks to human health and the environment*

*(ii) Practicability of achieving a shorter restoration time frame*

*(iii) Current & (iv) potential future use of the site, surrounding areas, and associated resources*

*(v) Availability of alternative water supplies*

*(vi) Likely effectiveness and reliability of institutional controls*

> *(vii) Ability to control and monitor migration of hazardous substances from the site*
>
> *(viii) Toxicity of the hazardous substances at the site*
>
> *(ix) Natural processes that reduce concentrations of hazardous substances at the site or under similar site conditions."*

Timely remediation is frequently valued by RPs, regulators, and stakeholders. Because reasonable restoration time frame is not defined in regulations, early stakeholder engagement on this issue can help to build consensus. Lack of consensus-building on restoration time frame can result in site objectives that do not reflect site complexities and are therefore unrealistic or unachievable.

## 1.5 What is Adaptive Site Management?

The term "adaptive site management" refers to a comprehensive, flexible, and iterative process that can be used to manage the remediation process. NRC (2003) coined the term "adaptive site management" referring to "a comprehensive and flexible approach… for dealing with difficult-to-remediate hazardous waste sites over the long term" or where "…current technologies have proved to be ineffective in reaching site objectives for many types of contamination." Adaptive site management can be used to make decisions in response to remedy performance, while considering changes in site conditions, the CSM, technology performance, and technological advances over time.

▼*Read more*

NRC recommends adaptive site management at complex Superfund sites, noting that "adaptive management is not synonymous with 'trial and error'" (NRC 2005). The adaptive site management process is instead a means to "…learn from, test, assess, and modify or improve remedies with the goal of meeting long-term objectives" (NRC 2007). Adaptive site management practices have been implemented at many sites, including the Watervliet Arsenal, New York (ITRC 2012).

USEPA guidance describes a process similar to adaptive site management. For example, the *Groundwater Remedy Completion Strategy* describes an iterative remediation process as follows (USEPA 2014b): "The schedule should reflect the dynamic and iterative nature of a groundwater strategy's implementation. With ongoing data collection, evaluation of the performance metrics and remedy assessment, the completion strategy process and findings should be updated periodically to facilitate open and transparent communications within the project team and external stakeholders." Elements in the stepwise completion strategy are stated as follows (USEPA 2014b):

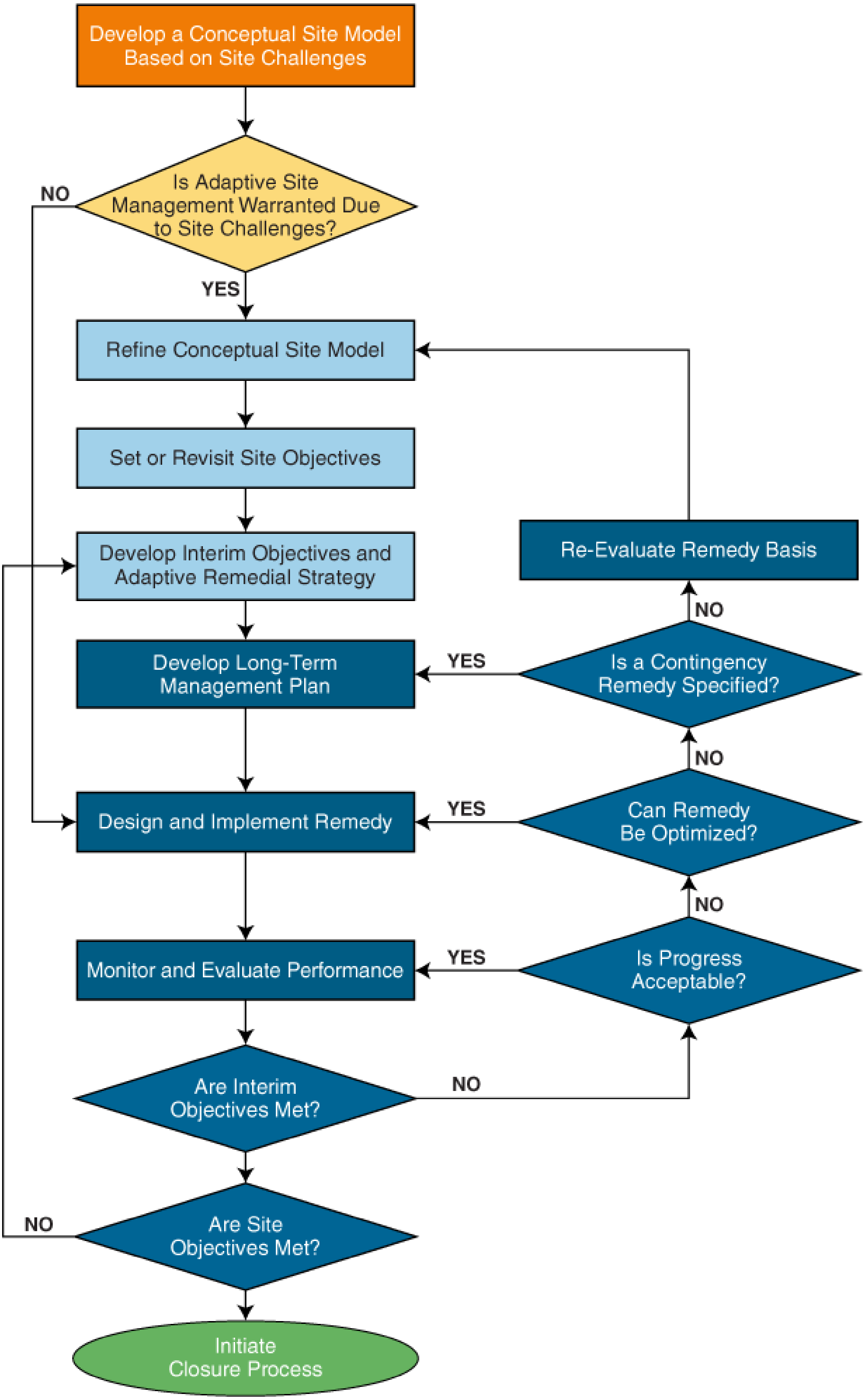
- Understand current site conditions.
- Design site-specific remedy evaluations.
- Develop performance metrics and collect monitoring data.
- Conduct remedy evaluations using site-specific metrics.
- Make management decisions.

ITRC's process for adaptive site management, as outlined in this guidance, is similar to the USEPA process and to NRC's recommendations.

Figure 1 shows how adaptive site management can be applied to the remediation of complex sites. ITRC's definition of "adaptive site management" consists of the following steps, repeated as needed:

1. Identify site challenges within the context of the CSM.
2. Conduct a remediation potential assessment to decide if adaptive site management is warranted due to site challenges.
3. Refine CSM.
4. Set or revisit site objectives.
5. Develop interim objectives and adaptive remedial strategy.
6. Develop a long-term management plan.
7. Design and implement remedy.
8. Monitor and evaluate performance.

9. Apply decision criteria to adjust, optimize, or reevaluate the remedy.



Develop a Conceptual Site Model Based on Site Challenges
Is Adaptive Site Management Warranted Due to Site Challenges?
NO
YES
Refine Conceptual Site Model
Set or Revisit Site Objectives
Develop Interim Objectives and Adaptive Remedial Strategy
Re-Evaluate Remedy Basis
NO
Develop Long-Term Management Plan
YES
Is a Contingency Remedy Specified?
NO
Design and Implement Remedy
YES
Can Remedy Be Optimized?
NO
Monitor and Evaluate Performance
YES
Is Progress Acceptable?
Are Interim Objectives Met?
NO
NO
Are Site Objectives Met?
Initiate Closure Process

**Figure 1. Framework for remediation of complex sites.**

▼*Read more*

Although adaptive site management can be used at any site, it is particularly useful at complex sites. Adaptive site management does not need to be applied sitewide—simple issues can be addressed in parallel using existing processes. Because of the technical uncertainties of applying remediation technologies in complex settings, several iterations may be needed at complex sites. Compared to simpler sites, complex sites may use the same remediation technologies, but require multiple remediation technologies across the site and throughout the remediation process. Complex sites may also require more diagnostic tools and data collection to guide technology implementation. It may be appropriate to reevaluate site objectives to align them with achievable goals.

Adaptive site management can be used at any stage of site remediation. The first steps of the adaptive site management process could be considered prior to the remedial alternative evaluation (such as the CERCLA feasibility study or RCRA corrective measures study). The adaptive remedial strategy could then be documented in the final remedy decision document. At other sites, a remedy may already be in place and adaptive site management practices could be integrated where appropriate. Adaptive site management goes beyond what is required under CERCLA or RCRA in assessing restoration potential, developing interim objectives, developing a long-term management plan, and following clear decision logic to refine the CSM and to adjust or even reevaluate the remedy. Note that the CSM may be refined at other times as a result of new data gathering. For simplicity, this detail is not shown in Figure 1. Site managers can also implement relevant phases of adaptive site management during remedy planning and implementation (remedy selection, remedial design, remedial action) or during long-term management, which includes postconstruction phases of remediation management, monitoring, and evaluation of remedy protectiveness. Early stakeholder involvement and continuing engagement after remedy selection and throughout the remedy has proven successful at complex sites).

Sites that have already selected a remedy may choose to integrate existing site operations into the adaptive management process by establishing interim objectives. Interim objectives can be developed for each component of the remedy, along with specific, relevant, and time-bound performance metrics. The next steps are remedy implementation, monitoring, and evaluation. Remedy performance is evaluated routinely against performance metrics to keep the remediation on track to achieve interim objectives. If performance is not acceptable, the remedy can be optimized, if feasible, replaced with a contingency plan, or reevaluated. Remedy reevaluation is a process that consists of refining the CSM to better describe site complexities, reevaluating site objectives if needed, and modifying the remedy.

Adaptive site management ends when all interim objectives have been met, site objectives have been achieved, and the closure process has been initiated. If a "no further action" site objective is unachievable or otherwise not applicable, then the remediation process may include long-term management of the site or portion of the site.

**Case Study: Adaptive Site Management at Naval Air Station Jacksonville (NAS JAX)**

*Operable Unit (OU) 3 at NAS JAX includes several comingled chlorinated solvent plumes resulting from historical operations at over 100 buildings. Optimization studies and Five-Year Review results revealed several data gaps, prompting the NAS JAX Team to use adaptive site management to refine the CSM, determine key exposure pathway risks, and develop a comprehensive remedial approach. Several pilot studies and ESTCP demonstrations of innovative tools and technologies have been conducted. Source area DNAPL and the risks of VI and contaminant migration to surface waters have been evaluated. An FS Addendum is being completed. More details are provided in the full case study.*

## 1.6 Notable Previous Guidance for Complex Sites

Although comprehensive guidance for complex sites is lacking, USEPA, DOD, and ITRC have published some prior guidance for these sites. Specifically, USEPA has published two documents to address management of sites that have contaminated groundwater, which often is present at challenging sites:

- *Groundwater Road Map – Recommended Process for Restoring Contaminated Groundwater at Superfund Sites* (USEPA 2011c). This guidance "summarizes the steps and decisions related to selecting a groundwater remedy; designing, constructing, and initiating the remedy; operating, monitoring, evolution, and optimizing the remedy; modifying the remedy, as appropriate; and documenting completion of the site response action."
- *Groundwater Remedy Completion Strategy: Moving Forward with the End in Mind* (USEPA 2014b). The purpose of this guidance is to "… help focus resources on the information and decisions needed to effectively complete groundwater remedies and to ensure that these remedies protect human health and the environment." This guidance also provides a technical and scientific process for evaluating whether sufficient data have been obtained to assess the likelihood that a groundwater remedy has or will achieve the site objectives in a reasonable time frame.

Additionally, DOD recognized the problem of complex sites many years ago and issued relevant guidance (United States Army 2002). In a more recent publication, the NRC described "transition assessments" as an approach to manage remediation decision making at complex sites that already have a remedy in place, but have reached asymptotic performance (NRC 2013).

The following ITRC guidance describes topics and tools that are relevant to site complexities, technologies for adaptive site management, and streamlining remediation management:

- *A Decision Framework for Applying Monitored Natural Attenuation Processes to Metals and Radionuclides in Groundwater* (ITRC 2010a)
- *Characterization and Remediation of Fractured Bedrock Guidance* (ITRC 2017a)
- *EMD – New Site Characterization and Remediation Enhancement* Tools (ITRC 2013b)
- *Enhanced Attenuation: Chlorinated Organics* (ITRC 2008a)
- *Evaluating LNAPL Remedial Technologies for Achieving Project* Goals (ITRC 2009a)
- *Evaluating Natural Source Zone Depletion at Sites with LNAPL* (ITRC 2009b)
- *Geospatial Analysis for Optimization at Environmental Sites* (ITRC 2016a)
- *Green and Sustainable Remediation: A Practical Framework* (ITRC 2011a)
- *Groundwater Statistics and Monitoring Compliance* (ITRC 2013c)
- *Improving Environmental Site Remediation Through Performance-Based Environmental Management* (ITRC 2007a)
- *In Situ Bioremediation of Chlorinated Ethene: DNAPL Source Zones* (ITRC 2008b)
- *Integrated DNAPL Site Characterization and Tools Selection* (ITRC 2015b)
- *Integrated DNAPL Site Strategy* (ITRC 2011b)
- *Long Term Contaminant Management Using Institutional Controls* (ITRC 2016b)
- *Permeable Reactive Barrier: Technology Update* (ITRC 2011c)
- *Planning and Promoting Ecological Land Reuse of Remediated Sites* (ITRC 2006b)
- *Property Revitalization – Lessons Learned from BRAC and Brownfields* (ITRC 2006c)
- *Use and Measurement of Mass Flux and Mass Discharge* (ITRC 2010b)
- *Using Remediation Risk Management to Address Groundwater Cleanup Challenges at Complex Sites* (ITRC 2012)

# 2. Site Challenges

Develop a Conceptual Site Model Based on Site Challenges

Remediation is inherently difficult—even at simple sites. Complex sites, however, have both technical and nontechnical challenges that can prevent remedial approaches from meeting site objectives or transitioning to long-term management within a reasonable time frame. CSMs traditionally focus on the technical aspects of a site and thus may not include the nontechnical issues, such as future land use or stakeholder concerns, that can create additional complexity for a site. If substantial complexities are identified, a remediation potential assessment is recommended to address the question of whether adaptive site management is warranted (see Figure 1).

## 2.1 Technical Challenges

Table 2 includes many, but not all, of the technical challenges that can result in a complex site.

**Table 2. Technical challenges of complex sites**

| Technical Challenges | Examples |
|---|---|
| Geologic conditions | • Geologic heterogeneity/preferential flow paths<br>• Faults<br>• Fractured bedrock<br>• Karst geology<br>• Low-permeability media |
| Hydrogeologic conditions | • Extreme or variable groundwater velocities<br>• Fluctuating groundwater levels<br>• Deep groundwater contamination<br>• Surface water and groundwater interactions and impacted sediment |
| Geochemical conditions | • Extreme geochemistry (such as unusually high or low pH or alkalinity, elevated electron acceptors, extreme redox conditions)<br>• Extreme groundwater temperatures |
| Contaminant-related conditions | • Light or dense nonaqueous phase liquids (LNAPL or DNAPL)<br>• Recalcitrant contaminants<br>• High contaminant concentrations or multiple contaminants<br>• Emerging contaminants |
| Large-scale site | • Location and extent of contamination<br>• Number, type and proximity of receptors<br>• Depth of contamination<br>• Extensive or comingled plumes |

Go to section 2.2 Nontechnical Challenges

Each of the technical challenges listed in Table 2 is described in more detail in the following subsections. The adequacy of characterization is important for each of these factors. ITRC has previously published guidance on the selection of site characterization tools that may be useful at complex sites (see for example, ITRC 2015b).

### Framework for Selecting Investigative Tools and Analyses

*ITRC (2015b) provides examples of how to implement site characterization tools, such as integrated site* *characterization (ISC), for different types of sites and objectives. To help identify applicable tools, ITRC also provides a Tools Selection Worksheet for the interactive selection of over 100 tools based on geologic, hydrologic, and chemical data needs at a site. The Tool Selection Worksheet is linked to more detailed descriptions of each tool—including its applicability, data quality capability, and limitations or challenges. Examples of tools listed in the worksheet include sampling and analysis methods, chemical screening methods, geochemical characterization tools, environmental molecular diagnostics, microbial diagnostics, hydraulic testing, tracer tests, geophysics and more. In addition to investigative tools, plume migration and contaminant transport can be analyzed and predicted using simple graphical techniques, modeling, or 3D visualization software.*

### 2.1.1 Geologic Conditions

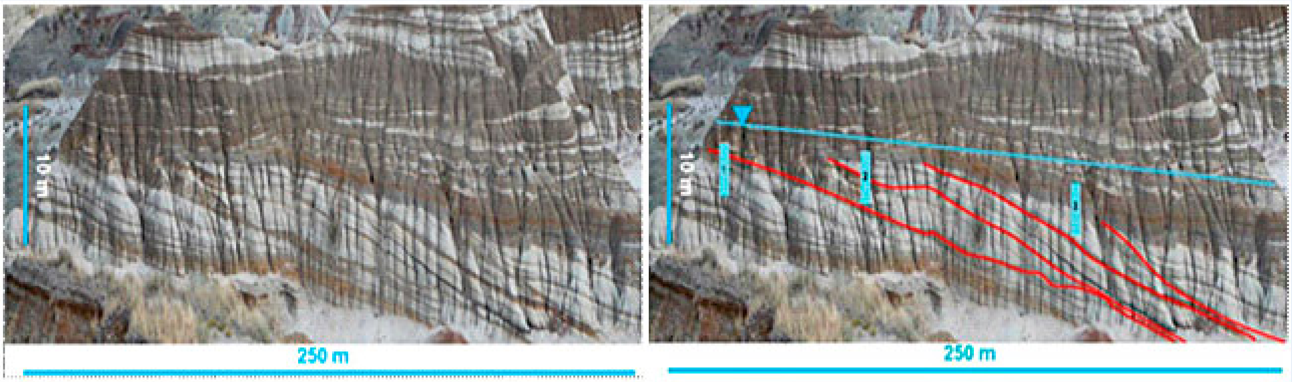
Complex geology at a site can lead to technical challenges when designing an effective remediation approach. Geologic conditions may complicate the development of a CSM, the selection of an appropriate remediation approach, and the time frame needed to meet site objectives. Complicating conditions can include geologic heterogeneity, fractured bedrock, karst geology, and low-permeability media—all of which can control contaminant migration because the geology forms the "plumbing" that influences fluid flow and contaminant transport in the subsurface. The geology thus determines contaminant migration pathways, the nature and extent of contamination, and contaminant transport and storage zones, which must be included in a representative subsurface CSM. Understanding the site geologic conditions is also critical for the subsequent analysis of hydrogeology and chemistry data sets.

#### 2.1.1.1 Geologic Heterogeneity/Preferential Flow Paths

The heterogeneity of the aquifer matrix can control contaminant migration; see *Integrated DNAPL Site Strategy* (ITRC 2011b) for detailed information on this topic. Varied stratigraphy can result in intermittent contamination that complicates characterization (USEPA 2016a). For instance, fluvial systems often produce interlayered clastic sedimentary deposits, in which higher permeability coarse-grained (sand/gravel) channel deposits are encased in lower permeability (silt/clay) floodplain deposits. Groundwater and related contaminants preferentially migrate through the more permeable channel deposits. Permafrost areas in northern regions may also create preferential flow paths (thaw channels) where intermittent melting has occurred or where discontinuous lenses occur. This preferential flow can be exacerbated when contaminants accumulate in less permeable zones because of the concentration gradients. These zones then serve as secondary sources of contamination via matrix diffusion back into the more permeable zones. Other primary and secondary sedimentary features can also affect groundwater pathways, making it difficult to anticipate and follow contaminant migration (USEPA 2016a).

**Complex Sites and the Value of Accurate Subsurface Characterization**

*The photos below illustrate a significant challenge to successful groundwater remediation: stratigraphic heterogeneity. This geological heterogeneity results from stratigraphic layering and is common at groundwater remediation sites where sedimentary aquifers are affected. Unfortunately, also common is the practice of "layer cake" designations of aquifers, in which it is assumed that the first sand encountered when drilling is a homogeneous, isotropic layer, followed by the next layer, and so on. At complex, heterogeneous sites this configuration is seldom present. In the example presented here, lateral shifting of the river channel through time has caused the sands to be deposited not from the bottom up (as commonly assumed), but rather from left to right as the channel migrated with time. In this meandering river deposit, clay units (dark colored) in the outcrop (Upper Cretaceous, Alberta, Canada) separate laterally offset-stacked, or shingled, sand units (point bar deposits, light colored). The right photo highlights clay units dipping from upper left to bottom right (red lines).*




*Blue rectangles indicate hypothetical well screens. Interwell communication is severely limited due to stratigraphic dip. The three hypothetical wells shown installed into the uppermost sand for monitoring or remediation are not in hydraulic communication with one another. High resolution subsurface data at these locations would look similar, and the lateral shingling would not be identified without knowledge of the depositional environment and stratigraphy. Depositional models, or facies models, predict such heterogeneity and should be applied at groundwater remediation sites where sedimentary aquifers are affected (Photo courtesy of Hubbard 2015).*

Mapping the heterogeneities can be helpful for determining the nature and extent of contamination, contaminant migration pathways, and contaminant transport and storage zones at complex sites. *Integrated DNAPL Site Characterization* (ITRC 2015b) provides methodologies for characterizing heterogeneous geologic features at complex sites.

### 2.1.1.2 Fractured Bedrock

Fractured bedrock aquifers can also be difficult to remediate. Groundwater flow and contaminant transport in fractured bedrock aquifers are typically dominated by secondary fracture porosity, with matrix diffusion of contaminants into and out of primary porosity significantly affecting contaminant flow and distribution (ITRC 2011b, NRC 2005). Because the hydraulic conductivity of the fracture zone is normally quite high, this secondary porosity is often the dominant pathway for rapid fluid flow in highly heterogeneous fractured rocks. It is extremely challenging to map out the fracture occurrence and nature and extent of groundwater contamination to the degree necessary to design an effective contaminant monitoring program and remediation system. This topic is addressed in ITRC's *Characterization and Remediation of Fractured Bedrock* guidance (ITRC 2017a).

#### Case Study: UGI Columbia Gas Plant Site

*The UGI Columbia Gas Plant Superfund site is located on less than an acre of a much larger industrial area of Pennsylvania near the Susquehanna River. A century of manufacturing gas products at the site has left volatile organic compounds (VOCs), polyaromatic hydrocarbons (PAHs), heavy metals, and cyanide in soil, sediments, groundwater, and surface waters. Residual DNAPL in overburden and shallow and deep fractured bedrock (to a depth of 160 feet) significantly affected the remedial approach. Remediation for this complex site includes on-site capping, institutional controls, industrial site use restrictions, interim actions, and a technical impracticability waiver. More details are presented in the full case study.*

### 2.1.1.3 Karst Geology

Karst topography forms when the soluble areas of sedimentary bedrock dissolve, leaving cavities that range from small voids to large caverns. Groundwater transport, permeability and flow velocities through these cavities can be orders of magnitude higher than in other bedrock settings, and contaminants can travel long distances with little dilution in karst, as compared to granular porous media aquifers (NRC 2013). Networks of karst conduits are also highly variable, resulting in unpredictable groundwater migratory pathways that are ill-suited to conventional monitoring techniques such as monitoring wells.

Further complicating this geology, shallow karst geology systems are often well connected to surface waters. Because of this connection, groundwater and contaminant mass discharges to perennial or temporal streams, springs, and other surface water bodies are often highly responsive to precipitation. Sinkholes and conical depressions in the ground surface may result. Tracer tests can aid in the characterization and remedial design for karst geology settings (ITRC 2015b).

#### 2.1.1.4 Low-Permeability Media

Contaminants in low-permeability areas of the subsurface diffuse back into higher permeability zones once concentrations in the higher zones decrease. Thus, back-diffusion from low-permeability media can sustain contaminant plumes in higher permeability zones long after the contaminant source is gone (ITRC 2011b). This situation should be evaluated on a site-specific basis, as heterogeneous and anisotropic conditions at a site may complicate the CSM and lead to erroneous conclusions.

Contamination that exists in low-permeability zones may still require extended remediation time frames even when remediation additives are injected (for example, injection of permanganate or adding engineered microorganisms). These additives do not contact the contaminants until they have diffused into the more permeable zones. Fluxes from low-permeability to higher-permeability zones can keep pump-and-treat (P&T) systems operating inefficiently, depending on the rate of diffusion, for decades.

### 2.1.2 Hydrogeologic Conditions

CSMs that assume homogenous and isotropic flow conditions can over-simplify aquifer analysis. These simplistic assumptions often do not reflect actual heterogeneous and anisotropic conditions and may cause an incomplete or incorrect CSM to be developed. Some of the specific hydrogeologic conditions that can make a site difficult to characterize and remediate include variable groundwater velocities, groundwater levels that fluctuate due to various local conditions, deep groundwater aquifers, and groundwater/surface water interactions. These conditions are described more fully in the subsections below.

#### 2.1.2.1 Extreme or Variable Groundwater Velocities

Low groundwater velocities often increase the time frame to reach site objectives. In addition, slow-moving groundwater also provides greater contact time for contaminants to adsorb to the aquifer solids. On the other hand, as with karst geology, high groundwater velocities may prevent adequate reductions in contaminant concentrations. Other factors may influence changes in groundwater velocity, such as changes in recharge. In addition, portions of an aquifer may discharge in specific areas, causing localized changes in gradients and velocities (magnitude and possibly direction), compared with the rest of the aquifer.

#### 2.1.2.2 Fluctuating Groundwater Levels

Groundwater levels typically fluctuate because of different influences, including:

- tidal changes in coastal areas
- changes due to barometric pressure
- increased or decreased recharge (often seasonal)
- changes in river stage
- changes in water usage

Water level fluctuations are typically determined during long-term monitoring programs. Changing water levels at some sites can complicate site characterization. Flow directions may change as the water levels move up and down, causing unusual plume migration patterns. The flow direction may change permanently due to changes in water usage. Rising water levels may also inundate LNAPL, trapping it beneath the water table and making it difficult to remove.

**Case Study: Velsicol Site, St. Louis, Michigan**

*Chemical plant operations at the Velsicol site contaminated subsurface groundwater, including the city's well field, and the nearby Pine River. DNAPL pools were detected 100 feet below ground surface in semi- to low- permeability fractured till units that transition to sands and gravels of the aquifer system. The semiconfining unit under the site was assumed to be an impermeable clay unit when a circumferential slurry wall remedy was constructed to prevent contaminants from migrating. The remedy failed, however, due to poor keying of the slurry wall and leakage through the low-permeability fractured till unit.*

*In the fall of 2015, the city shut down the contaminated regional aquifer well field, which had operated since the early 1900s and began operating a new, replacement well field. Although the regional aquifer had been artesian prior to well field operation in the 1900s, it was assumed that regional agriculture and other uses would prevent artesian conditions from being reestablished. Within several months of shutting down the well field, however, artesian flow conditions developed at observation wells and city water supply wells. Domestic wells beyond the city limits flooded basements and left front yards saturated. More details are presented in the full case study.*

#### 2.1.2.3 Deep Groundwater Contamination

Characterizing contaminant distribution and transport in deep aquifers is usually complicated by the scarcity of direct data, which can be limited by the cost and difficulty of deep boreholes. Characterization is often on a regional scale and increasingly uses geophysical methods borrowed from the oil and gas industry. Several surface geophysical methods can be used to image the structure of deep aquifers and estimate the water quality (Jansen 2014). While many of the most common methods are limited to a few hundred feet in depth, some methods can characterize aquifers to depths of several thousand feet. Deep groundwater methods include time domain electromagnetic induction (TEM), magnetotellurics (MT), seismic reflection, and gravity measurements. These methods can be used to map aquifers, find faults and fractures, map saline water, estimate lithology, and detect facies changes within an aquifer. Designing and implementing an effective remedial system for deep groundwater is therefore costly and difficult.

#### 2.1.2.4 Surface Water and Groundwater Interactions and Impacted Sediments

The interactions between groundwater and surface water can be complex even in the absence of contamination. These interactions can be influenced by climate, topography, geology, and human activity such as groundwater withdrawal or flood control measures. Recharge and discharge processes, along with biotic and abiotic chemical processes within the upper layer of sediments beneath surface water (hyporheic zone), can cause changes to the chemistry of the interchanged water. Furthermore, sediment transport and deposition varies spatially over time and is often challenging to model.

A multidisciplinary approach may be required to characterize the key groundwater hydrogeology, surface water hydrology, chemistry, and biological aspects driving the interactions. Investigation and remediation equipment and techniques deployed in aquatic settings are more specialized and complex than those used in terrestrial settings. The presence of contamination in an aquatic environment also introduces additional potential human and ecological receptors. The regulatory framework for a site with surface water and sediment contamination can also become more complex because site management and remediation activities often encompass multiple laws and regulations (for example, CERCLA and the Clean Water Act), agencies (such as states and tribes, USEPA, Army Corps of Engineers, U.S. Coast Guard) or even multiple programs within agencies (such as remediation and water programs).

Several references for more information on surface water and groundwater interactions and impacted sediments include the following:

- *Ground Water and Surface Water, A Single Resource* (Winter et al. 1998)
- *Proceedings of the Ground-Water/Surface-Water Interactions Workshop, Solid Waste and Emergency Response* (USEPA 2000)
- *Contaminated Sediment Remediation Guidance for Hazardous Waste Sites* (USEPA 2005a)
- *Characterization of Contaminated Ground Water Discharge to Surface Water Technical Guidance, Version 1.0* (NJDEP 2016)
- *Guidance on Evaluating Sediment Contaminant Results* (Ohio EPA 2010)

### 2.1.3 Geochemical Conditions

The geochemistry encountered in soil and groundwater is unique for every site. Differences in soil mineralogy, groundwater composition, and naturally occurring inorganic and organic materials can influence contaminant transport and transformation in the subsurface. The geochemical conditions identified in Table 2 are often associated with unique regional conditions, specific forms of contamination, or combinations of contaminants. These conditions may present remediation challenges either on their own or when coupled with other attributes. The geochemical conditions described in Table 2 induce other related processes that either limit remedial effectiveness or induce negative secondary effects.

#### 2.1.3.1 Extreme Geochemistry

Sites have extreme geochemistry when geochemical conditions are well outside of the range observed at typical sites. This geochemistry may limit the remedial technologies that can be applied, or may need to be a focal point of the remedial design. Under site-specific conditions, alkalinity, pH, redox conditions, salinity, ionic strength, and hardness are a few examples of the parameters that can result in extreme geochemistry.

Alkalinity is a measurement of an aquifer’s overall capacity to neutralize acids. While groundwater alkalinity is usually an indicator that quantifies this capacity, the neutralization capacity of soils must also be considered because they can account for 70–90% of an aquifer’s overall neutralization capacity. High or low alkalinity conditions contribute to a site’s overall complexity because they reflect an aquifer's ability to withstand pH modification. For example, fermentation of organic substrate (added to promote biodegradation) at sites with elevated alkalinity can generate dissolved carbon dioxide at levels exceeding its solubility. Consequently, bubbles or vapors can be generated in the saturated zone that limit solution injectability or contribute to reductions in hydraulic conductivity.

In these same treatment applications, poorly buffered aquifers (low alkalinity) can exhibit pH decreases. Volatile fatty acids are generated from fermentation processes following carbon delivery. In a poorly buffered aquifer, these volatile fatty acids will lower the groundwater pH. Biologically mediated processes are reduced at low pH (<6), as has been widely documented for *Dehalococcoides mccartyii* in chlorinated solvent dehalogenation.

Extremes in pH generally result from acid or base releases sufficient to cause a sustained decrease or increase in soil and groundwater pH conditions. Extreme pH values or changes in redox conditions can control the dissolution of toxic minerals/metals such as arsenic, lead, and a variety of heavy metals that are naturally present in native soils. The release of naturally occurring metals due to low pH, and in some cases low oxidation-reduction potential, can result in levels of these metals that exceed drinking water criteria. These metals must then be remediated, along with the other anthropogenic contaminants.

Aquifers with high salinity or ionic strength can also be challenging. For example, when selecting reagents for injection into a high ionic strength aquifer containing fine-grained materials, the concentrations of cations such as sodium and calcium in the groundwater should be considered. Using a freshwater reagent for injection in these environments can cause dispersion and increased hydration of clay particles (Kia et al. 1987, Zhou et al. 2009), which can irreversibly clog the injection well. Instead, a reagent created to match the key cation makeup of the high salinity aquifer (brackish aquifer) should be used.

Aquifers with high salinity or ionic strength may also contain elevated competing electron acceptors beyond those observed at typical sites. Elevated sulfate concentrations, for example, are found in coastal environments and some regional geologies. These elevated concentrations of electron acceptors require large, sustained quantities of organic carbon as an electron donor to promote the highly reducing groundwater conditions needed to achieve treatment. If too little organic carbon is applied, then contaminant concentrations do not decrease because the carbon is instead wholly used by organisms to deplete the elevated concentrations of the sulfate electron acceptors.

Another added complexity of extreme geochemistry aquifers is the potential for the remedy to create an increase in hardness, total dissolved solids, iron, heavy metals, and sometimes taste and odor in the aquifer (under either engineered or natural attenuation conditions). The presence of these minerals can present remedy design challenges. For example, in soils with naturally high ferric iron composition, reduced iron minerals can contribute to extensive equipment fouling as the iron reprecipitates with either sulfide (in reduced groundwater systems) or hydroxide species (in extraction wells, injection wells, or above-grade treatment systems). This fouling can impede fluid flow to and from groundwater systems. An aesthetic criterion can also cause the water supply to be deemed nonpotable for domestic or municipal consumption. Treating the degraded groundwater for the aesthetic criterion may also be required at a cost to the community or individual well owner.

### 2.1.3.2 Extreme Groundwater Temperatures

Groundwater temperatures influence both the kinetic rates of chemical reactions and the activity of microorganisms performing biodegradation. For physical or chemical remedies, extreme increases in temperature are a key component to successful chemical oxidation, contribute to enhanced hydrolysis of several key chlorinated ethane contaminants that are not readily biodegradable, and are the basis of thermal remediation designs. Extreme elevated temperatures can also complicate a CSM—for example, geothermal sources may have an impact on contaminant fate and transport and can mask other fate and transport properties such as sorption and desorption. Increased temperature enhances the rate of microbial enzymatic activity and in general is correlated with an increase in growth for each incremental increase of 10ºC. This convention holds true up to approximately 37ºC, above which cell wall lysis and enzyme denaturation occur.

Conversely, low temperatures decrease the rates of chemically and biologically mediated reactions and thus may preclude using injection-based remedial technologies that rely on these reactions. Sites with cold climates (low annual or seasonal groundwater temperatures) or permafrost layers exhibit low rates of natural attenuation and thus have fewer treatment options. When coupled with other technical characteristics (such as large-scale plumes or deep groundwater contamination), sites with low temperatures can require long cleanup time frames, may have fewer effective remedial technologies available for use, and may incur increased remediation costs. While low temperatures should be considered during remedy selection, they do not entirely preclude the use of biologically enhanced remedies or natural attenuation processes, as illustrated by the use of biologically based remedies in seasonally cold climates such as the Test Area North site in Idaho. The North Pole refinery site in Alaska is another example of a site where bioremediation has been a successful remedial strategy.

### 2.1.4 Contaminant-Related Conditions

Contaminant-related conditions that may contribute to a site being considered complex include the presence of NAPLs, recalcitrant contaminants, high concentrations or multiple contaminants, and emerging contaminants.

#### 2.1.4.1 NAPLs

Nonaqueous phase liquids are common but complicating contaminants. LNAPLs are less dense than water and form a separate phase in the subsurface if released in significant quantities. Examples of contaminants that form LNAPL include crude oil, gasoline, diesel fuel, and heating oil. LNAPL source zones can naturally degrade over time by processes including sorption, volatilization, and dissolution (ITRC 2009b). Large LNAPL releases, however, may migrate to the water table over a large area, leaving residual contaminant in the overlying soil that presents significant remediation challenges.

DNAPLs are denser than water and also form a separate phase in the subsurface if released in significant quantities. Examples of DNAPLs include chlorinated solvents, creosote, coal tar, chlorobenzenes, and polychlorinated biphenyls (PCBs) (USEPA 1993). Unlike LNAPL, DNAPL sinks in the subsurface below the water table and becomes sorbed into low-permeability zones or bedrock fractures. With time, DNAPL can then back-diffuse into more permeable zones and cause persistent groundwater plumes. Low-permeability zones are hard to treat with standard technologies and can act as a contaminant source to more permeable zones for decades or even centuries (ITRC 2011b). DNAPL transport varies with contaminant viscosity, solubility, and other properties. For example, chlorinated solvents behave differently than coal tar. The presence of DNAPL often makes in situ remediation more difficult and expensive (McCarty 2010, Stroo et al. 2012, Suchomel et al. 2014).

A range of technical challenges faced at DNAPL sites were described in the ITRC *Integrated DNAPL Site Strategy* (IDSS) guidance (ITRC 2011b) and by the NRC (2013). The overarching technical challenge is that many complex sites have a heterogeneous distribution of contaminant mass, leading to substantial back-diffusion from bedrock/soils to remediated groundwater. This condition, combined with the presence of high-concentration source areas at many sites, makes characterization and remediation difficult and leads to persistent and often large contaminant plumes in groundwater (USEPA 2004e).

#### 2.1.4.2 Recalcitrant Contaminants

Recalcitrant contaminants do not easily degrade and may exhibit other characteristics (such as radioactivity, phase change, molecular states, or molecular bonding) that resist remediation within a reasonable time frame. Examples of these chemicals include polyaromatic hydrocarbons (PAHs), PCBs, poly- and perfluoroalkyl substances (PFAS), several organochlorine pesticides, dioxins, furans, metals, and radionuclides. Brominated flame retardants are another newly identified class of chemicals in this category. The presence of bioaccumulative and endocrine disruptor compounds in the aquatic environment, food chain, and human population can also add significantly to site complexity. Sometimes treating these compounds may result in a byproduct that must also be managed as a waste (such as radionuclides) and may pose special management and disposal issues (USEPA 2004b, 2007b, Prakash et al. 2013). Treatment may also produce intermediate products of unknown toxicity.

#### 2.1.4.3 High Concentrations or Multiple Contaminants

In some cases, multiple contaminants create uniquely complex treatment difficulties. A treatment appropriate for one contaminant may not treat the entire mix or may even interfere with the remediation of another contaminant. Mixtures such as chlorinated solvents and 1,4-dioxane or a combination of metals and volatile organic compounds can be difficult to remediate because the chemical and physical properties differ, which creates different plume characteristics and requires different treatment technologies. For example, chlorinated solvents can be anaerobically bioremediated, but 1,4-dioxane generally requires advanced oxidation processes.

High concentrations of contaminants may result in the site becoming anaerobic or may overwhelm the natural attenuation capacity of the system. In other situations, the inherently difficult nature of even a single contaminant—such as a radionuclide that is resistant to removal, located in an inaccessible area, and persistent by nature—leads to complexity. This complexity limits treatment options, and, eventually, increases the time required for removing the contamination.

#### 2.1.4.4 Emerging Contaminants

Some of the emerging contaminants, such as PFAS or 1,4-dioxane, have only limited remedial technologies, making it difficult to reach site objectives. PFAS have been used for decades in products that resist heat, oil, stains, grease, and water and because PFAS were designed to be chemically and thermally stable, they are extremely resistant to breakdown in the environment. ITRC is currently developing guidance for addressing PFAS (ITRC 2017b). Often, as is the case with PFAS and 1,4-dioxane, these contaminants are soluble in water and are relatively resistant to biodegradation (USEPA 2014a). Some of these emerging contaminants (such as PFOS and PFOA) are also detected in water supply systems. Widespread groundwater effects, especially in water supply systems, may result in focused treatments at wellheads in the short term with much longer time frames required to meet all site objectives.

### 2.1.5 Large-Scale Sites

Although size alone does not make a site complex, contaminated sites often cover many square miles. Characteristics of large-scale sites contribute to several complications that even under the best of circumstances lead to longer time frames for characterization and remediation. Examples of characteristics that may result in a site being considered complex include location, nature and extent of contamination; depth of contamination; number, type and proximity of receptors; and comingled plumes. The complications and costs that accompany larger scale sites impose limitations on what can be accomplished within a given (presumably reasonable) time frame. The difficulties of responding to logistical challenges, workforce and workload management, responding to uncertainties, and technical difficulties increase with increasing scale of the area to be addressed and the number of potential sources identified. Case studies of large-scale sites are summarized below. Previous publications (such as NRC 2013) have also highlighted case studies of remediation complexities at large-scale sites.

**Hanford Site 200-ZP-1 Operable Unit Case Study: Complexities and Cleanup Path**

*DOE's Hanford Site, located in southeastern Washington State, was formerly used to produce plutonium for national defense under the Manhattan Project. This process used nuclear reactors to irradiate fuel elements, followed by chemical processing to separate isotopes of interest. During these processes, waste containing solvents, multiple organic compounds, a range of radionuclides, and inorganic compounds was disposed to the subsurface. The extent of groundwater contamination exceeds more than 12 square kilometers and includes comingled plumes of carbon tetrachloride, chloroform, TCE, nitrate, chromium, tritium, uranium, and technetium. Groundwater contamination extends to depths of about 250 feet. Waste inventory records show that carbon tetrachloride discharges alone range from 600,000 kg to 1,000,000 kg. Approaches to cleanup include source removal from the vadose zone and 30 years of active groundwater pump-and-treat. The treatment train consists of ion exchange, soil vapor extraction and vapor-phase granular activated carbon (SVE/GAC), and ex situ bioremediation, along with in situ monitored natural attenuation to achieve drinking water standards in approximately 130 years. More details are provided in the full case study.*

#### 2.1.5.1 Location, Nature, and Extent of Contamination

Many confounding factors may influence the size and distribution of a plume. Over decades, the practices resulting in a release may have been altered, stopped, or even shifted from location to location. Property downgradient from source area(s) that were originally undeveloped and open might now be developed, resulting in potential vapor intrusion (VI) concerns and lower groundwater cleanup objectives. In some cases, contamination may be present beneath densely populated areas (such as a large downtown). When an industrial facility occupies many square miles with many close or separated potential sources, the scale of both areal extent, number of activities to investigate, and the variety of sources and contaminants contribute to the complexity of the site. Among the challenges associated with a large and complex groundwater plume is the increasing chance that significant downward migration into productive high-yielding aquifer zones and entry into municipal supply well fields has already occurred. Alternatively, the plume may expand into brackish (>1,000 ppm total dissolved solids), nonpotable water that should not be pulled into the cone of depression from a remedial system.

#### 2.1.5.2 Depth of Contamination

Some sites, particularly in the western United States, are characterized by deep groundwater. Depths to groundwater greater than 250 feet exist at several well-documented complex sites. For example, depth to groundwater at the Hanford site in Washington State can reach approximately 350 feet (Looney 2012) and depth to water at the Pantex Plant in Texas is approximately 280 feet. Vadose zone characterization, monitoring and remediation at these depths is challenging because of limitations in instrumentation and monitoring technology, difficulties in drilling to greater depths, and challenges with injecting nutrients/reagents at depth. At the North Pole Refinery, Alaska, off-site contamination has been detected in the subpermafrost in private wells as deep as 320 feet (Alaska Department of Environmental Conservation 2015).

**Case Study: Test Area North**

*The Test Area North site at DOE's Idaho National Laboratory includes a two-mile trichloroethylene (TCE) plume with source area concentrations of over 20,000 µg/L. TCE is present at depths up to 200 to 300 feet. A ROD amendment signed in September 2001 documents regulatory approval of enhanced in situ bioremediation (ISB) as the final remedy for the plume hot spot and MNA as the final remedy for the distal portion of the plume. ISB has been implemented at the site since 1999. Both lactate and whey have been injected as electron donor biostimulants to promote microbial activity. Microbial community evaluation showed shifts in the microbial population in response to the electron donor injection. Complete dechlorination of TCE to ethene was observed in several monitoring wells at the site. MNA is predicted to achieve MCLs by 2095. More details are provided in the full case study.*

#### 2.1.5.3 Number, Type, and Proximity of Receptors

Plumes may be within or near drinking water aquifers or other receptors such as endangered species habitat, wetlands, or other environmentally sensitive areas. The likelihood for resource degradation may increase the difficulty of remediation. Protecting human health and the environment is paramount in these situations, often requiring interim and temporary systems while the project proceeds towards a more permanent solution. The presence of contamination in an aquatic environment introduces additional potential human and ecological receptors. Multiple ecological and human receptors also complicate a site.

#### 2.1.5.4 Extensive or Comingled Plumes

Large plumes may also have acquired additional contributing sources, both industrial and nonindustrial, through leaky sewers, agriculture, and landscaping practices. These contributing sources add to legal and risk management complications as well as remediation challenges. From a remediation perspective, comingled sources in a large plume make it difficult to find and remediate the sources and to know if all the sources have been identified. For naturally occurring compounds such as metals, natural variability in the environment may make it difficult to establish background conditions. Where plumes are viewed as regional or multisource, assigning liability and recouping expenditures becomes a challenge. Additionally, the options for remediation may be even more limited because the available financial resources are spent more for wellhead treatment than for identifying sources.

**Case Study: Rocky Flats**

*The Solar Ponds Plume at Rocky Flats is a mixed uranium and nitrate/nitrite plume, with a smaller colocated organic compound plume. Because these contaminants are now present as secondary sources within a low-permeability matrix, it will be many decades before the plume meets standards. Because the plume is comingled, it requires phased treatment. More details on this site are provided in the full case study.*

## 2.2 Nontechnical Challenges

Although nontechnical challenges exist at every site, it is often the combination of nontechnical and technical challenges that results in a complex site. Generally, the more technically challenging a site is, the longer it will take to achieve site objectives. Often because of the technical challenges and longer remediation duration, nontechnical challenges become more evident. Recognizing these relationships and identifying the nontechnical challenges early in the process helps to establish site objectives that can be achieved within a reasonable time frame. Table 3 summarizes some of the nontechnical challenges faced at complex sites. Additional information is provided in this guidance on setting and tracking ICs and the long-term management of complex sites.

**Table 3. Nontechnical challenges for complex sites**

| Nontechnical Challenges | Examples |
|---|---|
| Site objectives | • Societal expectations and social acceptability<br>• Changing site objectives<br>• Adopting site objectives that differ from promulgated screening levels or closure criteria (such as MCLs) |
| Managing changes that may occur over long time frames | • Phased remediation<br>• Future use<br>• Site management<br>• Multiple responsible parties<br>• Staff turnover/Loss of institutional knowledge<br>• Litigation |
| Overlapping regulatory responsibilities | • Federal and state cooperation<br>• Changing laws and regulation<br>• Financial responsibility<br>• Orphan sites<br>• Contaminants without regulatory criteria or guidance (such as emerging contaminants) |
| ICs | • Tracking and managing ICs<br>• IC enforcement<br>• Long-term management of institutional controls |
| Changes in land use | • Changing land use or water use<br>• Multiple owners<br>• Site access |
| Funding | • Lack of funding (state, federal, or private industry)<br>• Politics that alter funding/program priorities<br>• Unwilling or unknown RPs |

Similar nontechnical challenges have been identified by other agencies (such as International Atomic Energy Agency 2002). In addition to the nontechnical challenges listed, accounting for stakeholder perspectives is a significant challenge at some sites.

## 2.2.1 Site Objectives

A typical site objective is to restore groundwater to beneficial use. In some cases, this site objective cannot be technically achieved in a reasonable time frame, even though the objective was adopted in accordance with regulatory requirements that reflect societal expectations (ITRC 2011b). For sites where complete restoration/reuse is not the objective, alternative site objectives may be established based on site-specific conditions, such as classification of the underlying aquifer as a nondrinking water area (see, for example, ITRC team survey results from state regulators in Appendix A). If an alternative objective is to be

### Changing Site Objectives

*The site objective at a hypothetical site may be to restore the groundwater to beneficial use at some point in the future. In this case, a less aggressive remedy might be chosen based on the assumption of enough time (50 or more years) to achieve the site objective, because there was no foreseeable use of the resource. Drinking water standards are appropriate because the regulatory authority has classified the aquifer as a potential drinking water source. Five years into the remediation, it may be determined that the resource will be* established, however, it must be acceptable to the regulatory agencies and stakeholders. This guidance provides more detail on technical and nontechnical aspects of setting and revisiting site objectives, including management approaches that are allowable under certain regulatory programs for specific circumstances. Beyond site objectives, there may be additional societal expectations and social acceptability criteria for remediation projects. For example, land reuse while remediation is occurring may be important to stakeholders. The use of GSR practices may be important to some stakeholders. Social acceptability can also inform the selection of remedial technologies and associated interim objectives.

*needed more quickly because of unprecedented and unexpected local development. The site objective of restoration now must be achieved within 15 years as compared with 50 or more years on which the remedy was based. Therefore, the site objective should be modified and potentially a different remedy chosen to meet that new objective.*

### 2.2.2 Managing Changes that May Occur Over Long Time Frames

The long time frame for remediation adds to complexity because continuity must be maintained throughout remediation. Many complex sites may require different remedies (ex situ, in situ) that must be implemented in phases (ITRC 2011b). Each phase could last several years, during which time there may be regulatory changes that affect oversight (such as going from a process of approval at every step to a privatized program with minimal oversight). Other regulatory changes could include changes in cleanup requirements (for example MCLs or state groundwater standards), changes in risk assessment approaches, or changes in which agency has authority over the project. As with any long-term project, there is also the likelihood of changes in personnel and the loss of institutional knowledge. Changes in land use/redevelopment may change human health and ecological risk assessment scenarios. Water use may change along with land use; groundwater and surface water that was once used for irrigation or agricultural purposes may be converted to city water supplies. These changes can be monitored and mitigated using a project risk register.

### 2.2.3 Overlapping Regulatory Responsibilities

At some large complex sites, numerous regulatory agencies may become involved over the long time frames that these sites require. There may not be clear cut relationships between these agencies and each agency may follow different policies and practices in relation to these contaminated sites. One agency may be responsible for overseeing remediation and another may be responsible for long-term management or redevelopment. The remediation oversight agency may realize that it may be a very long time before redevelopment can occur, and the redevelopment agency may push for faster (and perhaps less thorough) remediation so that land can be reused faster. These conflicting goals can present nontechnical challenges to remediation management. On another level, decisions made by state and federal agencies may have long term effects on local authorities and programs. In addition, those local authorities may have responsibility for local planning, record keeping, and day-to-day oversight that have significant implications for the long-term management of contaminated sites.

**Overlapping Regulatory Responsibilities**

*An 850-acre Massachusetts Superfund site has multiple uses and multiple owners and, for the most part, does not appear to be contaminated. The primary issue is contaminated groundwater that affected two municipal wells. A portion of the site is owned by the municipality, which decided to erect a solar array on its property. The municipality applied to the state regional environmental regulatory office for permits (for wetlands issues) and was required to go to another state environmental agency for endangered species issues. Even though the property was located within the Superfund site, the state environmental agency overseeing the site cleanup was never informed of the project until after it was built.*

Sites can also transition from one regulatory program to another. For example, a site may start out under a state program and transition to a federal Superfund site. During the transitional period, some work may continue under the state program while other activities are directed by USEPA. Different programs may have different requirements (such as presumptive approval by the state agency versus a written letter of approval by USEPA). This situation can create confusion for the responsible parties and others conducting the work regarding what is required by each program, and the potential need to repeat or expand work due to different agency requirements. State and federal laws and regulations governing cleanups of contaminated sites can also change with time and administrations. Risk factors and standards can change, potentially requiring different remedial approaches.

At many large sites, the state and USEPA both have concurrent regulatory roles. Multiparty agreements at these sites serve to essentially combine the regulatory authorities and to determine which agency has a lead regulatory role in certain areas and projects. At some sites, such as Hanford and Rocky Flats, the division is generally geographic with an overlay of regulatory authority.

### 2.2.4 ICs

Use restrictions placed on sites in the form of ICs can add complexities as well. Once the ICs are established, a mechanism must be created to track and manage them. If the conditions of the IC are violated (for example a private drinking water well is drilled in an area where groundwater use for consumption is prohibited), an authority must exist that can address the violation and prevent anyone from drinking the contaminated water (ITRC 2016b). Often ICs are created in the form of deed restrictions; it may be up to a potential new owner to use due diligence to discover that a deed restriction exists. Once an IC is no longer necessary, a clearly defined process should describe how to remove the IC and what parties are responsible for removing it.

### 2.2.5 Changes in Land Use

Over the long term, land use changes are typically a result of changes in property ownership. Ownership, use, and zoning of adjacent lands may change over time, particularly for large-scale or regional sites. Off-site redevelopment may affect site objectives by introducing potential receptors or exposure pathways. For example, off-site zoning may change from industrial to residential, affecting site remediation goals. Vapor intrusion may be identified as a potential pathway if off-site redevelopment occurs. If possible, local land use agencies can be contacted and given an opportunity to comment on site remediation plans. These agencies may know of potential future development or have local master plans that call for redevelopment of properties near the site.

Any change in site ownership or the ownership of a portion of the site should be coordinated with the site remediation. Information to convey to the new owner includes property restrictions (such as groundwater use restrictions), access agreements, and active remediation components that may exist on different parcels (such as groundwater extraction wells). Restricting access to areas which may be covered by buildings that are part of an active facility may affect investigating, characterizing, or remediating portions of a property. Different regulatory agencies become involved with site redevelopment. Having a reliable means to track and communicate the state of remediation between agencies, owners, and prospective purchasers of affected properties is important to the long-term integrity of the remedy and ongoing protection to human health and the environment. Fortunately, many states, as well as independent organizations, have developed guidance to assist those who are responsible for long-term stewardship of affected lands (ITRC 2016b).

### 2.2.6 Funding

Complex sites by their nature often require significant financial resources. Long-term site management funding for complex sites can be a challenge, not only for the private sector responsible party, but for state and federal programs as well. In the private sector, setting aside funds for future environmental work affects profitability and investments in capital projects. On the other hand, cleaning up a site sooner adds to its value (International Atomic Energy Agency 2002). For governmental agencies, there are many competing needs for limited available funding and adequate financing to fully address orphan or fund-led sites may not be available. This situation is concerning because inadequate funding can lead to underdeveloped CSMs that do not account for key technical complexities, thus resulting in unrealistic site objectives, ineffective remedies, and overuse of ICs.

#### Splitting Costs at Superfund Sites

*In the federal Superfund program, states become responsible for long-term operation and maintenance (O&M) of remedies that may require decades to reach site objectives. If an entirely different remedy becomes necessary, states could find themselves paying 100% of a potential multimillion dollar remedy. The normal split for a remedy at a Superfund site is USEPA 90% and state 10% for the first ten years, with the state paying 100% of the costs after that.*

## 2.3 Developing a CSM Based on Site Characteristics

A thorough CSM describes the processes at a site that control the transport of contaminants from sources through environmental media to environmental receptors. It is a valuable tool for planning, data interpretation, and for communicating with the public. A CSM can also help identify where additional information is needed. Developing a CSM is a crucial step in setting both site objectives and interim objectives. Several reference documents provide detail on CSMs and their importance in understanding and remediating sites (USEPA 2011a, ASTM 2008, ITRC 2011b, USACE 2012). For complex sites, CSMs typically describe the technical characteristics but may not present context for nontechnical challenges. The focus on technical characteristics in a CSM could be balanced by considering nontechnical challenges and accounting for these in site decision documents, such as National Environmental Policy Act (NEPA)/California Environmental Quality Act (CEQA) reports.

USEPA (2011a) has summarized the development of a CSM throughout a project. In practice, the CSM should be treated as a dynamic tool to be updated throughout the stages of a project lifecycle. The flowchart in Figure 1 identifies when it is necessary to update the CSM within the adaptive site management process. In addition, it is a good practice to update the CSM whenever additional relevant data are acquired.

### "Six Stages of CSM Maturity" (USEPA 2011a)

***"Key Points in the Development of a CSM***

*1) **Preliminary CSM Stage** – Project milestone or deliverable based on existing data; developed prior to systematic planning to provide fundamental basis for planning effort.*

*2) **Baseline CSM Stage** – Project milestone or deliverable used to document stakeholder consensus/divergence, identify data gaps, uncertainties, and needs; an outcome of systematic planning.*

***Key Points in the Evolution and Refinement of a CSM***

*3) **Characterization CSM Stage** – Iterative improvement of CSM as new data become available during investigation efforts; supports technology selection and remedy decision making.*

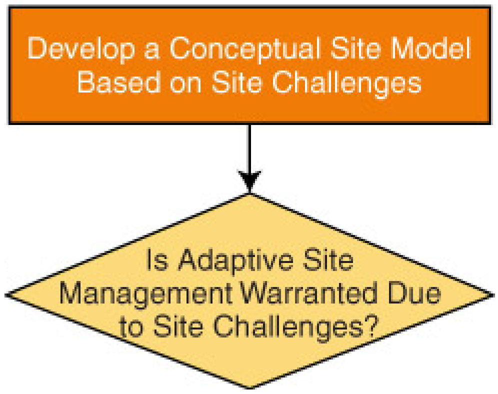
*4) **Design CSM Stage** – Iterative improvement of CSM during design of the remedy; supports development of remedy design basis and technical detail.*

*5) **Remediation/Mitigation CSM Stage** – Iterative improvement of CSM during remedy implementation; supports remedy implementation and optimization efforts, provides documentation for attainment of cleanup objectives.*

***Post Remedy CSM Stage –** Comprehensive site physical, chemical, geologic, and hydrogeologic information of CSM supports reuse planning; documents institutional controls and waste left on site; and other key site attributes."*

The goal of this process is to develop a CSM with sufficient depth and clarity to accurately assess risks and develop appropriate remediation strategies. To accomplish this goal, the CSM aligns contaminant distribution data with site geologic heterogeneity and groundwater flow conditions at a spatial resolution appropriate to the site-specific site objectives. The CSM includes all contaminated media, multiple types of contaminated media may increase the site complexity.

# 3. Remediation Potential Assessment




Assessing a site's remediation potential is a key step in selecting the most effective remedy and efficiently using often limited funds. The outcome of a remediation potential assessment can help to set site objectives and determine if adaptive site management is recommended. Once a CSM is in place, a site's potential for remediation can be evaluated. The remediation potential assessment uses a weight-of-evidence approach to determine if a site is likely to achieve remedial objectives within a reasonable time frame (which can be estimated), or if site challenges warrant use of an adaptive site management approach. This assessment relies on available site data, analogous site information, predictive assessments, or a combination of these to support the evaluation. The assessment does not produce a default decision, but rather aligns expectations with actual remediation potential for the site. Remediation potential can be evaluated for an entire site or for discrete site segments that represent parts of the site with different characteristics (such as source versus plume, or different water bearing units).

Assessments of remediation potential may be conducted at different points throughout all phases of the cleanup including remedy selection, remedial design, remedy implementation, monitoring and performance evaluation. The amount of characterization data available to support a remediation potential assessment depends on the remedial phase of the project. Each phase of a cleanup can supply additional data to support and further develop the CSM. If site characterization and feasibility study data are adequate (meaning the CSM is developed to at least the Baseline CSM Stage), then remediation potential can be assessed prior to a remedy decision. In some cases, such an early assessment could be supported by pilot test results, data from analogous sites, or predictive modeling. A preremedy remediation potential assessment typically requires more detailed supporting data on the nature and extent of contamination than an assessment at a later phase in the project. Evaluation criteria for preremedy remediation potential assessments may also be considered. In other cases, an assessment (or reassessment) of remediation potential might come later in the remedy process and can include remedy performance data. Additional metrics are appropriate for later phases of the remediation process (postremedy implementation). Metrics to assess remedy performance and the need for optimization or other remedy adjustments for a site are also addressed as part of long-term management.

***Remediation Potential Assessment Does:***

- *allow flexibility and site-specific input in an iterative process*
- *require detailed supporting data on the nature and extent of contamination*
- *consider remediation potential of individual factors in context of other pertinent factors*
- *use weight-of-evidence approach to determine if a site is likely to achieve remedial objectives within a reasonable time frame*

***Remediation Potential Assessment Does Not:***

- *provide a means to avoid requirements*
- *evaluate whether a site is complex*
- *directly consider cost*
- *produce a default decision*

The remediation potential assessment is applied for screening purposes and as a tool during regulatory decision making. This assessment is designed to be used at a wide range of sites under any regulatory program and at different points in the remediation process and site life cycle. While the assessment focuses on groundwater remedial objectives, it can be adapted to the remediation of other media as well.

The process for remediation potential assessment can help promote an effective and transparent interaction among the site owners, regulators, and stakeholders during regulatory decision making. Engaging in this process can align stakeholders' understanding of the site conditions and their expectations with the likelihood of achieving site objectives (for example, restoration to numeric criteria such as MCLs) in a reasonable time frame. Stakeholders are sometimes concerned about applying an assessment of remediation potential prior to implementing remedial options because of the subjective nature of such an evaluation.

**USEPA Perspective**

*"Determining the restoration potential of a site may be aided by employing a phased approach to site characterization and remediation. Each phase of site characterization should be designed to provide information necessary for the next phase of characterization. Likewise, site remediation activities can be conducted in phases to achieve interim goals at the outset, while developing a more accurate understanding of the restoration potential of the contaminated aquifer." (USEPA 1993)*

## 3.1 Whole Site versus Site Segment Analysis

At some sites, it may be useful to segment the site or contaminant plume, rather than consider the site or plume as a whole. Prior to a remedy decision (such as Interim Measures, Interim Remedial Action, Record of Decision (ROD), Corrective Action Decision, RCRA permit, or order), the whole site or plume may be divided into discrete subsets or segments that are candidates for different remediation management strategies. Under RCRA, sites may be administratively divided into solid waste management units (SWMUs); under CERCLA, sites are divided into operable units (OUs). The whole site can be considered in the assessment of remediation potential; however, for some sites that are not already divided into operable units, it is also reasonable to divide the site into segments for assessment purposes.

Examples of factors that may influence a decision to divide the site into different segments include the following:

- beneficial reuse of property and resources
- need for early actions to achieve significant risk reduction quickly
- need for a phased response given the size or complexity of the site
- unsaturated versus saturated source zones
- major hydrogeologic units (such as unconsolidated versus bedrock zones)
- different geochemical environments in the plume (such as aerobic versus anaerobic zone)
- source area versus nonsource (dilute plume) areas
- receptor impacted area versus nonreceptor impacted areas
- access, environmental, or legal restrictions
- dissimilarity of contaminants
- on-property versus off-property requirements

If segments are used, then the segments will represent portions of the site that can be managed separately with respect to site remediation, since it is not useful to define many small areas as segments. For instance, it may be useful to manage a source segment and a plume segment separately or to consider a large distal plume separately from a smaller, more concentrated core of the plume. This division could be important if there is a small shallow source that is easy to treat, but also a large dilute plume that may be difficult to treat. In an example given in USEPA guidance (1993), if an unrestorable source area is contained, restoration of the dilute plume beyond the isolated source area may still be feasible. If a large, deep source and a large dilute plume are both present and difficult to remediate, then it is likely sufficient to use the remediation potential assessment to evaluate the whole site rather than applying it to separate site segments. The case study on the Koppers Oroville wood treatment site (see summary also) provides an example of using different remedial approaches for the source zone, on-site plume, and off-site plume.

Remedial actions applied to a segment should be consistent with the expected final remedy for the site. For simplicity, references to a "site" in this guidance also include an entire plume or a site segment. If an ongoing remedy is not working as anticipated, then the site might benefit from division into site segments and a preremedy remediation potential assessment for the segments to evaluate alternative remedies.

## 3.2 Preremedy Implementation

Table 4 lists questions addressing different assessment evaluation criteria that can affect the likelihood of achieving site objectives, particularly groundwater remedial objectives, within a reasonable time frame. These questions are related to some of the site challenges and are based on the ITRC RMCS team members' professional experience with practical considerations for evaluating remediation potential early in the remediation process. The questions also closely follow the factors affecting groundwater remediation listed in USEPA guidance (1993) and New Jersey guidance (2013). The assessment can draw on available site data, analogous site information, or predictive assessments to answer these questions.

The assessment questions in Table 4 are appropriate prior to remedy selection and implementation, for instance, during the Feasibility Study (FS)/Corrective Measures Study (CMS) or Remedial Investigation (RI)/RCRA Facility Investigation (RFI) phases or analogous phases in state cleanup programs. The assessment metrics in this remediation potential assessment are not necessarily of equal significance, since a single factor or pair of factors can make remediation difficult. Site owners, regulators, and stakeholders can incorporate or substitute questions pertinent to their site.

An oversight agency could elect to use this information, with consultation from interested parties, to support decisions within an adaptive site management approach. Documenting the basis for choosing answers allows greater transparency and facilitates future reviews of the process. This documentation is especially important at complex sites where the project life cycle may last decades and knowledgeable stakeholders may be replaced with newer project participants. As with any site assessment, sufficient and appropriate site characterization is critical.

**Table 4. Key criteria for preremedy remediation potential assessment**

| Assessment Metric | Summary Discussion |
|---|---|
| 1. How difficult is it to work at the surface of the site? | How much of the potential site treatment zone is accessible (such as for drilling or excavating)? Are structures, active process units, sensitive environments, or other restrictions present? |
| 2. How difficult is it to drill at the site? | Is drilling difficult, slow, and resource-intensive in the site? For example, in uncomplicated conditions where contamination is shallow, direct push technologies can be used to install multiple wells. |
| 3. What is the scale of the source zone or plume? | What is the extent of source and plume contamination? Remediation potential may be significantly less if source volume or plume area is extensive. |
| 4. What contaminant concentration reduction is needed? | What is the reduction needed throughout the site to achieve interim objectives? If several orders of magnitude reduction in contaminant concentration is required to reach groundwater remediation goals, then a long remedial time frame is more likely. |
| 5. Do the key site constituents readily attenuate relative to the travel time to receptors? | What is the estimated rate of biotic and abiotic attenuation in the site? If contaminants and geochemical environment are amenable to natural attenuation processes, a site is likely to be remediated in a reasonable time frame. |
| 6. Does difficult-to-remove mass exist at the site? | How much contaminant mass is nonaqueous phase liquid (NAPL) or is present in the low hydraulic conductivity (low-K) zones in the site? If significant contaminant mass is in low-K zones (or in fractured or karst bedrock), the plume will likely persist for a long time without remediation of the mass. If contaminants are present as NAPL, contamination may also persist. |
| 7. What is the predicted remediation performance for available remedial technologies? | Are proven applicable technologies available to address the contamination at the site? Do direct observations at similar sites indicate significant uncertainty and long remedial time frames? |
| 8. What is the predicted time frame for achieving interim or site objectives? | Given available remediation approaches, how long would remediation of the site take? Calculation tools can be used to predict if any approach or combination of approaches could achieve interim objectives for the site in a reasonable time frame. |

Other site-specific concerns can be added to the list of questions as needed. The questions can also be adapted to focus on media other than groundwater. USEPA's nine CERCLA criteria (40 CFR 300.430(e)(9)) are not explicitly included in the Table 4 questions, but are related to many of the questions, particularly those focusing on effectiveness, implementability, and cost. The nine criteria were developed to evaluate remedial alternatives (USEPA 1997b) and are statutory requirements for CERCLA.

Cost is always an important consideration, but is not included as an explicit criterion since many regulatory programs do not rely on cost directly. Cost, however, is an indirect part of many of the questions, such as Questions 1, 2, 3, 7, and 8.

## 3.3 Answering Preremedy Questions

For some sites, the RI or RFI supplies sufficient data to answer the questions in Table 4. In some cases, the remediation potential assessment in Table 4 may identify additional studies needed to adequately answer the questions. Additional characterization and CSM updates may be conducted at any time during the process outlined in Figure 1.

The assessment questions do not define any specific remediation management approach. Some questions are related; each has a different perspective associated with it. The remediation potential methodology was developed assuming use of in situ technologies but is applicable to most ex situ technologies as well. In some cases, these questions pertain to the potential for ex situ treatment as well. The information in this guidance is referenced or is based on the professional experience of the ITRC RMCS team members and may change as new technology or products become available. Other potential questions suggested by ITRC RMCS team members are as follows:

- Are there known technologies that could be applied at the site?
- Are there multiple pathways?
- Has site been adequately characterized?
- What is the expected end use of the site?

### 3.3.1 Question 1. How difficult is it to work at the surface of the site?

Sites with poor access (physical or legal barriers to access) are more difficult to remediate than sites with unlimited access. Other constraints include logistics and harsh environments. To remediate a site, amendments or energy are delivered to the entire treatment zone. While there are ways to manage difficult access, such as horizontal wells, in almost all cases the presence of buildings, infrastructure, and topographic features make it more challenging to apply remediation technologies. Administrative factors such as property rights and sensitive environment designations can also complicate access. The greater the percentage of the site that is inaccessible to remedial activities, the greater the likelihood that remediation potential will be affected.

### 3.3.2 Question 2. How difficult is it to drill at the site?

Because most remediation efforts rely on drilling techniques, key assessment considerations include the available drilling methods, the site lithology, required spacing of remediation devices (such as injection wells) for implementing a remedy, and the depth of contamination. The USEPA's TI guidance (1993) notes that remediation difficulty increases with contaminant depth. Examples of uncomplicated conditions are sites where contamination is shallow, allowing the use of direct push rigs to install multiple injection wells. Examples of conditions that make drilling difficult and expensive are fractured rock, heaving sands, deep contamination, and requirements for tight spacing of injection wells to achieve adequate treatment. This question can also be applied at sites where excavation, rather than drilling, is part of the remedy.

### 3.3.3 Question 3. What is the scale of the source zone or plume?

The size of the treatment zone for a contaminant source zone or plume potentially affects the practicability of remediation. For example, the USEPA's guidance (1993) indicates that larger contaminated media volume increases remediation difficulty. This site characteristic often influences remediation decisions made at contaminated sites, but no guidance explicitly states that decision making should consider treatment volume. Volumetric source zone guidelines are available for chlorinated solvent sites and average areas are available for several different types of plumes. These data can be used as a reasonable starting point for evaluating the relative size of a specific source zone segment or a plume segment:

- *Volume of source zone*. A DOD research study (McGuire, McDade, and Newell 2006) conducted at 80 full-scale treatment sites examined the scale of source zone volumes. This study found that 25% of active in situ remediation projects at chlorinated solvent sites (such as chemical oxidation, thermal treatment, chemical reduction, and bioremediation) treated source zone volumes less than 2,000 cubic yards in size, while approximately 50% of active in situ remediation projects addressed source zone volumes greater than 2,000 and less than 25,000 cubic yards. Only 25% of these projects treated more than 25,000 cubic yards. These metrics serve as guidance in interpreting the relative scale of a given sites and are provided as context for the typical size of sites where active in situ remediation technologies have been applied. These size ranges, however, do not preclude the successful remediation of larger sites using these technologies or reflect any inherent limitations of these technologies at larger scale.

- *Plume extent.* The extent of a plume can affect the time frame for groundwater remediation, especially when combined with other factors such as depth of contamination, presence of NAPL, high contaminant concentrations, or a complex hydrogeological environment. According to one study (Wiedemeier et al. 1999, Figure 2.2), the average area of a gasoline station site plume was approximately 32,000 square feet; the average chlorinated ethene plume was about 500,000 square feet; the average for nonethene chlorinated plumes (mostly chlorinated ethane plumes) was about 200,000 square feet; and the average for non-gas-station hydrocarbon plumes was about 100,000 square feet. All other criteria being equal, plumes larger than the average plume size for a particular class of plume are likely to have lower potential for rapid groundwater remediation than smaller than average plumes.

### 3.3.4 Question 4. What contaminant concentration reduction is needed?

The groundwater monitoring well with the maximum concentration at a site is typically the key metric for site closure. Because concentration reductions are key, remediation based on orders of magnitude (OOM) to reach site groundwater goals can be a useful concept. To answer this question, a study compiled the OOM reductions of 216 different in situ remediation projects at chlorinated solvent sites. The study found that 75% of the in situ remediation projects had at least a 0.5 OOM (68%) reduction in parent concentration and 25% had more than 2 OOMs (99%) reduction (McGuire, McDade, and Newell 2006). Based on the experience of some team members, this type of performance can be expected at LNAPL sites as well as DNAPL sites.

Current recommendations for using OOMs to evaluate concentration reductions are included in ITRC's *Integrated DNAPL Site Strategy* guidance (ITRC 2011b). Based on these data, a threshold of 2 OOM reduction or more can be classified as a "Low Likelihood of Achieving Remediation Objectives." This recommendation may change over time as data are updated. A site evaluation should always include the latest available guidance when estimating the possible magnitude of contaminant reduction.

If multiple constituents are found at the site with different cleanup levels, then all the candidate contaminants for the greatest OOM required to reach remedial goals should be evaluated and the maximum result used to answer Question 4. Also, note that some difficult-to-remediate sites do not necessarily require a large reduction in contaminant concentrations.

### 3.3.5 Question 5. Do the key site constituents readily attenuate relative to the travel time to receptors?

Sites with high rates of natural attenuation for the major site contaminants tend to reach site objectives more quickly than sites with lower attenuation rates. Sites where the contaminant class and the geochemical environment are amenable to rapid, ubiquitous natural attenuation processes are likely to be remediated in a reasonable time frame. Examples include benzene, toluene, ethylbenzene, and xylene (BTEX) compounds, because they can degrade in either aerobic or anaerobic zones (note that attenuation of TPH-related metabolites currently is an active area of research). Although metal and radionuclide contaminants remain in place with any natural attenuation process (such as precipitation, adsorption, or radiological decay), MNA can provide an effective site remedy through the stabilization and sequestration of the contaminant of concern. A natural geochemical environment that is not conducive to MNA processes will likely lengthen remediation time frames. For more information about natural attenuation, see the textbook by Wiedemeier et al. (1999); a "Frequently Asked Questions" report about more recent MNA developments (Adamson and Newell 2014) and a free online course focusing on MNA (Alvarez, Newell, and Adamson 2016).

#### Relationship Between Geochemical Environment and Degradation Processes

*To better understand the relationship between geochemical environment and degradation processes, see these "Scenarios" documents:*

- *Scenarios Evaluation Tool for Chlorinated Solvent MNA (Truex et al. 2006)*
- *The Scenarios Approach to Attenuation-Based Remedies for Inorganic and Radionuclide Contaminants (Truex et al. 2011)*

*These two references divide the types of chlorinated solvent plumes into 13 different combinations of hydrogeology and geochemical environments, as well as six different scenarios of plumes of metals and radioactive compounds.*

*The following documents provide guidance on degradation processes for a variety of contaminants and environments:*

- *A Decision Framework for Applying Monitored Natural Attenuation Processes to Metals and Radionuclides in Groundwater (ITRC 2010a)*
- *Enhanced Attenuation: Chlorinated Organics (ITRC 2008a)*
- *Natural Attenuation of Hexavalent Chromium in Groundwater and Soils (USEPA 1994)*
- *Use of Monitored Natural Attenuation at Superfund, RCRA Corrective Action, and Underground Storage Tank Sites (USEPA 1999b)*
- *Framework Document for Monitored Natural Attenuation of Inorganic Contaminants in Ground Water (USEPA 2001a)*
- *Monitored Natural Attenuation of Inorganic Contaminants in Groundwater, Vol. 1: Technical Basis for Assessment (USEPA 2007a)*
- *Monitored Natural Attenuation of Inorganic Contaminants in Groundwater, Vol. 2: Assessment for Non-Radionuclides Including Arsenic, Cadmium, Chromium, Copper, Lead, Nickel, Nitrate, Perchlorate, and Selenium (USEPA 2007b)*
- *Monitored Natural Attenuation of Inorganic Contaminants in Groundwater, Vol. 3: Assessment for Radionuclides Including Tritium, Radon, Strontium, Technetium, Uranium, Iodine, Radium, Thorium, Cesium, and Plutonium-Americium (USEPA 2010b)*

### 3.3.6 Question 6. Does difficult-to-remove mass exist at the site?

This question addresses residual NAPL or the presence of contaminants that have diffused over time into low permeability zones, which are referred to as "low-K" zones by the Strategic Environmental Research and Development Program (SERDP) State-of-the-Science report (Sale et al. 2016). These contaminants then back-diffuse when the transmissive zone goes into a lower-concentration regime (such as after remediation, or after the source has weathered for a long time). If contaminant mass is contained in low-permeability media then it may be difficult to remove by most in situ remediation techniques such as chemical oxidation, bioremediation, and thermal treatment (Sale and Newell 2011, NRC 2013, Sale et al. 2016, ITRC 2011b). This contaminant mass may also serve as a long-term source of contaminants to groundwater.

To answer this question, estimates of relative mass distribution between transmissive zones (sands and gravels) versus zones of low permeability can be considered. High-resolution site characterization (HRSC) can directly assess the distribution and scale of contaminants in complex heterogeneous subsurface lithologies. For further information on specific HRSC sampling technologies and 3D visualization subsurface software, see *Integrated DNAPL Site Characterization and Tools Selection* (ITRC 2015b). Another approach that can support high-resolution sampling or support planning-level evaluations of mass distribution is to use matrix diffusion models such as the Environmental Security Technology Certification Program (ESTCP) Matrix Diffusion Toolkit (Farhat et al. 2012) or other calculations. Supporting site data may be speculative early in a remedial project, but additional characterization data can refine the understanding of contaminant mass over time. Typically, complex heterogeneous geology results in contaminant mass that is difficult to remove. If more than 20% of the contaminant mass is in low-K zones (or in fractured or karst bedrock), the plume will likely persist for a long time.

Key resource documents are based on research and experiences from chlorinated solvent sites (see Sale et al. 2008, Sale et al. 2014, Sale and Newell 2011). Research is also available on the effects of matrix diffusion at a methyl tertiary butyl ether (MTBE) site (Rasa et al. 2011). Additionally, numerous articles have addressed matrix diffusion as a process affecting metals transport at fractured rock sites. USEPA's TI guidance (1993) categorizes interbedded stratigraphy, fractured media, and karst as having increased difficulty in remediation.

While matrix diffusion has recently emerged as a key remediation constraint, other more familiar types of difficult-to-remove mass, such as residual NAPL, would also be relevant for this question (ITRC 2011b).

### 3.3.7 Question 7. What is the predicted remediation performance for available remedial technologies?

This question is related to Question 5, but compares the question of “how much concentration reduction is needed?” with “how much concentration reduction is possible, given the known performance of the remedial technology?” The answer to this question depends on the level of confidence that proven technologies can achieve interim objectives and metrics and site objectives in a reasonable time frame. The strongest line of evidence supporting predictions of remedy performance is actual performance data from active remediation efforts at the site, followed by pilot testing at the site, results at similar sites, and then multiple-site remedy performance data reported in the scientific literature (see ITRC 2011b, Stroo et al. 2012, McGuire, McDade, and Newell 2006). A feasibility study can also be used to assess this evaluation criterion. Some of these lines of evidence may not be available, depending on where in the remediation process the assessment occurs. In some cases, poor remedy performance reveals that the contaminant source has not been adequately addressed. Adequate characterization of the site is necessary to reliably answer this question.

### 3.3.8 Question 8. What is the predicted time frame for achieving interim and site objectives?

To answer this question, an engineering analysis (see Table 5) can be used to estimate the length of time for existing or proposed remediation projects to restore the site or to achieve interim objectives. Note that the hypothetical remediation projects (or continued operation of an ongoing project) should represent the current capabilities of the technology. An ongoing application of a remediation technology that has not been optimized would not be an appropriate basis on which to answer this question.

A remediation time frame analysis can be performed several ways, including estimating postremediation concentrations and then using degradation rates to determine the time required to reach the groundwater concentration goals. Estimating time frames by applying a groundwater model can provide another line of evidence (see Table 5). Estimates should ensure that site complexities do not exceed a groundwater model’s capabilities and limitations. Several resources are available to help estimate remediation time frames. See Frequently Asked Question (FAQ) 16 in the Adamson and Newell study (2014) for an overview of methods, as well as research by Wilson (2011) or Chapelle (2003) for more detailed information.

**Table 5. Groundwater computer models and analysis for estimating remediation time frames after hypothetical active remediation projects**

| Model/Analysis | Can You Simulate... | | | References |
|---|---|---|---|---|
| | **Input Required to Simulate Active Remediation?** | **Source Zone Matrix Diffusion?** | **Plume Matrix Diffusion?** | |
| USEPA REMChlor or REMFuel Model | Enter percent removal of source materials | Yes | No; new version being developed with this capability | (Falta et al. 2007, USEPA 2007d, 2012d) |
| Natural Attenuation Software | Enter percent removal of source materials and mass/concentration relationship | No | No | (Widdowson et al. 2005, Chapelle 2003) |
| Matrix diffusion | Assumes 100% removal of NAPL sources | Yes, if applied to source zone | Yes, if applied to plume | (Farhat et al. 2012) |
| Concentration vs. time first order rate calculations | Can be added to this analysis | Actual data will reflect effect of matrix diffusion | Actual data will reflect effect of matrix diffusion | (Newell et al. 2002) |

**Factors Affecting Remedial Time Frame Evaluations**

- *residual contaminant concentrations and rate of natural attenuation*
- *proximity of contamination to receptors*

- *presence of sensitive receptors*
- *presence of threatened or endangered species or habitats*
- *classification of the affected resource (for example, drinking water source or agricultural water source) and value of the resource*
- *current and potential use of the aquifer, including proximity to private and public water supplies*
- *relative time frame in which the affected portions of the aquifer might be needed for future water supply (including the availability of alternate supplies)*
- *geochemical and hydrogeologic conditions*
- *magnitude, mobility, and toxicity of the contamination*
- *uncertainties regarding the mass of contaminants in the subsurface and predictive analyses (for example, travel time for contaminants to reach points of exposure appropriate for the site)*
- *time frame for active remedial alternatives*
- *reliability of ICs over long time periods*
- *public acceptance of the extended time for remediation*

*(adapted from CDPHE 2014b)*

Methods for calculating key performance indicators range from simple arithmetic to highly sophisticated transport models incorporating chemical, physicochemical, and biological reaction rates. Using a specific method should be justified by the conditions to which it is being applied and supported by the appropriate quantity and quality of data. Subsurface contaminant transport models incorporate several theoretical assumptions about certain natural processes governing the transport and fate of contaminants. These assumptions may not apply at a given site, however, and these theories are often simplified when applied to practical problems.

A maximum remedial time frame for achieving interim objectives is approximately 20 years. This estimate is based in part on the ITRC finding that 20 years or less is a “credible period of time” in which to predict remedy progress and success (ITRC 2011b). ITRC establishes this period as the limit for “functional objectives,” which are referred to as “interim objectives and metrics” throughout this guidance. Determining a reasonable time frame for achieving final site objectives at complex sites is a site-specific decision agreed upon by site owners, regulators, and stakeholders and may exceed many decades. While not applied at all sites, this value is a useful metric that should be evaluated to avoid open-ended remediation commitments.

If multiple approaches can remediate the site within the time estimated for achieving interim objectives, then remedy completion within a reasonable time frame is likely. On the other hand, if no approaches are expected to meet the interim objectives, then for remedy potential assessment purposes, the likelihood of meeting those groundwater objectives in 20 years is low. A remedial time frame that is already established in a decision document can also be evaluated against a time frame analysis.

## 3.4 Weighing the Evidence

Remediation potential can often be better assessed by initially examining the component issues that comprise the whole project. Considering these individual issues can lead to a clearer definition of the underlying concerns and thus a more rational and objective overall conclusion.

The criteria for evaluating remediation potential assessment presented in Table 4 represent typical component issues that may affect attaining interim or site objectives at complex sites. Evidence for those issues at a site can be evaluated to determine the potential to achieve interim or site objectives in a reasonable time frame. This assessment process allows the effects of the individual criteria to be considered in context with all other criteria. For example, assessing the effects of factors such as the extent, depth, and concentration of a plume at a chlorinated solvent site in complex hydrogeology—as viewed together—may produce different results than assessing the individual factors. This process can be iterative, with refinement based on increased site knowledge and data, much like updating a CSM.

### 3.4.1 Evaluation Criteria

The evaluation criteria questions can be organized into a matrix and then individually answered as high, moderate, or low likelihood for achieving remediation objectives. Table 6 presents a matrix that can be used as a remediation potential assessment tool based on the evaluation criteria questions in Table 4.

**Table 6. Remediation potential assessment tool: Can groundwater remediation objectives for a site be**

**achieved in a reasonable time frame?**

| Evaluation Criteria | Likelihood of Achieving Remediation Objectives | | |
|---|---|---|---|
| | High | Moderate | Low |
| 1. Access for drilling/excavating | | | |
| 2. Well drilling feasibility | | | |
| 3. Scale of source zone or plume | | | |
| 4. Concentration reduction | | | |
| 5. Attenuation of site constituents | | | |
| 6. Difficult-to-remove mass | | | |
| 7. Remedial technology performance | | | |
| 8. Predicted timeframe | | | |
| Total checked: | | | |

The effect of the evaluation criteria on remediation potential is not likely to be equal. Sometimes, the likelihood of achieving remediation objectives may be high for most criteria, but a lower likelihood criteria may have fatal flaws that preclude achieving the objectives. While assessing the answers to the evaluation criteria questions, the site owners, regulators, and stakeholders may choose to give more weight to some questions than others or may substitute questions more pertinent to their site. The Remediation Potential Assessment Tool matrix in Table 6 is based on the assessment questions in Table 4. Neither the evaluation criteria nor the remediation potential matrix are derived from CERCLA regulations or guidance.

There are three possible outcomes from the remediation potential assessment:

- Objectives are attainable. If the remediation potential assessment determines that the remediation potential is high, then remedy components that involve treatment technologies at the site should achieve interim and site objectives in a reasonable time frame.
- Objectives are not attainable. If the remediation potential assessment determines that the remediation potential is low, then remedy components at the site will not likely achieve interim and site objectives in a reasonable time frame. In this case, the long-term adaptive site management approaches should be considered. Various options are available within adaptive site management, including more active remediation, active containment, passive remediation, passive containment, active and passive mitigation measures, and management elements such as ICs and ARAR waivers. These options may be considered after reassessing the evaluation criteria and optimizing the remediation potential assessment.
- No clear outcome can be predicted; more study is needed. If the remediation potential assessment does not clearly determine a high or low remediation potential, either because the “moderate likelihood” category dominates the assessment or because the weight of evidence is balanced among the categories, then the assessment evaluation criteria should be reevaluated. This process may reveal inherent biases. With this outcome, all options, including remedy optimization, should be further evaluated.

Table 7 includes an example of remediation potential rankings resulting in a high remediation potential for the following hypothetical site:The site has good access.

- The site has shallow contamination accessible by direct push.
- The source is moderate sized (about 10,000 cubic yards).
- Three orders of magnitude reduction in contaminant concentrations is required to reach cleanup goals.
- Contaminants consist of MTBE, BTEX, and TPH compounds which are readily attenuated.
- Significant residual LNAPL is present at site in the unsaturated zone, with some compounds found in low permeability zones.
- Experience at the site has shown that existing remediation technologies can achieve three orders of magnitude concentration reduction.
- REMFuel remediation timeframe model based on data in Questions 4 and 7 indicates 25 years would be required to remove the contamination left behind after remediation.

In this example, the four high, two moderate, and two low checks predict a high likelihood of achieving remediation objectives, assuming each question is equally weighted. [/wpex]

**Table 7. Remediation potential assessment tool: Example remediation potential determinations**

| Evaluation Criteria | Likelihood of Achieving Remediation Objectives | | |
|---|---|---|---|
| | **High** | **Moderate** | **Low** |
| Access for drilling/excavating | √ | | |
| Well drilling feasibility | √ | | |
| Scale of source zone or plume | | √ | |
| Concentration reduction | | | √ |
| Attenuation of site constituents | √ | | |
| Difficult-to-remove mass | | | √ |
| Remedial technology performance | √ | | |
| Predicted time frame | | √ | |
| Total checked: | 4 | 2 | 2 |

Various remediation potential matrices can be used during remedy selection phases. These matrices can be valuable tools to effectively summarize the rationale for the outcome and highlight areas of agreement among the site owners, regulators, and stakeholders. This process helps to inform the remedy selection process and determine if an adaptive management process is appropriate.

### 3.4.2 Value Engineering

Value engineering (VE) has become a widely used tool for optimizing remedy selection or elements of a remedial design prior to its completion. A VE evaluation can be performed at any time during a remediation project's life cycle, depending on the circumstances, needs, and costs involved. It is a formal, structured method for selecting the most cost-effective and efficient remedial solutions for a site. VE uses systematic and creative methods to reduce costs without sacrificing the reliability, efficiency, or original objectives of the project. A VE study differs from a traditional design/construction review in that it employs an independent, multidisciplinary team and group brainstorming techniques to recommend alternative concepts and approaches that achieve the overall project and design objectives, as opposed to simply concentrating on the technical aspects of a detailed design/construction project. A VE study differs from a traditional cost/benefit study in that the VE study seeks to improve a process, while a cost/benefit study compares alternatives. The overall goals of a VE study are to reduce capital investment and life cycle costs and improve long-term functionality of the design.

**Resources Describing Concepts Similar to VE**

- *Guidance for Optimizing Remedy Evaluation, Selection and Design (NAVFAC 2010a)*
- *Guidance for Optimizing Remedial Action Operation (NAVFAC 2012)*
- *National Strategy to Expand Superfund Optimization Practices from Site Assessment to Site Completion (National Optimization Strategy (USEPA 2012c)*
- *Optimization Strategies for Long-Term Ground Water Remedies (USEPA and USACE 2007)*
- *Integrated DNAPL Site Strategy Technology/Regulatory Guidance (ITRC 2011b)*

The Office of Federal Procurement Policy Act (U.S. Code 432, updated by 41 U.S. Code 1711, Jan 2011) requires executive agencies to establish VE procedures. The Office of Management and Budget Circular A-131 requires federal agencies to apply VE procedures to all projects with estimated costs of $2 million or more. USEPA's remedial project managers assure that VE screenings or studies are conducted on fund-financed remedial designs (USEPA 2006b). The U.S. Army Corps of

Engineers (USACE) has applied VE methodology to 770 projects through September 2015 and has had a return on investment of over $38 to every $1 spent. The average net savings and cost avoidance for USACE projects over the previous five fiscal years was $378,036,000 per year.

The VE study methodology guides the team in the development of project functionality and performance evaluation criteria (termed "performance attributes"). The methodology also helps to identify high cost areas, risk factors in the design/construction, and potential schedule bottlenecks or conflicts. The VE strategy is based on factors that include improved performance, likelihood of implementation, least community impact, cost savings, or any combination of a project's performance attributes.

To begin, the overall purpose of the VE exercise is documented. The next step in the VE strategy is to develop several alternatives. Typically, combinations of some alternatives may provide the best solution for the project. Some alternatives are proposed to answer a question raised by a decision maker or to resolve an open issue and may be found not to be beneficial to the ultimate purpose. Group brainstorming techniques identify alternative ways of performing the same functions more efficiently and cost-effectively by asking: "What else will satisfy the requirements?"

The results of a VE study are presented as individual alternatives to the baseline concept. Each alternative usually consists of a summary of the baseline concept, a description of the suggested change, a listing of its advantages and disadvantages, a cost comparison, change in performance and value, discussion of schedule and risk impacts (if applicable), and a narrative comparing the baseline design with the alternative. As part of the evaluation process, defining performance attributes are identified, which are aspects of a project's scope that may have a range of values. Those values represent the relationship between performance and cost and can be compared from alternative to alternative.

### Case Study: Rocky Flats

*Selected performance attributes:*

- *regulatory and stakeholder*
- *process effectiveness*
- *constructability*
- *maintainability*
- *environmental impacts*

*See the Rocky Flats full case study for more details.*

## 3.5 Postremedy Implementation

Determining whether an existing remedy can achieve remediation objectives requires a different set of assessment questions than those presented in Table 6. The questions in Table 8 are adapted from USEPA's *Groundwater Roadmap* (2011c) and can apply to both active remediation and MNA remedies at groundwater sites. Applying this assessment process can allow site owners, technical experts, regulators and private stakeholders to work together to determine if an existing remedy can achieve its objectives.

**Table 8. Remediation potential assessment: Postremedy implementation**

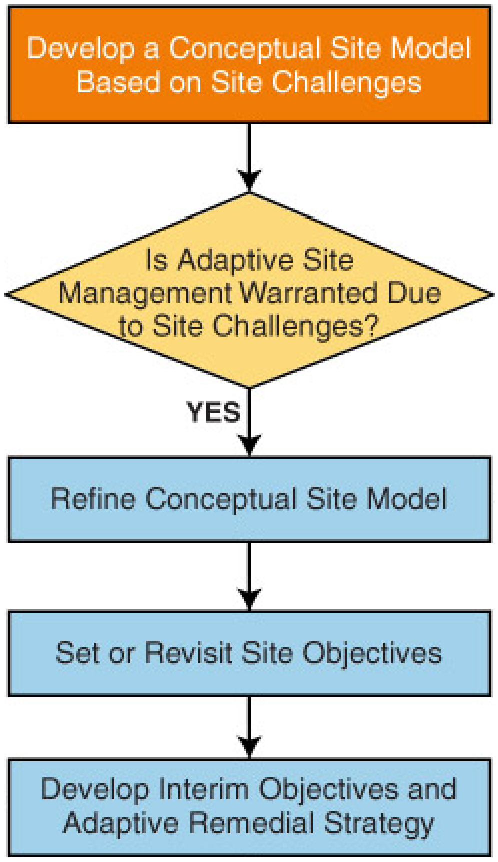
| Assessment Evaluation Criteria |
|---|
| 1. Is the monitoring program sufficient in quality and detail to evaluate remedy performance? |
| 2. Has the existing remedy been effectively operated and maintained? |
| 3. Are aquifer conditions or contaminant sources adequately characterized? Have they changed? |
| 4. Are concentrations reductions occurring at the rate anticipated? |
| 5. Are groundwater concentrations asymptotic or increasing? |
| 6. Is plume capture sufficient (or uncertain)? |
| 7. Does the selected remedy adequately address contaminants and/or hydrogeologic conditions? |
| 8. Can interim and/or site objectives (and contaminant-specific cleanup levels) be met with other technologies within a reasonable time frame? |

Evaluation criteria 1 through 7 concern the adequacy of the selected remedy in meeting the established remedial objectives.

At CERCLA sites, if it is determined that the current remedy is inadequate due to design, operation, or technology shortcomings, then USEPA may require that the remedy be “enhanced, augmented, or replaced” (USEPA 1993). Question 8 pertains to the potential of unproven technologies to achieve interim or site objectives in a reasonable time frame, much like the preremedy evaluation criteria in Table 4. After concluding that reaching interim objectives is unlikely and that other technologies cannot achieve interim objectives in a reasonable time frame, regulators (together with site owners and stakeholders) may choose to consider options within the adaptive site management approach. Further information about predicting and evaluating remedy performance is presented in the discussion of long-term management.

# 4. Adaptive Site Management

A remediation potential assessment can be used to decide whether adaptive site management is recommended due to site challenges identified within the context of the CSM. The adaptive site management approach may be adjusted over the site's life cycle as new site information and technologies become available. This approach is particularly useful at complex sites where remediation is difficult, the remediation potential is uncertain, and the remediation may require a long time.




## 4.1 Steps in the Adaptive Site Management Process

The first steps in the adaptive site management process are to identify complexity attributes within the CSM and assess whether adaptive site management is warranted. The next steps are as follows:

1. Refine the conceptual site model.
2. Set or revisit site objectives.
3. Develop interim objectives and adaptive remedial strategy.

These steps are particularly relevant at sites that are selecting an interim or final remedy or revisiting the existing remedial strategy because insufficient progress has been made towards meeting site remediation objectives. These elements can be used iteratively during the adaptive site management process (Figure 1). This process is eventually guided by the long-term management plan, which should be anticipated during remedy selection and implementation.

## 4.2 Refine the Conceptual Site Model

It is particularly important to revisit and refine the CSM periodically throughout the project life cycle. The CSM should be treated as a dynamic tool and updated as needed (for example, by using data generated during implementation of adaptive site management) to support remedy decisions throughout the adaptive site management process. It is a best practice to update the CSM during long-term management planning, remedy implementation, periodic evaluations of monitoring data and remedy performance data, and remedy optimization. If a remedy is not on track to meet interim objectives despite optimization, the CSM should be refined prior to revisiting the remedy (Figure 1). If additional site characterization is needed to fill data gaps and complete an effective remedy design, an integrated site characterization (ISC) process can improve site characterization and maximize the effectiveness of remediation (ITRC 2015b). Although it was developed for use at sites with DNAPL, the ISC process can be used at other sites as well. The ISC process is shown in Figure 2.

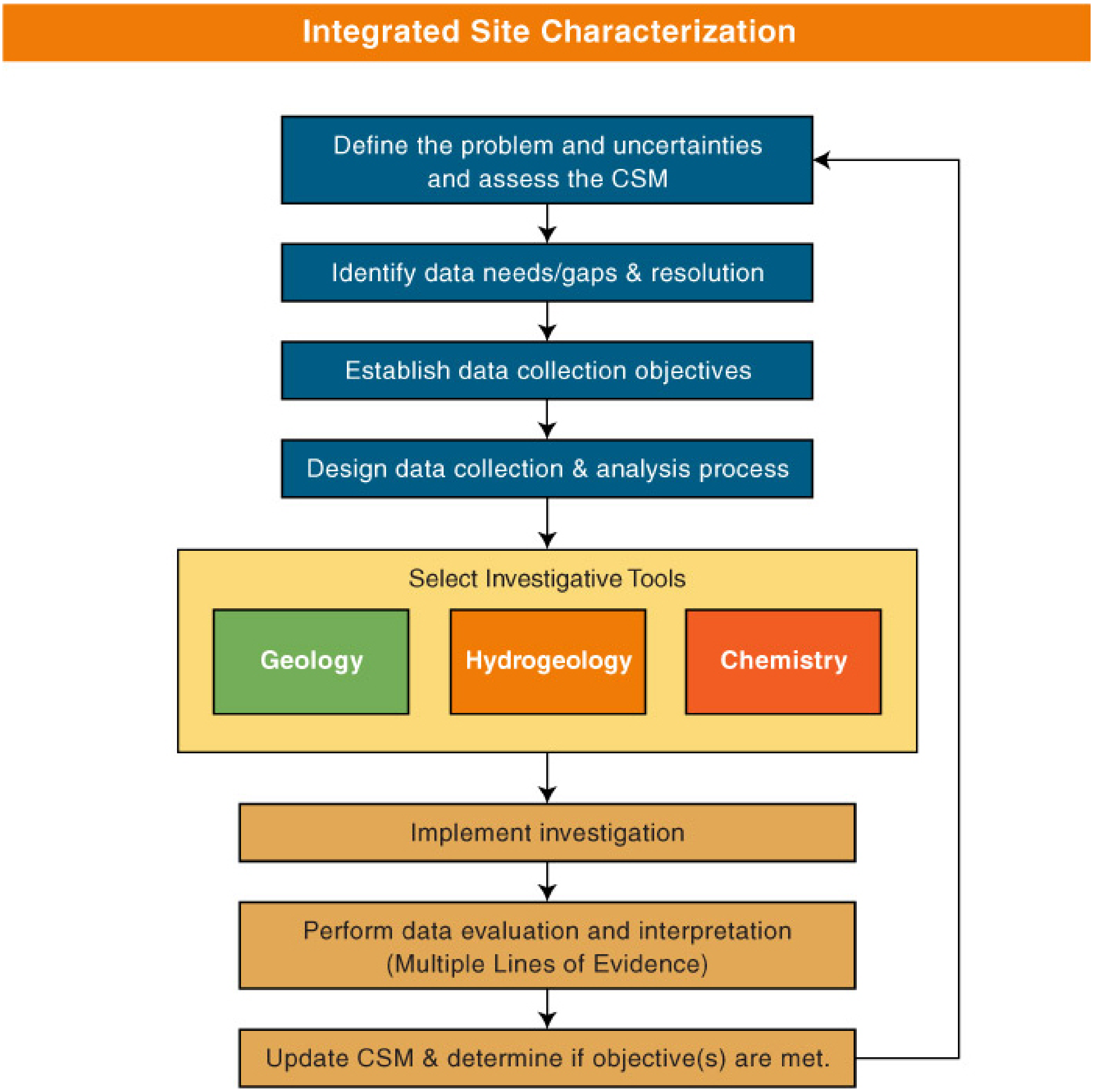



**Figure 2. ISC approach (ITRC 2015b).**

According to ITRC (2015b):

> *The ISC supports iterative refinement of the CSM over the project life cycle with information obtained during site investigation, remedy design, and remedy optimization. Similar to the USEPA's data quality objectives (DQOs), it relies on a systematic, objectives-based site characterization process that includes defining the uncertainties and CSM deficiencies; determining the data needs and resolution appropriate for site conditions; establishing clear, effective data collection objectives; and designing a data collection and analysis plan.*

Through ISC, the most appropriate and up-to-date site characterization tools are selected to effectively characterize site geology (for example, stratigraphy), permeability, and contaminant distribution. Once the data are collected, the process includes evaluating and interpreting the data and updating the CSM.

Note that additional site characterization may show that some sites are more complex than initially thought. For example, fractured bedrock poses challenges for mapping groundwater flow paths. More detail on characterization in fractured rock environments is provided in recent ITRC guidance (ITRC 2017a).

When refining the CSM, using GSR approaches (ITRC 2011a) to investigate the site can result in a quantitatively greener project by consuming fewer resources and by producing lower emissions and wastes. GSR can effectively bring stakeholders into the project so that their views and needs are reflected throughout the site remediation process. Investigation phase GSR options can be identified or implemented using a tiered approach ranging from very simple (best management practices) up to very sophisticated analysis (life cycle analysis).

### Case Study: Observational and Adaptive Approach to CSM Development

*Site characterization and CSM development is inherently complex at an industrial site in Australia, where over 100 metric tons of mixed chlorinated organic compounds were released into a variably weathered, fractured basalt aquifer. The CSM has been developed iteratively using an observational and adaptive approach for fractured rock sites recommended by NAS (2015). Site characterization approaches include long-screen monitoring wells, aquifer testing, basalt cores, rock crushing and extraction and analysis of VOCs in rock core samples, and FLUTe liners in open boreholes to test for DNAPL presence. Several remedial technologies were tested at scales ranging from laboratory microcosms to field pilot studies. Microbiological tools (QuantArray), passive flux meters, bioaugmentation, and compound specific isotope analysis were used to evaluate an ongoing enhanced in situ bioremediation remedy, optimize remedy performance and evaluate methods of accelerating DNAPL removal. More details are provided in the full case study.*

## 4.3 Set or Revisit Site Objectives

Site objectives must be determined before considering remedial strategies to achieve those site objectives. Site objectives are established based on remediation expectations and requirements for sites in CERCLA, RCRA, and other state and federal programs. Different regulatory programs may have different levels of flexibility in setting and revisiting site-specific objectives. These objectives are usually considered during remedy planning or when remedy performance is not sufficient to achieve site objectives within the expected time frame.

The process of setting objectives is addressed in *Integrated DNAPL Site Strategy* (IDSS), which uses the term "absolute objectives" instead of site objectives and "functional objectives" instead of interim objectives (ITRC 2011b). Chapter 3, Remediation Objectives, of the IDSS guidance describes a process for establishing absolute (site) objectives and developing functional (interim) objectives to achieve those absolute (site) objectives (ITRC 2011b). The document summarizes these terms as follows (ITRC 2011b):

In this document objectives are defined as either absolute [site] or functional [interim] (NRC 2005, ITRC 2008b). Absolute [site] objectives are based on broad social values, such as protection of public health and the environment. Functional [interim] objectives are the steps or activities that are taken to achieve absolute [site] objectives.

The IDSS guidance also provides references to examples of alternative objectives that can be used in specific instances, such as technical impracticability waivers, ACLs, and plume containment approaches.

Site and interim objectives need not be the same throughout the site. For example, off-site contamination, source areas, and plume areas may each require different objectives, remedial strategies, and remediation time frames.

One challenge at complex sites is how to identify and consistently use various regulatory approaches within their specific regulatory programs. Although some programs (particularly many state petroleum programs) permit flexibility in site objectives to achieve pragmatic results, site objectives other than MCLs are often perceived as less desirable and remain controversial to even discuss with many regulators.

At other sites, regulators have recognized that MCLs for groundwater are not an appropriate target and have approved ACLs or other site objectives for groundwater. For example, the use of non-MCL site objectives at a site with no present or future potable use has the potential benefit of reducing the remedial time frame. State programs may include nonpotable aquifer designations with non-MCL water quality standards or allow use of ICs and a designated point-of-compliance for MCLs (such as at an affected property boundary or at a point of use). CERCLA and RCRA programs have formal regulatory definitions of

ACLs and other types of regulatory flexibility in setting site objectives. These regulatory approaches, if appropriate, may establish site objectives that are higher than the MCL, yet protective under the site-specific conditions. In addition, because sites with complex attributes often will not achieve objectives within a reasonable time frame, site-specific interim objectives, as discussed in Section 4.4, must be developed so that remediation management can be implemented to protect human health and the environment over the long term.

The type of remediation program (such as CERCLA, RCRA, or other state regulatory agencies overseeing site remediation) prescribes the approach to defining and meeting site objectives. Although these various programs typically share the same nominal site objectives (protection of human health and the environment, remediation of resources), programmatic differences must be considered when developing specific site objectives. The following sections present elements of the CERCLA program that define remedial action objectives (RAOs) and site objectives, followed by a discussion of differences between the CERCLA approach and approaches for RCRA sites and state remediation programs and an overview of approaches used at other Federal facilities.

Incorporating GSR considerations into the project (ITRC 2011a) provides stakeholders with the opportunity to have their perspectives considered during the process of establishing the overall project's goals and can help maximize the environmental, social, and economic benefits.
▼*Read more*

## 4.3.1 Setting Site Objectives under CERCLA

USEPA administers the CERCLA remediation program. The National Contingency Plan (NCP 1990) describes the overall objective and purpose of remedial actions at CERCLA sites. According to the NCP preamble (1990), "…by stating 'expectations' rather than issuing strict rules, USEPA believes that critical flexibility can be retained in the remedy selection process." Two recent USEPA publications, *Memorandum: Summary of Key Existing USEPA CERCLA Policies for Groundwater Restoration* (USEPA 2009b) and *Groundwater Road Map: Recommended Process for Restoring Contaminated Groundwater at Superfund Sites* (USEPA 2011c), both provide information relevant to the remediation process for complex sites with impacted groundwater under CERCLA and the NCP.

All CERCLA site remedies must be protective of human health and the environment, as well as comply with ARARs. ARARs consist of multiple federal and state regulations. State standards that are more stringent than federal ARARs may also be applicable. The process for identifying ARARs is described in multiple USEPA guidance documents (see USEPA 2015a).

### 4.3.1.1 ARAR Waivers and Site Objectives

At some sites, ARAR waivers can be granted in accordance with 40 CFR 300.430(f)(1)(ii)(C). This regulation notes the circumstances under which these waivers are permitted: "an alternative that does not meet an ARAR under federal environmental or state environmental or facility siting laws may be selected under the following circumstances":

- *Technical Impracticability.* Compliance with the requirement is technically impracticable from an engineering perspective. Note that USEPA (1993) has published specific guidance on technical impracticability.

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*Technical Impracticability*
Sometimes a contaminant-specific site objective cannot be reached because the remedial technology selected cannot reduce contaminant concentrations to the desired levels. USEPA (1993) guidance states that "…restoration to drinking water quality (or more stringent levels where required) may not always be achievable due to the limitations of available remediation technologies." USEPA, therefore, must evaluate whether groundwater restoration at Superfund and RCRA groundwater remediation sites is attainable from an engineering perspective. This scenario may occur at complex sites. USEPA identified 85 sites where 91 TI waivers had been granted as of 2012; multiple TI waivers were used at some sites (USEPA 2012e). Chemical-specific ARARs for certain contaminants that cannot be achieved within a reasonable time frame due to technical challenges are then often waived. The final remedy decision document which can be a ROD, ROD amendment, or Explanation of Significant Differences (ESD), specifies the spatial (horizontal and vertical) extent of the aquifer within which the TI waiver applies (the areal footprint and depth or hydrogeologic unit, also known as the TI zone).

### Case Study: Koppers Oroville Wood Treatment facility

*The Koppers Oroville Wood Treatment facility operated from 1948 until 2001. Wood treatment operations and several fires contaminated the site with several wood-treatment related chemicals, including pentachlorophenol, creosote, polynuclear aromatic hydrocarbons (PAHs), as well as heavy metals including copper, chromium, and arsenic. Pentachlorophenol and creosote migrated from site soils into groundwater, where creosote DNAPL formed pools above groundwater and pentachlorophenol formed an off-site plume and contaminated a drinking water aquifer.*

*This site demonstrates several complexities: presence of creosote DNAPL contaminating on-site groundwater, contamination of a drinking water aquifer, and widespread recalcitrant contaminants (creosote, pentachlorophenol, dioxins, and PAHs). The site remedy includes a technical impracticability waiver for groundwater in the DNAPL source area, creosote recovery, an on-site capped landfill, deed restriction, and long-term O&M. The remedial approach was refined based on success/failure of previous remedial approaches and the refined CSM.*

*USEPA is the lead agency for the site, and the responsible party funded the cleanup. The 1989 ROD proposed several soil treatment technologies and a groundwater pump-and-treat system. The ROD proposed residential cleanup standards for soil and health-based (drinking water) standards for groundwater. However, results from soil treatability studies and additional site investigation revealed that soil treatment would not likely achieve cleanup standards. Therefore, in 1996, a ROD Amendment was issued to change the soil remedy to a capped on-site landfill and establish industrial cleanup standards for site soils. A deed restriction for site soils was subsequently established restricting future site use to industrial use. A second ROD amendment in 1999 modified the groundwater remedy to provide for a four-acre TI zone and added enhanced in situ bioremediation to the remedy.*

*Rationale for the TI waiver approval was stated as follows: “The nature and extent of DNAPL at the site has become better defined than at the time of the RI, and technical issues regarding DNAPL are better understood than during the FS and original ROD (1989). The ROD Amendment changes the goal for groundwater from within the 4-acre TI Zone from restoration to containment. A TI waiver is justified based on the following: (1) surface and near surface soil contamination have been remediated and the DNAPL has been contained; (2) it is not technically feasible to meet the cleanup standards within the TI Zone; (3) deed restrictions can provide adequate protection; (4) contaminants will be monitored inside the TI zone; and (5) operation of P&T will be resumed as a contingent remedy if contaminants migrate outside the TI Zone. Groundwater is approximately 30 feet bgs with an estimated volume of 67 million gallons in the TI Zone. The DNAPL likely resides on three clay layers separating the different aquifers, and based on RI data, more than 1 million gallons of free creosote may be present at these layers” (USEPA 2012e).In December 1995, the off-property pump-and-treat system was shut down because monitoring results revealed that the plume had retreated upgradient of the extraction wells, and thus the system could no longer effectively capture the plume. A bioremediation program for the off-site plume was implemented in 1998 to continue advancing remedial progress. Bioremediation continued until 2009, when USEPA determined that remedial goals for off-site groundwater (restoration of drinking water) had been achieved. See the Koppers full case study for more details.*

USEPA (1993) determines technical impracticability based on site-specific characterization and, where appropriate, remedy performance data. Among other elements, an evaluation of restoration potential of the site is needed, including data and analyses that support any assertion that attainment of ARARs or media cleanup standards is technically impracticable from an engineering perspective. Where complete remediation is found to be technically impracticable, USEPA selects an alternative remedial strategy that is technically practicable, protective of human health and the environment, and satisfies the statutory and regulatory requirements of the Superfund or RCRA programs, as appropriate. Alternative remedial strategies typically address three types of problems at contaminated groundwater sites (USEPA 1993):

- prevention of exposure to contaminated groundwater
- remediation of contamination sources
- remediation of aqueous contaminant plumes

TI waivers are one component of the final remedy, which may include source zone treatment, plume treatment, containment, monitoring, ICs, and engineering controls (USEPA 1993
).

A TI waiver may be considered during any stage of the remedial process. USEPA believes that, in many cases, TI decisions should be made only after full-scale interim or final remediation systems are implemented, because it is often difficult to predict the effectiveness of remedies based on limited site characterization data. TI decisions may be made at the beginning, or "front end" (USEPA 1993) of the site remediation process as part of the original final remedy. Front-end TI waiver decisions are documented in a ROD and must be supported adequately by detailed site characterization and data analyses that define critical limitations to groundwater restoration. These decisions may be based on interim remedy performance or the performance of pilot-scale studies (USEPA 1993). A postimplementation or "back-end" decision (USEPA 1993) is based on data from the remediation system and is documented in a ROD amendment or ESD.

After USEPA published its primary guidance document on TI waivers in 1993, several subsequent documents reiterated and clarified the evaluation process and appropriate use of TI waivers. The USEPA Regional Administrator usually makes TI decisions, although USEPA Headquarters is typically consulted as well. A summary of key USEPA publications is provided in Table 9.

**Table 9. Summary of key USEPA documents pertaining to TI waivers**

| Date | USEPA Document | Description |
|---|---|---|
| 1993 | Guidance for Evaluating the Technical Impracticability of Ground Water Restoration. USEPA/540/R-93/080, Office of Solid Waste and Emergency Response (OSWER) Directive 9234.2-25 | Primary guidance document on TI waivers that is still used today. This document outlines USEPA's approach to evaluating the technical impracticability of attaining required groundwater remediation standards and establishing alternative, protective remedial strategies where restoration is determined to be technically impracticable. |
| 1995 | Memorandum: Consistent Implementation of the FY 1993 Guidance on Technical Impracticability of Groundwater Restoration at Superfund Sites. OSWER Directive 9200.4-14 | This memorandum addressed implementation of the TI waiver 1993 guidance. The purpose of the memorandum was to promote national consistency in TI decision making, facilitate transfer of information pertinent to TI decisions between headquarters and the Regions, identify the appropriate persons to conduct reviews of TI related documents, and clarify the role of Headquarters consultation. |
| 2007 | Recommendations from the USEPA Ground Water Task Force. USEPA/500/R-07/001 | The mission of the USEPA Groundwater Task Force was to identify and prioritize groundwater issues that will benefit multiple remediation programs and make recommendations to USEPA senior management on the best course of action. Among other recommendations, the task force recommended developing guidance on how to acknowledge technical limitations posed by DNAPL in USEPA remediation decisions, including updated guidance on the use of TI decisions in the Superfund program, and a discussion of mechanisms for acknowledging technical limitations posed by site complexities other than DNAPL. The report included as an attachment a discussion paper on site objectives appropriate for DNAPL source zones. |
| 2009 | Summary of Key Existing USEPA CERCLA Policies for Groundwater Restoration. OSWER Directive 9283.1-33. | The purpose of this memorandum is to provide a compilation of some key existing USEPA groundwater policies to assist USEPA regions in making groundwater restoration decisions pursuant to CERCLA and the NCP. This memorandum did not create any new guidance. Among other things, the memo addressed expectations for groundwater restoration and TI waiver consideration in the context of principles for groundwater remediation. |
| 2011 | Memorandum titled "Clarification of OSWER's 1995 Technical Impracticability Waiver Policy" OSWER Directive #9355.5-32. | The purpose of this memorandum is to provide clarification to the 1995 OSWER memorandum entitled "Superfund Groundwater RODs: Implementing Change this Fiscal Year" regarding the use of TI waivers at CERCLA sites with DNAPL contamination. This memorandum clarifies that (1) the 1995 memorandum was intended to apply only to remedy decisions made in FY 1995 and that (2) DNAPL contamination in and of itself should not be the sole basis for considering use of a TI waiver at any given site. |

| Date | USEPA Document | Description |
|---|---|---|
| 2011 | Groundwater Road Map: Recommended Process for Restoring Contaminated Groundwater at Superfund Sites. OSWER Directive 9283.1-34. | This fact sheet focuses on those groundwater response actions in which the decision has been or may be made to restore all or part of the aquifer and that are undertaken using remediation authority under CERCLA, as amended. Portions of this guidance may also be useful for groundwater remedial actions that do not have restoration as an objective. The document does not provide new guidance but compiles key relevant highlights of Superfund law, regulation, policy, and guidance. |
| 2012 | Summary of Technical Impracticability Waivers at National Priorities List Sites. Report with General Technical Impracticability Site Information Sheets. OSWER Directive 9230.2-24. | This report provides a summary of TI waivers issued by USEPA regions, and brief summaries of the completed TI waiver decisions, including a summary of the site conditions and the Regions' rationale for adopting a TI waiver. A total of 91 waivers at 85 sites were identified. |
| 2014 | Groundwater Remedy Completion Strategy: Moving Forward with the End in Mind. OSWER 9200.2-144. | This document presents a recommended "groundwater remedy completion strategy" for evaluating Superfund groundwater remedy performance and making decisions to help achieve RAOs and associated remediation standards. Section 7 of this document, "Make management decisions," describes some of the key options to consider if it appears that a remedial action will not be able to achieve the groundwater RAOs and associated remediation standards selected in the ROD. |

- *Greater Risk.* Compliance with the requirement would result in greater risk to human health and the environment than other alternatives.

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*Greater Risk*
Few sites have been granted ARAR waivers based on greater risk. At sites that have been granted greater risk waivers, ARARs have been waived because meeting them would entail remedial actions that pose a greater risk to human health and the environment than not meeting ARARs. Examples of scenarios that could constitute greater risk include the following (Deeb et al. 2011):

- mobilization of contaminants during remedial activity, causing greater risk to deeper or nearby drinking water aquifers
- dewatering or land subsidence as a result of P&T systems
- disturbance of wetlands or other sensitive ecosystem areas as a result of remedial activity
- contaminant resuspension and mobilization that would be caused by dredging, adversely affecting sediment and surface water quality
- explosive hazards or other health and safety hazards associated with the implementation of specific remedial technologies (such as chemical oxidation remedies or excavation of pyrophoric wastes)
- reduced natural flushing due to liner/cap installation, extending the time frame for natural attenuation of underlying groundwater contaminants

CERCLA sites adopting ARAR waivers based on greater risk did so in the late 1980s and early 1990s. The Superfund ROD database for "greater risk" shows no recent CERCLA sites referencing a greater risk ARAR waiver from 2000 to 2012. Although this type of waiver may have been recently considered at complex sites, there are no recent examples of its successful adoption and integration into a CERCLA decision document.

- *Equivalent Standard of Performance.* The alternative will attain a standard of performance that is equivalent to that required under the otherwise applicable standard, requirement, or limitation through use of another method or approach.

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*Equivalent Standard of Performance*
This type of ARAR waiver is appropriate if "the alternative will attain a standard of performance that is equivalent to that required under the otherwise applicable standard, requirement, or limitation through use of another method or approach" (40 CFR 300.430(f)(1)(ii)(C)). No CERCLA sites have used this ARAR waiver since 2000, although the use of this waiver was considered during the FS at one site (USEPA 2002c). Prior to that, this type of waiver was used to waive action-specific and location-specific ARARs and was not applied to ARARs for contaminated groundwater. For example, RCRA landfill cap requirements have been waived based on equivalent standard of performance of an alternative landfill cap design (Deeb et al. 2011).

- *Inconsistent Application of State Standards.* With respect to a state requirement, the state has not consistently applied, or demonstrated the intention to consistently apply, the promulgated requirement in similar circumstances at other remedial actions within the state.>

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*Inconsistent Application of State Standards*
This type of waiver applies if "with respect to a state requirement, the state has not consistently applied, or demonstrated the intention to consistently apply, the promulgated requirement in similar circumstances at other remedial actions within the state" (40 CFR 300.430(f)(1)(ii)(C)). This waiver was intended to prevent the state from imposing unjustified or unreasonable restrictions at CERCLA sites. No CERCLA sites have used this type of ARAR waiver. Considerable discussion of an ARAR waiver based on inconsistent application of state standards is documented in the Rocky Mountain Arsenal off-post operable unit ROD. Interested parties discussed waiving Colorado Basic Standards for Groundwater that had been adopted contemporaneously with the ROD for contaminants unique to the site. However, an ARAR waiver was never used (Deeb et al. 2011).

- *Fund Balancing.* For Fund-financed response actions only, an alternative that attains the ARAR will not provide a balance between the need for protection of human health and the environment at the site and the availability of Fund money to respond to other sites that may present a threat to human health and the environment (USEPA 1991).

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*Fund Balancing*
This ARAR waiver is appropriate if the cost of complying with the ARAR is high enough to threaten the ability of the CERCLA Fund to respond to and achieve protectiveness at other sites (USEPA 1991). The waiver is only to be considered at CERCLA sites that receive Superfund financial support. There is no set dollar amount at which this waiver should be invoked. In 1991 guidance, USEPA stated that "the fund-balancing waiver is to be routinely considered when the cost of meeting an ARAR for an operable unit is four times the national average cost of remediation of all operable units." Previously published USEPA guidance had stated that the "waiver should be considered when the cost of attaining an ARAR is 20 percent of the annual remedial action budget or $100 million, whichever is greater" (USEPA 1989a). Regardless of these details, the fund-balancing ARAR waiver has never been used in practice. An option for this waiver, however, remains open in the ROD for the Upper Tenmile Creek Mining Area. This ROD stated that although the intention of the final remedy was to fully attain water quality standards, USEPA would consult with the state during the five-year review process to assess whether a Fund-Balancing ARAR waiver was appropriate in the future to waive specific standards in particular stream reaches or groundwater areas (USEPA 2002d).

- *Interim Measure.* The alternative is an interim measure and will become part of a total remedial action that will attain the applicable or relevant and appropriate federal or state requirement.

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*Interim Measures*

ARARs are not expected to be met if "the alternative is an interim measure and will become part of a total remedial action that will attain the applicable or relevant and appropriate federal or state requirement" (40 CFR 300.430(f)(1)(ii)(C)). Interim measures can therefore function as temporary ARAR waivers at complex sites until agreement is reached on the final remedy. For example, interested parties at the Hastings Groundwater Contamination site area-wide groundwater operable unit (OU 19) issued an interim ROD in 2001 because they were unable to reach agreement on a final ROD. None of the remedial alternatives were expected to meet ARARs, yet data were not deemed sufficient to support an ARAR waiver based on technical impracticability (Deeb et al. 2011). Therefore, interested parties issued an interim ROD which stated that monitoring would be conducted and used as a basis for assessing technical impracticability or ACLs as part of a final ROD. Subsequent five-year review reports have not further commented on the potential use of an ARAR waiver or ACLs. The 2012 five-year review report states that a final ROD is still needed. This situation is likely common at other complex sites operating under interim remedies.

#### 4.3.1.2 ACLs

Three criteria for ACLs are included in CERCLA Section 121(d)(2)(B)(ii):

…a process for establishing alternate concentration limits to those otherwise applicable for hazardous constituents in groundwater under subparagraph (A) may not be used to establish applicable standards under this paragraph if the process assumes a point of human exposure beyond the boundary of the facility, as defined at the conclusion of the remedial investigation and feasibility study, except where:

- There are known and projected points of entry of such groundwater into surface water
- On the basis of measurements or projections, there is and will be no statistically significant increase of such constituents from such groundwater in such surface water at the point of entry or at any point where there is reason to believe accumulation of constituents may occur downstream
- The remedial action includes enforceable measures that will preclude human exposure to the contaminated groundwater at any point between the facility boundary and all known and projected points of entry of such groundwater into surface water then the assumed point of human exposure may be at such known and projected points of entry.

In addition to meeting these three criteria, USEPA published a policy memorandum stating several other factors to consider before establishing an ACL (USEPA 2005b). Examples include whether all groundwater plumes are discharging to surface water and the potential accumulation or effect of degradation byproducts in groundwater or surface water (USEPA 2005b). A keyword search of the CERCLA database revealed no sites using ACLs since 2005 and one site at which ACLs were rescinded based on the USEPA memorandum, with a TI waiver issued instead (Deeb et al. 2011).

### 4.3.2 Setting Site Objectives under RCRA and Other Remediation Programs (Brownfields, Petroleum/UST, Voluntary Cleanup, and Others)

Most remediation sites in the United States are not under the jurisdiction of the CERCLA remediation program, but instead are identified and administered by states and territories under the RCRA Corrective Action program, Brownfields and Land Revitalization programs, Underground Storage Tank remediation programs, and Voluntary Cleanup programs. The RCRA Corrective Action program regulates the remediation of nearly 4,000 active hazardous waste management facilities with spills or releases. USEPA has generally delegated RCRA program management to the states (43 of the 54 states and territories are authorized). Like CERCLA, the overall goal of RCRA and its implementing regulations is to protect human health and the environment, meet site objectives, control sources to reduce further release of hazardous waste, and comply with applicable standards for waste management.

Remediation programs have typically been designed to achieve specified site objectives for groundwater, sometimes point-based concentrations below federal MCLs or similar drinking water quality criteria, before site closure is allowed. Several regulatory-approved approaches for setting site objectives in groundwater, however, can be used as an alternative to MCLs (NRC 2013). It is beyond the scope of this document to comprehensively describe the different state and federal remediation program approaches to setting or revisiting site objectives. Instead, this guidance presents results from a survey of ITRC state Points of Contact (POCs) and offers several examples of goal-setting under these remediation programs.

To gauge state regulatory practices regarding site objectives, ITRC surveyed the ITRC state POCs. Survey results indicated that several methods were commonly used as a basis for setting or revisiting site objectives.

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State representatives were asked the following two questions:

1. Does your state/tribal program allow the following as a primary means to meet RAOs?
2. Does your state/tribal program allow the following after the original selected remedy fails to reach the RAOs within the planned remedial time frame?

The term "RAOs" was used in the survey to encompass a broad range of state remediation program objectives (site objectives). Several methods of designating alternative points of compliance, contaminant management areas (areas subject to institutional controls, plume containment), criteria adjustment, schedule adjustment, technology adjustment, and other alternatives were then listed. Note that the second survey question referred to a "planned remedial time frame"; however, there is little evidence that states or tribes establish a planned remedial time frame during remedy selection. With this qualifier, the results of the survey are summarized below.

#### 4.3.2.1 Summary of State Practices based on ITRC Survey Results

ITRC received responses from 40 of the 50 states (see Appendix A for detailed results). Results for the first question are summarized in Figure 3, ordered by frequency of use of the different alternative compliance options/adjustments. Results for the second question are shown in Figure 4.

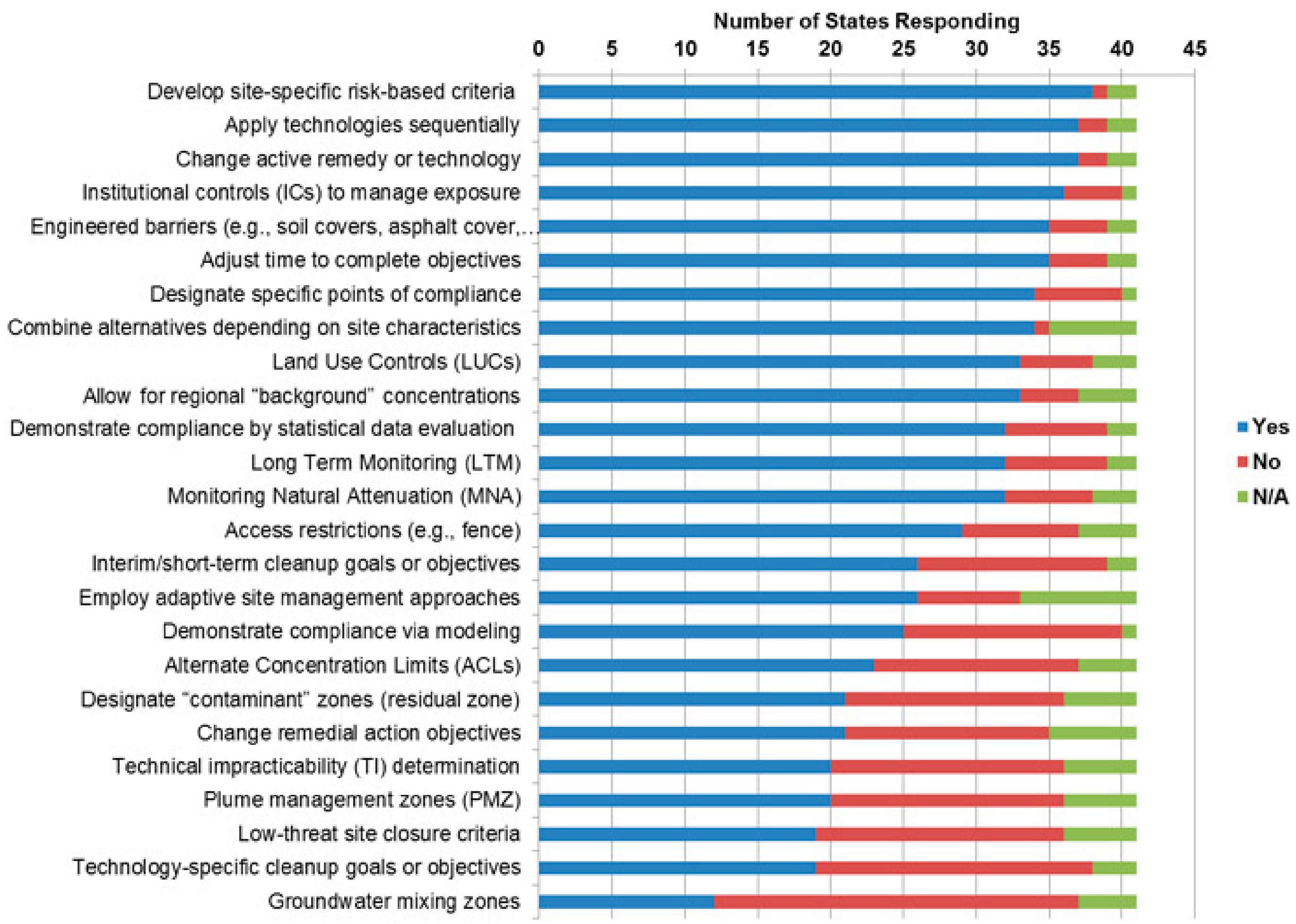



**Figure 3. State survey responses to Question 1: Does your state/tribal program allow the following as a primary means to meet RAOs?**

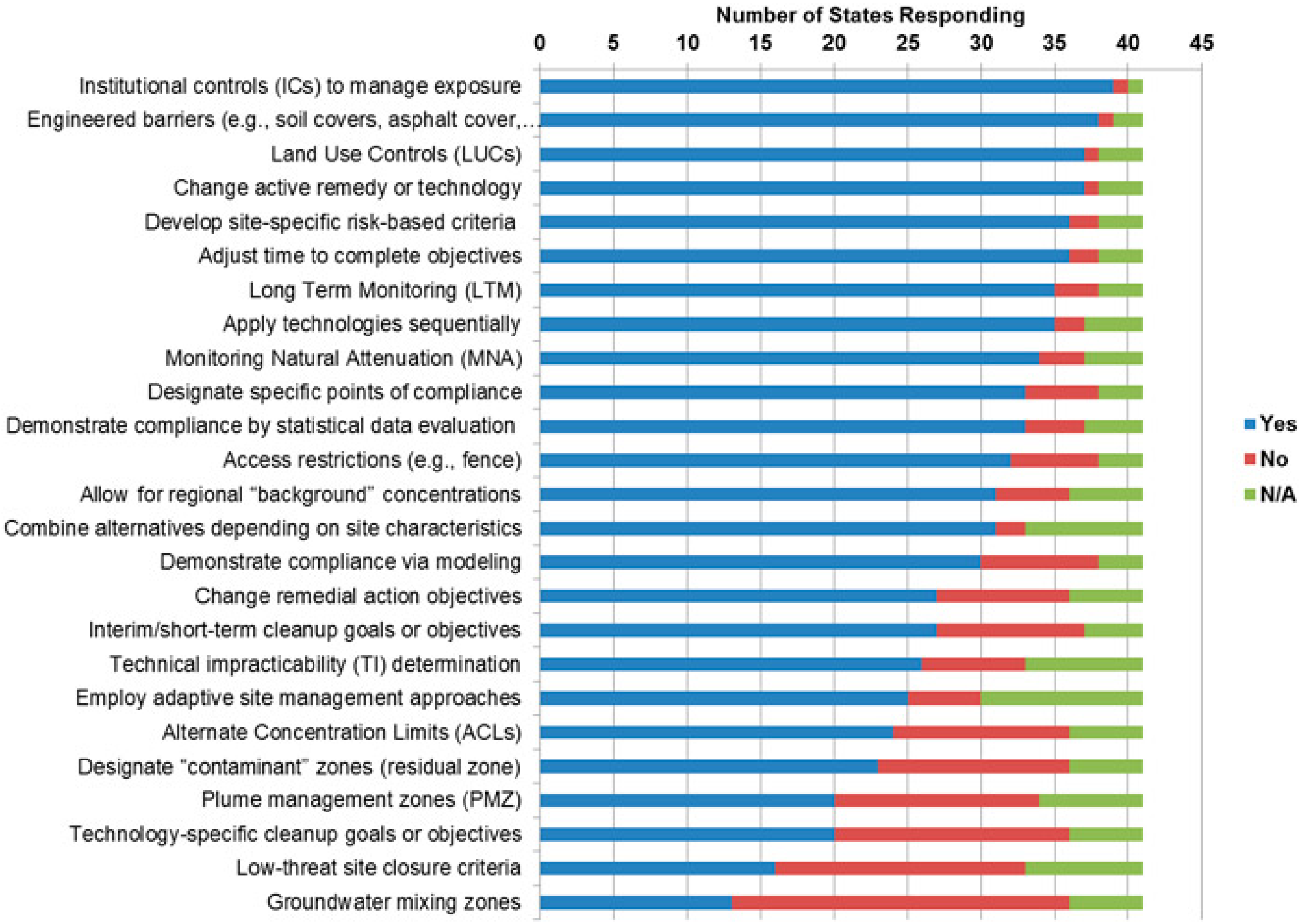



**Figure 4. State survey responses to Question 2: Does your state/tribal program allow the following after the original selected remedy fails to reach the RAOs within the planned remedial time frame?**

The survey results indicate the following:

- Almost all the states responding to the survey allow for the use of site objectives based on risk assessment as a primary means of adjusting site objectives. Most also allow for site objectives adjustments due to regional background concentrations. States may have specific guidance for determining background concentrations or may reference USEPA (2002b) CERCLA guidance. In contrast, only about half of the states responding indicated that site objectives could be adjusted by changing site objectives, using ACLs, issuing TI determinations, designating plume management zones or plume containment zones, or adopting interim objectives. Note that some states (such as Alaska) may not have formal guidance or policy on TI determinations, but instead refer to requirements for cleanup to the lowest extent practicable or allow a demonstration that a prescribed cleanup level is not practicable.
- States indicated that contaminant management approaches (ICs, engineered barriers, land use controls (LUCs), and access restrictions) are commonly used as a primary means of meeting site objectives.
- Adjustments to schedule and technology selection were also commonly used as a primary means of meeting site objectives. Applying several technologies sequentially, changing the remedy, and adjusting the time planned to reach the site objectives were used by 85% to 90% of the states who responded to the survey.
- At sites where the original remedy failed to meet site objectives within the planned time frame, many states indicated that several approaches were then more likely to be considered. Six more states indicated that a TI determination could then be considered; another six states replied that they could then change site objectives. Five states accept a demonstration of compliance based on modeling. Several more states would consider adopting LUCs, access restrictions, engineered barriers, ICs, and long-term monitoring. Two states consider designated contaminant zones or MNA and one additional state would consider interim objectives, groundwater mixing zones, ACLs, compliance based on statistical data evaluation, technology-specific objectives or would

then adjust the time frame to reach site objectives.

Note that the results of this survey cannot be used to make conclusions about using these approaches at CERCLA sites. Additionally, an individual state remediation program may accept an approach that is not necessarily accepted statewide. State regulators should be consulted regarding the applicability of any of these remediation management approaches at a specific site.

#### 4.3.2.2 Risk-Based (Site-Specific) Criteria

Most practitioners are familiar with using site-specific criteria in a risk assessment process to develop site-specific risk-based criteria as site objectives. As shown in the ITRC survey, nearly all state programs have regulatory flexibility to accept site-specific, risk-based criteria in place of published screening levels. State regulators should be consulted regarding the potential use of site-specific criteria at a particular site. The risk assessment process is the basis for remediation at RCRA sites. Although most investigation and remedial actions use risk-based screening levels published by the state, site-specific risk and exposure criteria have been used as the basis for remediation requirements at several complex sites. One state survey responder commented that DOD sometimes prepares detailed risk assessments at more complex sites. For these sites, the state also required the evaluation to address nontoxicological effects of contaminants such as flammability, leaching, odor/nuisance concerns, and impacts to aquatic habitats. Site-specific risk assessments have also been conducted to address newly-identified exposure pathways such as vapor intrusion (see Case Study 2). Several guidance documents provide more information on how to conduct a site-specific risk assessment (ITRC 2015a, 2008c, NRC 2014).

#### 4.3.2.3 Designated Points of Compliance

Designating specific points of compliance (for example, specific monitoring wells) is another approach that has been accepted as the basis for site objectives. According to the ITRC state survey, approximately 75% of state remediation programs have the flexibility to accept this approach to meeting site objectives. State responders commented that the flexibility to accept designated points of compliance depended on the regulatory program involved. Several survey responders emphasized the need for the compliance locations to be within the property boundary; off-site compliance locations were not acceptable. Another survey responder commented that specific locations were also commonly designated as monitoring locations (for example, sentinel wells) to define the restricted area under ICs. Similarly, designated sentinel wells could be used as a trigger for determining whether to implement a contingency plan. Compliance points can be used in a long-term management monitoring program to also detect external changes that may affect the basis of site-specific risk assumptions or exposure assumptions (such as the effect of a rising water table, or geochemical changes that may affect an MNA remedy).

**Case Study: Groundwater Management Zone at JOAAP**

*Groundwater management zones (GMZs) were used at an Illinois Superfund site to identify areas that do not currently meet drinking water standards. GMZs restrict the use of groundwater and other activities to prevent human exposure to contaminated groundwater. Monitoring wells between the plume and the GMZ boundary provide early warning of plume migration and serve as points of compliance. GMZs include a buffer zone outside of the plume to prevent well installation. At JOAPP, GMZ borders were extended in response to a five-year review to prevent groundwater withdrawals from within the GMZ. The designation will be in place until site objectives have been achieved. More details are provided in the full case study.*

Finally, note that compliance locations within a specific boundary or plane can be used to calculate mass flux; therefore, a designation of specific points of compliance opens the door for consideration of flux-based criteria for evaluating progress towards site objectives.

#### 4.3.2.4 ACLs

At sites where groundwater discharges into surface water, regulatory programs may have the flexibility to establish an ACL for groundwater that protects the surface water body. For screening criteria, some states require an assumption of no dilution, unless risk

**Waste Management Areas/Points of**

assessment demonstrates no risk to drinking water resources or benthic or pelagic organisms. At RCRA sites, the term ACL has a different meaning and is less prescriptive. ACLs can be used at RCRA sites if the alternate concentration does not pose a substantial risk to human health or environment (40 CFR 264.94). This determination is made after considering the potential adverse effects on the quality of groundwater and hydraulically connected surface water. Several important factors to consider include the following (40 CFR 264.94):

- 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
- permanence of potential adverse effects

**Compliance**

*Points of compliance were recently documented in a ROD at a Superfund site in Massachusetts (USEPA Region 1). A "Potentially Productive Aquifer" (potential drinking water source) was present within the site boundaries. Several source areas (prior areas of disposal) were located throughout the site and over the aquifer, making it nearly impossible to meet MCLs. The aquifer is also within an area that is zoned for industrial use, however, so it is highly unlikely that a drinking water well would ever be installed. USEPA and MassDEP agreed that the groundwater within site boundaries did not need to meet drinking water standards, but would do so at a "Point of Compliance" that was just beyond the site and beyond the source areas.*

*USEPA used the concept of Point of Compliance from the RCRA program (40 CFR 264.95)(USEPA 2004b), along with the designation of "Waste Management Unit" for the source areas. A boundary was drawn around all source areas making one Waste Management Area where MCLs do not have to be met. Groundwater must meet MCLs "at and beyond the waste management unit" (terminology from RCRA) at an established "point of compliance."*

Several sites have used surface water quality criteria in conjunction with dilution calculations, mixing zone modeling, fate and transport modeling, or a combination of these approaches to determine the numerical value of the ACL for groundwater. Note that Florida does not allow surface water dilution unless it is shown to be acceptable via an ecological risk assessment. Instead, compliance with surface water standards is to be met in groundwater prior to surface water recharge pursuant to 376.30701(2)(g)2, Florida Statutes. Other groundwater ACLs have been determined based on site-specific risk assessments (Deeb et al. 2011).

#### 4.3.2.5 Site Objectives (Site-Specific) Criteria

Several states allow for site-specific criteria to be adopted as site objectives. For example, Tennessee Code Title 68, Chapter 215-127(b) requires that all petroleum-contaminated sites in Tennessee be subject to soil and groundwater classification and site objectives established under the provisions of the Petroleum Underground Storage Tank Act. The Division of UST regulations established site objectives for the specific gasoline constituents as well as for various parameters based on the type of petroleum/petroleum product released. The initial screening limits are largely based on whether the site is in a drinking water or non-drinking-water area. According to the General Water Quality Criteria Rules Chapter 0400-40-03-.07(4)(b), all groundwater in Tennessee is considered general use groundwater. However, based on the Tennessee Petroleum UST Act (68-215-127 et seq.) and the exclusivity provisions provided in this Act, Section K of the Division of UST environmental assessment guidelines is used in determining if petroleum contamination constituents in groundwater are to be considered under the drinking water or nondrinking water classification. If the chemicals of concern exceed the non-drinking water standards, then establishing a site objective based on the Division of UST TGD-017 would be done prior to remediation activities.

#### 4.3.2.6 State Technical Impracticability Provisions

Several states have provisions similar to a TI waiver. During the state POC survey, the following 29 states indicated that TI determinations could be used to create alternative points of compliance: Alaska, Arkansas, California, Colorado, Connecticut, Washington DC, Delaware, Florida, Hawaii, Illinois, Iowa, Kentucky, Louisiana, Minnesota, Missouri, Montana, Nebraska, Nevada, New Jersey, New Mexico, North Carolina, Pennsylvania, Puerto Rico, Rhode Island, South Dakota, Texas, Utah's CERCLA program, Vermont, and Virginia. Utah indicated that TI determinations were not accepted under the UST/LUST program. Eleven other states (Alabama, Arizona, Georgia, Kansas, Maryland, Mississippi, New York, Oregon, South Carolina, Tennessee, and Wisconsin) indicated that TI determinations not accepted or were not applicable.

The New Jersey Department of Environmental Protection (NJDEP) Site Remediation Program recently published a guidance document to help responsible parties determine whether, when, and how to seek a TI determination for groundwater contamination (NJDEP 2013). A TI determination is accompanied by a Classification Exception Area (CEA) and a groundwater remedial action permit, per New Jersey Code of Regulations. The purpose of CEAs in New Jersey is to provide ICs for the use of groundwater in and around the areas where groundwater contamination exceeds applicable NJDEP Ground Water Quality Standards.

The Louisiana Administrative Code (Title 33, Part VI, Chapter 5, Section 509) states the following:

…potentially responsible parties may demonstrate in the CAS [Corrective Action Study] that compliance with the preliminary RECAP [Risk Evaluation/Corrective Action Program] standards is technically infeasible and may propose alternative preliminary RECAP standards. The development and evaluation of alternatives in the CAS shall reflect the scope and complexity of the site problems being addressed.

At a highly complex site in Louisiana, a provision was recently included for alternative remedial standards in a Cooperative Agreement between the Louisiana Department of Environmental Quality's Underground Storage Tank and Remediation Division and four petrochemical companies that were identified as responsible parties. Site complexities included extensive DNAPL-impacted areas and associated groundwater contamination. Groundwater was beneath and adjacent to a bayou and groundwater flow directions varied from northeast to south to southwest, depending on the location relative to the bayou and the depth within the subsurface. Residual-phase DNAPL was present to depths of 100 feet below ground surface or more. DNAPL had diffused into fine-grained units including interbedded laterally discontinuous layers of fine- and coarse-grained sediments. In lieu of meeting numerical site objectives, RCRA corrective action objectives were proposed for the site, as follows:

- reducing contaminant of concern (COC) mass and mass flux from the DNAPL-impacted zone to the extent practicable
- preventing plume expansion to the extent practicable
- preventing COC migration off-property at concentrations above numerical remediation standards
- cap maintenance
- ICs to prevent groundwater use and surface access
- using remedial actions that are sustainable and do not increase risks to human health, safety or the environment during or after their implementation

### 4.3.2.7 Partial Cleanups

Several states have state-specific considerations to move sites to closure following partial cleanups, primarily for petroleum sites. A partial cleanup is a remediation in which current conditions meet adequate standards to protect human health and the environment where groundwater contamination is either not present, or is present at concentrations where further groundwater remediation is unnecessary at this time. The term "partial cleanup" is most commonly used in state petroleum remediation programs. This term is also consistent with approaches adopted in state RCRA programs for short-term protection, interim objectives, and for sites that have not selected a final remedy. Acceptable site objectives for partial cleanup typically include the following:

- Protect human health and the environment.
- Control the source of release so as to reduce or eliminate, to the extent practicable, further releases of hazardous waste or hazardous constituents that may pose a threat to human health and the environment.
- Ensure that remaining contaminants are stable and not migrating beyond a designated regulatory boundary at concentrations of concern.

Contaminants may remain in the groundwater where exposure is unlikely (for example, beneath a parking structure or active gas station). Groundwater may remain contaminated where free-phase and dissolved-phase plumes are stable, the designated beneficial use of the groundwater is not impaired, and adverse effects (for example, vapor intrusion) to on-site or off-site structures are unlikely.

At least three states—Virginia, California, and Colorado—recently developed policy or guidance to move sites to closure following partial cleanups without achieving complete cleanup of soil or groundwater. For these sites, MCLs are not achieved and, in some cases, free-phase hydrocarbons are left in place. These states use similar approaches to achieving site objectives for partial cleanup.
Read More

***Virginia***

Virginia's Petroleum Program has long adopted a risk-based remediation approach, based on actual or likely exposure of existing human or environmental receptors. Groundwater is specifically a receptor of concern only where the groundwater is currently in use and that use results in exposure—for example, through a well, or migration to surface water (Virginia Department of Environmental Quality 2011):

> *Releases from tanks or other containment systems commonly result in contamination of ground water. Once the source of contamination has been neutralized or eliminated, decisions regarding the necessity of and extent to which ground water must be remediated should be based upon a combination of risks and applicable remedial technologies. Groundwater is not necessarily a receptor, but rather a medium through which constituents may migrate to a receptor.*

Section 5.5 of Virginia's technical guidance notes that "Section 9 VAC 25-580-270 of the UST Technical Regulation requires the removal of free product to the maximum extent practicable." The Virginia Department of Environmental Quality issued guidance in December 2011 to identify those cases in which continued attempts to reduce free product to an arbitrarily measured thickness (for example, 0.01 feet) is neither practicable or even necessary, or in which continued recovery of product beyond a practicable achievable thickness may provide little or no positive environmental protection.

***California***

In May 2012, the California State Water Board adopted a "Low-Threat Underground Storage Tank Case Closure Policy." The California State Water Board recognized that knowledge and experienced gained from 25 years of investigating and remediating petroleum storage tank sites had identified "conditions and characteristics…that, if met will generally ensure the protection of human health, safety and the environment." The California State Water Board established the following criteria (California State Water Board 2012) to identify low-threat cases:

- The unauthorized release is located within the service area of a public water system (thus it is unlikely that new water supply wells will be installed in developing areas and inadvertently contaminated).
- The unauthorized release consists only of petroleum.
- The unauthorized (primary) release from the UST system has been stopped.
- Free-phase product has been removed to the maximum extent practicable.
- A CSM has been developed that assesses the nature, extent, and mobility of the release.
- The secondary source has been removed to the extent practicable.
- Soil or groundwater has been tested for MTBE and results reported in accordance with Health and Safety Code section 25296.15
- Nuisance as defined by Water Code section 13050 does not exist at the site.

The policy further identified certain conditions for sites where a groundwater beneficial use does exist, but where closure may still be appropriate with groundwater contamination present. For example, there can be no free-phase product present. The criteria depend on distance of the release from supply wells, the size of the dissolved-phase plume, and the concentrations of petroleum contaminants within those plumes. Criteria for dissolved-phase concentrations range, depending on other conditions at the release site, but are significantly greater than MCLs (such as 1,000 to 3,000 micrograms per liter for benzene). Finally, the policy requires site managers to notify local water districts, planning authorities, and affected and neighboring property owners, as well as the public through a 60-day comment period.

***Colorado***

In October 2014, Colorado's Hazardous Materials and Waste Management Division published its "Policy for conditional closure of low threat sites with residual groundwater contamination" (CDPHE 2014b). The policy does not apply to regulated RCRA sites or NPL sites. Sites are granted conditional closure rather than no further action.

The Colorado policy applies at sites where the source area has been remediated to the extent practicable, plume size is stable or decreasing, and the concentrations are decreasing or are predicted to decrease in the absence of an engineered remedial system. In addition, the applicant must demonstrate that the remaining contaminant will not likely cause human or environmental exposures. ICs are typically required. The policy notes that the applicant is expected to demonstrate that the decreasing concentrations will achieve a remediation goal "within a reasonable time frame" after conditional closure, that ICs apply on site and off site if the plume has migrated beyond the property, and that reasonably anticipated future land use (and groundwater use) should be considered. Public notification is required to all property owners and occupiers within the plume.

Also in October 2014, Colorado's Division of Oil and Public Safety (OPS) published its Closure Criteria Guidance (CDPHE 2014a). The guidance notes that OPS will issue a no further action letter "once it has been demonstrated that the petroleum release is considered to be low risk to human health and the environment." OPS noted that a well-developed CSM greatly increases the chances of the state issuing a no further action letter. OPS developed two additional tiers for closure:

- Tier III closure can be granted when petroleum concentrations exceed Tier I risk-based screening levels beyond the site boundary, but not across an adjoining roadway. Impacted media must be remediated to achieve Tier I or II concentrations (described below) before a Tier III closure will be considered. OPS will formally notify the roadway owner and the Utility Notification Center of Colorado with the address details of all Tier III closure sites to protect workers from exposure during future construction or maintenance activities.
- A Tier IV closure can be granted at sites that no longer have storage tank systems and where dissolved-phase contamination has migrated to adjacent properties and is defined by downgradient point-of-compliance monitoring wells. Contaminant mass must first be removed to the maximum extent practicable. As with Tier III closures, OPS will formally notify the off-site property owners and record the closure address with the Utility Center.

These supplemented previously developed Tier I and Tier II closure criteria that had been in effect for many years:

- Tier I allows closure if all concentrations in soil and groundwater are below Tier I risk-based screening levels.
- Tier II allows closure of sites with concentrations above Tier I levels, but where site-specific modeling can be used to show that Tier I levels will be achieved at an on-site point of compliance closer to the release than the nearest point of exposure. LNAPLs must be removed to the maximum extent practicable.

### 4.3.3 Setting Site Objectives for Federal Facilities Remediation Programs

DOD and DOE have lead agency authority for cleanup conducted under CERCLA authority per Executive Order 12580 as amended. The process for setting site objectives at RCRA and CERCLA federal facilities follows RCRA and CERCLA guidance. Case studies of federal sites were described in an ESTCP publication on alternative endpoints (Deeb et al. 2011). As of March 1, 2016, these programs include 157 federal NPL sites and 4 more proposed NPL sites (USEPA 2016e). There are approximately 200 RCRA Corrective Action sites at federal facilities (USEPA 2013d).

Federal facilities also have sites under the Installation Restoration Program to address contamination at active installations, Formerly Used Defense Sites (FUDS) and Base Realignment and Closure (BRAC) locations. These projects advance the goal of cleaning up sites so that they are safe for human health and the environment, as well as returning these properties to productive reuse. Per the Base Realignment and Closure Act of 1988 and the Defense Base Closure and Realignment Act of 1990, DOD must comply with a variety of environmental laws, including RCRA and CERCLA. NEPA also has requirements that must be met when DOD transfers property. In 2001, DOD also established a Military Munitions Response Program (MMRP) to address sites with unexploded ordnance, discarded military munitions, and munitions constituents (MC).

#### RMA: Case Study of Remediation Oversight at Federal Facilities

*Rocky Mountain Arsenal (RMA), Colorado, has a long history of regulatory and legal involvement. A Supreme Court ruling on RMA recognized the state's newly delegated RCRA authority to enforce state environmental laws at federal facilities. Currently, USEPA, the state of Colorado, and the Tri-County Health Department provide ongoing oversight of RMA as it transitions from active remediation to long-term O&M. Following multiple interim response actions focused on contaminant removal, remediation, and containment, the selected final remedy at RMA addresses multiple contaminants of concern in 15 separate plumes, with institutional controls and land reuse as a wildlife refuge. More details are provided in the full case study.*

## 4.4 Develop Interim Objectives and an Adaptive Remedial Strategy

Developing interim objectives as part of an adaptive site strategy includes selecting the remedial strategy (which may be comprised of multiple phases and technologies), identifying components of each remedial approach, setting interim objectives, and documenting the selected remedial strategy. Interim objectives include short-term or technology-specific interim objectives and metrics to guide progress towards site objectives. These topics are usually considered during remedy planning or when the existing remedial strategy performance is not on track to meet interim objectives despite optimization.

The CSM should be up-to-date prior to establishing interim objectives, because inaccuracies in the CSM can affect technology implementation and performance monitoring. Original objectives may need to be revised based on new information. The concepts of applying interim objectives, optimization activities, and assessing performance relative to expectations are all aspects of adaptive site management (Figure 1) and can be incorporated into potential remedial approaches. Additional resources for decision makers in developing interim objectives as part of potential remedial approaches include USEPA guidance for optimization and phased remediation (USEPA 1990, 1992, 2004c); see also CLU-IN optimization guidance, USEPA guidance for documenting remedy changes (for example, USEPA 1990, 1999a), and the ITRC IDSS guidance (ITRC 2011b).

A comparative evaluation of potential remedial approaches can be conducted using the evaluation criteria that are appropriate for the regulatory agency overseeing site remediation (for example, CERCLA nine criteria, or analogous criteria under RCRA or other state-led programs). For complex sites, this evaluation may incorporate the following considerations:

- how each potential remedial approach addresses site complexity issues
- confidence in each potential remedial approach in terms of implementation and control of exposure during the remediation time frame
- for phased approaches, whether the first phase of the potential remedial approach could hinder use of other approaches later
- whether the potential remedial approach is particularly well suited to later modifications or synergistic with other technologies/approaches
- the type of information that could be gained by implementing the potential remedial approach and whether that information could be used to improve the CSM and better inform future remediation decision-making
- the ability to adjust and optimize the remedial approach based on performance data
- the robustness of remedial strategy design such as clear definitions of interim objectives, performance metrics, and ability to collect data that can be used to monitor performance
- whether any predictive analysis of remedy performance is needed to support the selection of the remedial approach or provide a baseline for evaluating performance after implementation (see tools in Appendix B).

The comparative evaluation of potential remediation strategies typically uses some form of weighting that creates a combined evaluation for each potential remedial approach based on how well the potential remedial approach meets the individual evaluation criteria. Following this comparative evaluation and discussion of considerations outlined in pertinent regulatory guidance, one of the potential remedial approaches is typically recommended and selected for implementation. Recommended strategies are subject to modifications based on input from the public and regulators following the remedy selection process mandated by the regulatory remediation program.

To determine the most appropriate remediation strategy, the components needed to achieve the strategy must be identified. The term “components” refers to remediation technologies, containment methods, institutional controls, and any other technical or management approaches that can be used in combination at a site in order to address the site objectives.

Potential remedy components are listed in Table 10. Key resources for information about these components include the USEPA CLU-IN website (USEPA 2017b), the Federal Remediation Technology Roundtable (FRTR 2016), the Naval Facilities Engineering Command website (NAVFAC), and the Center for Public Environmental Oversight website (CPEO 2010).

**Table 10. Examples of potential remedy components**

| Options | Description and References |
|---|---|
| In Situ Biological Treatment | Applying an amendment into the aquifer to bioremediate a targeted volume of the aquifer (ITRC 2002, 2008b, Parsons 2004, USEPA 2000, DOE 2002a) |
| In Situ Chemical Treatment | Applying an amendment into the aquifer to chemically remediate a targeted volume of the aquifer. General categories of treatment include in situ chemical oxidation (ITRC 2005, USEPA 2012c, 2006a), and in situ chemical reduction. |

| Options | Description and References |
| --- | --- |
| Thermal Treatment | Applying thermal energy to extract and/or degrade contaminants in an aquifer (USEPA 2004d, 2012c, USACE 2014, ESTCP 2010) |
| Removal | Excavating material to remove contaminants from the subsurface (see general sources, such as CLU-IN (USEPA 2017b) |
| Capping | Placing a cover over contaminated soils or other material to prevent or reduce contact and exposure and, in some cases, reduce infiltration and contaminant leaching to groundwater (see general sources, such as CLU-IN (USEPA 2017b)) |
| Stabilization and/or solidification | Treatment technology for contaminated soils to reduce contaminant mobility and leaching potential, encapsulate contaminants and, in some cases, strengthen soil structural properties (see general sources, such as CLU-IN (USEPA 2017b)) |
| Enhanced Extraction | Applying an amendment (such as a surfactant) to enhance the ability to extract contaminants from an aquifer (see general sources, such as CLU-IN (USEPA 2017b)) |
| Soil Vapor Extraction | Extracting contaminated vapors and treating them in aboveground systems (see general sources, such as CLU-IN (USEPA 2017b)) |
| Air Sparging | Injection of air or oxygen into the saturated zone to flush contaminants into the vadose zone. Often used in combination with soil vapor extraction (see general sources, such as CLU-IN (USEPA 2017b)) |
| Source Flux Reduction | Applying remediation or containment to reduce the flux of contaminants moving from the source zone to the plume (ITRC 2008b, 2010b, Looney et al. 2006) |
| Contaminant Mass Flux Reduction | Applying remediation or containment to reduce the flux of contaminants moving downgradient from a targeted zone (ITRC 2008b, 2010b) |
| P&T Systems | Extracting contaminated groundwater with treatment of the contaminants (USEPA 1996, 1997a, 2012c) |
| Permeable Reactive Barriers | Placing reactive materials in a portion of the aquifer that are retained and treat contaminants as the contaminants flow through this zone (ITRC 1999b, c, 2011c) |
| Enhanced Attenuation | Applying an amendment to an aquifer to enhance an attenuation process in a way that enables MNA to meet site objectives (ITRC 2008a, Early et al. 2006) |
| MNA | Relying on natural processes to attenuate contamination with monitoring to verify processes are working to meet site objectives (ITRC 1999a, 2010a, USEPA 1998b, 2007a, b, 2010b, 2012c, Wiedemeier et al. 1999) |
| Hydraulic Containment Pumping | Extracting and/or injecting groundwater to manipulate aquifer hydraulic conditions in a way that helps prevent contaminant migration (see general sources such as CLU-IN (USEPA 2017b), and P&T information) |
| Passive Hydraulic Barrier | Installing impermeable materials in the subsurface to alter groundwater flow patterns. Phytoremediation may also be used as a passive hydraulic barrier or as a method to lower the groundwater table (see general sources such as CLU-IN (USEPA 2017b)). |
| Discharge Zone Treatment | Applying remediation techniques within or adjacent to a groundwater discharge to protect receptors at the discharge (see general sources such as CLU-IN (USEPA 2017b)) |
| Vapor Intrusion Mitigation | Applying techniques that protect buildings from contaminated vapors (ITRC 2007b, c) |
| Institutional Controls | Applying administrative restrictions to prevent contaminant exposure or other actions that would negatively impact contamination (USEPA 1997a, 2009b, 2010a, ITRC 2016b) |
| Bifurcation | Administratively dividing a site to facilitate better implementation of a remedial approach |
| Alternative Water Supply | Providing water from another source to eliminate the need to use a specified portion of an aquifer |

A complex site may be divided into multiple segments (for instance, source and plume, sands and clays, on-site and off-site contamination) and components of the remedial approach can be identified for each segment. Table 11 provides an example of how options can be identified for each component of the remedial approach and site segment. Table 11 also identifies the potential remedy components for a hypothetical site and illustrates how a similar site-specific table could be used.

**Table 11. Potential remedy components identified at a hypothetical site**

| Site Objectives | Potential Remedy Components | |
|---|---|---|
| | **Source** | **Plume** |
| Remediate contamination | In situ treatment<br>Enhanced extraction<br>Thermal treatment | In situ treatment<br>Enhanced attenuation<br>MNA |
| Control migration | Source flux reduction<br>Enhanced extraction<br>Permeable reactive barrier | In situ treatment<br>Enhanced attenuation<br>MNA |
| Prevent exposure | Engineering controls, Fencing, Institutional controls,<br>Alternative water supply | Institutional controls<br>Alternative water supply |

When compiling candidate remediation approaches, it may be useful to develop a conceptual design for each option to describe how it could be configured and to evaluate the predicted performance and viability as part of an adaptive remedial strategy (see tools in Appendix B). Candidate remedial approaches can be developed using remedy components identified for specific site segment. When assembling remedy components into viable candidate remedial approaches, it may be useful to vet each remedial approach by considering its value in advancing the site towards achieving its objectives and managing contamination during that time.

## Case Study: Combined Remedy at Paducah Gaseous Diffusion Plant

*The Paducah Gaseous Diffusion plant (PGDP) employed a "combined remedy" approach to address TCE and Technetium 99 plumes in low- permeability, fine-grained sediments as well as a deeper regional aquifer. Proven and innovative technologies were selected as an interim action to achieve source remediation, hydraulic control, and natural attenuation. Technologies include electro-thermal heating (known as the Lasagna process), electrical resistive heating (ERH) with SVE, groundwater extraction and treatment and optimization over time, and MNA. See the full case study for more details.*

Viable remedial approaches should include provisions to be managed and adapted over time to meet the remediation challenges posed by site complexities. Interim objectives can then be established associated with remedy management and adaptation. Interim objectives should be selected to guide the specific actions taken to achieve short-term and long-term progress towards the site objectives. Interim objectives are specific, measurable, attainable, relevant, and time-bound (SMART) objectives and are further described in the IDSS guidance (ITRC 2011b). According to ITRC (2011b), "functional objectives (interim objectives) should have relatively short time frames–years to less than one generation– to encourage accountability for specific actions and to make it easier to measure progress towards the objectives."

As shown in Figure 1, this process of remedy evaluation may be repeated as appropriate as the remedy progresses, until long-term site objectives are reached. Note that optimization is not typically the focus of adaptive site management, but is often appropriate as part of the adaptive site management process.

## 4.5 Document Interim Objectives and the Remedial Approach

The selected remedial approach is documented by describing each component of the remedial approach, articulating how the components of the remedial approach work together, setting interim objectives associated with each component of the remedial approach, and listing performance metrics that can guide evaluations of remediation progress. Documentation should clearly state how the performance of each component will be evaluated to meet interim objectives (see tools in Appendix B). This type of documentation describing how the remedial approach will be implemented can facilitate the transition to remedy design, implementation, and long-term management. Documentation is subject to the requirements of the site's regulatory program.

When documenting the interim objectives and remedial approach, consider ways to incorporate flexibility into the remedial system design to provide opportunities to optimize or enhance the system performance without special approval for significant system modifications. For example, flexibility to redirect or adjust extraction and injection rates at various monitoring wells can maintain an effective dynamic groundwater recirculation program.

The remedial approach may include adaptive design elements. For example, a remedial strategy may plan to use multiple technologies in combination or sequentially, guided by technology performance. If the remedial strategy incorporates multiple technologies, documentation can also include a site-specific process and metrics to evaluate when and how to transition from one technology to the next. For example, CERCLA decision documents can specify a contingency remedy as part of the final remedy with guidelines or criteria on when the contingency remedy would be considered for implementation. More detail on establishing performance metrics and evaluating performance is provided in this guidance, along with details on strategy adaptation guided by performance.

### 4.5.1 Transition Assessment

When remediation strategies include a transition from one technology to another, NRC guidance NRC (2013) may offer potentially useful concepts regarding remedy transition and documentation of decisions. The NRC document describes the concept of a transition assessment, which NRC developed after it concluded that the decision-making process of existing remediation programs should more fully reflect the fact that drinking water standards will not be attained for decades at most complex sites. NRC's alternative decision-making approach includes the explicit charting of risk reduction over time. A transition assessment would be considered at sites where the effectiveness of remediation reaches a point of diminishing returns (evaluated on a basis of future risk reduction) prior to reaching site objectives, and optimization has been exhausted. In particular, NRC proposed that a key trigger for a transition assessment would be asymptotic behavior of plume conditions or remedy performance. USEPA guidance on optimization and phased remediation (USEPA 1990, 1992, 2004c); see also CLU-IN optimization guidance) and documenting remedy changes (for example, USEPA 1990, 1999a) should also be considered, although USEPA does not use the term "transition assessment."

Upon reaching asymptotic performance, NRC (2013) suggests that transition to MNA or some other management approach be considered using this transition assessment. The transition assessment is similar to a focused feasibility study (FFS) and considers alternatives for site management—choosing a new remedy or transitioning to long-term management or other alternative site objectives (Deeb et al. 2011). The transition assessment concept is consistent with the adaptive site management concept developed in "Environmental Cleanup at Navy Facilities: Adaptive Site Management" (NRC 2003), but focuses specifically on complex sites where long-term management will be a likely component of any remedy completion strategy.

The NRC 2013 report did not present a specific process for conducting a transition assessment. Based on the supporting discussion in the NRC report, a transition assessment should include an assessment of site complexities and the limitations they impose on remediation, such as asymptotic plume behavior. Then, the transition assessment would identify and evaluate options for remediation strategies to make progress toward site objectives, recognizing that a long remediation time frame will be required. Strategies would be expected to include the following:

- control of contaminant exposure pathways during the remediation process
- mitigation of plume or source expansion, especially to maintain contamination within an area where institutional or engineering controls to limit exposure can be applied during remediation
- an appropriate approach to contaminant reduction, realizing that contaminant reduction may be difficult or require a long time
- an implementation approach using adaptive site management to address the uncertainties inherent in the site

complexities that lead to remediation difficulties

**Asymptotic Behavior and Performance Metrics**

*Asymptotic behavior is a key concept for evaluating remediation performance. Remediation metrics such as mass removal versus time or concentration versus time curves are often evaluated to see if these metrics are approaching an asymptote.*

*Technology performance at complex sites may reach asymptotic behavior, and interim objectives and performance metrics can be based on this behavior. For example, a hypothetical site may use asymptotic performance as an interim objective and state that interim objective as follows: "Begin groundwater restoration at source area within three years and continue O&M until* ***asymptotic*** *performance is reached." In 2013, the NRC suggested that asymptotic behavior applied to plume behavior (for example, groundwater concentration versus time) or remedy performance (mass removal versus time) could be a key trigger for conducting a transition assessment.*

*While asymptotes are fundamental to evaluating remediation performance, one case study highlights that merely reaching an asymptote is not sufficient to suspend remediation activities. The MEW site in California experienced a 65% reduction in mass removal over a 12-year period, but the decrease was not indicative of "asymptotic conditions" nor did it indicate that the remedy is less effective than anticipated in the ROD.*

*In general, asymptotic behavior in performance metrics is less meaningful at sites where the overall goal of the remediation system is containment or control. But at sites where the key metrics are mass removal, mass removal to reduce the remediation timeframe, or concentration reduction, then having these metrics reach asymptotic behavior is an important trigger for considering optimization or a potential transition.*

NRC's transition assessment is relevant to complex sites because these sites may not achieve site objectives in a reasonable time frame, and remedial efforts may eventually reach the asymptotic performance considered by the NRC as indicating a need for a transition assessment. While not specifically mentioned by NRC, monitoring after a remedy is turned off can detect aquifer rebound dynamics and clarify fate and transport mechanisms that can improve the CSM and subsequent remedies.

### 4.5.2 Maintaining Protectiveness and Preventing Exposure over Long Time Frames (ICs and LUCs)

Documentation of interim objectives and the remedial approach should describe how protectiveness of human health and environment will be maintained. This element of a remedy is common to CERCLA, RCRA, and other state and federal regulatory remediation programs. This protection is especially important at complex sites, where long time frames are required for remediation. Including protective elements such as ICs and LUCs as part of the remedy approach and these elements should be integrated into a long-term management approach.

State survey results highlighted that ICs and LUCs are commonly accepted components of remedial strategies to prevent exposure until groundwater standards are met. Examples of ICs and LUCs include deed restrictions (with landowner concurrence), fish advisories, and fencing. However, ICs and LUCs are rarely approved as stand-alone remediation strategies and are not a driver for changing site objectives or a substitute for remediation. Maintaining and monitoring ICs and LUCs over long time frames are addressed when planning for long-term management of a complex site.

In *Long Term Contaminant Management Using Institutional Controls* (ITRC 2016b), ITRC has identified critical elements of an effective ICs management program based on successes from established state and federal agency programs, along with other available innovative tools. In developing this guidance, ITRC surveyed state programs and determined what kinds of IC programs are in place across the country, what makes these programs effective, and what common issues affect the durability of ICs. This information can assist decision makers with developing, improving, and stewarding ICs over long time frames. In order to best apply ICs, ITRC also developed a tool to help create a long-term ICs stewardship plan tailored to a specific site (ITRC 2016b). This guidance is relevant to state, federal, and tribal agencies, municipal and local government, private and public/governmental responsible or obligated parties (OPs), current site owners and operator, environmental consultants, and prospective purchasers of property and real estate agents. Additionally, stakeholders who have an interest in a property will find this guidance helpful in understanding the elements required to manage ICs throughout the life cycle

(ITRC 2016b).

Because the IC guidance focuses on long-term management of ICs that are already in place, it does not address the details of selecting ICs. Properly selecting and implementing ICs, however, is essential for the long-term durability and effectiveness of a remedy. The guidance summarizes some of the key components that should be considered when choosing ICs, including decision-making aspects of IC implementation and planning that can affect the long-term durability of an IC, with links to additional guidance on IC selection.

# 5. Long-Term Management

Long-term management of complex sites begins with remedial design and includes all postconstruction phases of remediation management, monitoring, and evaluation of remedy protectiveness. At complex sites, long-term management may last several decades; projected time frames to meet site objectives can sometimes exceed 100 years. These long time frames increase uncertainties. For example, engineered remedy components can fail or underperform over time unless they are routinely maintained and modified. Systems designed for initial mass loading may not perform effectively if the mass loading changes over time. Furthermore, long-term performance and potential replacement of caps, slurry walls, and other containment technologies are assessed by monitoring and periodic evaluation of these components.

An adaptive site management approach can identify and account for these uncertainties over a project life cycle using a long-term management plan. This approach informs decision makers of remedy progress, expedites remedy reevaluations, and eases transitions to alternative remedies or contingency actions. As part of the adaptive site management of a complex site, decisions need to be fully scoped as early in the decision-making process as possible. These decisions and other key project evaluations are maintained in a long-term management plan, which is a living document that is revised based on periodic performance evaluations. Some states, including New York, require a long-term management plan in the environmental review process of Brownfield remediation sites. For CERCLA NPL sites, long-term management and its related costs and risks may be first considered at the FS stage and then further developed throughout the remedial design/remedial action phase. A long-term management plan can help achieve goals of protecting human health and the environment and making progress toward the site objectives.

Because adaptive site management repeats the remediation potential assessment and remedy evaluation steps, decisions are based on the current CSM (USEPA 2011a) as well as the state of science and practice. As part of this iterative process, additional site characterization may also be performed under the long-term management phase. For example, additional site characterization may be performed if at any time data show unexplainable gaps, if contaminant concentrations are not decreasing as anticipated, or if new contamination is identified that requires additional investigation. Changing site conditions are charted and documented. These changes are evaluated to determine their influence on the remedy effectiveness, which is reflected in the periodic performance evaluations. The effects of ICs, such as deed restrictions that limit exposure to residual contamination, are also included in periodic performance evaluations.

Figure 5 summarizes the long-term management phase of the adaptive site management process. Once the long-term management plan is developed, site operations consist of the following steps:

- implementing the remedy
- monitoring and conducting scheduled periodic evaluations to assess protectiveness and remedy progress
- deciding to evaluate, optimize, modify, or transition the remedial approach if the remedy is no longer protective or if remedial progress is inadequate

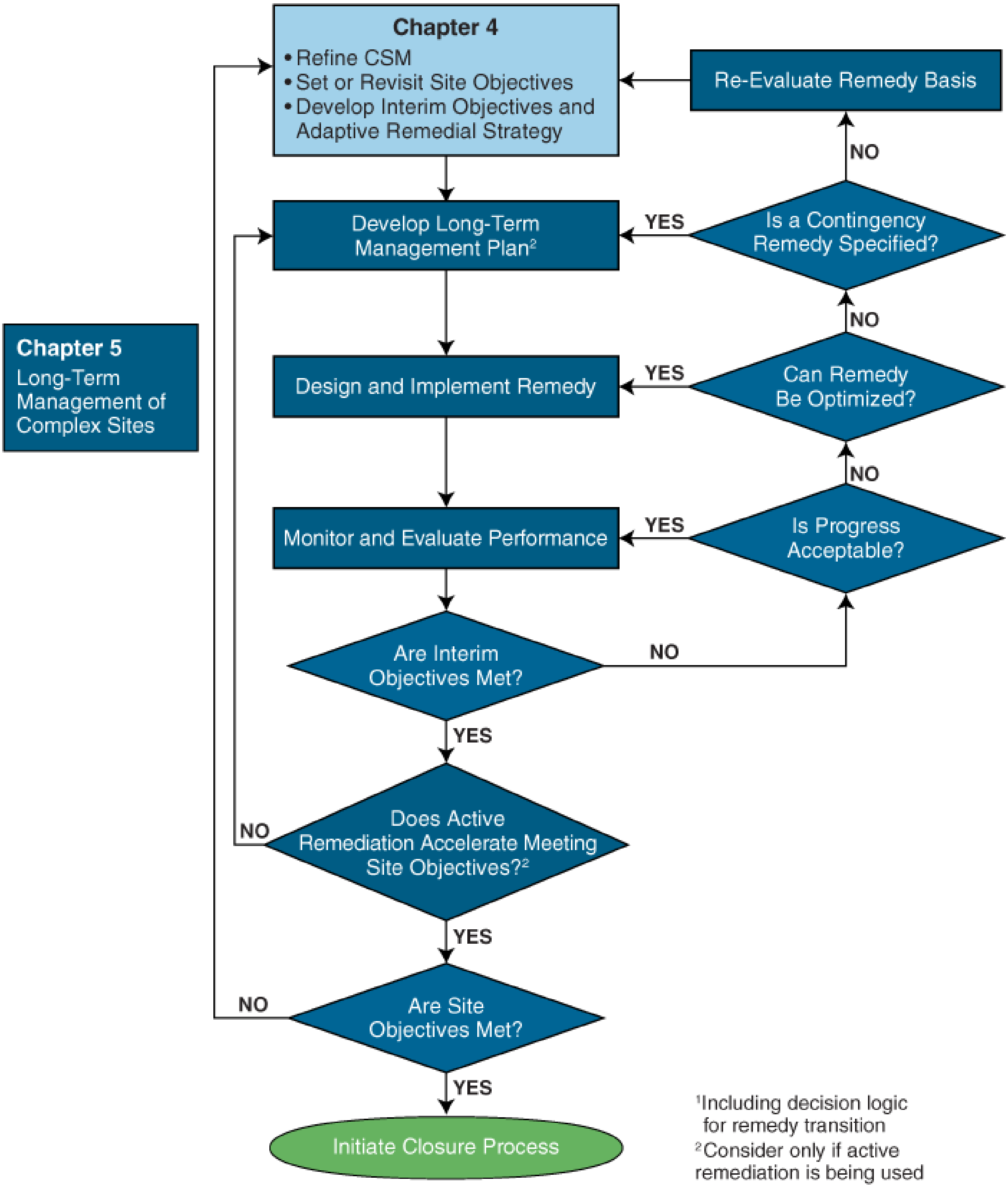



**Figure 5. Long-term management flowchart.**

A long-term management plan includes the following sections:

- remedy components
- basis for predicting performance and decision criteria
    - performance baseline
    - performance model
    - performance metrics
    - interim objectives
    - decision criteria

- periodic evaluations (may supplement Five-Year Review reports at CERCLA sites).
- decision logic for remedy evaluation, optimization, modification, or transition
- completion strategy
- project risks and uncertainty

The planning process includes developing metrics for how remedy performance will be measured and evaluated, metrics for each major remedy component, and metrics for each interim objective. Planners can collaborate and agree on the interim objectives and performance metrics, then adapt the remedial design accordingly. Planning also includes monitoring and administrative controls of the site-specific infrastructure management. Using the DQO process, monitoring data are reviewed to evaluate system performance versus performance metrics and progress towards meeting interim or site objectives for the duration of remedial activities. Scheduled periodic evaluations compare expected to actual progress toward meeting interim or site objectives and reflect changes in the remedial strategy, site knowledge (such as the discovery of previously unknown contamination), or other changing conditions (such as changes in regulations).

## 5.1 Remedy Components

Remedy components can be implemented singly or in series (such as treatment trains) for treating the site as a whole or targeting specified segments. The long-term management plan decision logic describes any phased remedy components that focus on plume segments, such as the source area or an off-property groundwater plume. Reductions in contaminant mass or contaminant concentrations at compliance locations could be another area of focus. For example, the decision logic could consider a pilot study or interim action to reduce the extent of off-site groundwater migration.

The plan also includes the projected time frame required to accomplish the interim objectives for each major remedy component for the selected remedial approach. The plan should reference the site decision document, if needed, for a full description of the remedial strategy, site objectives, and possibly the interim objectives and corresponding performance metrics. This level of detail provides the basis for establishing effective monitoring program schedules and effective frequency of periodic evaluations. The planning process may involve changes in the remedy and thus be shared with stakeholders as part of the site's communication strategy. More details regarding the elements and process of developing a long-term strategy for the remedial approach and selection of specific remedy components are included in this guidance.

Both engineered and administrative remedy components are described in the decision document and listed in the long-term management plan, along with corresponding interim objectives and performance metrics. The plan describes how specific remedy components will reduce risks to human health or the environment, achieve protectiveness, and control direct exposure to contamination and migration to potential receptors (such as discharge of contaminated groundwater to surface water, or VI), as well as prevent migration that increases the volume of contamination.

Engineered remedy components include technologies designed to remove or degrade contaminants or prevent/contain subsurface contaminant movement. Examples of active engineered remedies include source excavation, soil vapor extraction, in situ treatment (such as chemical oxidation, bioremediation, or thermal treatment), and P&T systems to reduce contaminant mass or affect migration control. Passive engineered remedies can include landfill caps, impermeable barriers for containment, and MNA. Although administrative remedies (such as ICs) and passive engineered components do not entail day-to-day operation, they require periodic inspections and maintenance, monitoring, and administrative oversight, all of which are documented in the plan.

### 5.1.1 ICs

ICs are frequently used for long-term management of complex sites. ICs are nonengineered methods that include any type of physical, legal, or administrative mechanism that restricts the use of, or limits access to, real property to prevent or reduce risks to human health and the environment (USEPA 2010a). ICs are part of a remedial action, can be short-term or long-term, and are often placed in perpetuity. At complex sites, ICs may be useful in returning parts of a site to some form of beneficial reuse (for example, recreational use limitations). ICs may be used when contamination is first discovered, when remedies are ongoing, and when residual contamination remains on site at a level that does not allow for unrestricted future land use after remediation. ICs and other LUCs, such as fencing and security guards, are typically meant to supplement engineering controls and are rarely stand-alone remedies (USEPA 2010a). These controls will be clearly specified in the appropriate decision document.

At sites where ICs are part of environmental remediation activities, the use restriction needs to be clearly defined, documented, and enforceable. Implementing use restrictions through established real property and land use management mechanisms provides a means to ensure that the restrictions remain effective. ICs can be reviewed for compliance with legislation in individual states, local agencies requirements, and property law, as well as with remediation requirements. ICs can be implemented, maintained, and monitored at the local level whenever possible. ICs can be included in the appropriate documents such as real property records, maps, and land use and related planning documents. The following are the primary components to incorporate into a site IC management plan:

1. Establish appropriate mechanisms to manage ICs and incorporate ICs into the existing land use management processes. ICs are designed to prevent contact with contaminated media under current and future use. ICs also inform site visitors of locations of contamination and remedial system, as well as establish restrictions that

prevent activities on site from damaging remedial components.
2. Develop a document that defines the responsibilities of all parties involved in implementing, maintaining, and monitoring the ICs, and document or annotate a reference to the comprehensive plan.
3. Identify contingency actions if an IC is breached that include appropriate corrective measures that will be taken and notifications made to regulators and other stakeholders.
4. Record an environmental notice of contamination or place a location on a state IC registry or other similar location if available.
5. Budget for the necessary funding to implement, maintain, and monitor ICs.

If the integrity of the ICs cannot be maintained, then the IC will be modified or terminated and other remedy components modified as needed to ensure the remedy is protective of human health and the environment. If an IC is terminated, then it also will be removed from the mechanisms that recorded its existence (such as the Recorder of Deeds Office or master planning maps). Stakeholders and property owners affected by the ICs are involved in all restrictions placed on other properties. The IC register or other mechanism can be used to notify potential buyers of ICs when a property is listed for sale and notify the state when a property is sold.

### 5.1.2 Other Maintenance and Monitoring Considerations

A long-term management plan accounts for the useful life span of slurry walls, barriers, caps, and other remedial system components. Many elements of these systems undergo preventive maintenance and repairs or require periodic replacement. Monitoring wells are periodically redeveloped as well.

Maintenance activities for remedial strategies may include the following:

- O&M requirements for engineered remedy components for contaminated groundwater or soil are documented in the site O&M plan. The O&M plan specifies the system description, including but not limited to: facility operation and control records/reporting, contingency or emergency operation and response, utilities, and roles and responsibilities. Migration control/containment systems, such as engineered landfill caps, may need periodic repair. For engineered containment barriers (such as slurry walls), the projected expected life cycle can be validated by monitoring. For example, the slurry walls built at the MEW site to contain the most highly contaminated groundwater showed signs of leaking after about 30 years. Some of these slurry walls required extra pumping to maintain the required containment.
- Maintenance and repairs may be needed for IC components (such as signs and fences) or irrigation systems. Cover maintenance may include cutting vegetation or selectively applying fertilizer, herbicides, or rodent control. Additionally, the knowledge, data, and information required by the IC needs to be kept current.
- Long-term monitoring systems also have O&M requirements. Activities may include: maintaining electrical supplies; collecting multimedia samples; and redeveloping, repairing, and replacing monitoring wells, pumps, sensors, and other monitoring equipment. An O&M plan, similar to that required for engineered remedy components, can also be prepared for monitoring activities.

Groundwater monitoring conducted during long-term management (for example, before site objectives are achieved) is either associated with compliance or performance. Both compliance and performance monitoring are likely to improve by refreshing the DQOs and long-term management plan so that the right type, quantity, and quality of data are generated at the right time with zero data surplus.

#### Case Study: Passive Remediation Approach for Long-Term Monitoring at NWIRP McGregor

*To address perchlorate in groundwater at the NWIRP McGregor site in 2002, the Navy used an innovative passive remediation approach in two drainage basins with low concentrations of perchlorate. Segmented three-foot-wide trenches were keyed into the non-water-bearing zone and filled with a mixture of gravel, wood chips, and mushroom compost soaked in vegetable oil. Piping in the trench allowed emulsified oil to be injected to rejuvenate the biowall. In total, 35 biowalls were constructed in up to three staggered lines (depending on the topography) totaling 11,200 feet of biowalls. The perchlorate plume footprint has receded over time. Biowall performance is also assessed by semiannual sampling from biowall ports and analysis of total organic carbon, nitrate, methane, and perchlorate. Carbon is replenished if needed, in response to these data. Long-term monitoring optimization over time has reduced* *the number of site wells from 800 to approximately 100, with most sampled annually. More case study details are provided in the full case study.*

## 5.2 Basis for Predicting Performance and Decision Criteria

The long-term management plan documents the predicted performance of each remedy component. The planning process identifies how performance will be assessed regarding the attainment of the interim objectives and ultimately site objectives (for example, rate of decreasing contaminant concentrations, plume stability, plume capture, or mitigation of VI). Monitoring data from startup or the initial operation of remedial systems may be used as the basis for performance predictions. Initial site evaluations that determine baseline site conditions include: estimations of contaminant mass, measurements of contaminant level, the rate of contaminant migration, and the rate of contaminant attenuation.

Predicted remedy performance is documented in the long-term management plan as a baseline for evaluating actual remedy performance. The plan clearly identifies the interim objectives for making long-term management decisions, including the DQOs for future decision making. The processes to be incorporated into the long-term management plan include identifying key remedy decisions, as well as the nature, type, and quality of data required to support decisions. Properly applied, the DQO process and long-term management plan guide the collection of the right data at the right time with no data gaps and no surplus data. With this data, remedial decisions and actions drive the remediation to the desired endpoint at maximum efficiency and effectiveness—which also minimizes the project costs. The following sections describe the performance baseline, performance models, performance metrics, interim objectives and decision criteria in more detail. An example is also provided.

### 5.2.1 Performance Baseline

Baseline conditions are established and documented prior to remediation system operations. Baseline data can be used for a trend assessment of contaminant concentrations at selected monitoring locations. Baseline conditions also provide a basis for predicting performance data for key remedy components. This assessment provides a basis for evaluating remedy performance and progress using the established performance data and corresponding interim objectives and metrics. A fully developed performance model includes the technical rationale leading from the baseline conditions to reaching the interim objectives, as described in the long-term management plan.

### 5.2.2 Performance Models

A performance model is one way to develop transparent and comprehensive decision logic for assessing remedial progress. Precise, quantitative performance models may be developed as soon as site-specific data are available to support targeted characterization activities. Site information incorporated in the performance model and relevant performance metrics inform both system operation and remediation decisions.

A performance model is a predictive graphic model or other predictive software model or tool (such as a statistical application or numeric/analytical software models) that describes the expected course of the remedial approach. Performance models are used to project future progress towards the attainment of the interim and site objectives. Performance models and prediction tools demonstrate, quantify, track, and support remedy progress. A performance model can be prepared for each major remedy component.

Performance models are often used to project overall performance and time frames to achieve the interim or site objectives. Depending on the site, projections for each of the primary remedy components are often broken out by area or target zone (for example, the source area may have a separate performance model from the dissolved-phase plume) and potentially by COCs. The performance model documentation reflects the established decision criteria and interim and site objectives documented in the long-term management plan.

Performance metrics and corresponding interim objectives may be updated during periodic evaluations as additional data are collected and trend analyses performed. The performance modeling may be repeated as new data become available. Models can also be recalibrated using recent data. The outcomes for the repeat runs of the performance model can be compared to earlier outcomes and gross discrepancies identified and reconciled (with reasons for the discrepancies identified). Once the outcomes and discrepancies have been supported or reconciled, criteria outlined in the long-term management plan may also include a CSM reassessment, with the flexibility to design and implement a contingency action (such as a change in remedy component) or remedial approach.

Early in site remediation (FS or remedial design phases), the performance model may be conceptual, indicating how concentrations and mass are reduced over time or how other factors that drive cost and time will be reduced. If a quantitative model is not provided, the long-term management plan can indicate the degree to which the selected approach will reduce the time required to achieve the interim or site objectives, if at all. For those sites which do not have baselines, the performance model can be refined and interim objectives and projected time frame milestones quantified during the development of the long-term management plan. The long-term management plan can provide sufficient information to explain the basis for the model. Previous ITRC guidance may be useful in developing performance models and associated performance metrics. For example, the ITRC IDSS document includes a spreadsheet tool for estimating contaminant mass based on the 14-compartment model which may be appropriate at complex sites with DNAPL (ITRC 2015b).

### 5.2.3 Performance Metrics

A performance metric provides a specific measurable indicator of remedy performance and can be measured and evaluated to distinguish successful remedial progress from insufficient progress. The "USEPA Groundwater Remedy Completion Strategy" (USEPA 2014b) describes performance metrics as follows: "site-specific remedy performance criteria, hydrologic parameters or contaminant concentration trends typically used to evaluate remedy performance and measure progress (e.g., effluent discharge concentrations, contaminant concentration trends in a monitoring well)." Examples of performance metrics include percent mass reduction, mass flux reduction, removal rate/efficiency, concentration reductions, reduction in groundwater plume footprint, and volume of soil removal. For complex sites, performance metrics can be used as a measurement of remedy progress over shorter time increments.

Selected performance metrics demonstrate achievement of interim and site objectives, not merely progress towards meeting them. For example, a performance metric of "volume of soil removed" may not be sufficient to demonstrate achievement; many cubic yards of soil could be removed without meeting the soil site objectives. At many groundwater sites, the most critical performance metrics for demonstrating attainment of interim or site objectives are the contaminant concentration trends.

Note that performance metrics do not necessarily provide information on the causal factors for remedy performance. Causal factors, including changes in broader site circumstances (for example, source remediation, changes in flow regimes, changes in land use, or drought) also are considered as part of periodic evaluations.

### 5.2.4 Interim Objectives

Interim objectives represent short-term decision-making goals that guide progress towards achieving the final site objectives. An interim objective may represent a technically achievable endpoint for an engineered remedy component that depends on site-specific conditions such as initial contaminant mass and site hydrogeologic conditions. These interim objectives can serve as decision-making criteria to discontinue using an engineered remedy component, or a transition point to a less aggressive remedy component such as MNA until the site objectives are achieved.

Performance metrics represent a larger set of measurements/criteria that are used to evaluate remedy progress. These metrics include the subset of measurements/criteria used to develop interim objectives. A specific quantitative value, rate, or time frame can be assigned to one or more performance metrics used to evaluate remedy progress that can then serve as an adaptive management interim objective. For example, for an in situ treatment remedy component, the reduction in a 95% UCL source area groundwater contaminant concentration could be a performance metric. Achieving an 85% reduction in the respective 95% UCL source area groundwater contaminant concentration within a five-year timeframe could then be a specific interim objective that represents a technically achievable endpoint for discontinuing the in situ treatment.

Performance metrics and interim objectives can be modified, added, or deleted throughout a project's life cycle as part of an adaptive site management approach as more data are collected and certain trends are identified. The applicability of these measurements is linked to the technical limitations of a remedy component that can depend on many factors. Since performance metrics represent a larger set of measurements, and interim objectives are developed from the larger set of performance metrics based on site-specific needs, these terms are often referenced together.

The long-term management plan identifies interim objectives and corresponding performance metrics that will be used to evaluate remedy progress, which is especially critical for engineered remedy components. Multiple performance metrics and corresponding interim objectives can be tailored to specific types of site objectives and remedy components. Selecting performance metrics and the respective interim objectives for a site is somewhat subjective and depends on the site-specific circumstances, priorities, and available monitoring data.

Presented below are examples of interim objectives that can be tailored to address certain types of site objectives and remedy components:

***Risk Reduction***

- Reduce risk for drinking water impact over [value]% within [number] years, updated for regulatory changes.
- Eliminate vapor impact over [number] years.
- Reduce environmental impact (further risk) to the aquatic environment within [number]

***Plume Dynamics***

- Plume area exceeding site objectives decreases [value]% within [number]
- Statistical approach shows decreasing trends in total contaminant mass or concentrations in source area or at downgradient locations.
- Criteria that define asymptotic performance are consistent with technology limitations or need for optimization.
- Predictions of remediation time frames are developed to attain interim objectives within [number]
- Groundwater concentrations meet interim objectives at specified remedial progress monitoring wells within [number]

***Mass Flux/Discharge Reduction***

- Contaminant mass flux or discharge decreases by [value]% within [number]
- Contaminant mass flux or discharge decreases to an asymptotic value.
- Target degradation/attenuation or removal rates are met.

Table 12 includes some more examples of interim objectives and performance metrics that can be tailored to specific remedy components:

**Table 12. Examples of interim objectives and performance metrics that can be used for various remedy components**

| Site Objectives | Source Area | | Plume | |
|---|---|---|---|---|
| | **Remedy Component** | **Interim Objective/ Performance Metric** | **Remedy Component** | **Interim Objective/ Performance Metric** |
| Remediate contamination | In situ treatment | Reduce contaminant concentrations by one order-of-magnitude | Enhanced attenuation | Reduce concentrations in specific wells to MNA target concentrations |
| Control migration and prevent off-site impacts | In situ treatment | Reduce mass flux from source area by 50% | Permeable reactive barrier (PRB) | Reduce concentrations across PRB to MNA target concentrations |
| | P&T system | Demonstrate capture using multiple lines of evidence | MNA, monitoring | Confirm stable or decreasing plume size; no detections at sentinel wells near property boundary; target attenuation rate to meet site objectives in estimated timeframe |
| Prevent exposure | Engineering controls | Maintain engineering controls and fencing per O&M plan | ICs | Groundwater use restrictions within designated area |
| | ICs | Deed restriction for land use; groundwater use restrictions | Alternative water supply | Provide alternative water supply within plume/IC boundary |

### 5.2.5 Decision Criteria

The established interim objectives and associated performance metrics distinguish acceptable from unacceptable remedial progress at key milestones. Establishing criteria for insufficient remedy progress as early as possible in the planning process prevents wasted efforts. Furthermore, if performance outcomes lag the design predictions beyond a threshold milestone identified as a trigger point, then contingency actions can be identified and implemented. The contingency actions can reflect lessons learned from past experiences at the site or similar sites. Practitioners in the environmental remediation industry can advance the development and use of decision criteria at complex sites and actively communicate or publish examples to provide others with greater detail on methods and strategy for developing robust quantitative criteria.

Performance results for a functioning system can often be improved. The performance model example shows a range of acceptable results in the yellow zone that do not trigger contingency actions. Remedy optimization can improve performance within this range.

### 5.2.6 Example: Using a Performance Model, Performance Metrics, and Decision Criteria

Figure 6 illustrates a typical performance model. The plotted performance data are contaminant concentrations over time.

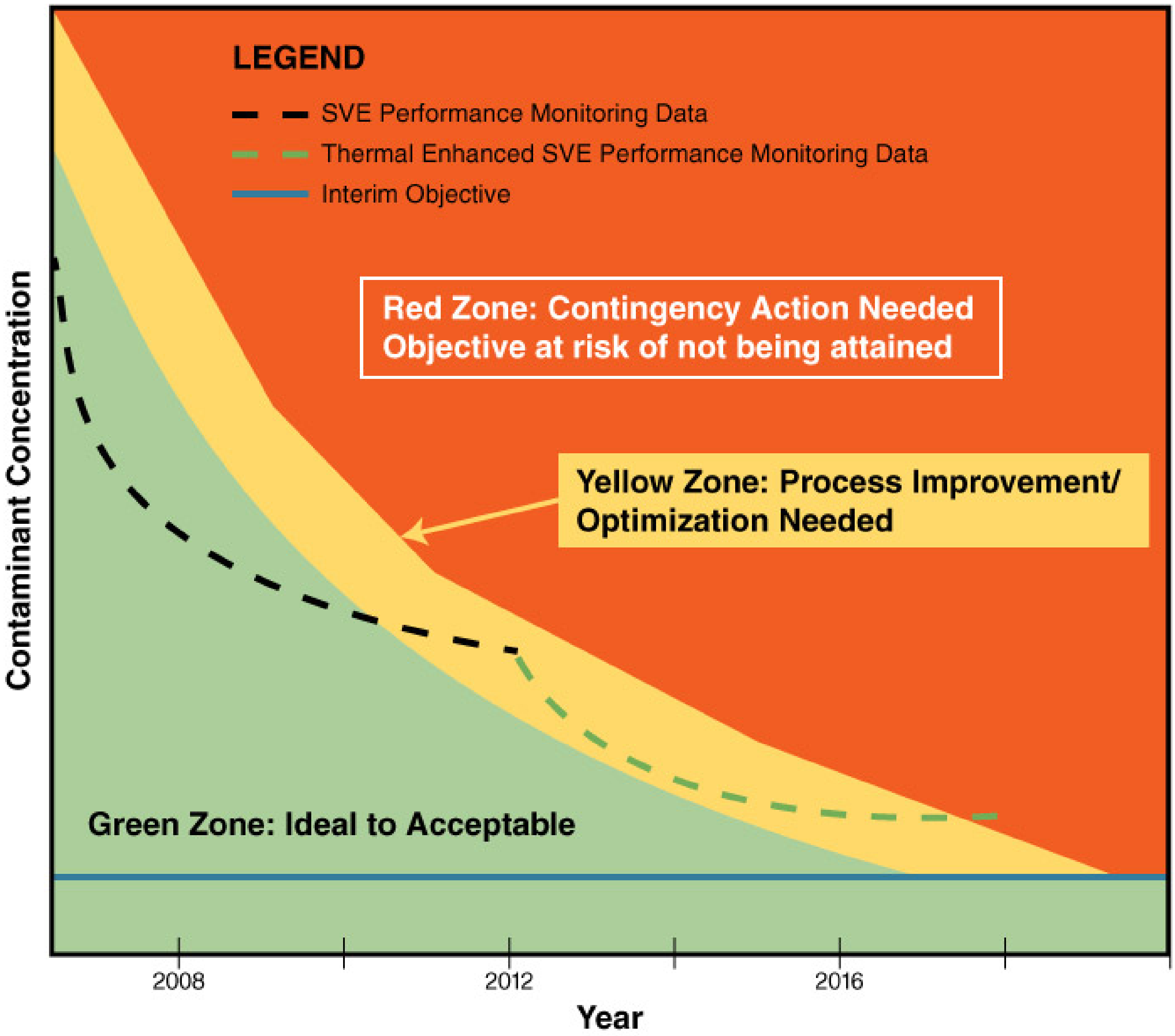



**Figure 6. Example of a performance model.**

The range of projected performance data values shown in green represents acceptable performance. The values in the red range represent a performance result that would require alternatives and contingency actions to improve performance. The yellow range depicted may benefit from process improvement. Actual performance data, based on site monitoring, are plotted as the black dashed line. The interim objective in this example is the targeted endpoint contaminant concentration represented by the horizontal blue line, below which the actual data must extend for the remedy component to be verified as a success.

***Green Zone: Ideal to Acceptable***

The ideal or acceptable range of performance data is projected from the current conditions to achieving the interim objective or specific performance goal by the end of a predetermined monitoring period. Although there is no upper bound on performance, a lower bound distinguishes acceptable from unacceptable performance. A result in the green zone is a confirmation that the system is performing as anticipated and no changes are needed.

***Yellow Zone: Process Improvement and Corrective Action***

A result in the yellow zone triggers process improvements, because actual remedy performance is lower than predicted performance, or remedy performance is not optimal. This decision criterion uses interim objectives and performance metrics to trigger process improvements before actual performance data indicate failure. The range of actual performance data spans from the least satisfactory but acceptable performance results to unacceptable performance as described by the failure criteria.

Once actual performance metrics are observed in the yellow or process improvement range, optimization and process improvement efforts can increase remedial effectiveness and efficiency, as well as return performance to the acceptable range (green zone). Process improvements continue until acceptable performance results are consistently maintained. After several iterations of process improvement, performance may still be in the yellow or red zone, triggering a contingency action.

***Red Zone: Contingency Action***

If performance does not meet the established long-term management plan decision criteria and established interim or site objectives, even after process optimization efforts, then a contingency action is evaluated. For example, the effectiveness of the selected remedy component may have tapered off, signaling that it is time to adapt to a preplanned contingency action. Transitioning to an alternate technology or remedial approach may also increase or maintain remedy effectiveness and efficiency. The Moffett-MEW Regional Plume case study includes a discussion of the East Side of Moffett Field, where a remedy was changed after the Navy requested a TI waiver.

The contingency actions that are triggered by observing actual performance data values below the acceptable threshold depend on specific conditions, and are described explicitly for each site. Typically, data below the acceptable threshold either trigger process modifications to improve the current approach or contingency actions that are substantially different from the initial approach.

In general, the contingency trigger takes the form of an if/then statement such as: “if contaminant concentration is not reduced to a value below “X” by a certain milestone date, then contingency action or system reconfiguration will then be implemented.”

If all known, reasonably available technologies fail, or the possible contingency actions could be more harmful than the site conditions present, then a critical objective analysis of the CSM is performed. This examination determines viable alternate methods of risk reduction. Alternatively, a contingency action may include pursuing a TI waiver consistent with the respective regulatory program under which the site is being managed, or perhaps providing evidence for adopting revisions to the decision document or associated site objectives. For CERCLA sites, this contingency action process may involve formally waiving compliance with justifiable ARARs. In some special circumstances, contaminant isolation measures may be addressed in the long-term management plan. The long-term management performance model focuses on each major remedy component and monitoring remediation performance. Additional characterization during planning phases or as a contingency action may help to mitigate these uncertainties.

## 5.3 Periodic Evaluations

Periodic evaluations are performed by the project team or an independent review team. The evaluation of remedy performance and optimization (USEPA 2014b) compares actual remedy performance to the interim and site objectives, and any other performance criteria described in the decision documents and other plans. The long-term management plan includes a schedule for conducting periodic evaluations, who is responsible for performing the periodic evaluations, data that will be collected, documentation, and the decision-making process. Periodic evaluations can be done at any time during the remediation life cycle, and are scheduled to evaluate technical parameters such as contaminant migration for each major component of the selected remedial approach. The periodic evaluations could also include a postremedy implementation remediation potential assessment. At CERCLA sites, this process is formalized in five-year reviews. In addition to formal periodic evaluations, technology performance is routinely evaluated by the O&M team to determine its success or the need to modify or adjust specific remedy components.

Scheduled periodic evaluations compare predicted and actual progress toward meeting interim and site objectives. Remedy performance can be graphed and evaluated in real time relative to the predicted performance for each key remedy component. For example, the rate of contaminant migration and attenuation could be compared to the expected change (calculated or modeled) after implementing each remedy component. Interim objectives and corresponding performance metrics may include contaminant concentration trends, mass flux reduction, plume stability, plume capture, and more. The long-term management plan describes the monitoring program needed to collect data that corresponds to the performance metrics so that progress towards meeting interim objectives can be evaluated. The plan specifies monitoring locations, analyses, sampling frequency, and DQOs. The selected remedy components, performance model, and baseline conditions inform the specifics of the monitoring plan. Such a monitoring program produces the necessary data to evaluate remedy performance over the duration of the remedial approach using the DQO process.

The following list presents a typical remedy performance process and the metrics that can be used during periodic evaluations for some common remedy components. Actual details will vary depending on site-specific remedy components, interim objectives, and performance metrics.

***Compare performance metrics***

- Compare actual and predicted contaminant concentrations for each major element of each key remedy component implemented.
- Compare actual rate of change to predicted rate of change for each key remedy component implemented.
- Evaluate data to determine whether the remedy is progressing toward interim or site objectives at a satisfactory pace.

***Based on these comparisons of performance metrics***

- Determine whether optimization or modification can correct an inadequate remedy. If not, reevaluate alternative technologies and remedial approaches and determine the remediation potential.
- Implement necessary steps required to correct the remedy component performance.

***Evaluate the performance of engineered remedy components***

- Evaluate actual performance indicators (such as run time efficiency, capture zone, mass removed, and performance trends).
- Compare actual performance to design specifications, interim and site objectives, and corresponding performance metrics documented in the long-term management plan.
- Evaluate potential outside influences, including contamination that may influence remedy protectiveness.
- Consider other variations, such as weather, new groundwater withdrawals, groundwater flow fluctuations causing or resulting in a rise or lowering of the water table, and contaminants in groundwater flowing on to the site from another source.

***Evaluate the performance data for attenuation-based remedy components (such as MNA, engineered caps,***

***and hydraulic migration control systems)***

- Develop multiple lines of evidence consistent with design conditions (groundwater geochemical parameters, levels of degradation products, and contaminant concentrations at compliance monitoring points).
- Determine plume behavior (expanding, stable, or contracting within the site/site segment?).
- Evaluate contaminant trends in the plume (decreasing, stable, or increasing).

***Evaluate other factors***

- Evaluate effectiveness of ICs.
- Confirm barriers to accessing contaminated media, such as buildings and other structures, surface activities, wetlands, and endangered species habitats and subsurface hydrogeologic difficulties.
- Estimate new influx of residential housing that may impact risk assumptions.

Periodic evaluations include a site inspection and evaluation of IC implementation, effectiveness, and stakeholder roles and accountabilities. The IC evaluation includes zoning and other local code and use restrictions, and verifies that any proposed changes are consistent with provisions in the decision documents. The periodic evaluations also verify that ICs are being implemented and any gaps in performance are identified. Monitoring may also identify shifts in compliance that indicate a need for revision or increased attention to ICs. When warranted, decision documents can be modified to set forth changes to ICs while maintaining protective site conditions. Monitoring confirms that access controls and markers designated in the long-term management plan are in place over the duration of the project life cycle (see Figure 6). Results of periodic evaluations become a part of the Administrative Record at CERCLA sites (USEPA 2010a, ITRC 2016b) or the analogous documentation for sites in RCRA, state or other federal cleanup programs.

The long-term management plan includes an evaluation of the effectiveness of ICs and zoning requirements. USEPA (2012a, 2012b) also details required components and implementation of ICs; USEPA (2011d) provides guidance on the evaluation and validation of ICs during CERCLA five-year reviews, which can also be used for any type of periodic evaluation.

The periodic evaluation checklist shown in Table 13 includes additional example questions for key topics, which further augment the example presented above. The decision logic applied to the site performance metrics is designed to aggressively and efficiently advance the remedial approach towards meeting developed interim and site objectives. Note that the objectives of the periodic evaluations are broader than CERCLA five-year reviews, and therefore the criteria in Table 13 are more extensive.

**Table 13. Periodic evaluation example checklist for specific topics**

| | |
|---|---|
| **Source Characterization** | |
| | Does remedy operation data indicate that the source may not be fully characterized? |
| | Are contaminant properties known and considered? |
| | Are COCs site specific behavior patterns and conditions fully identified and understood? |
| | Has the level of uncertainty in the horizontal and vertical mapping of source area mass and lithology been identified? |
| | Has the mass been evaluated? |
| | Have distal plume portions been characterized, sufficiently? |
| | Evaluate the ability of current technology to effectively characterize the site (for example, bedrock geology) |
| **CSM** | |
| | Does the CSM reflect current understanding of site conditions? For example, how has land use changed? |
| | Does the current CSM adequately explain plume behavior and remedy performance? |
| | Based on the current CSM, are all receptors adequately protected? |
| | Is the site adequately characterized to support meaningful evaluation of remedy performance and remediation potential? |
| **Hydrogeology and Plume Behavior** | |

| | |
|---|---|
| **Source Characterization** | |
| | Are plume dynamics well understood? Is plume increasing, shrinking, or stable? |
| | Is the influence of any off-site extraction wells (pumping rates) well understood? |
| | Are contaminant concentrations decreasing at a rate that will achieve site objectives within the time defined by the decision document? |
| | Has the influence of uncertainty associated source mass, hydrogeology, mass flux, matrix diffusion, and other parameters been evaluated and accounted for in the time frame estimate? |
| | Is the evaluation of the mass balance sufficient to determine: |
| | • original mass released |
| | • mass removed by remedial operations |
| | • remaining residual mass in the dissolved plume and immobilized within the soil lithology (lower permeability units in particular)? |
| **Technology Performance – Evaluate Site Specific Challenges** | |
| | Evaluate intrinsic recalcitrant contaminants/complex hydrogeology or technology. |
| | Evaluate measurement methods (performance metrics) used to assess the technology performance. |
| | Evaluate level of technology performance needed to meet site objectives or interim objectives. |
| | Evaluate potential challenges for meeting site objectives and time frame based on appropriate technical factors and limitations (such as continued NAPL dissolution remaining immobilized residual mass in lower permeability or difficult to access lithology, capillary smear zone, or matrix back-diffusion limitations). |
| | Is achieving site objectives technically feasible? |
| **Technology Alternatives Cost Effectiveness Analysis** | |
| | Has a cost effectiveness analysis been conducted if an alternate technology is considered as a potential replacement of a technology currently in operation? |
| | Does a completed technology pilot test indicate that site objectives can be achieved? |
| | Is the proposed technology schedule to complete more favorable (based on time or resource consumption) than the current technology in operation, and is it acceptable to interested parties? |
| | Is the proposed alternative approach sustainable? |
| | Is an appropriate modification to the decision document required based on data gaps, source characterization, plume behavior and/or technology performance? |

## 5.4 Decision Logic for Adaptive Site Management

Decision-making criteria to implement adaptive site management strategies are incorporated into the long-term management plan. These criteria are used as a guide for adapting the remedy if needed, based on the results of the periodic evaluations. Open, transparent discussions among all the interested parties on contingency actions and remedy transitions and corresponding decision-making criteria are planned in case the remedial approach fails to meet interim or site objectives. Public participation is always recommended and is typically required when a significant change to the remedial approach and an updated decision document is warranted. Transition assessments can apply to any remedy transition decision when a determination has been made that continued implementation of the current remedy components will not meet interim or site objectives.

### 5.4.1 Potential Outcomes of Periodic Evaluations

Potential decision outcomes of periodic evaluations include the following (see Figure 5):

- Performance is found protective and adequately progressing towards interim and site objectives, so the remedy will continue to operate as is.
- Interim objectives have been met that allow for transition to a less aggressive remedy component (for example, MNA).
- Remedy optimization is needed to improve operation of engineered remedy components or revise the remedial approach. In this case, the CSM would be revised to reflect the latest knowledge of site conditions. Remedy revision may be needed due to one the following identified conditions:
    - Operating conditions are outside the expected design range or specifications.
    - Contaminant concentrations are not decreasing as anticipated.
    - Plumes are expanding or migrating unexpectedly.
    - Treatment efficiencies are not being met (for example, extraction/injection rates are not being met, or discharge limitations have been exceeded).

Two circumstances can warrant reevaluation of an ongoing remedy component or the overall remedial approach. First, recalcitrant contaminants and complex subsurface conditions can cause asymptotic contaminant levels above the interim or site objectives. In this situation, meaningful additional progress toward site objectives is not technically feasible. At a minimum, the long-term management plan lays out a procedure to follow when the remedy is determined to no longer be protective of human health or the environment, or if progress towards interim and site objectives is not satisfactory. Contingency actions or possible modifications to the remedial approach are identified in the long-term management plan to address reasonably anticipated scenarios. Site objectives and the overall remedial approach may need to be reevaluated to determine an appropriate revised long-term management strategy.

In a second situation, interim objectives have been met, but site objectives have not been achieved. The long-term management plan includes provisions for the transition to either a less aggressive remedy component such as MNA, or an alternative “treatment train”

#### Reaching Technology Limits

*At a chlorinated solvent site, interim objectives were achieved even though site objectives were not. The proposed remedy was enhanced in situ bioremediation to promote reductive dechlorination. The primary contaminants were TCE and N-nitrosodimethylamine (NDMA). These were present at 125 feet below ground surface in complex geology (bedrock) that prevented contaminant extraction and effective substrate addition. Enhanced in situ bioremediation was not effective against NDMA, but it achieved substantial dechlorination of TCE, reaching asymptotic conditions above action levels. Pilot studies demonstrated that additional, currently available in situ technologies were ineffective for remediating NDMA (red zone per Figure 7). Based on available technologies and site conditions, stakeholders concluded that technologies were at their practicable limit/potential. The remedial approach was modified to implement natural attenuation and an enforceable environmental covenant to maintain protectiveness.*

polishing technology, based on reaching a practical design limitation for the current remedy component. Provisions for remedy component transition and corresponding interim objectives and corresponding performance metrics are included in long-term management plans that allow for discontinuing more aggressive engineered remedy components that are found to no longer appreciably contribute to progress toward site objectives, such as reaching an asymptotic condition.

For each of the above scenarios, adaptive site management can help to determine the data, evaluations, and procedures necessary to determine the technical basis for further long-term management approaches. The reevaluation of interim objectives and corresponding performance metrics could logically transition to strategies employing less aggressive remedy components. It may also be necessary to revisit the remediation potential assessment which may now have a different outcome with the availability of a more comprehensive CSM, monitoring history, and actual site-specific remediation data. For example, at the Savannah River Site, a P&T system was replaced by a hybrid funnel-and-gate system to slow the migration of contaminated groundwater and funnel it through in situ treatment zones at the gates. Periodic injections of an alkaline solution at each gate neutralizes groundwater and promotes contaminant sorption and uranium precipitation. More details on this site are provided in the full case study.

A contingency action or remedial approach is identified and implemented (or may have already been identified in the long-term management plan) when the initial remedial technology fails to perform as predicted (interim objectives are not met) and optimization measures do not significantly improve performance. Criteria for deciding to implement a contingency action or remedial approach can be agreed upon and used to measure remedy component performance.

Finally, it is essential to evaluate remedy protectiveness and to summarize any key data gaps for each site or area of the site (for example, source area, or off-site dissolved-phase plume area) with regards to characterization needs, plume behavior, recent advances in technology or other factors. Periodic evaluations can also identify more sophisticated optimization tools and applications for their use. Causal factors, including changes in broader site circumstances (such as source remediation, changes in flow regimes, changes in land use, and drought) can also be considered.

If monitoring data or new information shows changing conditions that were not anticipated, then a reevaluation of the risk assessment, overall remedial approach, and site objectives may be warranted. Other factors (such as changes in land use, the installation of a nearby water supply well, a new exposure pathway receptor such as VI, or the identification of a new source) may prompt a transition to an alternative overall remedial approach. Site objectives for specific contaminants may also change. Emerging contaminants such as 1,4-dioxane may not have been considered for routine analysis based on previous risk assessments. Research and

### Use of a Treatment Train and Interim Objectives

*When progress toward interim objectives became unsatisfactory at an SVE remediation system, the remedy was optimized. At a VOC-contaminated landfill, SVE was used to achieve at least 97% reduction in VOC soil gas concentrations relative to baseline conditions. Initial high VOC removal rates on the order of 10 kg/hour exponentially declined the first year. By the end of the second year of operation, the VOC removal rate had attained asymptotic conditions at 5 kg/hour (yellow zone per Figure 8). Thermal technology was introduced during the third year of SVE system operation to optimize system performance. At the end of the fourth year, the SVE system operation was terminated after successfully achieving reduction of VOC concentrations in soil gas (0.27 kg/hour) by 97% or more.*

### Criteria for Triggering a Contingency Action

*Performance metrics can specify criteria that trigger a contingency action based on insufficient progress towards interim objectives. For example, an interim objective may be defined for a pump-and-treat system as decreasing contaminant concentrations from 300 to 30 micrograms per liter (µg/L) in eight years based on initial remedy timeframe projections. A performance model can be developed to predict remedy progress over time. For this example, contingency actions (such as, further characterization or targeting “hot* development and other advancements in technology that increase the understanding of site conditions may present opportunities to optimize the remedial approach. The likelihood of these changes and their potential impact on site operations can be accounted for through maintaining a project risk register (ITRC 2011d, 2012).

*spots" with in situ amendment injections) may be triggered if contaminant concentrations are not reduced to a shorter-term performance metric of 150 µg/L or less within the first three years. The design basis (such as trend plots, calculations, and modeling results) of the performance model is documented in the long-term management plan.*

### 5.4.2 Remedy Optimization

Another possible outcome of the periodic evaluation may be a recommendation for formal remedy optimization to evaluate improvements, modifications, or other remedial approaches to improve performance and cost effectiveness of current remedy components. Under the NCP, cost effectiveness is one of the criteria to be considered for remedy selection under 40 CFR 300.430(f)(5)(ii)(g)(D), which is addressed by performing periodic remedial performance optimization evaluations (ITRC 2004). The framework for a remedy's long-term management strategy is identified in the decision document or revised decision document based on the remedy selection (or revision) process. The USEPA definition of remediation optimization in the context of its "National Strategy to Expand Superfund Optimization Practices from Site Assessment to Site Completion" is stated on USEPA's CLU-IN website (USEPA 2017b) on optimization as follows:

> *Efforts at any phase of the removal or remedial response to identify and implement specific actions that improve the effectiveness and cost-efficiency of that phase. Such actions may also improve the remedy's protectiveness and long-term implementation which may facilitate progress towards site completion. Remediation optimization uses defined approaches to improve the effectiveness and efficiency with which an environmental remedy reaches its stated goals. Optimization approaches might include site-wide optimization reviews conducted by a team of independent experts, the use of statistical evaluation tools to determine optimal operating parameters or monitoring networks, the consideration of emerging technologies as the basis for remedy modifications or changes, review of operating systems costs, and the identification of methods for cost reduction without the loss of protectiveness.*

Beyond the Superfund program, numerous definitions of remedy optimization are used, which could range from routine informal ongoing evaluation of operating data to adjust treatment component operating and design parameters to more formal optimization reviews similar to the USEPA's Remediation System Evaluation program, which is analogous to the RPO process defined by ITRC. RPO is a dynamic and flexible management strategy that can be applied at any stage of the remediation life cycle. An RPO evaluation during the remedial action phase can offer many opportunities for improving effectiveness of the remedy and reducing cost without adversely impacting protectiveness.

An RPO assessment evaluates the progress toward meeting developed interim and site objectives and other technology-specific treatment performance objectives. This evaluation is highly recommended at sites that are not adequately progressing towards interim objectives and other performance indicators. This assessment also includes evaluating whether a particular remedy component is meeting its respective design expectations. RPOs may be performed for each of the remedial technologies and other remedy components. The elements of periodic evaluations also apply in general to RPOs, except for the greater level of detail that may be evaluated for each technology and remedy component as part of an RPO. An RPO typically includes comparative cost analyses to evaluate alternative equipment or operating procedures.

Recommendations from RPOs may include any combination of the following:

- transition to a less aggressive remedy component or remedial approach if interim objectives are met, or asymptotic conditions that cannot be improved by further optimization efforts identified
- further refining the CSM
- consideration of a "treatment train" approach using multiple technologies or other proven or emerging technologies to expedite remedial progress
- modifying the existing remedy components or operating parameters (such as adding treatment wells, increasing pumping rates or amendment injection volumes)
- optimizing the monitoring program

An example of a recommendation from an RPO might be redevelopment of groundwater extraction and monitoring wells. When wells become fouled, they often provide less accurate contamination levels. Wells are typically periodically redeveloped to remove fine-grained sediments, minerals, and biogrowth to maintain extraction performance and water quality. Redevelopment can reduce the energy cost, as well as provide better remedy performance, especially if the pumping wells have reduced capture influence due to declining pumping rates. The same is true for monitoring well chemistry results.

Numerous additional resources available on optimization and periodic evaluations for remedial systems (USEPA 2015d, ITRC 2004, 2007a, USEPA 2013e, b, USACE 1999, NAVFAC 2012, 2010a, Air Force Center for Environmental Excellence and Defense Logistics Agency 2001, USEPA and USACE 2007, FRTR 2016).

### 5.4.3 Community Awareness and Engagement during Remedy Adaptation

Community involvement begins early in site remediation and continues throughout long-term management. Because of the long time frames anticipated at complex sites, it is important to monitor community awareness and continue to engage the community according to the long-term management plan. Engaged communities are already knowledgeable about the site history and key issues. These community members tend to benefit the site because they offer a stable repository for site-specific knowledge. Those most affected by site activities have the largest stake in its outcome. Information handed down through the community safeguards knowledge about the site and its potential hazards.

## 5.5 Completion Strategy

The long-term management plan includes a completion strategy for eventually achieving site objectives. Completion strategies are a best practice to establish sequentially devised actions based on site-specific decisions. While a straight-line concept for a completion strategy might be appropriate for typical sites, an iterative adaptive site management approach is better at complex sites. This strategy could include transition to the next phase of the remedy from more aggressive engineered remedy components to less aggressive remedy components, with separate sets of interim or site objectives and performance metrics. Completion strategies are often developed through a collaborative process, with decision documents and work plans to memorialize agreements, including interim and site objectives and performance metrics. The site closure completion strategy may also consider options to maximize future land use. ITRC offers guidance on developing completion strategies (ITRC 2006a).

Another useful reference when developing a completion strategy is the USEPA *Groundwater Remedy Completion Strategy* (USEPA 2014b). This document recommends a completion strategy for all CERCLA, Superfund, PRP and federal groundwater sites. USEPA includes the following steps for a groundwater completion strategy: understand the site conditions, design site specific remedy evaluations, develop performance metrics and collect monitoring data, conduct remedy evaluations, and make management decisions. At CERCLA sites, remedy evaluations are conducted during Five-Year Reviews, which is also a good time to review the long-term site management plan.

## 5.6 Project Risks and Uncertainty

Successful long-term management is flexible enough to adapt to technical difficulties, changing site conditions (for instance, as a result of changes in regional pumping or climate change), changes in available technologies, stakeholder involvement, regulatory compliance, and other financial and legal factors. These variables are included in the process through the long-term management plan's evaluation of project risks and uncertainty.

The long-term management plan includes a comprehensive and descriptive strategy to identify and respond to key project risk events that warrant planning a contingency response (ITRC 2011d, 2012). The risk register and contingency planning tools described in previous ITRC guidance (ITRC 2012) may be particularly useful for assessing long-term risk at complex sites. This guidance includes a risk management checklist to help identify significant site-specific uncertainty factors that may result in project risks and uncertainties, including stratigraphy, contaminant behavior, effects of climate change and other changing site conditions, technology implementation, and regulatory issues. Project risks and uncertainty can also result from inadequate site characterization, CSM data gaps, and from design assumptions and limitations in technology application. Appropriate steps (for example, characterization to fill data gaps, pilot testing, and monitoring) may be added to the long-term management plan to address significant uncertainties.

# 6. Case Studies

The case studies presented in this guidance represent regional differences in geology, climate, and regulatory programs. Many case studies include sites that were overseen by the USEPA through CERCLA regulations rather than state regulations. The survey of states (Appendix A) presents a guide to approaches accepted in the sites overseen by states. One international case study, located in Australia, is also included. Case studies for European sites were not available.

The cases highlighted in this guidance have long and intricate histories, consistent with an adaptive management approach. Stakeholders are often more engaged at these complex sites than at less complex sites. Stakeholder involvement, however, often is not as well documented as other technical or regulatory aspects of site histories. Several case studies include detailed descriptions of stakeholder involvement based on the experience of stakeholder representatives on the authoring team who were familiar with (or helped write) the case studies. A list of site attributes and remedial approaches for each case study site is presented in Table 14.

**Table 14. Index of case studies**

| Site Name | Location | Complexities/Site Attributes | Remedial Approach |
|---|---|---|---|
| 1. Koppers Oroville Wood Treatment | California | Multiple contaminants<br>DNAPL<br>Impacts to drinking water aquifer<br>Surface water impacts<br>Recalcitrant contaminants | CSM revision<br>On-site landfill<br>TI waiver<br>Deed restrictions<br>Phased remedy (P&T system followed by bioremediation) |
| 2. Moffett-MEW Regional Plume | California | Multiple source areas<br>Multiple responsible parties<br>Comingled plumes<br>Large scale site (“regional plume”)<br>Multiple aquifers (8 zones)<br>Geologic heterogeneity<br>VI | High resolution sampling<br>Adaptive site management<br>Redevelopment<br>Excavation<br>SVE<br>Groundwater P&T system<br>Slurry walls<br>VI ventilation<br>VI barriers<br>Multiple remedial technologies<br>LUCs<br>ICs<br>Long-term management |
| 3. Rocky Flats Solar Ponds Plume | Colorado | Contaminated structures (800)<br>Large scale site (421 SWMUs)<br>Comingled plumes<br>Elevated background concentrations | Long-term monitoring<br>Landfills<br>Groundwater treatment<br>Interim actions/removal actions<br>ICs<br>Remediation potential assessment<br>Remedy optimization |

| Site Name | Location | Complexities/Site Attributes | Remedial Approach |
|---|---|---|---|
| 4. Rocky Mountain Arsenal | Colorado | Geologic heterogeneity<br>Fractured bedrock<br>Fluctuating groundwater levels<br>Arid climate/scarce water resources<br>Impacts to drinking water aquifer<br>Comingled plumes<br>LNAPL<br>DNAPL<br>Recalcitrant contaminants<br>Emerging contaminants<br>High contaminant concentrations<br>Multiple contaminants of concern (15 separate plumes)<br>High cumulative risk<br>Elevated background concentrations<br>Vapor issues (highly odorous)<br>Unexploded ordnance<br>Large-scale site (25 square miles, 10 square miles off-site)<br>Changing site objectives<br>Multiple PRPs<br>Litigation (ambiguity in state enforcement authority) | ICs<br>Redevelopment (wildlife refuge) |
| 5. Naval Air Station Jacksonville OU 03 | Florida | Site includes over 100 buildings<br>Multiple source areas (8)<br>DNAPL<br>VI risk | Air sparging with soil vapor extraction (SVE)<br>MNA<br>High resolution site characterization |
| 6. U.S. DOE Test Area North, Idaho National Engineering and Environmental Laboratory (INEEL) | Idaho | Deep contamination (200-300 feet)<br>Long plume (2 miles)<br>High contaminant concentrations (>20,000 µg/L TCE)<br>Fractured basalt geology | Pilot test of multiple technologies: metal-enhanced reductive dechlorination, monolithic confinement, in situ chemical oxidation, enhanced in situ bioremediation (ISB), MNA<br>Final remedy: ISB in high concentration areas and MNA in distal area |
| 7. Joliet Army Ammunition Plant | Illinois | Extensive contamination (36 square miles)<br>Multiple contaminants and sources<br>Low-permeability heterogeneous glacial till overlying limestone dolomite bedrock | MNA<br>Groundwater management zones<br>ICs<br>Monitoring<br>Contingency phytoremediation |

| Site Name | Location | Complexities/Site Attributes | Remedial Approach |
|---|---|---|---|
| 8. Tri-State Mining District | Kansas<br>Oklahoma<br>Missouri | Large site (2,500 square miles)<br>Mining wastes<br>Impacts to drinking water aquifer<br>Geologic heterogeneity<br>Fractured bedrock<br>Karst-like conditions<br>Ecological impacts | Reuse and reprocessing<br>Backfilling and subaqueous disposal<br>Capping<br>Chemical stabilization<br>Excavation and disposal<br>Covers<br>Grading<br>Administrative controls<br>Alternate water supply<br>Residential buyout<br>Engineering controls |
| 9. Paducah Gaseous Diffusion Plant (PGDP) Groundwater | Kentucky | Geologic heterogeneity<br>Low permeability zones<br>LNAPL or DNAPL<br>High contaminant concentrations<br>Multiple COCs<br>Long-lived contaminants<br>Large site<br>Depth of contamination<br>Comingled plumes | Source removal<br>Hydraulic control<br>Natural attenuation<br>Interim actions (source control)<br>Innovative technologies testing and implementation |
| 10. Velsicol Chemical | Michigan | Multiple aquifers<br>Geologic heterogeneity<br>Impacts to drinking water aquifer<br>High contaminant concentrations<br>Highly toxic contaminants<br>Contaminated sediment<br>Ecological impacts<br>DNAPL<br>Fluctuating water levels<br>Deep groundwater contamination<br>Residential soil impacts | ICs<br>Slurry wall, clay cap<br>Leachate collection<br>Sediment removal<br>Excavation<br>Impoundment, capping<br>Sheet piling<br>TI waiver<br>In situ thermal treatment<br>In situ chemical oxidation<br>City wellfield replacement<br>DNAPL extraction and incineration<br>Groundwater extraction and treatment (planned) |

| Site Name | Location | Complexities/Site Attributes | Remedial Approach |
|---|---|---|---|
| 11. Onondaga Lake | New York | Multiple sources including industrial discharges, stormwater runoff and wastewater treatment plant effluent<br>Sediment contamination<br>Artesian conditions (mudboils) | DNAPL removal from wells<br>Sewer retrofits<br>Metro treatment system upgrades<br>Lakeshore barrier wall and groundwater collection/ treatment system<br>Removal of contaminated sediments, dredging, disposal in an on-site containment facility<br>Isolation and thin-layer capping<br>Pilot and treatability testing<br>Calcium nitrate addition to inhibit MeHg formation<br>Revegetation<br>Slurry wall, groundwater collection system, cap<br>Rehabilitate storm drain system<br>ICs<br>Landfill waste consolidation and capping<br>Excavation<br>Retention pond<br>Leachate collection system<br>Settling basins<br>Depressurization wells<br>Five-year reviews |
| 12. UGI Columbia Manufactured Gas Plant (MGP) | Pennsylvania | DNAPL<br>Fractured bedrock<br>Contaminated sediment | On-site capping<br>ICs<br>Interim actions<br>TI waiver |
| 13. Savannah River Site (SRS) F-Area Seepage Basins Groundwater | South Carolina | Impact to surface water system<br>Low pH plume<br>Multiple contaminants of concern (tritium, uranium (U), radioactive iodine (I) and technetium)<br>Diversity of contaminants (radiologic, cationic, anionic)<br>Cumulative risk associated with long lived radionuclides, primarily U, I, and strontium Sr<br>Large-scale site (extent of groundwater plume) | Funnel-and-gate for groundwater<br>In situ treatment of groundwater<br>multiple remedial strategies |

| Site Name | Location | Complexities/Site Attributes | Remedial Approach |
|---|---|---|---|
| 14. Former Naval Weapons Industrial Reserve Plant, McGregor | Texas | Comingled plumes (TCE/TCA plume with perchlorate plume)<br>Fractured limestone<br>Emerging contaminant (perchlorate)Porpoising effect created three separate plumes miles downstream | Bench-scale studies to evaluate remediation methods<br>Multiple pilot studies including active and passive anaerobic bioremediation systems (fluidized bed reactor [FBR], biowall)<br>Maintain groundwater elevation to prevent discharge to streams<br>Remedy expand passive anaerobic biowall with emulsified vegetable oil (EVO) and maintain FBR<br>Optimize system, transition fully to biowalls |
| 15. Hanford 200 Area | Washington | Large scale site (12 square kilometer plume)<br>Multiple contaminants<br>Radionuclides<br>Comingled plumes<br>DNAPL<br>Deep groundwater | Source removal<br>Interim actions<br>MNA<br>Technology demonstrations<br>Multiple treatment trains |
| 16. Industrial Site | Australia | Saline groundwater<br>Geologic heterogeneity<br>Fractured bedrock (basalt)<br>Multilayer aquifers<br>Low-permeability zones<br>DNAPL<br>Large source area<br>High dissolved phase concentration<br>Competing electron acceptors | Source area remediation<br>Air sparge and SVE<br>Enhanced in situ bioremediation (EISB)<br>Bioaugmentation<br>Adaptive management<br>Groundwater recirculation<br>Blast fracturing<br>Natural attenuation<br>Optimization and monitoring<br>PRBs<br>P&T system<br>Plume containment<br>Radiofrequency heating of groundwater<br>Multiple remedial technologies<br>Flux mass discharge (passive flux meters)<br>Cleaned up to the extent practicable |

## 6.1 Koppers Oroville Wood Treatment Facility, California

The Koppers Oroville site is a former wood treating facility that operated from 1948 until it closed in 2001. The site occupies approximately 205 acres in Butte County, California, near the City of Oroville (Figure 7). The site is bounded by the former Louisiana-Pacific Lumber Mill to the west, Georgia Pacific Way to the north, and Bagget-Marysville Road to the south and east. Land use surrounding the site is a mixture of residential, industrial, and agricultural uses. As of 2015, approximately 10,650 people lived within a three-mile radius of the site and rely on groundwater as their source of drinking water.

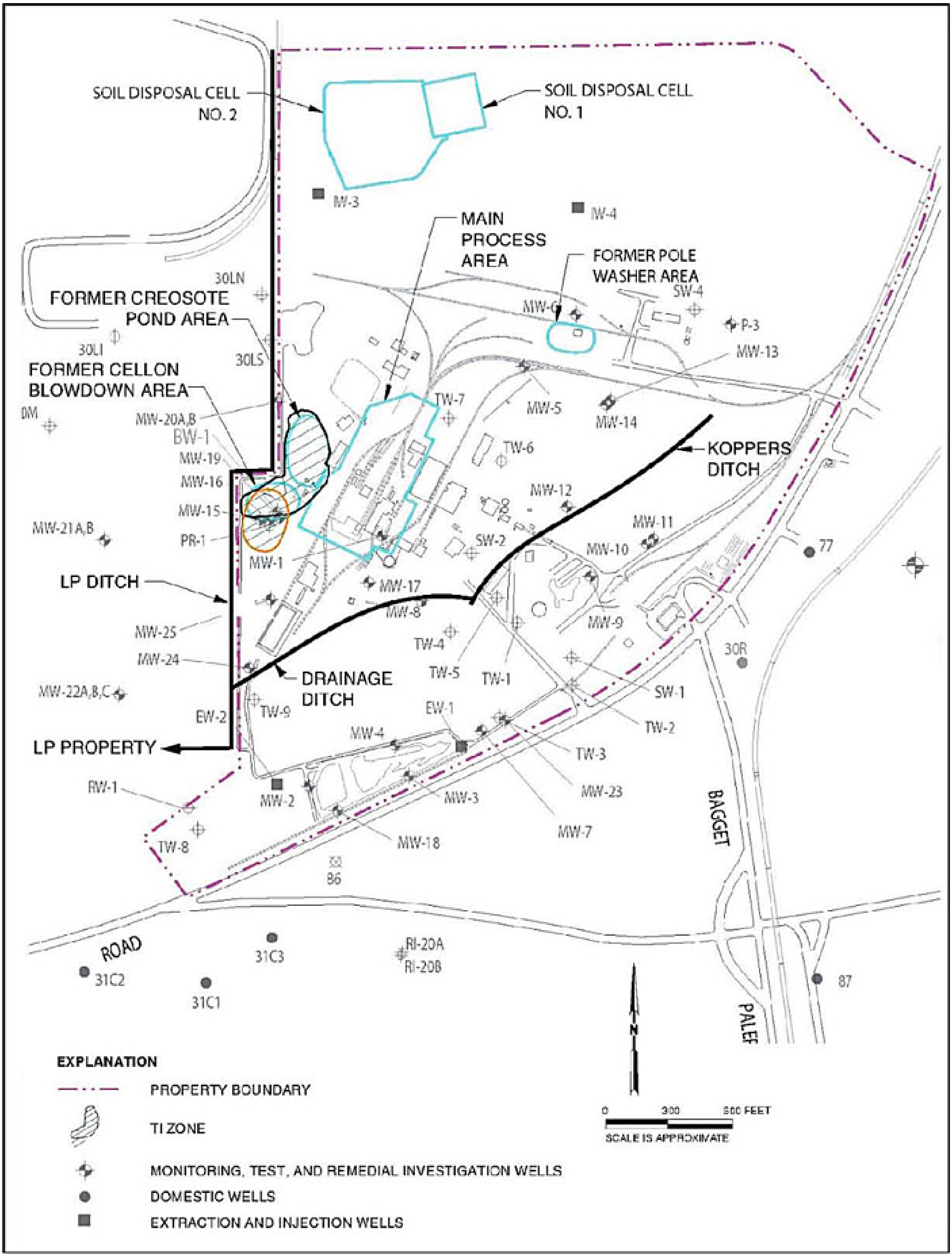



**Figure 7. Site features, former Koppers Oroville Wood Treatment Facility** (USEPA 2013a)**.**

During the early 1900s, the area around the Koppers site was used for gold mining dredge operations. From approximately 1920 to approximately 1948, the site was operated by Hutchison Lumber Mill. In 1948, National Wood Treating Company purchased the site and began operating a wood treatment plant. In 1955, Koppers Company purchased the site and continued wood treating operations. In 1988, Beazer East, Inc (Beazer) purchased Koppers Company. Beazer later resold the wood treating operation back to Koppers Industries, Inc, which continued to operate the plant until 2001. Beazer retained responsibility for all cleanup actions.

The main areas of operation at the site (Figure 7) included a wood processing area (main process area) and creosote settling ponds. From 1961 until 1973, blowdown from a Cellon wood treatment process was released into about an acre near the western site boundary (Cellon blowdown area). In 1963, a pole washing unit was installed in the northern portion of the plant site. From 1963 through 1973, equipment was used to spray a solution of water and sodium hydroxide on the Cellon-treated poles to both remove excess pentachlorophenol (PCP) from the pole surface and to prevent formation of PCP crystals on the wood surface. Wastewater from the process was not contained, and much of this wastewater flowed to a small depression just south of the pole washer.

Because of wood treating operations, the site became contaminated with wood-treatment chemicals, including PCP, creosote, and polynuclear aromatic hydrocarbons (PAHs), as well as heavy metals including copper, chromium, and arsenic. Wood treatment solutions dripped onto the ground as the treated woods were removed from process areas and otherwise handled. Wastewater from wood-treating processes were collected in unlined ponds. Boron, which was used as a fire suppressant, is also present. Two fires (1963 and 1987) resulted in releases of PCP and dioxins/furans to site soils. PCP is present as DNAPL at the site.

The geological formations underlying the site include alluvial gravels, sands, and clays that were deposited by the Feather River and its ancestral river systems. Several interconnected aquifer zones have been defined in the area. The first encountered groundwater at the site occurs in the gravels of the Laguna formation and in the Mehreten formation in some areas. Groundwater in the Ione formation is brackish and saline and is separated from overlying freshwater aquifers by low permeability clays. Perched groundwater exists in areas scattered throughout the site.

The complexities at the site include creosote DNAPL in the vadose zone, groundwater contamination off site and on site, off-site contamination of private drinking water wells, and extensive soil contamination requiring on-site landfilling. Although off-site groundwater contamination has been significantly abated, DNAPL remains on site. Long term groundwater monitoring and long-term maintenance of the on-site landfills are required.

### 6.1.1 Technical Basis for Remedial Action

In 1988, an RI report summarized the results from soil sampling investigations in 1981, 1986 (Phase 1), and 1987 (Phase 1B). Soil samples were analyzed for a variety of chemical constituents. The major contaminants found in on-site soils include PCP, creosote compounds, and metals used in the chromated copper arsenate treatment process. Other chemical species detected included isopropyl ether, boron, PCP breakdown products, and dioxins/furans. Contaminated areas included the PCP mix area, the PCP treated wood quality control area, the pole washer area, the chromated copper arsenate treated wood storage areas, and areas along all tram tracks used to transport PCP-treated poles.

Other areas investigated in a subsequent Phase IB investigation in 1987 included former disposal or accidental wastewater spill areas, an ash pile located southwest of the Eastern Spray Field, oily soils found in and near the drainage ditch along the property boundary, background soil conditions, and soil conditions at locations where new construction had been proposed. Although not part of the RI program, soil samples were also collected adjacent to the process area (actively used at the time the RI was performed) following the 1987 fire.

Chemical preservatives including PCP, creosote, and chromated copper arsenate were dripped onto site soils as the treated wood was handled. Additionally, wastewaters from creosote and PCP wood treating processes were discharged directly to unlined ponds near the western boundary of the plant. Contaminated soil became airborne due to traffic and wind erosion. Surface water runoff passing over contaminated soils resulted in contaminated surface waters and sediments. Contaminants in soil leached into groundwater beneath the site. The following COCs were present in groundwater above their respective ROD cleanup levels: PCP, isopropyl ether, dioxins/furans, PAH, boron, and benzene. Contaminated groundwater migrated beyond the site boundary in a plume that extends approximately two miles south of the site. Two distinct PCP plumes on the property are attributed to activities at the former pole washer area and process area (eastern plume) and to PCP cosolved in creosote DNAPL under the former creosote pond area and former Cellon blowdown area (western plume).

### 6.1.2 Decisions

The remedy for the site was described in the original 1989 ROD, 1991 ESD, and ROD Amendments 1 and 2 (1996 and 1999).

Four soil operable units, OU S1 through OU S4 were designated (Figure 8), as well as two groundwater units: on-property and off-property. Cleanup standards for soil were based on direct contact with surface soil and were set to residential standards. The ESD provided separate cleanup standards for subsurface soil to protect underlying groundwater. Cleanup goals for groundwater were established as MCLs for PCP, total carcinogenic PAHs, dioxins/furans, and background levels for arsenic and chromium.

Selected remedies for the soil units were as follows:

- S1: in situ biodegradation
- S2: excavation and soil washing
- S3: capping with groundwater extraction
- S4: excavation and chemical fixation

The facility conducted bench-scale and pilot treatability studies of bioremediation, soil washing, and soil fixation from 1992 through 1994 to evaluate the soil remedies selected in the ROD. Treatability study results indicated that the technologies could not achieve residential cleanup standards, nor could they effectively treat the combination of COCs in surface soils. Dioxin and furan concentrations were detected in surface soils above the industrial standard for workers in 1993. USEPA authorized the removal of soils with concentrations of dioxins/furans greater than 1 µg/kg. The facility excavated and placed over 15,000 cubic yards of dioxins/furans impacted soil and debris in an on-site soil disposal cell.

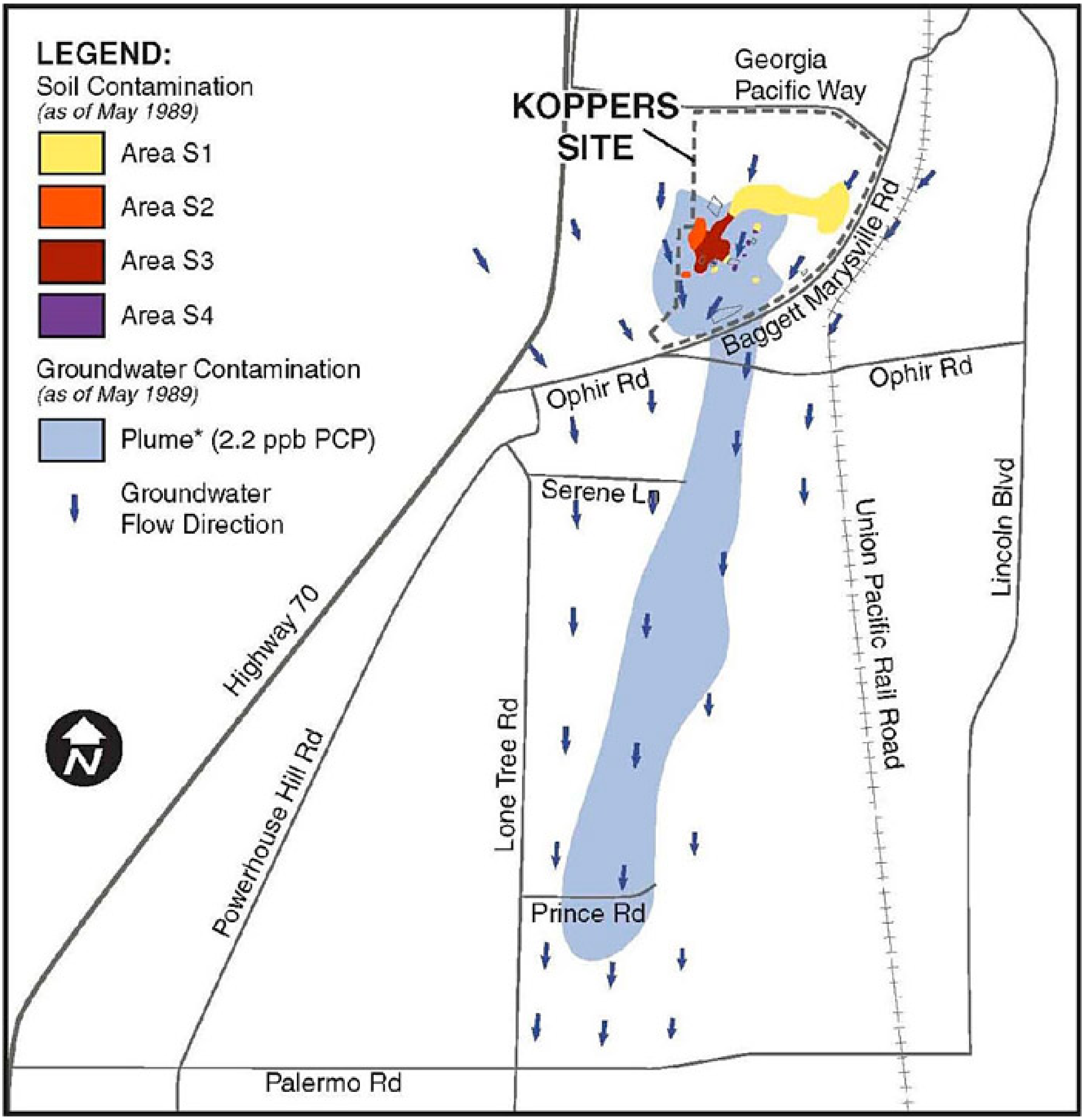



**Figure 8. Soil and groundwater units, former Koppers Oroville Wood Treatment Facility** (USEPA 2013a)**.**

ROD Amendment 1 changed the remedy as follows: (1) modified soil cleanup standards to be industrial cleanup standards; (2) called for excavation of contaminated surface and subsurface soils and placement of these soils in a new on-site landfill; and (3) required a deed restriction to prohibit future residential use of the site. The site soils were landfilled because treatability studies demonstrated that the previously selected remedies for site soils could not achieve cleanup goals.

ROD Amendment 2 modified the groundwater remedy by providing for (1) a TI waiver for on-site groundwater due to creosote DNAPL contamination; (2) adding enhanced in situ bioremediation to the remedy to augment PCP destruction; and (3) adding MNA as a contingency remedy should enhanced in situ bioremediation nutrient distribution not be fully achieved in the aquifers.

The TI waiver was granted after the nature and extent of DNAPL in the subsurface on the site became better understood. The DNAPL consists of PCP with entrained dioxin and PAH. USEPA determined that the P&T remedy for groundwater proposed in the ROD would not restore groundwater to the proposed cleanup standards even though surface and near surface contamination were removed. The major components of the TI waiver were:

- sampling and COC analysis from monitoring wells within and downgradient of the TI zone
- installation of a new monitoring well down-gradient of the TI zone
- developing a contingency plan to maintain the P&T facility and resume operation if the USEPA determines that a contaminant is leaving the TI zone
- implementation of ICs through land use covenant deed restrictions to prevent exposure to contamination remaining in the TI zone, prohibit drilling of wells within the TI zone for purposes other than monitoring or remedial activities, prohibit use of groundwater within the TI zone except for wood-treating operations, and limit future land use to industrial
- continuing operation of the existing product recovery well until creosote recovery is less than one gallon per year
- implementing enhanced in situ bioremediation outside the TI zone
- implementing MNA as a contingency remedy outside the TI zone

MNA was included as a contingency remedy because site data showed that PCP degraded naturally both on and off the property. MNA will be implemented as a contingency remedy if the USEPA determines that (1) enhanced in situ bioremediation nutrient distribution cannot be adequately achieved; (2) other active restoration measures are not necessary; (3) site conditions continue to demonstrate that PCP degradation is occurring; and (4) natural attenuation is expected to achieve cleanup levels within a reasonable time frame achievable by a treatment remedy.

In summary, the site remedy included the following:

- excavation of contaminated soils, debris and sediment and disposal of excavated material into on-site landfill cells and capping
- P&T (using activated carbon treatment) contaminated groundwater, reinjection of treated water, and enhanced in situ bioremediation
- a TI waiver for on-site groundwater
- recovery of creosote DNAPL
- providing an alternate drinking water supply to community members impacted by contaminated groundwater
- implementing ICs to prevent future residential use of the property and to restrict use of on-site groundwater

## 6.1.3 Assessment

Remedial actions were implemented for soils and for groundwater plumes both on and off the property.

### 6.1.3.1 Soil Remedial Actions

The remedies described in the ROD, ESD, and ROD Amendments 1 and 2 have now been implemented, including soil removal in the former process area (Area 8C). Two on-site soil disposal cells were created. Soil Disposal Cell No. 1 accepted 15,000 cubic yards of soil from the bioremediation test plot with high dioxin/furan levels and was completed and closed in 1995. Soil Disposal Cell No. 2 was constructed adjacent to Soil Disposal Cell No. 1, near the northern boundary of the Site in August 1996 (see Figure 8) and received excavated soil from the top 14 feet of former creosote pond (11,216 cubic yards), the top 20 feet of the pole washer area (4,830 cubic yards), the top 10 feet of the former Cellon blowdown area (11,130 cubic yards), and approximately 40,000 cubic yards from the process area. Soil remediation was completed and the Soil Disposal Cell No. 2 was closed in September 2002.

### 6.1.3.2 Groundwater Remedial Actions

Groundwater treatment systems for on-property and off-property plumes began operating in 1993 and 1994. As mentioned in the discussion of the site CSM, two distinct on-property plumes are present, eastern and western. The on-property plumes have become hydraulically separated from the off-property plume because of the on-property P&T system operation.

***Eastern On-Property Plume***

The groundwater P&T system for the eastern plume includes two extraction wells (EW-1 and EW-2) and two injection wells (IW-3 and IW-4) for reinjecting the treated water. Extracted groundwater is treated by an air stripper, a multimedia filter, and granular activated carbon to remove PCP, isopropyl ether, and PAHs. Currently, PCP is the only COC detected in the influent at concentrations exceeding the ROD standards. In August 2002, groundwater extraction began from monitoring well MW-8, which is near the center of the eastern PCP plume to address boron contamination in groundwater.

In situ bioremediation was conducted to remediate PCP in 1998. Oxygen-releasing compounds (ORCs), including magnesium peroxide and diammonium phosphate (DAP), were periodically added to six on-property wells to supply nitrogen and phosphorous and enhance bioremediation.

***Western On-Property Plume***

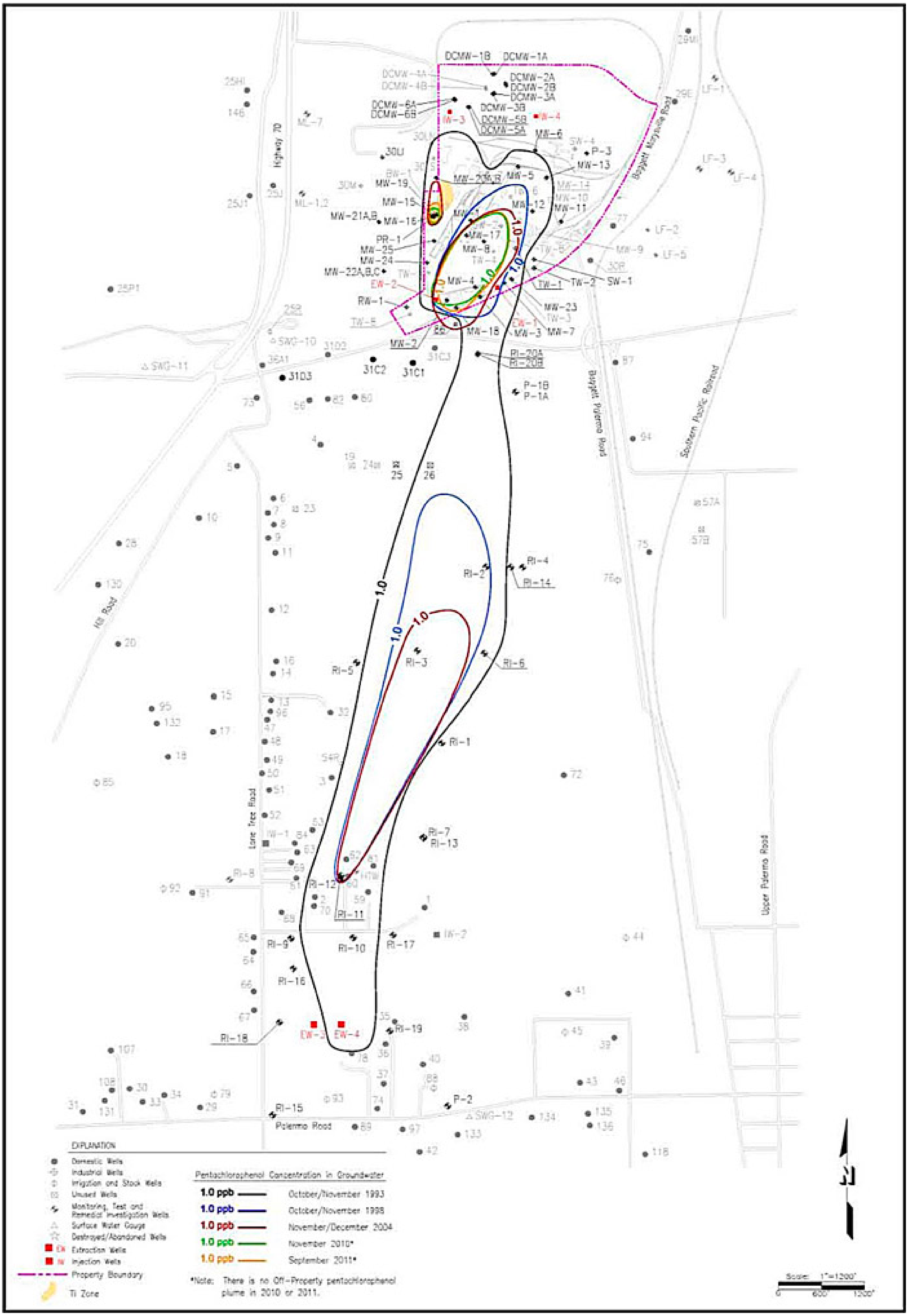
The western plume is located below the former Cellon blowdown area and former creosote pond area. In September 1994, a passive recovery well (PR-1) was installed in the western plume to evaluate whether the subsurface pools of creosote at the site could be effectively remediated by draining the fluid into a recovery well. The well has two separate screened intervals. Each 10-foot screen is located immediately above a clay lens, where free creosote is perched. The mobile creosote enters the well through the screened intervals and collects in a 5-foot deep sump at the bottom of the well. Fluid is purged periodically from the well and taken to an off-site location for disposal. From 1994 to July 2007, approximately 1,300 gallons of DNAPL were recovered.

In 1999, about four acres surrounding the former creosote pond and Cellon blowdown areas were declared a TI zone in the ROD Amendment No. 2. This TI zone occurred because both the existing P&T system and in situ PAH bioremediation failed to remedy the DNAPLs present in the clay layers beneath this area. Currently, monitoring for carcinogenic PAHs (cPAHs) continues downgradient of the TI zone to ensure that the ROD standard for total cPAHs is not exceeded.

***Off-Property Plume***

Beginning in March 1986, an alternate water supply was provided to 34 residences downgradient of the site, within the off-property plume area. The alternate water supply for those affected by the groundwater contamination was formalized in the ROD. A total of 26 residents were taken off the alternate water supply in 1998 after their wells met the cleanup criteria, as well as another residence in 2001.

An off-property groundwater treatment system was installed south of Prince Road (Figure 9). Two extraction wells (EW-3 and EW-4) were installed at the toe of the two-mile plume (Figure 9) along with a treatment plant, two injection wells, and approximately 1,500 feet of pipelines. Initially, treated water was discharged to Wyman Ravine. Later, this water was reinjected upgradient of the off-property plume into injection wells IW-1 and IW-2. The P&T system was shut down in December 1995 and dismantled in 2007, after monitoring indicated that the plume had retreated upgradient of the extraction wells. During its operation, the system treated over 626 million gallons of contaminated groundwater.


Highway 70
Baggett Marysville Road
Baggett Palermo Road
Southern Pacific Railroad
Upper Palermo Road
Lone Tree Road
Hill Road
Palermo Road
DCMW-1B
DCMW-1A
DCMW-2A
DCMW-2B
DCMW-3A
DCMW-3B
DCMW-5B
DCMW-5A
DCMW-6A
DCMW-6B
IW-3
IW-4
MW-6
MW-5
MW-13
MW-12
MW-11
MW-19
MW-15
MW-16
MW-21A,B
MW-20A,B
MW-17
MW-8
MW-25
MW-24
MW-22A,B,C
MW-4
MW-23
MW-18
MW-3
MW-7
MW-2
PR-1
EW-2
EW-1
RW-1
TW-1
TW-2
SW-1
P-3
P-1B
P-1A
P-2
RI-20A
RI-20B
RI-2
RI-4
RI-14
RI-3
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RI-10
RI-17
RI-9
RI-16
RI-18
RI-19
RI-15
EW-3
EW-4
31C2
31C1
31D3
1.0
EXPLANATION
Domestic Wells
Industrial Wells
Irrigation and Stock Wells
Unused Wells
Monitoring, Test and Remedial Investigation Wells
Surface Water Gauge
Destroyed/Abandoned Wells
EW Extraction Wells
IW Injection Wells
Property Boundary
Ti Zone
Pentachlorophenol Concentration in Groundwater
1.0 ppb October/November 1993
1.0 ppb October/November 1998
1.0 ppb November/December 2004
1.0 ppb November 2010*
1.0 ppb September 2011*
*Note: There is no Off-Property pentachlorophenol plume in 2010 or 2011.
N
Scale: 1"=1200'
0 600' 1200'

**Figure 9. On property and off property PCP plume, comparison from 1993 through 2011 for the former Koppers Oroville Wood Treatment Facility**
(USEPA 2013a)

An in situ bioremediation program was implemented in August 1998 to augment degradation of PCP in off-property groundwater. Magnesium peroxide and diammonium phosphate were periodically added to wells 26, RI-11, and RI-20A and performance evaluation data collected from monitoring wells RI-2, RI-3, RI-10, RI-12, and RI-16B (see Figure 9) and two private wells (59 and 81). The in situ bioremediation program continued until September 2009, when PCP was no longer detected in any of these wells for four consecutive quarters.

The site achieved construction completion on September 4, 2003. The preliminary close-out report documented that all remedial construction activities for the site had been completed in accordance with closeout procedures for NPL sites.

Groundwater is monitored using a dynamic groundwater monitoring optimization program. Monitoring is based on recent analytical results from individual wells. If a parameter is detected above its respective ROD standard, it is analyzed during the next quarterly event. If the detection is verified, the sampling frequency for that parameter is increased. If a constituent is not detected in a specific well above the ROD standard for four consecutive sampling rounds, its sampling frequency is decreased. The minimum sample frequency is once every two years. Remedy O&M is administered by the state of California. Currently, monitoring for carcinogenic PAHs (cPAHs) continues downgradient of the TI zone to ensure that the ROD standard of 0.007 ppb for total cPAHs is not exceeded.

### 6.1.4 Summary of Alternatives

The FS was conducted in 1989, and for purposes of evaluating alternatives, site soils were divided into four operable units. Remedial options for soils that were evaluated in the FS included capping, biological treatment (in situ biodegradation), physical treatment (soil washing), thermal treatment (off-site incineration), chemical treatment, and disposal by landfilling. During remedial design, it was determined that the dioxin/furan contamination was more widespread than originally estimated, making the alternatives listed in the ROD infeasible. ROD Amendment 1 therefore changed the remedy for soils to on-site landfilling. The selected remedial alternatives for soil are summarized in Table 15.

**Table 15. Remedial alternatives, modified from Table 4-2 of Third 5-Year Review Report** (USEPA 2008b)

| Unit Designation | ROD | ROD Amendment 1 |
|---|---|---|
| S1 | In situ biodegradation by applying water with nutrients and oxygen to soil contaminated with PCP, dioxins, furans | • Soil remedies in ROD were modified to on-site landfill in Cell No. 2 for contaminated soils from all four units (S1 through S4), as well as other contaminated soil areas not addressed in the ROD. Total area of soil to be cleaned up was 25 acres, with estimated soil volume at 100,000 cubic yards.<br>• Cleanup goals were changed to industrial use standards.<br>• ICs were implemented via a land use covenant (deed restriction). |
| S2 (includes TI zone) | Soil excavation and washing of soil contaminated with PAHs, metals, PCP, and dioxins/furans | |
| S3 | Capping of the former process area to contain PCP, PAHs, dioxins/furans, and metals until soil beneath the treating operations is accessible, with groundwater pumping to control leaching | |
| S4 | Excavation and chemical fixation of soils contaminated with arsenic and chromium. Small volume of contaminated soil can be disposed off site at a permitted landfill | |

Treatment technologies for groundwater were evaluated for the two operable units for groundwater, on-property and off-property, including physical and chemical pretreatment, bioremediation and biofiltration and carbon adsorption. Two methods for treated water discharge were evaluated: surface water discharge and recharge wells. Recharge wells had less impact on the environment than discharge to surface water, and could influence groundwater flow to enhance extraction. ROD Amendment No. 2 added in situ bioremediation to the groundwater treatment remedy and declared a TI zone for areas contaminated with PAHs and creosote DNAPL. The selected remedial alternatives for groundwater are summarized in Table 16.

**Table 16. Remedial alternatives, modified from Table 4-3 from Third Five-Year Review Report** (USEPA 2008b)

| Unit Designation | ROD | ROD Amendment 2 |
|---|---|---|
| On-property groundwater | Installation of extraction wells and treatment plant to treat contaminated water by carbon adsorption. Pretreatment required for water containing contaminants not treatable with carbon. Treated water disposed to surface water or reinjected into groundwater via injection wells. | • Augment the P&T remediation by enhanced in situ bioremediation to on-property eastern plume treatment by adding nutrients (oxygen, nitrogen, phosphorus) to on-site wells with downgradient monitoring.<br>• TI waiver for the groundwater cleanup at the former creosote pond and Cellon blowdown areas due to the presence of DNAPL (on-property western plume). Allow monitored natural attenuation (MNA) as a contingency remedy (on- and off-property plumes).<br>• Revised groundwater standards for PCP from 2.2 to 1.0 ppb and for barium from 680 ppb to 1,000 ppb. |
| Off-property groundwater | Installation of extraction wells, with contaminated water treated by carbon adsorption. Provide an alternate water supply to those residents with contaminated wells until remedial standards are met. | • Augment the P&T remediation by enhanced in situ bioremediation (on-property eastern plume). Allow MNA as a contingency remedy.<br>• Revised groundwater standards for PCP from 2.2 to 1.0 ppb and for barium from 680 ppb to 1,000 ppb.<br>• Modify alternate water supply termination criteria to provide conditions under which the use of the alternate water supply can cease. |

### 6.1.5 Regulatory and Stakeholder Involvement

USEPA encouraged public participation throughout the RI/FS process and remedial design/remedial action of the project. Fact sheets were sent to the public at key progress points in the investigation and site cleanup. Informational meetings and site tours were held during remedial design/remedial action process and representatives of public agencies and local citizen groups invited to attend. Remedial design/remedial action documents were also sent to local libraries.

## 6.1 Koppers Oroville Wood Treatment Facility, California

The Koppers Oroville site is a former wood treating facility that operated from 1948 until it closed in 2001. The site occupies approximately 205 acres in Butte County, California, near the City of Oroville (Figure 7). The site is bounded by the former Louisiana-Pacific Lumber Mill to the west, Georgia Pacific Way to the north, and Bagget-Marysville Road to the south and east. Land use surrounding the site is a mixture of residential, industrial, and agricultural uses. As of 2015, approximately 10,650 people lived within a three-mile radius of the site and rely on groundwater as their source of drinking water.

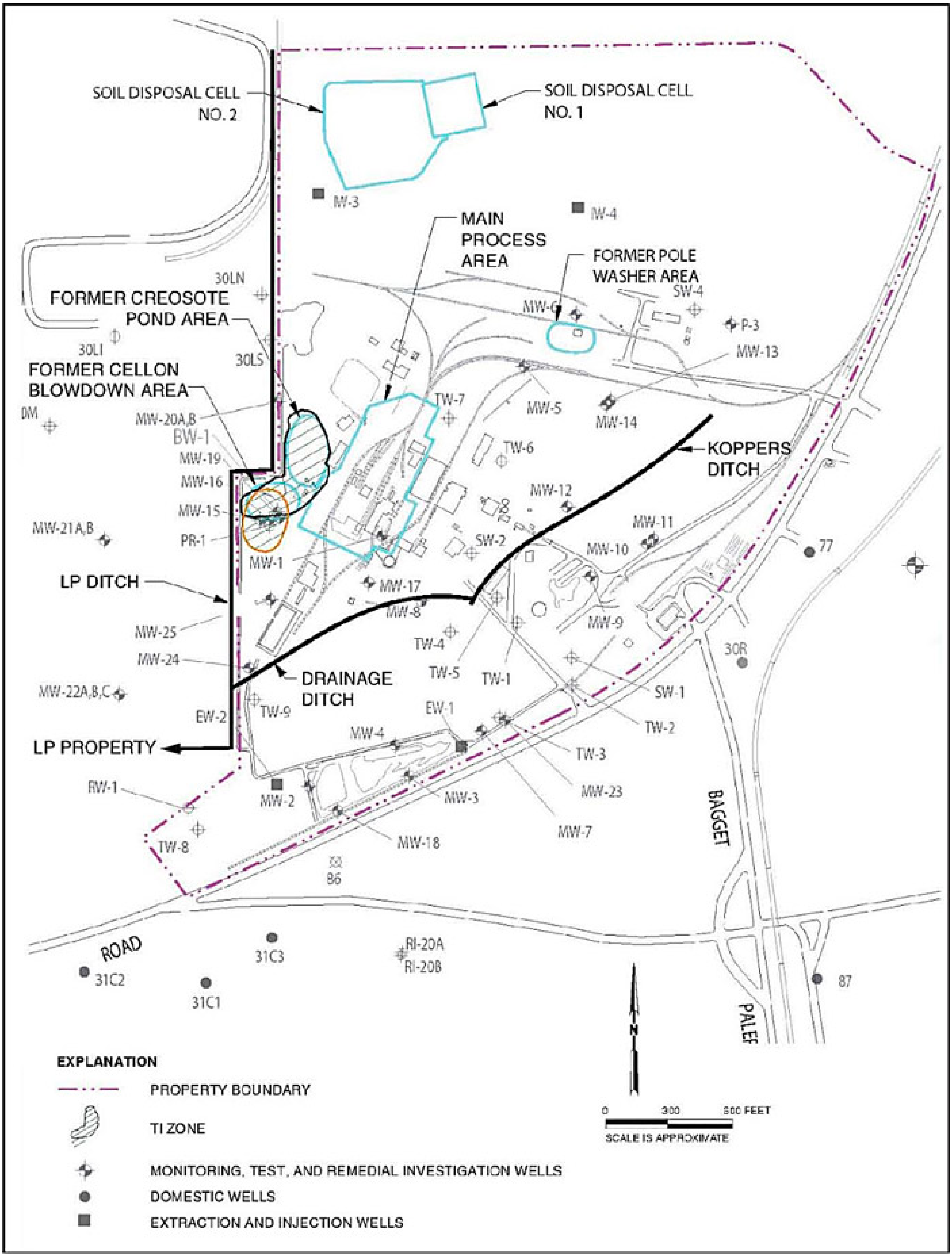


**Figure 7. Site features, former Koppers Oroville Wood Treatment Facility** (USEPA 2013a)**.**

During the early 1900s, the area around the Koppers site was used for gold mining dredge operations. From approximately 1920 to approximately 1948, the site was operated by Hutchison Lumber Mill. In 1948, National Wood Treating Company purchased the site and began operating a wood treatment plant. In 1955, Koppers Company purchased the site and continued wood treating operations. In 1988, Beazer East, Inc (Beazer) purchased Koppers Company. Beazer later resold the wood treating operation back to Koppers Industries, Inc, which continued to operate the plant until 2001. Beazer retained responsibility for all cleanup actions.

The main areas of operation at the site (Figure 7) included a wood processing area (main process area) and creosote settling ponds. From 1961 until 1973, blowdown from a Cellon wood treatment process was released into about an acre near the western site boundary (Cellon blowdown area). In 1963, a pole washing unit was installed in the northern portion of the plant site. From 1963 through 1973, equipment was used to spray a solution of water and sodium hydroxide on the Cellon-treated poles to both remove excess pentachlorophenol (PCP) from the pole surface and to prevent formation of PCP crystals on the wood surface. Wastewater from the process was not contained, and much of this wastewater flowed to a small depression just south of the pole washer.

Because of wood treating operations, the site became contaminated with wood-treatment chemicals, including PCP, creosote, and polynuclear aromatic hydrocarbons (PAHs), as well as heavy metals including copper, chromium, and arsenic. Wood treatment solutions dripped onto the ground as the treated woods were removed from process areas and otherwise handled. Wastewater from wood-treating processes were collected in unlined ponds. Boron, which was used as a fire suppressant, is also present. Two fires (1963 and 1987) resulted in releases of PCP and dioxins/furans to site soils. PCP is present as DNAPL at the site.

The geological formations underlying the site include alluvial gravels, sands, and clays that were deposited by the Feather River and its ancestral river systems. Several interconnected aquifer zones have been defined in the area. The first encountered groundwater at the site occurs in the gravels of the Laguna formation and in the Mehreten formation in some areas. Groundwater in the Ione formation is brackish and saline and is separated from overlying freshwater aquifers by low permeability clays. Perched groundwater exists in areas scattered throughout the site.

The complexities at the site include creosote DNAPL in the vadose zone, groundwater contamination off site and on site, off-site contamination of private drinking water wells, and extensive soil contamination requiring on-site landfilling. Although off-site groundwater contamination has been significantly abated, DNAPL remains on site. Long term groundwater monitoring and long-term maintenance of the on-site landfills are required.

### 6.1.1 Technical Basis for Remedial Action

In 1988, an RI report summarized the results from soil sampling investigations in 1981, 1986 (Phase 1), and 1987 (Phase 1B). Soil samples were analyzed for a variety of chemical constituents. The major contaminants found in on-site soils include PCP, creosote compounds, and metals used in the chromated copper arsenate treatment process. Other chemical species detected included isopropyl ether, boron, PCP breakdown products, and dioxins/furans. Contaminated areas included the PCP mix area, the PCP treated wood quality control area, the pole washer area, the chromated copper arsenate treated wood storage areas, and areas along all tram tracks used to transport PCP-treated poles.

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Chemical preservatives including PCP, creosote, and chromated copper arsenate were dripped onto site soils as the treated wood was handled. Additionally, wastewaters from creosote and PCP wood treating processes were discharged directly to unlined ponds near the western boundary of the plant. Contaminated soil became airborne due to traffic and wind erosion. Surface water runoff passing over contaminated soils resulted in contaminated surface waters and sediments. Contaminants in soil leached into groundwater beneath the site. The following COCs were present in groundwater above their respective ROD cleanup levels: PCP, isopropyl ether, dioxins/furans, PAH, boron, and benzene. Contaminated groundwater migrated beyond the site boundary in a plume that extends approximately two miles south of the site. Two distinct PCP plumes on the property are attributed to activities at the former pole washer area and process area (eastern plume) and to PCP cosolved in creosote DNAPL under the former creosote pond area and former Cellon blowdown area (western plume).

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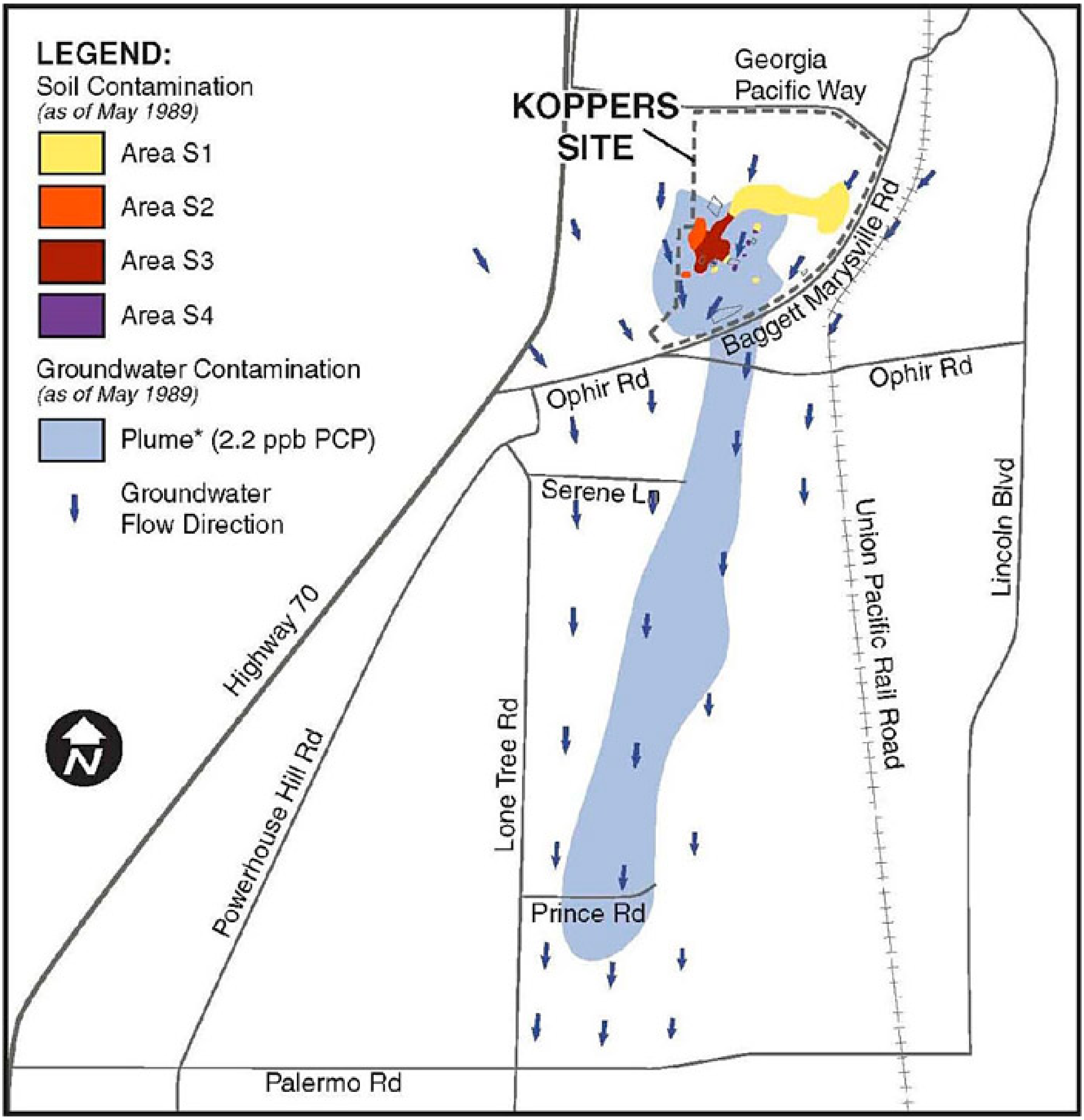


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In situ bioremediation was conducted to remediate PCP in 1998. Oxygen-releasing compounds (ORCs), including magnesium peroxide and diammonium phosphate (DAP), were periodically added to six on-property wells to supply nitrogen and phosphorous and enhance bioremediation.

***Western On-Property Plume***

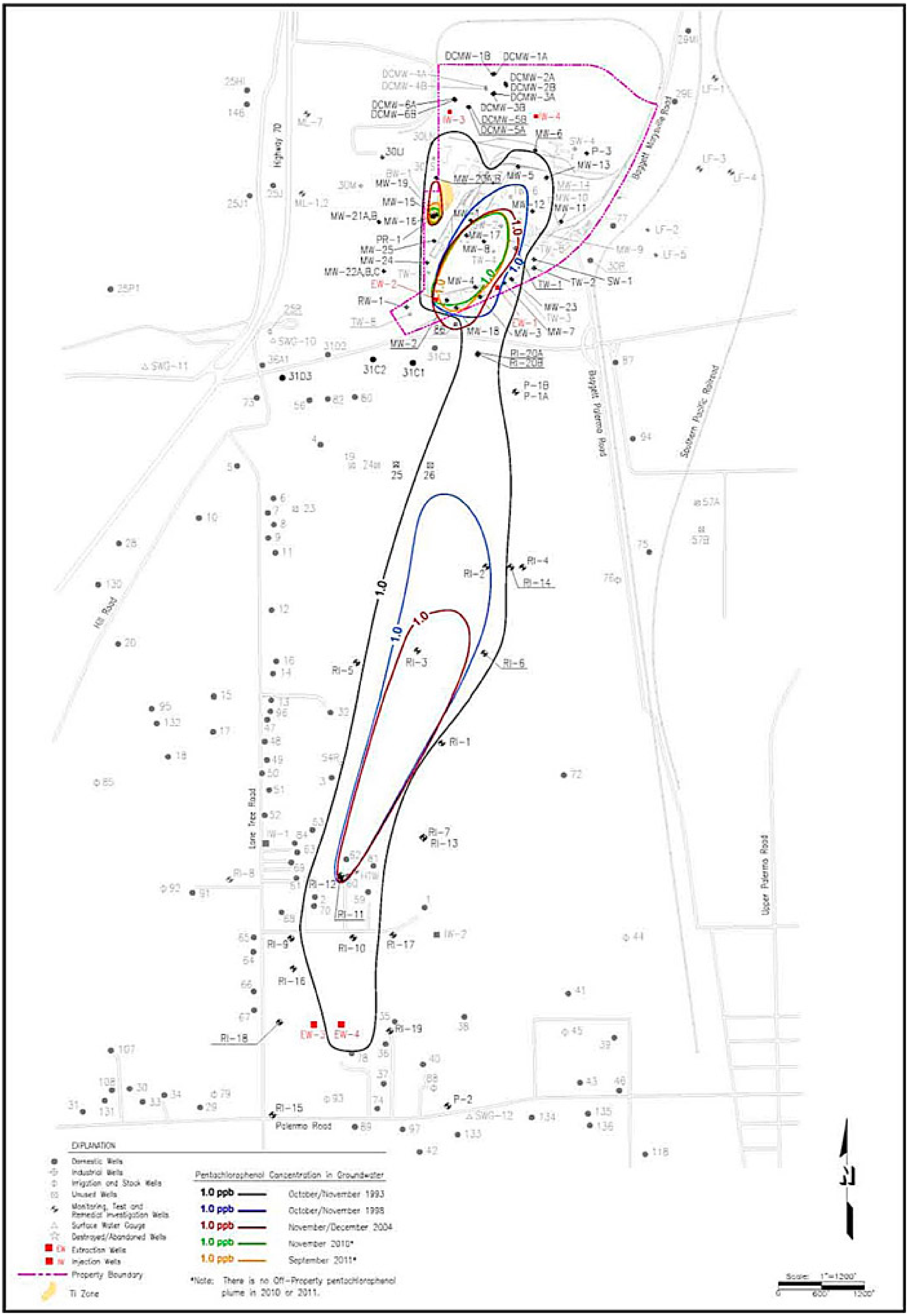
The western plume is located below the former Cellon blowdown area and former creosote pond area. In September 1994, a passive recovery well (PR-1) was installed in the western plume to evaluate whether the subsurface pools of creosote at the site could be effectively remediated by draining the fluid into a recovery well. The well has two separate screened intervals. Each 10-foot screen is located immediately above a clay lens, where free creosote is perched. The mobile creosote enters the well through the screened intervals and collects in a 5-foot deep sump at the bottom of the well. Fluid is purged periodically from the well and taken to an off-site location for disposal. From 1994 to July 2007, approximately 1,300 gallons of DNAPL were recovered.

In 1999, about four acres surrounding the former creosote pond and Cellon blowdown areas were declared a TI zone in the ROD Amendment No. 2. This TI zone occurred because both the existing P&T system and in situ PAH bioremediation failed to remedy the DNAPLs present in the clay layers beneath this area. Currently, monitoring for carcinogenic PAHs (cPAHs) continues downgradient of the TI zone to ensure that the ROD standard for total cPAHs is not exceeded.

***Off-Property Plume***

Beginning in March 1986, an alternate water supply was provided to 34 residences downgradient of the site, within the off-property plume area. The alternate water supply for those affected by the groundwater contamination was formalized in the ROD. A total of 26 residents were taken off the alternate water supply in 1998 after their wells met the cleanup criteria, as well as another residence in 2001.

An off-property groundwater treatment system was installed south of Prince Road (Figure 9). Two extraction wells (EW-3 and EW-4) were installed at the toe of the two-mile plume (Figure 9) along with a treatment plant, two injection wells, and approximately 1,500 feet of pipelines. Initially, treated water was discharged to Wyman Ravine. Later, this water was reinjected upgradient of the off-property plume into injection wells IW-1 and IW-2. The P&T system was shut down in December 1995 and dismantled in 2007, after monitoring indicated that the plume had retreated upgradient of the extraction wells. During its operation, the system treated over 626 million gallons of contaminated groundwater.



DCMW-1B
DCMW-1A
DCMW-2A
DCMW-2B
DCMW-3A
DCMW-3B
DCMW-4A
DCMW-4B
DCMW-6A
DCMW-6B
DCMW-5B
DCMW-5A
IW-3
IW-4
MW-6
MW-5
MW-13
MW-19
MW-15
MW-16
MW-21A,B
MW-12
MW-11
MW-17
MW-8
MW-25
MW-24
MW-22A,B,C
MW-4
MW-23
MW-18
MW-3
MW-7
MW-2
MW-9
PR-1
RW-1
EW-1
EW-2
EW-3
EW-4
TW-1
TW-2
TW-3
TW-6
SW-1
SW-4
P-3
P-1B
P-1A
P-2
RI-20A
RI-20B
RI-1
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RI-10
RI-11
RI-12
RI-13
RI-14
RI-15
RI-16
RI-17
RI-18
RI-19
IW-1
IW-2
LF-1
LF-2
LF-3
LF-4
LF-5
ML-7
ML-1,2
SWG-10
SWG-11
SWG-12
31D3
31C2
31C1
31C3
31D2
36A1
Highway 70
Baggett Marysville Road
Baggett Palermo Road
Southern Pacific Railroad
Upper Palermo Road
Lone Tree Road
Hill Road
Palermo Road
1.0
EXPLANATION
Domestic Wells
Industrial Wells
Irrigation and Stock Wells
Unused Wells
Monitoring, Test and Remedial Investigation Wells
Surface Water Gauge
Destroyed/Abandoned Wells
EW Extraction Wells
IW Injection Wells
Property Boundary
Ti Zone
Pentachlorophenol Concentration in Groundwater
1.0 ppb October/November 1993
1.0 ppb October/November 1998
1.0 ppb November/December 2004
1.0 ppb November 2010*
1.0 ppb September 2011*
*Note: There is no Off-Property pentachlorophenol plume in 2010 or 2011.
Scale: 1"=1200'
0
600'
1200'
N

**Figure 9. On property and off property PCP plume, comparison from 1993 through 2011 for the former Koppers Oroville Wood Treatment Facility**
(USEPA 2013a)

An in situ bioremediation program was implemented in August 1998 to augment degradation of PCP in off-property groundwater. Magnesium peroxide and diammonium phosphate were periodically added to wells 26, RI-11, and RI-20A and performance evaluation data collected from monitoring wells RI-2, RI-3, RI-10, RI-12, and RI-16B (see Figure 9) and two private wells (59 and 81). The in situ bioremediation program continued until September 2009, when PCP was no longer detected in any of these wells for four consecutive quarters.

The site achieved construction completion on September 4, 2003. The preliminary close-out report documented that all remedial construction activities for the site had been completed in accordance with closeout procedures for NPL sites.

Groundwater is monitored using a dynamic groundwater monitoring optimization program. Monitoring is based on recent analytical results from individual wells. If a parameter is detected above its respective ROD standard, it is analyzed during the next quarterly event. If the detection is verified, the sampling frequency for that parameter is increased. If a constituent is not detected in a specific well above the ROD standard for four consecutive sampling rounds, its sampling frequency is decreased. The minimum sample frequency is once every two years. Remedy O&M is administered by the state of California. Currently, monitoring for carcinogenic PAHs (cPAHs) continues downgradient of the TI zone to ensure that the ROD standard of 0.007 ppb for total cPAHs is not exceeded.

### 6.1.4 Summary of Alternatives

The FS was conducted in 1989, and for purposes of evaluating alternatives, site soils were divided into four operable units. Remedial options for soils that were evaluated in the FS included capping, biological treatment (in situ biodegradation), physical treatment (soil washing), thermal treatment (off-site incineration), chemical treatment, and disposal by landfilling. During remedial design, it was determined that the dioxin/furan contamination was more widespread than originally estimated, making the alternatives listed in the ROD infeasible. ROD Amendment 1 therefore changed the remedy for soils to on-site landfilling. The selected remedial alternatives for soil are summarized in Table 15.

**Table 15. Remedial alternatives, modified from Table 4-2 of Third 5-Year Review Report** (USEPA 2008b)

<table>
<tr><th>Unit Designation</th><th>ROD</th><th>ROD Amendment 1</th></tr>
<tr><td>S1</td><td>In situ biodegradation by applying water with nutrients and oxygen to soil contaminated with PCP, dioxins, furans</td><td rowspan="4">• Soil remedies in ROD were modified to on-site landfill in Cell No. 2 for contaminated soils from all four units (S1 through S4), as well as other contaminated soil areas not addressed in the ROD. Total area of soil to be cleaned up was 25 acres, with estimated soil volume at 100,000 cubic yards.<br>• Cleanup goals were changed to industrial use standards.<br>• ICs were implemented via a land use covenant (deed restriction).</td></tr>
<tr><td>S2 (includes TI zone)</td><td>Soil excavation and washing of soil contaminated with PAHs, metals, PCP, and dioxins/furans</td></tr>
<tr><td>S3</td><td>Capping of the former process area to contain PCP, PAHs, dioxins/furans, and metals until soil beneath the treating operations is accessible, with groundwater pumping to control leaching</td></tr>
<tr><td>S4</td><td>Excavation and chemical fixation of soils contaminated with arsenic and chromium. Small volume of contaminated soil can be disposed off site at a permitted landfill</td></tr>
</table>

Treatment technologies for groundwater were evaluated for the two operable units for groundwater, on-property and off-property, including physical and chemical pretreatment, bioremediation and biofiltration and carbon adsorption. Two methods for treated water discharge were evaluated: surface water discharge and recharge wells. Recharge wells had less impact on the environment than discharge to surface water, and could influence groundwater flow to enhance extraction. ROD Amendment No. 2 added in situ bioremediation to the groundwater treatment remedy and declared a TI zone for areas contaminated with PAHs and creosote DNAPL. The selected remedial alternatives for groundwater are summarized in Table 16.

**Table 16. Remedial alternatives, modified from Table 4-3 from Third Five-Year Review Report** (USEPA 2008b)

| Unit Designation | ROD | ROD Amendment 2 |
|---|---|---|
| On-property groundwater | Installation of extraction wells and treatment plant to treat contaminated water by carbon adsorption. Pretreatment required for water containing contaminants not treatable with carbon. Treated water disposed to surface water or reinjected into groundwater via injection wells. | • Augment the P&T remediation by enhanced in situ bioremediation to on-property eastern plume treatment by adding nutrients (oxygen, nitrogen, phosphorus) to on-site wells with downgradient monitoring.<br>• TI waiver for the groundwater cleanup at the former creosote pond and Cellon blowdown areas due to the presence of DNAPL (on-property western plume). Allow monitored natural attenuation (MNA) as a contingency remedy (on- and off-property plumes).<br>• Revised groundwater standards for PCP from 2.2 to 1.0 ppb and for barium from 680 ppb to 1,000 ppb. |
| Off-property groundwater | Installation of extraction wells, with contaminated water treated by carbon adsorption. Provide an alternate water supply to those residents with contaminated wells until remedial standards are met. | • Augment the P&T remediation by enhanced in situ bioremediation (on-property eastern plume). Allow MNA as a contingency remedy.<br>• Revised groundwater standards for PCP from 2.2 to 1.0 ppb and for barium from 680 ppb to 1,000 ppb.<br>• Modify alternate water supply termination criteria to provide conditions under which the use of the alternate water supply can cease. |

### 6.1.5 Regulatory and Stakeholder Involvement

USEPA encouraged public participation throughout the RI/FS process and remedial design/remedial action of the project. Fact sheets were sent to the public at key progress points in the investigation and site cleanup. Informational meetings and site tours were held during remedial design/remedial action process and representatives of public agencies and local citizen groups invited to attend. Remedial design/remedial action documents were also sent to local libraries.

## 6.2 Moffett-MEW Regional Plume, California

For more than three decades, the Former Naval Air Station Moffett Field and Middlefield-Ellis-Whisman (MEW) Superfund Site regional plume (Moffett-MEW Regional Plume) has been one of the most challenging groundwater remediation projects facing the nation. Despite the hundreds of millions of dollars spent on characterization and remediation, it is likely to take many more decades to achieve RAOs. The site is complex in its sources, hydrogeology, pathways, and land use. Multiple source areas contribute to comingled source areas and comingled groundwater plumes. Complex hydrogeology makes characterization and remediation challenging. The multiple responsible parties performed numerous site investigations over many years, and making sense of the massive amount of data has proven challenging. The regional plume has multiple responsible parties, including two federal agencies and six large industrial companies. State agencies are party to the original Navy and recent NASA Federal Facility Agreements, but USEPA is the sole oversight authority for the private-party portion of the plume. The site has served as a national model for both public participation and property reuse, and is emerging as a model for adaptive site management.

The Moffett-MEW project consists of four NPL sites in Mountain View: Fairchild Semiconductor, Intel, Raytheon, and portions of the former Moffett Naval Air Station, also known as Moffett Field. Beginning in 1981, investigations conducted under the supervision of the Bay Area Regional Water Quality Control Board identified groundwater and soil contamination caused by leaking underground industrial storage tanks throughout Silicon Valley, where Mountain View is located. The largest releases took place in or near a 0.5 square mile industrial park roughly bounded by U.S. Highway 101 and Middlefield Road, Ellis Street, and Whisman Road. Some of the groundwater contamination flowed North under U.S. Highway 101, where it mixed with the largest of three groundwater plumes at Moffett Field. In 1990, USEPA issued a Unilateral Administrative Order to Fairchild, its successor Schlumberger, and seven other companies, and early the next year Intel and Raytheon signed a Consent Decree with USEPA.

The MEW site was home to several semiconductor and other electronics manufacturing facilities and metal finishing facilities. While in operation, these former facilities required the storage, handling, and use of a variety of chemicals, particularly volatile organic compounds (VOCs). The primary chemicals of concern at the MEW site are trichloroethene (TCE) and its degradation products: cis-1,2-dichloroethene and vinyl chloride. During operations, some of the chemicals leaked or were otherwise released to the ground, contaminating soil and groundwater. In 1981 and 1982, investigations at these facilities confirmed that high concentrations of these contaminants remained in the soil and groundwater.

Much of the area has been either redeveloped or proposed for reuse by tech companies, after the original manufacturing companies moved to cut costs. For the most part, the reuse has been considered a great success, and in 2000 it was documented in USEPA's Superfund Reuse Initiative brochure. Today the MEW area houses companies such as Google and Symantec and has desirable commercial real estate. Developers are now interested in building new tech-industry offices above the source areas and in residential redevelopment of contaminated areas just west of the main plume. The area land use is now a mix of industrial and residential facilities, creating a complex mix of complete pathways that must be evaluated in any risk assessment. Drinking water wells for the City of Mountain View are located a half mile upgradient of the site to the southwest. These wells provide a fraction of the city's current supply and serve as a contingency supply. In 1986, Mountain View shut down its largest supply well, in part because it was a half-mile from the regional plume.

### 6.2.1 Technical Basis for Remedial Action

Each individual MEW company is responsible for investigation, remediation, and source control for soil and groundwater contamination at their individual properties south of U.S. Highway 101. By 1988, the private parties had installed more than 400 monitoring wells in eight aquifer zones. In 1989, the Navy began a thorough investigation to determine the type and extent of contamination throughout the base. The areas investigated included: east and west side contaminated soils, the west side aquifers, the east side aquifer, three landfills, and the wetlands area. By 2004 there were more than 1,200 monitoring wells throughout the plume. Contaminated groundwater that bypassed the source control areas and mixed together with other contaminated groundwater from other source areas is considered part of the regional groundwater contamination plume, or the "regional plume."

TCE has been the principal risk driver. Using conventional groundwater sampling techniques, concentrations in the upper aquifer reached 1,000,000 ppb. Other chemicals of concern include: tetrachloroethene (PCE), cis- and trans-1,2-dichloroethene, vinyl chloride, 1,1-dichloroethane, 1,1-dichloroethene, 1,1,1-trichloroethane, Freon-113, chloroform, and 1,2-dichlorobenzene. At the Raytheon site 1,4-dioxane was also detected, prompting a change in treatment technology in 2003. Contamination has been identified in the vadose zone and in all aquifers, including localized detections of TCE in the deep aquifer (at depths up to 500 feet). The main shallow A-zone aquifer plume is nearly two miles long and more than a half mile wide (Figure 10).

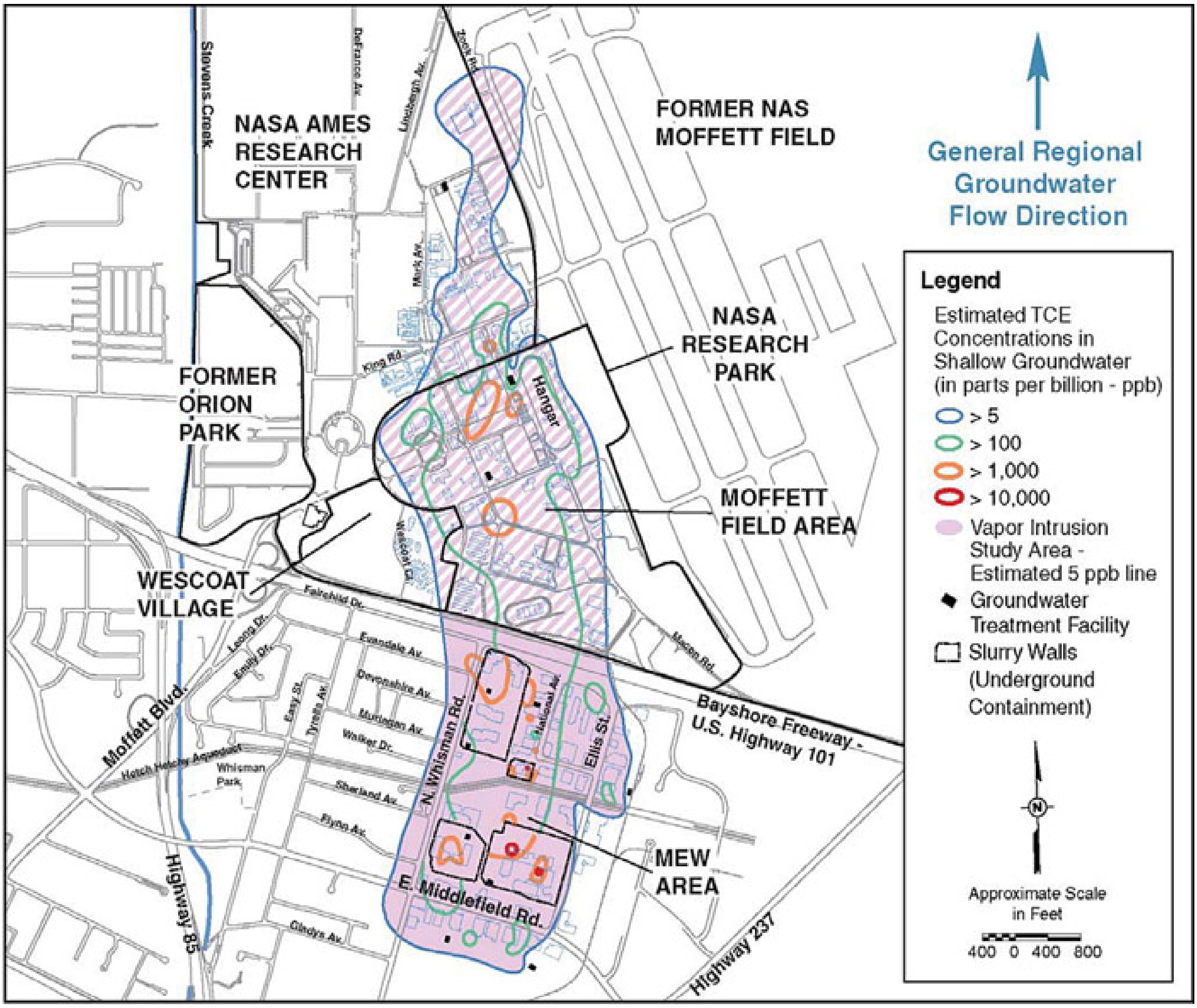



**Figure 10. Estimated extent of regional TCE in shallow groundwater and vapor intrusion study area** ([USEPA 2010d](#))**.**

In general, contamination migrated northward in groundwater flowing toward the San Francisco Bay. Some TCE also moved downward, into several aquifers in a mix of interbedded sands, silts and clays, and some dechlorination occurred, as evidenced by the appearance of TCE degradation products. On Moffett Field federal facility property, degradation was more pronounced as PCE and TCE came into contact with a separate petroleum spill. Under California's Porter-Cologne Act, all aquifers not affected by naturally occurring saltwater intrusion are protected as potential drinking water sources, but a special effort was made to identify and contain the descent of TCE and other compounds to the deep "C" aquifer. Cross contamination of aquifers occurred despite these efforts. When officials discovered that TCE had passed through two abandoned but unsealed agricultural wells and into the deep aquifer, the companies found and sealed as many as 16 old, deep wells (Figure 11).

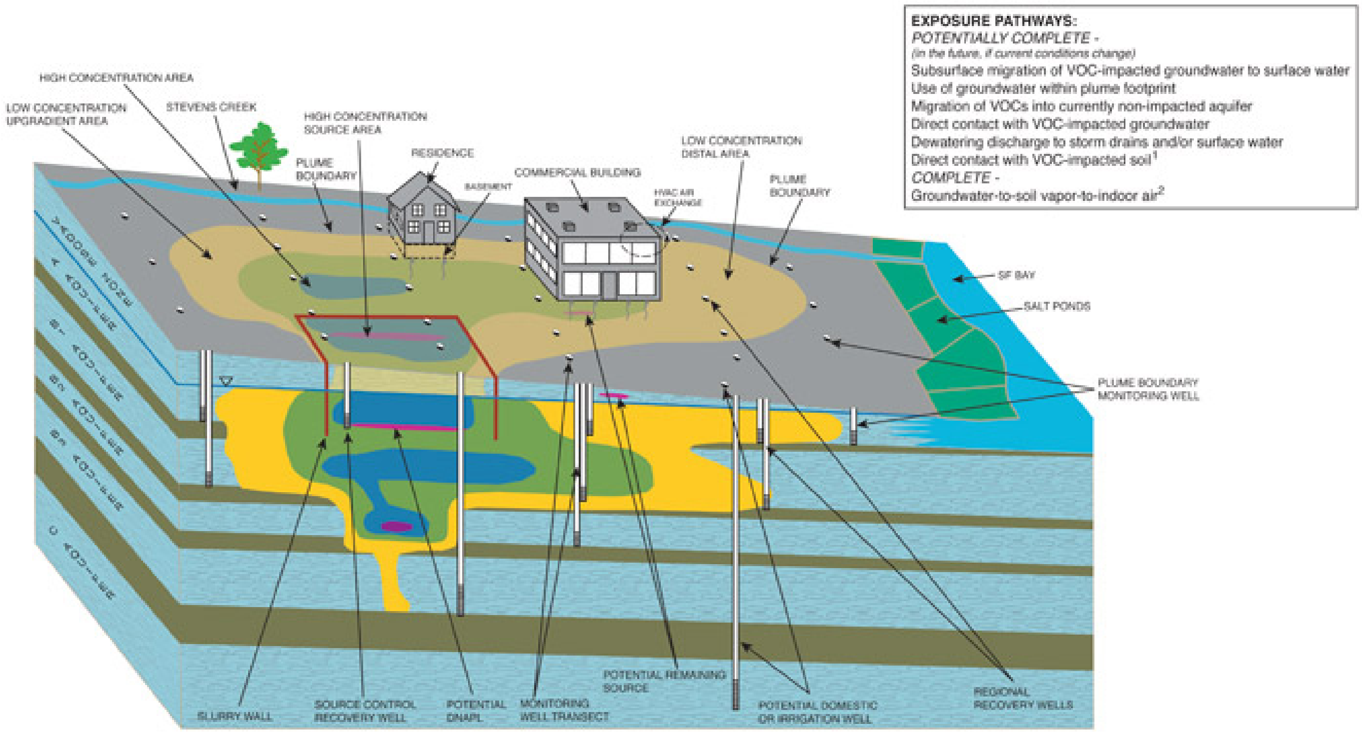



**Figure 11. CSM for Moffett-MEW regional plume** (USEPA 2012f)**.**

### 6.2.2 Decisions

At varying speeds and at different times, each of the responsible parties responded to the discovery of subsurface contamination at over 30 areas of concern by excavating contaminated soil, operating SVE systems, beginning localized groundwater extraction and treatment, and building slurry walls around four source zones.

In June 1989, USEPA issued a ROD selecting the soil and groundwater remedy for the MEW Site. The soil remedy included: (1) excavation, with treatment by aeration; and (2) SVE, with treatment by vapor phase granular activated carbon. Soil remediation has been completed at all the former MEW facilities.

The ROD and subsequent Unilateral Administrative Order and the Consent Decree to allocate responsibility and funding obligations for the regional plume specified the following groundwater remedy:

- slurry wall installation, and the maintenance of upward, inward gradients within the slurry walls, to contain contaminant source areas
- two regional groundwater treatment systems (north and south of U.S. Highway 101) to contain and clean up groundwater contamination using granular activated carbon and/or air strippers.

Groundwater extraction and treatment began at the MEW site in the 1980s and is ongoing. Groundwater remediation is expected to continue for many decades until concentrations of TCE and other COCs meet site objectives. The ROD established a TCE site objective of 5 ppb in the shallow aquifers and 0.8 ppb in the C aquifer and below. Groundwater is not currently used for drinking water or other household uses.

In 1990 and 1996, USEPA issued ESDs to clarify soil and groundwater site objectives and specify the use of liquid-phase granular activated carbon for groundwater treatment. By 2002, soil cleanup had been completed, the plume had been stabilized, and TCE concentrations had been reduced by more than 75%. The site was considered a Superfund success story, and the reuse was well underway with high profile companies occupying the site. The first Five-Year Review (USEPA 2004a) made the following recommendations:

- Continue to verify long-term protectiveness by monitoring the extent of groundwater contamination along the A/A1 and B1/A2 Aquifer plume boundaries.
- Optimize both the regional and facility-specific systems to enhance plume capture, and evaluate applicable technologies to expedite mass removal and decrease remediation time frames.
- Evaluate buildings overlying the shallow TCE plume to identify potential pathways into buildings, and implement

mitigation measures to reduce elevated levels in indoor air.

The last finding incorporated new understanding about subsurface migration of TCE and other VOCs into overlying buildings through the vapor intrusion (VI) pathway and new or revised toxicity information for TCE from 2001. Regulators, responsible parties, and the community are still addressing all three of these issues.

A ROD Amendment was issued in 2010 for a newly designated operable unit and described a VI remedy. USEPA established a new site objective as follows:

> *To accelerate the reduction of the source of VI (i.e., Site contaminants in shallow groundwater and soil gas) to levels that are protective of current and future building occupants, such that the need for a VI remedy would be minimized or no longer be necessary.*

The ROD Amendment required indoor air sampling and other lines of evidence to assess VI in existing buildings and the installation, O&M, and monitoring of a subslab/submembrane ventilation system (or use and monitoring of current mechanical ventilation systems for commercial buildings) to meet performance criteria and RAOs. Any new construction was required to install a vapor barrier and passive subslab ventilation system that could be made active. ICs and monitoring were required to ensure long-term effectiveness of the VI remedy. The VI remedy is currently being implemented.

VI was not the only argument for reopening the MEW remedy. The regional extraction system worked well—over 104,000 pounds of TCE and other VOCs had been removed. The average TCE concentration had fallen 90% by 2009, with up to 40,000 ppb TCE remaining south of Highway 101 and up to 4,700 ppb at Moffett. However, the Second Five-Year Review in 2009 found that the remedy's cost efficiency and potential for achieving cleanup goals were decreasing and that optimization evaluations were needed. The same review found that slurry walls were not fully functioning as intended and that some chemical migration was occurring across the slurry walls (meaning that despite two decades of pumping, the plume had not separated itself from the source areas). USEPA consequently prepared a Supplemental FS to update the groundwater remedy and is currently conducting optimization and pilot studies.

### 6.2.3 Assessment

The RI/FS for MEW was completed in 1988. The Navy signed a Federal Facility Agreement in 1993 to implement the remedy. The RI indicated that contaminated groundwater posed the highest risk to human health. Incremental lifetime cancer risks (ILCR) without remedial action from drinking from hypothetical shallow wells on the property ranged from $1\times10^{-2}$ to $9\times10^{-3}$. In 2002, the VI pathway was recognized as a possible risk and actual indoor air concentrations exceeding USEPA's cancer and noncancer exposure standards were found in several commercial and a few residential buildings.

Although groundwater extraction and treatment has been the principal groundwater remedy for the regional plume, numerous projects have demonstrated or used innovative technologies at the site. In 1996, the Navy teamed with Stanford University in one of the earliest demonstrations of permeable reactive barriers. In 2005, the Navy conducted an optimization analysis and installed an additional extraction well in the lower A Aquifer to enhance plume capture in that hydraulic zone. The same year, Raytheon and Intel employed enhanced in situ bioremediation at a site on the southern side of Middlefield Road where groundwater capture was weak. Over the course of the next nine years, they injected multiple rounds of carbon substrate, such as emulsified soybean oil, with and without bioaugmentation. Ongoing monitoring shows that enhanced bioremediation continues to be effective and that the pilot test has not affected indoor air. Between 2010 and 2012, the Navy conducted an in situ anaerobic biotic/abiotic treatment pilot test at three Regional Plume locations, with similar success.

By the time the groundwater treatment systems were activated, MEW parties prepared a Plume Definition Report showing that the plume's boundaries, in all contaminated zones, had been well defined. One polluted private well remained, about 1,000 feet west of the identified plume, but no proof connected this contamination to the main site. For years, most plume maps drew the TCE 5 ppb isopleth down the middle of Whisman Road. Around 2004, when VI became a major community issue, a resident on the west side of Whisman Road, just outside the official plume, requested that the air inside her home be tested. When the indoor air was eventually tested, unacceptable levels of VI were confirmed. The responsible parties installed mitigation fans in her dirt basement. When this information came before the Northeast Mountain View Advisory Council, community members suggested that the extensive groundwater monitoring network was not dense enough to define areas susceptible to VI.

Gradually, USEPA and the responsible parties installed more wells along the plume boundaries (Figure 12). While most of the sampling confirmed the interpolated values shown on contour maps, in 2012 high levels of TCE were found in the shallow aquifer along Evandale Ave, west of the plume near U.S. 101. USEPA identified four TCE hotspot areas exceeding 1,000 ppb away from the major plume. Soil gas sampling suggested these were not the results of localized surface releases, but they did coincide with a zig-zagging municipal sewer line. In 2015 USEPA concluded, after extensive investigation, that the historical TCE releases from industrial facilities into the sanitary sewer line, which had served the MEW industrial area until 1966, was the source of high TCE groundwater hotspot areas to the west of the previously defined 2012 TCE Regional Plume boundary. USEPA considers the TCE hot spot areas and extent of TCE contamination as part of the MEW Superfund site and has designated another Operable Unit 3 to which the groundwater and VI remedies in the 1989 ROD and 2010 ROD Amendment applies. USEPA continues to investigate all PRPs related to the new Operable Unit contamination.


**Figure 12. Delineating the plume in the adjacent residential area.**
(CPEO 2016b, inset from USEPA 2015b)

In October 2002, launching one of USEPA's first major VI investigations nationally, the agency sent letters to the MEW Responsible Parties requiring that they submit work plans "to conduct a human health risk assessment to evaluate the groundwater to indoor air exposure pathway by collecting indoor air, outdoor air, and soil gas samples at each Facility." Concurrently, USEPA's RCRA Corrective Action program undertook a similar investigation at the nearby former GTE property. When local citizens heard about the new investigations, they requested a public meeting. USEPA convened a meeting in January 2003, which over 400 people attended. Many attendees were from the new, upscale Whisman Station housing development located above and around GTE's smaller, lower concentration TCE plume areas.

Between 2003 and 2009, the MEW Companies, NASA, Navy, and USEPA "collected over 2,800 indoor, outdoor, ambient, pathway, background, and duplicate samples at 47 commercial buildings and 31 residences in the VI Study Area (defined as the area over the estimated 5 ppb TCE concentration in the shallow groundwater plume, with an additional 100-foot buffer). Buildings with various types of foundations (concrete slab-on-grade, crawlspace, and earthen cellar) were sampled." (USEPA

2009a). As USEPA better delineated the shallow plume, it found that a 100-foot buffer was unnecessary, but the Study Area grew.

A Supplemental RI supported the following key conclusions:

- There were no immediate or short-term health concerns.
- TCE was detected above USEPA's long-term health-protective levels in several commercial buildings and a few residences within the VI Study Area.
- Discrete mitigation measures (for example, sealing cracks/conduits, upgrading/modifying ventilation systems, and installing air purifying systems) that were implemented in buildings with indoor air concentrations exceeding USEPA's health-protective levels were successful in reducing indoor TCE concentrations to below the health-protective levels.

To date, at least 117 nonresidential buildings have been sampled, with over 40 requiring some form of mitigation beyond the normal operation of heating, ventilation, and air conditioning systems (Figure 13). Over 140 residences along the plume's western boundary, near the Evandale Operable Unit of the plume, and at Moffett's Wescoat Military Housing area have also been sampled, along with schools and childcare centers in the area. Only a handful have required active mitigation as described in the 2010 ROD Amendment.


**Figure 13. Building where TCE VI is being addressed** (CPEO 2016a)**.**

## 6.2.4 Summary of Alternatives

In the 1980s, the FS identified an array of remediation technologies that were potentially applicable and then screened those technologies. A list was prepared of applicable technologies, and alternatives were considered from this list if they were appropriate for soil, disconnected shallow aquifers (mostly those areas already inside slurry walls), connected shallow aquifers, and deep aquifers. An early application of slurry walls was already in place and accepted as part of the treatment plan. The following technologies were evaluated:

- no further action
- in situ soil aeration (with carbon adsorption and regeneration)

- partial excavation with ambient temperature aeration (with carbon adsorption and regeneration)
- partial excavation with ambient temperature aeration and in situ aeration (with carbon adsorption and regeneration)
- hydraulic control by groundwater extraction and treatment
- hydraulic remediation by groundwater extraction and treatment
- vertical impermeable barriers
- maintain inward and upward hydraulic gradients (with treatment of extracted water)

### 6.2.4.1 Supplemental FS

After the Second Five-Year Review in 2009, USEPA began a systematic effort to replace the primary remedy, groundwater P&T systems, with more innovative, sustainable technologies. Progress has been slowed by the size and complexity of the site. As stated in the Second Five-Year Review:

> *At several of the facilities, the remedy's cost efficiency and potential for achieving cleanup goals are decreasing with continued operation, due to decreasing influent VOC concentrations and declining mass removal efficiency. Estimates in the 1989 ROD for the time required to reach the TCE cleanup level for the Deeper Aquifers is between 2 to 45 years. For the shallow aquifers, the cleanup time was estimated to be considerably longer—from 46 years into the indefinite future—because the shallow aquifers are low-yielding and contain soils with high clay content that attracts and retains site chemicals.*

USEPA consequently began work on a Supplemental FS to update the groundwater remedy, focusing on the uppermost aquifer. Contamination in the shallow aquifer is the source of VI risks; existing remedies in the lower aquifers were on track to achieve the site objectives. In 2012, the Supplemental Site-wide Groundwater FS for the MEW Site considered the following technologies to optimize or expedite groundwater remediation (USEPA 2012f):

- in situ oxidation or reduction (redox) treatment
  - in situ chemical oxidation (ISCO)
  - enhanced reductive dechlorination (ERD)
  - abiotic dechlorination using zerovalent iron (ZVI)
- extraction, removal, treatment and disposal
  - in situ flushing
  - air sparging
  - groundwater circulation wells, in-well vapor stripping
  - groundwater extraction and treatment (GWET)
  - multiphase extraction
  - thermal treatment
  - excavation
- subsurface barriers
  - permeable reactive barriers (PRB)
  - slurry walls
  - phytoremediation
- MNA

The Supplemental FS identified five alternatives that combined groundwater extraction and treatment, MNA, targeted in situ redox treatment, and permeable reactive barriers. Targeted in situ redox treatment referred to using any of three in situ redox technologies (in situ chemical oxidation, enhanced reductive dechlorination, or zero valent iron injection). Areas proposed for treatment included all high-concentration areas (concentrations exceeding 1,000 µg/L) in the shallow aquifer and facility-specific source areas with low- to medium- concentrations. Areas where the technologies were demonstrated to be infeasible would use optimized groundwater extraction and treatment.

USEPA estimated that in situ treatment would reduce high concentrations in the target areas approximately 50% more in the first decade as compared to the current groundwater extraction remedy. Time frame estimates for the in situ treatment alternatives in the upper aquifer were based on Cleanup Time Evaluation modeling. USEPA stated that the model underestimated source zone efficacy by not accounting for surfactant effects that can greatly enhance desorption and dissolution from soil into the dissolved phase. Modeling assumed an even distribution of contaminants throughout low permeability zones; however, treatment may be more effective than modeling suggests if contaminants only partially penetrated the low-permeability zones.

Several lines of evidence suggest that natural attenuation processes are occurring in certain portions of the plume. By including MNA in three of the alternatives, USEPA indicated at some point engineered remediation could be terminated and natural processes would be relied upon to achieve the RAOs, such as a TCE groundwater concentration of 5 ppb. While the FS set criteria for transition to MNA, it did not list specific concentrations. The FS assumed, however, that 50% of the wells with a concentration of 200 ppb or lower would make the transition to MNA.

USEPA provided a detailed comparison of the alternatives, using the nine criteria of the NCP. It also estimated the cost of each alternative, based on a 50-year period. Table 17 summarizes the cost for each alternative.

**Table 17. Estimated costs for remediation alternatives**

| System | Estimated Cost |
|---|---|
| Current system (without sunken costs being accounted for) | $131 million |
| Alternative 2 (optimized system) | $162 million |
| Alternative 3 (optimized system with MNA) | $89 million |
| Alternative 4 (in situ redox, optimized system, MNA) | $141 million |
| Alternative 5 (in situ redox, PRBs, optimized system, MNA) | $171 million |

Adopting some of the newer or alternative technologies could expand the existing groundwater extraction and treatment remedy. This effort is currently on hold pending the results of additional pilot studies.

USEPA did not select a preferred alternative. Alternative 4 was considered the most protective, but difficult to implement. At the time, it appeared that in situ treatment would be applied where feasible while groundwater extraction would continue elsewhere. At some point in the future each area of the plume would transition to MNA, but the FS did not clarify when that would be.

Following significant local input from stakeholders, in January 2013 USEPA's National Remedy Review Board issued its own review of the draft FS with comments for USEPA Region 9 to address. USEPA Region 9 decided to move forward by optimizing the existing groundwater extraction and treatment systems and conducting pilot tests of alternative groundwater technologies at specific source area locations to obtain more information about what technologies and optimization efforts might work in the different facility-specific areas. The final remedial decision is currently on hold pending the results of additional pilot studies.

### 6.2.4.2 Pilot Study Phase

Pilot study characterization was conducted in several facility-specific source areas, using high-resolution sampling and tools such as the membrane interface probe. The results from high-resolution instruments supplemented data from conventional sampling and found compact hotspots with TCE concentrations in groundwater orders of magnitude higher than monitoring well concentrations. At many facility-specific source areas, existing extraction well networks were optimized and pilot tests of in situ treatment technologies were initiated. The Third Five-Year Review report lists 14 specific areas, with P&T optimization underway at most of the areas.

In 2014, responsible parties implemented an ISCO pilot study using sodium permanganate at two TCE hotspot areas in a residential area (Evandale Avenue). TCE concentrations decreased from 9,600 to 2,700 ppb at one hot spot and from 100,000 to 28 ppb at the second hot spot (USEPA 2014d). Subsequent sampling detected a rebound in concentrations and additional rounds of injections were completed (Geosyntec Consultants 2015). USEPA reported that ISCO was effective to the extent that the oxidant could be directly delivered to where the contamination was located. Use of ISCO is likely to be constrained by the presence of subsurface infrastructure and city restrictions on the timing of activity in a residential area.

A second pilot project was more controversial. At the former Fairchild Semiconductor Building 9, a site where a 40-foot-deep slurry wall had been placed, a large commercial office building and parking structure was planned. In 2013, Schlumberger Technology (which owned Fairchild from 1979 to 1987) proposed replacing the four extraction wells within the slurry wall with in situ bioremediation. It also proposed replacing a portion of the slurry wall with a permeable reactive barrier. Maintaining an upward, inward groundwater gradient within the slurry wall no longer made sense, because of the risk of VI.

In response to a concern about mobilizing metals, Schlumberger proposed using ISCO instead of in situ bioremediation, based in part on the success of the Evandale Avenue project. The removal of the building above the contamination initially appeared to open opportunities for in situ remediation; however, the pressure of timely redevelopment limited what could be done.

### 6.2.5 Regulatory and Stakeholder Involvement

The long history of public oversight of Moffett-MEW remediation illustrates how informed community members can be constructive partners in the remediation decision-making process, and how communities often contain multiple interests with divergent stakes in that outcome.

In 1985, the regional Silicon Valley Toxics Coalition organized citizens who then worked with the city of Mountain View to demand that the Bay Area Regional Water Quality Control Board take prompt action to advance remediation and to urge that the site be placed on the Superfund National Priorities List. The first public meetings about the MEW contamination were convened in 1986.

In 1990, the Navy established a Technical Review Committee (TRC) at Moffett Naval Air Station, and it invited local environmental organization representatives to join. Broader than most federal Technical Review Committees, the Moffett TRC was used by the Federal Facilities Environmental Restoration Dialogue Committee as the model for their proposed Site-Specific Advisory Boards. DOD incorporated those recommendations in its 1993 RAB concept, and the Navy converted the TRC to a RAB in 1994. Similarly, both USEPA and the state of California used Moffett as one of the models for their Community Advisory Groups. RAB members worked with congressional delegates to ensure that Moffett remediation was adequately funded.

Meanwhile, the Silicon Valley Toxics Coalition first received Technical Assistance Grants (TAGs) from USEPA for both Moffett Field and the MEW Superfund Study Area in 1994. The Coalition formed a Community Advisory Board that selected a technical consultant and directed his work. Those grants have been repeatedly renewed, with the Mountain View-based Center for Public Environmental Oversight taking over management in 2006, reforming a new Community Advisory Board. Through advisory groups, technical assistance, and public meetings, affected residents and other members of the public have had the opportunity to learn about the Regional Plume and to influence remediation decisions. In addition, the TAG recipients have joined USEPA in answering questions from residents, other building occupants, and the press about potential exposures, property values, and remediation decisions.

**Figure 14. USEPA-sponsored community meeting in May 2014** (CPEO 2014)**.**

USEPA and the Navy have held a long series of public meetings, working with neighborhood associations, local schools, and even unaffiliated military families living above the plume at Moffett Field (see, for example, Figure 14). In early 2003, shortly after the first VI investigations were launched, 400 people attended at USEPA meeting at Mountain View Recreation Center. Most of those were residents of the homes recently built on the former GTE property, site of smaller groundwater plumes just south of MEW. That meeting led to the formation of the Northeast Mountain View Advisory Council, which met through early 2006.

The City of Mountain View has participated in public meetings and the various advisory groups, and has played a central role in two specific activities. First, when asked by USEPA to develop an ordinance requiring VI mitigation, in line with USEPA's tiered VI response, the city instead created a groundbreaking permitting process. New or reconstructed buildings above or near the MEW plume are required to follow USEPA's standards for preemptive mitigation. In fact, the city has applied these requirements at other contamination sites. Second, whenever redevelopment is proposed within the MEW area, city staff check with USEPA to ensure that development will not interfere with remediation. USEPA officials routinely attend city council meetings to answer questions. Today, USEPA and city staff are evaluating the possibility, raised in the original MEW ROD, of recycling water being released into storm drains from the groundwater treatment systems.

Perhaps unusual for Superfund sites, the land above and near the Regional Plume is highly desirable for both commercial activity and residential use. None of the original MEW property owners and operators—the responsible parties—remain on site. Located in the heart of Silicon Valley, MEW office buildings are occupied by high-tech giants such as Google and Symantec. NASA and the Army took over Navy property at Moffett Field. The Army's housing area is operated by a private developer, and NASA has leased most the former Navy property to Google, other companies, and universities.

Mountain View Commercial Owners (MCO) members own 37 properties comprising 85% of the commercial space in the MEW area south of 101. For ease of access alone, their cooperation is key to both VI mitigation and continuing or enhanced groundwater remediation. Though many of the owners voluntarily share in vapor mitigation activities, they objected to elements of the draft VI remedy that would have made them responsible. For fear of business disruption, their representatives have repeatedly challenged USEPA's finding that pregnant women exposed to low concentrations of TCE have an elevated risk of bearing children with cardiac birth defects. As described above, this group objects to remediation activity that they believe may spread contamination or interfere with business activity.

In July 2012, responsible parties, concerned citizens, and commercial property owners within the MEW source areas, among others, submitted detailed and diverging comments on the FS. For example, responsible parties observed:

> *While the existing remedy is becoming less efficient over time due to an expected decline in mass removal rates, it is protective of human health and the environment and is not becoming less effective over time. The existing remedy continues to meet the RAOs in that it provides hydraulic containment of the source areas and the regional plume and is reducing VOC concentrations in groundwater. With the implementation of the VI ROD Amendment, the potential for VI exposure from shallow groundwater is being addressed, and the existing groundwater remedy remains protective. Although the second Five-year review and the GWFS identified some uncertainties in the hydraulic containment and protectiveness achieved by the current remedy, those issues are being addressed and do not indicate a fundamental limitation of the remedy. In 2011, the combined VOC mass removal rate from the MEW P&T systems was approximately 35% of the mass removal rate in 1999. This decrease is not indicative of "asymptotic conditions" nor does it indicate that the remedy is less effective than anticipated in the ROD. Although the existing groundwater remedy will not achieve groundwater RAOs for a long period of time due to matrix diffusion effects, that is equally true for all alternatives considered in the GWFS.*

The responsible parties also suggested that the in situ treatment technology might be less effective than USEPA found for several reasons, including the difficulty delivering treatment media near and under buildings. The Navy generally agreed with the private parties, but did not "see the logic behind accelerating reduction of a high concentration area that may or may not contribute to unacceptable indoor air concentrations after the VI remedy has been implemented."

The Mountain View Commercial Owners asked to what degree USEPA shared the time-to-remediation projections of the MEW Companies, and they expressed concern that in situ treatment would disrupt business activities both within buildings and outdoors. They questioned the feasibility of treatment media injections under large buildings, and they asked:

*If treatment is limited to areas outside of existing buildings, would Alternative 4 meet the site objectives for VI given that treatment would not occur at locations where VI is most likely to be an issue? Would it make sense to implement a remedy if coverage of the hot spot is less than 100%, i.e. if the remedy can only be feasibly be deployed outside the general footprint of existing buildings? Could such partial implementation increase VI risk through the creation of a partially-treated transition zone beneath buildings that could contain breakdown products such as vinyl chloride?*

The Center for Public Environmental Oversight, the recipient of USEPA's TAGs for both Moffett and MEW, was generally supportive of USEPA's approach, but it questioned USEPA's negative assessment of permeable reactive barriers. It also expressed concern "that the concentration target for transition to MNA may end up unacceptably high."

During the Supplemental FS process and subsequent testing of innovative technologies, citizens also provided comments. Concerned citizens submitted a memo which acknowledged that new technologies could not be applied to the entire contaminated aquifer and suggested decisions to enhance remedies be based on the reasons remediation was begun in the first place. These citizens recommended that new remedies focus on areas with high mass, areas that continue to act as a source, areas that reduce the need for long-term VI mitigation, areas where the detectable plume encroaches on residential areas, schools, and other sensitive uses and enabling reasonable future use of the property. Stakeholders requested that the draft FS include more discussion on the facility-specific limitations and advantages for each of the in situ reductive dechlorination and oxidation technologies.

Commercial property owners questioned the Communications Plan, announced by USEPA Region 9 in May 2014 as a mechanism for carrying out pilot projects and groundwater extraction optimization prior to completing the Supplemental FS. USEPA promised to post pilot work plans on its web site, circulate fact sheets summarizing pilot proposals, and "provide a time frame for interested parties and stakeholders to review and provide written comments." USEPA also promised to "provide an opportunity for interested parties to meet with USEPA to discuss comments received and determine whether any revisions to the work plans are needed."

In June 2014, commercial property owners wrote that they were concerned that the Communications Plan was deficient because it did not include a formal comment period, require a written response to comments from USEPA, or provide an administrative record associated with USEPA meetings with interested stakeholders. Most critically, commercial property owners were concerned about the lack of a formal mitigation plan to identify and prevent adverse impacts to properties affected by the remedies. Concerned citizens welcomed the Communications Plan, but called for transparent decisions and decision documentation, a formal opportunity for comment on proposed remedies, USEPA's process for responding to comments, and flexibility in the cleanup strategy.

In April 2015, citizens expressed concern that neighboring property owners "repeatedly opposed the use of innovative groundwater treatment technologies, despite the positive track record of those technologies" to accelerate groundwater cleanup. Citizens supported USEPA's plan to restart the FS process and did not agree with the property owners that the process would delay cleanup, particularly where construction is underway or planned. Citizens urged USEPA to act quickly, implementing new technologies on parcels before construction took place.

USEPA's 2015 Final Vapor Intrusion Guide highlighted Mountain View's permitting process as a model for cooperation between environmental regulators and local land use planning jurisdictions:

*In 2009, USEPA published the Proposed Plan for the MEW Study Area that identified USEPA's preferred alternatives for the VI remedy. The Proposed Plan identified the adoption of a municipal ordinance as USEPA's preferred IC, but the City of Mountain View and concerned property owners raised concerns that this was not necessary. Instead, USEPA worked with the City of Mountain View, California, to have the City formalize its permitting procedures that apply to future construction. These permitting procedures oblige those proposing new building construction within the MEW Study Area to obtain USEPA approval of construction plans to ensure that, where necessary, the appropriate VI control system is integrated into building construction.*

This approach proved protective for a recent housing development along Evandale Avenue. When the Evandale OU plume was discovered, residents were already protected by built-in passive mitigation systems, confirmed by subsequent USEPA indoor air sampling.

Well over 100 nonresidential buildings, as well as several hundred residences, today lie within the plume's VI Study Area, complicating subsurface response activity and creating multiple opportunities for VI. In fact, the Moffett-MEW Plume was one of USEPA's first and largest VI responses.

> *The VI remedy includes ongoing ICs to ensure that the remedy is properly implemented over time and that all parties are aware of the remedy's implementation and ongoing requirements. There are three categories of ICs specifically selected for the VI remedy. First, for all properties with an implemented VI control system, the remedy requires recorded proprietary controls which run with the land that inform future property owners of the ongoing operation of the remedy at the property. Second, the remedy requires governmental controls in the form of City of Mountain View planning and permitting procedures. These procedures are intended to inform and allow for USEPA to comment when work conducted anywhere overlying the shallow TCE regional groundwater contamination plume may either impact the remedy itself or cause a new pathway for vapors to enter any overlying structure. The ICs also include the implementation of informational mechanisms, which are two-fold: 1) use of an information-gathering service that can keep USEPA and the MEW Companies informed of property ownership changes in the MEW Site area and 2) provision of information to owners and occupants in the MEW Site area to ensure understanding of the remedy and its requirements.*

At Moffett Field, similar ICs are incorporated into USEPA-approved environmental plans prepared by NASA and its principal lessee, Google's Planetary Ventures subsidiary.

## 6.2.6 Conclusion/Lessons Learned

The lessons learned from the more than three decades of environmental response at the Moffett-MEW Regional Plume are as complex as the site. This site is characterized by willing responsible parties, competent and innovative consultants, diligent and capable regulators, and an active, constructive, diverse community. Despite those advantages, key remediation decisions will be pending for years. Project completion is decades, if not centuries, away.

### 6.2.6.1 The Process is Nonlinear

Official descriptions of the CERCLA process are generally linear. USEPA identifies a site, then assesses it. Note that federal agencies usually function as lead agencies at their own properties, and frequently state agencies serve as lead regulators. If the site is hazardous, USEPA places it on the NPL. USEPA then investigates the site and develops remedial alternatives, formalizing the chosen remedy in a ROD. If remediation is not complete enough to allow unlimited use and unrestricted exposure, five years after implementing the remedy it conducts a Five-Year Review to determine whether the remedy is protective.

In reality, remediation is more like the children's board game, Chutes and Ladders. Often interim remedies designed for control of contaminant sources are implemented early in the process, long before remedial alternatives are evaluated. Nearly as frequently, it is necessary to conduct substantial characterization after remedies are in place, and particularly if a Five-Year Review finds a problem, to reconsider the entire remedial strategy. At the Regional Plume, the parties have had to take steps backward (down the chutes) to address a new pathway (VI), address new areas of contamination (the Evandale area), and accommodate intense and continuing redevelopment.

### 6.2.6.2 Recurring Reviews

At the Regional Plume, the finding of nonprotectiveness in the 2009 Second Five-Year Review was decisive. This result led not only the promulgation of a separate, innovative ROD for VI, but also launched a process to implement new groundwater remedies over much of the plume. Under USEPA Guidance, the review of protectiveness should evaluate all exposure pathways and performance of all parts of the remedy, including engineered remediation systems as well as any ICs, LUCs, engineering controls, and public education efforts. The same review elements can be used to determine whether the remedy is efficient, cost-effective, sustainable, and likely to achieve RAOs in a reasonable amount of time.

The Moffett-MEW project was fortunate in that the original remedy was not found sufficient to protect building occupants from VI, because that finding triggered an adaptive site management process through which newer technologies are being introduced. Those newer remedies are likely to lead to a faster, cheaper, and resource-saving remediation. Perhaps Five-Year Reviews could be used for adaptive site management at sites where the remedies are still considered protective.

Furthermore, in the dynamic world of new investigative tools and remedial technologies, more frequent but perhaps less comprehensive interim reviews might trigger changes to remedies earlier and more efficiently. USEPA's minimum requirements are for such a review to occur every five years after a construction or implementation a remedy at sites where contamination remains in place. It may be advantageous for site management teams to evaluate the remedies on a site-specific basis and decide on a periodic schedule for the review that is appropriate for each site.

#### 6.2.6.3 New Technologies

At the regional plume, the parties have not hesitated to implement emerging technologies. From the early demonstration of permeable reactive barriers to current in situ pilots, they have remained on the cusp of innovative treatment. From the pioneering use of passive air samplers to high-resolution measurements of groundwater, USEPA and the responsible parties have used the latest in characterization technologies.

Although the engaged public has supported these technologies, one segment of the community, neighboring commercial property owners, has challenged innovative treatment approaches. High-resolution groundwater sampling, producing reported TCE concentrations orders of magnitude above those identified earlier, have also caused concern in the community. New technologies, therefore, are not panaceas. They should be introduced carefully to ensure that they do not generate new roadblocks to remediation.

#### 6.2.6.4 Complex Decisions: One Size Does Not Fit All

Experience thus far at the Moffett-MEW Regional Plume shows that it is possible to introduce innovative remedial technologies to accelerate the remediation of a physically complex site. The parties disagree as to whether accelerated remediation will influence the date by which this heavily contaminated site achieves RAOs—the drinking water standard—throughout the aquifer. Accelerated remediation, however, is expected to reduce the risk of VI and make it easier for site redevelopment to occur.

Because there are many source areas and even more property owners—who are distinct from the responsible parties—the decision-making process for considering new remedies is particularly complex. USEPA Region 9 delayed completion of its Site-Wide Groundwater Supplemental FS because it was not clear which new remedies or optimization would be applied where, opting instead to move forward using an informal communications strategy. It is important that facility-specific projects move forward, both to inform the FS and to take advantage of the enhanced access to the subsurface provided by property redevelopment. Yet, at least in the view of some key stakeholders, the interim process does not provide adequate opportunities for all affected parties to influence the transition from conventional to innovative technologies. It would be helpful to establish practices that not only enable the transition of technologies but guide complex decisions during the period of transition. Community engagement has been constructive in resolving disputes among regulatory authorities and responsible parties, as witnessed by the solution to the Navy’s TI Waiver request.

### 6.2.7 Moffett Field East Side VOC Plume, Technical Impracticability

Discussion of remedial optimization and new remedies at the Moffett-MEW Regional Plume was influenced by earlier negotiations over the remediation of a smaller VOC plume on the eastern side of Moffett Field, an area not covered by the MEW ROD. The Navy had built a groundwater extraction and treatment system, known as the East-Side Treatment Systems (EATS), using an air stripper to remove TCE, PCE, and other contaminants. This area is difficult to remediate because much of the contaminant mass resides in dense clay layers. In July 2003, after four years of operation, the Navy shut down the system to evaluate its performance. In 2007 the Navy requested that the system remain shut down for a pilot study using enhanced biodegradation. Afterwards, the Navy prepared a Technical Memorandum (Tetra Tech 2008), a draft FFS, and a TI Evaluation. At the time, the Navy requested a TI waiver, which would release it from achieving ARARs for TCE and PCE. Although biodegradation enhancements had some good results, the Navy proposed using natural attenuation, which was considered more cost effective.

USEPA and the Regional Water Quality Control Board rejected the proposal and ordered that the EATS system be turned back on. They found that the Navy had not proven that engineered remediation would not bring timely results. EATS thus would to operate longer, with attempts made to enhance its performance, to gather the information necessary to consider shutting it down.

In 2007 USEPA concluded that the pilot study had some positive results:

> *It should be recognized that while anaerobic conditions are necessary for dechlorination of the VOCs, other more specific conditions are also critical for an effective remediation alternative. For example, as recognized in the Draft Report, the failure to attain a persistent culture of Dehalococcoides (DHC) may be one reason for the shortcomings of the pilot test. Another reason may be that the hydrogen concentrations are too high, which has been reported to favor hydrogen usation for methanogensis rather than dechlorination (low hydrogen concentrations of 2 to 10 nanomolar [nM] have been*

*considered optimum for the latter process). It appears that optimization (e.g., additional HRC® and/or amendments) may be needed.*

The community, represented by a RAB and an USEPA TAG recipient, agreed with USEPA's assessment. These groups were concerned that after four years of spending an estimated $250,000 annually to operate the system, the Navy had concluded that an attenuation-based remedy was warranted. A community comment on the draft FFS pointed out that the Navy used a similar argument prior to building the EATS, that was rejected both by the USEPA and community commenters.

One reason the Navy cited for abandoning the biotreatment pilot test was that concentrations of cis-1,2-DCE increased in samples from some wells with no change in vinyl chloride (VC) concentrations, despite decreasing TCE and PCE concentrations in a majority of the pilot test area samples. Reductive dechlorination was occurring, but was not likely proceeding to completion. The Navy suggested that *Dehalococcoides* spp. was not present in sufficient quantities or was incompetent to complete the reductive dechlorination process. Yet, community representatives noted that at a nearby site at MEW, with a similar hydrogeological setting, Intel and Raytheon had successfully completed dechlorination by augmenting the population of bacteria and adding other nutrients.

The Navy's Tech Memo (Tetra Tech 2008) established a 50-year time frame, considered arbitrary by community members, for achieving site objectives. The USEPA Guidance on TI waivers states that estimates of the time frame to achieve groundwater remediation may be considered. While this is important, "no single time frame can be specified" (during which remediation is technically practical). Very "long time frames (e.g., longer than 100 years) may be indicative of hydrogeological or contaminant-related constraints to remediation."

The TAG recipient explained that in situ bioremediation for this area and the Intel/Raytheon site had shown targeted reductions in VOC concentrations. It supported achieving site objectives within a reasonable time. However, it argued, even if this might not be possible, making progress towards those goals could still be accomplished with some of the technologies identified.

The draft FFS for the eastside area observed that there is no current exposure pathway, but the community argued that this was insufficient to allow contamination to remain above drinking water standards. The contaminated groundwater is defined as a "potential drinking water source" by the state of California and is therefore legally protected. California faces water shortages, and "we expect that it will face them for some time to come. Preservation of potential drinking water sources—as well as the protection of aquifers as storage basins—is essential." The no-exposure pathway argument did not take into consideration future uses of the site, or the fact that a VI pathway may be relevant to these future uses.

The Tech Memo asserted that continued treatment would be too costly, but the NCP Preamble states that TI determinations should be based on "…engineering feasibility and reliability, with cost generally not a major factor unless compliance would be inordinately costly" (Tetra Tech 2008). Thus, community members argued that the Navy could not halt treatment simply because it cost more than doing nothing.

The TAG Recipient recommended that the Navy follow the adaptive site approach put forward in the NRC report (NRC 2003). Adaptive management stimulates the search for new, innovative technologies to replace older or inefficient approaches, and it stresses the need for pilot programs to test both new technologies as well as modifications of existing technologies that might enhance their effectiveness.

In a meeting with USEPA, the Regional Board, the Navy and the TAG recipient, all parties agreed to stop the request for a TI waiver and continue with in situ bioremediation at the most highly contaminated areas of the east-side aquifer, while allowing MNA to treat the rest of these areas. USEPA and the Regional Board agreed that they would not require the Navy to start the P&T system again.

## 6.3 Rocky Flats Solar Ponds Plume, Colorado

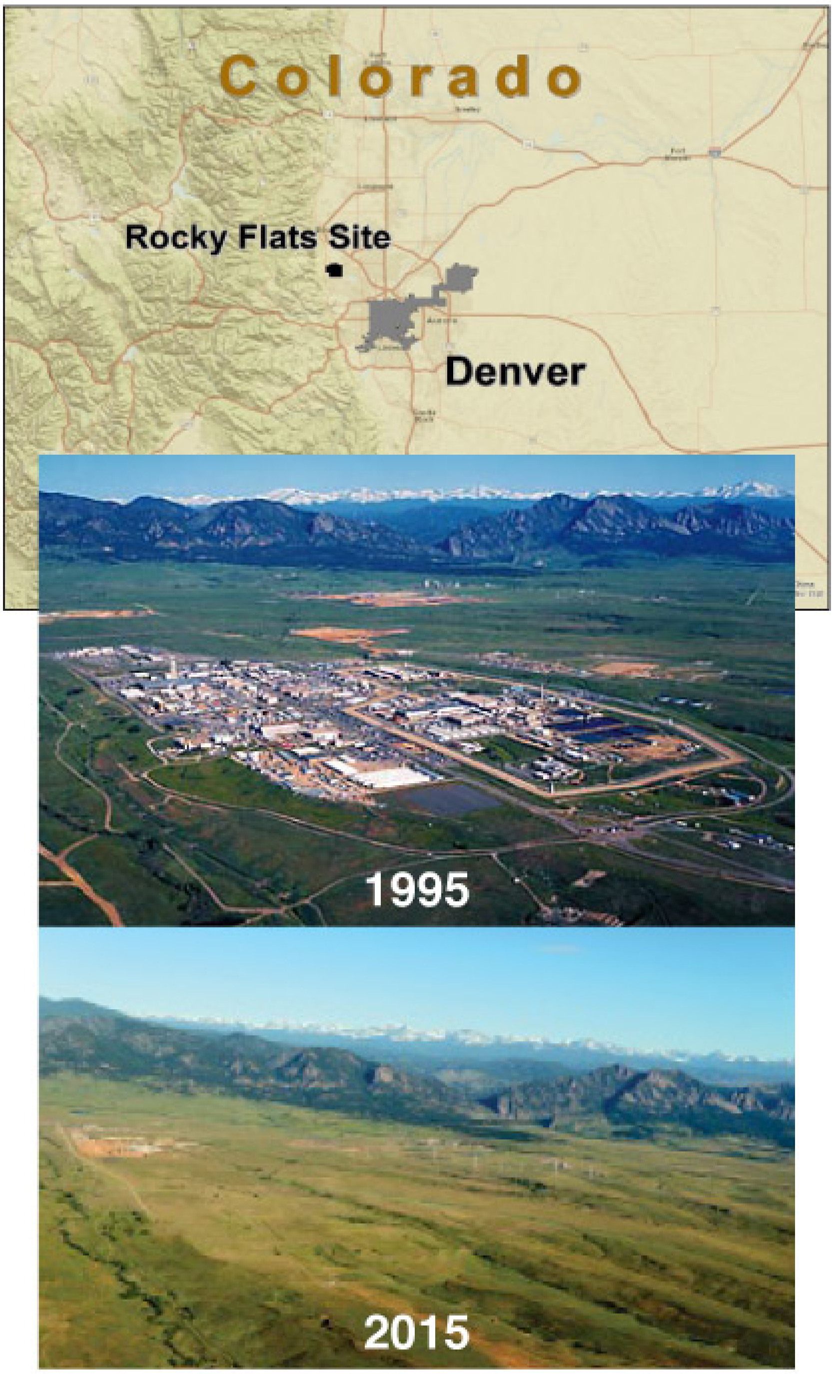



**Figure 15. Location and aerial views of the Rocky Flats Site** (modified from DOE 2017)**.**

The Rocky Flats Plant, located outside of Denver, Colorado at the base of the Rocky Mountains, was a 10-square-mile facility in the DOE's nationwide nuclear weapons complex (Figure 15). From 1951 to 1992, DOE and its predecessor agencies manufactured both radioactive and nonradioactive metal parts, primarily for nuclear weapons.

The site mission changed in 1992 to decontamination and decommissioning of all nuclear facilities, and cleanup and closure of the entire site. The cleanup schedule and budget were compressed considerably by completing many remediation activities as interim measures, leaving the final site wide remedy decision to the end. One of the U.S. Government

Accountability Office (GAO) reports (2006) on the Rocky Flats cleanup effort stated: “An accelerated cleanup process allowed cleanup actions to proceed much more quickly and collaboratively than a traditional cleanup process would have allowed.” The report recommended that the Rocky Flats approach be applied as a lesson learned at other DOE sites.

Physical cleanup was completed in October 2005. The $7 billion cleanup was the largest environmental cleanup of a CERCLA site at that time and was completed in an accelerated 10-year schedule. Over 800 structures were decontaminated and demolished, including five major plutonium facilities and two major uranium facilities. An additional 421 areas thought to have been contaminated with hazardous substances were investigated and remediated if necessary.

The Corrective Action Decision (CAD)/ROD document that closed the site divided it into two parts: a closed/delisted area and a long-term management area. Most of the site meets unlimited use/unrestricted exposure criteria and was delisted. The U.S. Fish and Wildlife Service now operates this area as a wildlife refuge. The former production area (Central Operable Unit) was also closed, but has use restrictions with requirements for long-term monitoring and maintenance of groundwater treatment systems and landfills. This case study describes one of four groundwater plume treatment systems being operated on site in postclosure.

The Solar Evaporation Ponds (SEPs) were used primarily to store low-level radioactive wastes contaminated with high concentrations of nitrate (DOE 2002b). The first pond was constructed in 1953, and eventually five ponds were in use. The SEPs were also used to dispose of various other difficult-to-treat wastes including cyanide wastes, acid wastes, radiography solutions, sanitary landfill leachate, sewer sludge, treated sanitary sewage effluent, reverse osmosis treatment plant brine, and contaminated groundwater. While their main purpose was liquid waste storage and evaporation, most SEP water was treated by a flash evaporation system and some pond effluent was discharged to a sanitary wastewater treatment plant.

A variety of liners were constructed, all of which eventually leaked to some extent. Leakage from the SEPs created a mixed uranium and nitrate/nitrite plume, which covers about 50 acres (DOE, USEPA, and CDPHE 2012). A smaller organic compound plume is colocated within the main Solar Ponds Plume (SPP). Because these contaminants are now present as secondary sources within a low-permeability matrix, it will take many decades to bring the SPP to standards. Treatment is included in the budgetary baseline through 2089. Groundwater modeling performed for the SEP decision document (DOE 1999) indicated that groundwater adjacent to North Walnut Creek would continue to exceed 100 mg/L beyond the modeled period (year 2100).

Beginning in 1970, the plume was collected by a groundwater interceptor trench system (ITS), which was a series of trenches to which an array of French drains was later added. The purpose of the ITS was to collect contaminated water that drained by gravity to a pump station located near North Walnut Creek and was pumped back uphill to the SEPs. The French drain included gravel backfill from the drain to the surface so that it would collect both groundwater and surface water runoff. This extension of the original ITS also collected footing drain flows from major plutonium processing buildings. Beginning in 1993, water collected in the ITS was transferred to storage tanks prior to a flash evaporation process. The evaporation process treated two to three million gallons every year at the cost of approximately $2 per gallon.

The SEPs were drained and activities began in 1986 to remove the pond sludges, a process completed in 1995. Removal of the sludges eliminated the nitrate and uranium source for the SPP. The SEPs were RCRA interim status units, which were closed in 2002 following accelerated remedial actions (DOE 2002b). Those accelerated actions also closed other RCRA units within the SEP Area of Concern and removed soil with contaminant concentrations greater than soil action levels (DOE, USEPA, and CDPHE 2003). Contaminants included plutonium, americium, and cadmium. After these removal actions, results of a risk assessment indicated low risk to future users from the former SEPs, therefore the final decision document (DOE 1999) required no further action at this source area. As a best management practice, the berms surrounding the SEPs were pushed in, clean fill soil was brought in and the area was regraded. This accelerated action was confirmed and approved as a final action by the CAD/ROD in September 2006.

### 6.3.1 Characterization

A study conducted in 1997 (DOE 1997) identified more detailed site characterization that was necessary to complete a robust evaluation of the remedy alternatives. The SPP was already characterized by data collected at 66 existing groundwater wells; 19 other wells were sampled to establish background and impacts to surface water. Prior to designing a treatment system, additional wells were installed to enhance the conceptual site model and to develop a groundwater flow model for a fate and transport evaluation of site contaminants.

The SEPs were located on a flat surface at the edge of an alluvial pediment. The Quaternary alluvium is up to 23 feet thick and overlies poorly lithified weathered and unweathered Cretaceous claystones, which include incised sandstone lenses that direct groundwater flow. Colluvium covers the slope down to North Walnut Creek. Groundwater flow is mainly restricted to the alluvium/colluvium and weathered bedrock (Upper Hydrostratigraphic Unit); competent bedrock contains very little water. Hydraulic conductivity in the alluvium is typically about $10^{-5}$ cm/sec ($3.0 \times 10^{-1}$ feet/day). Flow is to the east beneath the SEPs, where it is bifurcated by a bedrock high and by proximity to the hillside. Most of the plume is mapped downslope to the north-northeast toward North Walnut Creek; a smaller portion is mapped south-southeast toward South Walnut Creek.

Most contamination is in the plume portion that flows north-northeastward toward North Walnut Creek, which is approximately 1,000 feet north of the SEPs and 100 feet lower in elevation. In the source area for this segment, nitrate levels reach 4,500-5,000 mg/L; uranium concentrations have been measured up to 1,000 µg/L (Figure 16 and Figure 17).

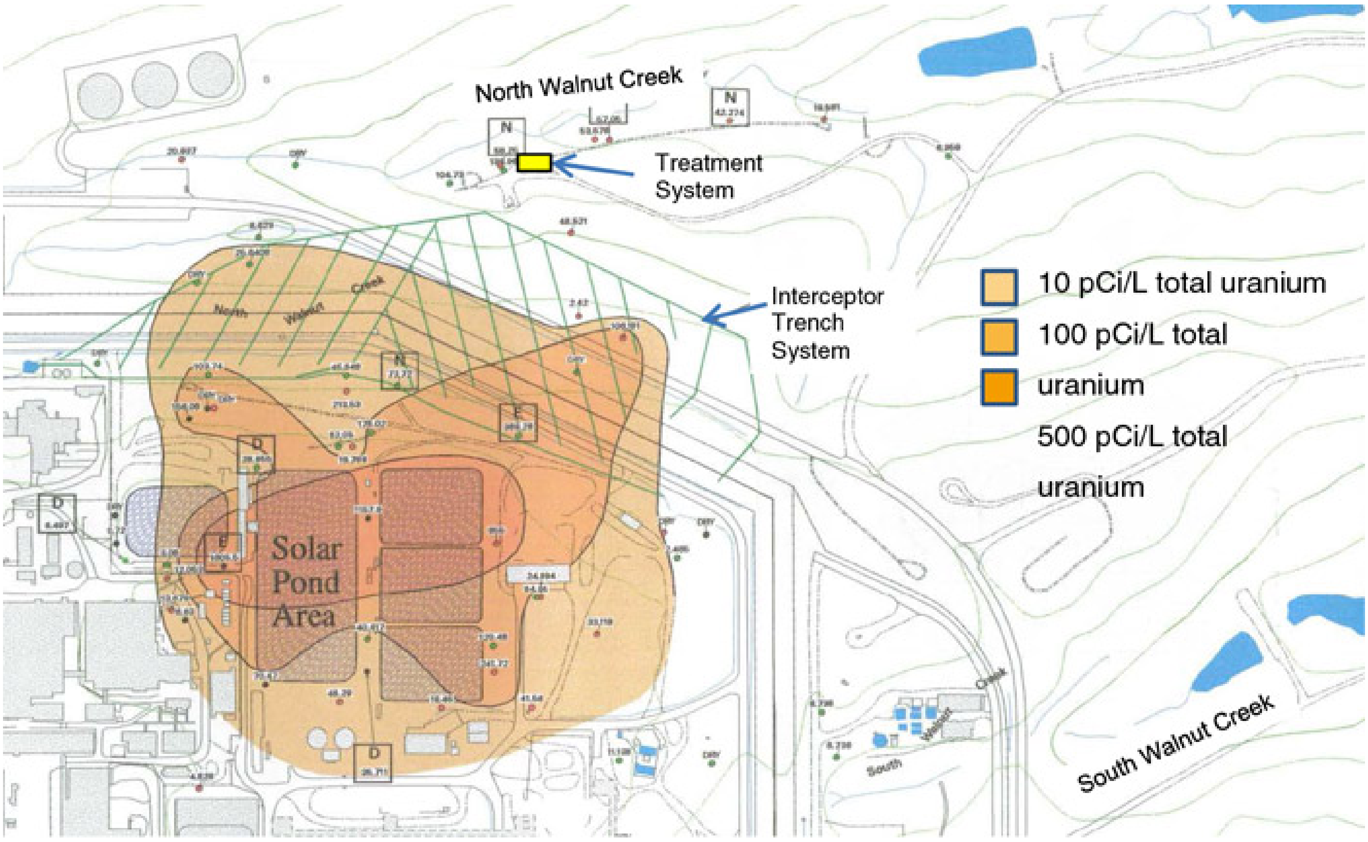



**Figure 16. Solar Ponds Plume showing total uranium in the Upper Hydrostratigraphic Unit** (modified from DOE 1999)**.**

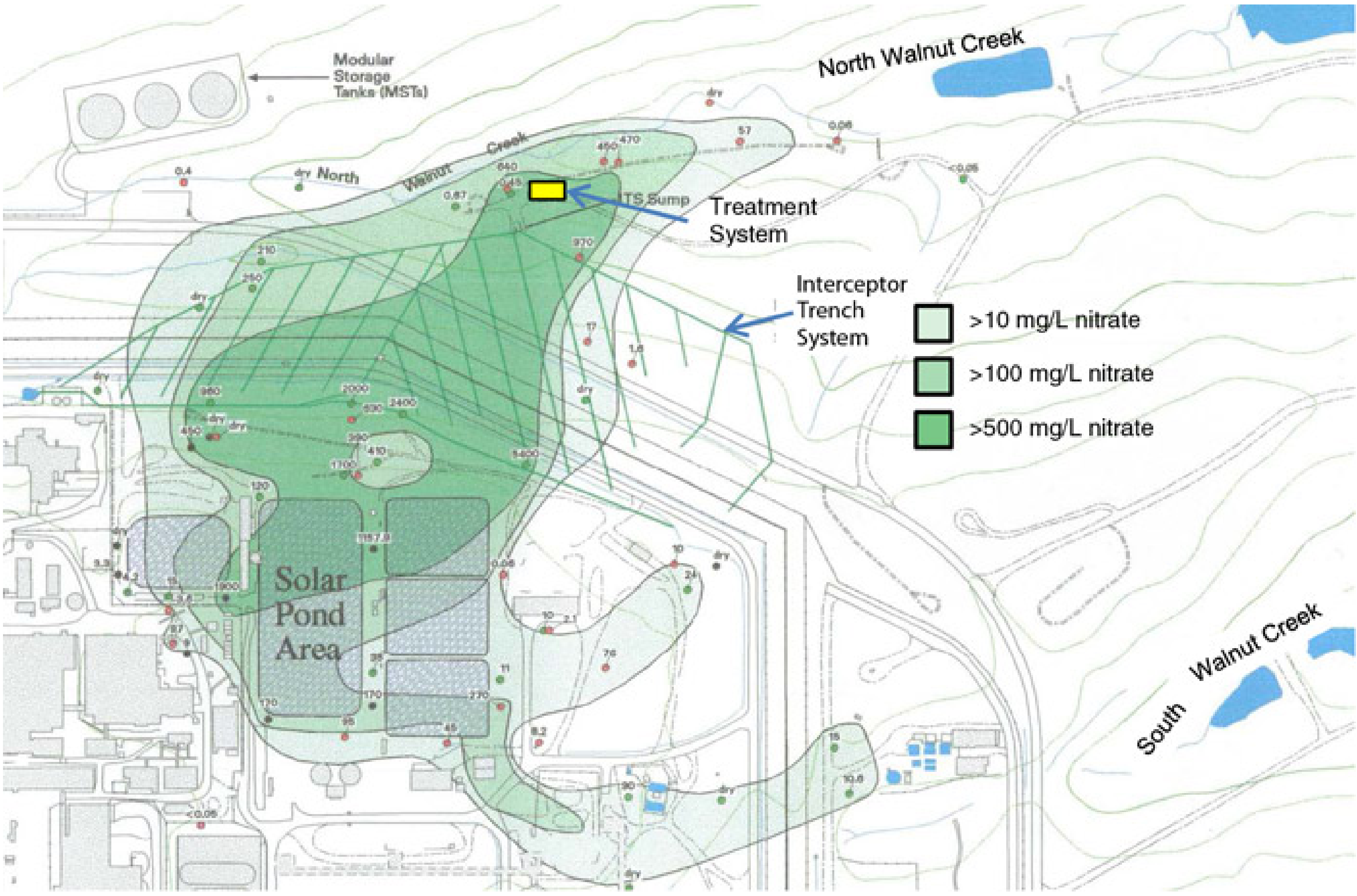



**Figure 17. Solar Ponds Plume showing nitrate concentrations in the Upper Hydrostratigraphic Unit** (modified from DOE 1999)**.**

As the site closed, impervious surfaces (pavement, buildings) were removed and sources of imported water were turned off. Natural groundwater recharge conditions were gradually restored. These postclosure conditions generate less than half the previous stream flow in Walnut Creek. This much lower natural flow revealed the natural uranium concentrations that had been masked by the diluting effects of the extra runoff from impervious surfaces and the imported water.

Colorado's geology accounts for elevated concentrations of natural uranium in the area groundwater—above the maximum contaminant level (MCL) of 30 µg/L in many cases. The largest vein-type uranium deposit in the United States is located approximately five miles southwest of Rocky Flats. Natural uranium is composed of three isotopes in the following approximate percentages: 0.006% U-234, 0.72% U-235, and 99.27% U-238. Well samples collected within 100 feet of the SEPs indicate the presence of both depleted uranium and enriched uranium. The well samples that indicated an anthropogenic source of uranium had activities between 6.5 and 1605.5 picoCuries per liter (pCi/L); samples that indicated a natural source of uranium had activities between 42.3 and 72.7 pCi/L.

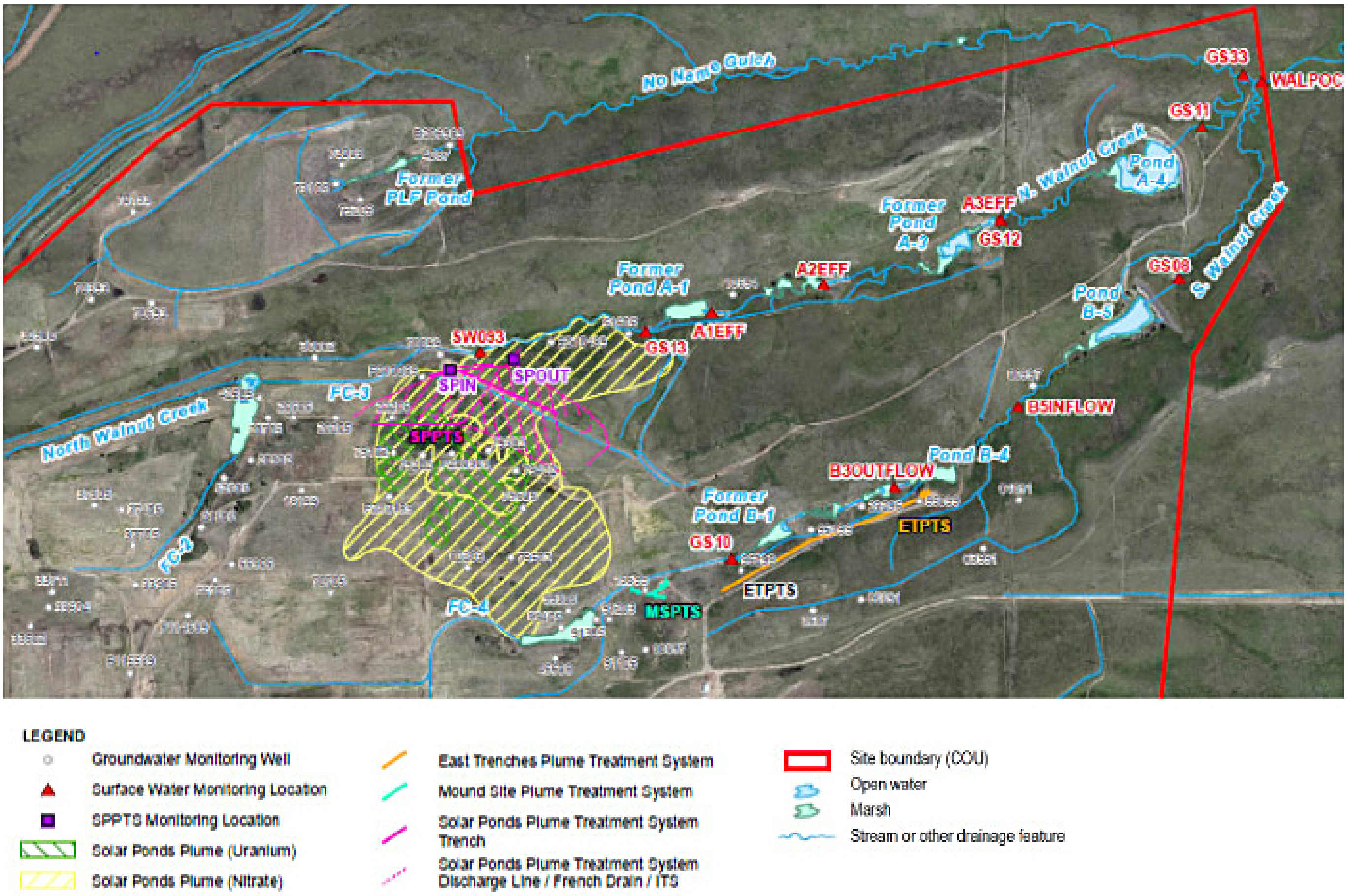



**Figure 18. Walnut Creek drainage with monitoring locations** (Navarro Research and Engineering Inc. 2017)**.**

Uranium concentrations in continuous flow-paced composite samples collected at the point of compliance on Walnut Creek (WALPOC) were below the stream standard until a 100-year flood event occurred in September 2013 (Figure 18 and Figure 19). Immediately following the flood, uranium concentrations increased above the surface water standard and did not return to normal levels for approximately eight months (mid-May 2014) (Figure 19).

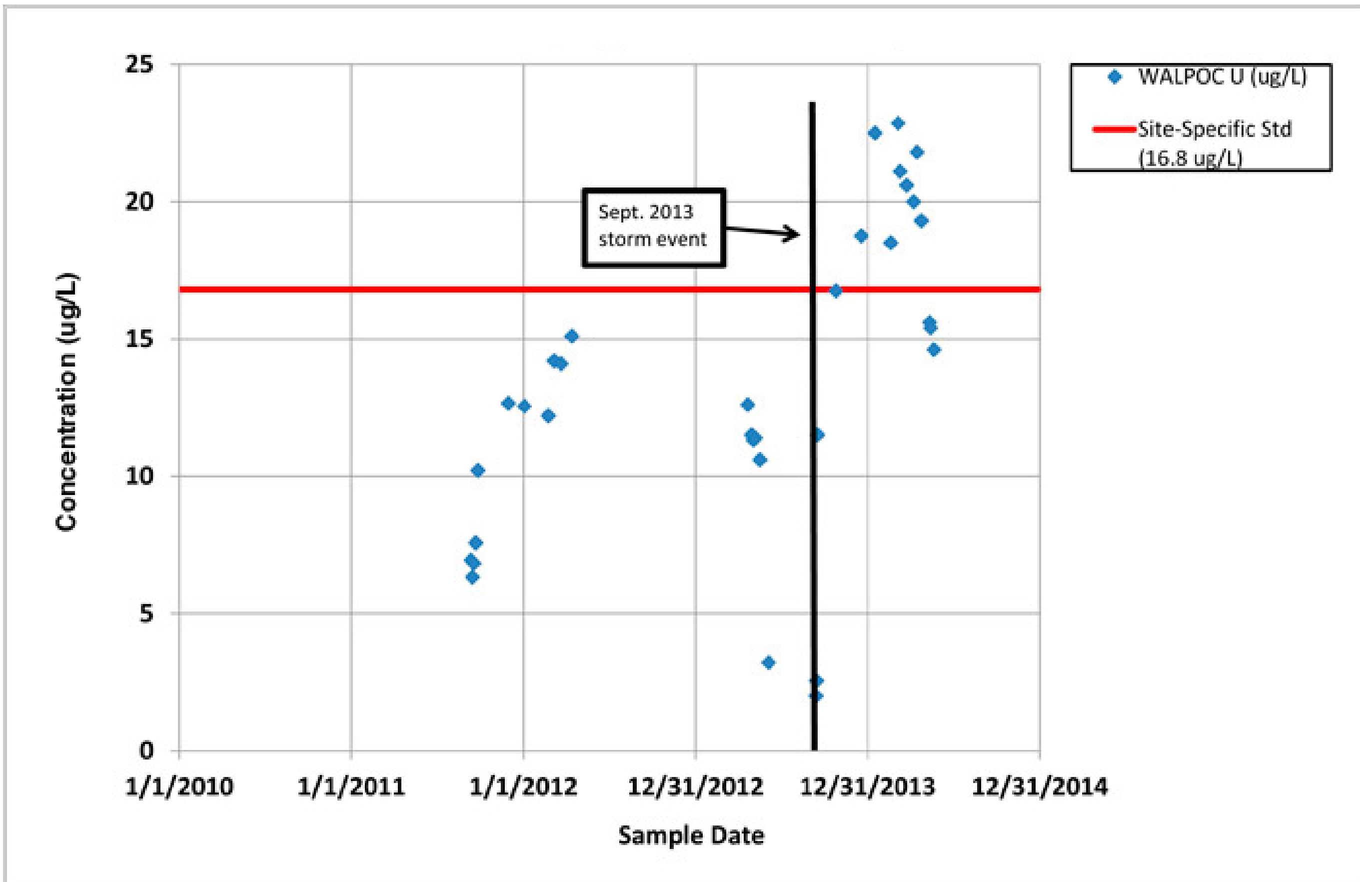



**Figure 19. Uranium concentration at WALPOC (September 2011 – May 2014)** (Wright Water Engineers Inc. 2015)**.**

This exceedance of the site's surface water standard underscored the value of a study that was underway to address the distribution, transport mechanisms, and sources and composition of uranium with a focus on the Walnut Creek drainage (Wright Water Engineers Inc. 2015). Conclusions from the study include:

1. The major source of anthropogenic uranium in North Walnut Creek is the SPP. The average percentage of natural uranium at the monitoring location just upstream of the SPPTS at the time of this study was 92%, the highest measurement in the drainage (Figure 20). The effluent of the SPPTS, which discharges to the subsurface adjacent to the stream, averages 61% natural uranium and the percentage gradually increases in downstream monitoring locations until WALPOC, where 77% of the uranium is natural.
2. The percentage of natural uranium does not vary substantially with changes in measured uranium concentrations or stream flow rate.
3. Four chemical processes (precipitation, complexation, sorption, and colloid formation) generally control uranium concentration and mobility in aqueous environments.
4. These processes are influenced by redox potential, pH, and water quality, which determine the aqueous speciation and dissolved/solid equilibria of uranium and thereby govern the movement of uranium in the environment.
5. Of these three factors, redox potential generally has the greatest influence on uranium behavior in the environment, because it determines the state in which uranium occurs.
    1. Reducing conditions (negative redox potentials) – relatively insoluble and less mobile uranium species form and sorption to matrix solids is enhanced.
    2. Oxidizing conditions (positive redox potentials) – more soluble and mobile species are formed.
6. Oxidizing (mobilizing) conditions are favored by:
    1. the $CaCO_3$-type waters at the site;
    2. shallow or turbulent surface waters; and
    3. groundwater that is rapidly recharged by oxygenated precipitation.
7. Because redox reactions are reversible, soluble uranium species that have been reduced to low solubility uranium species can be reoxidize In water, sediments, and soils with negative redox potentials, oxidants other than oxygen, such as nitrate, can restore and maintain significant levels of soluble uranium species.

8. In segments of North Walnut Creek affected by the SPP, the presence of nitrate is one of the most important chemical characteristics of the surface water and groundwater affecting uranium mobility. In-stream monitoring locations have measured nitrate concentrations as high as 140 mg/L (as nitrogen) as recently as December 2012. High levels of nitrate in oxygen-depleted groundwater and surface waters can facilitate the microbially mediated oxidation of immobilized uranium species to highly mobile dissolved species.

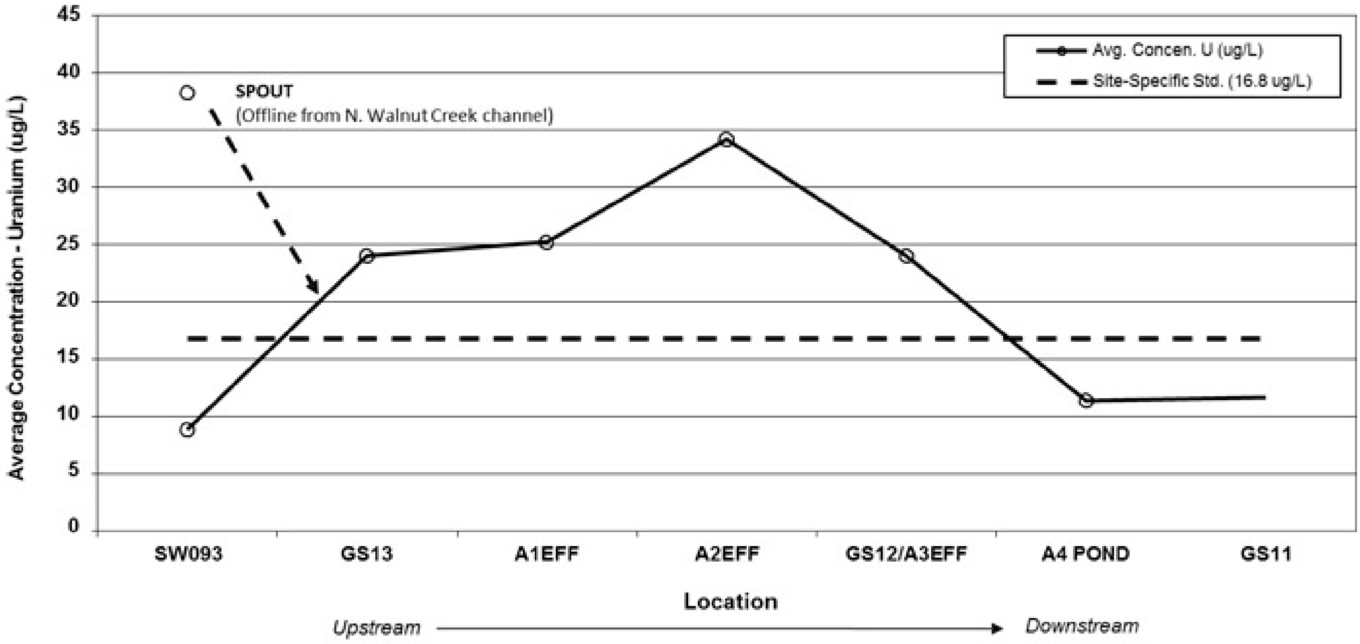



**Figure 20. Average concentrations of uranium at North Walnut Creek monitoring locations (1/27/10 – 4/30/14)** (Wright Water Engineers Inc. 2015)**.**

## 6.3.2 Remedy Alternatives/Remedy Decision

The 1997 study also evaluated 11 remedial alternatives. The following four alternatives were retained for further study:

- managed release of ITS water to a retention pond
- treatment of ITS water at an on-site water treatment facility
- phytoremediation
- enhanced evaporation at modular storage tanks

The Solar Pond Plume Decision Document (DOE 1999) listed permeable reactive barrier technology among the remedial options. Later studies also considered constructed wetlands. Evaluations of these remedial alternatives included consideration of:

- effectiveness (proven method, ability to meet water quality standards)
- implementability (such as sensitive habitat disruption and electrical needs)
- costs (such as installation, O&M including media replacement, and repairs)

When the original Solar Ponds Plume Treatment System (SPPTS) was installed in 1999, it was designed to passively capture and treat the uranium and nitrate-contaminated groundwater. The permeable reactive barrier option was modified to incorporate an impermeable groundwater collection wall with a subsurface treatment vault containing the reactive media. This design has also been applied at two other groundwater treatment systems at Rocky Flats and accommodates the low flow rates at the site. The design also allows more control over treatment rates and reduces the effort required to change out the reactive media.

A trench, approximately 20 to 30 feet deep and 1,100 feet long, was dug into the colluvium, cutting across the plume and sloped toward treatment cells. An impermeable barrier consisting of 80-mil high-density polyethylene panels was installed in this trench. These 15-foot-wide panels are anchored in claystone bedrock and sealed at the bottom with bentonite. A four-inch perforated groundwater pipe (bedded in sand laid on top of the bentonite) collects the groundwater and routes it to the treatment cells. The collection trench cuts across the preexisting ITS, and the portion of the ITS upgradient of the trench was used to enhance groundwater collection.

A concrete treatment box, 46 feet by 21 feet, was installed below grade, extending 25 feet into the subsurface. Originally intended to be constructed adjacent to North Walnut Creek, it was moved 400 feet upgradient out of the drainage to avoid the habitat of the Prebles Meadow Jumping Mouse (a federally listed endangered species). This move reduced the head at the lower end of the collection system and required a 12-foot head to build up in the collection trench before water could flow into the treatment box. A solar-powered sump pump was later installed to more effectively lift the collected groundwater up into the treatment box.

Because the SPP is a comingled plume, it requires phased treatment. Within the treatment box, two cells generally operated in series. The first cell was filled with sawdust (as a carbon source) mixed with zero-valent iron (ZVI) and removed nitrate. The second, smaller cell was filled with ZVI and gravel to treat uranium. Effluent was piped to a subsurface discharge gallery near the creek. System influent and effluent grab samples are routinely collected for uranium and nitrate. Downstream, automatic flow-paced samplers collect surface water samples for uranium; downstream nitrate is collected as grab samples.

### 6.3.3 Remedy Optimization

The original SPPTS was effective in lowering uranium and nitrate concentrations, but by the time effluent discharged to the stream, it had become recontaminated by mixing with plume water that had not been captured by the interceptor trench. Although the SPPTS is not consistently meeting treatment targets, the system continues to reduce uranium and nitrate load while improvements are being implemented.

The reduction in uranium load through the SPPTS (influent load compared to the system effluent) varies widely over time. The most effective uranium treatment, better than 80% removal of uranium, occurred in early 2011. Since then, the system's overall effectiveness for uranium removal has trended downward while the uranium concentration in discharges to the stream has trended higher. The uranium load contributed from the SPPTS effluent to the stream has been estimated at 5%. When the SPPTS has been least effective removing uranium, uranium concentrations downstream have not increased, which suggests that SPPTS effluent does not have a significant effect on uranium concentration in North Walnut Creek.

The treatment system design has been revised to overcome operational limitations and upgraded several times since site closure to improve system effectiveness. The lack of line-power has substantially limited treatment options. Because the SPP is a mixed contaminant plume, it requires phased treatment and so treating the contaminants with different methods and media and in the right sequence continues to be challenging.

Treatment system repairs and maintenance, including plumbing reconfigurations and media replacement, have been costly. Treatability studies were initiated to increase system effectiveness and reduce maintenance. Batch tests evaluated a variety of microbial inocula (such as sewage sludge, manure, and soil), water additives (such as phosphate and yeast extract), carbon sources (ethanol, methanol, corn syrup, and others), and substrates (pea gravel and plastic high-surface-area media) to support microbiological denitrification. Optimization tests were run using different flow rates and additive application rates, as well as different organic media (sawdust, composts, corn stover, and others) that represented a combined carbon source and substrate.

Treament system components are currently evolving from flow-through reactive media to lagoons for nitrate treatment, and a different configuration of flow-through ZVI for uranium treatment. The Walnut Creek drainage study indicated that effective control of the uranium content in surface water must consider nitrate treatment, because nitrate can facilitate uranium mobility through oxidation processes. Preliminary samples show a dramatic improvement in nitrate effluent from the system. The September 2016 samples measured nitrate + nitrite concentrations of 65–90 mg/L as nitrate; after the treatment system became operational in October 2016, samples were nondetect for nitrate.

### 6.3.4 Regulatory Determinations

The Rocky Flats Legacy Management Agreement (RFLMA) (DOE, USEPA, and CDPHE 2012) requires that each groundwater treatment system "will be monitored, at a minimum, for untreated influent and treated effluent, and for impacts to surface water downstream of the effluent discharge point." RFLMA also establishes sampling criteria and decision-rule flowcharts for the treatment systems. The systems must be maintained to ensure the effluent meets state surface water quality standards. Meeting surface water standards in every stream on site was also a RAO in the Rocky Flats CAD/ROD. That RAO is generally met at all surface water points of compliance at the site boundary; however, surface water does not always meet surface water standards at monitoring points in the Central Operable Unit upstream of the points of compliance.

The applicable surface water standards have changed since the treatment system was installed. The original standard for nitrate was 100 mg/L, which is the agricultural standard applied on a temporary basis during the cleanup period. In 2009, that temporary modification reverted to the underlying standard, 10 mg/L—an order of magnitude difference.

The original uranium standard at the Rocky Flats Site was 10 picocuries per liter, an ambient value calculated for the Walnut Creek drainage. Although not applied at the site, in 2011 a new statewide Domestic Water Supply standard for uranium of 16.8 µg/L–30 µg/L (30-day standard) established by the Colorado Water Quality Control Commission took effect. This standard is measured in units of mass per volume of water, versus radioactivity per unit volume of water as previously measured. The 16.8 µg/L lower limit of the statewide stream standard for uranium is based on protection of human health from chemical toxicity. The 30 µg/L upper limit of the statewide stream standard for uranium is the USEPA drinking water MCL.

Instead of the statewide standard of 16.8 µg/L–30 µg/L, a separate regulation establishes a site-specific uranium standard of 16.8 µg/L, the lower end of the range for the statewide standard for stream segments on the Rocky Flats Site. According to the RFLMA, compliance with the 16.8 µg/L stream standard in Walnut Creek is monitored at the Walnut Creek Point-of Compliance (WALPOC) monitoring location. Per RFLMA, at WALPOC, a 30-day average concentration of uranium that exceeds 16.8 µg/L defines a “reportable condition” (regulators are consulted and the public is notified); a 12-month rolling average concentration of uranium that exceeds 16.8 µg/L also triggers an evaluation of compliance with the remedy performance standard.

A reportable condition occurred in 2014 when the 12-month rolling average of uranium measurements at WALPOC (17.2 µg/L) exceeded the standard. In response to this event, DOE consulted with the regulatory agencies to determine what actions would be required. This determination considered that the exceedance was due to the extraordinary 100-year flood events in September 2013 and that the concentrations remained well below the drinking water standard (30 µg/L MCL). The remedy, therefore, remained protective of the downstream water uses. Actions taken as a result of the consultation included:

- Additional samples were analyzed using high-resolution methods to determine the isotopic uranium distribution.
- Flow-paced composite samples analyzed on a two-week turnaround were continued.
- The ongoing geochemical study was used to evaluate the effects of environmental variability on uranium distribution.

Regulatory options to address the exceedances of the surface water standard upstream of the points of compliance include:

- Remove the water supply use classification and change the site stream standard for nitrate to the agricultural standard (100 mg/L) and the site standard for uranium to the state-wide standard. This reclassificiation is appropriate because conditions at the site have changed since the original use classification was assigned:
    - The source has been removed.
    - A treatment system has been installed.
    - Groundwater and surface water flows are greatly reduced.
    - Use of the stream segment as a water supply is prohibited by agreement and by an environmental covenant with the state.
    - Surface water exiting the site (via Walnut and Woman creeks) is now diverted around two downstream reservoirs and therefore no longer affects drinking water supplies.
- A use attainability analysis may be performed to determine if the stream segment cannot attain the standard.
- A postclosure ambient concentration can be calculated to apply as a stream-segment-specific standard.

### 6.3.5 Remedy Potential Assessment

To develop a better and more cost-effective solution for the SPP, potential remedy options were evaluated during a value engineering session in April 2016. This multiday exercise identified a list of possible remedies intended to help reach the goal of meeting stream standards along the on-site segment of the creek. These alternatives were grouped into the following categories:

- reduce infiltration
- treat groundwater
- promote favorable chemistry
- exit water rights
- create wetlands
- adjust water quality requirements

The alternatives were measured against performance attributes, which represent those aspects of a project's scope that may possess a range of potential values:

- stakeholder and regulatory
- performance effectiveness
- constructability
- maintainability
- environmental impacts

### 6.3.6 Stakeholder Involvement

Actions taken in response to exceedances of standards or to upgrade treatment systems are reviewed and approved by the Colorado Department of Public Health and Environment. These action approvals, as well as regulatory consultations, are documented in contact records, which are made available to the public by posting them on the Rocky Flats website and notifying interested members of the public. Significant modifications to the remedy decision or to the RFLMA require a public comment period.

The Rocky Flats Stewardship Council is a forum of local government officials and stakeholder organizations. This organization has met regularly since site closure to inform these governments and stakeholders of monitoring results, current issues, and actions. These meetings also serve as an opportunity for the interested public to interact.

Because the Central Operable Unit has ongoing groundwater treatment and use controls, CERCLA Five-Year Reviews are necessary. Although public comment is not required, the Rocky Flats Stewardship Council provides occasions for discussion of the Five-Year Review topics and the continued protectiveness of the remedy.

## 6.4 Rocky Mountain Arsenal, Colorado

The Rocky Mountain Arsenal (RMA) is a former chemical weapons manufacturing facility located just outside and northwest of the Denver, Colorado metropolitan area (Figure 21). The facility was built in 1942, in response to the outbreak of World War II in Europe. Approximately 27 square miles of arid prairie land northwest of Denver was appropriated by the U.S. War Department for construction of RMA facilities, which were built in the center of the property. This area was strategically chosen because it was unpopulated, landlocked deep into the continent's interior, inaccessible, and outside the flight range of enemy aircraft.

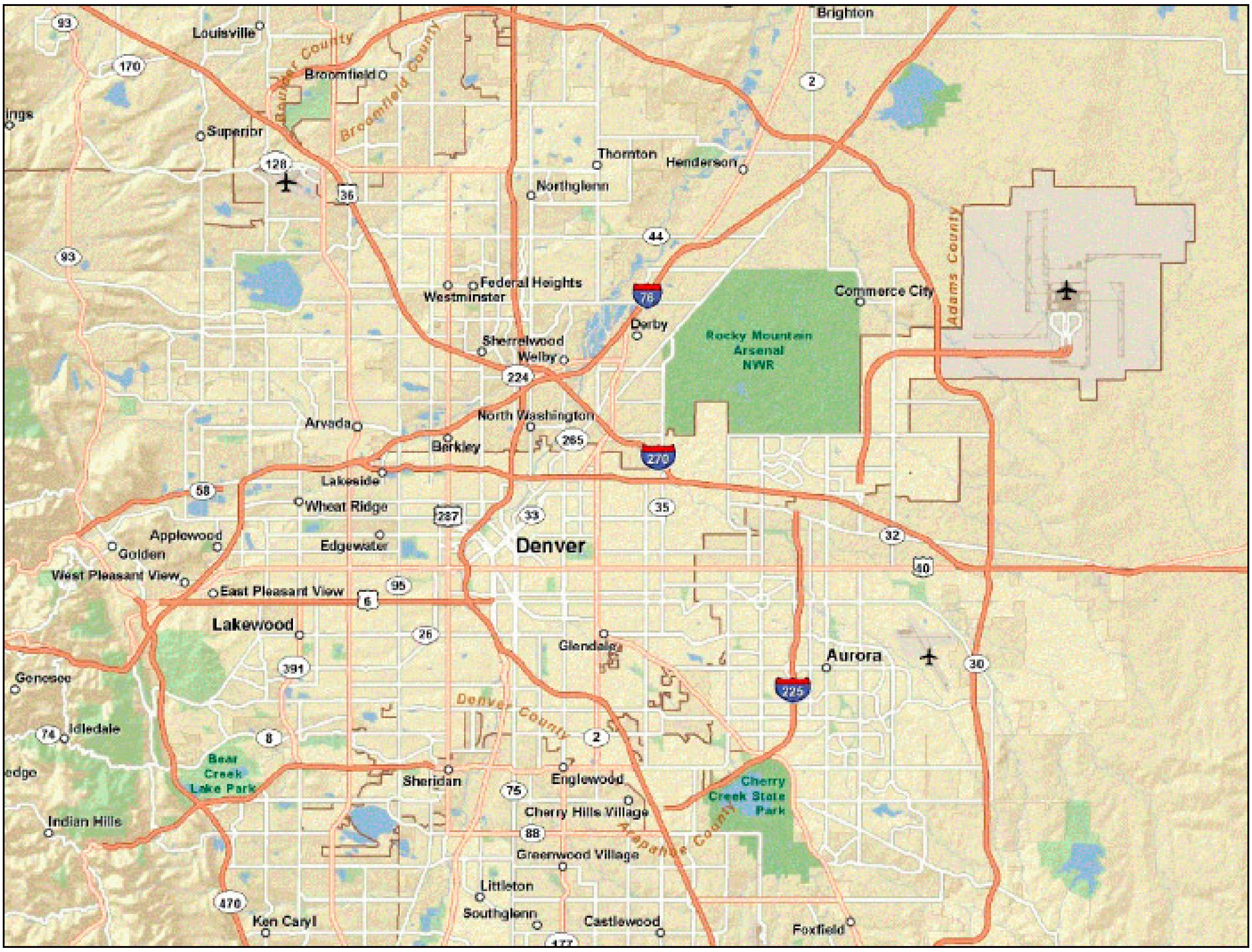



**Figure 21. RMA location** (GoogleMaps 2017)**.**

RMA manufacturing complexes were large and the extensive construction was completed in a short time. Only six months elapsed from the time that the land was acquired to the time the RMA facilities were physically completed. Crews worked around the clock to construct the facilities referred to as the "South Plants" (Figure 22).

**Figure 22. Photo of the South Plants with the old Stapleton Airport runways in the background and the Denver skyline in the background, c. 1980** (CDPHE 1980)**.**

Mustard agent, Lewisite, and other chemical agents were manufactured at the South Plants (SPs), stored in bulk, and injected into munitions. Manufacturing capability was extended to include napalm, white phosgene, and rocket fuel. During the 1950s, a second complex, the North Plants (NPs), was built on the north central portion of the property to manufacture Sarin gas. Sarin gas (O-isopropyl methylphosphonofluoridate), also called GB, is one of the most dangerous and toxic chemicals known. Sarin belongs to a class of chemical weapons known as nerve agents, all of which are organophosphates. Venomous Agent X, also known as VX gas (O-ethyl S-[2-(diisopropylamino)ethyl] methylphosphonothioate), one of the most dangerous chemicals created, was also manufactured at NPs (Figure 23). VX gas is a nerve agent containing organic phosphorous compounds and sulphur. The NPs facility was a windowless, five-story concrete monolith. By this time, war technology had improved to the point that the area could be reached by aircraft. Consequently, the five-foot thick concrete walls were built to withstand a direct hit from a nuclear warhead.

**Figure 23. North Plants looking north toward Wyoming, c. 1990** (CDPHE 1990)**.**

Also during the 1950s, the War Department attempted to recoup some of the costs to construct the North and South Plants facilities by leasing certain portions of the RMA to XXX Oil Company. The XXX Oil Company used the facilities to manufacture pesticides. By then, the RMA was also being used as a weapons research/military base, and munitions testing and exercises were conducted on site (Foster Wheeler 1996).

Napalm and rocket fuel (hydrazine) were also manufactured at RMA. A rail spur in the southwest portion of RMA transported the manufactured products off site. Spills occurred within the SPs buildings and during the transfer of chemical materials to the rail cars.

In aggregate, the operations at RMA were large-scale, complicated endeavors, involving explosive materials and over 650 different chemicals over the course of several decades. During this time, waste chemical releases into the environment were unregulated, and waste disposal practices were somewhat ad hoc.

Initially, the Army discharged chemical waste from North and South Plants into a large, open lagoon (Basin A). Basin A was created by enhancing a large natural depression in the ground surface. At first, chemical wastes were transported by truck to Basin A. Open ditches were also used to convey waste chemicals to the Basin A. Eventually chemical sewers were constructed to transport the wastes from the plants to Basin A directly. When Basin A overflowed, Basin B was constructed. When Basin B reached capacity, Basin C was constructed, followed by Basins D and E. These new basins required more sewers and more ditches.

By the time even more waste storage was needed, problems were beginning to surface north and northwest of the RMA boundary. Chemicals had spread into groundwater and far past RMA's boundaries. Farms and ranches north and northwest of RMA began to suffer crop damage and livestock deaths. The Army tried to construct Basin F, another open lagoon but lined with asphalt. Unfortunately, the asphalt liner failed because it was not resistant to the chemicals it was designed to contain. By this time, the contamination footprint was massive: Basin F alone was 93 acres. To reduce the volume of liquid waste material in Basin F, spray nozzles were installed in the lagoon to spray waste chemicals in the air. This activity resulted in a widespread, diffuse surface soil contamination footprint downwind of the lagoon. In addition to the six basins (A-F), other chemicals and solid wastes were disposed of and stored at RMA.

In the central/east portions of the RMA, Army and Complex Trenches were used to dispose of all types of wastes, from surplus desks and vehicles to off-spec munitions and chemicals. Wastes were placed in the trench, covered with napalm, and burned. XXX Oil Company had its own set of trenches (the XXX Oil Company Trenches) for the same purpose. Soil was pushed over the trenches as backfill when waste burning was complete. In addition to the trenches, several one-acre unlined pits were also constructed in central RMA to dispose of off-spec mustard and Lewisite, waste mercury, and other chemicals. The chemical waste was mixed with caustic lime to neutralize the agent; these pits were known as the Lime Basins. Mercury was dumped into similar pits (M1 Pits). Large quantities of a tarry chlorinated material, hexachlorocyclopentadiene, a process intermediate, were placed in unlined Hex Pits.

Chemical sewers crossed the site, emptying into Basins A and F; eventually, they too leaked. A large storage yard contained rows of palettes of waste chemicals and off-spec pesticides in drums, many of which leaked and were subject to wind-blown dispersion. Another large storage yard stored chemically configured munitions that were brought out of the bunkers because they were leaking. Other portions of the site were used as a firing range for testing munitions.

In 1962, the Army attempted a pilot project to manage the increasing quantities of chemical wastes that were being produced at the RMA. A 12,000-foot deep injection well was installed at RMA. The Army injected more than a million gallons of chemical wastes into the well at high pressure and set off a series of earthquakes that began to rock the Denver metropolitan area from the long-dormant Golden Fault. Injection activities ceased.

In 1982, the Army and XXX Oil Company ceased all manufacturing and storage functions at RMA. The only remaining mission at the RMA was cleanup. The physical, scientific, legal, social, and political issues left by facility operations and waste disposal were so complex and severe, however, that a ROD was not signed for another 14 years. Completing remedy construction took an additional 14 years after the ROD was signed.

Several Interim Response Actions (IRAs) were implemented on an emergency basis to stabilize the most pressing and immediate areas of RMA. One of these IRAs, Basin F stabilization, was problematic because the stabilization process created its own set of severe environmental problems, elicited public concern about the safety of the cleanup efforts, and affected ROD negotiations.

The RMA has two RODs: (1) On-Post ROD (Foster Wheeler 1996) and (2) Off-Post ROD (Harding Lawson Associates 1995). The On-Post ROD addressed the extensive contamination found at its source on site in Operable Unit 4. The Off-Post ROD primarily addressed the vast groundwater plume that had spread off site, affecting domestic wells in the largely rural farm and ranchland north and northwest of RMA, known as Operable Unit 3. The Off-Post ROD was signed in 1995, about a year before the On-Post ROD. The Off-Post ROD established a water treatment plant and a replacement municipal water supply for the residences north of RMA and established a water quality testing program for the domestic wells that still exist in the area. This testing program is implemented through Tri-County Health Department and is ongoing.

During the late 1970s, groundwater P&T systems had been installed at the north and northwest boundaries of RMA. During the 1980s and early 1990s, fourteen interim response actions (IRAs) were completed by the Army and XXX Oil Company on an emergency basis in an initial attempt to halt exposures and prevent the spread of contamination. Some efforts were eventually incorporated into the final remedy; others were enhanced or subjected to another, final remedy project. Although the IRAs were successful in breaking immediate pathways to the most grossly contaminated parts of the RMA, the final ROD was not signed until 1996. Some of the IRAs were incorporated into the remedy; others were only temporary solutions that were redesigned into more permanent projects for the ROD.

These IRAs are briefly described as follows (Foster Wheeler 1996):

1. Groundwater Intercept and Treatment Off-Post, North of RMA – This IRA addresses groundwater contamination that had migrated off post prior to installation of the boundary extraction and treatment systems on post. This system was constructed downgradient and well north of the RMA Boundary, in the middle of the most highly contaminated portion of the plume, and continues to operate. Construction of this IRA was completed in 1993; treatment of groundwater at the north boundary continues.
2. Enhancement/Improvement of Groundwater P&T Systems (North Boundary Containment System, (NBCS) Northwest Boundary Containment Systems (NWBCS), Irondale Containment System (ICS)
    1. The NBCS was originally designed to remove and treat contaminated water reaching the north boundary of RMA. Although originally installed in the 1970s, this system still operates and will continue for the foreseeable future. Groundwater is extracted, treated by granular activated carbon (GAC), and reinjected into the ground. The primary contaminants at this location are chloroform, dieldrin, DIMP, DCPD, and organosulfur compounds. The original system consisted of extraction wells, a 6,740-ft slurry wall, a recharge sump, filters to remove particles from water, three large (20,000 lb) carbon adsorbers to treat organic contaminants to containment system remediation

goals (CSRGs) from groundwater, and reinjection wells. Operational improvements were implemented as part of the IRA and the reinjection system for treated water was improved by addition of recharge trenches along the entire portion of the extraction well system and the slurry wall. The improvements to the NBCS were completed in 1993; treatment is ongoing.

   2. The Northwest Boundary Containment System (NWBCS) was designed to remove and treat contaminated groundwater migrating toward and beyond the northwest boundary. The original system included extraction wells, GAC treatment, and a reinjection system as well as a slurry wall to control contaminant migration. The slurry wall, which originally measured 1,425 ft, was extended by 665 ft. Five new extraction wells were added to the original 15, and the number of reinjection wells was increased from 21 to 25. The IRA modifications increased the amount of water treated in the NWBCS from approximately 900,000 to 1.4 million gallons per day. Groundwater is treated to CSRGs for organic contaminants and reinjected. Construction of the improvements to the NWBCS was completed in 1993, but use of this system is ongoing.
   3. The Irondale Containment System (ICS) was designed to remove and treat contaminated groundwater migrating from the Railyard and the Motor Pool toward the western boundary. The original system included two parallel rows of extraction wells, one row of reinjection (recharge) wells, and GAC treatment, and improved during the IRA. Groundwater was treated to CSRGs for organic contaminants. Construction of the improvements was completed in 1991. Groundwater in this area has since attained standards and this boundary P&T system has been shut off.

3. Groundwater Intercept and Treatment North of Basin F (interior of RMA) – The purpose of the Basin F Groundwater IRA was to intercept and remove contaminated groundwater migrating from the Basin F area toward the northern boundary. The IRA included extraction, treatment to CSRGs, and reinjection of groundwater. Water was extracted from a well north of Basin F at a rate of 1 to 4 gpm, or approximately one million gallons per year. The extracted water was piped to a treatment system located at Basin A Neck for removal of volatile contaminants (solvents) by air stripping and the remaining contaminants, such as pesticides, by GAC. Treated water was reinjected in recharge trenches at the Basin A Neck area. Construction of this IRA was completed in 1990.
4. Closure of Abandoned Wells – At numerous locations throughout RMA, old or deteriorating farm wells and unused on-post wells have been located and cemented shut. This IRA was completed in 1990.
5. Groundwater Intercept and Treatment System in the Basin A Neck Area – The Basin A Neck IRA, located on the interior of the RMA, was designed to capture and contain contaminated groundwater migrating from Basin A. The system uses extraction wells for removal of groundwater from the aquifer, has a slurry wall to minimize migration of contaminated groundwater, a water treatment system, and a reinjection system consisting of several recharge trenches. Approximately 5 to 10 million gallons per year of groundwater are extracted and treated to CSRGs by GAC at the Basin A Neck IRA treatment system. The contaminants removed from water include solvents and pesticides. Construction of the Basin A Neck system was completed in 1990; treatment of groundwater is ongoing.
6. Basin F Liquids, Sludges, and Soil Remediation – The Basin F IRA was an emergency action to stabilize Basin F. This IRA was noteworthy because of problems encountered during its implementation. These issues were severe and complicated the negotiation and drafting of the final ROD (see below for details). The IRA included transfer of the basin liquids and decontamination water into temporary storage tanks and a lined, covered surface impoundment (Pond A); construction of a 16-acre lined waste storage pile with a leachate collection system; excavation of 600,000 cubic yards of Basin F soil, air drying of the wastes, and subsequent placement into an unlined waste pile; and incineration of the stored liquids by Submerged Quench Incineration (SQI). All field and administrative closure activities were completed by May 30, 1996.
7. North Plants Building 1727 Sump Liquid – Liquid in the Building 1727 sump was treated by activated alumina and GAC to remove contaminants that included arsenic and DIMP (by-product of degraded sarin nerve agent). This IRA eliminated any remaining threat of liquid release from the sump; it was completed in 1989.
8. Closure of the Hydrazine Facility – This facility was used as a depot to receive, blend, store, and distribute hydrazine fuels. Wastewater stored at the facility was treated on post at the SQI facility, the structures demolished, and the debris removed. Uncontaminated materials at the site were salvaged for recycling and reuse, and contaminated materials were disposed at an off-post permitted hazardous waste landfill. The area encompassing the former facility was regraded and revegetated following demolition and debris removal. This IRA was completed in 1992.
9. Fugitive Dust Control – In 1991, the Army completed the reapplication of a dust suppressant in Basin A as part of

this IRA. Hydroseeder trucks were used to spray a nontoxic, water-based dust suppressant. This action minimized off-site transport of windblown dust.

10. Sewer Remediation – As part of this IRA, sanitary sewer manholes were plugged to eliminate the transport of contaminated groundwater that may have entered the sewer system via cracks or loose connections. This IRA was completed in 1992.
11. Asbestos Removal – This IRA is part of the Army's ongoing survey of asbestos on post, including removal and disposal activities. The survey and removal of friable asbestos from occupied buildings were completed in December 1989. The Asbestos IRA activities continue as part of the final structures remediation.
12. Remediation of Other Contamination Sources – Under this IRA, the following contamination sources were addressed:
    1. Motor Pool – A groundwater extraction system was constructed to remove trichloroethylene (TCE) in groundwater in the Motor Pool area. Approximately 100 gpm of water is extracted from the Motor Pool area. A soil vapor extraction (SVE) system was also constructed to draw vapors containing volatile contaminants from the soil. Extracted vapors were sent first to a separation tank to remove the water vapor and then to a treatment system where the volatile contaminants were treated. Soil vapor extraction was conducted at the Motor Pool area between July and December 1991 to remediate TCE-contaminated soil.
    2. Rail Yard – The Rail Yard IRA extraction system consisted of a row of five wells that extracted approximately 230 g/min of groundwater containing low levels of dibromochloropropane (DBCP) resulting from spills at the Rail Yard. The water is piped to the ICS where DBCP is removed by GAC. Two additional wells further downgradient acted as a backup system. Currently, the system is being evaluated for shutoff.
    3. Lime Settling Basins – Workers constructed a soil cover over the Lime Settling Basins area to isolate the basins from the ground surface and minimize the amount of rainwater seeping into the basins. The construction of the cover was completed in 1993.
    4. South Tank Farm Plume – This area included tanks used for storage of alcohol, BC1HPD bottoms, DCPD, D-D soil fumigant, and sulfuric acid. Records indicate benzene was also used or stored in this area. The South Tank Farm Plume, located between South Plants and the South Lakes area, consisted of two separate groundwater plumes extending toward the lakes, one of which consists of light nonaqueous phase liquids (LNAPLs). The IRA alternative consisted of continued groundwater monitoring to verify that no further actions were necessary due to the natural degradation of the contaminants. Alternative assessment activities were completed in 1994. In 1991, an SVE field demonstration, which included collection and analysis of soil, LNAPL, SVE off-gas, and soil gas samples, was designed for specific application to the South Tank Farm Plume. The resulting data were used to evaluate the performance, effectiveness, and operating parameters for an SVE system. Based on the results of the demonstration, it would take more than 10 years for the SVE process to remove most of the mass of contaminants that would remain after LNAPL recovery was no longer feasible.
    5. Army Trenches – Soil samples collected from representative trenches showed elevated concentrations of ICP metals and relatively low concentrations of arsenic, mercury, and many organic contaminants, including members of all the analyte groups except pesticide-related organophosphorous compounds and organo-nitrogen compounds. Several tentatively identified compounds were also detected in the trench soil. High concentrations of some organic contaminants exist in groundwater in portions of this area. The IRA alternative consisted of continued groundwater monitoring in this area. Alternative assessment activities were completed in 1994.
    6. XXX Oil Company Trenches – Under this IRA, the trenches were covered with soil and revegetated. A slurry wall that surrounds the trench area reduces the lateral movement of contaminants away from the trenches. Construction of this IRA was completed in 1991.
13. CERCLA Hazardous Wastes – The initial action was pretreatment of CERCLA liquid wastes. This IRA was later expanded to include identification, storage, and disposal of a variety of CERCLA wastes. The initial action and expanded elements are as follows:
    1. Wastewater Treatment Plant – A wastewater treatment plant was constructed by 1992 under the first phase of the CERCLA Liquid Waste IRA. This facility is currently used to treat wastewater generated from laboratory operations, field sampling, decontamination, and other sources such as equipment washing. Several treatment technologies are used at the CERCLA Wastewater Treatment

Plant including activated GAC, advanced oxidation using ultraviolet light, air stripping, chemical precipitation, and activated alumina adsorption. This facility will be used to treat similar wastewater streams during remediation.

2. Waste Management – Waste streams were managed on an emergency basis, including miscellaneous wastes from vehicles, grounds, and building maintenance, and items found on post.
3. Polychlorinated Biphenyls (PCBs) – The purpose of this element was to inventory and sample PCB contaminated equipment followed by remediation off post. This IRA included characterization of spill sites (soil and structures) associated with PCB contamination and is ongoing. PCB contamination not addressed in this IRA was addressed as part of the final remedy.
4. Waste Storage – This element included an on-post facility for temporary management of solids that are bulk hazardous wastes, primarily, contaminated soil and building debris. Analysis resulted in the decision to eventually dispose of the wastes in the on-post hazardous waste landfill when it became available during remedy.

14. Chemical Process-Related Activities – Agent-related and non-agent-related process equipment and piping located in North Plants and South Plants was sampled, decontaminated, and dismantled. Although much of the equipment in these areas was removed and recycled under the IRA, the process-related equipment not remediated as part of this IRA was disposed in the on-post hazardous waste landfill. Asbestos-removal activities as required for equipment removal continued as part of the final response action at RMA.

The implementation of the Basin F IRA was especially challenging because of the number of problems encountered and the effect of those problems on the future course of the project**.** During the winter of 1988, the Army drained the liquid off the 93-acre Basin F (Figure 24) and stored it in three large tanks to later be incinerated. Highly contaminated sediment that had accumulated at the bottom of the impoundment was piled in large piles and stacks with the intention of drying them before their secondary impoundment into a waste pile. These contaminated sediments were hazardous and odorous. The attempts to dry the sediments resulted in chemical odors and thick, noxious fumes. These fumes quickly accumulated and spread into nearby neighborhoods, causing illness in residents. The arrival of winter, and Denver's notorious poor atmospheric dispersion conditions, coincided with the maximum areal extent of the excavation. The entire 93 acres were exposed and there was no means by which it could be covered. The resulting trapped odors and fumes that had spread into the neighboring communities, at one point, resulted in closure of major thoroughfares in and out of the surrounding community.

News media provided daily coverage of the story. There was no public outreach and no clear communication with the surrounding community about what was creating the toxic fumes that were making residents ill. Because the RMA site was associated with secret military activities and the actual excavation was located too far into the interior to be viewed, fear and panic spread throughout the community. Neighbors knew only that the facility manufactured "nerve gas."

The situation became a state of emergency, further confused by legal ambiguity about whether the state could enforce its newly delegated RCRA authority on federal facilities. As the situation escalated into a crisis, the governor attempted to visit community members to speak directly to them. The governor tried to calm the neighborhood's anxiety, but instead was chased down the street by angry civilians (KMGH-TV 1988).

This situation was resolved by completion of the IRA, but it complicated the eventual signing of the ROD. Not surprisingly, the Basin F IRA created uncertainty and concern among surrounding residents and stakeholders that the RMA could in fact, be safely excavated and cleaned up without exposing the surrounding communities via the air pathway. Eventually, concern about Basin F was resolved in the ROD by including certain requirements in the ROD. Most notably, the ROD established a medical monitoring program that consisted of several key requirements:

- Extensive air quality monitoring was conducted at sites around the RMA perimeter, interior, and within the surrounding community.
- An innovative air modeling system using local air data was incorporated into the design for each project. This system identified "no dig' days for each project based upon forecast meteorology, and employed a full-time meteorologist to develop a daily forecast that would guide the rate of excavation for that day.
- Extensive odor monitoring 24/7 at the fence line provided immediate feedback about the potential for any emissions to reach the fence line or beyond.
- A hotline was set up for the Rocky Mountain Poison and Drug Center. Staff were trained to respond to calls from concerned citizens around RMA during the cleanup.
- Local physicians were trained to look for any potential effects in their patients that might relate to the Rocky Mountain Arsenal.

- Newsletters were developed and sent to the local communities on a regular basis to keep them informed about the RMA cleanup, and a Citizens' Advisory Group was set up specifically to respond to citizen health concerns.

These efforts were largely effective and successful. With the remedy underway and the ROD projects implemented, these measures alleviated citizen concerns. The remedy was implemented without any further significant impact to the community (Figure 25).

**Figure 24. Image of Basin F, prior to the 1988 IRA, c. 1980. From archived files of Colorado Attorney General's Office** (CDPHE 1980)**.**

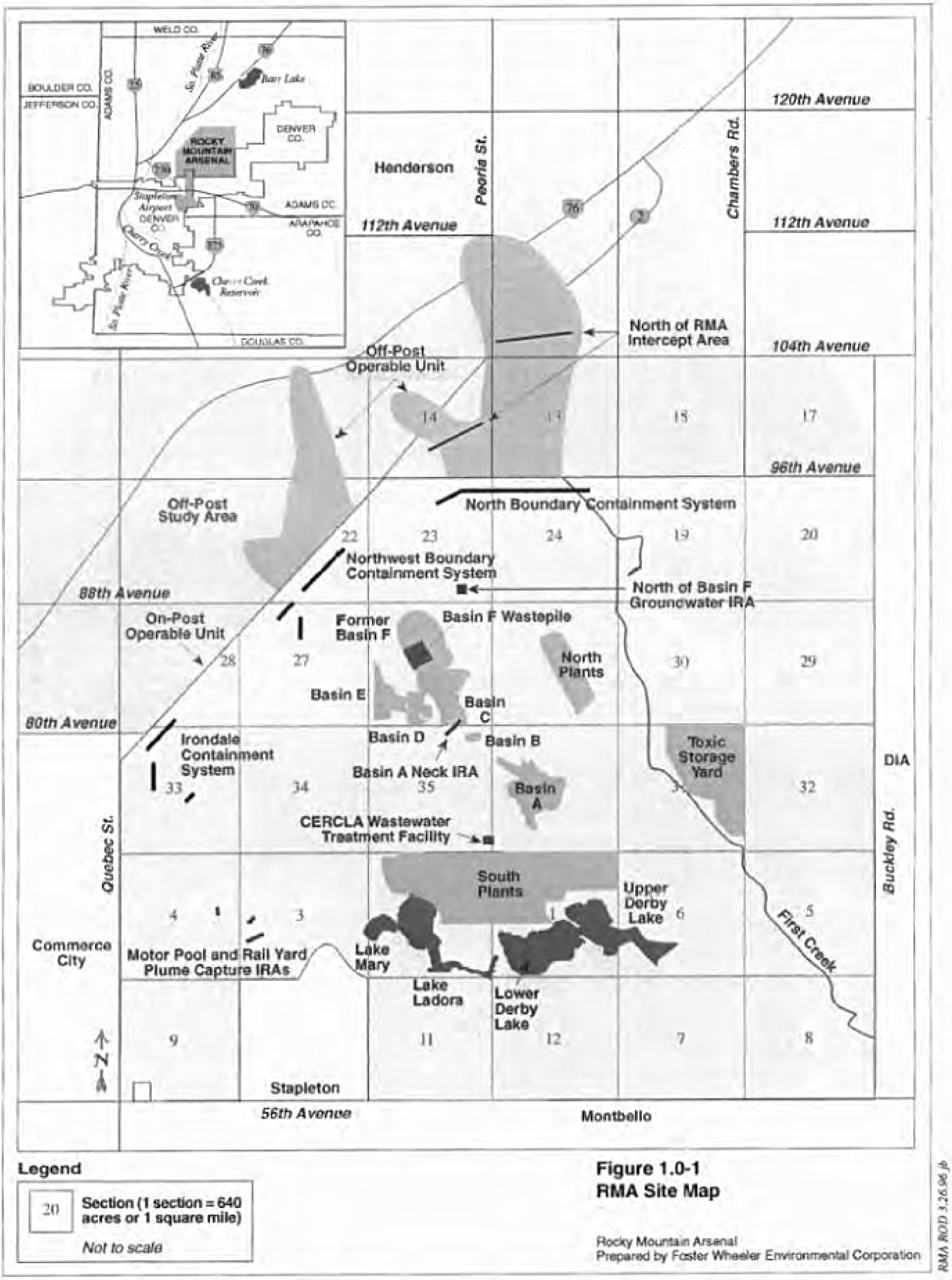



**Figure 25. Map of project areas and IRA at RMA** (Foster Wheeler 1996)**.**

### 6.4.1 Technical Basis for Remedial Action

Under the On-Post ROD, the RMA was broken into 36 separate projects for eventual cleanup. Some of these projects incorporated or improved upon the IRAs. Overall, the selected remedy at RMA was essentially a large-scale "dig-and-haul" operation, with several opportunities for innovative technologies selected for certain projects. Due to the extensive amounts of contaminated soils and their depth, excavating to the water table was considered impractical (over 40 feet in most locations). It was eventually decided only to excavate the upper 10 feet of soil at RMA, and to leave the remaining waste under caps and covers.

Because of the sheer volume of soil to be disposed, the remedy was negotiated as a fixed volume, which meant that only a predetermined amount of soil—that for which the landfills could be designed—would be excavated. All structures with no future use were demolished. Less contaminated soils and less contaminated debris from structures were placed as grade fill over the footprint of South Plants, Basin A, and Basin F. More contaminated soils were excavated to 10 feet and placed in one of two on-site landfills built specially for this purpose. The basins with the consolidation debris and other areas where most highly contaminated soil remained at depth were interred under RCRA-equivalent evapotranspiration covers with geotextile capillary break liners and a biota barrier filled in with chokestone (Figure 26). Less contaminated soils with no consolidation debris were covered with two and three-foot covers without the biota barrier.

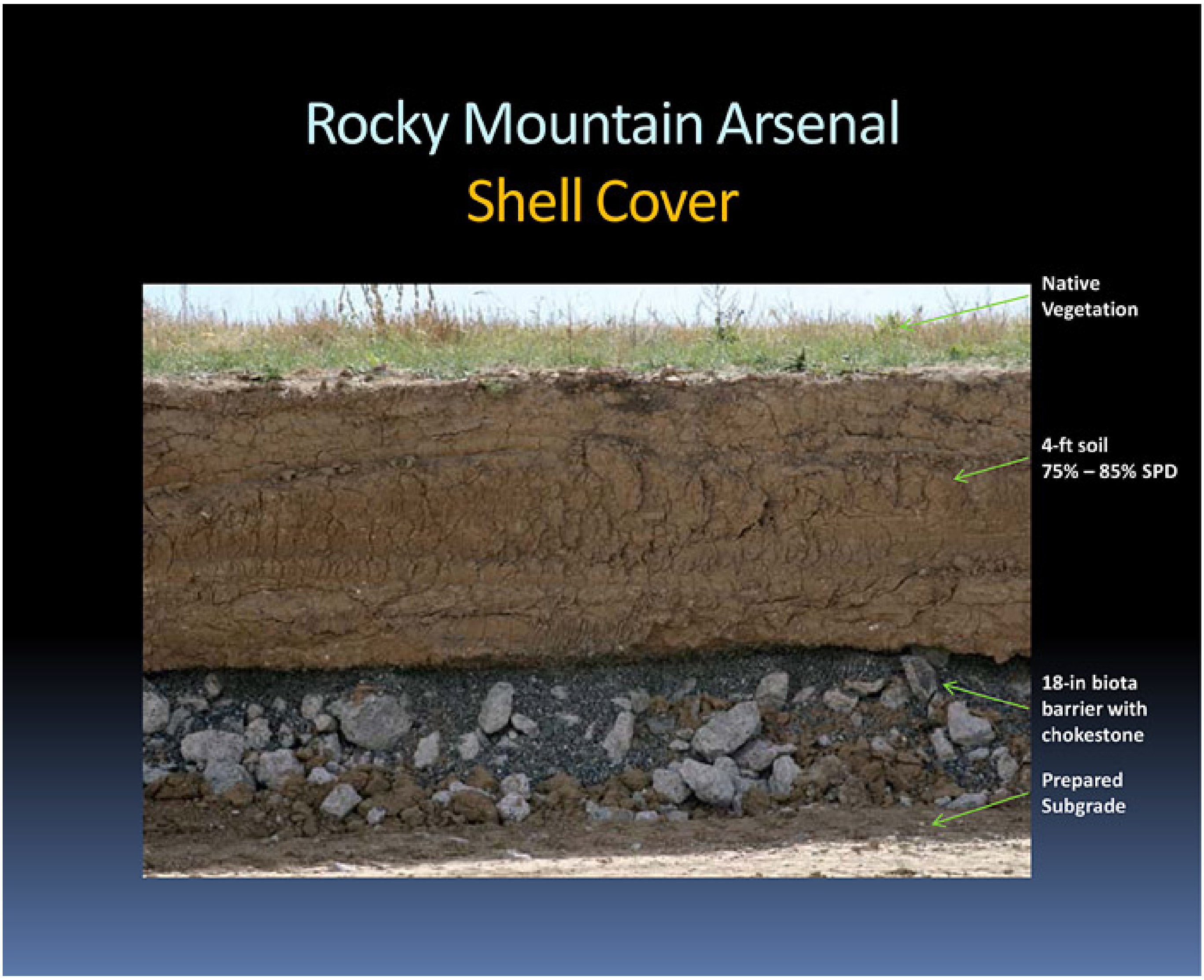



**Figure 26. Image of RCRA-equivalent cover cross-section exposed while under construction** (CDPHE 2000)**.**

The most highly contaminated structures, including those with known agent history, were demolished, caustic washed, or both and the debris placed in the on-site landfills.

Munitions were located using geophysical methodology and archived aerial photographs. Extensive unexploded ordnance (UXO) removal was conducted. Areas that had been lightly contaminated by the windblown spray from the Basin F aerator spray system were tilled to redistribute surface contamination. The groundwater P&T systems that had been installed to intercept the contaminated plumes at the site boundary were enhanced, expanded, and incorporated into the final remedy. These systems continue to operate, and will continue to treat groundwater until it is no longer necessary (estimated to be another 100 years). Chlorides and sulfates are expected to attenuate naturally.

Off-post, the Army set up a municipal wastewater treatment plant and all off-site users of domestic wells were allowed a hookup to the new municipal system at no cost. Additionally, remaining off-site domestic water wells may be sampled annually at the owner's request under a contract with the local county health department (this program is PRP funded). Any remaining wells found to exceed standards will be eligible for a hookup. Some soils on properties that lie on the immediate north boundary of the RMA off site were tilled to redistribute surface contamination (Harding Lawson Associates 1995).

Because the scope of cleanup of the site is limited and waste remains in place, the RMA site is subject to land use restrictions in perpetuity that restrict residential development and use, restrict any agricultural use or human consumption of fish and game from the RMA, and limit access to capped and covered areas (Navarro Research and Engineering Inc. 2013). The RMA site has been inducted into the USFWS refuge system in perpetuity as a wildlife refuge (Congress 1992). Because of the nature of the cleanup and the prospective future use of the land, the ROD did not call for confirmatory sampling of excavations at RMA. Some limited further sampling was conducted, but the samples were only identified during final inspection and the locations based only upon a visual assessment (for example, visible soil staining).

### 6.4.2 Decisions

Initial characterization of the RMA was hampered by its sheer size and number of chemicals involved. Efforts were made to streamline the areas to be investigated by using archived aerial photography to identify the former use areas and known areas of severe contamination, mostly within the RMA's core. Soil sampling was concentrated in those areas, leaving sparser areas of sampling at the RMA's perimeter. Many of the samples were composites, both horizontal and vertical. Twenty-seven risk driving chemicals of concern were identified out of over 660 compounds originally known to have been used or disposed of at the Arsenal, including VOCs, pesticides, and more.

Most importantly, in 1987, before site or remedial investigations had been completed for RMA, a Federal Facility Agreement (FFA) was signed for RMA—the first in the country (USEPA 1989c). In a reversal of what would later become standard procedure for most sites, a series of land use restrictions, to be imposed in perpetuity on the RMA, were agreed upon and adopted into the FFA. At that time, the future use for the site began to be envisioned as open space/wildlife refuge. As such, these land use restrictions that were originally established in the Federal Facility Act of 1987 became a foundational basis for all future use assumptions. The rest of the Superfund process, including RI/FS, Risk Assessments, and eventually, the On-Post ROD, was designed around these restrictions.

The land-use restrictions served to limit the number of samples and influenced the selection of chemicals that would be selected as COCs (for example, the prohibition on consumption of fish and game caused the chemicals known to present a bioaccumulation hazard not to be included as COCs). Presupposing the land use restrictions and building the remedy around them caused a chain of events that affected the remedy all throughout its life cycle and beyond.

## Timeline of Decisions

***Inception and Completion Dates for Major RMA Documents***

| Document | Start Date | Finish Date |
|---|---|---|
| Federal Facility Agreement | February 1987 | |
| Remedial Investigation | October 1984 | January 1992 |
| Human Health Exposure Assessment | October 1986 | September 1990 |
| Human Health Exposure Assessment Addendum | August 1990 | December 1992 |
| Human Health Risk Characterization | September 1992 | May 1990 |
| Ecological Risk Characterization | October 1987 | July 1994 |
| Development and Screening of Alternatives | February 1989 | December 1992 |
| Detailed Analysis of Alternatives | January 1993 | October 1995 |
| Rocky Mountain Arsenal National Wildlife Refuge Act | 1992 | |

| Document | Start Date | Finish Date |
| --- | --- | --- |
| Off-Post ROD | July 1995 | |
| On-Post ROD | 1996 | |

At RMA, direct and indirect future exposure pathways were evaluated, and ROD removal criteria were developed to accommodate the presumed future exposures only. The direct pathways included ingestion (consumption of contaminated soil), dermal absorption (contacting contaminated soil), and inhalation (breathing contaminated dust particles). The indirect pathways included inhalation of contaminated vapors in open areas (such as during work performed outdoors) and enclosed spaces (such as in basements). Dermal contact with metals in soil was not evaluated for any receptor population because of negligible contaminant absorption through this exposure pathway.

The five potentially exposed populations/subpopulations and their respective current and future exposure pathways included the following:

- biological worker, for example, a wildlife biologist working on the refuge—all direct pathways and open space vapor inhalation
- regulated/casual visitor, for example, someone (adult or child) visiting the wildlife refuge—all direct pathways and open space vapor inhalation
- recreational visitor, for example, someone (adult or child) jogging or playing on areas of the wildlife refuge—all direct pathways and open space vapor inhalation
- commercial worker, for example, a person working inside a building on the wildlife refuge—all direct pathway and enclosed space vapor inhalation
- industrial worker, for example, a person working outside and potentially exposed to soil—all direct and indirect pathways

### 6.4.2.1 Summary of the FS Process

The FS process involved two phases: (1) development and screening of alternatives and (2) the detailed analysis of alternatives. Contaminated media at RMA, including water, structures, and soil, was subdivided into several groups with similar contamination to organize and streamline the FS process.

RAOs were identified at the outset of the development and screening of alternatives. These goals provided general guidance for the FS by identifying the contaminants and media of interest, potential exposure pathways, and preliminary remediation goals. For the On-Post OU, RAOs were developed for water, structures, and soil based on ARARs specified in federal and state environmental laws and regulations, and the provisions of the FFA. The human health and biota remediation goals aimed to achieve appropriate remediation so that the selected remedy was protective of both humans and biota. Further specific considerations taken at RMA include Army safety procedures and USFWS guidance regarding the future land use of the site as a national wildlife refuge.

A range of alternatives was developed for each of the water, structures, and soil medium groups, including: no action (NA), no additional action (NAA), institutional controls, containment, and treatment options. The NA alternative (as required by USEPA) and the NAA alternative were also developed and used as a baseline against which other alternatives were evaluated. The NA alternative represents current site conditions with no remedial actions undertaken, ongoing, or planned. The NAA alternative involved no action beyond the IRAs currently being implemented on post.

No Action and NAA alternatives were developed for each contaminated medium. These alternatives were eliminated from consideration during the comparative analysis conducted for site-wide alternatives because they were not sufficiently protective. The identified alternatives had several features in common:

- *Land Use Restrictions*. The Rocky Mountain Arsenal National Wildlife Refuge Act of 1992 restricts current and future land use, specifies that the U.S. government shall retain ownership of RMA, and prohibits certain activities such as agriculture, use of on-post groundwater as a drinking source, and consumption of fish and game taken at RMA. Continued restrictions on land use and access were included as an integral component of all on-post alternatives. Long-term management includes access restrictions to capped and covered areas to ensure the integrity of the containment systems.
- *Five-Year Review.* In accordance with CERCLA, a review will be performed a minimum of every five years after initiation of remedial action to ensure that the various remedial actions where contamination continues to exist,

such as the capped areas or the hazardous waste landfill, remain protective of human health and the environment and comply with ARARs.

- *Site Monitoring*. The Army will continue to conduct air, groundwater, and surface water monitoring programs at RMA. The Army will continue to fund USFWS to conduct on-post wildlife monitoring programs. Samples will be collected periodically to assess the effectiveness of the remedy for protection of human health and the environment. The actual compliance monitoring program for each of the environmental media will be finalized during the remedial design.
- *Revegetation*. When vegetation is disturbed during remedial construction, the disturbed areas will be revegetated consistent with a USFWS refuge management plan.
- *Long-Term O&M*. Areas remediated will be operated and maintained as required. Management activities may include maintaining capped and covered areas or operating the on-post hazardous waste landfill or groundwater treatment systems.
- *On-Post Water Supply*. A sufficient on-post water supply will be maintained.

Other additional components included in the overall on-post remedy were considered in the selection of the preferred alternatives include:

- provision of $48.8 million held in trust to provide for the acquisition and delivery of 4,000 acre-feet of potable water to SACWSD and the extension of the water-distribution lines from an appropriate water supply distribution system to all existing well owners within the plume footprint north of RMA
- an RMA Medical Monitoring Program (implemented by CDPHE, discussed above)
- a trust fund requested by members of the public and some public officials to address concerns about the stability of long term O&M costs (a joint trust fund between XXX Oil Company and the Army was unsuccessful due to regulations regarding joint federal and private funds)
- biomonitoring
- UXO disposal

An expanded discussion of remedial alternatives is presented in the Rocky Mountain Arsenal On-Post ROD.

### 6.4.3 Cost Assessment

The estimated cost for the selected On-Post Remedy for the RMA was $2.2 billion. The Army assumed 80% of that cost and XXX Oil Company assumed 20%. Table 18 gives a rough breakdown of estimated cost for the remedy.

**Table 18. Total estimated cost of the selected RMA remedy[1,2]**
(adapted from DOE, USEPA, and CDPHE 2003)

| Cost Element | Capital ($ M) | | Operating and Maintenance ($ M) | | Total Cost ($ M) | |
|---|---|---|---|---|---|---|
| | Total[3] | Present Worth | Total[3] | Present Worth | Total[3] | Present Worth |
| Soil | 530 | 380 | 41 | 17 | 570 | 400 |
| Water | 19 | 18 | 130 | 85 | 150 | 100 |
| Structures[4] | 7 | 6.5 | 140 | 130 | 150 | 140 |
| Pre-ROD Costs[5] | 750 | 750 | — | — | 750 | 750 |
| PMRMA Mission Support | 550 | 430 | — | — | 550 | 430 |
| **Total Cost ($ M)** | 1,900 | 1,600 | 310 | 230 | 2,200 | 1,800 |

[1] Detailed cost information is provided in the Detailed Analysis of Alternatives report

[2] All costs are presented in 1995 dollars

[3] Total cost does not account for inflation over the time frame for remediation

[4] Structures cost includes $35 million to complete ongoing IRAs

[5] Pre-ROD costs include RI/FS and IRA costs and are listed to illustrate the total costs for complete remediation of RMA

### 6.4.4 Monitoring/Optimization

Currently, the RMA remedy construction has been completed by the Army as lead agency, in cooperation with XXX Oil Company and the U.S. Fish and Wildlife Service, with oversight provided by USEPA, Colorado Department of Public Health and Environment, and Tri-County Health Department. Air monitoring is no longer necessary and has been discontinued. The landfills and covers are in postclosure care. All munitions and explosives of concern/UXO clearances have been completed. Groundwater continues to be monitored on and off-post and the groundwater P&T systems are still operating at the boundary as well as the off-post and on-post P&T systems. Off-post plume maps are generated every few years. Resident domestic wells continue to be monitored for RMA contaminants upon request. Groundwater on- and off-post is sampled every 2.5 years for RMA COCs. Biota continues to be monitored for residual contamination.

Understanding postremedy soil conditions is hampered by a lack of confirmatory sampling post-excavation. This decision, originally negotiated in the on-post ROD, created a data gap that has hindered some postremedy optimization efforts. The remedy envisioned that the land use restrictions would remain in place in perpetuity; lack of data makes it unclear whether land use restrictions are still necessary. ICs are now hampering USFWS land management activities in ways not anticipated by the original remedy.

Other postremedy management challenges have arisen. In 2007, USFWS introduced 13 bison onto RMA from another Western wildlife refuge. The herd has grown exponentially; excess bison will be an ongoing problem. USFWS wishes to make excess bison available to the public for human consumption. This situation brings USFWS needs for managing the RMA refuge into conflict with the long-standing prohibition on human consumption of fish and game from RMA. Furthermore, USFWS wishes to use hunting and fishing as a tool to manage wildlife populations in the increasingly urban-locked Rocky Mountain Arsenal National Wildlife Refuge. Additionally, the RMA National Wildlife Refuge is increasing in popularity, receiving over 1 million visitors per year in 2016. There is increasing public pressure for more intensive uses of the RMA National Wildlife Refuge as a recreation area. Figure 27 shows RMA today.

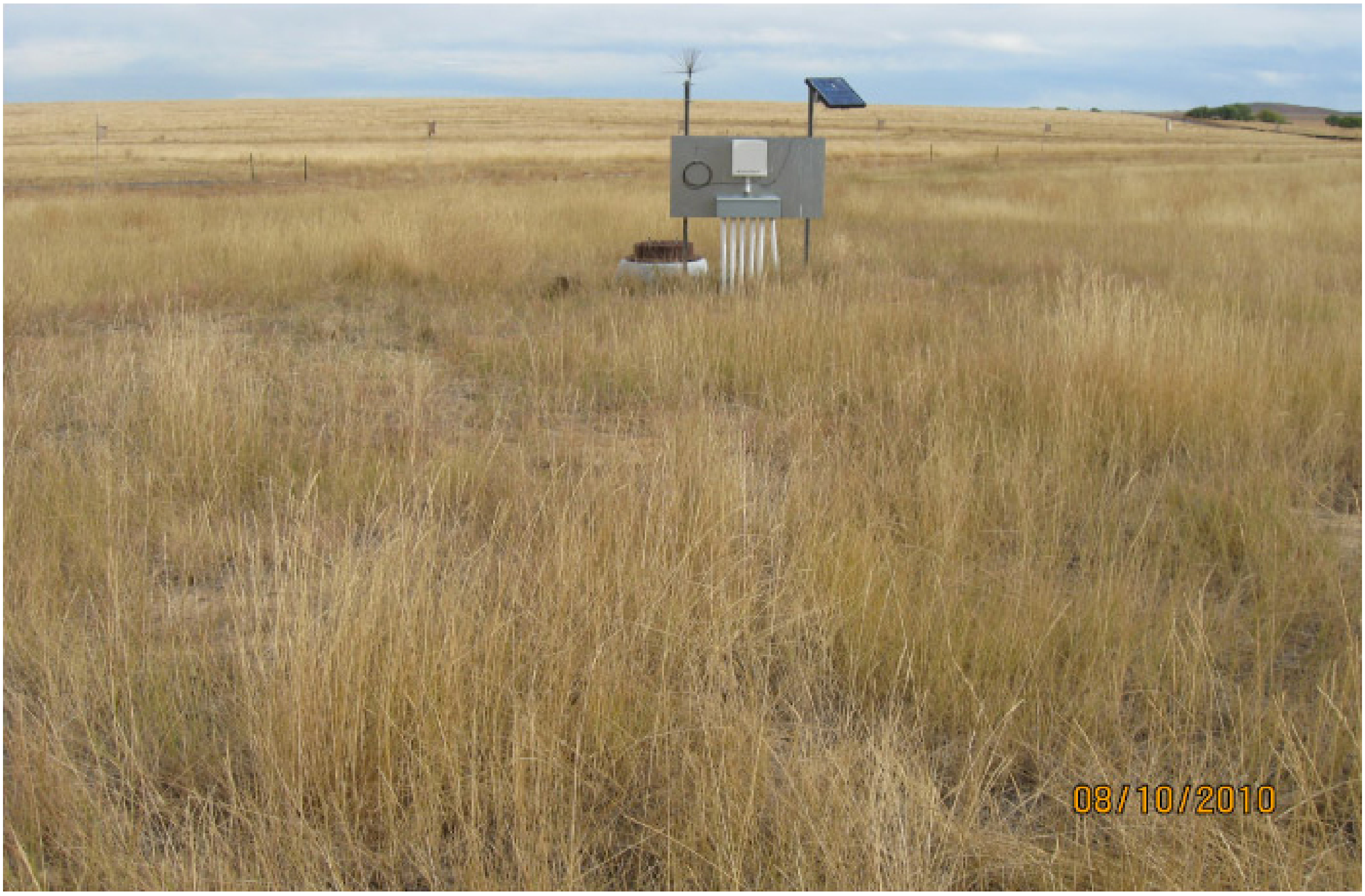



**Figure 27. XXX Oil Co.: Trenches RCRA-equivalent cover, postremedy, 2010** (CDPHE 2010)**.**

Additionally, land values in and around the RMA have changed dramatically since the signing of the ROD and original vision for a wildlife refuge. Commerce City, which now owns some portion of RMA with the original land use restrictions intact, would like to develop the property for residential use. Any future investigation into the suitability of these lands for residential use will require a comprehensive risk assessment.

## 6.4.5 Regulatory and Stakeholder Involvement

The RMA has a long history of regulatory involvement—a history almost as old as CERCLA and RCRA themselves. Of interest, RMA was the subject of a Supreme Court ruling that recognized the state's authority to enforce state environmental law on federal lands. A brief history, taken from the On-Post RMA ROD, is provided below. Currently, USEPA and state of Colorado, as well as Tri-County Health Department, all provide ongoing oversight of the RMA as it transitions from active remedy status to long term O&M. The RMA still has closure/post-closure ongoing issues that will continue to require federal, state, and local involvement for the foreseeable future. Roles and responsibilities, as well as dispute resolution procedures for the Army, XXX Oil Company, USFWS, and the agencies are still defined by the Federal Facility Agreement of 1987. The state, wishing to retain its enforcement discretion and rights, was not a signatory to the FFA.

At the height of its active remedy, the RMA hosted a Remediation Advisory Board (RAB) which consisted of local community representatives and local officials. The RAB was disbanded after the active remedy operations were completed in 2010. In addition to the RAB, a Citizen Advisory Board (CAB) was convened to provide guidance and advice to the Medical Monitoring Program. The CAB voted to disband itself in 2008, in response to vastly diminished concerns about the remedy's impact to the community. Currently, a third group, the Site-Specific Advisory Board (SSAB) still exists and is an active participant during the Five-Year Reviews and on specific issues as needed.

### 6.4.5.1 Regulatory and Legal Site History of CERCLA Enforcement Activities (from RMA ROD)

In December 1982, the USEPA, Army, XXX Oil Company, and Colorado Department of Health entered into a Memorandum of Agreement outlining joint participation in the Amy's study of decontamination at RMA. Although the parties followed the process outlined in the Memorandum of Agreement until 1986, they also pursued litigation with respect to issues relating to legal authority over RMA remediation efforts, payment of natural resource damages (NRDs), and reimbursement of costs expended for cleanup activities (response costs).

USEPA, the Army, Department of Interior, and XXX have established a protocol for resolving disputes that arise at RMA concerning CERCLA cleanup actions. This dispute resolution process is set forth in the FFA (USEPA 1989c). The state of Colorado became a party to the FFA dispute resolution process on June 13, 1995, when it signed, along with the above entities, the Agreement for a Conceptual Remedy for the Cleanup of the RMA (Conceptual Remedy). The only provisions of the FFA that are binding for the state are those related to dispute resolution. The state declared its intention to use the FFA dispute-resolution process in a good-faith effort to resolve all issues informally. For issues that were not subject to dispute resolution under the FFA, and for those issues over which the state has independent authority pursuant to U.S. v. State of Colorado and the Colorado Department of Health, Civil Action No. 89-C-1646, 990 F. 2d 1565 (10th Cir. 1993), cert. denied 114 S. Ct. 922 (1994), the state reserved any rights and authorities it may have.

### 6.4.5.2 State Enforcement Activities

The state of Colorado has been involved in two civil actions related to RMA activities:

- *State of Colorado v. Department of the Army, Civil Action No. 86-C-2524*. The state filed an action against the Army in state court in 1986. The state's original complaint alleged violations of the Colorado Hazardous Waste Management Act (CHWMA) groundwater monitoring regulations. The complaint was amended in 1987 to include claims of failing to close Basin F in accordance with the closure plan issued under CHWMA and later conducted under CERCLA as well as failure to pay fees due under CHWMA. In 1989, the Court held that CHWMA enforcement was not precluded by CERCLA (State of Colorado v. Department of the Army, 707 F. Supp. 1562, 1569-70, D. Colo. 1989).
- *United States v. State of Colorado and the Colorado Department of Health, Civil Action No. 89-C-1646.* Following inspections of the Basin F site in 1989, CDPHE issued a compliance order against the Army, citing 42 violations of CHWMA and its implementing regulations regarding hazardous waste management. The U.S. filed suit in federal court seeking a judgment that CDPHE had no authority to enforce the compliance order and that the U.S. was not liable for civil penalties under RCRA or CHWMA. In 1991, the Court ruled in the U.S.'s favor. The state appealed and the Tenth Circuit Court of Appeals reversed the ruling (United States v. State of Colorado and the Colorado Department of Health, 990 F. 2d 1565, 10th Cir. 1993). In 1993, the U.S. petitioned the U.S. Supreme Court to review the Tenth Circuit court's decision but their petition was denied (114 S. Ct. 922 1941). In 1994, the U.S. and the state of Colorado entered into a Consent Decree to resolve remaining litigation issues. The Army agreed to submit closure plans for Basin F and the Basin F Waste-pile for CDPHE approval.

## 6.5 Naval Air Station Jacksonville OU 03, Florida

Naval Air Station Jacksonville (NAS JAX), located along the west bank of the St. Johns River in Jacksonville, Florida, is a 3,400-acre facility. NAS JAX was established in 1940 as an air defense strategic base to protect Florida's 1,200 miles of coastline from enemy attack. As a master antisubmarine warfare (ASW) and industrial base, NAS JAX maintains and operates facilities and provides services and materials to support aviation operations. Tenants include the Fleet Readiness Center Southeast (FRCSE), Fleet Logistic Center Jacksonville, seven air reconnaissance squadrons, four helicopter squadrons, one reserve air reconnaissance squadron, and two Fleet Logistics Support Squadrons.

The Navy Environmental Restoration Program (ERP) oversees environmental remediation activities at the base, mostly conducted under the CERCLA program. NAS JAX has eleven designated CERCLA OUs. The NAS JAX Partnering Team (NAS JAX Team) oversees the implementation of the ERP and comprises representatives of the Navy, the Florida Department of Environmental Protection (FDEP), USEPA, and Navy environmental contractors.

The most challenging sites at NAS JAX includes several chlorinated solvent plumes and other contaminant areas at OU 3 (Figure 28). OU 3 is the largest site at NAS JAX and includes over 100 buildings that historically housed dry cleaning, painting, stripping, degreasing, and electroplating operations. These operations resulted in significant soil and groundwater contamination. The OU 3 primary tenant is FRCSE. In 1993, the NAS JAX Team began a multiphase RI/FS that supported the development of the September 2000 ROD. This ROD documented the selected remedies for six of the eight source areas for chlorinated solvent plumes. The remaining two source areas require further assessment and will be addressed later.

A former dry cleaner (former Building 106, Source C) and a former solvent recycler (Building 780, Source D) located in the northern area of OU 3 were the subject of interim remedial actions (IRAs). These remedies were adopted as final remedy components in the 2000 ROD and consisted of air sparging with soil vapor extraction (AS/SVE) at former Building 106 and groundwater P&T and SVE at Building 780.

Source Areas A, B, and E are in the central areas of OU 3. These areas did not initially require active remedial action because there was no documented impact to receptors and therefore no completed exposure pathways. Areas A and B eventually were placed in MNA programs. Source Areas F and G were identified in the southern area of OU 3. Initially, chemical oxidation was selected to treat Source Area F; however, studies found that conditions were not suitable for chemical oxidation and no source treatment was conducted at that time. The selected remedy for Area G is MNA.

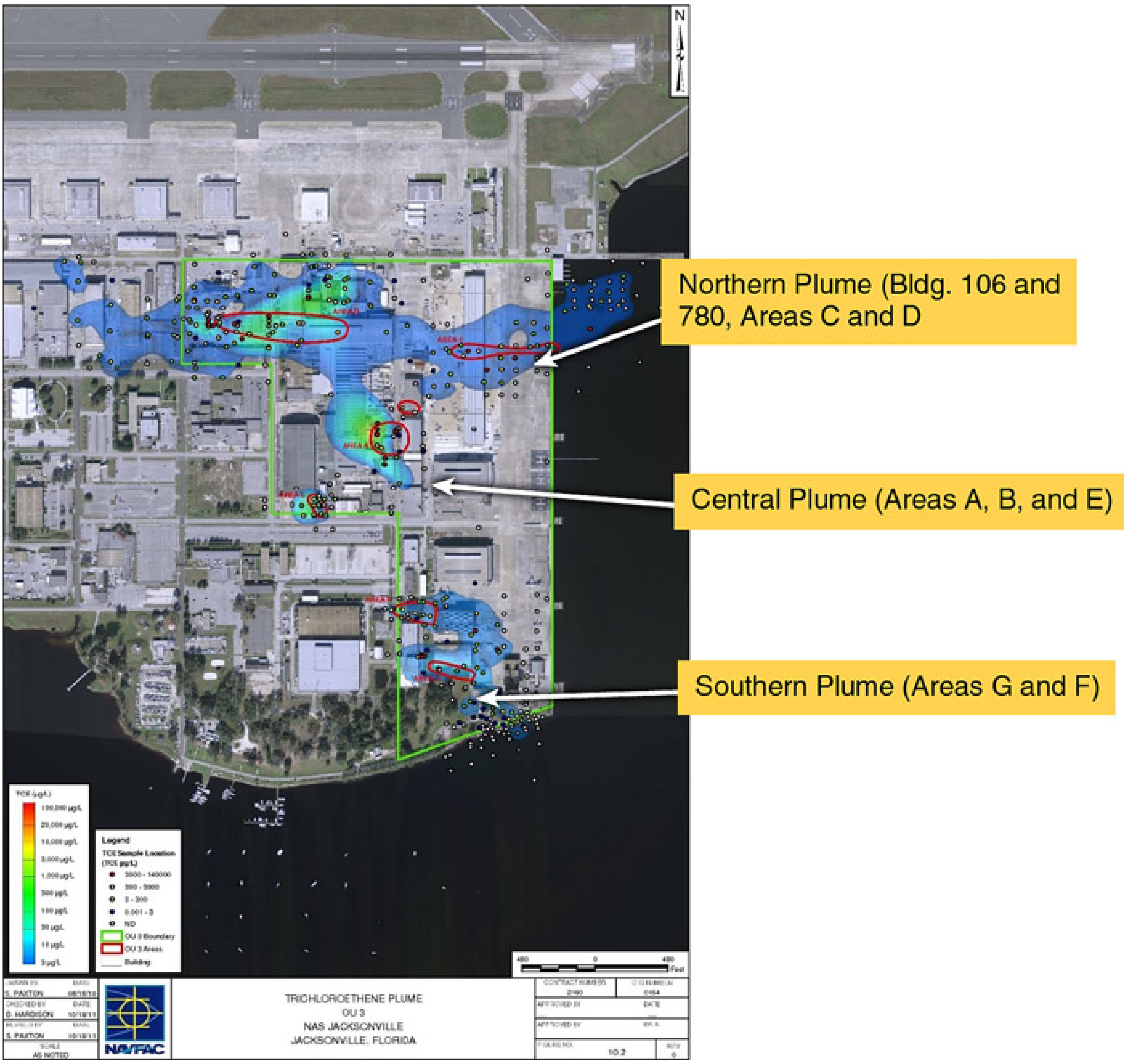



**Figure 28. Major groundwater plumes at OU 3 NAS JAX** (Goodwin et al. 2010)**.**

### 6.5.1 Technical Basis for Remedial Action

Following initial remedial actions, several optimization studies were conducted. Results of the optimization studies and Five-Year Reviews conducted in 2005 and 2010 recommended the following tasks to resolve CSM data gaps:

- Improve information about DNAPL contaminant mass that has diffused into an extensive clay layer and acts as a continuing source to the groundwater plume.
- Evaluate risks posed to site workers and building occupants through potential indoor air VI.
- Verify that the groundwater plume has not entered the St. Johns River via discharge from the storm sewer network or via direct migration and discharge, adversely impacting surface water and sediment.

Because of these findings, initial remedial actions adopted for Buildings 106 and 780 in the north end of the site were discontinued and additional site risk characterization was planned.

### 6.5.2 Decisions

After the findings of the optimization studies and Five-Year Review process, the NAS JAX Team reached consensus that adaptive site management and a comprehensive remedial approach was needed to protect potential receptors, including additional site characterization, CSM refinement, and exposure pathway risk determination (Figure 28). NAS JAX Team concluded that the original area-by-area approach was ineffective in reaching site objectives. The team adopted an OU-wide risk-based remediation approach in which RI and FS Addendums and a single replacement ROD would be developed to address the multiple source areas and comingled plumes at OU 3 (Figure 29).

The OU 3 RI Addendum, FS Addendum, and ROD documents are being prepared under the Navy Clean Contract program. Pilot Studies, Remedial Design, and Remedial Actions are being completed by the Navy Remedial Action Contract (RAC) program. Innovative research technology demonstrations have been performed by DOD's Environmental Security Technology Certification Program (ESTCP 2010) to better characterize source area DNAPL diffused in clay layers and the risk to workers posed by potential VI. In addition, ESTCP and the Navy Environmental Technical Services (Amonette et al. 2012) contracts are being used to efficiently perform treatability and pilot studies for innovative remediation technologies applicable to similar source areas across OU 3.

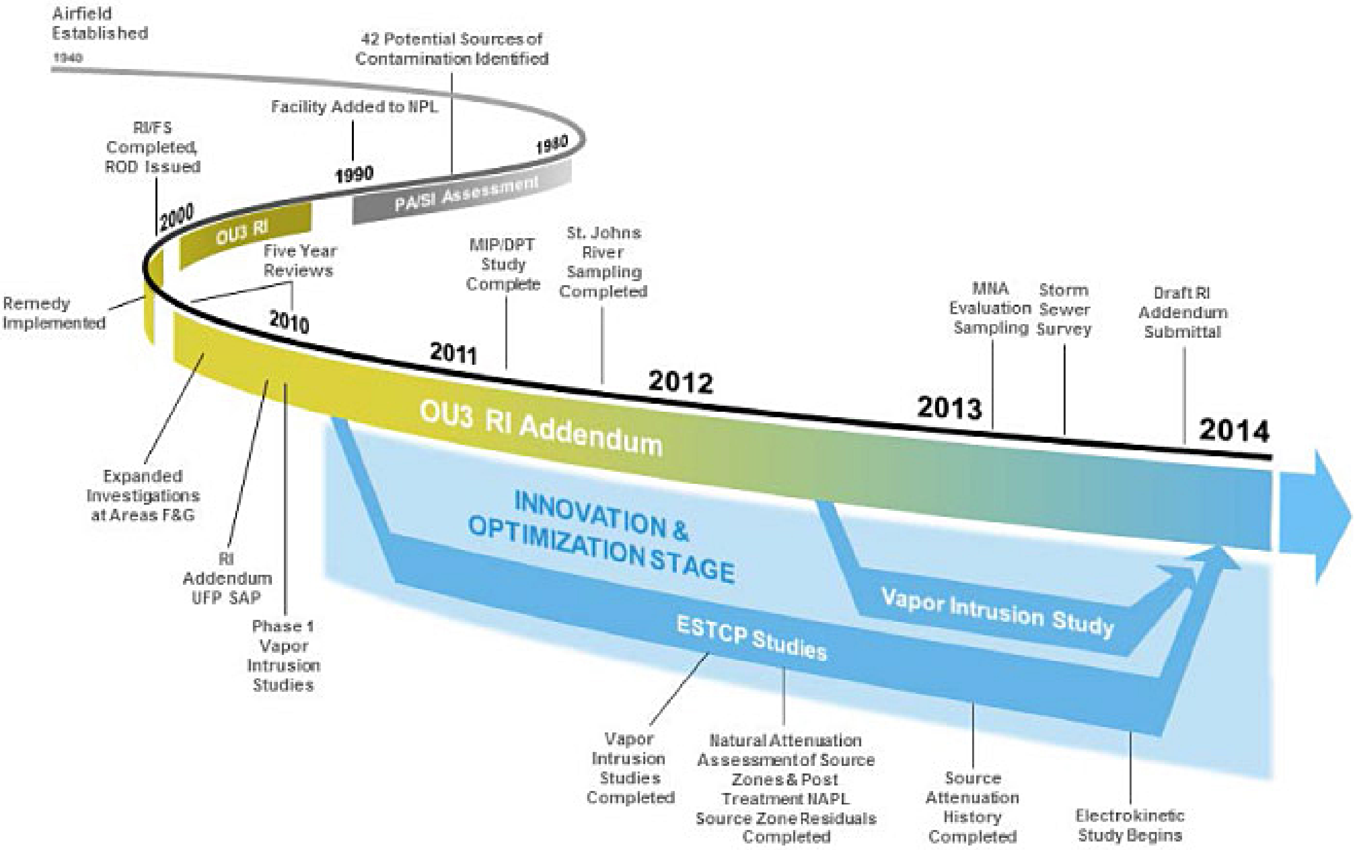



**Figure 29. Adaptive site management and site risk characterization process at NAS JAX OU 3** (NAVFAC SE, 2016)**.**

## 6.5.3 Assessment

OU 3 RI/FS Addendum activities have been conducted to evaluate COC migration to potential human or ecological receptor exposure points. Site media have been assessed using innovative approaches. State-of-the-science technology demonstrations have assessed VI potential, characterized the nature and extent of DNAPL and contaminant mass in key source zones, and evaluated potential COC transport to surface water including groundwater migration into storm sewers and directly to the St. Johns River.

### 6.5.3.1 VI

The NAS JAX Team developed and implemented innovative methods to investigate subsurface to indoor air VI within and near FRCSE. This project included a systematic screening and prioritization process to select the highest priority buildings, the use of emerging field and laboratory analytical methods, and stakeholder involvement throughout the project. Accomplishments included the following:

- Identification of 12 priority buildings out of 167 that were potentially impacted. This screening and prioritization significantly reduced investigation costs.
- Implementation of emerging sampling techniques with potential to provide significant long-term cost savings to

the Navy.

- Minimized impact on NAS JAX operations by reducing the number of buildings identified for further evaluation.
- Demonstrated minimal VI risks at buildings of interest.

Phase 1 of the VI investigation identified buildings of potential interest for further investigation. Only 37 out of 167 buildings within the study area were retained for analysis during Phase 2. Phase 2 consisted of Summa canister sampling and emerging sampling techniques, including Vapor Pin subslab soil gas sampling equipment, HAPSITE portable gas chromatography/mass spectrometry (GC/MS) units, and passive samplers. Results highlighted 12 primary buildings of interest.

### 6.5.3.2 DNAPL Characterization

Proven and innovative site characterization methods were used to develop a more thorough understanding of COC distribution in the subsurface at OU 3. NAS JAX Team used the Triad Approach to iteratively address groundwater data gaps using direct push technology (DPT) and other screening methods to efficiently locate additional monitoring wells and refine the CSM. ESTCP demonstrations of innovative technologies were used to characterize the distribution of DNAPL contamination present in low-permeability layers at OU 3 and the potential for back-diffusion to serve as a long-term source to groundwater plumes. An ESTCP demonstration also characterized the potential for source zone natural attenuation.

The following innovative technologies were demonstrated at OU 3 to improve understanding of DNAPL distribution and aid in the design of remediation systems:

- High-resolution sampling of aquifer sediment and groundwater to delineate and estimate the amount of DNAPL mass diffused into low-permeability layers
- Membrane interface probe (MIP) to characterize the geotechnical properties of clay layers and the presence of DNAPL contamination
- On-site mobile laboratory and multilevel sampling equipment for real-time delineation of clay layers and detailed profiles of contaminant mass in those clay layers
- Modeling tools to evaluate the natural attenuation of contamination in the clay layers, through long-term diffusion and biodegradation.

### 6.6.3.3 Storm Sewers and Groundwater Water Exposure Pathways to Surface Water

NAS JAX Team also evaluated the potential impacts to surface water in the adjacent St. Johns River via infiltration of contaminated groundwater into storm sewers and direct migration of contaminated groundwater to the river.

Studies evaluated the tidally influenced stormwater system by conducting sampling throughout tidal cycles at various locations upgradient and downgradient of the point of entry for source areas at Areas A, E, F, and G. The potential impacts of COCs in storm sewers was then evaluated using mixing zone models to estimate the mass and concentration of COCs at discharge points to the St Johns River that were not directly accessible. Results demonstrated that storm sewer discharge of contaminated groundwater to the St. Johns River did not pose a significant ecological or human health risk.

In addition, offshore sampling was conducted through a variety of methods to characterize the nature and extent of COCs migrating beyond the shoreline in groundwater below a clay layer that extends beneath the river. Sediment pore water quality was evaluated by collecting samples at the interface zone in shallow sediments. Sampling tools included DPT methods from a barge anchored in target off shore areas and use of the Trident Probe to collect pore water samples within shallow sediment horizons (Figure 30).

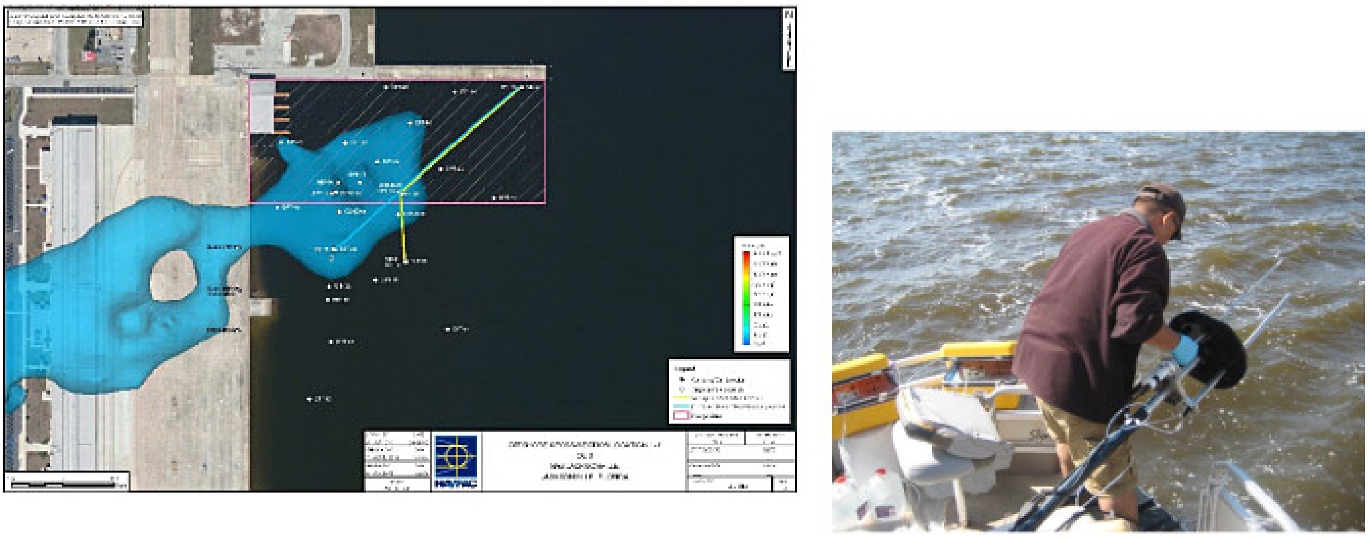


**Figure 30. COC plume migrating beneath clay layer in St. Johns River was assessed using trident probe** ([NAVFAC SE, 2016](#)).

Results of the offshore investigation supported the conclusion that biodegradation processes within organic rich sediment of the river effectively reduce COC concentrations to below applicable regulatory thresholds and there is no significant exposure risk from direct migration of contaminated groundwater to surface water.

### 6.5.3.4 Refined CSM

Data collected during these studies were used to develop new CSMs for OU 3. Source areas and related comingled plumes were grouped based on similar potential exposure pathways. This approach resulted in groups of plumes in the northern, central, and southern areas of OU 3 and a distinct CSM for each area. In the northern area, potential exposure pathways include VI, contaminated groundwater infiltration into storm sewers, and direct migration of contaminated groundwater to the St. Johns River (Figure 31). In the central area, potential exposure pathways include VI and contaminated groundwater infiltration into storm sewers. In the southern area, potential exposure pathways include contaminated groundwater infiltration into storm sewers and direct migration of contaminated groundwater to the St. Johns River.

The RI Addendum (2015) includes the results of the additional site characterization, including detailed evaluations of nature and extent of contamination, fate and transport, and risk assessment.

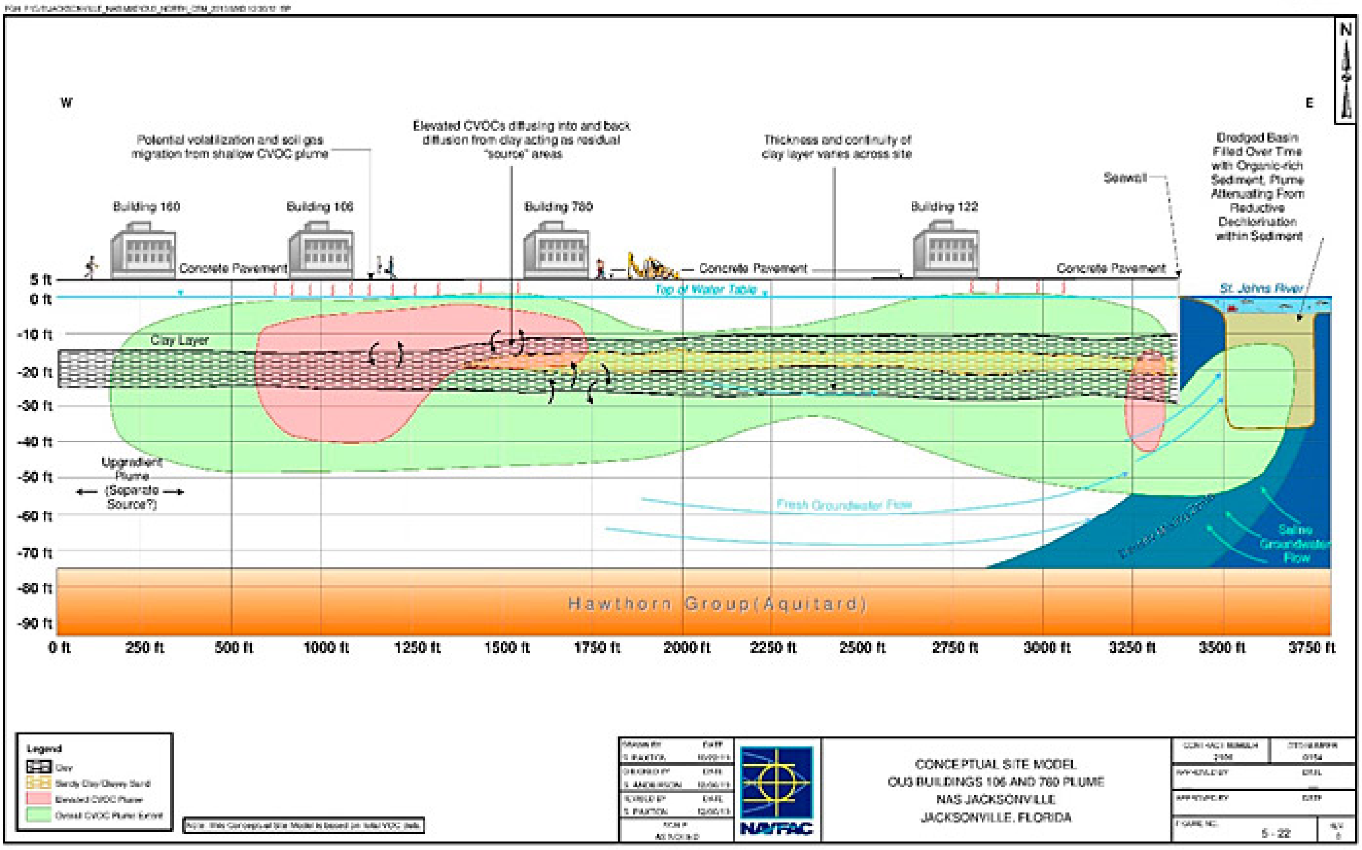



**Figure 31. Refined CSM for Northern Area at NAS JAX OU 3** (Tetra Tech 2015)**.**

## 6.5.4 Monitoring/Optimization (Source Area Treatability/Pilot Studies)

An FS addendum will evaluate further remedial options for the northern, central, and southern source areas at OU 3 to support the site objectives. Long-term monitoring to ensure protection of receptors will be part of any remedy selected. To assist with the remedy evaluation and selection process, the NAS JAX Team commissioned a series of source zone technology demonstrations and pilot studies in the northern and southern areas of OU 3. Demonstration project results will be evaluated in the FS Addendum to support the site-wide replacement ROD. Treatability/pilot studies include the following:

- Enhanced in situ bioremediation (EISB) is being investigated to treat recalcitrant DNAPL and contaminant mass tied up in fine-grained silts and clays within the source area at Building 106. This ESTCP study is being conducted in two phases: Phase I is designed to reduce mass in the surficial aquifer and Phase II will use electrokinetic methods to deliver EISB substrates to DNAPL mass tied up in the silty and clayey aquitard that lies at the base of the surficial aquifer.
- In situ bioremediation pilot test of COCs in the Building 780 source area is being conducted, which includes a significant trichloroethane (TCA) component.
- A full-scale in situ biodegradation pilot study is underway for two source areas in the southern area of OU 3 (Areas F and G) and their comingled plume. The plume is near a primary storm sewer that is a potential pathway for groundwater infiltration and migration to the St. Johns River.

The combined results of these pilot studies will be evaluated during the sitewide FS Addendum.

## 6.5.5 Regulatory and Stakeholder Involvement

USEPA and FDEP regulators are partnering members with the Navy on the NAS JAX Team, which typically meets bimonthly to review current data and reach consensus on the path forward for OU 3 and other sites at NAS JAX. The formal partnering process at NAS JAX has improved communications and decision making, and has resulted in an efficient and protective site remediation program. NAS JAX Team’s commitment to continuous optimization and the use of innovative technologies at OU 3 has saved approximately $2.5 million to date. In addition, successes and lessons learned through innovative technology demonstrations at NAS JAX have been shared throughout the Navy.

Community involvement in this process is provided by the Regional Advisory Board (RAB). Annual updates on the progress of work at NAS Jacksonville and OU 3 are provided to the RAB for their input. After the FS Addendum is completed, a proposed plan will be developed and broader community input solicited and addressed in the selection of a final replacement remedy for OU 3.

## 6.6 DOE Test Area North, INEEL, Idaho

The Test Area North (TAN) site covers 890 square miles in the northern portion of the Idaho National Laboratory (INL), which is about 50 miles northwest of Idaho Falls, Idaho. This facility is operated by the U.S. Department of Energy (DOE) and was historically used for nuclear energy knowledge and applications such as the experimental breeder reactors, EBR-I and EBR-II. TAN was developed by the Atomic Energy Commission and the U.S. Air Force to develop nuclear-powered aircraft in support of the Aircraft Nuclear Propulsion program. From 1950 to 1972, all liquid waste streams generated at TAN were introduced directly into the basalt aquifer (Snake River Plain Aquifer), approximately 200-300 feet below ground surface, through injection wells. Waste streams included low-level radioactive wastewater, industrial wastewater (including organic liquids), and sanitary sewage. Historical records provide little information on the types and volumes of organic wastes injected into the groundwater; estimates of total TCE injection range from 350 to 35,000 gallons. The direct result of these injection activities was a two-mile trichloroethene (TCE, $C_2HCl_3$) plume at concentrations >20,000 µg/L.

### 6.6.1 Technical Basis for Remedial Action

The vadose zone of the Snake River Plain Aquifer consists of fractured basalt lava flows with rhyolite and unconsolidated sediments. The aquifer beneath this plain covers approximately 10,800 square miles and is composed of layered basalt lava flows and sediment. Water from this aquifer is important for agricultural purposes and spring flows.

The CSM for TAN was developed through an iterative process of identifying data gaps, conducting activities to fill those data gaps, reporting on the results of those activities, and identifying new data gaps. Examples of characterization activities that were conducted in the source area after the sludge removal activity was completed included:

- wells installation within or adjacent to the source area
- pumping tests, slug tests, and tracer tests
- standard geophysical, gamma spectroscopy, and acoustic logging
- cross-well seismic tomography
- groundwater sampling

These activities greatly improved the understanding of aquifer hydraulic conductivity, porosity, and preferential flow paths; dissolved contaminant composition and distribution; and residual contaminant source distribution.

### 6.6.2 Decisions

The original ROD (DOE-ID 1995) for the TAN groundwater contamination selected P&T as the default remedy. Additionally, five innovative technologies were evaluated for their potential to enhance or replace P&T. These technologies included: metal-enhanced reductive dechlorination, monolithic confinement, in situ chemical oxidation, enhanced in situ bioremediation (ISB), and MNA. A ROD amendment signed in September 2001 (DOE-ID 2001) documents regulatory approval of enhanced ISB as the final remedy for the plume hot spot and MNA as the final remedy for the distal portion of the plume.

### 6.6.3 Assessment

A nine-month full-scale field evaluation of ISB was performed at TAN beginning in January 1999. The overall objective of the enhanced ISB field evaluation, focused in the high-concentration source area of the plume (>20,000 µg/L TCE), was to determine whether the intrinsic biodegradation of TCE could be enhanced through addition of an electron donor. Sodium lactate was injected from 1999 to 2004, followed by single-well injections of whey in 2004, alternating and multiple well injections from 2006 to 2007. In 2008, Lactate was added back-coupled with whey to reduce the pH of the system, and in 2012 ISB was transitioned into a rebound test.

The Air Stripper Treatment Unit (ASTU) was operated from November 1998 through December 2000 to provide containment during the ISB field demonstration. The ASTU was placed on standby shortly before the NPTF became operational. At the time, the ASTU was expected to remain on standby. However, concentrations of TCE remained elevated near the ASTU. Because operation of the ASTU had been shown to reduce TCE concentrations in its vicinity, the ASTU was restarted in January 2011 as a component of the P&T remedy for the medial zone. When the reinjection well TAN-49 started backing up in July 2011, the ASTU was shut down and once again placed on standby. A timeline of the TAN remediation technologies is shown in Figure 32.

Full-time operation of the NPTF occurred for 3.5 years from 2001 to 2005, and decreased TCE concentrations to approximately 100 µg/L. The Rebound Test Plan for OU 1-07B (ICP 2004) from March 1, 2005, to March 5, 2007, assessed the overall impact of NPTF operations on remediation of the medial zone. Based on results obtained during the rebound test, the long-term operational strategy of NPTF was modified to a pulsed-pumping strategy. The objective of pulse-pumping operations was to maintain TCE concentrations in the medial zone below 200 µg/L through a cycle of operation and standby modes. From November 16, 2007, to December 7, 2009, NPTF was operated in standby mode. Since December 7, 2009, NPTF has been operated voluntarily approximately 4 days a week, except when shut down for maintenance.

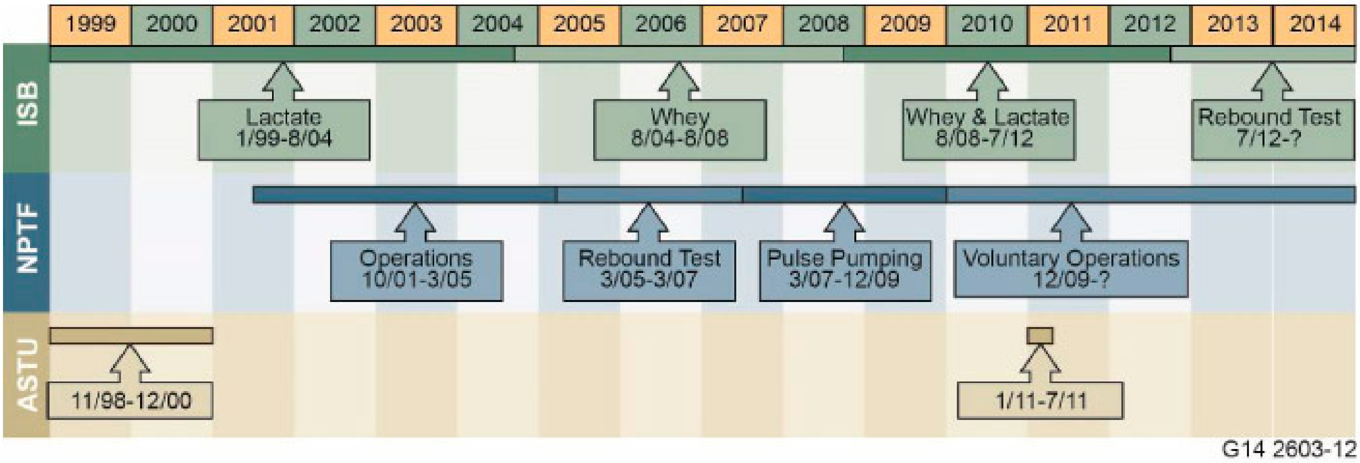



**Figure 32. Test Area North groundwater remediation timeline (1999–2014)** (DOE-ID 2016)**.**

MNA was evaluated in 1999-2001, and the results showed that TCE attenuation was occurring through multiple lines of evidence, including use of the tracer corrected method, biological assessments, and overall concentration trend analysis. A lines of evidence approach was used to provide quantitative biological attenuation of the contaminants in groundwater, including the use of quantitative polymerase chain reaction, and enzyme activity probes coupled with lab microcosm studies. These data supported the ROD amendment for MNA. The restoration time frame for MNA is to achieve MCLs by 2095.

### 6.6.4 Monitoring/Optimization

The ISB rebound test must continue to assess the residual source in the aquifer because reducing conditions are needed to maintain enhanced dissolution of the contaminant in the basalt matrix. The rebound test may continue for up to five years. The vadose zone investigation indicated that the vadose zone is not the source of TCE impacting TAN-28 (sentinel groundwater monitoring well which has not decreased in concentration over the duration of evaluation), and is probably a minor contributor to aquifer TCE contamination. Additional vadose zone investigation is not required at this time. The TAN-28 TCE source assessment indicated that an untreated portion of the aquifer is responsible for the elevated TCE concentrations in TAN-28.

Compliance monitoring results indicate that NPTF operated within established limits throughout 2014. Routine inspections were performed, as required. TCE concentrations were less than 75 µg/L in monitoring wells TAN-33, TAN-36, and TAN-44, and NPTF influent concentrations were at the low end of the historical range. Concentrations of VOCs in NPTC effluent samples all met the water effluent-discharge criteria for the last five years. Sr-90 results for the effluent were below detection limits and MCLs in all samples since last year.

More time is needed to determine whether natural degradation rates will meet MCLs by 2095 for all areas of the plume. The TCE plume has expanded in the direction of TAN-57 from 2009 to 2015 (Figure 33); however, this expansion is within that predicted by the conceptual model developed in 1999-2005. TCE was not detected in TAN-56 in 2015. The TCE concentration in TAN-57 was less than the 10-µg/L criteria for drilling an additional down-gradient well. Plume expansion was less than the 30% allowed in the ROD Amendment.

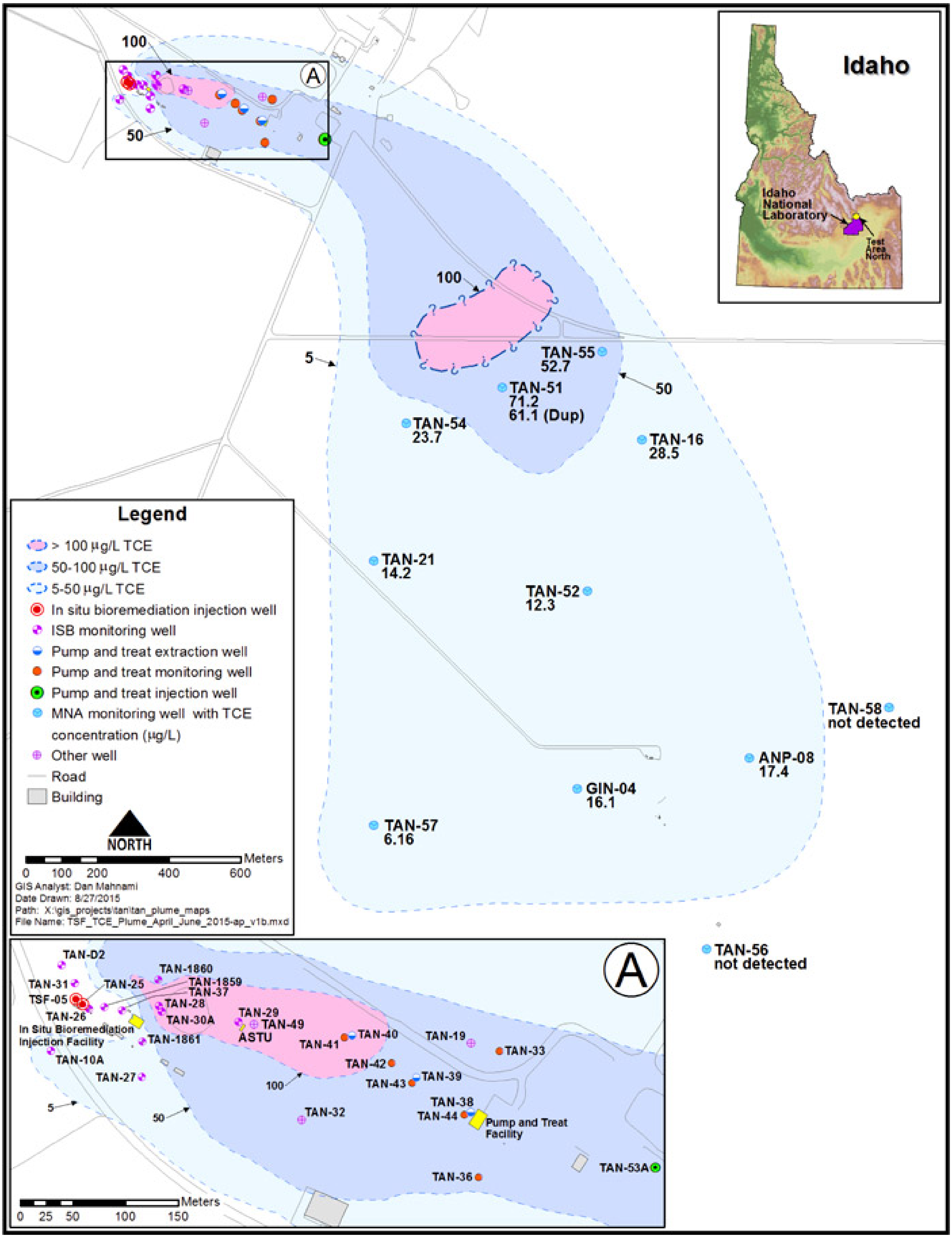



**Figure 33. TCE distribution in the aquifer at the TAN site in 2015 (DOE-ID 2016).**

### 6.6.5 Summary of Alternatives

Alternatives include a holistic systems-based approach, consisting of the following:

- Interagency project team consisting of USEPA, DOE, IDEQ, and public was formed.
- The scientifically defensible strategy for the site was reevaluated when new technologies or approaches were applicable and available (mass flux, revise CSM, molecular tools).
- Strategies were optimized throughout the plume to save money and increase performance. For example, the PNT rebound study and shut down resulted in an estimated cost savings of $8 million over PNT for the lifetime of plume.
- The monitoring program was modified (reduced on year to year basis) based on defensible data (concentration, risk).

### 6.6.6 Regulatory and Stakeholder Involvement

The state of Idaho (ID-DEQ), DOE-ID, and USEPA regulators have worked together with the technical project teams and the stakeholder organizations since the beginning of the evaluations at the TAN site. The integration of innovative research and remedial operations, as agreed upon by the agencies, has been a novel approach to the CERCLA process and has proved particularly successful at the TAN site.

## 6.7 Joliet Army Ammunition Plant, Illinois

Joliet Army Ammunition Plant (JOAAP Project Delivery Team 2008) was the site of explosives manufacturing during World War II and the Korean and Vietnam wars. The site consists of old waste burial areas with an unknown mass of COCs. After the plant was decommissioned in the late 1970s, the Army began characterization efforts. In 1978, U.S. Army Environmental Command published an overall Installation Assessment that identified 53 areas of concern (AOCs) for environmental impacts. Installation and Restoration Surveys, Preliminary Assessments, Phase II RIs, and FSs were prepared for each of the identified AOCs. Two areas within JOAAP were listed on the NPL and addressed under the CERCLA program: the Manufacturing (MFG) Area and Load-Assemble-Package (LAP) Area (in 1987 and 1989, respectively). A 1998 ROD redefined the previously 53 AOCs as soil and groundwater OUs. Responsible parties, stakeholders, and decision makers include the Army, USEPA Region 5 and the State of Illinois EPA (IEPA).

The primary soil and groundwater contaminants are explosives, including munitions constituents (MCs) such as RDX, NT, DNT, and TNT. Other contaminants include VOCs, PCBs, metals and sulfate. The extent of contamination and the site hydrogeological setting make groundwater remediation complex. The site hydrogeology consists generally of low-permeability formations made up of a heterogeneous glacial till overburden and an underlying shallow limestone dolomite bedrock. The site has many contaminant sources; contaminant plumes cover 36 square miles (629 million gallons of contaminated groundwater). There are multiple contaminants with different chemical properties and many plumes are comingled. Contaminant plumes reached the deeper fractured limestone matrix, which has low transmissivity and yield properties that make contaminant extraction and treatment difficult. Shallow contaminant plumes are in lower permeability, heterogeneous glacial till soil units. Waste burial areas include a mix of inorganic and organic contaminants that require conflicting treatment methods. It is difficult to treat the mix of contaminants in soil or groundwater (either above or below grade) using a single treatment technology.

### 6.7.1 Technical Basis for Remedial Action

The first ROD for JOAAP (1998) identified four groundwater OUs—one of which was specific to groundwater zones that required no further cleanup action. A human health and ecological risk assessment was performed on 40 groundwater COCs. State potable and industrial groundwater standards were used as site objectives. For compounds that did not have IEPA standards, risk-based concentrations (RBCs) were developed and used as site objectives. RBC calculations assumed that groundwater would be used by an industrial worker and corresponded to $1 \times 10^{-6}$ incremental carcinogenic risk for carcinogens and 1.0 hazard index for noncarcinogens. Remedial goals for groundwater depend on the aquifer classification. Contamination present in glacial till is subject to Illinois Class II groundwater quality standards; contamination present in the Silurian Dolomite is subject to Illinois Class I groundwater quality standards. Thirteen COCs exceeded site objectives for groundwater. Groundwater management zones (GMZs) were established for areas where groundwater was contaminated.

### 6.7.2 CSM

Three areas within the site exceeded Class I and Class II state standards for groundwater. Site hydrology and hydrogeology and potential exposure routes are described in Figure 34 and Figure 35. As determined through risk assessments, there are currently no human or ecological receptors of the contaminated groundwater at JOAAP because there is no pathway for exposure or contact. ICs (deed restrictions and GMZs) are in place to prevent a pathway from being created.

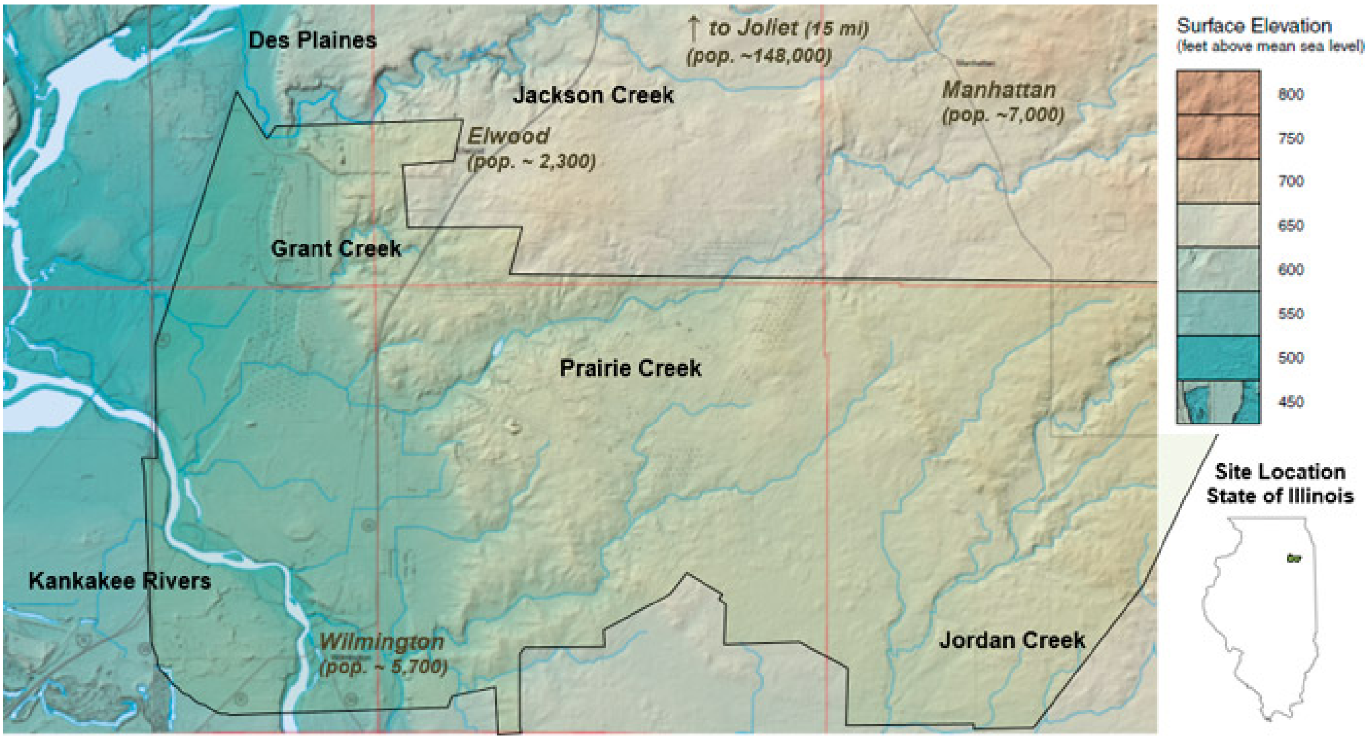



**Figure 34. Site boundaries on surface elevation map showing surface hydrology** ([adapted from USEPA 1998a]()).

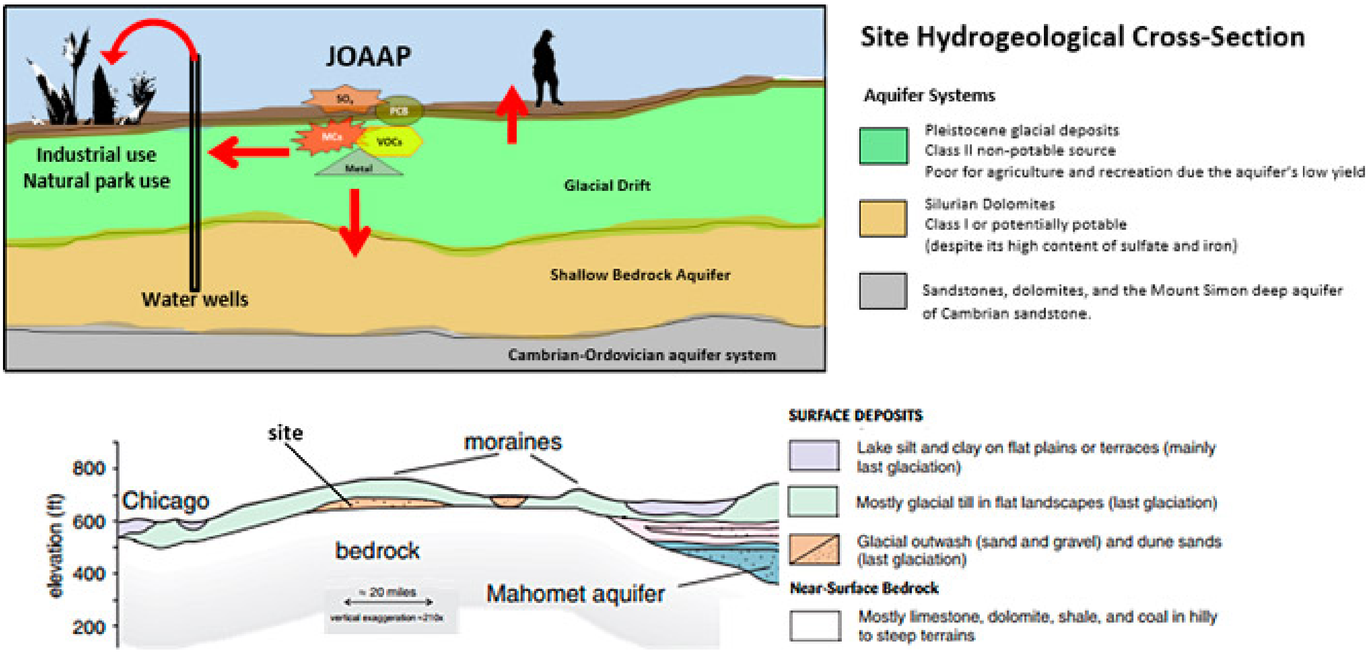



**Figure 35. CSM showing surface waters, elevations, and site geological cross-section** ([adapted from USEPA 1998a]()).

### 6.7.3 Decisions

After the Army declared JOAAP to be unneeded excess property in 1993, a 24-person Joliet Arsenal Citizens Planning Commission was created through grassroots efforts of local community members and political activists. The Citizens Planning Commission consisted of representatives from federal, state, local governmental, and nongovernmental organizations. This planning group formulated a reuse plan for the property that was thoroughly vetted by agency representatives and included input from a mix of local stakeholders. A bill that led to passage of the Illinois Land Conservation Act of 1995, Public Law 104-106, authorized the cleanup and transfer of JOAAP land as follows (Figure 36):

- Approximately 19,100 acres to the U. S. Forest Service for establishing the Midewin National Tallgrass Prairie
- 982 acres to the U.S. Department of Veteran's Affairs for the Abraham Lincoln National Cemetery
- 455 acres to Will County for a landfill
- 3,000 acres to the state of Illinois for two industrial parks

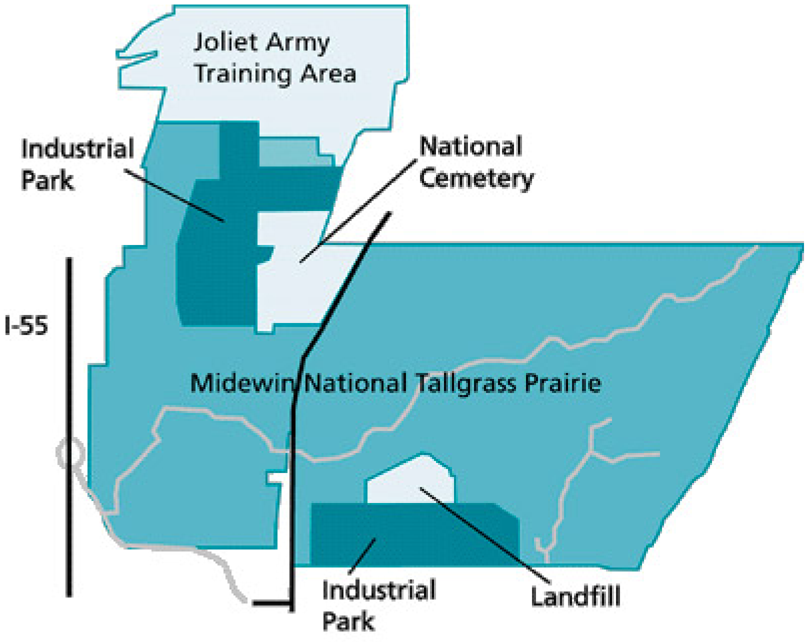



**Figure 36. Map of proposed future uses for the Joliet site** (adapted from USEPA 1998a)**.**

The final reuse plan enacted into law provided a clear framework for the remedy selection. The scope of groundwater remedy for both NPL sites consisted of MNA and the establishment of three GMZs to track required ICs until final cleanup levels are reached. Alternatives considered and reported in the 1998 ROD include no action, groundwater pumping, treatment using activated carbon, and removal of metals by precipitation.

In addition to MNA, the Army also removed contaminated soils and surface waters that acted as a source to groundwater. Deeding and zoning restrictions, notifications to future JOAAP land owners, phytoremediation to enhance bioattenuation and periodic site inspections, and surface water monitoring were all elements of the limited action remedy.

GMZs are required by Illinois regulations to identify areas that do not meet drinking water standards until cleanup activities are complete. GMZs delineate the areas where restrictions prohibiting groundwater use and uncontrolled soil excavation are necessary to prevent human contact with groundwater. The GMZs comprised both the glacial drift and shallow bedrock aquifers. Monitoring wells were located to confirm that no groundwater exits the GMZ at concentrations above the remedial goals (RGs).

A second area of wells will be placed at locations downgradient of the plume and between the plume and the GMZ boundary. The purpose of these wells will be to provide early warning for action to prevent groundwater with concentrations of contaminants above the RGs from reaching the compliance point. The third area of well placements will be around the perimeter of the GMZ. These wells will serve as compliance points and will be preferentially located downgradient of the plume. The purpose of these wells is to assure compliance with the conditional requirements of a GMZ.

The GMZs were established with buffers to prevent groundwater wells from being installed within their borders. These restrictions are attached to land deeds and leasing agreements. Deed restrictions have been developed separately from the ROD by the Army, USEPA, IEPA and the future land users. The deed restrictions run with the land until there is agreement among the Army, USEPA, IEPA, and the current landowner to remove them. The deed restrictions were recorded with the local Will County Recorder (302 N. Chicago Street, Joliet, IL 60432).

A Five-Year Review Report will provide an updated GMZ description, monitoring program implementation, and groundwater modeling. If the Army, USEPA, and IEPA determine that the limited action remedy timeframes are unacceptable, alternative remedial actions will be developed. For example, if groundwater plumes migrate beyond the boundaries of the established GMZs, or if groundwater is discharged to surface water at concentrations that exceed the water quality criteria established for JOAAP at the boundaries of the GMZs, or the natural attenuation process proves ineffective, then a contingency plan involving phytoremediation will be implemented. If phytoremediation proves ineffective, then a contingency plan involving a groundwater P&T system will be implemented.

The 2004 Five-Year Review found that although the remedy was complying with requirements of the 1998 ROD, the GMZ required extension to prevent potential groundwater withdrawals from outside the GMZ borders. On the other hand, the number of sites was reduced because a site achieved remedial goals.

### 6.7.4 Regulatory and Stakeholder Involvement

Community involvement in remediation efforts was initiated with a Technical Review Committee (TRC) in 1988, after the Manufacturing Area was placed on the NPL. The TRC was replaced with a JOAAP Restoration Advisory Board (RAB) in December 1995. The RAB’s goal was to ensure that diverse interests within the local community were considered. The RAB facilitated public participation during the Proposed Plan and RODs for the soil cleanup, and played a critical oversight role and link to the community throughout the cleanup process, holding regular meetings from January 1996 through September 2007.

In 1997, copies of Proposed Plans for the Soils OU and Groundwater OU were mailed to those who had expressed an interest. The Army held a public comment period. The RAB was briefed on the Proposed Plans and met again to discuss issues. Seventy-one sets of comments were received from the RAB, raising a total of 217 issues. The RAB met a third time to further discuss and vote on the proposals. Critical issues discussed included remediating the site quickly, using local or union labor in remedial actions, and improving the tax base. RAB concerns did not influence choice of remedial alternatives but were considered during remedy implementation.

Some concerns brought up by the RAB relate to the selected MNA remedy. Public comments documented in the 1998 ROD included requests to detail contingency plans covering unacceptable performance (such as migration of contaminated groundwater beyond the GMZs, discharge of groundwater to surface water, causing water quality criteria to be exceeded). In response, contingency plans were incorporated into the ROD. The Army noted in one response that the likely timeframe for determining the effectiveness of MNA is 10 to 15 years. Based on a biomonitoring request, a site-specific JOAAP Biological Technical Assistance Group (BTAG) was formed to establish exposure levels for ecological resources that were protective of the environment and compatible with development of the tallgrass prairie. The Army, USEPA, and IEPA will consider the advice of the BTAG as they evaluate the need for a biomonitoring plan and for further study of MNA. Deed restrictions and monitoring also raised concerns among commenters. At that time, deed restrictions were being negotiated between the Army and future landowners, USEPA, and IEPA. In 2008, JOAAP soil cleanup activities were completed, three years ahead of schedule. Nearly all the land has been transferred and is being redeveloped in ways that are already accruing large-scale economic and ecosystem restoration benefits for the community and the region. ICs are still in place; long-term management and remedy O&M continue.

### 6.7.5 Conclusions

The cleanup and redevelopment of JOAAP is a good example of how federal, state, and local governments can work effectively over time with communities, nongovernmental organizations, and the private sector to develop win-win solutions to a difficult problem.

JOAAP’s hydrogeological setting makes the implementation of traditional remediation difficult and costly. Therefore, JOAAP’s groundwater contamination was addressed through the establishment of GMZs, deed and excavation restrictions, monitoring, and modeling. Resourceful methods allowed for land reuse while protecting human health and the environment. Groundwater plumes have remained within JOAAP property lines, allowing monitoring points of compliance to be established for each plume to demonstrate that no further migration is occurring. The GMZ designation will be in place until cleanup activities are complete.

Printed from: Interstate Technology & Regulatory Council (ITRC). 2017. *Remediation Management of Complex Sites*. RMCS-1. Washington, D.C.: Interstate Technology & Regulatory Council, Remediation Management of Complex Sites Team. http://rmcs-1.itrcweb.org.

## 6.8 Tri-State Mining District (Kansas, Oklahoma, Missouri)

The Tri-State Mining District is an approximately 2500 square mile area located in southeast Kansas, southwest Missouri, and northeast Oklahoma (see Figure 37). This district was mined for lead and zinc, beginning in about 1859 and ending around 1970. This case study includes four example sites within the Tri-State: (1) the Oronogo-Duenweg Mining Belt site in Missouri; (2) the Treece and Baxter Springs sites in Cherokee County, Kansas; (3) the Galena site in Cherokee County, Kansas; and (4) the Tar Creek superfund site in Oklahoma. To address widespread contamination of surface water, soils and groundwater resulting from mining activities, these sites have incorporated remedies including:

- reuse and reprocessing
- backfilling and subaqueous disposal
- capping
- chemical stabilization
- excavation and disposal
- covers and grading
- administrative and engineering controls

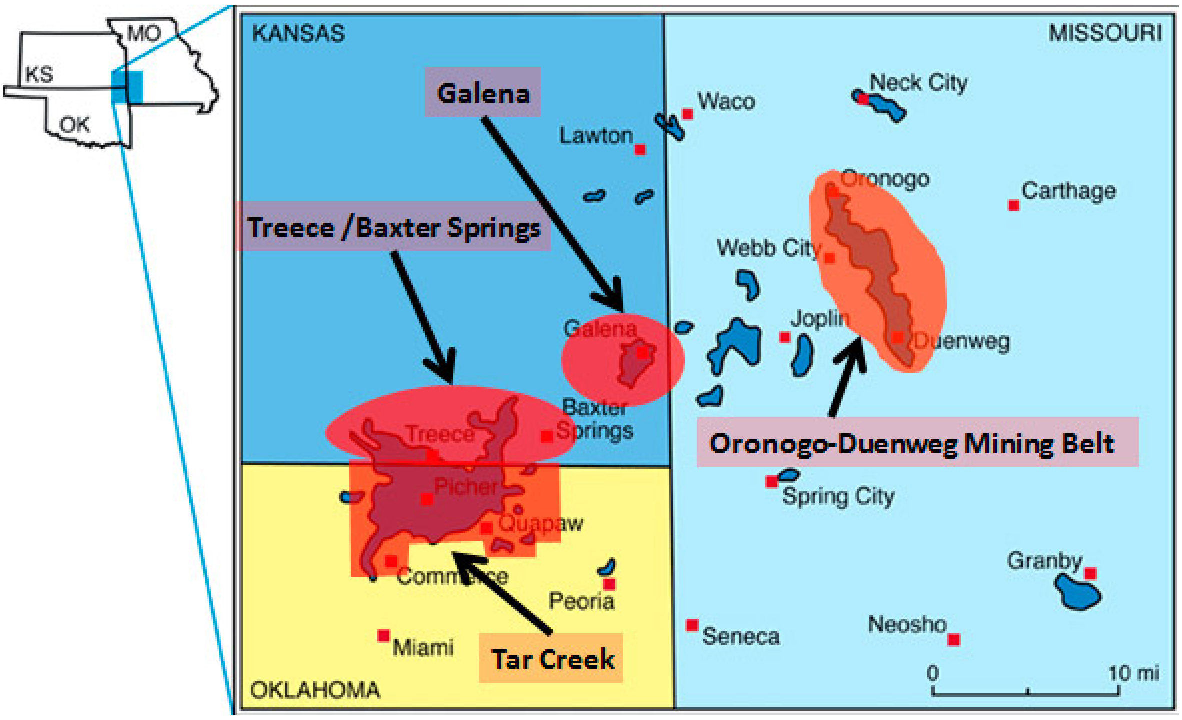



**Figure 37. Location of mining sites in the Tri-State Area** (modified from Kansas Geological Survey 2001)**.**

### 6.8.1 Oronogo-Duenweg Mining Belt, Missouri

The Oronogo-Duenweg Mining Belt site is located within Jasper County and entered the NPL in 1990, along with 10 other designated areas that cover over 270 square miles. Oronogo-Duenweg had over 10 million tons of surface mining and smelter waste (chat piles). At the time, these waste piles were uncovered and unstable, allowing leachate and runoff from the piles to enter groundwater and surface streams that supplied drinking water to about 500 homes. Human health impacts were assessed by ATSDR in a controlled "Lead and Cadmium Exposure Study" (Phillips et al. 1995). Both the actual blood-lead data from local children and a risk assessment concluded that health risks existed due to exposure to lead and cadmium in groundwater, soils, and locally grown produce. To manage remediation activities, USEPA assigned the following four OUs: OU-01, Mining and Milling Waste; OU-02, Smelter Waste Residential Yards; OU-03, Mine Waste Residential Yards; and OU-04, Ground Water. COCs included lead, zinc, cadmium, manganese, nickel, copper, and arsenic.

### 6.8.2 Galena, Treece, and Baxter Springs Cherokee County subsites, Kansas

Galena, Treece, and Baxter Springs sites are all lead and zinc mining areas in Cherokee County, southeastern Kansas. Treece and Baxter Springs sites, two different mining locations, are themselves operable units. The Galena site, which has several operable units (alternate water supply, residential soils and groundwater/surface water) covers 25 square miles of areas covered by mine wastes, water-filled subsidence craters, and open mine shafts. Many of the shafts are direct conduits to the shallow groundwater aquifer that is the sole source of drinking water for approximately 1,050 residents outside of the Galena city limits. COCs include lead, zinc, and cadmium.

### 6.8.3 Tar Creek, Ottawa County, Oklahoma

The Tar Creek Superfund Site in Ottawa County, Oklahoma, is the Oklahoma portion of the former Tri-State Mining Area. The site covers approximately 40 square miles and includes the towns of Miami, North Miami, Quapaw, and Commerce. The towns of Picher and Cardin also were part of the site, but were dissolved as part of a residential relocation and buyout effort.

Tar Creek is a stream that drains the most intensively mined areas of the site and is significantly contaminated with mining-influenced water. Mining here consisted of underground room and pillar mines about 200 feet below land surface. Processing of the lead and zinc sulfide ores occurred at mills located about every 40 acres and resulted in many large piles of chat covering the site. The frequency of mill sites at Tar Creek was the result of unique leasing requirements of the Native American–owned lands. Shallow and deep aquifers underlie the site. Groundwater in the shallow aquifer in the Boone formation has been contaminated with acid mine water, but it is unclear as to whether the contamination has reached as far as the deeper Rubidoux aquifer. Figure 38 shows the various sources of contamination and the pathways leading to media for exposure at this site.

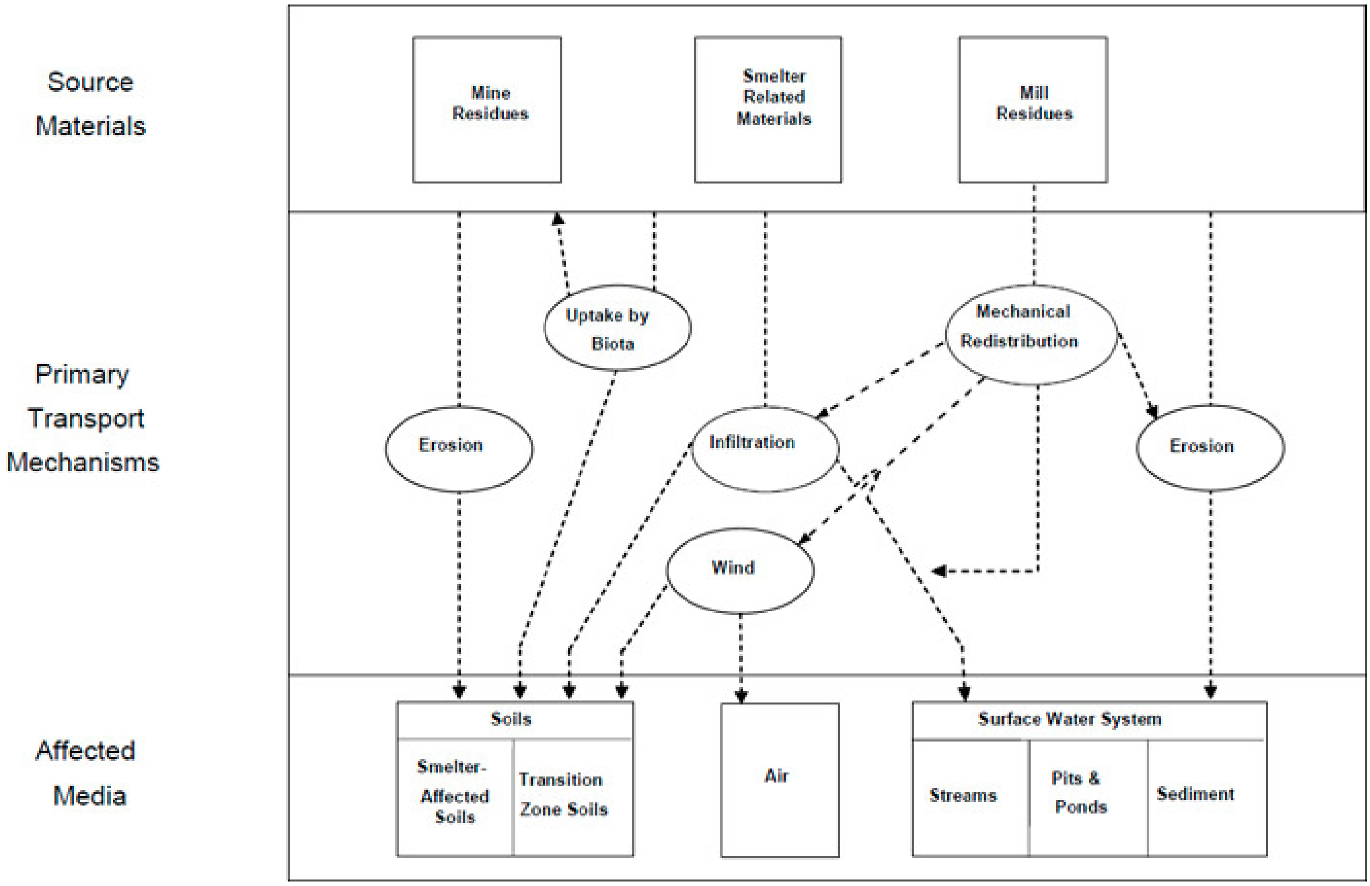



**Figure 38. Tar Creek Superfund Site CSM diagram** (USEPA 2008a)**.**

### 6.8.4 Overview of Complexities at the Sites

The Tri-State area includes widespread regional contamination of soil and surface water, as well as shallow groundwater. Forty million tons of chat remain at the Tar Creek site alone. Geological complexities include karst-like topography from mine voids with conduit flow and fractured breccia zones with secondary openings created by mining. Portions of the ground are subject to collapse or subsidence due to the presence of subsurface mine workings. Mining-influenced water containing dissolved heavy metals contributes to the transport of heavy metals into the water bodies, causing ecological impacts. Drinking water has been contaminated in many areas. Several residential properties at the site are eligible for relocation buyout. Numerous PRPs, along with the portions of the area for which no responsible party can be determined, make remediation responsibility and cost approvals for remedies or investigations legally complex. Stakeholders include local Native American tribes in addition to government and private landowners and users, making stakeholder involvement an essential, time consuming, and potentially expensive component of any remediation process.

## 6.8.5 Technical Basis for Remedial Action

Most sites in the mining district have over ten years of characterization efforts available describe the nature and extent of contamination of the mining wastes for different USEPA operable units.

### 6.8.5.1 Oronogo-Duenweg Mining Belt, Missouri

Although initial actions at sites such as the Oronogo-Duengweg site included providing bottled water to residents, initial characterization efforts generally focused on the nature and extent of mining waste contamination, as well as the transport mechanisms for pathways that could result in exposure. As part of the smelter waste residential yards operable unit, all residential yards were divided into quadrants and sampled for lead. In this case, if the sample results exceeded 800 mg/kg in any quadrant, the first action item consisted on excavating and removing the first 12 inches of soil.

### 6.8.5.2 Cherokee County (Treece/Baxter), Kansas

USEPA initiated investigation activities at the Treece subsite in 1988. The parties potentially responsible for contamination of this area took over the study in early 1990. This investigation explored the nature and extent of soil and water pollution at the subsite and recommended the best strategies for final remediation. The study of the Baxter Springs Subsite was grouped with the Treece subsite.

USEPA initiated an investigation at the Baxter Springs subsite in 1987. The parties potentially responsible for contamination of this area took over the study in conjunction with the Treece investigation in early 1990. This study also explored the nature and extent of soil and water pollution at the subsite and recommended the best strategies for final remediation. Residential yard studies and initial remediation efforts similar to those at the Oronogo-Duengweg site were conducted at the Treece and Baxter Springs subsites, where soil was excavated to a maximum depth of 12 inches or until lead and cadmium levels were less than 500 ppm and 75 ppm, respectively.

### 6.8.5.3 Galena Subsite

At the Galena site in Cherokee County, remedial investigations included field, leachate, and metallurgical testing to understand the geochemical behavior of these wastes and to assist in estimating total waste volume. Residential yards were contaminated in Galena from a historical primary lead/zinc smelter (EaglePicher), in addition to mine wastes. USEPA investigated the nature and extent of contamination and completed characterization reports in 1996.

### 6.8.5.4 Tar Creek, Oklahoma

Extensive lead and zinc mining began in the early 1900s and ended by 1970. With few exceptions, the crude ore produced at the site was mined using underground mining methods. For the mines to operate, groundwater from the Boone aquifer was continually pumped out of the mines. When the mines closed and pumping stopped, the mines began refilling with groundwater. The metal-bearing minerals, which had reacted with oxygen during mining, were more soluble than they had been prior to mining. This increased solubility created highly mineralized acid mine water when groundwater returned to the previously pumped areas.

Contaminated groundwater at the site occurs within the Boone formation (also known as the Boone Aquifer). The Boone formation is composed primarily of limestone, dolomite, and chert, with lesser amounts of sandstone and shale. Lead and zinc ore were mined from various members of the Boone formation.

Also of interest at the site is the Roubidoux aquifer. The Roubidoux aquifer is composed of cherty limestone with several sand sequences near its base. The Roubidoux aquifer lies beneath the Boone aquifer, and the two are separated by 410 to 520 feet of limestone and shale of the Chattanooga group, the Jefferson City dolomite, and the Cotter dolomite. These units act as an aquitard and restrict groundwater flow between the Boone and Roubidoux aquifers. The Roubidoux aquifer is a major source of drinking water for the area near the site. The cities of Picher, Quapaw, Cardin, Commerce, Miami (located south of the site), and several rural water districts obtain their water supplies from the Roubidoux aquifer.

Tar Creek and its primary tributary Lytle Creek comprise the principal drainage system within the Picher Field mining area, which is the main mining area of the Tar Creek site. Tar Creek is characterized as a small ephemeral stream with standing pools. The headwaters of Tar Creek are in Cherokee County, Kansas (located north of Ottawa County on the Kansas-Oklahoma border). Tar Creek then flows southward through the Picher Field between the towns of Picher and Cardin, to the east of Commerce and Miami, and it then flows to its confluence with the Neosho River. Tar Creek and Lytle Creek drain approximately 53 square miles.

### 6.8.6 Conceptual Site Models

CSMs vary slightly from site to site. In general, the primary sources of contamination are the residual metal sulfides in the abandoned mine workings, chat piles, and tailing impoundments as well as historical impacts from smelting operations. Upon atmospheric exposure, metal sulfides can become oxidized and mobilize as dissolved metal compounds. These mobilized compounds create mining-influenced water that can further leach metals from bedrock, allowing high concentrations of dissolved metals to migrate into groundwater or run off into surface waters.

Mining activities were often conducted below the water table. Groundwater was continually pumped out of this shallow aquifer to enable mining activities to take place. When operations ceased however, pumping ceased and mine shafts refilled by natural recharge. Heavy metals including lead, cadmium, and zinc leached out of the oxidized mine waste and have contaminated shallow groundwater.

At other sites, such as those in the Tar Creek Superfund site, mining-influenced water contaminating groundwater in karst-like topography has the potential to migrate to the deeper aquifers and contaminate drinking water. In addition to voids in the natural strata, poorly constructed (or failing) deep water wells and borings could serve as a conduit for contaminant transport to the deeper aquifer. RODs included the identification, closure, and proper abandonment of deep wells and ICs on further development.

Finally, mine water can discharge to surface water. The Kansas Department of Health and Environment (KDHE) has determined that Tar Creek and streams within the Spring River watershed (Willow Creek and Spring Branch) are either partially or not at all supporting aquatic life due to metals loading. More specifically, mining-related zinc load contributions to the Spring River by Willow Creek and Spring Branch and to the Neosho River by Tar Creek and its tributaries are documented in the ROD at 24,000 pounds per year and 220,000 pounds per year, respectively.

The mining tailings piles, locally known as chat, cover large areas of the ground surface. These waste piles are uncovered and unstable. Leachate and runoff from the piles enter groundwater and surface streams. Wind can blow contaminants from the chat piles onto neighboring properties; see Figure 39 for an example of weathered Tar Creek chat pile.

**Figure 39. Weathered Chat Piles at the Tar Creek Superfund Site** (ODEQ 2008)**.**

Although wind and water have spread this contamination to human and ecological receptors, the Tri-State mining district has a long history of using tailings and chat for different purposes such as in asphalt; in cement used for footings, basements, sidewalks; and in driveways, landscaping, walking paths, and sandboxes. Residences have even been built on chat fields.

### 6.8.7 Assessments and Decisions

### 6.8.7.1 Oronogo-Duenweg Mining Belt, Missouri

After the 1991 initial investigations of the Oronogo-Duenweg Mining Belt site, USEPA issued a Unilateral Administrative Order to the PRPs to provide bottled water to residents and to conduct additional private water well sampling and provide bottled water where exceedances of action levels were found. In 1991, the Missouri Department of Health began a large-scale health study to evaluate the effects of mining waste on local residents' health; in 1994, the results of the study found elevated lead levels in blood of local children. In 1996, USEPA issued a ROD for remediation of contaminated soil at residences in former smelting areas and mining waste impacted areas (OUs 2 and 3); this remediation took place from 1996 to 2002. A health education program was also established to educate residents about the health effects of mine waste (particularly lead). Remediation of soil was completed at 2,600 properties. In 1998, USEPA issued a ROD to address contaminated groundwater. This ROD called for implementation of alternate public water supply and point-of-use treatment to replace private wells contaminated by mining waste. The 1998 ROD was signed with a TI waiver for groundwater due to the extent of contamination and inordinate cost to remediate the groundwater. Both the 1996 and 1998 RODs called for ICs to set limits on new construction on contaminated property and prevent installation of groundwater wells in contaminated groundwater.

To address the health and ecological impacts of the extensive mining waste remaining in the area, USEPA issued a ROD in 2004 for remediation of mine waste (OU1) not addressed by the residential property remediation. This ROD called for the following actions:

- removal of mine/mill wastes, contaminated soil, and selected stream sediments
- subaqueous disposal of excavated source material in mine subsidence pits
- recontouring arid revegetating excavated areas
- plugging of selected mine shafts and surface water diversion from mine openings
- a monitoring program for assessing the effect of remediation on-site streams
- continuation of the Health Education Program established under OUs 2 and 3
- ICs to regulate future residential development in contaminated areas and the use of the disposal areas

Remediation of OU1 is currently underway. OU5 was established to address perennial streams that have been affected by the mine waste. OU5 will be addressed once remediation of OU1 has been completed.

The following list provides a timeline of key site decisions:

- 1990: Listed on the NPL
- 1994: Bottled water supplied to residents
- 1995: Site investigations completed
- 1996: ROD for remediation of residential soil (OUs 2 and 3)
- 1996–2002: Remediation of residential soils
- 1998: ROD with TI waiver (OU 4), which called for implementation of alternate public water supply and point-of-use treatment to replace private wells contaminated by mining waste
- 2001–2007: Implementation of remedy for OU4
- 2001–2008: Non-time-critical removal action, highway construction using mine waste (partial remediation of OU1)
- 2004: ROD for remediation of mine waste (OU1)
- 2006–present: Remedial action for mine waste (OU1)
- 2006–present: RI/FS for perennial streams (OU5)

Numerous other actions have been taken at the site – hundreds of residential yards were cleaned up, HEPA vacuums were provided to residents to eliminate the interior dust exposure pathway, and the county established an ordinance which requires testing of soils for lead, cadmium, and zinc before residential development (including standards for construction and clean fill) (Figure 40).


**Figure 40. Photographs showing before and after remediation activities at Oronogo, MO**

(Missouri Department of Natural Resources 2017).

### 6.8.7.2 Cherokee County (Treece/Baxter), Kansas

Following the completion of investigation activities in 1994, USEPA and the responsible parties entered into a Consent Decree in 1999. The Consent Decree required the responsible parties to complete remedial designs and remedial actions at the Baxter Springs and Treece subsites.

The following list provides a timeline of key site decisions:

- 1986-1987: Investigation at Baxter Springs. USEPA installed water treatment units on 8 contaminated wells, completed a countywide survey of wells, added 2 water treatment units later replaced by an alternate water supply, and drilled new wells.
- 1988: Investigation started at Treece subsite
- 1995: Interim removal actions for soil at 62 properties including daycare centers. USEPA investigated using phosphorus to sequester metals instead of excavating.
- 1997: ROD for OU 3 and 4 with TI waiver
- 2000: Construction completion
- 2006: Amended ROD for OU3 and OU4
- 2010: ESD facilitating relocation

The investigation was completed in the summer of 1994 and a remedy was selected in 1997. Negotiations with the responsible parties were conducted in 1998 and 1999. The responsible parties agreed to perform the remediation in 1999 and formalized this commitment by entering into a Consent Decree with the USEPA. The Baxter Springs and Treece subsite remedial actions were grouped into a single ROD. Remedy implementation began in late 1999 and was completed in 2000. At Treece, approximately 150 residential properties were sampled and 41 properties were remediated. The remediation of the Baxter Springs subsite began in late 1999 and was completed in 2004. Over 440 residential properties were tested and 46 properties remediated. The Baxter Springs and Treece remedies also included the abandonment of wells.

A Consent Decree addressing the nonresidential PRP portions of the Treece subsite was successfully negotiated in 2008. The Consent Decree has been lodged and is currently pending, but is expected to be entered and final in 2012, followed by the initiation of PRP-led remedial design activities for nonresidential mining wastes at the Treece subsite. Air monitoring activities resumed at the Treece subsite in 2009 and continued through 2011, when they were halted.

Three RODs have been fully implemented in the Galena subsite portion of the site and are now in the O&M phase. A fourth and related ROD has been fully implemented at the Baxter Springs and Treece subsites and is also in long-term O&M. A total of 18 remedial alternatives and subalternatives were initially reviewed prior to the 1997 ROD. The selected remedy included the following for both subsites:

- investigation and potential remediation of residential yards impacted by mining/milling wastes
- closure/abandonment of poorly constructed existing deep water wells and borings to protect the deep aquifer
- ICs for future development
- O&M of all remedy aspects which include, but are not limited to, the capped areas, stream diversion/control structures, ICs, and long-term monitoring

Selected remedies at Baxter Springs also included the following:

- excavation, relocation, regrading, capping, and revegetation of mine/mill waste piles, tailings impoundments, and tailings outwash deposits
- stream rechannelization and construction of stream diversion/control structures
- prevention of mine water discharges

The ROD for Treece and Baxter Springs was amended in 2006 to include the following actions:

- Excavate, consolidate, and/or cap all surficial mine waste followed by disposal and capping.
- Use subaqueous mine waste disposal to the maximum extent practicable.
- Encourage source reduction via responsible chat sales before and during remedy implementation.
- Adopt ICs for future development specified in an earlier ROD.

An ESD for voluntary residential relocations at the Treece subsite was released in 2010 by USEPA Region 6 for the Tar Creek

Superfund site. Mine wastes in Oklahoma affect areas in Kansas, thus the decision document was released by USEPA Region 6 and covers the Treece subsite in USEPA Region 7. The Relocation Trust was formed by the governor of Kansas and supported by Kansas Department of Health and Environment to facilitate relocation from 2011 to 2014.

Modified Alternative 8A (the selected alternative) estimated approximately $66 million as a cost-effective permanent solution to mine waste impacting the Baxter Springs and Treece subsites of the site. Modified Alternative 8A will achieve all RAOs, meet all ARARs, require no additional ARARs waivers, and may provide substantial future monetary gain or benefit by providing toxic tort relief. The remedy will also provide more suitable natural habitats. Modified Alternative 8A is especially cost effective compared to the benefits derived from reducing or eliminating future environmental or legal claims under other statutes or laws.

In 2007, Congress provided USEPA with an exemption from the Uniform Relocation Assistance and Real Property Acquisition Policies Act of 1970, which enabled USEPA to offer relocation at much lower cost. The exemption applied first to Oklahoma residents in the Tar Creek subunit, then the act was extended to Treece, Kansas, residents in 2009. The ESD in 2010 primarily established a revised cost estimate and a framework for other policy decisions that would need to be made to relocate the residents of the area in both Oklahoma and Kansas.

### 6.8.7.3 Cherokee County (Galena), Kansas

The selected remedial action for this site included the removal, consolidation, and on-site placement in mine pits, shafts, and subsidences of surface mine wastes; diversion and channelization of surface streams with recontouring and vegetation of land surface; and investigation of deep aquifer well quality followed by plugging all abandoned and inactive wells and rehabilitating active wells, if necessary.

The following summarizes a timeline of key site decisions:

- 1986–1987: Investigation. USEPA installed water treatment units on 8 contaminated wells. Countywide survey of wells, added 2 more water treatment units that were later replaced by an alternate water supply. New wells were drilled in the area
- 1989: ROD with TI waiver
- 1993: Remedial design
- 1994: Construction completion
- 1995: Interim removal actions for soil at 62 properties including daycare centers. USEPA investigated using phosphorus to sequester metals instead of excavating.
- 2005: Five-year review

USEPA released the ROD for the remediation approach for metals-impacted residential yards in 1996. The remedy included excavation and disposal of contaminated soils, followed by placement of clean backfill and grass sod or seed. The approach also included evaluating the feasibility of using phosphate treatment methods in the future, in lieu of excavation. The total number of properties remediated in Galena, inclusive of removal work, is 702; over 1,500 properties were tested.

The 1988 OUFS evaluated five remedial alternatives and the 1989 OUFS Supplement evaluated additional remedial actions after more site information became available. Early metallurgical test results from initial (1988) investigations in Galena indicated metals removal from waste rock and chat would be much more complicated than previously envisioned. This result drove decision makers to evaluate the following remedial options in 1989:

- Take no action.
- Remove and treat surface mine wastes via milling and flotation to remove the surface source of the contaminants.
- Recontour and revegetate the land surface to control erosion and to reduce surface water infiltration to the mineralized zone.
- Channelize and divert stream channels to reduce metals loadings in the streams and to reduce surface water infiltration into the mineralized zone.
- Investigate deep aquifer wells and remediate as necessary to protect the Roubidoux aquifer.

The preferred alternative had several components:

- Remove and treat surface mine wastes via milling and flotation to remove the surface source of the contaminants.

- Recontour and revegetate the land surface to control erosion and to reduce surface water infiltration to the mineralized zone.
- Channelize and divert stream channels to reduce metals loadings in the streams and to reduce surface water infiltration into the mineralized zone.
- Investigate deep aquifer wells and remediate as necessary to protect the Roubidoux aquifer.

The 1989 OUFS Supplement considered two alternatives to the first component of the 1988 preferred remedy:

- Remove and transport all mine waste rock and chat to a single containment unit.
- Remove all mine waste rock and chat and selectively place the material in available pits, shafts, and subsidences. Place waste rock below ground based on size. Characterize chat as to lead and zinc content and place below ground or use for surface cover based on metal content.

Based on the OUFS results, the 1989 ROD selected remedy components included:

1. Characterize and selectively place surface-deposited mine wastes (waste rock and chat) in open subsidences, pits, and shafts.
2. Divert and rechannel certain surface drainages and recontour and vegetate the ground surface to the extent possible.
3. Investigate and remediate, as necessary, wells penetrating the deep aquifer to protect against contamination from the shallow aquifer and mining-related activities.

Component 1 of the selected remedy would essentially eliminate human exposure via ingestion to contaminated mine wastes and reduce long-term shallow groundwater and surface water metals loading. Component 2 of the selected remedy would minimize recharge to the shallow groundwater system, reduce infiltration through the cover material, promote proper surface drainage, and control erosion. Component 3 of the selected remedy would protect the deep aquifer against contamination from the shallow aquifer.

The estimated present worth cost for the selected remedy was $8,295,215, which included an annual O&M cost of $14,963.

### 6.8.7.4 Tar Creek, Oklahoma

USEPA began environmental investigations at the Tar Creek Site in 1982. The first ROD was issued in 1984 to address surface water degradation of Tar Creek by the discharge of acid mine water, and to address the threat of contamination of the Roubidoux aquifer. The ROD called for plugging of wells penetrating the Boone aquifer (where lead ore was mined) to the deeper Roubidoux aquifer to prevent mining-influenced water from contaminating the deeper aquifer. Groundwater monitoring is ongoing. The ROD also called for diversion of surface water to improve water quality of Tar Creek.

After an RI/FS showed elevated concentrations of metals (cadmium, lead and zinc) in the mined areas of Ottawa County, the site was added to the NPL in 1983. USEPA and the state of Oklahoma then initiated several RIs and identified five Operable Units, or OUs, at the Tar Creek site.

The following list summarizes a timeline of key site decisions:

- 1982: USEPA began environmental investigations at the Tar Creek site.
- 1984: ROD issued for surface water and groundwater.
- 1994: USEPA conducted a five-year review and found that children living in Ottawa County had elevated blood-lead levels. This finding resulted in USEPA evaluating lead contamination in soils surrounding residential properties, and finding elevated lead levels in soil.
- 1995: Remediation of residential soils was conducted.
- 1997: Second ROD was issued for OU2.
- 2007: Remediation should be completed by the end of 2007 (USEPA Superfund ESD, Tar Creek Superfund Site, OU2, August 2007).

The following five OUs have been designated at the site:

- OU1 – surface water/groundwater
- OU2 – residential properties and high activity areas such as schools and parks
- OU3 – EaglePicher complex – abandoned mining chemicals
- OU4 – chat piles, mine and mill residue, smelter waste, and flotation ponds

- OU5 – sediments/surface water

The ROD for OU4 (chat piles, other mine and mill waste, and smelter waste) was signed in February 2008 (during the fourth five-year review period). OU4 addresses the undeveloped rural and urban areas of the site where mine and mill residues and smelter wastes occur as a result of mining, milling, smelting, or related operations. This ROD includes relocation of residents, removal of chat piles (sale of useable chat, relocation or reinjection into mine workings of unusable chat). A recent pilot study examined mixing the chat with water to form a slurry, then injecting it back into the workings of the mine. This project has been ongoing for approximately four years.

OU5 consists of sediment and surface water in Elm Creek and Tar Creek starting at the confluence of Tar Creek and Lytle Creek to the Neosho River down to the point where it flows into Grand Lake. Investigations related to OU5 are ongoing, and a remedy has not yet been selected.

The diversion of surface water has not significantly improved the water quality of Tar Creek. Within the last few years, two biochemical reactors have been installed to remediate mining-influenced water surface runoff at the Tar Creek site. A biochemical reactor is an engineered remediation system, similar to a constructed wetland, in which mining-influenced water enters an engineered cell. Sulfate-reducing bacteria and associated microorganisms in this cell, as a result of their metabolic activity, raise pH and precipitate metals as sulfides. More information on biochemical reactors is available from the ITRC *Biochemical Reactors for Mining-Influenced Water* guidance (ITRC 2013a). The two biochemical reactors are located at the Beaver Creek Mine Discharge Area and Mayer Ranch/Commerce site.

For Tar Creek, the ROD for Residential Areas (OU2) in 1997 included the following:

- Excavate lead-contaminated surface soil in residential areas.
- Replace excavated soil with clean soil and remediation of the remediated areas.
- Dispose of excavated soil on site in dry mining waste areas remote from the residential areas or, in the event of inability to dispose of excavated materials on site, disposal off site in an approved landfill.
- Cover or replace mining waste in traffic areas located near residences.
- Restrict access to mining waste areas located near residences by use of physical barriers (for example, fences and warning signs).
- Implement county-wide ICs, including community protective measures, to supplement engineering remedial actions.

In 2008, a ROD was accepted for OU4 of the Tar Creek Superfund site. Phase 1 addressed the voluntary relocation of residents, chat sales and source material to reduce the overall footprint of contaminant and the need for land use restrictions, ICs, and O&M as follows:

- Residents located in Picher, Cardin, and Hockerville will be voluntarily relocated following the procedures and priorities established by the Lead Impacted Communities Relocation Assistance Trust (LICRAT).
- Chat and chat bases from distal areas, including associated historical chat covered haul roads and nonoperating railroad grades, will be excavated to the underlying native soil, transported and released to an on-site chat processor or future processing location located in a previously contaminated area of the site, injected into mine workings, or disposed in an on-site repository.
- Transition zone soils (soils around and underneath source materials) will be addressed by excavation followed by natural soil rebuilding.
- Smelter wastes will be excavated and disposed of in an on-site repository. Smelter affected soils will be managed in the same manner as transition zone soils.
- Fine tailings will be injected into mine workings or covered in place. The covered fine tailings may be consolidated to reduce the footprint of the final cover.
- Source material in Tar, Lytle, Elm, or Beaver Creek or other site waterways will be addressed on a priority basis through either excavation, the installation of a flexible membrane liner, or both as determined by USEPA.
- As an interim measure, sheet piling, berms, constructed wetlands, or other engineering controls will be installed for near-stream source materials to help prevent contamination from migrating to surface water.
- An alternative water supply will be provided to any household where mining-related contaminants in water drawn from rural residential wells exceed 0.015 mg/L for lead for rural households.
- Rural households that are within the area that has been designated for relocation under the Lead Impacted Communities Relocation Assistance Trust (LICRAT) relocation program, but which do not elect to participate in the relocation program, would be included in the households eligible for an alternative water supply (estimated

two residences).

- Rural residential yards that are found to have concentrations of soil lead that exceed 500 ppm will be excavated to a maximum depth of 12 inches, and the excavated area will be backfilled with clean soil, contoured to promote drainage, and revegetated. This action includes residential yards that are identified for relocation. These provisions apply to approximately 4 households, based on the RI sampling. If those eligible for relocation decide not to relocate, their yards will be remediated.
- On-site repositories will be constructed to accept site source materials for final disposal. On-site repositories will be closed when they reach capacity or at completion of the remedial action. Closure will be accomplished by covering the repository with a soil cover, contoured to promote drainage, and revegetated.

Phase 2 activities included the following:

- The remedy will be reviewed, at a minimum, every five years because hazardous substances remain on site with concentrations that exceed concentration levels that allow for UU/UE. The remedy will be reviewed to ensure protection of human health and the environment.
- As part of the five-year review, USEPA will evaluate the progress of chat sales. Chat piles and bases remaining after 10 years will be evaluated for commercial viability. This determination will be made using input from the chat/land owners, appropriate tribal representatives, and the commercial operators.
- Unmarketable chat piles and bases will be excavated, transported and released to an on-site chat processor or future processing location in a previously contaminated area of the site, injected into mine workings, or disposed of in an on-site repository.
- Abandoned chat haul roads and nonoperating railroad grades that are contaminated will be managed the same as unmarketable chat piles and bases. That is, they will be excavated, transported to an on-site chat processor, and released to that processor, or disposed of in an on-site repository.
- ICs and O&M activities will be implemented, as determined by USEPA, at repositories and covered, fine tailings ponds. Environmental monitoring will be conducted, as determined by USEPA, to test for contamination in ambient and near source air, surface water, groundwater, and sediment during remediation activities.

Per the ROD, in situ treatment of mine water and P&T of mine water were considered too expensive.

## 6.8.8 Monitoring/Optimization

Post-remediation blood lead studies have demonstrated a 43% reduction in elevated blood-lead levels of children at the site and multiyear ecological studies have demonstrated the benefits of the mine waste remediations. Health education, blood lead screening, physician/health care worker education/training, and dissemination of lead hazard/identification information has been prolific. A follow up lead exposure study showed that blood lead levels in the area had decreased after many of the actions had been completed (Missouri Department of Health 2002).

Mining waste is no longer used as road surface material on the 1,000 miles of unpaved roads throughout the county. There are 1,300 miles of roads in the county; thus, the use of non-mining wastes for 1,000 miles is a significant environmental benefit. A summary of site progress to date includes the following:

- Nearly 1,400 acres of mining-impacted land have been restored.
- Over 4,000,000 cubic yards of wastes have been remediated.
- Nearly 3,000 residential properties have been sampled.
- Nearly 800 residential properties have been remediated.
- Over 500 homes have been provided with a permanent source of clean drinking water.
- Chemical characterization of several thousand samples of water, wastes, and soil was performed.
- Significant 43% reduction of elevated blood lead levels of children was achieved.
- The use of mining wastes on 1,000 miles of roads throughout the county was ended.
- Several million dollars were collected or recovered from responsible parties.
- Several hundred air samples have been collected and analyzed in various areas of the site.

### 6.8.8.1 Oronogo-Duenweg Mining Belt, Missouri

Three five-year reviews have been conducted, in 2002, 2007, and 2012. As of 2002, the contaminated soil at almost all the resident properties (except for a few where access was denied) were cleaned up. A subsequent blood-lead study showed that child blood-lead levels were well below the established target, indicating that the residential property remediation had achieved the objectives. As of 2007, the alternate water supply has been constructed and bottled water is no longer needed.

Remediation of the mining waste (OU 1) began in 2007 and is expected to continue through at least 2018. Remediation of perennial streams will be addressed once remediation of OU 1 is complete.

### 6.8.8.2 Cherokee County (Galena), Kansas

Four five-year reviews have been conducted, in 1995, 2000, 2005, and 2010. There are three operable units within the Galena subsite; OU1 provides an alternate water supply to residents. Initially, bottled water and subsequent construction of an alternate water supply (two rural water wells constructed to approximately 1500 feet below ground surface) replaced contaminated water. OU5 is Galena Groundwater and Surface Water, and OU7 is Galena Residential Soils.

The remedy for OU1 is in the O&M phase and is being overseen by the state of Kansas. The alternate water supply has been expanded to include 100 new hookups (500 total) since completion of the remedial action in 1994.

Work at OU5 has been conducted by USEPA and PRPs and is in different phases. The USEPA fund-led remediation was completed in 1996 and the PRP work is ongoing. Approximately 2.1 million cubic yards of mining wastes have been addressed to date. The USEPA portion of the remedy included remediation of approximately 900 acres of nonresidential land surrounding Galena. Mining wastes were segregated and placed at the surface or used as fill material for open dry shafts. The PRP work involves remediation of former smelter buildings and associated grounds. The buildings have been decontaminated and are currently being reused. The work for the surrounding lands is currently under design.

O&M activities for OU5 consist of maintenance of revegetated areas and engineered drainages (enhanced by rip rap and geotextile). O&M of several of these areas has been difficult. The difficulties include areas with steep slopes, highly acidic conditions, and poor soil conditions that make it difficult to maintain vegetation. The state of Kansas is considering several alternatives to address the difficulties. These include reducing the slope/grade and adding terraces, and addition of soils, nutrients, fertilizers, and refined seed mixtures.

The remedy for OU7 was remediation of several residential properties with lead-impacted soil. A smelter in the town of Galena was responsible for a much larger residential lead problem than at Treece or Baxter Springs because of the wind dispersion of smelter emissions over a large area. More than 1,500 properties were sampled in the Galena area, and over 700 residential properties were remediated. Approximately 180,000 cubic yards of impacted residential soils were remediated. This work was funded by USEPA under a 1996 ROD and was completed by 2001. A follow-up study of blood-lead levels in children revealed a significant decrease in blood levels following remediation. ICs implemented at Galena OU7, as well as other Cherokee County subsites, include health education regarding all aspects of lead exposure, blood-lead testing, physician education on the awareness and symptoms of lead poisoning, in-home lead assessments performed by nurses from the county health department, provision of a high efficiency particulate vacuum upon request by county residents, and quarterly reporting of all aspects of the ICs program.

Other ICs implemented at both Galena and Treece/Baxter include restrictions on the inappropriate use of chat mining wastes, LUCs in contaminated areas and locations where wastes are capped, building permits, testing requirements for development in mining-impacted areas, and restrictions on use of the upper contaminated aquifer as a source of drinking water.

### 6.8.8.3 Cherokee County (Treece/Baxter), Kansas

Three five-year reviews have been conducted, in 2000, 2005, and 2010. The Baxter Springs subsite has two components to the remedy: a residential remediation and a mine waste remediation. The residential remediation includes sampling and remediation, if necessary, of residential soils. The residential contamination resulted from the import of mining wastes for use as driveway construction, landscaping, fill material, and alley/road construction. Contaminated residential soils will be maintained in a fenced soil repository in Galena. The mine waste remediation includes removal of wastes from minor streams and drainages, draining and capping tailings impoundments, and capping and revegetation of chat piles. The mine waste remediation addresses mine waste accumulations that potentially affect surface water bodies. Mining wastes are being cleaned up by both PRPs and USEPA.

A first phase of mine waste remediation was conducted by PRPs under a Consent Decree signed in 1999 and included residential and mine waste portions that were completed and are now in O&M. A second PRP remediation (pursuant to a 2008 Settlement Agreement and Consent Agreement between the PRP and the state of Kansas) is currently ongoing. For several hundred additional acres of land for which no viable PRPs exist, USEPA is funding the remediation and a ROD amendment has been approved. This work is in the design phase. The USEPA-led design and remediation work addresses both the Baxter Springs and Treece subsites. Approximately 1.5 million cubic yards of mining wastes have been remediated by USEPA and PRPs to date.

The components of the remedy for the Treece subsite are similar to those of the Baxter Springs subsite. The remedy components consist of a residential portion and a mine waste remediation portion. Both USEPA and PRPs are funding portions of the remediation. Additionally, due to impacts to the community of Treece by the Tar Creek Superfund site, USEPA is implementing a residential buy-out for the community of Treece, Kansas similar to Oklahoma communities adjacent to Treece. The state of Kansas is overseeing the implementation of the buy-out program.

### 6.8.8.4 Tar Creek, Oklahoma

Four five-year reviews have been conducted, in 1994, 2000, 200,5 and 2010. To date, the remedial approach for protecting groundwater in the Rubidoux aquifer (plugging wells) has successfully protected the aquifer from contamination from the Boone aquifer (in which the mining activities were conducted). The remedial approach for preventing discharge of groundwater to the surface from the Boone aquifer (by preventing recharge of the Boone aquifer by diking and diverting water) has not been effective. This portion of the remedy diverted water from two mine shafts that were thought to be the main points of recharge to the Boone aquifer. However, it is now believed that there are many other significant points of recharge to the Boone aquifer, rendering this approach ineffective. A new approach to improving surface water quality in the Tar Creek area is the construction of biochemical reactors, a type of treatment wetland, to treat the mining-influenced water after it reaches surface water. As of the 2010 five-year review, the pilot studies are still in progress.

The 2010 five-year review made the following recommendations to further address contamination at the site:

1. Complete the effectiveness of the well plugging program and perform field work to identify the 19 additional wells penetrating both the Boone and Roubidoux aquifers and determine whether these wells need to be plugged.
2. Complete remedial activities for OU2, including cleaning up additional residential properties and assessment of chat remaining in in driveways and alleyways.
3. Complete the evaluation of surface water and sediments in Tar Creek to verify that no unacceptable human health or environmental risks exist.
4. Implement ICs to limit use of shallow groundwater, including the Boone aquifer, that has been contaminated by mining activities.

In 2006 USGS performed a revised groundwater modeling project to simulate groundwater flow in the formations underlying the Tar Creek site (Figure 41). This model will help USEPA and others refine their remediation efforts so that the lower aquifers are not affected by various remediation scenarios.

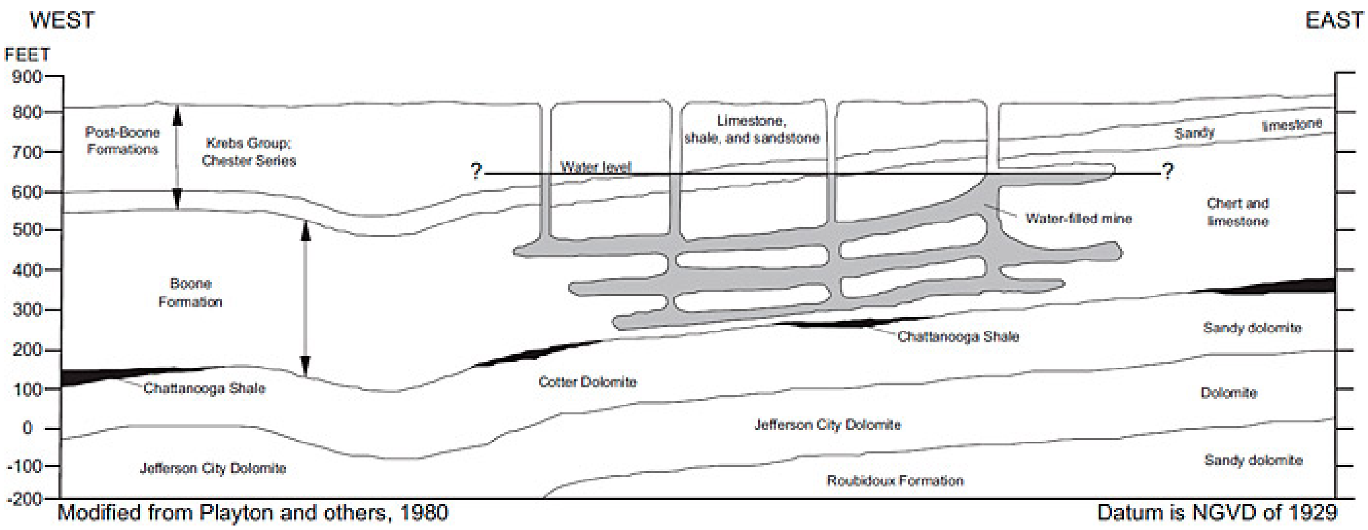



**Figure 41. Revision of the CSM at Tar Creek site** (USGS 2006)**.**

The use of advanced tools, as well as collecting information from remediation programs and other sources, will allow regulators to safely design chat impoundments and disposal methods. The scenarios below evaluate a 100-year estimated flow path for particles mobilized by infiltration that eventually will make their way to the nearby larger river drainage (Figure 42).

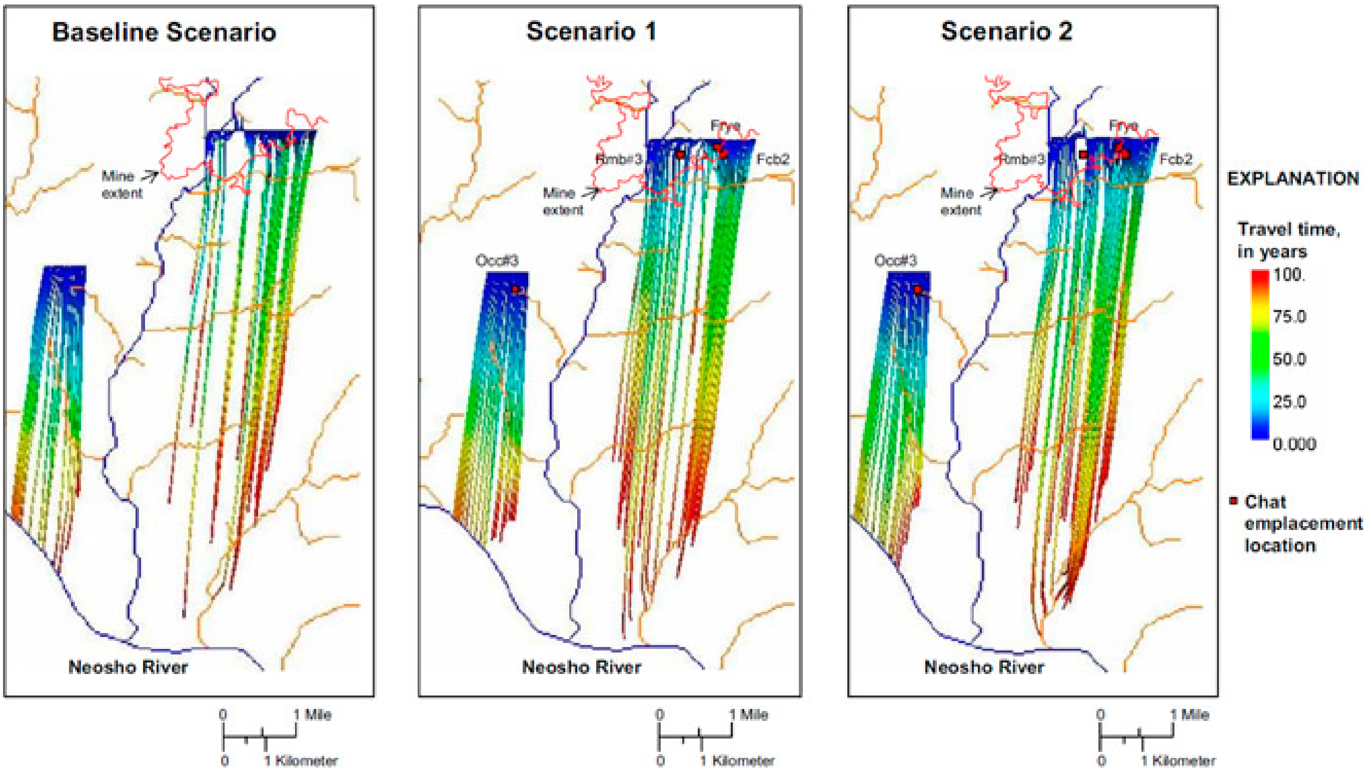



**Figure 42. Modeling scenario results for Tar Creek site** (USGS 2006)**.**

In 2006 The U.S. Army Corps of Engineers (USACE) released a report concerning the threat of subsidence in Ottawa County. This report caused USEPA to reevaluate its plans for remediation of the site.

## 6.8.9 Regulatory and Stakeholder Involvement

### 6.8.9.1 Oronogo-Duenweg

There was a very active community action group at the Jasper county site, headed by the mayor pro-tem of Joplin. The group received a grant to hire a consultant to help them understand the information provided by the agencies on sampling and actions taken at the site. Community participation was essential, because many of the risk reduction strategies required the community to change their daily activities (gardening in raised beds, using HEPA vacuums indoors, and finding alternate sources of fill materials for sandboxes or other areas where exposure was possible). Community participation in the 1998 FS resulted in eliminating as many point-of-use treatment systems as possible and including extension of existing public water supply lines projects where practical and cost effective.

### 6.8.9.2 Treece and Baxter Springs

Several public meetings and availability sessions have been conducted for the various remediations at the Cherokee County Superfund site, in addition to many discussions and meetings with citizens and local officials at several city council meetings held in the various communities at the site. The Cherokee County Health Department, County Commission, and County Engineer have been instrumental in supporting the USEPA's environmental characterization and remediation activities. In general, the community and local officials have been supportive of all remediation actions conducted at the site. Establishing a local field office in 2007 facilitated the community involvement process.

Extensive activities and communication among USEPA Region 7, USEPA Region 6, and Kansas Department of Health and Environment surrounded the buyout of Treece, Kansas. Numerous newspaper and magazine articles described the buyout process, the community's response to the proposal, and community member perceptions about losing their identities and interaction with their neighbors. USEPA also continues to maintain a customer service toll-free phone number for its office personnel, making contact easier for the affected communities.

USEPA Region VII encouraged public review and comment on the preferred remedial alternative by providing the public with the proposed plan and supporting documents included in the Administrative Record file. To provide the community with an opportunity to submit written or oral comments, USEPA extended the public comment period due to public interest. A public meeting was held to present the proposed plan, accept written and oral comments, and to answer questions concerning the preferred alternative. At this meeting, representatives from USEPA and the Kansas Department of Health and Environment answered questions about the subsites and the remedial alternatives under consideration. Responses to the questions and comments received during the public comment period are included in the Responsiveness Summary, which is provided as Attachment 1 to the ROD. The decision for these two subsites is based on the information contained in the Administrative Record file which is located at the earlier referenced repositories.

The public was encouraged to participate in the Proposed Plan and ROD Amendment process at OU-3 and OU-4. The Proposed Plan highlighted key information from the RI and FS Reports, FS Addendum Report, ROD dated August 1997, final Remedial Action report for 1 the Baxter Springs subsite, final residential remedial action report for the Treece subsite, Five-Year Review Reports, and Administrative Record. Additionally, the public historically has been made aware of the environmental issues in the county through the many public meetings, public availability sessions, newspaper articles, television coverage, radio broadcasts, and press releases that have occurred at the site for the many environmental remediations conducted to date.

To provide the community with an opportunity to submit written or oral comments on the OU-3 and OU-4 Proposed Plan, USEPA established a 30-day public comment period from July 24 to August 22, 2006. A public meeting was held at the Baxter Springs Community Center, Baxter Springs, Kansas, to present the Proposed Plan, accept written and oral comments, and answer any questions concerning the proposed remediation remedy. Over 60 people attended the public meeting and the event was covered by a local newspaper and television affiliates. A summary of the verbal questions received at the public meeting, inclusive of responses, was provided in a Responsiveness Summary. The Responsiveness Summary also contained a summary of written correspondence received during the public comment period, as well as written responses to that input. The Proposed Plan and supporting AR file were made available for public review during normal business hours at the Johnston Public Library in Baxter Springs, Kansas, and at the Region 7 office in Kansas City, Kansas. Additional AR files supporting the USEPA's historical remediations at the Badger, Waco, Lawton, and Crestline subsites and Galena subsite are also available at the Region 7 office and at the Columbus Public Library in Columbus, Kansas, and the Galena Public Library, respectively. These additional ARs are incorporated into the OU-3 and OU-4 AR by reference. Moreover, the OU-3 and OU-4 AR has been updated with additional information to support this ROD Amendment.

### 6.8.9.3 Galena Subsite

Remediation reduced the health risks from contamination for over 4,500 people in the Galena area, and improved the appearance of the local countryside. City officials are delighted with the improvements and have developed a tax incentives program to help attract new light industry. Community support for site remediation is strong. Preliminary results from the Kansas Biological Survey's study of the site show improvement in environmental health.

Collaboration with the state of Kansas and the KDHE was a key factor in USEPA's successful implementation of a remedy to mitigate the contamination. The assistance of federal partners was instrumental in the design and execution of the remediation, and analysis of the health and environmental threats. The Agency for Toxic Substances and Disease Registry assessed the health effects of the contamination, and the U.S. Bureau of Mines helped the other agencies locate and plan remediation of the mine shafts, pits, and unstable areas.

### 6.8.9.4 Tar Creek

At the Tar Creek site, USEPA, in coordination with the Oklahoma Department of Environmental Quality (ODEQ) and the Quapaw Tribe, has kept the community, public, governmental entities, citizen advisory groups, and interested parties informed of Superfund remedial actions, and involved these groups in planning. USEPA used various methods for informing communities about on-site activities at Superfund sites and for seeking public participation in the NCP process. One routine activity USEPA uses is the development of site fact sheets and newspaper notices. Informational fact sheets at Superfund sites are routinely mailed to individuals on the site mailing list, which includes community members located within approximately one mile of the site, elected officials, and other interested parties who have requested information or who have attended public meetings. At the site, USEPA met with community members and performed various outreach activities in response to the site-specific needs of the community. This activity included responding to citizens, neighborhood associations, and other community organizations through informal discussions, community open houses, and public meetings.

Multiple five-year reviews have been performed at the Tar Creek Site. The most recent Five-Year Review Report (ODEQ 2015) is available online and includes USEPA interviews with local citizens.

## 6.9 Paducah Gaseous Diffusion Plant (PGDP) Groundwater, Kentucky

The DOE's Paducah site in McCracken County, Kentucky, is approximately 10 miles west of the city of Paducah. Within the 3,556-acre site is the Paducah Gaseous Diffusion Plant (PGDP). The PGDP consists of over 500 facilities, with 19 miles of roadway and 5 miles of fence. PGDP was constructed in the early 1950s as a uranium enrichment facility to support the fabrication of fuel assemblies for commercial and military nuclear reactors and military weapons. Four large cascade process buildings that enriched uranium by the gaseous diffusion process served as the hub of the PGDP until the commercial uranium enrichment process was terminated in July 2013. The U.S. Enrichment Corporation (USEC), a private company, handled commercial operations until 2013; DOE retains primary control of the facilities.

Past PGDP operations generated hazardous substances, some of which were released into the environment. Spills, leaks, and other releases allowed large quantities of contamination to reach the regional groundwater aquifer. In 1988, environmental monitoring and investigation began at PGDP and identified contaminant plumes that extended off site. Primary contaminants are TCE and the radionuclide technetium 99 ($^{99}$Tc), an element with a half-life of over 200,000 years.

PGDP demonstrates several complexities including extensive plumes, multiple long-lived contaminants and contaminant sources, heterogeneous geologic conditions, and off-site contaminant migration. The main technical complexities include DNAPLs, multiple contaminants (VOCs and $^{99}$Tc), challenging geological heterogeneity (lower permeability fine-grained sediments in the vadose zone and shallow groundwater), and an important aquifer (Figure 43).

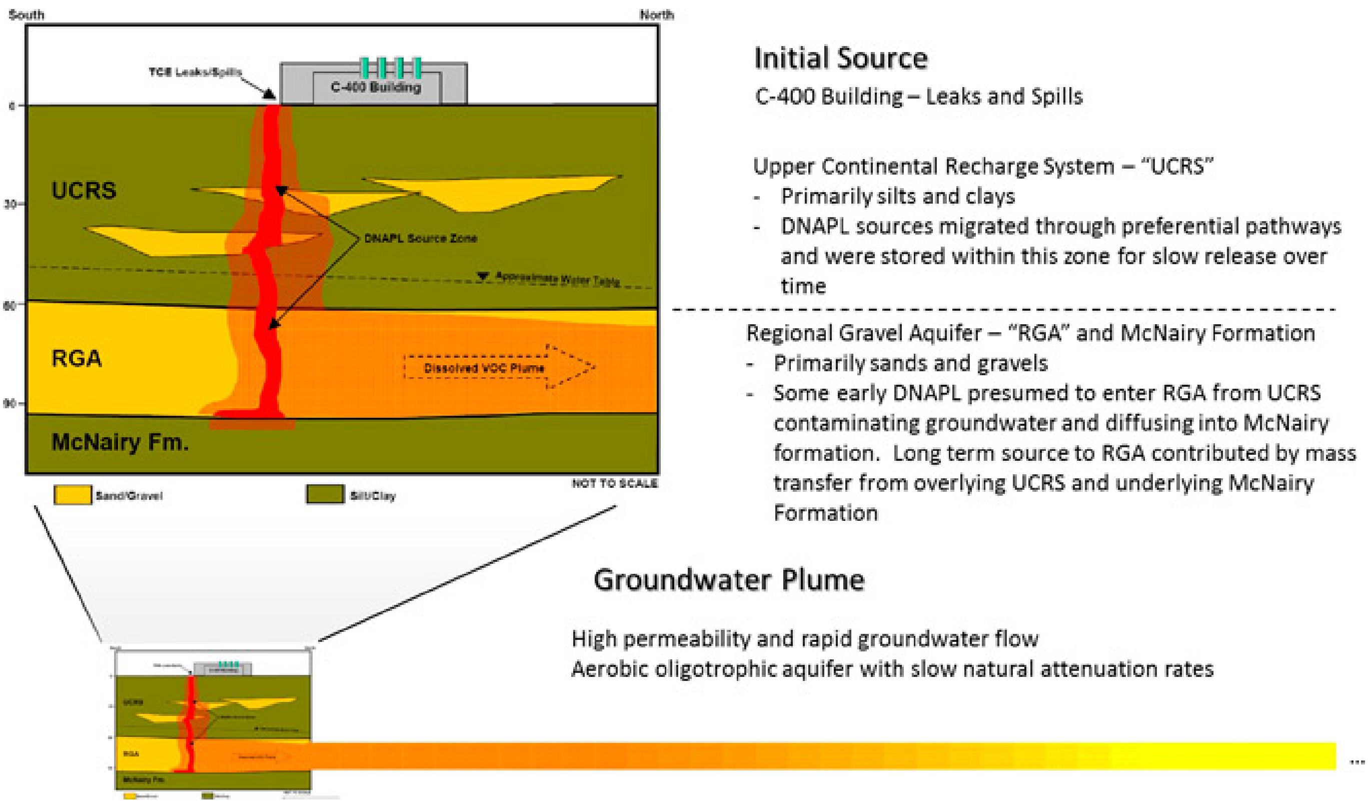



**Figure 43. Simplified depiction of primary PGDP groundwater contaminant source (C-400 Building) showing the fine over coarse lithology, DNAPL, and the resulting slow-release challenge** (DOE 2010a)**.**

Site geology significantly limits the performance of remedial technologies and is representative of many contaminated sites. At PGDP, the lower permeability Upper Continental Recharge System (UCRS) overlies a higher permeability Regional Gravel Aquifer (RGA). VOC contamination moves downward through the UCRS and feeds into the RGA. Some VOCs migrate through relatively direct transport pathways and enter the RGA in concentrated form as DNAPL. DNAPL can continue to migrate downward in the RGA, coming to rest at the McNairy/RGA interface. A significant amount of contamination is also retained in the silts and clays of the UCRS. Thus, the overlying UCRS vadose zone and the underlying RGA-McNairy interface act as a contaminant reservoir that slowly discharges (like a capacitor or a battery) over a long time into the flowing groundwater aquifer. Once contaminants dissolve in the RGA, they rapidly move downgradient toward the Ohio River.

A groundwater project team was formed, which included DOE, USEPA, and the Commonwealth of Kentucky Department of Environmental Protection (KDEP). The team is supported by technical resources from universities, national laboratories, and contractors. This team currently works together to address PGDP groundwater contamination. In response to the site-specific complexities, the team’s approach has focused on source removal from the UCRS (and RGA), hydraulic capture, and long-term MNA. Remedial activities include two groundwater P&T systems, thermally enhanced extraction as an interim action, and research studies to quantify natural attenuation.

## 6.9.1 Technical Basis for Remedial Action

Groundwater under the PGDP site is contaminated by VOCs, primarily TCE (Figure 44) and $^{99}$Tc. Facility operations began in 1952 and released TCE into the subsurface. Diffusion of the high-strength contamination into less permeable zones over many decades “loaded” contaminants into these zones, forming secondary sources that continue to slowly “unload” long after the primary contamination source was removed. The area that includes the C-400 Cleaning Building and nearby facilities (such as the former cylinder drop test area and burial grounds) coincides with the highest TCE concentrations and comprises the centroid of the groundwater plumes at PGDP (Figure 44). This area is the dominant historical and current source of TCE solvent contributing to the PGDP groundwater plumes.

The subsurface near the C-400 Cleaning Building (Figure 43) has three relevant hydrogeologic zones: (1) the UCRS, about 0-65 feet deep; (2) the RGA, about 65-87 feet deep; and (3) the underlying McNairy Formation, which is greater than 87 feet deep. Groundwater (the “water table”) is at a depth of about 34 feet and occurs within the lower UCRS. Near the C-400 Building, DNAPL was identified both above and below the water table in the UCRS, in the RGA, and in the upper portion of the McNairy Formation (Figure 43). Following downward transfer of TCE from the source zone into the UCRS, the dissolved-phase plume is transported laterally, primarily in the RGA, by groundwater flow. The RGA is much more transmissive than the overlying UCRS or underlying McNairy Formation.

Consistent with the site-specific conditions, the groundwater project team recognized that a combination of technologies was needed to effectively and efficiently address the varying conditions within the plumes. Technologies are used for the following tasks:

- maintain hydraulic control of the dissolved plume
- remove primary and secondary DNAPL source areas near the C-400 Building
- quantify natural attenuation to better inform groundwater management decisions

Several innovative technologies were tested at PGDP and promising technologies were deployed at full scale. Progress toward site objectives for PGDP groundwater has been achieved through a combination of standard and innovative technologies.

## 6.9.2 Decisions

Groundwater remediation at PGDP is part of a larger environmental effort that also addresses contaminated soil, sediments, and former burial grounds. The process for managing these activities is governed by a 1998 Federal Facilities Agreement (FFA) negotiated between DOE, USEPA, and the Commonwealth of Kentucky. The FFA defined a set of consistent requirements for comprehensive site remediation in accordance with RCRA and CERCLA. Under the FFA, an outline was established to achieve remediation targets and work toward achieving site objectives. Remediation targets and overall site goals are described in the annual Site Management Plan (SMP), End State Vision, and related documents.

### 6.9.2.1 Hydraulic Control

Early responses to contaminated groundwater focused on mitigating and eliminating potential exposure pathways. DOE placed areas with contaminated drinking water wells on an alternate water supply. In 1993, DOE prepared two RODs to address contaminated groundwater. A key early action was to install P&T systems on two major PGDP plumes, the Northwest and the Northeast Plumes. These systems were constructed and placed into operation in 1995 and 1997, respectively. The P&T systems have stopped the two plumes from spreading and have substantially reduced the amount of contamination migrating towards the Ohio River. Periodic adjustments were made to optimize the P&T systems over time. For example, in August 2010, the Northwest Plume P&T system was modified by installing two new recovery wells and taking two other wells offline to refocus the recovery zone and to increase contaminant mass removal. Following optimization, the system is projected to recover more than 90% of the mass discharging from the C-400 Building source area. Optimization of the Northeast Plume P&T system is ongoing. Any future modifications to the P&T system (for example, pumping rates, extraction well locations, collateral impacts, and shut-down criteria) will be determined by the core team based on monitoring data, groundwater modeling, and applicable regulations.

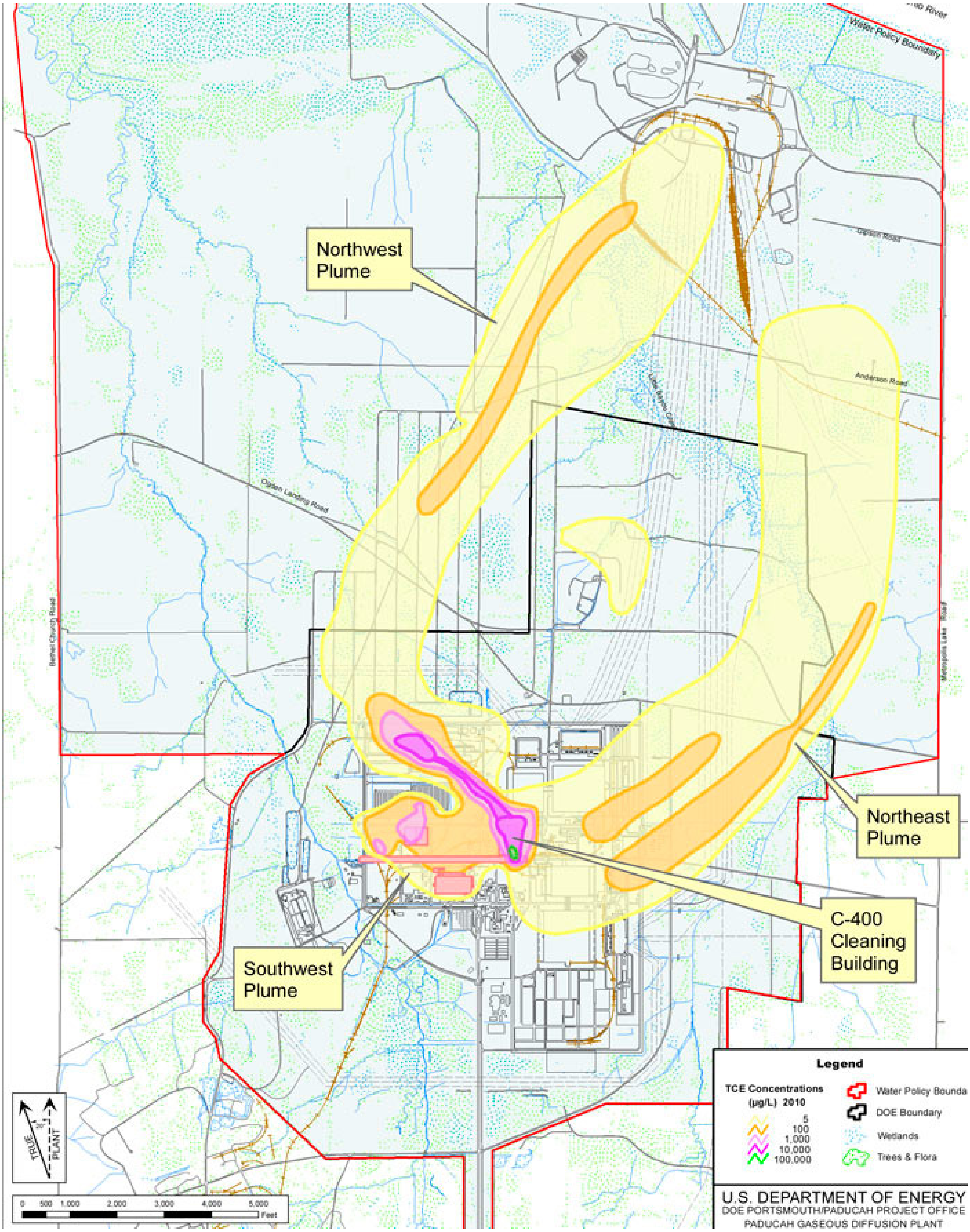


**Figure 44. TCE plumes at PGDP** (DOE 2015c)**.**

Innovations related to hydraulic control of groundwater have included strategies for system optimization (for example, pumping locations and treatment processes), and improved methods for characterization, monitoring and modeling/visualization.

### 6.9.2.2 Source Zone

Removal of primary and secondary sources near the C-400 Cleaning Building has been a primary focus of groundwater project team. Several innovative approaches were tested to determine whether they could effectively remove contaminants from the lower permeability UCRS, the most contaminated areas of the RGA, and the underlying McNairy Formation. Two promising removal technologies, electro-thermal and thermally enhanced steam injection, were tested as pilot projects and deployed at production scale to reduce the source term. These two technologies were useful in removing source contamination from the UCRS, thus limiting future mass discharge to the RGA.

In the 1990s, Monsanto, General Electric (GE), and DuPont developed an electro-thermal remediation process (Lasagna) that applies electrical energy to the subsurface to accelerate contaminant removal and destruction. Lasagna creates an electric field underground via the installation of layered anode and cathode electrodes. This electric current creates osmotic gradients that induce the movement of water through defined treatment zones containing a treatment material such as zero-valent iron. The electric current also heats the soil (through resistive heating), which mobilizes contaminants for treatment or collection. Pilot studies for this technique were deployed in 1995 and 1996 at the Cylinder Drop Test Area (SWMU 91). The pilot studies demonstrated an average TCE removal effectiveness of 95%. The pilot studies also identified several advantages of the method: reuse of infrastructure, minimal or no extraction equipment needed, and low O&M costs. The system was installed using a sheet pile technique that generated minimal wastes.

Lasagna was selected as a full-scale remedy for source area TCE at SWMU 91 and operated for two years following deployment (from 1999 to 2001). The technology was applied to approximately 10,000 cubic yards of low-permeability contaminated UCRS soil containing up to 1,500 mg/kg TCE (indicative of DNAPL). Pilot and full-scale systems reduced TCE soil concentrations from 1,500 mg/kg to 4.5 mg/kg; average TCE soil concentrations were reduced from 84 mg/kg to 0.38 mg/kg. The full-scale technique was more than 90% effective in reducing source TCE, achieved regulatory objectives, and reduced costs by approximately 1/3 compared to identified alternatives.

Electrical resistive heating (ERH) was identified to remediate the primary and secondary source contamination associated with Building C-400. This technology heats the subsurface by applying an electric current between electrodes networked in the target volume. Heat is generated from the resistance to current flow, which increases the vapor pressure and volatility of solvents such as TCE. Volatilized contaminants are then captured using soil vapor extraction (SVE) wells along with groundwater/steam extraction wells. In 2003, PGDP performed a successful small-scale pilot test of ERH and demonstrated that significant amounts of TCE mass could be removed from both the UCRS and the RGA near Building C-400. However, the high hydraulic conductivity in some portions of the RGA (about 425 feet/day) limited the ability to heat the base of the aquifer because the inflow of water. The pilot test results highlighted the need to carefully design ERH for PGDP to make sure that all parts of the RGA could be heated to target temperatures (especially the RGA-McNairy interface in locations, where TCE penetrated to the bottom of the RGA and into the upper portion of the McNairy).

Based on the success of the pilot demonstration, the FFA Core Team selected ERH for full-scale application at the C-400 Cleaning Building. ERH remediation is being performed as a CERCLA §121 Interim Action. The FFA Core Team has emphasized that the C-400 CERCLA Interim Action will mitigate the dominant contaminant sources in the UCRS, RGA and McNairy; this Interim Action is a crucial component and an early focus of PGDP groundwater activities. According to the ROD, the C-400 CERCLA Interim Action has the following site objectives and expectations:

- Contribute to the final remediation of the Groundwater OU by removing a significant portion of the contaminant mass of TCE and other VOCs at the C-400 Cleaning Building.
- Reduce the time that TCE concentration in groundwater remains above the MCL, and meet the statutory preference for attaining permanent solutions through treatment.
- Satisfy the requirements set forth in 40 CFR 430(f)(1)(ii) for interim measures that will become part of the total remedial action that will attain ARARs. As an interim measure, it is not expected to meet MCLs.
- Be cost-effective, based upon the estimates available at the time of the ROD.
- Permanently remove a significant portion of TCE near the C-400 Cleaning Building area through treatment. Hazardous substances, pollutants or contaminants will remain on site at levels precluding unlimited use and

unrestricted exposure.
- Meet CERCLA's preference for remedies that employ treatment as a principal element of the remedy and permanently and significantly reduce toxicity, mobility, or volume of hazardous substances, pollutants, or contaminants.

To ensure optimum performance, the ERH interim action for the VOC source removal near the C-400 Cleaning Building was performed in phases. In 2010, Phase I heated two highly contaminated areas of the UCRS near the C-400 Cleaning Building and a less contaminated area of the RGA adjacent to the southeast corner of the C-400 Cleaning Building. A postoperational review of Phase I ERH performance found that ERH had effectively heated the UCRS and removed the associated source VOCs. However, Phase I data from the RGA indicated that ERH underperformed in the highly permeable formation and did not heat to target temperatures in the lower part of the aquifer.

Based on the Phase I data, the PGDP groundwater project team recommended proceeding with ERH in the highly contaminated UCRS near the southeast corner of the C-400 Cleaning Building (Phase IIA) and developing an alternative approach to address the significant RGA contamination in that same area (Phase IIB). Phase IIA ERH treatment in the UCRS was performed and completed in 2014. Two alternative technologies are being considered for Phase IIB: in situ chemical oxidation (a chemical destruction method) and steam enhanced extraction, which is a thermal method that will likely work better than ERH for permeable aquifers. Preliminary plans for both alternatives have been developed. A treatability study of steam injection to assess the viability of the technology for Phase IIB has been completed, and results are being evaluated by the groundwater project team.

Finally, a separate CERCLA remedial action is underway to remediate VOC sources associated with a 2.2-acre former oil landfarm area. Deep soil mixing was the remedy chosen for the landfarm area. The source removal/treatment makes use of an eight-foot-diameter auger to mix soil to a depth of roughly 60 feet in the remedial area located in the southwestern part of the site's fenced boundary. Steam will be injected through the auger; volatilized TCE will be recovered at the surface and captured in a treatment system. Soil will be mixed, and 0.5 to 2.5 % (weight) zero valent iron will be added to address residual VOC contamination.

Based upon current information, most known VOC source material will have been removed from PGDP soil and groundwater following completion of all phases of this interim action and related decontamination and decommissioning activities for the C-400 Building, implementation of Lasagna at SWMU 91, and soil mixing at former landfarm area.

### 6.9.2.3 MNA

Coupled with hydraulic control and source removal, MNA is integral to effective long-term environmental management of the PGDP groundwater. In 2007, a TCE fate and transport project scoping team (including regulators, DOE, and technical support organizations) was assembled to coordinate the study of TCE migration and controlling processes in the groundwater at PGDP. This team focused on the important site-specific degradation and attenuation processes that impact TCE fate in PGDP plumes and TCE degradation rates for these processes.

Recent and emerging data from diverse sites across the United States (such as the Test Area North Site at the Idaho National Laboratory) suggest that co-metabolism can be a significant TCE degradation mechanism in aerobic oligotrophic (low nutrient) contaminant plumes such as PDGP. The PGDP aerobic co-metabolism assessment was conducted in the Northwest Plume. This assessment was based on enzyme activity probe (EAP) assays supplemented by multiple lines of supporting evidence, including molecular characterization techniques, stable carbon isotope analysis, and geochemical measurements for ten RGA wells that are located along the plume centerline and two control wells located outside the footprint of the Northwest Plume. The various EAP assays each provide a clear, definitive fluorescent signal if a certain oxygenase enzyme is active at the time of analysis. The assays test either for the enzyme that oxidizes methane (soluble methane mono-oxygenase, sMMO) or for one of a suite of enzymes that oxidize aromatic compounds (for example, toluene oxygenases). The specific enzymes that are targeted with EAPs are representative of those documented to break down TCE. These enzymes result in degradation and subsequent mineralization of TCE to end products such as carbon dioxide and chloride ions. If detected, the enzymes are active and capable of co-metabolic degradation of TCE.

Results from the tested wells were as follows: 80% showed significant presence of toluene oxidizers, 50% showed significant sMMO activity, and 90% showed at least one type of oxidizing capability. Data indicated that aerobic co-metabolic activity is occurring throughout the Northwest Plume and is contributing to the attenuation/degradation of TCE. The positive EAP responses in the control wells from outside the plume suggest that there is a widespread potential for the aerobic degradation of TCE. The geochemistry throughout the Northwest Plume was spatially variable, but all the wells had geochemical conditions that are generally consistent with those required for aerobic co-metabolism. Supplementary data confirmed that the groundwater sampled and analyzed for enzyme probe activity primarily represents the groundwater plume (formation water), rather than microcommunities present in specific and individual well casings, or biofilms present therein. In general, the MNA study indicated as follows:

- Bacteria capable of aerobically biodegrading TCE are present in the Northwest Plume.
- The number and distribution of bacteria appear sufficient to contribute to TCE biodegradation in RGA groundwater.
- The microbial community appears to be stable and sustainable.
- Previously estimated degradation rates for PGDP are consistent with the published literature for aerobic co-metabolism in large aerobic plumes, with a half-life in the range of 9 to 25 years. A site-specific study of degradation rates was recommended.

### 6.9.3 Assessment

The overall objective for PGDP groundwater is to remove/mitigate ongoing sources and remediate to below target concentrations of contaminants. Toward this end, DOE and supporting contractors have made extensive efforts to control the migration of contaminated groundwater and to identify, investigate, and remediate sources of groundwater contamination. A successful approach for PGDP groundwater, like other large complex sites, requires a combined remedy that employs several technologies synergistically to effectively achieve remediation objectives.

At PGDP, technologies focused on hydraulic control (groundwater P&T), source removal/destruction (Lasagna, ERH, chemical oxidation or steam enhanced extraction, and deep soil mixing), and natural attenuation. Remediation efforts to date have removed significant VOC contaminant sources and partially mitigated the migration of the groundwater plumes. Efforts continue to understand and control both VOCs and $^{99}$Tc plumes. For example, a preliminary study of the potential VI into nearby structures was recently completed; this study deemed that the VI pathway is incomplete due to the low-permeability UCRS separating the groundwater plume from receptors. Additional studies of the downgradient seep areas (along Little Bayou Creek) are planned to better understand the distal portions of groundwater plumes. Finally, actions are planned to stabilize remaining burial ground areas (continuing through the mid-2020s). These activities will further reduce potential sources and impacts to PGDP groundwater. Table 19 provides an estimate of TCE mass removed by the various remediation actions through March 31, 2015.

**Table 19. Cumulative VOCs removed from subsurface plume and source areas through March 2015** (DOE 2015b)*

| **Source Area** | **VOCs Removed (gal)** |
|---|---|
| Northwest Plume P&T | 3,339** |
| Northeast Plume P&T | 292** |
| C-400 Six-Phase Treatability Study | 1,900 |
| C-400 Phase I | 535 |
| C-400 Phase IIa and Phase IIb | 1,137 |
| Dissolved-Phase Plume | N/A |
| Southwest Plume** | 0 |
| SWMU 4*** | 0 |
| Other sources (such as SWMU 91, LASAGNA™) | 246 |
| **Total** | 7,449 |

*VOC values are primarily TCE and include liquid VOCs and VOCs on carbon.
**Cumulative through December 31, 2014.
***No remedial action tabulated to date.

### 6.9.4 Monitoring/Optimization

Remediation of PGDP groundwater contamination involves both innovative and standard technologies that target contaminant sources and the plume. Standard groundwater monitoring, supplemented by special studies, is used to identify technologies, design treatment systems, and monitor remedial progress.

The PGDP groundwater project team and DOE have focused on periodic optimization, for example, making several adjustments to the groundwater treatment system in the early 2000s to increase efficiency. Additional improvements to the existing hydraulic control (P&T systems) to better control the potential for off-site migration of groundwater contamination are in progress. In the case of ERH, a phased implementation was used to help determine whether the technology could effectively treat the permeable RGA. Based on the data collected during Phase I, the treatment technology for Phase IIB is being modified to provide improved performance in a highly contaminated lower portion of the aquifer.

### 6.9.5 Summary of Alternatives

PGDP has employed a combined remedy approach that provides hydraulic control, source removal, and natural attenuation. The technologies selected include both standard and innovative approaches. A key, site-specific complexity that the selected technologies must address is the geologic setting of a low-permeability interval overlying a highly permeable regional aquifer. In some cases, a different technology is needed for the near-field vadose zone and shallow groundwater versus the deeper regional groundwater. Based on these conditions, the PGDP groundwater project team has prioritized interim actions that focus on source removal to reduce the future reservoir of contamination feeding the RGA.

### 6.9.6 Regulatory and Stakeholder Involvement

Since the initial discovery of site contamination, DOE, USEPA and the Commonwealth have worked with the community to develop a long-term remediation plan for the site. Outreach efforts have included public notices, interviews, and public meetings. PGDP representatives have also held environmental workshops to inform the community of any upcoming public meetings about proposed future remediation plans for the site. DOE also commissioned a Citizens Advisory Board (CAB), which meets monthly to discuss remediation activities and potential health issues associated with past operations and disposal activities at the site. The purpose of the organization is to keep local citizens up to date on site remediation progress and related issues. Both USEPA and KDEP participate in CAB activities.

Through the Federal Facilities Agreement and groundwater project core team, DOE and PGDP contractor/support organizations work with regulators and stakeholders to address soil and groundwater contamination and to develop a risk-based end-state goal for the site.

## 6.10 Velsicol Chemical, Michigan

The Velsicol Chemical site is located in St. Louis, Michigan. In the mid-1930s, the 52-acre site housed a lumber mill, oil refinery, salt processing plant, and chemical manufacturing plant. Michigan Chemical Corporation purchased the property in 1935 and conducted chemical manufacturing from 1936 through 1977. A wide variety of chemicals were made at the site including fire retardants (hexabromobenzene, PBB, and tris (2,3-dibromopropyl) phosphate) and pesticides such as dichlorodiphenyl trichloroethane (DDT) and 1,2-dibromo-3-chloropropane (DBCP). Para-chlorobenzene sulfonic acid (p-CBSA), one of the site contaminants of concern, was a byproduct of manufacturing DDT. In 1965, Velsicol Chemical Corporation gained a controlling interest in Michigan Chemical Corporation. Velsicol Chemical closed the site in 1977 and decommissioned it in 1978. The site was razed and buried in place along with the historical production products, oils, brines, and hazardous waste products, including radioactive and rare earth elements.

### Michigan Chemical Company Fire Retardant Was Mistakenly Distributed as Livestock Feed

*An agricultural disaster 40 years ago decimated 500 Michigan dairy and cattle farms and one Michigan city. In the early 1970s, the fire retardant Firemaster BP-6 (PBBs) was produced by the Michigan Chemical Company (McCarty 2010) of St. Louis, Michigan. MCC mislabeled bags of Firemaster as Nutrimaster and shipped the bags to the Michigan Farm Bureau, who mixed the PBBs with livestock feed. The product was distributed to farms across the state and Midwest. Some 1.5 million chickens, 30,000 cattle, 5,900 pigs, and 1,470 sheep consumed the feed and became contaminated with PBBs. Effects included farm quarantines and the destruction of animal feed, chickens, eggs, and dairy products. Over 9 million Michiganders consumed potentially tainted meat and milk for a year until the mistake was discovered. Generational health effects for Michiganders have been documented but are still not fully known.*

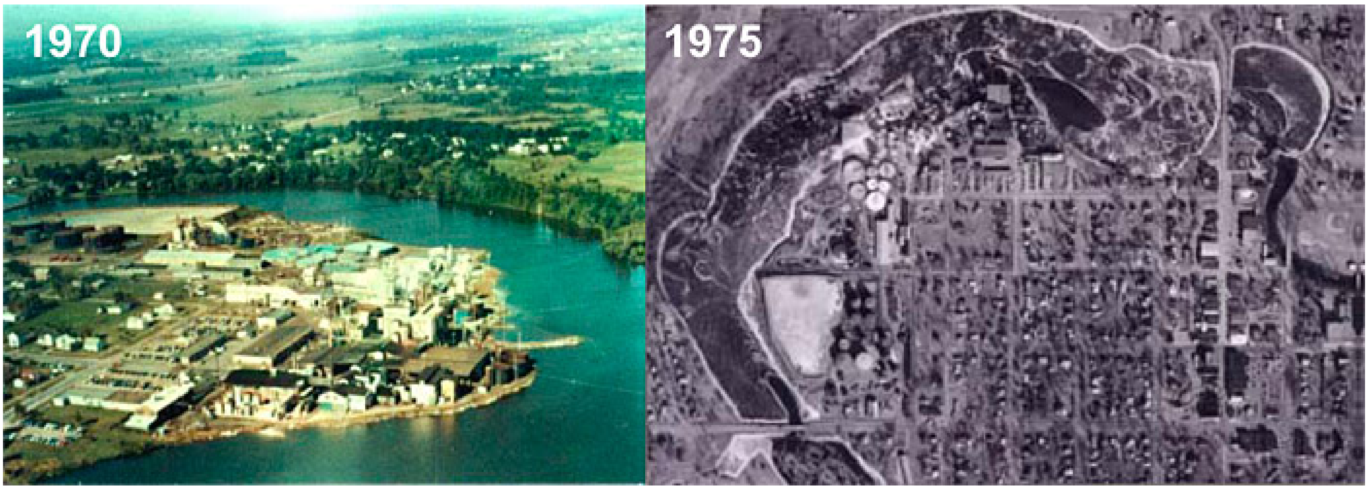



**Figure 45. Aerial photographs of the Velsicol Chemical site** (Pine River Citizen Task Force 2017, E2 Inc. 2004)**.**

Early studies from 1978 to 1980 revealed contamination in site soils, groundwater, river sediments, and fish. To address this contamination, Velsicol, USEPA and the State of Michigan signed a consent judgment in 1982. Velsicol agreed to excavate soils from a nearby Former Burn Area and place them on the main site, construct a slurry wall around the site, and install a clay cap. Velsicol was also released from any liability under CERCLA, RCRA, and state environmental laws for the site, with a limited reopener. The judgement did not require remediation of the contaminated sediments in the Pine River. All the tasks associated with the 1982 consent judgment were completed by 1986.

In 1986, as part of a complicated confidential buyout arrangement, Velsicol Chemical transferred site ownership to a Fruit of The Loom subsidiary, NWI Land Management. Fruit of the Loom agreed to assume 100% of the liability for the site previously owned by Velsicol Chemical in an Assumption and Indemnity Agreement. Velsicol continued to manage the site for Fruit of the Loom under a contract with NWI. Fruit of the Loom filed for bankruptcy in 1999, at which point USEPA learned that Velsicol Chemical did not own the site. In 2002, a bankruptcy settlement vested title to the site in a newly established Custodial Trust, which currently holds the title to the property. Some trust fund money became available through FTL bankruptcy settlements and was used to cleanup waste disposal areas and assist with replacing the city's water supply. However, the site was classified as a Superfund (Fund) Lead site; thus funding is dependent on annual congressional appropriations to Superfund.

Figure 45 shows local and regional connectivity around the Velsicol Chemical site and its proximity to the Pine River, a natural resource that serves as a vital economic and recreational hub. Figure 45 and Figure 46 demonstrate the proximity of the site to the heart of the community and its historical interaction with the Pine River.

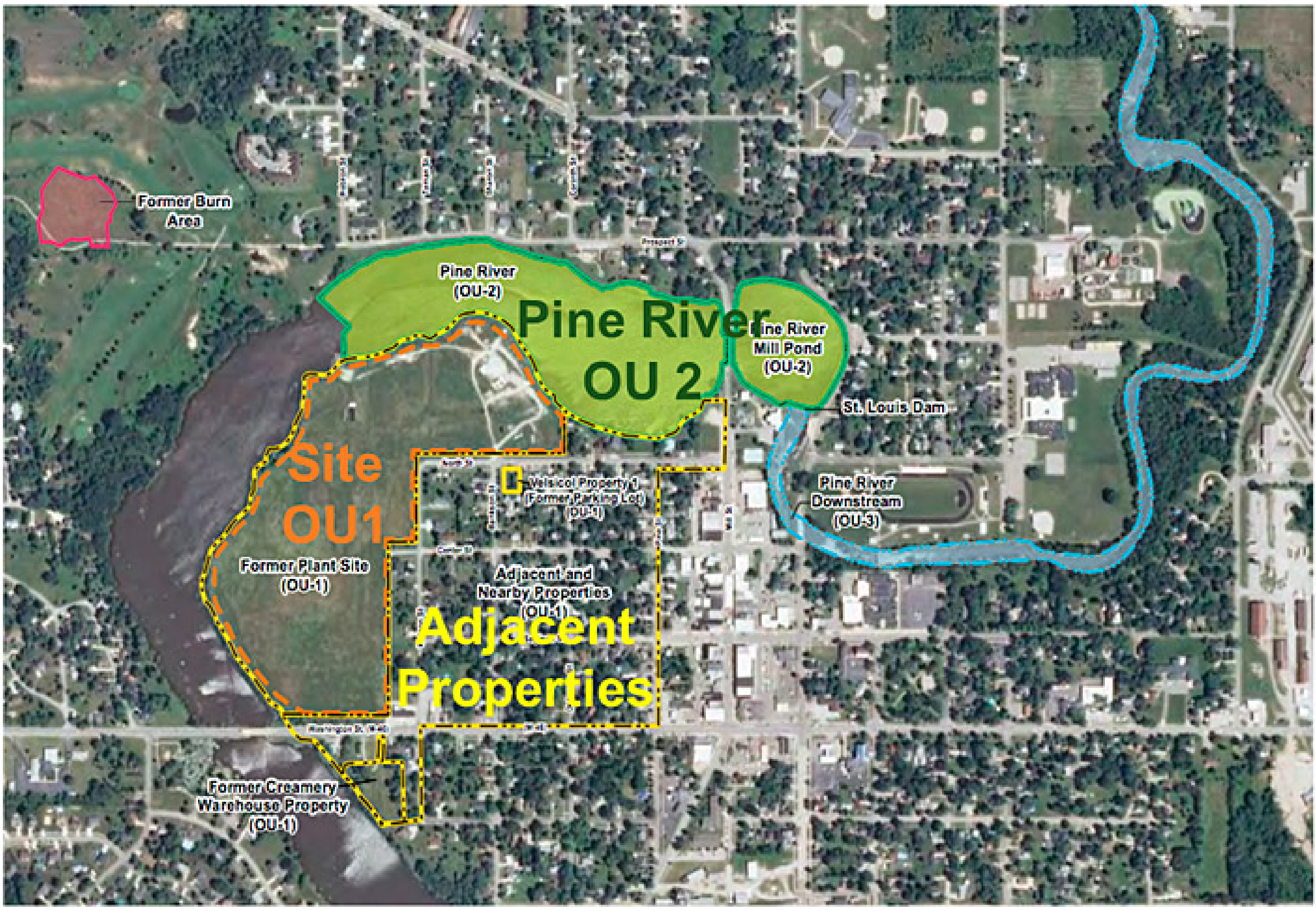



**Figure 46. Velsicol Chemical Site OU 1, OU2 and adjacent or nearby properties in 2002**
([modified from Heidlauf 2017](#)).

The former plant site and adjacent and nearby residential properties are both included in OU 1. Nearby properties are separated from the site by a fence. Some of the residential properties had direct contact exceedances for the site chemicals. DDT was present in the residential soils at concentrations high enough to cause acute DDT brain poisoning in robins. Green areas illustrate areas where contaminated sediments were addressed as OU2. Downstream of OU2 is the Pine River Downstream OU 3 (shown in blue on Figure 46), where ecological risk assessment and studies were conducted. The red area in the northwest corner of Figure 46 shows the Former Burn Area, where chemical production wastes from the site was incinerated using open air burning. The Former Burn Area is now a separate Superfund site.

Two other related sites not shown on Figure 46 received wastes from the site through illegal disposal. These include farmland south of St. Louis, Michigan, in Bethany Township now known as Gratiot County Landfill and a property in Breckenridge, a small community east of St. Louis. Gratiot County Landfill received PBB waste, other plant-derived wastes, and slaughtered livestock. Gratiot County Landfill is now a Superfund site and continues to conduct monitoring, maintenance, and five-year reviews. Velsicol Chemical Corporation disposed of low-level radioactive wastes in shallow burial trenches at the Breckenridge property following then-applicable Atomic Energy Commission requirements. Subsequently, when the Fruit of the Loom Bankruptcy Trust contractor excavated and removed the low-level radioactive compounds following current Nuclea Regulatory Commission requirements, previously unknown and nonpermitted chemical lab wastes were encountered and subsequently removed by an USEPA emergency response contractor.

### 6.10.1 Technical Basis for Remedial Action

The initial CSM suggested that the site was underlain by impermeable clay that would prevent downward migration of leachate. This condition influenced the selection of the basic remedy components in the 1982 consent judgement and these assumptions were used as rationale that the 1982 remedy was working. It is now known that the CSM assumptions were false and were based on a flawed remedial investigation rather than scientific evidence. The clay layer under the plant was later determined to be a highly fractured till permeated with sand and gravel lenses.

The containment system was installed per the specifications described in the consent judgement, and included a low permeability clay cap, slurry wall to contain leachate on site and prevent contaminants from reaching Pine River, and a leachate collection trench to intercept any leachate produced from buried contaminated fluids. Since the level of leachate within the disposal landfill did not exceed the generous remedial action height standard, the remedial action appeared to be effective. In a 1984 report, Velsicol Chemical concluded that site containment had been successfully achieved.

From 1993 to mid-1998, Velsicol pumped groundwater within the slurry wall and disposed of it off site to maintain water levels below levels established by the consent judgement. From 1994 to 1996, USEPA and the Michigan Department of Environmental Quality (MDEQ) noticed increased levels of DDT in fish tissue and sediment in Pine River and began questioning the remedy effectiveness. In 1997, a Final Containment System Assessment Report, commissioned by Velsicol Chemical, detailed the results of the containment system assessment. The report did not document any problems within the slurry wall. The report concluded that 94% of the water infiltrating the cap was migrating vertically through the underlying clay till unit rather than moving laterally through the slurry wall. The report erroneously concluded that the containment system was working as designed.

Several factors explained why little leachate was ever recovered from the collection system. As indicated in the 1997 report, the clay cap was not clay and was not constructed properly; therefore, there was significant recharge to the buried plant site. The city of St. Louis municipal well field had created significant downward heads that were confirmed to be present in shallow, intermediate and deep units that form the semiconfining aquifer characteristics. These downward heads caused site contaminants to move downwards to the city wellfield and contributed to the downward and lateral movement of DNAPL and dissolved-phase chlorinated compounds.

In addition, the slurry wall was not constructed properly and allowed contaminants to discharge directly off site into the Pine River. Slurry wall boring samples were taken in February 2002; photos are shown in Figure 47 and Figure 48. Slurry was found to not be keyed into the underlying clay layer in some areas; deeper sand and gravel deposits were present beneath the base of the slurry wall in those areas. Gaps in the wall explained the extensive seepage and DNAPL exiting the site into the Pine River.

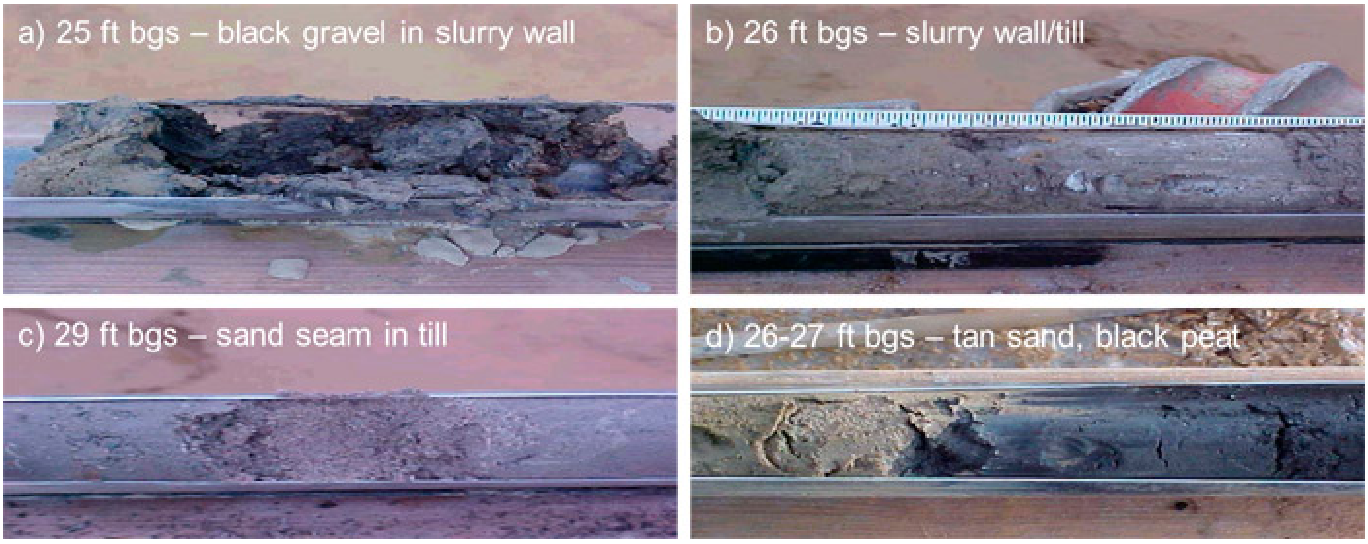



**Figure 47. Boring WPZ-10S and WPZ-11S taken in the slurry wall, illustrating gaps in the wall and variation in slurry placement at different depths below ground surface** (Weston Solutions 2006)**.**

**Figure 48. Boring WPZ-11S from 28-30 ft. bgs, showing the presence of gravel** (Weston Solutions 2006)**.**

Remedial investigations from 2002 to 2012 identified extensive surface and subsurface contamination including soil and groundwater contamination and extensive NAPL and DNAPL pools. An RI report for OU 1 was finalized in 2006. Soils contained DBCP. Contamination is found in the shallow, intermediate and deep aquifer systems. DNAPL has moved through semiconfining units to a depth of 99 feet below the site at a location adjacent to the Pine River (Figure 49).

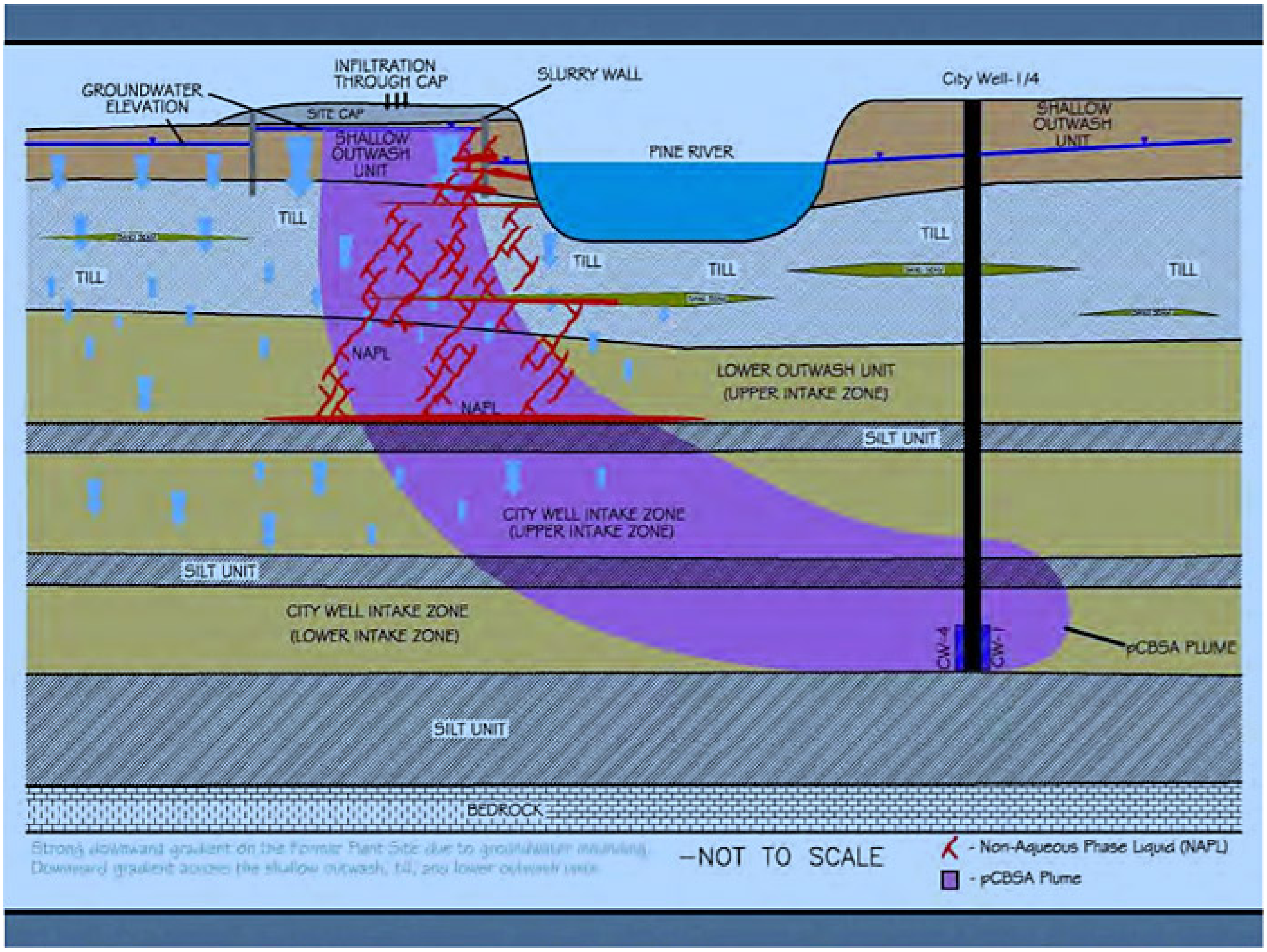



**Figure 49. Conceptual contaminant transport model** (Weston Solutions 2008)**.**

Multiple NAPL and DNAPL disposal areas were identified and found to contain DDT and its congeners. DNAPL was visually identified during soil sample collection and subsequently recovered in quantities from an observation well placed in the saturated unit where DNAPL had been observed. An extensive near-surface DNAPL pool was present close to the Pine River. DNAPL was also present under the Pine River. DNAPL is present in an area of aquifer that transitions from dirty sands to the more permeable regional aquifer system that supplies city drinking water. All remedial investigation wells below semiconfining units had to be double or triple cased to prevent aquifer cross-contamination. A Rotosonic drill was used so that the presence of DNAPL deposits could be observed in the intact sediment core. DNAPL would flow out of the sediment cores. On-site investigation of soils contamination and test pit excavation also identified significant amounts of chlorinated and brominated contamination.

NAPL and DNAPL in the unsaturated zone leached dissolved-phase contaminants into the shallow and intermediate aquifers and to the deep aquifer which was used as a drinking water supply. Leachate was also found to be flowing toward Pine River. Two types of DNAPL were discovered at the site. “Hot Spot NAPL” discovered in 2001 contained approximately 70 to 80% DDT, with approximately 10 to 20% chlorobenzene and lesser amounts of benzene. The second type, called “Area 3 NAPL,” was discovered in 2002 in a remediation cell farther west (upriver) that contained brominated and other halogenated organic compounds.

The extremely high concentrations of DDT and other site COCs in sediments and fish tissue prompted removal actions in Pine River. From 1998 to 2006, over $120 million dollars were spent to address Pine River contamination. Sediment removal was conducted under an emergency removal action from 1999 to 2000 and was conducted as remediation from 2000 to 2006 (Figure 50). During sediment removal from the Pine River, sand and gravel seams within the till were encountered that contained free-flowing NAPL with high concentrations of DDT and chlorobenzene. Some of the river deposits were full of DNAPL.


**Figure 50. Views of the site from across the Pine River a) in 2003 and b) in 2004, following the Superfund redevelopment initiative pilot project** (E2 Inc. 2004)**.**

### Acute DDT Poisoning of Robins

*For years, robins had been dying shortly after their return to the Velsicol Chemical site neighborhood every spring. A resident collected dead robins and took them to the Michigan State Department of Natural Resources Wildlife Disease Laboratory for autopsy. Extremely high concentrations of DDT were found in the robins' brains, spurring a study by toxicologists from Michigan State University, Michigan Department of Environmental Quality, and USEPA. Robins in a nine-block residential area were found to have the highest recorded levels of DDT in brain tissue and acute DDT brain poisoning was found to be the cause of death. This study spurred the ecological cleanup of neighborhood soils as part of the OU 1 ROD.*

Ecological risk assessment and studies are continuing, with a focus on OU3 downstream of the impoundment. Studies will include the synergistic effects of the multiple bioaccumulative contaminants found in the ecosystem. Bioaccumulatives have already been demonstrated to be present in site mammals, fish, and birds. The objective of these continued studies is to determine whether the ecological risk standard used for the impoundment will need to be lowered to protect the downstream ecological receptors.

## 6.10.2 Decision Summary

The 1982 consent judgment between Velsicol, USEPA, and the state of Michigan included the construction of a slurry wall around the site and a clay cap over it. Pine River sediment contamination was addressed at that time by the state of Michigan, which issued a no-consumption advisory for all species of fish in the Pine River—an advisory that remains in effect today. With oversight from USEPA and MDEQ, Velsicol Chemical then constructed and installed a containment system. The slurry wall was set back approximately 50 to 140 feet from the bank of the Pine River. Velsicol Chemical was required to maintain groundwater levels inside the slurry wall and beneath the cap to a specified elevation (724.13 feet above mean sea level).

The Former Burn Pit, which had been used for open air burning of hazardous NAPL and DNAPL wastes, was remediated in the early 1980s. Velsicol's remediation contractor excavated visibly impacted soils from the Former Burn Pit and placed them on top of the main plant site area that was to be capped. These soils contained concentrations of multiple chlorinated compounds well above groundwater protection criteria. At that time, USEPA did not proceed to nominate the Former Burn Pit as a Superfund site. Subsequent investigations performed by the state of Michigan found volatile exceedances of cleanup criteria in near surface soils and extensive DNAPL deposits at depth. After the community pointed out that the Former Burn Pit had been delisted without ever being listed in the first place, USEPA reviewed the data and the Former Burn Pit was added to the NPL. The Former Burn Pit ROD identified thermal treatment to address DNAPL at depth, followed by groundwater monitoring to determine thermal treatment effectiveness.

USEPA funded sediment cleanup and removed over 750,000 cubic yards of DDT-contaminated sediment, which was disposed of in an approved off-site landfill. Dry sediment removal was conducted by driving interlocking sheet piling down the center of impoundment zones (shown in green on Figure 46), dividing, and dewatering half of the Pine River and performing sediment removal actions. Once completed, river flow was restored on the remediated side and the other, contaminated, side was dewatered so that dry excavation activities could be completed. As a result, DDT levels in fish tissue decreased by over 98 percent, downstream of the city dam. The state of Michigan plans to keep the fish advisory in place until the entire site has been remediated.

In response to discovering migration through the slurry wall, USEPA undertook an interim response action in 2002 to prevent recontamination of the Pine River by future migration of DNAPL and contaminated groundwater from the site. Collection trenches were constructed in the top of the till unit underlying sediments along the Pine River shoreline where DNAPL had been observed. In addition to the collection system, a layer of compacted clay at least two feet thick was placed on the till unit to cap areas within the sediment removal cells where DNAPL-impacted till remained (Figure 51).

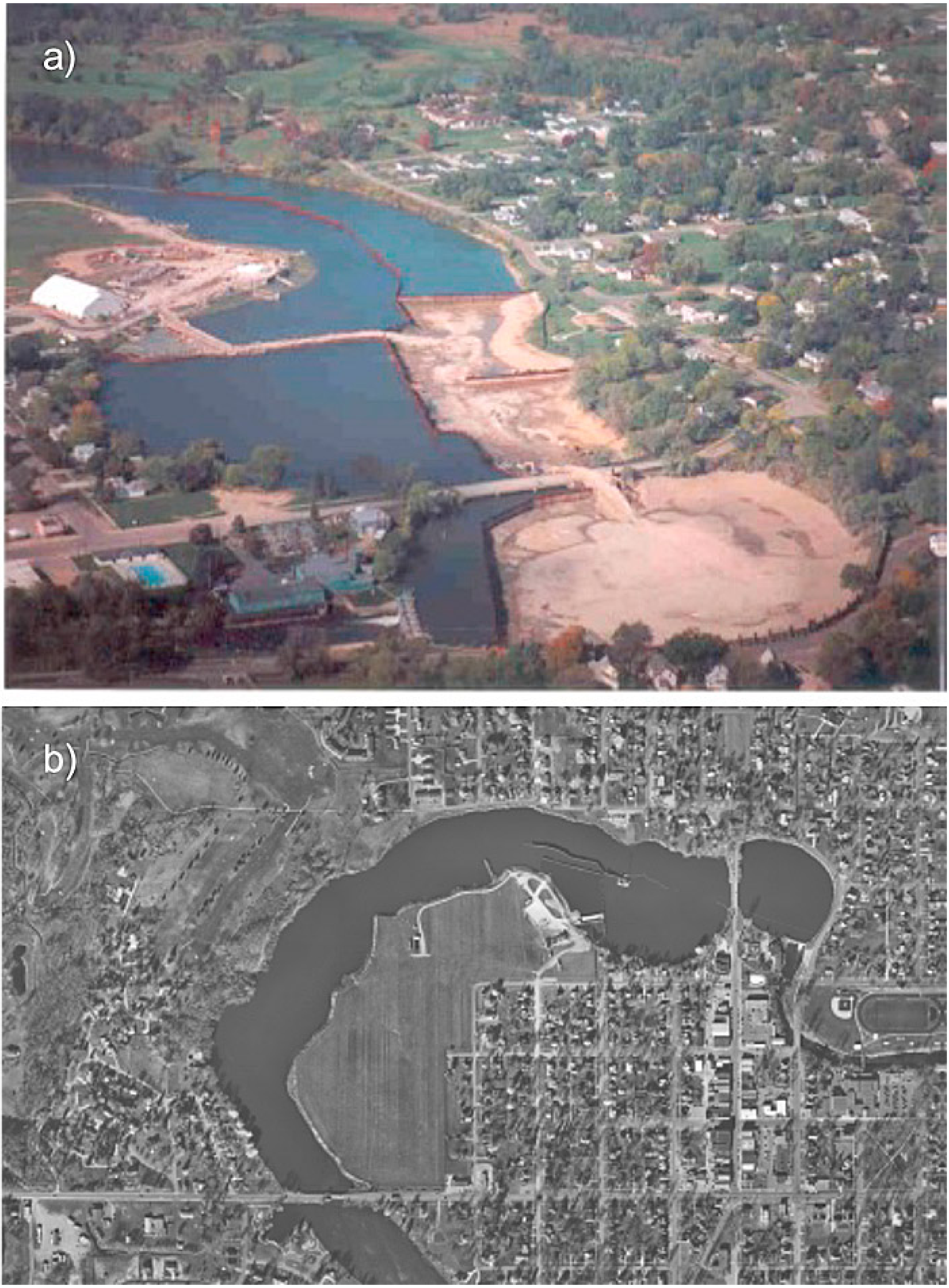



**Figure 51. Aerial photographs of the site a) during sediment removal in 2002 and b) after sediment removal, showing cap cover** (E2 Inc. 2004, modified from Heidlauf 2017)**.**

Following a detailed FS report in 2011, USEPA selected a final remedy for OU 1 in June 2012. The final remedy includes both the cleanup of contaminated soil in residential areas and comprehensive site cleanup. The remedy centered on significantly reducing the risk of site-related contaminants migrating to the Pine River. Remedy components included the following:

- Excavate and remove on-site sources of concentrated contamination where practical; use in situ thermal treatment or in situ chemical oxidation in areas where removal is not practical.
- Install sheet piling to separate the impoundment from site wastes.
- Operate the leachate collection system inside of the site wall and keep leachate levels consistently below the elevation of the Pine River.
- Continuously operate a groundwater P&T system to reduce off-site groundwater contamination and to control the loss of dissolved-phase contaminants from DNAPL pools residing under the Pine River.
- Restore aquifers beyond the site boundaries, except for aquifers under the Pine River impacted by DNAPL. A TI waiver was used to acknowledge that the groundwater under the river and near the DNAPL pools would not be remediated to drinking water standards.

The full extent of DNAPL under the Pine River has not been investigated or characterized. The removal of 3,000 gallons of product from an open pit, where it accumulated, did not reduce or change the DNAPL elevation. Extensive deposits of DNAPL are therefore present under the Pine River. The ROD stated that DNAPL pool remediation was technically impracticable. DNAPL is collected from the trench when the site remedy is operational. Currently, both NAPL and dissolved-phase groundwater is collected from the trench and is sent off site for disposal. It is assumed that the dissolved-phase contaminants in the permeable sand and gravel lenses in the till will be captured and controlled by a site groundwater P&T system that has yet to be installed. By 2016, soil removal actions from residential areas were complete.

The risk to the city drinking water supply was addressed by shutting down the city well field and bringing in a source of clean water for the city residents. The new water supply was brought on line in the fall of 2015. When the city well field was shut down, the area rapidly returned to flowing (artesian) conditions. Residential wells at the city limits are now flowing. The rapid return to flowing conditions was not anticipated since expectations were that the aquifer would never flow again. These conditions are expected to be alleviated when the site P&T system goes on line. However, as there are no funds to implement the remedy, these conditions may present to new risk to Pine River and city residents. It is too soon to know if there will be new contamination problems due to the rapid rise in head levels under the city. USEPA and MDEQ are also in the process of completing remedial investigation downstream of the former chemical plant property for the new operable unit, OU 3.

### 6.10.3 Community Involvement

The community has been involved with the cleanup process since cleanup work began on the former Velsicol Chemical Corporation site. Over the past several years, USEPA and MDEQ have taken steps to increase communication with the city, Community Advisory Group (CAG), and community members. The CAG, formally known as the Pine River Superfund Citizen Task Force, was formed in 1997 by residents in and around St. Louis to connect community members with government and technical experts. The CAG holds monthly meetings and maintains a website with overviews of the community's experiences with the site. USEPA and MDEQ attend these meetings to provide site-related updates, answer questions, and address concerns.

The MDEQ and USEPA have conducted multiple rounds of community interviews with St. Louis residents as well as with CAG members to gain insight into the community's primary concerns, how they viewed engagement efforts, and how USEPA's community involvement plan (Participedia 2017) could be improved. The responses have informed updates to the CIP which was written to outline ways to enhance community engagement in decisions about the site.

Community engagement is an important component of ongoing cleanup efforts. USEPA actively communicates with residents throughout the cleanup through regular public meetings, newsletters and email updates. During the removal action, USEPA developed an excavation plan based on residents' input concerning dust, noise, and traffic disruptions; the plan included steps for dust suppression, air monitoring, and treatment and control of toxic surface and groundwater. The residential cleanup required removal of contaminated soil from private properties, which necessitated extensive communication between USEPA and property owners. After the contaminated soils were removed, the properties were relandscaped with new sod, trees, and flowers. USEPA and MDEQ continues to work closely with the community as cleanup continues and work with the City on opportunities for redevelopment of the former plant site.

Printed from: Interstate Technology & Regulatory Council (ITRC). 2017. *Remediation Management of Complex Sites*. RMCS-1. Washington, D.C.: Interstate Technology & Regulatory Council, Remediation Management of Complex Sites Team. http://rmcs-1.itrcweb.org.

## 6.11 Onondaga Lake, New York

Onondaga Lake is located along the north side of the City of Syracuse in Onondaga County, New York. The lake itself covers an area of 4.6 square miles, has an average depth of 35 feet, and a maximum depth of 63 feet. Its drainage basin covers approximately 285 square miles. The lake flows into the Seneca River, then into the Oswego River, and ultimately into Lake Ontario. Nine Mile Creek and Onondaga Creek together account for 70% of the lake inflow. The Metro Wastewater Treatment Plant (Metro) located on the south side of the lake supplies another 20% of Onondaga Lake inflow. Figure 52 shows the lake, tributaries and some of the sites. Pollution in Onondaga Lake comes from three main sources dating from the 1880s forward: industrial discharges, municipal wastewater effluent, and stormwater runoff. The Onondaga Lake Superfund site consists of the lake itself, seven major and minor tributaries, and twelve upland sources of contamination to the site (called subsites). The twelve subsites are listed below, along with the responsible party name for each, and are shown on Figure 53.

- Onondaga Lake Bottom (Honeywell from Solvay and AlliedSignal)
- Geddes Brook/Ninemile Creek (Honeywell from AlliedSignal and Linden Chemical and Plastics)
- Willis Avenue (Honeywell from AlliedSignal, chlorobenzene DNAPL)
- LCP Bridge Street – OU 1 (AlliedSignal sold to Linden Chemical and Plastics (LCP) who later filed for bankruptcy; responsibility for the site's cleanup reverted to Honeywell)
- Wastebed B/Harbor Brook (Honeywell from Solvay)
- Semet Tar Beds (Honeywell from Semet-Solvay; tar wastes with pH <1 from a benzol production plant disposed over Solvay Wastebed A)
- Town of Salina Landfill (municipal and industrial landfill, and Ley Creek PCB sediment dredgings)
- Lower Ley Creek (several upland sources have contributed contamination; the most significant sources are the General Motors Inland Fisher Guide (IFG) Facility/Ley Creek Deferred Media, Ley Creek PCB Dredgings and Salina Landfill subsites).
- Ley Creek PCB Dredgings (General Motors, Carrier Corp., Syracuse China, Cooper Crouse-Hinds, Town of Salina, Onondaga County, Oberdorfer Inc., and National Grid)
- General Motors – Inland Fisher Guide/Deferred Media (General Motors)
- National Grid – Hiawatha Boulevard (Niagara Mohawk – Syracuse MGP)
- Wastebeds 1-8 (Honeywell from Solvay, 400 acres)

Two additional polluted sites (Wastebeds 9-15 that cover 663 acres and LCP Bridge Street – OU 2) are being remediated by Honeywell under state of New York enforcement agreements. The Onondaga Lake Superfund site is being addressed through federal, state, and potentially responsible party actions pursuant to enforcement agreements with New York State Department of Environmental Conservation (NYSDEC). NYSDEC is the lead agency for the lake bottom cleanup and all but one of the subsites. USEPA is the lead agency for the remaining subsite, Lower Ley Creek.


**Figure 52. View of Onondaga Lake, showing important tributaries, contaminated waste sites, wetlands and landmarks (facing north)** (TAMS Consultants Inc. and NYSDEC 2002)**.**

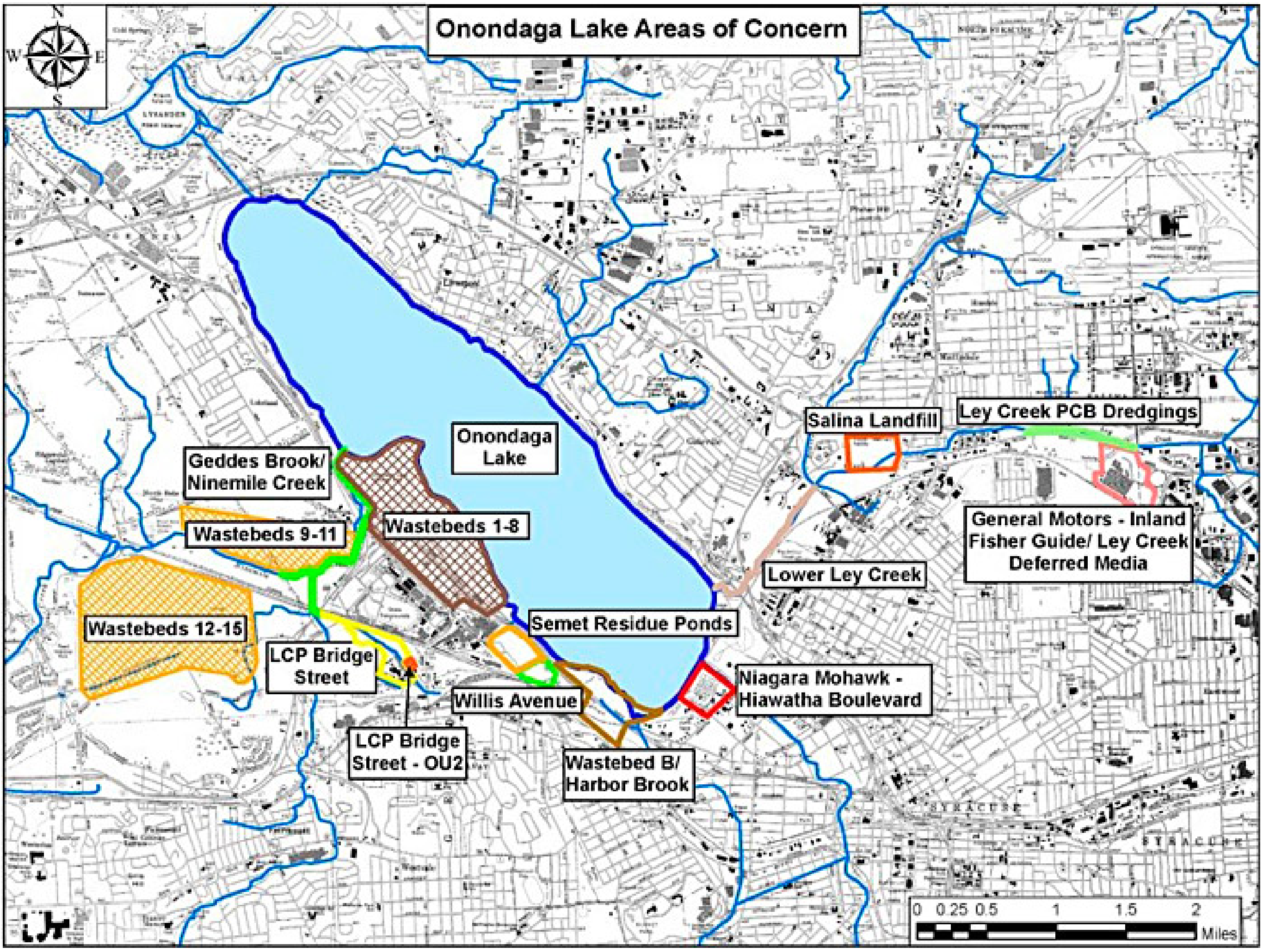



**Figure 53. Onondaga Lake areas of concern** (NYSDEC 2017)**.**

Onondaga Lake suffers from three principal impacts: industrial/chemical discharges that began in the late 1880s, municipal sewage wastes, and stormwater runoff. From 1946 to 1970, approximately 165,000 pounds of elemental mercury were reportedly discharged to the lake. Sediments were contaminated with PCBs; pesticides; creosotes; heavy metals including lead, cobalt, and mercury; polycyclic aromatic hydrocarbons (PAHs); and VOCs such as chlorobenzene. Groundwater at many of the upland source areas was also contaminated with mercury, VOCs, PAHs, metals, and inorganics from the Solvay waste. Several species of fish native to the lake have elevated concentrations of mercury. Ecological and human health risk assessments conducted for the Lake Bottom subsite indicated that contaminants associated with the lake sediments resulted in risks which exceeded threshold levels to the ecological community and potentially to people who consume fish caught from the lake.

Ammonia and phosphorus in sewage from Onondaga County-owned Metro contributed to impacts on fish migration and reproduction, led to algal blooms and poor water clarity, and decreased oxygen levels. In addition to the ammonia and phosphorus, stormwater runoff entering Syracuse's combined sewer system overwhelmed the system during heavy flows and sent untreated sewage and stormwater to Onondaga Lake's tributaries. These combined sewer overflows (CSOs) are a major source of bacteria, trash, organic material, solids and grit. Stormwater runoff in the Onondaga Lake watershed also carries pollutants to the lake and its tributaries. Pollutants include sediment from the Tully Valley mudboils, salt from highway ice removal, fertilizers and pesticides from lawns, gardens and farms, animal waste, and debris and floating trash from nearby streets (NYSDEC 2010).

Onondaga Lake has received industrial and municipal sewage discharges for more than 100 years. Honeywell International, Inc.'s (Honeywell's) predecessor companies (Solvay Process Company, Allied Chemical Corp. and AlliedSignal, Inc.) have been major industrial waste contributors; other industries in the area contributed contamination as well. Other contaminant sources to the Lake include the Metro facility, industrial facilities and landfills along Ley Creek, the Crucible Materials Corporation (via Tributary 5A), and the former giant bulk petroleum-products storage and transfer facility located north of the Barge Canal known as “Oil City.”

Major products manufactured during this period included soda ash (sodium carbonate) and related products; benzene, toluene, xylenes, naphthalene at the Syracuse Works’ Main Plant; chlorinated benzenes, chlor-alkali products, and hydrochloric acid at the Willis Avenue Plant; and chlor-alkali products and hydrogen peroxide at the Bridge Street Plant. The manufacturing processes resulted in releases of primarily mercury, BTEX, chlorinated benzenes, PAHs (especially naphthalene), PCBs, polychlorinated dibenzo-p-dioxin/polychlorinated dibenzofurans (PCDD/PCDFs), and calcite-related compounds (USEPA 2015c).

Wastes were discharged to Onondaga Lake via the East Flume and West Flume/Geddes Brook/Ninemile Creek, the Solvay wastebeds and Semet Residue Ponds. The wastebeds were the primary means of disposal of inorganic waste from the production of soda ash. Initial Solvay waste disposal practices consisted of filling low-lying land adjacent to Onondaga Lake. Later, disposal areas were built using containment dikes constructed with native soils, Solvay waste, and cinders, or bulkheads made with timber along the lake shore. The Solvay wastebeds and the East Flume also reportedly received chlorinated benzene still bottoms and portions of waste streams from the Willis Avenue and Bridge Street chlor-alkali plants (Figure 54).

Municipal sewage waste and CSOs discharges historically went to Onondaga Lake. Metro (see Figure 53 for location) has (1) upgraded to secondary and tertiary treatment (phosphorus reduction of 86%), (2) by 2010 reduced CSOs by an 85% volume, and (3) added green infrastructure to capture and reuse stormwater runoff. Ammonia and phosphorus concentrations in the lake have since declined significantly. Since 2007, the lake has been in full compliance with ambient water quality standards for ammonia and was officially delisted for that parameter in the state’s 2008 list of impaired water bodies. The lake is still impaired for mercury and fish advisories remain for PCBs, mercury, and dioxin.

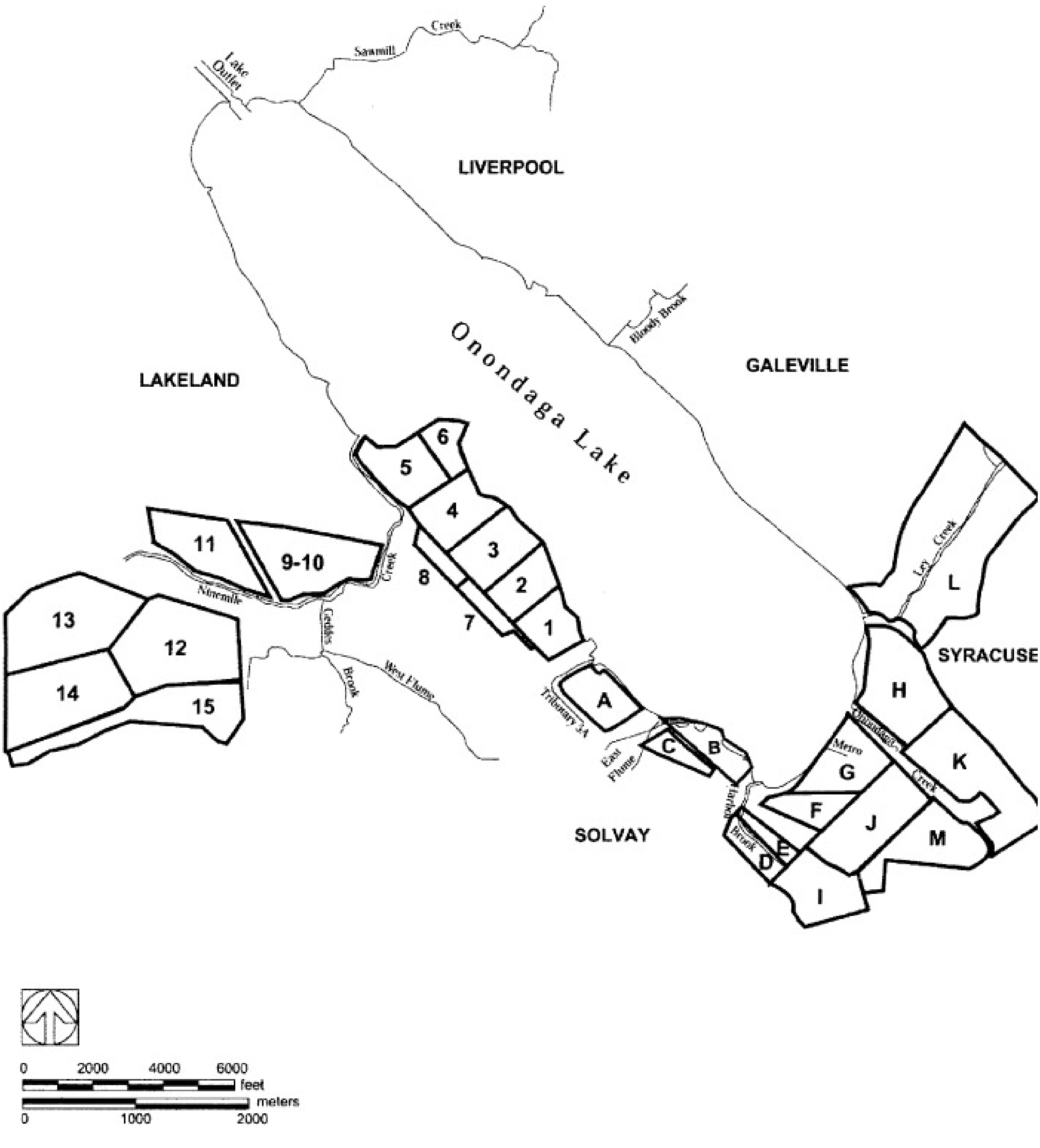



**Figure 54. Historical locations of Solvay wastebeds** (NYSDEC 2005)**.**

Stormwater runoff (also known as nonpoint source pollution) has also contributed to poor lake water quality. Land use activities in the watershed include agriculture (soil erosion, manure, fertilizers, pesticides), urbanization (litter/street debris, petroleum products/metals from roads, salt from highway ice removal, lawn fertilizer, pesticides) and construction (runoff/erosion during construction). Stormwater trash removal is now provided by vacuum truck for the stormwater catch basins and by skimmer vessels from the Inner Harbor. The Onondaga County Soil and Water Conservation District oversees the Environmental Management Program within the Onondaga Creek and Ninemile Creek watersheds to reduce farming related impacts. Other local efforts have provided stream bank stabilization, switching to phosphorus-free fertilizers and measures to control stream bank erosion and runoff.

Natural mudboils produced by artesian groundwater within the Tully Valley impact the lake water quality, clarity, and aquatic habitat for insects, fish spawning, and plant growth along Onondaga Creek, the Inner Harbor, and Onondaga Lake. Mudboils are volcano-like cones of sediment one to several feet high and up to a diameter of 30 feet. The very fine clay and silt sediment load from the mudboils flows into Onondaga Creek, which flows north to Onondaga Lake and contributes half of the lake sediment load. The source of the mudboils is an 80 foot-depth semiconfined aquifer whose pressure is controlled by precipitation seasonal recharge. Seasonal variations increase/decrease artesian pressure and the mud flow discharge rate increases/decreases accordingly. The artesian head in Tully Valley aquifer was about 20 to 30 feet above land surface in 2014.

### 6.11.1 Technical Basis for Remedial Action

An RI was completed in 2002. Mercury contamination is found throughout the lake, with the most elevated concentrations detected in sediments in the Ninemile Creek delta and in the sediments and wastes present in the southwestern portion of the lake. Other contaminants present within Onondaga Lake sediments are primarily found in the southwestern portion of Onondaga Lake.

Glaciers carved the hills and valleys to the Upper Silurian through Middle Devonian bedrock, and upon retreat deposited a mixture of unconsolidated glacial sediments in Onondaga Valley, leaving Onondaga Lake and scattered moraine deposits. Industrial operations and waste discharges have impacted the sedimentary deposits, groundwater, stream and lake sediments, and surface water of feeder streams and Onondaga Lake.

The geology is highly variable, and consists of noncontinuous sedimentary layers of fill material, a marl/peat layer, silt and clay, fine sand and silt, sand and gravel, till, and bedrock. The fill ranges from 5 to 40 feet thick and consists of broken brick, cinders, gravel, crushed limestone, sand, and ash. In some locations, the fill is interlayered with Solvay waste. At some places, the fill material lies directly on the till or bedrock. Groundwater has been defined as shallow, intermediate, and deep. Where present, the low permeability silt and clay layer acts as a confining layer for the deep hydrogeologic unit that exhibits artesian water pressure.

### 6.11.2 Decisions

In 1988, Atlantic States Legal Foundation filed suit against Onondaga County for Clean Water Act violations. A Consent Judgment dated February 1, 1989, required Onondaga County to perform studies to evaluate the need for upgrading Metro and for providing treatment of CSOs. In 1989, the state of New York filed a lawsuit in federal court against Allied-Signal Inc. (a predecessor company to Honeywell) for pollution violations and resource damage. In 1992, (1) the U.S. Army Corps of Engineers completed the Onondaga Lake Water Quality Technical Report with lake remediation alternatives, (2) the Onondaga Lake Management Conference funded a USGS study of the Tully Valley mudboils, and (3) a federal court approved a consent order for study of industrial pollution and development of a cleanup plan. In 1993, the Onondaga Lake Management Conference (OLMC) drafted “A Plan for Action” to become the basis of the Onondaga Lake Management Plan (OLMP). In 1999, the Onondaga Lake Partnership, led by the U.S. Army Corps of Engineers, was tasked with implementing lake improvement projects consistent with the OLMP and the 1997 Amended Consent Judgement.

In 2005, NYSDEC issued a ROD for the Onondaga Lake Bottom NPL Subsite. Honeywell entered into a Consent Decree with NYSDEC in 2007.

Court-ordered studies, studies by the USGS and U.S. Army Corps of Engineers, and potentially responsible party RI/FS documents have provided the data and resources supporting remedy evaluation and selection. The remedies have been selected by the state of New York, supported by USEPA Region 2, and documented using RODs and Consent Agreements. Pilot and treatability testing have been used to validate selected technologies and optimize full-scale remedy design. Five-Year Reviews are conducted to monitor continued protectiveness over the long-term. As of 2010, RODs have been signed for cleanup plans at ten Superfund subsites.

The Onondaga Lake Superfund site is being addressed through federal, state, and potentially responsible party actions pursuant to enforcement agreements with New York State. New York State is the lead agency for the lake bottom cleanup and all but one of the subsites. USEPA is the lead agency for the remaining subsite, Lower Ley Creek. USEPA provided approximately $16.5 million to the state, through a cooperative agreement, for the performance of RI/FS activities, coordination and management of the independent subsite studies, oversight of PRP-conducted activities, implementation of a site-wide citizen participation program, creation and maintenance of a site-wide data base, and establishment of a comprehensive enforcement program. Other lake partners include the City of Syracuse, County of Onondaga, and the U.S. Army Corps of Engineers.

### 6.11.3 Assessment

The Onondaga Lake Superfund cleanup is being addressed in two stages: 1) interim remedial measures (IRMs) and 2) long-term remedial actions focusing on cleanup of the subsites. IRMs undertaken at the site include: removing chlorobenzene DNAPL from existing wells; retrofitting existing on-site sewers; on-site demolition, removal, decontamination and recycling of former mercury cell processing buildings and building materials; cleaning storm drainage systems; investigation of berms surrounding the Semet Tar Ponds; design and construction of a 7800-foot lakeshore barrier wall and groundwater collection/treatment system (Willis Avenue); and removal of contaminated sediments and floodplain soils from Geddes Brook and the East Flume. More details are below for each subsite.

*Onondaga Lake Bottom Subsite.* 2.2 million cubic yards of contaminated wastes/lake sediment were dredged between 2012 and 2014 with disposal at a Sediment Consolidation Area containment facility. Isolation and thin-layer capping of approximately 475 acres of lake bottom was completed in 2016. Following a three-year in-lake pilot study conducted between 2011 and 2013, addition of calcium nitrate on the lakebed in the deep-water portion of the lake began in 2014 to inhibit methylmercury (MeHg) production. Since 2009, MeHg in the lake has been reduced by and estimated 98%. According to USEPA's First Five-Year Review Report released September 2015, implementation of the remedy is progressing as expected.

Based upon the results of this first five-year review, USEPA concluded as follows:

- Concentrations of dissolved mercury are significantly lower in surface water samples collected between 2008 and 2014 relative to samples collected during the RI. This result is likely attributable to reductions in mercury loading to the lake from external sources such as tributaries and groundwater. Further reductions in dissolved mercury are expected from the implementation of the selected remedy.
- As a result of Metro upgrades and adding diluted calcium nitrate near the sediment/water interface in the deep-water portions of the lake since 2011, MeHg concentrations in lake water and in zooplankton have declined dramatically. Lower MeHg exposures from the water column and through the food chain are expected to contribute to lower mercury concentrations in fish.
- The combination of lower than projected concentrations of mercury in surface sediment and settling sediments, and higher average annual sedimentation rates than the rate assumed in the Final Design indicate that natural recovery in the lake is progressing faster than predicted.
- Due to the scheduling of various aspects of the remedial program and the nature of biological systems, it is premature in this first five-year review to determine whether the remediation has achieved the goals for mercury in fish tissue identified in the ROD.
- Future five-year reviews will have the opportunity to review data over sufficiently long time frames to determine the extent of compliance with the goals in the ROD.

*Geddes Brook/Ninemile Creek Subsite*. An IRM removed 117,000 cubic yards of contaminated sediment and floodplain soil from Geddes Brook, a tributary to Ninemile Creek, which was impacted by mercury transported from the LCP Bridge Street subsite, between May 2011 and February 2013. The 16-acre wetland complex has been vegetated with nearly 90,000 native trees, plants and shrubs and is now supporting more than 80 species of fish, birds and mammals.

*Willis Avenue Subsite*. Several IRMs have been completed for the chlorobenzene/chlorinated benzenes, and benzol production tar recovery of DNAPL that migrated to the lakeshore, a barrier wall, and a groundwater collection/treatment system (Willis/Semet GWTP processes 600 gpm) for caustic groundwater of pH>11 and contaminants related to the mercury cell, chlorinated benzene products, and Solvay processes. The effluent of the GWTP is discharged to Metro for further treatment. The 2014 RI/FS documented remaining soil contaminated with mercury, TCDD/furans, Aroclors 1254 and 1260s, and phenolic compounds.

*LCP Bridge Street – OU 1 Subsite.* CERCLA IRM actions included removal of tanks, containers, and transformers; building demolition; sediment excavation and restoration of the West Flume and wetlands; soil washing, which reclaimed approximately 8 tons of elemental mercury; soil excavation of the Brine Mud Area and North Ditch; excavation of pipes and sewers and plugging the downgradient ends of these sewers, which provided preferential pathways for contamination to enter into the West Flume and East Ditch; and installation of a 50 foot deep slurry wall, groundwater collection and cap system for the contaminated soil (USEPA 2010c). The Diaphragm and Mercury Cell building demolition IRM consisted, in part, of removing and recycling elemental mercury from cells inside the Mercury Cell building, followed by its decontamination and demolition.

*Wastebed B/Harbor Brook Subsite.* An underground steel barrier wall was constructed as part of an IRM. The barrier wall intercepts contaminated groundwater and chlorinated benzene DNAPL for treatment/separation. An RI/FS investigation is ongoing.

*Semet Tar Beds Subsite*. Cleanup activities to date have included placement of an isolation layer beneath the Tributary 5A stream bed and construction of a groundwater collection system and on-site groundwater treatment plant. All major groundwater-related cleanup activities were completed in 2013. Additional IRMs have been completed to (1) clean and rehabilitate the I-690 storm drainage system, including adding an underdrain isolation system, located downgradient of the Semet Residue Ponds and Willis Avenues sites, (2) identify and investigate seeps in and around the berms which enclose the Semet Residue Ponds, (3) prevent human exposure to the seeps, and (4) provide engineering details as to the structural integrity of the berms. A study to evaluate potential remedial cleanup options for the Semet Residue Ponds material is ongoing as of 2015.

*Town of Salina Landfill Subsite.* A waste consolidation of the five-acre landfill to the top of the main 50-acre landfill located north of the Creek and landfill cap was completed in 2013. A system to pretreat the contaminated groundwater/leachate collected from the closed landfill is expected to be completed in late 2014. The pretreated groundwater/leachate will be conveyed to Metro.

*Lower Ley Creek Subsite*. Per the OU 25 ROD issued September 2014, PCB-contaminated soil and creek/wetland sediment will be excavated and disposed as appropriate for the PCB concentration, providing clean backfill, and vegetation per the habitat restoration plan, an IC restricting intrusive activities and commercial/industrial use will be executed, and a Soil Management Plan will be developed. PCBs are the main COCs but PAHs, mercury, chromium and arsenic are also present. Benzo(a)pyrene and dioxin are considered contaminants of potential concern (COPCs).

*Ley Creek PCB Dredgings Subsite.* In 2001, historical spoil TSCA PCB dredgings left on the banks of Ley Creek were removed and properly disposed and a clean soil cover was installed over the remaining dredge spoils. Requires cover maintenance and five-year reviews.

*General Motors – Inland Fisher Guide Subsite.* Completed IRMs include (1) capping an industrial landfill containing chromium and PCB waste; (2) removal of 26,000 tons of PCB highly contaminated soil from a liquid process waste discharge swale to Ley Creek; (3) construction of a retention pond to collect all water that accumulates on the IFG property in the former storm sewers and abandoned process sewers; and (4) water treatment system prior to discharge to Ley Creek. The RI/FS is in progress for the facility and groundwater.

*National Grid – Hiawatha Boulevard Subsite.* Between September 2001 and May 2002 an IRM at the Syracuse Former Manufactured Gas Plant (MGP) subsite included excavation and removal of wood foundation pilings associated with former MGP structures and approximately 73,000 cubic yards of contaminated soils beneath the footprint of an Onondaga County sewage treatment facility upgrade.

*Wastebeds 1-8 Subsite.* These Solvay wastebeds cover approximately 400 acres. DEC issued remedial action plans in 2014. The plans call for installation of cover systems and planting native vegetation. A 17,500-seat Lakeview Amphitheater was built on a portion of the site in 2015. Additionally, just over three miles of a groundwater collection system has been installed on the western shoreline (including collection systems installed at this site, as well as Semet Residue Ponds, Willis Avenue, and Wastebed B/Harbor Brook sites). The systems collect contaminated groundwater so that it does not enter the lake and send it to Honeywell's Willis Avenue Groundwater Treatment Plant for treatment (NYSDEC 2017).

*LCP Bridge Street OU2 Subsite.* A former hydrogen peroxide plant was located on this 1.6-acre area (USEPA 2010c). The selected remedy includes injection of chemical oxidants into the ground to treat the contaminated soil and groundwater; construction of a cover to prevent contact with contaminated soils and migration via stormwater runoff; development of a site management plan; long-term monitoring: and an IC to (1) limit the use and development of the property to commercial/industrial use; (2) insure compliance with the site management plan; and (3) restrict the use of groundwater for drinking. The remedial design was projected to be completed in 2012.

*Wastebeds 9-15 Subsite.* These former settling basins located on 663 acres were used for disposing residue from the Solvay Process. The waste is primarily nonhazardous calcium carbonate/chlorides from the manufacturing of soda ash but included other area wastes. These waste sources are from the Bridge Street Chlor-alkali plant (spilled materials, mercury, asbestos, lead, and wash water), chlorinated benzene manufacturing at the Willis Avenue plant (asbestos, wash water, spilled material, lead, mercury, and heavy organic residue), Allied Chemical plants (fly and bottom ash), County's wastewater treatment plant sewage sludge, Anheuser-Busch brewery sludge, and brine purification muds. Wastebed 15 also received demolition debris and soil from decommissioning the Allied Chemical main plant. A portion of the old Erie Canal, which lies beneath Wastebed 15, was used as a landfill by the Town of Camillus. Under authorization from NYSDEC, the Town of Camillus operates a construction and demolition waste landfill in portions of Wastebed 15. Sediments removed from Onondaga Lake as part of the Lake Bottom remedy have been dewatered and are permanently stored in an engineered Sediment Consolidation Area (SCA) located on Wastebed 13 (USEPA 2010c). While hazardous substances are present at the Wastebeds, the available data indicates that the levels of contaminants from the Wastebeds that are adjacent to Ninemile Creek are minimal and that they do not impact Onondaga Lake. NYSDEC is currently negotiating a consent order with Honeywell for an engineered cover and long-term maintenance and monitoring of Wastebeds 9 to 15 to mitigate environmental concerns.

*Onondaga County Metropolitan Syracuse Wastewater Treatment Plant (Metro).* Metro has upgraded to secondary and tertiary treatment achieving a phosphorus reduction of 86%, reduced CSOs by an 85% volume, and added green infrastructure to capture and reuse stormwater runoff.

*Natural Mudboil.* In 1995, The Onondaga Lake Management Conference authorized the construction of two settling basins and several depressurization wells to reduce the mudboils flow of sediment to Onondaga Creek (an average of 30 tons per day has been reduced to one ton per day). In 2010 a new mudboil area began downstream of the remediation projects, but with higher salinity. Control of the mudboil discharges will require continuous, long-term attenuation of aquifer pressures to reduce groundwater upwelling. Mudboil reduction will also reduce land subsidence and abate sediment discharges into Onondaga Lake. Via a separate 2010 Consent Order associated with an Onondaga Lake subsite, Honeywell agreed to an Environmental Benefit Project to provide funding for five years to help address the mudboil problem on Onondaga Creek. Kappel (2014) recommends actions that achieve a careful balance among (1) reducing the head in the aquifer to slow mudboil activity; (2) reducing concurrent turbidity discharges to Onondaga Creek; and (3) minimizing land-surface subsidence associated with mudboil activity to maintain the chemical quality of Onondaga Creek.

Total cost for remediation efforts by Honeywell has been estimated by NYSDEC to be $451 million. Upland waste closed in place will require perpetual groundwater treatment and ICs to prevent groundwater use and restrict land use to commercial/industrial. The contaminated lake bottom sediments will require perpetual calcium nitrate injections to prevent mercury methylation.

### 6.11.4 Regulatory and Stakeholder Involvement

The Onondaga Lake Superfund site is being addressed through federal, state, and responsible party actions pursuant to enforcement agreements with NYSDEC. Each of the state and Federal actions comply with the regulatory requirements for formal public comment on draft decisions (Proposed Plans and RODs).

NYSDEC and Honeywell are required to keep the public informed and engaged in the cleanup decisions and lake bottom construction activities as outlined in the 2008 Citizen Participation Plan (CPP) for the Lake Onondaga Lake Bottom Subsite Remedial Design Program. Honeywell provides financial and administrative assistance for the Community Participation Working Group (CPWG), an independent panel of community stakeholders that inform, discuss, make recommendations, and offer opportunities for community involvement and input throughout all phases of the cleanup. Their work includes an emphasis on reviewing project progress and community outreach activities. The CPWG is a self-governing voluntary group dedicated to providing a forum for enhancing public dialogue, fostering public understanding, and encouraging input and discussion for the Onondaga Lake bottom remedial design. The CPWG meetings are open to the public and consist of public officials, community leaders, citizens, and conservation and environmental group leaders. Technical experts from NYSDEC and Honeywell provide support to the group. The CPWG maintains a website to keep the public informed of current and historical activities, including legal decisions and news articles.

Onondaga County is one of the responsible parties from their historical discharge of municipal wastewater to the lake. The Onondaga County Water Environment Protection maintains a website regarding lake restoration progress, including ambient monitoring results.

The Onondaga Nation is a major stakeholder because the lake area is their homeland. The Nation and its people have a unique spiritual, cultural, and historic relationship with the land, which is embodied in Gayanashagowa, the Great Law of Peace. The Onondaga Nation is a federally recognized tribe whose 9.3 square mile reservation is located a few miles away. The Onondaga Nation sued the State of New York, the City of Syracuse, Onondaga County, and five corporations for illegal land takings and damage inflicted on Central New York's environment. In 2014, a federal judge dismissed the lawsuit. The

Onondaga Nation is involved through government-to-government consultations. They chose to be considered a separate nation rather than to be considered as a community partner in the OLP, and thus chose to be involved solely through discussions between their attorney general and New York State or USEPA officials.

## 6.12 Former UGI Columbia Manufactured Gas Plant, Columbia, Pennsylvania

The UGI Columbia Gas Plant site is located on less than 1 acre in an industrial area of the Borough of Columbia, Lancaster County, Pennsylvania, near the Susquehanna River. Site soils and groundwater became contaminated due to the manufacture of gas products beginning in 1851 and ending about 1950. The Remedial Investigation (RI) identified approximately 16,000 cubic yards of contaminated soils and between 345 and 34,500 gallons of DNAPL in fractured bedrock under the site and under surrounding land parcels in the site vicinity. The DNAPL source has been present for about 150 years. A dissolved phase plume has also been identified near the DNAPL. This dissolved phase plume discharges to the Susquehanna River, where it becomes significantly diluted below state of Pennsylvania water quality standards.

From 1851 to 1935, the Columbia Gas Company (Columbia Gas) used the site for manufacturing gas for distribution in the City of Columbia. The site changed hands several times, with subsequent owners including PP&L Co., Lancaster Gas, UGI Utilities Inc., the Crouse family, the Roach family, the Judd family, and PPL Electric Utilities. PPL is the current owner of the MGP Facility (USEPA 2016c).

### 6.12.1 Facility Operations

Gas was historically produced at the site through a coal gasification process which included reacting steam with hot coal, coke, and wood. The gas went from two gas generating sets through a washbox, condenser, washer cooler, and then was stored in a gas holder. From the gas holder, the gas went through a coal tar separator and a purifier and finally to a relief holder for distribution in the City of Columbia.

The primary waste streams generated during the coal gasification process were liquid coal tar, boiler ash, and spent gas purifying materials. Coal tar is a mixture of volatile organic compounds (VOCs) including BTEX; semivolatile organic compounds (SVOCs) including polycyclic aromatic hydrocarbons (PAHs); and inorganics including metals and cyanide (collectively referred to as “MGP-related wastes”).

Coal tars were generated from the coal tar separator, which separated coal tar from liquid waste. The coal tar separator received liquids from the washer cooler, drip pumps, and overflows from the gas holder. Coal tars generated from the tar separator were stored in the relief holder pit, which had a 46,000-cubic foot capacity, to allow for separation of the tar/water emulsion. The relief holder pit was constructed of riveted steel plates and was held within a pit that was approximately 30 feet deep. The relief holder pit failed in 1947, and its foundation was used, thereafter, for tar separation. Marketable coal tar was removed for sale and below-grade tar was left in the pit. Overflows of the tar separator, which occurred during periods of heavy rainfall and in the winter, were discharged to an open ditch that led to the Susquehanna River.

The purifier wastes were generated from iron-oxide treated wood chips arranged on wooden racks. When the wood chips could no longer be regenerated, they were removed from the purifier. The wood chips were subsequently disposed of on site as paving and dust control material. The wood chips contained cyanide, which is a contaminant of concern at the site.

MGP operations at the site resulted in the release of VOCs, PAHs, heavy metals, and cyanide into soil, groundwater, and surface water at the site (USEPA 2016c).

### 6.12.2 Technical Basis for Remedial Action

To address contamination remaining in site soils, two caps have been installed. Contaminated sediments in the Susquehanna River have been excavated and disposed of off site. The contamination remaining in groundwater consists of a dissolved plume and between 345 and 34,500 gallons of approximately 150-year old DNAPL. The range in this estimate is primarily a function of the estimated potential variance in the fractured bedrock pore space in the DNAPL source area. The DNAPL is composed of tar-like liquids resulting from the former MGP operations which do not easily dissolve in water. The DNAPL is located within fractured bedrock (karst terrane) and under adjacent properties. The DNAPL is located mainly in two fracture zones, which are oriented in an east-west direction and extend approximately 880 feet away from the source area. The more soluble and mobile fractions of the contamination have likely been removed through natural attenuation processes, leaving behind the largely immobile fractions of the original DNAPL.

A dissolved phase plume has been identified near the DNAPL. Since the DNAPL has a low solubility and does not mix well with groundwater, the dissolved plume area is relatively small and is found in the area immediately adjacent to the DNAPL. The DNAPL and the portion of the dissolved phase plume which is immediately adjacent to the DNAPL is referred to as the "DNAPL Zone." All DNAPL is believed to be in the DNAPL Zone illustrated on Figure 55. The DNAPL Zone has a spatial extent of approximately seven acres and a depth of 160 feet below ground surface as illustrated on Figure 56. The dissolved phase plume discharges to the Susquehanna River where it is quickly diluted to significantly less than Pennsylvania water quality standards (USEPA Region 3 2016).

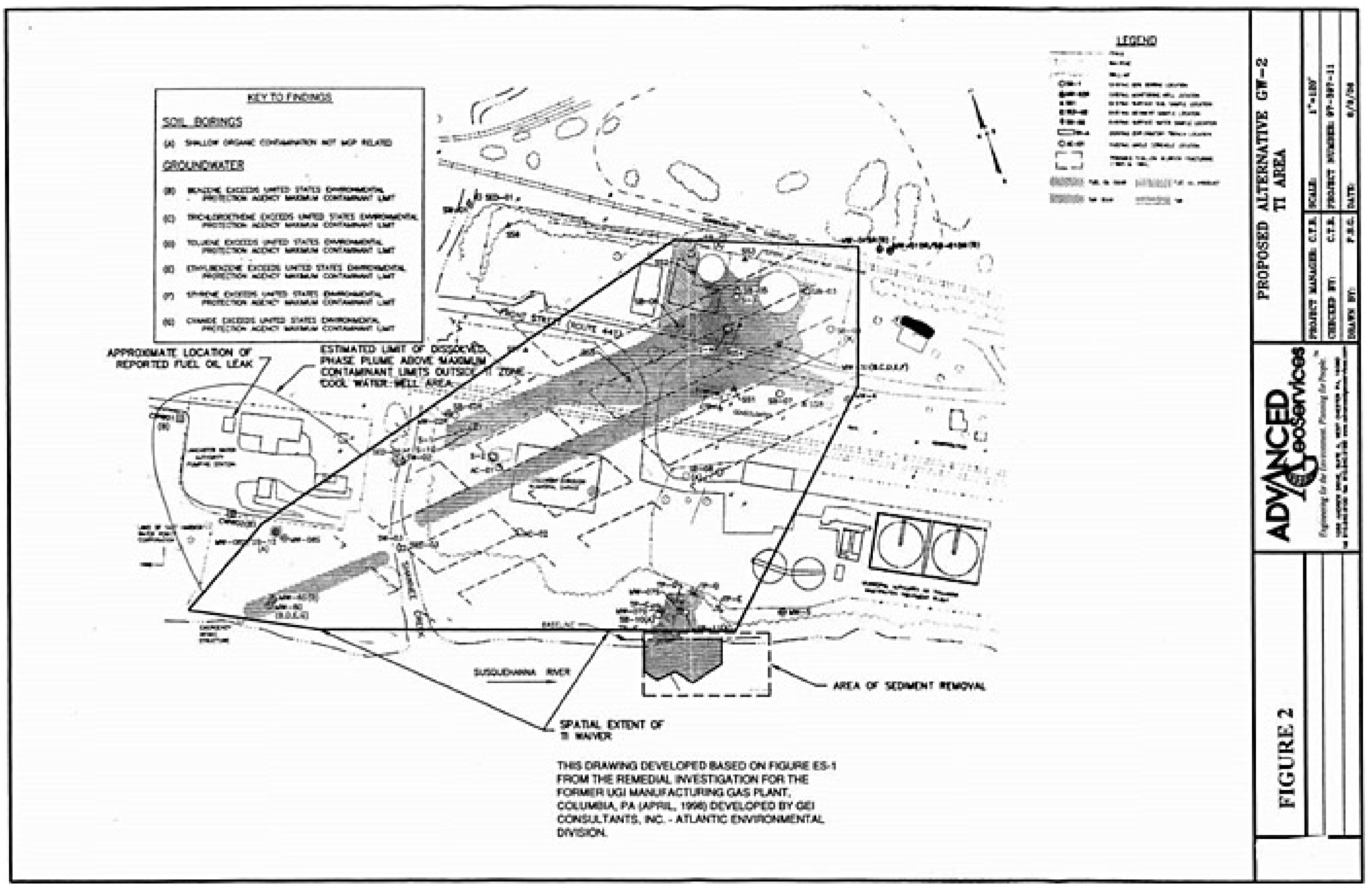



**Figure 55. Plan view showing extent of groundwater designated in the TI waiver** (Charsky et al. 2012)**.**

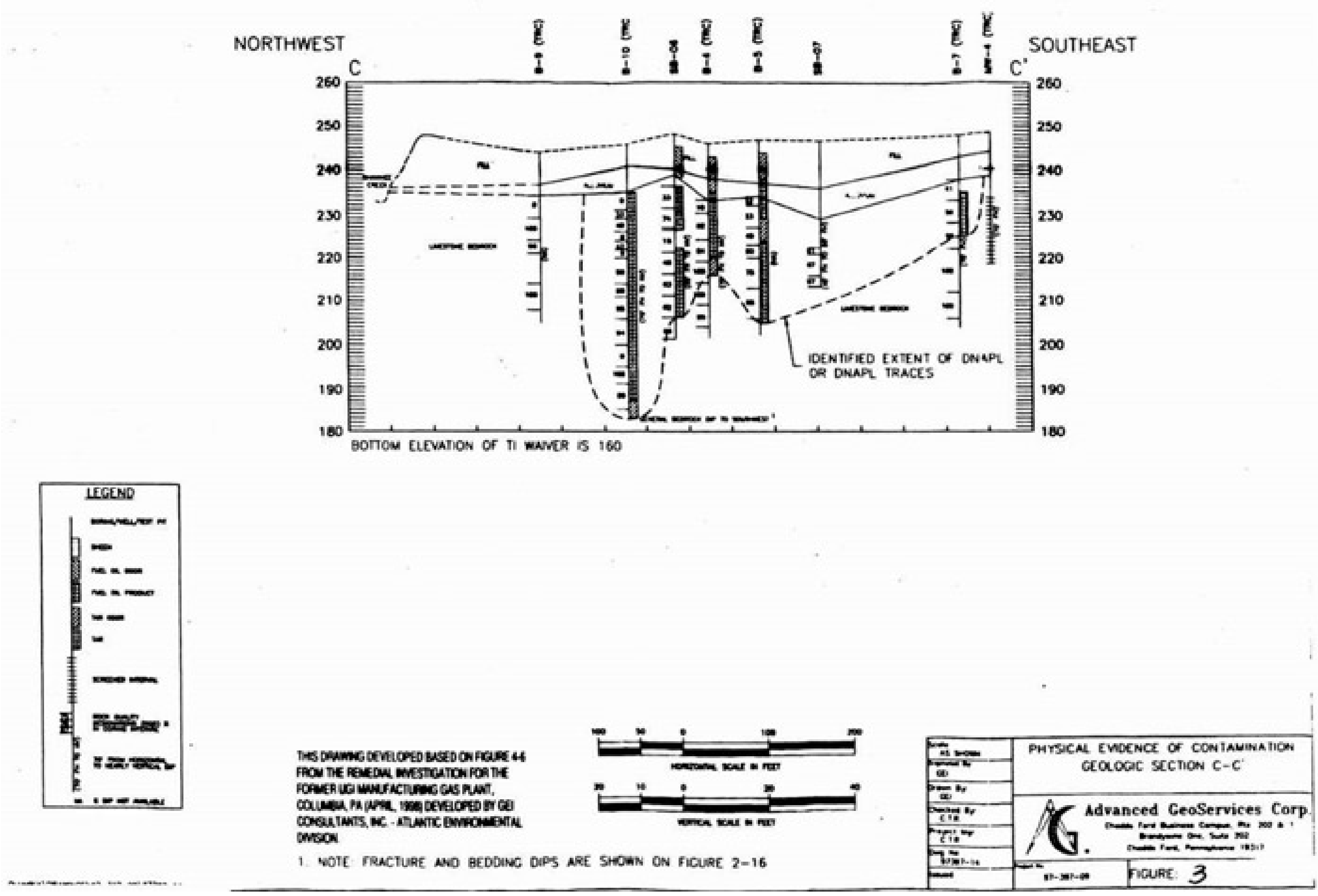



**Figure 56. Cross section view showing extent of groundwater designated in the TI Waiver** (Charsky et al. 2012)**.**

The operation of cooling water wells in groundwater to the west of the facility by the Lancaster Water Authority has drawn a portion of the dissolved phase plume toward these wells. These wells supply cooling water to a pumping station which supplies Susquehanna River water for drinking water purposes. The cooling water comprises approximately 0.1% of the public water supply provided by the pumping station. The water supplied by the pumping station is treated to make it potable prior to being supplied to residents.

ICs have been implemented for both soils and groundwater, restricting the site to industrial use and prohibiting use of groundwater under the site for drinking water.

### 6.12.3 Decisions

Because of early investigations which revealed the presence of VOCs, PAHs, heavy metals, and cyanide in soil, groundwater and surface water at the site, USEPA proposed the site for inclusion on the Superfund NPL in June 1993 and added the site to the NPL in May 1994 (USEPA 2007c).

In April 1996, PP&L entered into a Consent Order and Agreement with Pennsylvania Department of Environmental Protection (PADEP) to conduct a Remedial Investigation/ Feasibility Study (RI/FS) to determine the nature and extent of contamination at the site, to characterize the risks to human health and the environment, to evaluate alternatives to clean up the contamination at the site, and to initiate interim actions on the gas and relief holders and for the Susquehanna River (USEPA 2007c).

In 1997, PP&L applied steam and hot water injection to the two gas and relief holders. In addition, approximately 3,350 gallons of tar were extracted from the two holders and taken for off-site thermal treatment and disposal. Following the tar extraction, coal tar remained in subsurface soils below the holders. The holders were then injected with over 760 cubic yards of a grout and cement mixture to stabilize and solidify them. In addition, in 1998, approximately 700 tons of contaminated sediments were removed from the Susquehanna River and shipped off site for thermal treatment and disposal. A sheet pile wall was installed along the river bank in the area adjacent to the sediments. The area was regraded and covered with a geosynthetic cloth, rock, and stone.

In April 1998, PADEP approved the Remedial Investigation (RI) and in June 1998, it approved a Risk Assessment Report. The RI identified approximately 15,000 cubic yards of contaminated surface and subsurface soil on site. The RI also identified contamination in on-site groundwater that had migrated off site and was detected in deep groundwater near the Susquehanna River. In 2002, PADEP approved PP&L's FS Report, which determined options for addressing the remaining contamination at the Site.

In October 2006, USEPA approved a Groundwater Engineering Analysis Report (Groundwater Report) for the site. In the Groundwater Report, PP&L provided documentation for a request for a TI waiver for the ARARs for groundwater due to the presence of DNAPL in the fractured bedrock under the MGP facility. The MGP-related wastes form the DNAPL under the MGP facility.

On November 29, 2006, PP&L, UGI, and USEPA entered into an Administrative Settlement and Order on Consent. Under the Settlement Agreement, PPL and UGI agreed to, among other things, install caps over two areas where MGP-related wastes remained on site and excavate and dispose of soil and MGP-related wastes as necessary.

In 2007, USEPA issued the ROD for the site (USEPA 2007c). Remedy for soils includes maintenance of the capping agreed to in the 2006 settlement Agreement, and ICs restricting use of the site to industrial use.

ICs were implemented between 2007 and 2009 for a portion of the site to prohibit residential use or any use that could impact the remedy. In June and September 2007, the potentially responsible parties (PRPs) recorded four Environmental Protection Easements and Declarations of Restrictive Covenants (2007 Restrictive Covenants) in Lancaster County as follows (USEPA 2016c):

- Former Safe Harbor Power Corporation Parcel – groundwater use restrictions
- LWA Pumping Station Parcel – land and groundwater use restrictions
- Part of the Columbia Borough WWTP – land and groundwater use restrictions
- Shawnee Run Greenway parcel – perpetual stormwater easement for the purpose of constructing and maintaining a stormwater conveyance system

On February 20, 2009, an Environmental Covenant pursuant to the Pennsylvania Uniform Environmental Covenants Act was recorded as follows:

- MGP Facility – land and groundwater use restrictions.

Remedy for groundwater includes the monitored natural gradient flushing (contaminants from the dissolved plume associated with DNAPL migrate and merge with the Susquehanna River where they are diluted to below water quality standards) with institutional controls, TI Waiver for the DNAPL zone, and continued groundwater monitoring to verify that the remedy is operating as expected. ICs consist of local zoning restrictions prohibiting installation of new wells, restrictions, or notices on site property deeds regarding the extraction and use of groundwater for any purpose, and permanent access to site wells for monitoring purposes (USEPA 2016c).

## 6.12.4 Summary of Alternatives

CERCLA requires that any remedy selected to address contamination at a hazardous waste site must be protective of public health and welfare and the environment, be cost-effective, be in compliance with regulatory and statutory provisions that are ARARs, and consistent with the NCP to the extent practicable. The ROD for the site provided a detailed analysis of the remedial alternatives for soil and groundwater.

### 6.12.4.1 Alternatives for Soil

Two alternatives for soil were evaluated: no action and no further action and ICs. The purpose of the no action alternative is to provide a baseline for comparison against the other alternatives. Under this alternative, no remedial action would be taken to remove, control migration from, minimize exposure to or otherwise reduce the risks associated with site-related contaminated soils. In addition, no efforts would be made to control the future use of the areas containing contaminated soils. This alternative controls risks through the implementation of ICs to maintain the integrity and protectiveness of the remedial actions previously taken at the site.

The no further action and ICs alternative requires no further remediation of on-site soils because those areas where MGP-related waste remains in the soil have been capped. To ensure that the integrity and protectiveness of those caps are maintained, this alternative requires that the responsible parties to maintain the caps and implement ICs at the site. This alternative would allow for the commercial and industrial reuse of the site. Because contaminated soils would remain in place under the caps at the site, USEPA would conduct five-year reviews as required by Section 121(c) of CERCLA. This alternative was selected by USEPA.

The no further action and ICs met the NCP criteria for overall protection of human health and the environment, long-term effectiveness and permanence, short-term effectiveness, implementability, state acceptance and community acceptance, and was the alternative selected for soil in the ROD (USEPA 2007c).

#### 6.12.4.2 Alternatives for Groundwater

The alternatives for groundwater included no action, monitored natural gradient flushing and institutional controls, and groundwater extraction and treatment. The monitored natural gradient flushing and institutional controls alternative consists of a TI Waiver in the seven -acre area shown on Figure 55 and referred to as the DNAPL Zone, and natural gradient flushing of the dissolved phase plume from the DNAPL Zone into the Susquehanna River. With natural gradient flushing, the dissolved MGP constituents will continue to be diluted, dispersed, and biodegraded to nondetectable levels in the Susquehanna River. This natural flushing effectively contains the plume and prevents it from expanding. The ICs component of this alternative consists of administrative and legal controls that help to minimize human exposure to contaminated groundwater.

Groundwater extraction and treatment includes the extraction and treatment of the dissolved phase plume to hydraulically control the contaminated groundwater and prevent the migration of the dissolved plume towards the cooling water wells and the Susquehanna River. Groundwater extracted would be treated and discharged to the Susquehanna River. A TI Waiver would be established for the portion of the plume contained within the DNAPL zone.

Monitored natural gradient flushing and institutional controls met the NCP criteria for overall protection of human health and the environment, short term effectiveness, implementability, costs and was the alternative selected for groundwater in the ROD.

The TI waiver was approved for the following reasons:

- Primary reason: Presence of a large amount of viscous residual DNAPL in fractured rock, that will slowly dissolve over centuries.
- Secondary reasons: No known technologies to address residual DNAPL in fractured rock; attempts to mobilize DNAPL may cause ecological and human health risks.

The TI waiver was part of the original ROD (a front-end waiver). The TI evaluation report was part of the 2006 Groundwater Engineering Analysis report, issued four years after the RI/FS and one year before the ROD. ARARs waived included federal MCLs and state risk-based concentration ARARs. The TI zone includes the DNAPL zone (about 6 acres) to a depth of 160 feet (overburden, shallow, and deep bedrock). This zone also includes the site and off-site areas to the south and west. The data used as a basis for waiver was presented in the RI/FS report and post-FS analysis.

This site required 15 years of characterization and is expected to require a remedy time frame of several centuries to 1,000 years, based on DNAPL dissolution. The present worth cost estimate ranges from $0.9 to $10 M for groundwater remediation.

### 6.12.5 Regulatory and Stakeholder Involvement

The ROD was public noticed in 2007 and public concerns were addressed in the Responsiveness Summary. A public meeting was held on July 19, 2007. The first Five-Year Review Report for UGI Columbia Gas Plant site was dated May 2016 (USEPA 2016c). The report concluded that the remedy is protective of human health and the environment in the short-term due to concrete and asphalt caps that prevent unacceptable exposure from occurring. The report suggested the following three actions to take to enhance remedy protectiveness over the long-term (USEPA 2016c).

- Evaluate soil and groundwater institutional controls for the Site contamination and modify or add controls, as necessary.
- Evaluate groundwater data and DNAPL extent to determine whether an alternate remedial method for groundwater is necessary.
- Continue monitoring manganese and cyanide concentrations to establish trends and to determine whether unacceptable ecological risk is present.

Groundwater and land use controls were established by the 2007 Restrictive Covenants and 2009 Environmental Covenant on several Site properties. The five-year review report found that not all properties had the necessary ICs in place to restrict groundwater use and to prevent residential use. ICs need to be implemented for all properties at the Site to ensure the long-term protectiveness of the remedy.

The five-year review report also reported that USEPA had achieved the RAO of preventing exposure to contaminated soil and groundwater and was working toward achieving the RAOs of preventing migration of the dissolved groundwater contamination and fully implementing institutional controls. Toxicity factors had changed since the 2007 ROD, causing some of the groundwater ARAR values to change. However, the changes in toxicity did not impact the protectiveness of the groundwater remedy. Groundwater contaminant concentrations outside the DNAPL Zone in the LWA Lobe and at MW-5(T) currently exceed groundwater ARARs. USEPA is currently evaluating if additional groundwater response actions are warranted or if the boundary of the DNAPL Zone needs to be modified (USEPA 2016c).

## 6.13 Savannah River Site (SRS) F-Area Seepage Basins Groundwater, South Carolina

The Savannah River Site (SRS) is a 310-square mile (803 square kilometer) site that is owned and operated by the DOE. The site is in South Carolina, southeast of Augusta, Georgia. The site was built during the 1950s to produce the basic materials used in the fabrication of nuclear weapons, primarily tritium and plutonium-239. Currently, a major focus at SRS is remediation activities associated with the production of these materials.

The F-Area Hazardous Waste Management Facility at SRS consisted of three unlined, earthen surface impoundments called “seepage basins.” From 1955 through 1988, the F-Area seepage basins (FASB) received approximately 1.8 billion gallons (7.1 billion liters) of low-level waste solutions originating from the processing of uranium slugs and irradiated fuel in the F-Area Separations Facility (Figure 57). The effluents were acidic (wastewater with nitric acid) and low activity waste solutions containing a variety of radionuclides and dissolved metals (Killian et al. 1987). After entering the basin, some wastewater evaporated, and the rest seeped into the underlying soil and layered Coastal Plain sediments.

When the FASB were constructed, the conventional belief was that most of the radionuclides would be bound in the soils beneath the basins and would not pollute groundwater. Though the seepage basins functioned as designed, the acidic basin influent mobilized some metals and radionuclides, resulting in groundwater contaminant plumes. Many radionuclides migrated to the groundwater, including: plutonium isotopes, cesium-137 (Cs-137), strontium-90 (Sr-90), uranium isotopes, iodine-129 (I-129), technetium-99 (Tc-99), and tritium. Currently, the main risk drivers for the groundwater are Sr-90, uranium isotopes, I-129, Tc-99, tritium, and nitrate (Denham and Vangelas 2008). The pH of the groundwater within the plume is as low as 3.2 near the basins and increases to the background pH of 5.5–6 at the plume fringes and upgradient of the basins. Figure 58 shows the distribution of tritium in 2014 in relation to seepage basins, funnel and gate treatment system, seepline, and receiving stream.

The geochemical complexity of both the impacted zone and comingled plume constituents provide the greatest challenges to efficient and effective remediation activities. The strong acidity of the affected groundwater contributes significantly to increased mobility of metals and radionuclides. The diversity of the comingled radiologic, cationic, and anionic species in the plume requires multiple remedial strategies to address the full range of contaminants.

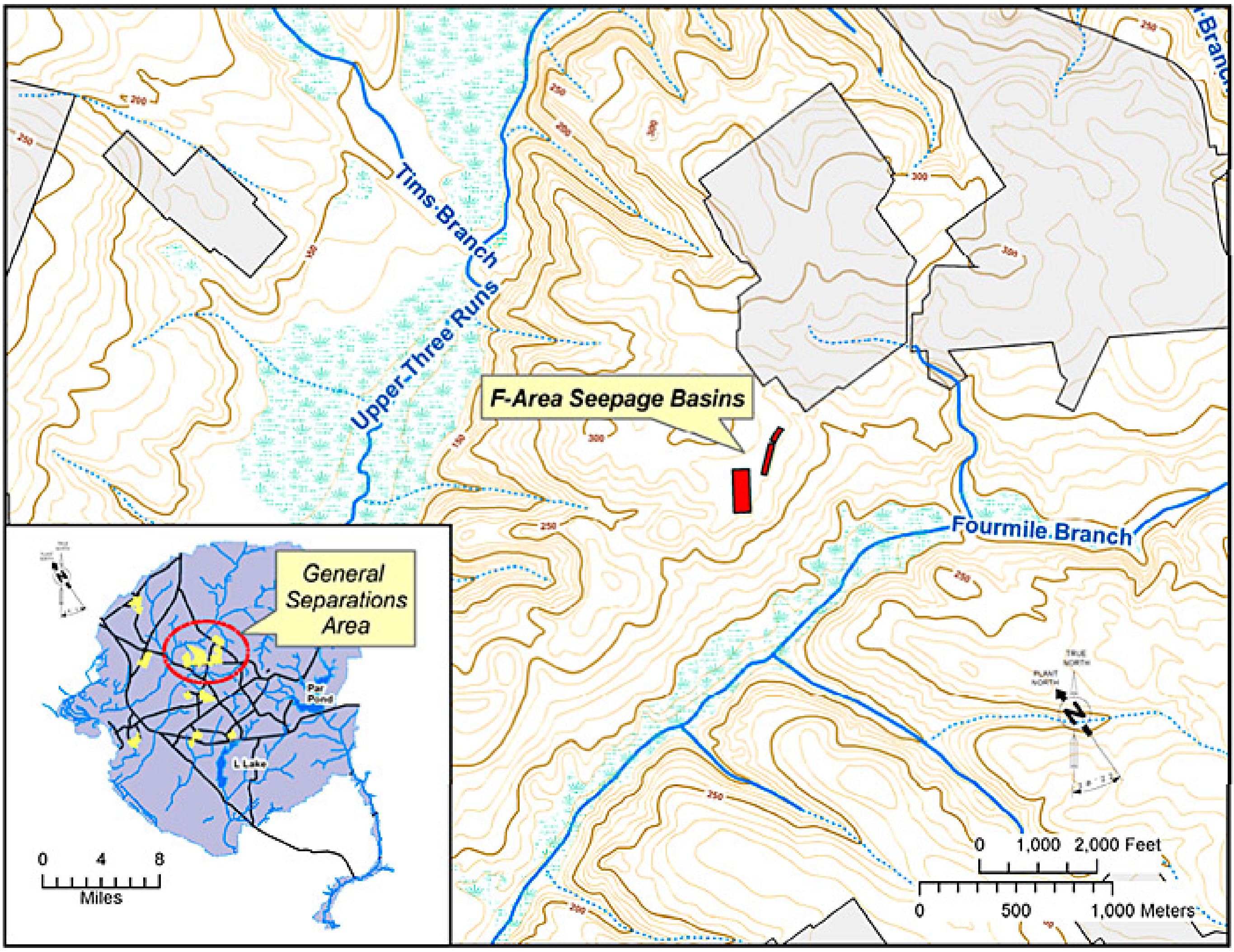



**Figure 57. Location of the F-Area Seepage Basins at the Savannah River Site** (Millings et al. 2013)**.**

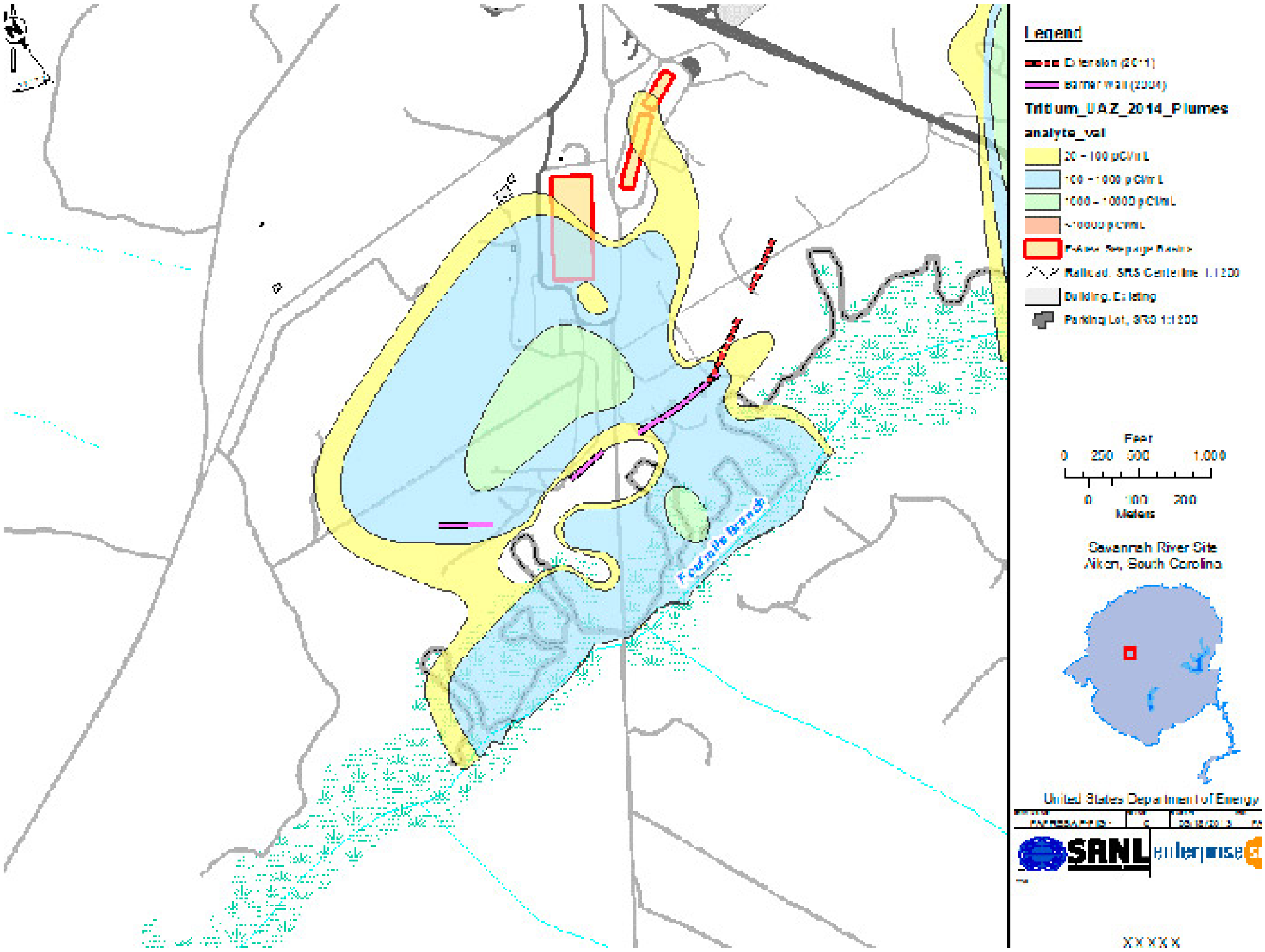



**Figure 58. Distribution of tritium in 2014 in relation to seepage basins, funnel and gate treatment system, seepline, and receiving stream** (SRNL 2017)**.**

## 6.13.1 Technical Basis for Remedial Action

Over seventy site investigations have been conducted near the basins since the 1960s. Groundwater monitoring at the basins began in the late-1950s and has continued since that time. Over the years, various types and numbers of wells, seepline monitoring points, and surface water locations have been used for assessing impacts and remedial efforts associated with the FASB.

The geology of the site is heterogeneous, consisting of poorly consolidated quartz sands and clays that are typical of coastal plain deposits (Figure 59). The plume is stratified within the water-table aquifer, moving mostly within a highly transmissive unit along the top of a clay layer that confines the aquifer below and cropping out at the seepline along Fourmile Branch (a stream approximately 1,600 feet downgradient from the basins). The groundwater remains acidic, with pH as low as 3.2 near the basins and increasing to a pH of approximately 5 downgradient.

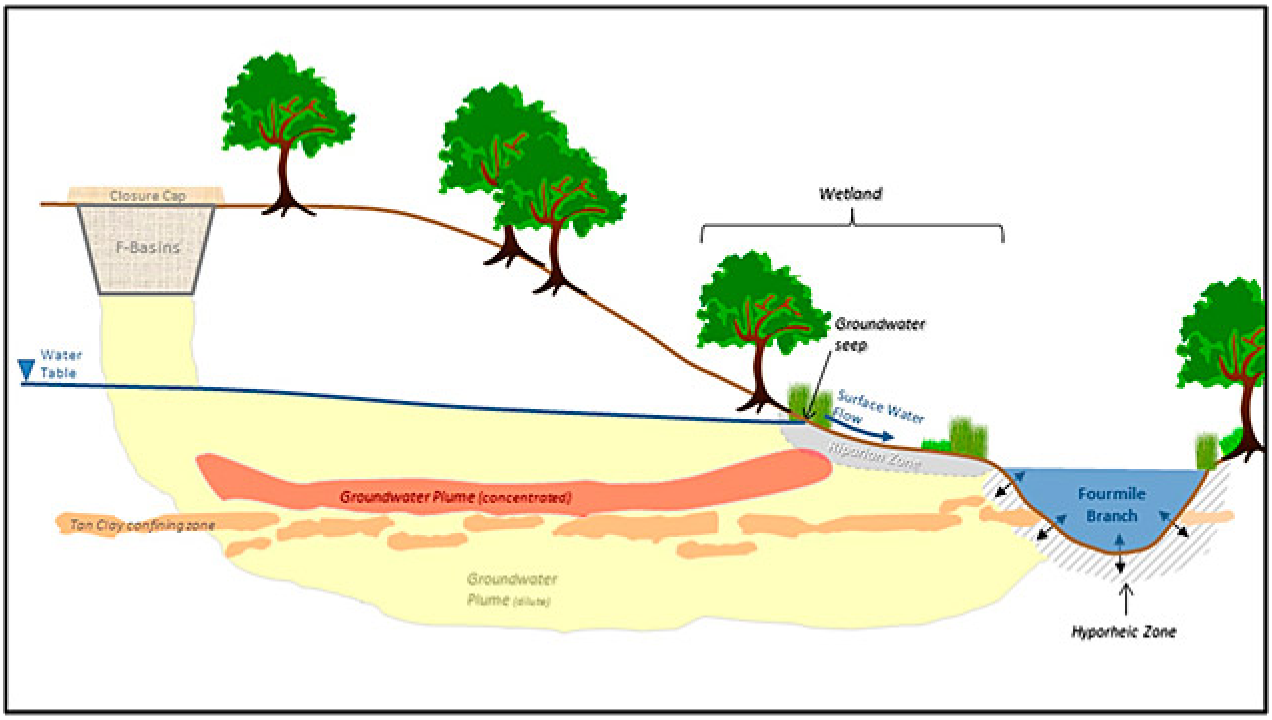



**Figure 59. Schematic cross section of F- area groundwater plume** (Eddy-Dilek, Kostelnik, and Denham 2016)**.**

## 6.13.2 Decisions

As early as 1962, some contaminants had migrated to groundwater from the basins. Later, visual signs of vegetative stress suggested the plume had reached the seepline, which sampling later confirmed. Extensive sampling and monitoring were completed to delineate the plume, which had a footprint of approximately 0.38 square mile. In 1986, it was determined that the basins should be regulated under RCRA as hazardous waste disposal facilities, and closure plans were initiated. The Natural Resources Defense Council sued the Savannah River Site in 1988, which accelerated treatment of this waste unit and associated groundwater under RCRA.

The RCRA permit issued in 1992 specifies the regulatory requirements for the groundwater corrective action program, as well as other appropriate local, state, and federal laws and regulations. The corrective action plan specifies a phased remediation approach to implement the basic remedial system, followed by evaluation the effectiveness of corrective action design and system components. This evaluation is used to design and implement additional corrective action elements, as necessary. The corrective assessment plan goals account for technical impracticability and economic feasibility considerations.

## 6.13.3 Remedial Approach

The basins were closed in 1991 by dewatering, physically and chemically stabilizing the remaining sludge, and covering them with a protective multilayer system to reduce rainwater infiltration. In 1997, SRS designed and installed a pump-treat-and-reinjection system with a water treatment unit that trapped the untreatable tritium in a continuous loop. This system extracted downgradient groundwater, removed contaminants other than tritium, and then reinjected the treated water upgradient of the seepage basins. The treatment system consisted of precipitation/flocculation, reverse osmosis, and ion exchange. Operation of the water treatment unit began in 1999 and was continued until 2003.The system operated as designed, but had two significant drawbacks: high cost and large amounts of radioactive solid waste as a byproduct. SRS sought another, more efficient way to treat the groundwater contaminant plume.

In 2004, the P&T system was replaced by a hybrid funnel-and-gate system that was installed about 1,000 feet upgradient from Fourmile Branch. The purpose of the funnel-and-gate is to slow migration of contaminated groundwater and to funnel it through in situ treatment zones at the gates. Extensive geologic characterization showed that much of the plume migrated along “troughs” at the top of the clay layer that confines the lower aquifer. The walls (or engineered subsurface barriers) were installed across these features to slow contaminant migration and force it through the gates (Figure 60). The treatment zones at the gates attenuate migration of uranium, Sr-90, and I-129 by sorption or precipitation. Tritium migration is slowed by the walls and additional decrease in tritium concentrations is achieved when the stratified plume mixes with less contaminated groundwater as it migrates up through the gates.

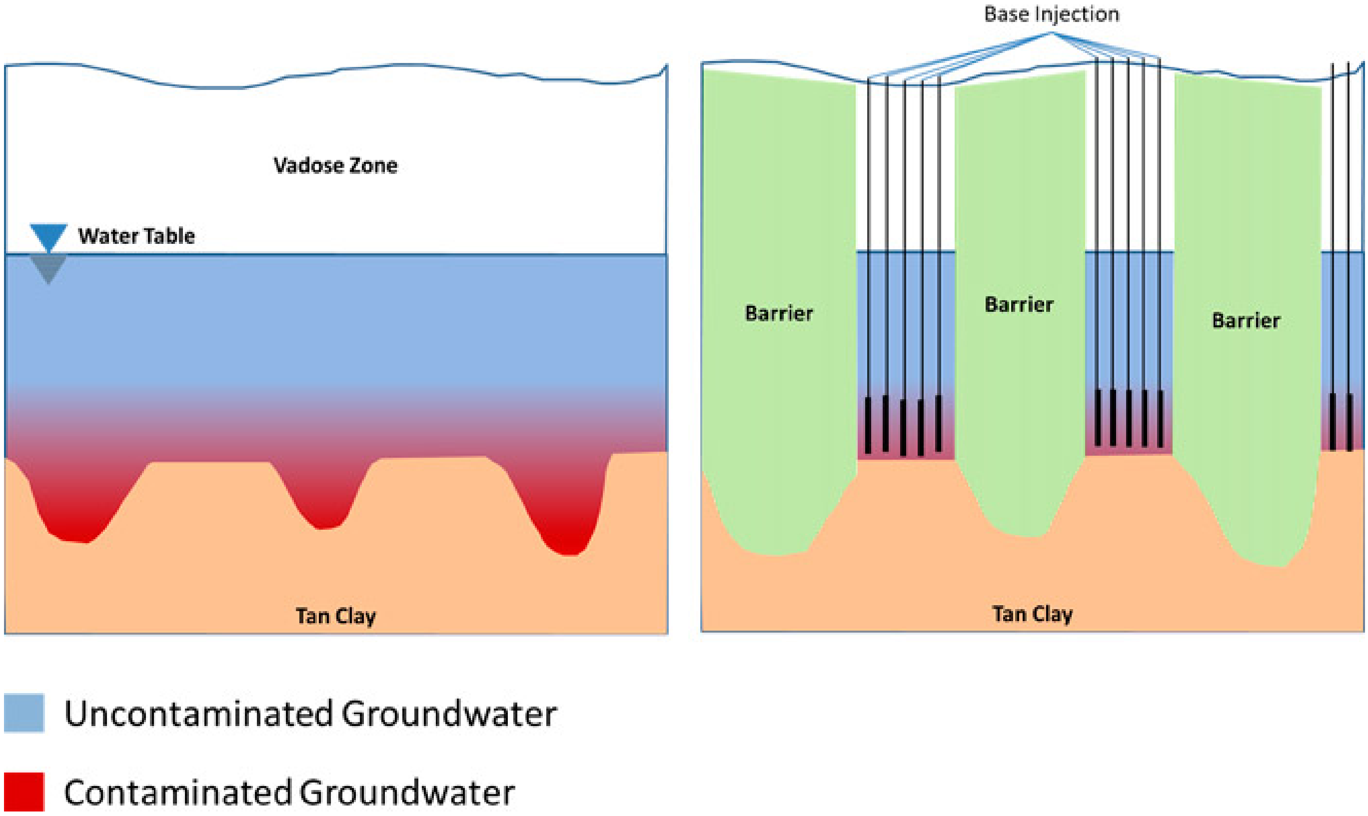



**Figure 60. Cross-sectional conceptual model of funnel-and-gate with base injection system before (left) and after installation** (Eddy-Dilek, Kostelnik, and Denham 2016)**.**

Treatment zones for uranium and Sr-90 at the gates are maintained by neutralizing acidity of the groundwater and mineral surfaces with injections of an alkaline solution. This treatment causes sorption of the contaminants and precipitation of uranium phases. Periodic injections are performed, with the frequency at each gate dictated by sentry monitoring wells located downgradient.

### 6.13.4 Monitoring/Optimization

Monitoring of the performance of the funnel-and-gate with base injection over the past seven years indicates that it has functioned as planned. Analysis of subsurface cores collected downgradient of the middle gate shows that an elevated pH treatment zone has been established. Groundwater monitoring indicates that tritium flux has been reduced to interim objectives and regulatory limits on concentrations of Sr-90 and uranium have been achieved downgradient of the treatment system.

In 2009, a pilot study evaluated the removal of I-129 by the injection of particles of solid silver chloride. Contaminant I-129 and natural iodine-127 react with the silver chloride to form insoluble silver iodide, thus removing I-129 from the groundwater. In 2011, the RCRA permit was modified to deploy silver chloride technology at the middle gate as part of the corrective action. The treatment zone extended from the top of the water table down to a local clay layer (25 to 50 feet below ground surface). Injection was performed starting at the bottom of the aquifer and proceeded upward pumping a specific volume of amendment into each zone at 2.5-foot intervals. Evaluation of the performance of the silver chloride treatment zones continues.

Implementation of long-lived, attenuation-based remedies such as the funnel-and-gate system at the FASB will require adequate levels of monitoring to ensure that the remedies continue to be effective over long time frames. This monitoring will be required to demonstrate to regulators and stakeholders that attenuated contaminants are behaving as predicted by site conceptual model and that they will not remobilize.

In 2014, a pilot field test was initiated to test an alternative approach for long-term monitoring that should simultaneously improve the monitoring systems and lower costs. The new approach measures the controlling variables that are leading indicators for changes in the stability of the plume; these indicators would be supplemented by a substantially reduced number of well measurements. The controlling variables include boundary conditions, master variables, and plume/contaminant variables.

Boundary conditions control plume movement and therefore indicate changes in plume stability. Master variables are the key variables that control the chemistry of the groundwater system, and include redox variables (ORP, DO, chemicals), pH, specific conductivity, biological community (breakdown/decay products), and temperature. A robust suite of tools is commercially available to measure these variables. Concentration measurements for all types of contaminants in groundwater are a lagging indicator plume movement—significant changes indicate that contamination has already migrated. The new paradigm relies on leading indicators, which alert site managers that conditions at the site are changing in ways that could lead to plume expansion.

### 6.13.5 Regulatory and Stakeholder Involvement

Since 1993, SRS has managed regulatory compliance activities through a Federal Facility Agreement (FFA) with DOE, USEPA Region 4, and South Carolina Department of Health and Environmental Control (SCDHEC). The FFA, which includes both USEPA and the state of South Carolina, specifies how SRS will address contamination at waste units. SRS uses a Core Team process that was established 1999 and was implemented to improve management of the regulatory and remediation decision-making process at the site. Core team members include DOE, USEPA Region 4, and SCDHEC. The team operates on the following core principles:

- An effective Core Team is essential.
- Clear, concise, and accurate problem definitions are critical.
- Early identification of likely remedial actions is possible, prudent, and necessary.
- Uncertainties are inherent and will always need to be managed.

The Core Team process enhances communication and productivity to streamline the decision process and facilitates remediation problem solving at an early stage. Thus, SRS has built a highly productive working relationship not only with its regulators but also with other public stakeholders such as the SRS Citizens Advisory Board (CAB). Once a waste unit has been fully characterized, remediation alternatives evaluated, and a preferred method proposed, SRS solicits comments from the public, which includes representatives from the media, legislators, educators, and other citizens.

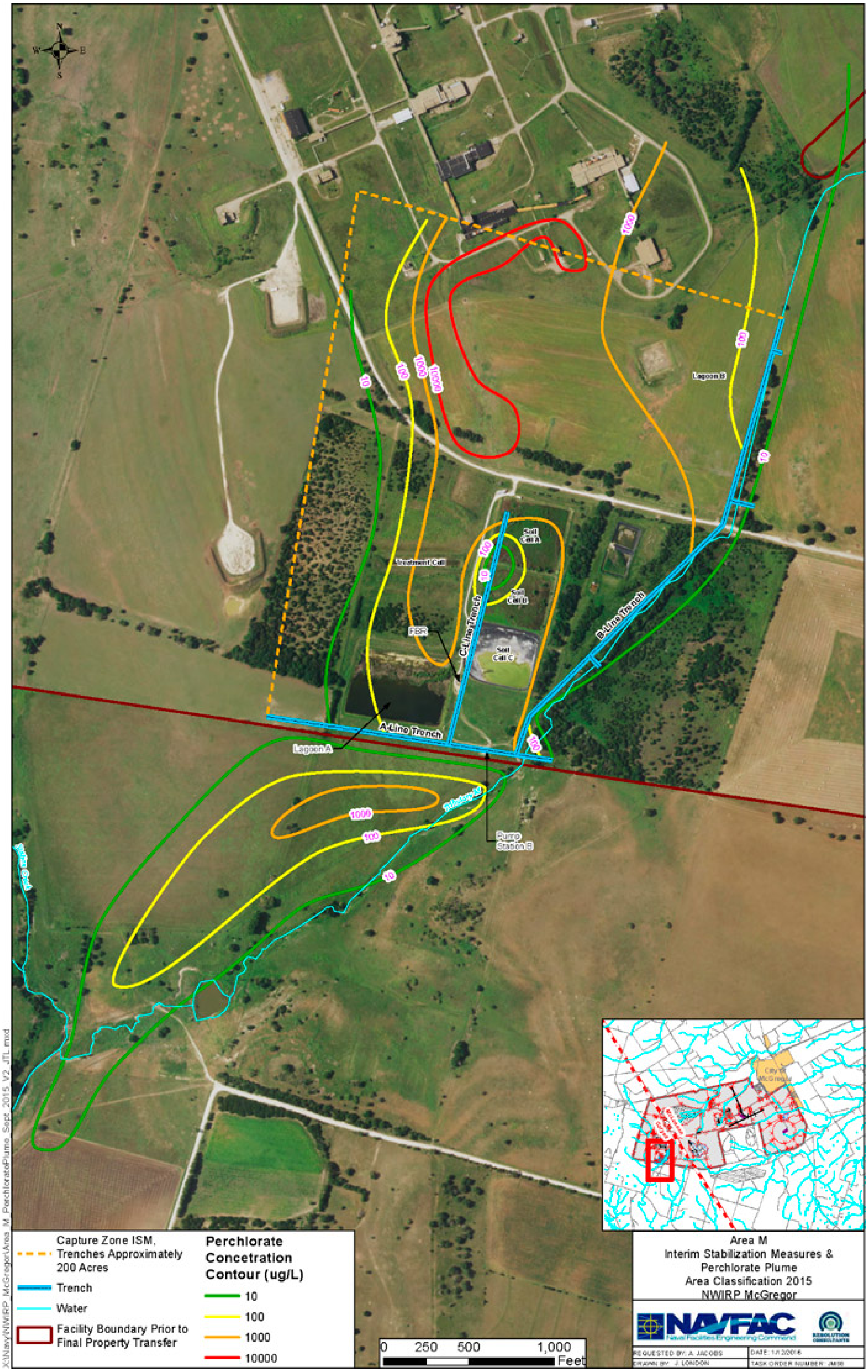
During the public comment period, SRS also seeks comments from the CAB. The CAB is an appointed advisory group of citizens that makes recommendations to the DOE, USEPA Region 4, and SCDHEC regarding SRS remediation. Once comments are received from stakeholders and considered, a ROD is issued that documents the selected remedial alternative. DOE gives regular briefings to the CAB committees on remediation projects that are in progress, upcoming remedial decisions, and the programmatic and upcoming actions or administrative matters under the FFA and RCRA permits.

## 6.14 Former Naval Weapons Industrial Reserve Plant, McGregor, Texas

The former Naval Weapons Industrial Reserve Plant (NWIRP) is in McGregor, Texas, which is 20 miles west of Waco, Texas. Before closure in 1995, the facility consisted of isolated industrial sites located on 9,700 acres. Over its history, the facility transitioned from bomb manufacturing in the 1940s to rocket motor development and testing from the 1950s until closure.

VOCs such as TCE and 1,1,1-trichloroethane (1,1,1-TCA) were used as solvents and released into the environment at some of the industrial sites. In addition, ammonium perchlorate, a chemical oxidizer used in rocket motor engines, became an emerging contaminant at the time of the facility's closure. This case study focuses on ammonium perchlorate because it is the main risk driver at the site.

Ammonium perchlorate quickly disassociates when it comes in contact with water. The ammonia is taken up by plants, and the perchlorate anion is conservative and does not degrade under the naturally aerobic aquifer conditions found at the site. Because of perchlorate's fate and transport characteristics, it can pass through the thin soil cover at the site and enter the 20 to 30-foot thick upper water-bearing zone of weathered limestone. The site's groundwater hydraulic gradient parallels the topography through secondary porosity features, such as fractures, small solution cavities, and bedding planes. When groundwater elevations are high during the wetter parts of the year, perchlorate contaminated groundwater can surface along hillside springs, tributaries, and streams. When perchlorate enters the surface water regime, its travel time increases until it encounters a losing stream segment. These leaps in travel time, called a "porpoising effect" has created thin plumes in three separate drainage basin miles downstream from the facility's boundary (Figure 61).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Lagoon B
Soil Cell A
Treatment Cell
Soil Cell B
FBR
C-Line Trench
Soil Cell C
B-Line Trench
A-Line Trench
Lagoon A
Pump Station B
10
100
1000
10000
Capture Zone ISM, Trenches Approximately 200 Acres
Trench
Water
Facility Boundary Prior to Final Property Transfer
Perchlorate Concetration Contour (ug/L)
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Area M
Interim Stabilization Measures &
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NWIRP McGregor
NAVFAC
Naval Facilities Engineering Command
REQUESTED BY: A. JACOBS
DRAWN BY: J. LONDON
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**Figure 61. McGregor site drainage basins** (NAVFAC SE, 2016)**.**

Ultimately the remedial investigations expanded to approximately 22,000 acres before the plumes were fully delineated to the protective concentration levels (PCLs) that the state of Texas established for Class 2 Groundwater Resource (17 µg/L, residential, and 51 µg/L, commercial/industrial). The VOC plumes are colocated within the perchlorate plume, however, their footprints have remained on site and within or adjacent to the industrial complexes.

## 6.14.1 Technical Basis for Remedial Action (Characterization/CSM)

In the 1990s, perchlorate was identified as an emerging contaminant by USEPA and NWIRP McGregor was listed as a facility that used ammonium perchlorate in the production of rocket motors. In 1998, the Texas Natural Resource Commission, now the Texas Commission of Environmental Quality (TCEQ), instructed the Navy to begin investigating environmental media at the site for evidence of perchlorate contamination. Perchlorate was detected in three drainage basins at the former NWIRP McGregor facility.

In 1999, bench scale studies were conducted to determine the best approach for remediating perchlorate in the geologic and hydrogeologic environments found at the site. Anaerobic biological degradation was selected as the best remediation approach. Two biological systems were designed, one active and one passive. The active system, located in the southwest drainage basin where the highest perchlorate concentrations were found, came on line in 2002 and consisted of the following:

- three cutoff trenches (totaling approximately 6,000 feet) keyed into a non-water- bearing zone 15 to 25 feet below ground surface and 3 feet wide
- a 400 gpm capacity anaerobic fluidized bed reactor (FBR)
- storage lagoons within the footprint of the cutoff trenches capable of managing approximately 16 million gallons of water
- a permitted discharge outfall when needed (Figure 62).

As of 2014, the system has processed and degraded approximately 70% of the 8,200 pounds of perchlorate mass originally thought to be present in the shallow water bearing zone within the 200-acre footprint of the cutoff trenches (Figure 63).


**Figure 62. Fluidized bed reactor (FBR) on the left and treatment system components and water management system on the right** (NAVFAC SE, 2016)**.**

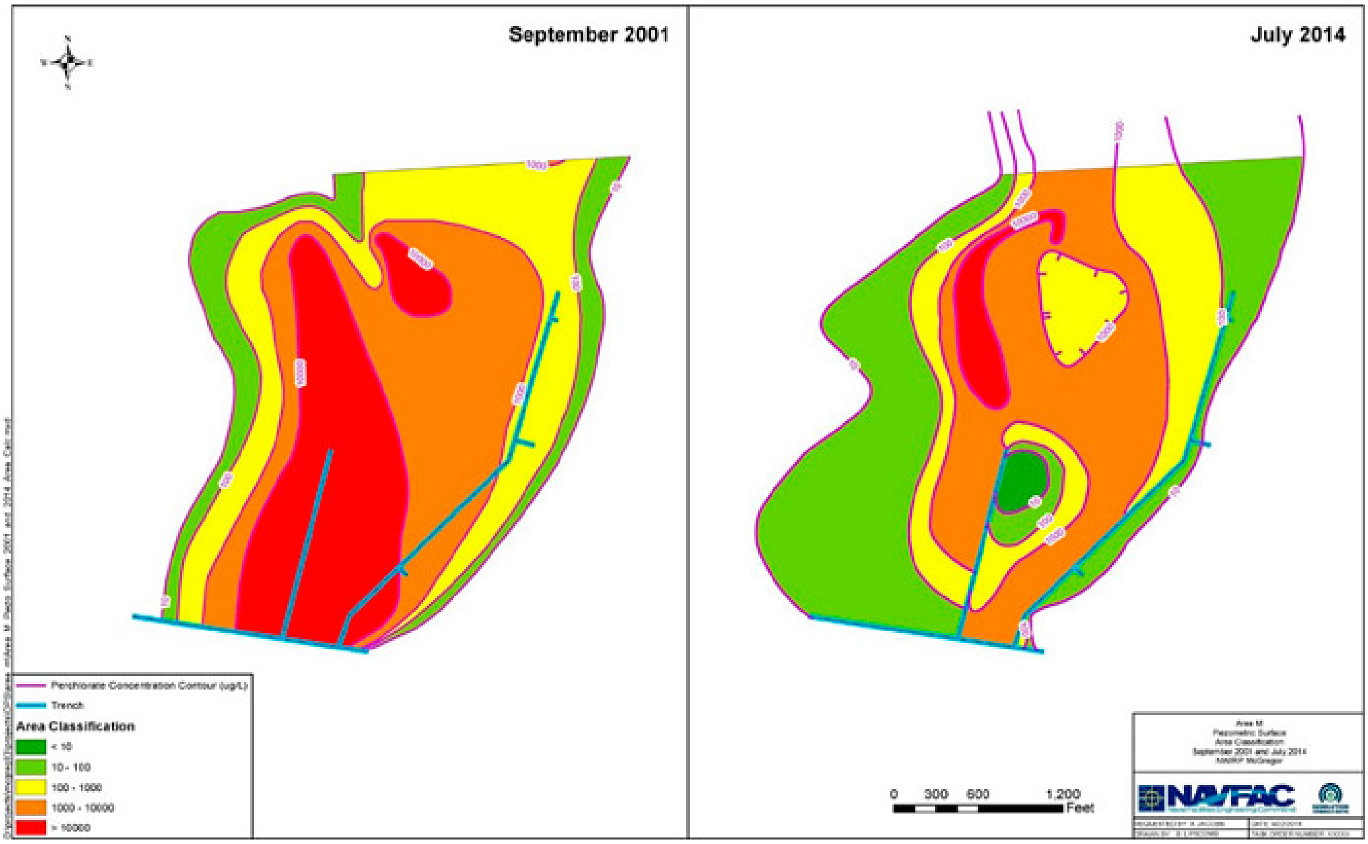


**Figure 63. Estimated plume mass in 2001 (8,200 lbs) and in 2014 (2,600 lbs)** (NAVFAC SE, 2016)**.**

Water storage is managed through a combination of reinfiltration, evaporation, and active discharge. Groundwater elevation in the trenches is maintained to prevent perchlorate-contaminated groundwater from discharging into surface water.

Because the 1999 pilot studies demonstrated that perchlorate degraded almost instantaneously when the groundwater was exposed to anaerobic conditions, the Navy decided to use an innovative passive remedial approach in the northeastern and southeastern drainage basins where lower perchlorate concentrations plumes had been delineated. The NWIRP McGregor project team agreed to this approach and remedial action plans were developed with the provision that the passive system and associated plumes be monitored under a long-term monitoring (LTM) groundwater program. In areas of low topographic relief, the passive system consisted of segmented 3-foot wide trenches keyed into the non-water bearing zone. The trenches (called “biowalls”) were filled with a mixture of gravel combined with wood chips and mushroom compost soaked in vegetable oil. The trench design included piping that would allow emulsified oil to be injected when necessary to rejuvenate the carbon content so the localized anaerobic conditions could be maintained. This passive system consisted of 35 segments ranging in length from 42 feet to 1,000 feet; in all, approximately 11,200 feet of biowalls were constructed between 2002 and 2005. In areas where topographical relief was steeper and the biowall seeps were likely, the passive system consisted of three staggered lines of 12-inch borings (bioborings) keyed into the non-water-bearing zone. Once drilled, the bioborings were filled with the same mixture of gravel with wood chips and mushroom compost soaked in vegetable oil to create a localized anaerobic zone. Unlike the first generation of bioborings, a second generation of bioborings are being designed with piping to allow emulsified oil to be injected when necessary. Because of these efforts, the distal parts of the perchlorate plumes have receded towards the former facility.

## 6.14.2 Monitoring/Optimization

### 16.14.2.1 Monitoring

O&M of the FBR, biowalls, and LTM have been ongoing since 2002. Because the facility is closed, operation of the FBR is performed remotely through an internet portal that is checked twice daily and through site visits twice a week. If an operational issue develops while no one is on site, the system is designed to automatically send out an alarm to the operator. Depending on the situation, the operator may be able to solve the issue via the portal or, if need be, make an unscheduled trip to the site for repairs. During weekly visits, influent and effluent samples are collected and the system is inspected.

The FBR maintains biological reducing conditions through a chemical feed system that is regulated continually according to influent flow and perchlorate and nitrate concentrations. The main chemical carbon source is 6% acetic acid. Effluent water can be directed to the various holding lagoons, where it can be stored for evaporation and/or discharge through a permitted outfall.

Water samples are collected from ports in the biowalls on a semiannual basis along with field measurements. Effectiveness is monitored through the following screening parameters that are scaled and then added to determine if carbon replenishment is required:

- total organic carbon
- nitrate
- methane
- oxidation-reduction potential
- perchlorate

Carbon is replenished by mixing emulsified oil and water, then transporting the mixture to the injection ports by trailer. The mixture is then pumped into the biowall.

During the remedial investigations and evaluation of groundwater, approximately 800 monitoring wells were installed across the former facility and on off-site property. In 2006, when the LTM program was initiated, the number of active monitoring wells that were to be used to monitor the effectiveness of the remedial program was approximately 160; the rest had been abandoned. The LTM program consists of an annual sampling with a few select wells sampled on a semiannual basis. The analytical suite performed on each well is perchlorate, VOCs, or a combination of the two. Results from the monitoring are reported to TCEQ and USEPA on a biennial basis. The number of wells currently being monitored has been reduced to approximately 100 wells through optimization of the long-term management monitoring program. The elimination of monitoring wells is a good indication that remedial systems remain effective and that the size of the groundwater plumes are decreasing.

#### 6.14.2.2 Optimization

The Navy has embarked on a holistic optimization program consisting of the following three elements:

- Transition the FBR, the cutoff trenches, and water storage management structures to a remediation system consisting of combination biowalls and bioborings in the southwestern plume area.
- Reevaluate Groundwater Resource Classification based on data collected during remedial activities with the goal of changing the Resource Classification from Class 2 to Class 3. If approved, the PCL screening values will be raised by a factor of 100 (perchlorate residential screening PCL value would be 1,700 µg/L and commercial/industrial value PCL 5,100 µg/L).
- Reevaluate the groundwater to surface water migration pathway in regards to dilution factors that will influence perchlorate concentrations before becoming a risk to human health and the environment.

#### 6.14.2.3 Status of the Optimization Program

The FBR will remain online during a transition period while evaluations of other remediation systems (including pilot tested biowalls) are evaluated. A set of second generation bioborings are scheduled to be installed in parts of the southwestern plume area the first quarter of 2016. The goal is to reduce perchlorate concentrations before groundwater enters the cutoff trenches and is processed through the FBR. If successful, this action will reduce O&M costs.

A technical memorandum has been submitted to TCEQ and USEPA presenting groundwater hydrogeologic data collected during remedial activities. The team has since approved the recommendation to change the Groundwater Class Resource from Class 2 to Class 3. A dilution study was conducted during a 6 month period from April through September 2015. The data have been processed and will be presented to TCEQ and USEPA for evaluation.

### 6.14.3 Regulatory Involvement

The Navy, TCEQ, and USEPA are working closely together to institute an innovative, cost-effective, and multifunctional approach to remediating perchlorate and VOCs. Future optimization planning will continue to focus on innovative passive methods to treat perchlorate in groundwater, and institutional controls to ultimately phase out the FBR system and bring the site to closure.

## 6.15 Hanford 200 Area ZP-1 OU, Washington

DOE's Hanford site, located in southeastern Washington state, was formerly used to produce plutonium for national defense. Nuclear reactors irradiated uranium fuel elements, followed by chemical processing to separate the isotopes of interest. During these processes, some of the liquid processing waste was disposed of in the subsurface. DOE manages the cleanup of these wastes and associated contaminated environmental media. Contamination includes organic compounds, such as solvents used in chemical processing, and a range of radionuclide and inorganic compounds.

DOE (2010b) estimates that liquid waste containing about 0.9 million kilograms of carbon tetrachloride was released to the soil column, out of which about 120,000 kg is in the aquifer (DOE 2008b). The groundwater is located 260 to 330 ft below the ground surface. The groundwater is contaminated with multiple contaminants, with the most prevalent including carbon tetrachloride, technetium-99, iodine-129, tritium, uranium, chromium, and nitrate. The contaminant plumes in the groundwater are large, with a carbon tetrachloride plume size of about five square miles (Figure 64). Extensive characterization through the installation of wells and sampling was conducted from 2004 to 2006 as a part of the remedial investigation and feasibility studies. The vadose zone and the groundwater in the 200-ZP-1 OU were studied to identify and locate carbon tetrachloride dense nonaqueous phase liquid (DNAPL) source terms. The results of this characterization are documented in *Carbon Tetrachloride Dense Non-Aqueous Phase Liquid (DNAPL) Source Term Interim Characterization Report* (DOE/RL-2006-58) and its addendum (DOE/RL-2006-22). The conceptual site model developed in those reports supports a DNAPL source term in the vadose zone at the 216-Z-9 Trench at a depth of 65 ft. The data obtained do not indicate a DNAPL source in the 200-ZP-1 OU groundwater.

Aquifer materials are an interstratified fluvial lacustrine sequence of unconsolidated to semiconsolidated clay, silt, sand, and granule-to-cobble gravel deposited by the ancestral Columbia River. A tall (up to 80 feet), extensive groundwater mound that was created while wastewater was discharged during former site operations is diminishing to the point that the water table has decreased by several yards over the last 25 years, resulting in significant changes in groundwater flow velocity and direction.

Remediation objectives target drinking water standards. Protection of the Columbia River is also of concern, but the river is more than 12 miles downgradient of the area of contamination. In addition to federal and state regulatory agencies, tribal rights affect the site and active stakeholder organizations are present.

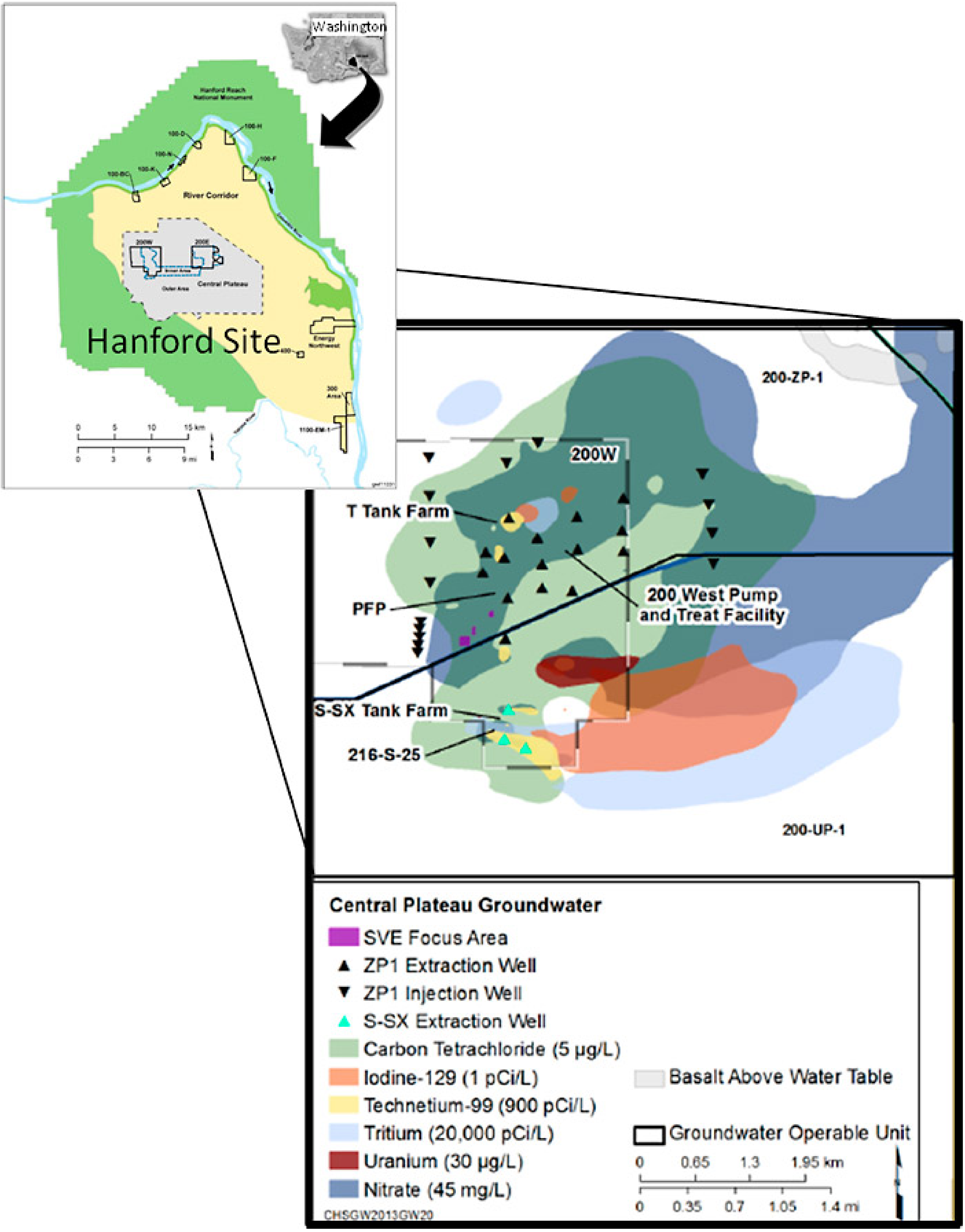


**Figure 64. Major groundwater plumes in the DOE Hanford Site 200 West Area, including 200-ZP-1 (top) and 200-UP-1 (bottom) operable units** (adapted from DOE 2014)**.**

### 6.15.1 Technical Basis for Remedial Action

To stop contaminant loading to groundwater through vapor phase transport, especially from the vadose zone source of carbon tetrachloride, an active SVE system was installed (DOE 2007b). SVE was initially installed as a part of the CERCLA interim action and expanded after a final ROD in 2011 (Smith and Stanley 1992).

The primary sources for this carbon tetrachloride are three waste sites (216-Z-9 Trench, 216-Z-1A Tile Field, and 216-Z-18 Crib) used from 1955 to 1973 for the disposal of waste liquids from historical Plutonium Finishing Plant process operations (Figure 65). Figure 65 shows all wells located near the three waste sites that are used to support active SVE operations.

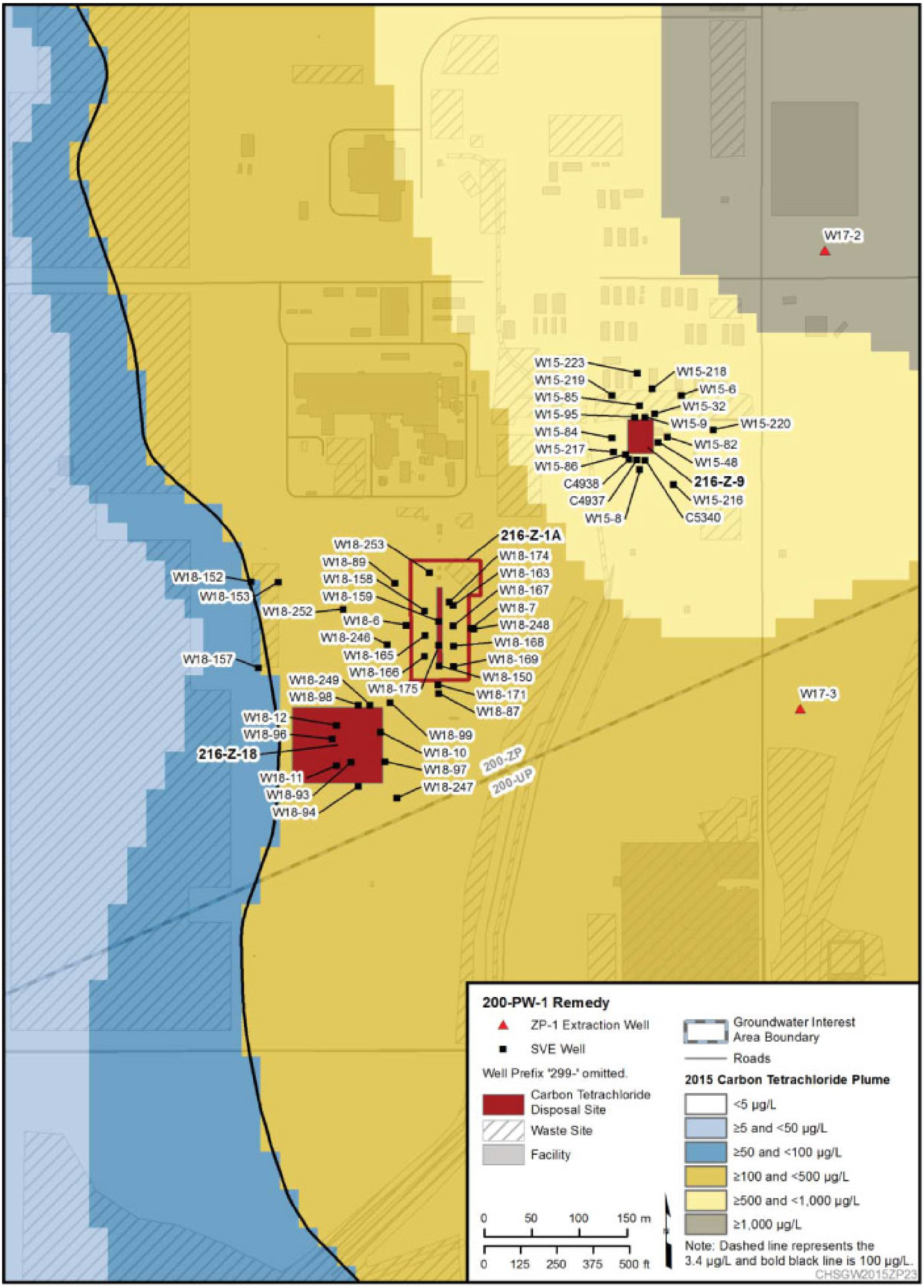


**Figure 65. Waste site sources of carbon tetrachloride** (DOE 2015a).

The purpose of the SVE operations near these waste sites is to mitigate the threat of carbon tetrachloride vapors migrating through the soil column and contaminating the underlying groundwater. A total of 80,107 kg of carbon tetrachloride have been removed from 1992-2012 from the vadose zone (Figure 66) through the processing of 118 billion cubic meters of soil vapor (USEPA and United States Department of Energy and Ecology 2011). The concentration of carbon tetrachloride declined from approximately 30,000 ppmv in 1993 to below the final clean up level of 100 ppmv in 2013. In November 2015, USEPA concurred that the SVE remedy met the RAOs in the ROD and that the soil vapor extraction activities could end. A response action report was prepared in 2015 to close out the SVE portion of the 200-PW-1 OU remedy in the ROD. During SVE operations, vapor-phase carbon tetrachloride was extracted through multiple vadose zone locations.

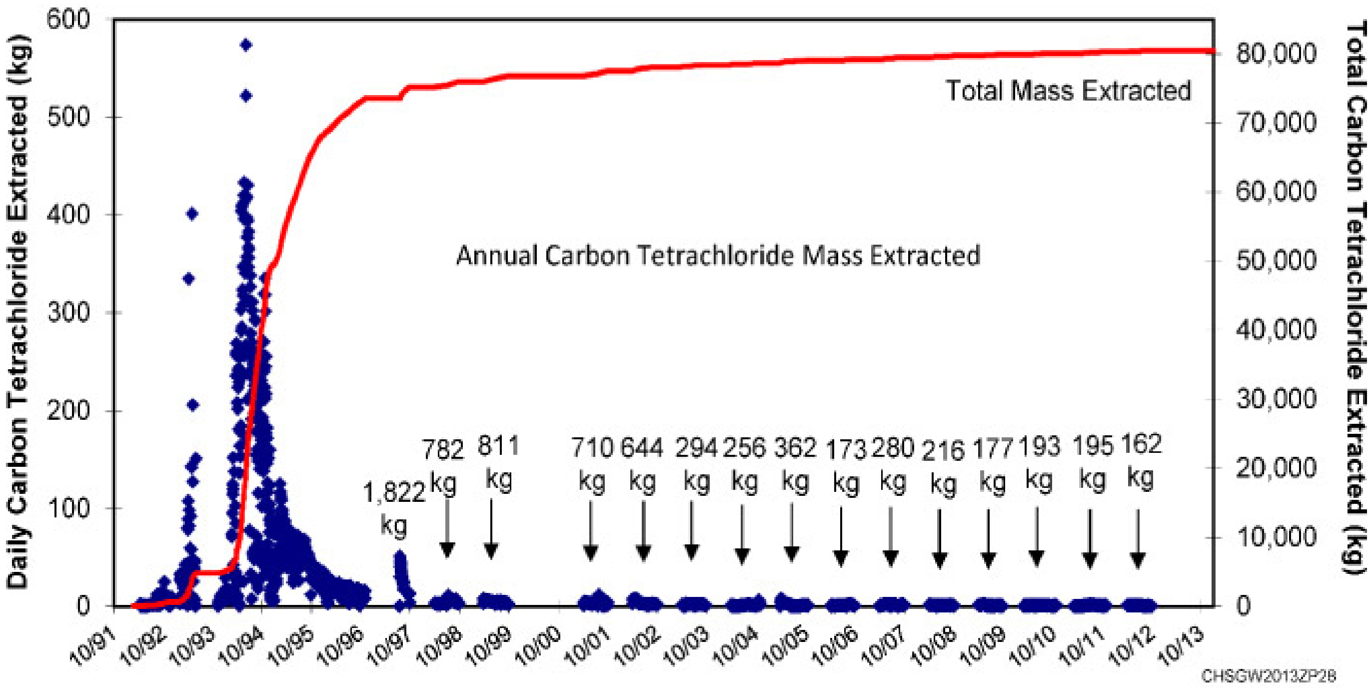


**Figure 66. Carbon tetrachloride extracted from soil vapor** (DOE 2013)**.**

Passive SVE systems were also installed in 1999 at eight wells near the vadose/groundwater interface at the 216-Z-1A/216-Z-12/216-Z-18 well field. The passive systems have check valves that allow only soil vapor flow out of the borehole (one-way movement) and canisters holding granular activated carbon that adsorbs carbon tetrachloride upstream of the check valves before the soil vapor is vented to the atmosphere. The check valve prohibits flow of atmospheric air into the borehole during a reverse barometric pressure gradient, which tends to dilute and spread carbon tetrachloride vapors in the subsurface. The wells are sampled periodically upstream of the granular activated carbon canisters. During 2009, the maximum carbon tetrachloride concentrations ranged from 5 to 17 ppmv. Because of low extraction and high maintenance, the system is no longer in operation.

In the groundwater, numerous wells have been installed and monitored over the last 25 years as part of remedial investigation activities (DOE 2006). An interim remedial measure P&T system was initiated in 1994 to prevent carbon tetrachloride from spreading. During the interim remedial measure, carbon tetrachloride concentrations decreased in the original target area and more than 24,000 lb of carbon tetrachloride were removed from groundwater and treated. The interim remedial measure and remedial investigation provided data to define the nature and extent of the plumes. In addition, laboratory studies have been conducted to provide a technical basis to estimate the important contaminant fate and transport parameters. These studies have determined sorption parameters and natural attenuation evaluations, such as evaluating the rate of carbon tetrachloride abiotic hydrolysis under aquifer conditions (for example, Amonette et al. 2012, Truex et al. 2001). With the groundwater hydraulic gradient declining toward pre-Hanford conditions, groundwater flow is slowing. Because of the current high mass of contaminants in the aquifer, natural attenuation alone will not be sufficient to reach remediation objectives. If a portion of the contaminant mass is removed, however, then natural attenuation can then be effective in reaching remediation goals and can limit plume migration until concentration targets are reached. These objectives will require a lengthy time frame. DOE has administrative control over the site and it is expected to remain under federal control throughout the duration of the remedy.

### 6.15.2 Decisions

In addition to remedial investigation characterization, site activities leading to a remedy decision have included treatability tests (such as in situ bioremediation), scientific studies of biogeochemical processes relevant to natural attenuation and candidate remediation technologies, and an interim remedial action consisting of targeted P&T operations (Hooker et al. 1998, Truex et al. 2001, Murray, Bott, and Truex 2007, DOE 2007, 2008a, Amonette et al. 2012). Numerical modeling studies have been applied to evaluate plume behavior and to support evaluation of remedial alternatives in the feasibility study (DOE 2007).

A ROD was completed in 2008 and signed by USEPA, the DOE, and the Washington State Department of Ecology (USEPA and United States Department of Energy and Ecology 2008). The ROD specifies a period of P&T remediation to reduce the mass (by about 95%) and concentration of contaminants in the aquifer over an expected 25-year operational period. The remedy then transitions to a period of natural attenuation expected to control plume migration. Up to 100 years will be required to achieve RAOs.

### 6.15.3 Assessment

The feasibility study included evaluation of three remedial alternatives. These alternatives were selected from a screening evaluation of multiple options, most of which were not suitable because of challenges associated with the significant depth to groundwater, variety of contaminants, and plume thickness and lateral extent. The remedial alternatives included

- no action
- ICs and MNA
- a phased remedy consisting of P&T, MNA, flow path control, and ICs

The selected remedy was Alternative 3 (P&T, MNA, flow path control, and IC). The system was designed to capture and treat contaminated groundwater to reduce the mass of carbon tetrachloride, total chromium (trivalent and hexavalent chromium), nitrate, trichloroethylene, iodine-129, and technetium-99, throughout the 200-ZP-1 OU by a minimum of 95% in 25 years. The P&T component was designed and implemented in combination with MNA to achieve cleanup levels for all COCs in 125 years. Carbon tetrachloride concentrations in the groundwater above 100 µg/L correspond to approximately 95% of the mass of carbon tetrachloride currently residing in the aquifer. The estimated pumping rate required to reduce the mass of COCs by 95% in 25 years is 1,600 gpm for this action. The fate and transport evaluation estimated that a system comprised of 27 extraction and 27 injection wells would be needed to achieve the design requirements.

For the MNA component, fate and transport analyses conducted as part of the feasibility study (DOE 2007) indicate that the time frame necessary to reduce the remaining COC concentrations to acceptable levels will be approximately 100 years. Modeling also indicates that this portion of the plume area will remain on the Central Plateau geographic area during this time frame. Flow-path control is also required and will be achieved by injecting the treated groundwater into the aquifer to the northeast and east of the groundwater contaminant plumes to reduce and locally reverse the natural eastward hydraulic gradient in the aquifer. The mounding of groundwater in the aquifer from these wells slows the natural eastward flow, keeps most of the COCs within the hydraulic capture zone of the extraction wells, and allows natural attenuation to reduce contaminant concentrations.

Injection wells installed to the west (upgradient) are used to recharge the aquifer, steepen hydraulic gradients to the east, and minimize the potential for groundwater in the northern portion of the aquifer to flow northward through Gable Gap toward the Columbia River. At present, an average of 25 extraction wells and similar number of injection wells are operating with an average extraction rate of 2,000 gpm. The extraction rate is planned to as high as 2,500 gpm soon. Figure 67 shows the configuration of the P&T system in the area.

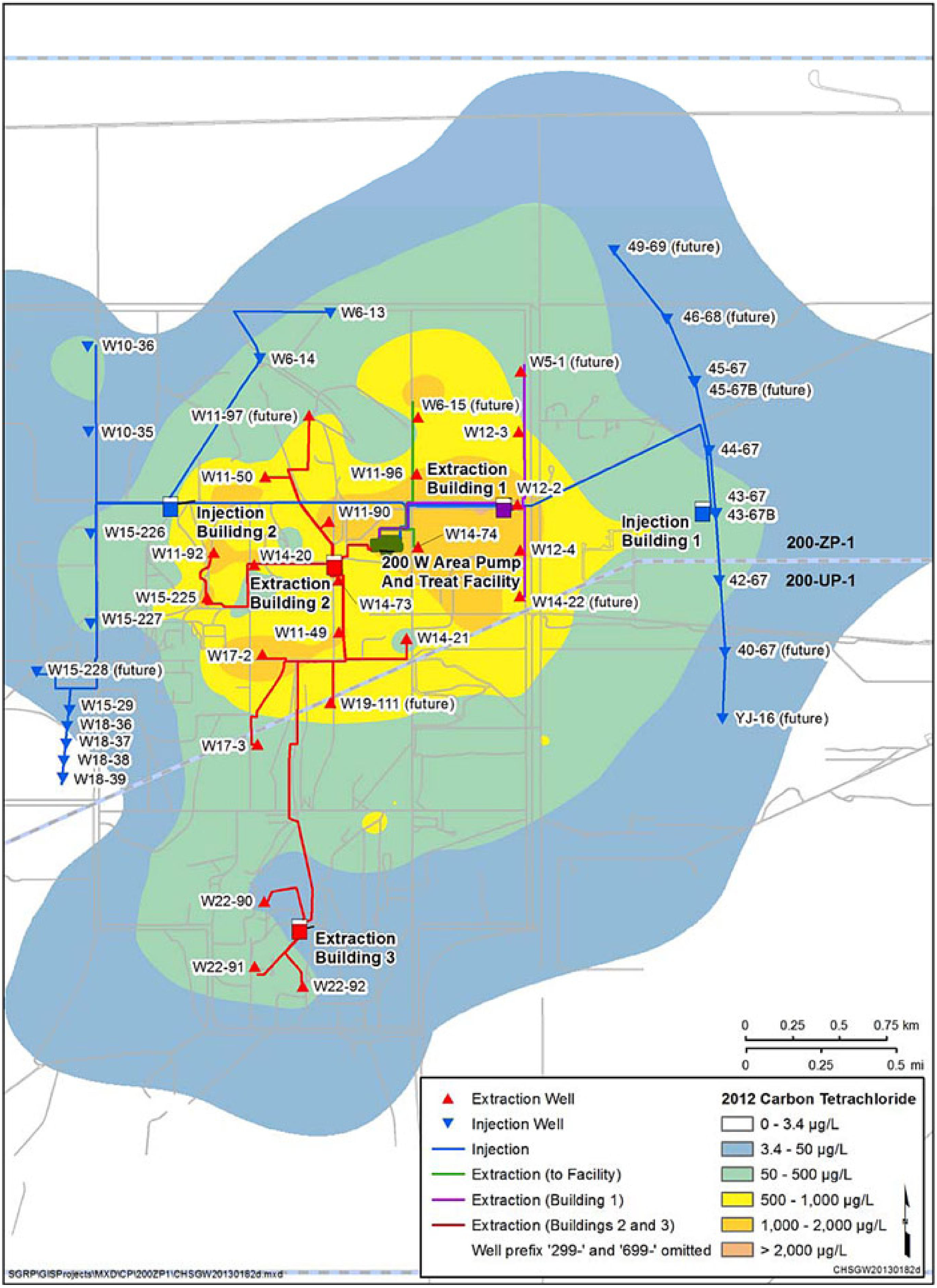


**Figure 67. 200 West Area groundwater extraction and treatment system** (CH2M Hill 2009).

The P&T is applied to contain the plume and remove contaminant mass under conditions where P&T can be effective. Given the expected diminishing effectiveness of P&T in addressing the heterogeneous aquifer and reaching low concentrations, the remedy transitions to MNA. MNA has been evaluated as an effective means to reach RAOs and prevent plume migration once COC concentrations are lower. Because of the large plume and slow attenuation rates, a long time will be required to meet the RAOs. Federal control of the site will enable application of suitable ICs to prevent exposure during the remedy time frame.

### 6.15.4 Monitoring/Optimization

Monitoring will be implemented in conjunction with the remedy and will verify that plumes are being reduced to obtain conditions suitable for a transition to MNA. P&T operations can be optimized as needed based on these data. Monitoring is also planned during the natural attenuation period to fulfill the requirements of a MNA remedy. ICs will be administered by the DOE as part of their ongoing management of the site.

### 6.15.5 Regulatory and Stakeholder Involvement

The Tri-Parties developed the *Hanford Site Tri-Party Agreement Public Involvement Community Relations Plan* (CRP) in 1990 as part of the overall Hanford Site cleanup process. The CRP was designed to promote public awareness of the investigations and public involvement in the decision-making process. The CRP emphasizes an ongoing, interactive relationship with stakeholders.

A Federal Advisory Committee Act (FACA) chartered board was created specific to Hanford, and is called the Hanford Advisory Board (HAB). All discussions and meetings are open to the public. The HAB issued formal advice that was either specific to (Israel 2006) or relevant to (NAVFAC 2010b) this remedial action. The HAB, the state of Oregon, and stakeholders have had a long-standing focus on groundwater cleanup, and have influenced the remedy selection both directly and indirectly.

The following activities were conducted as part of the community participation process specific to CERCLA remedial action decisions:

- A 30-day public comment period for the Proposed Plan (DOE/RL-2006-33) ran from July 21 through August 19, 2008. This comment period was publicized via a newspaper advertisement in the *Tri-City Herald* on July 21, 2008, and a fact sheet was mailed or sent electronically to more than 1,500 individuals on the Tri-Party Agreement mailing list. The public was provided the opportunity for public meeting, but no request for a meeting was received.
- The Tri-Parties' responses to all significant comments received during this period are included in the Responsiveness Summary, which is Part III of the ROD.

DOE also directly interacts with affected tribal nations to obtain input on all remedy decision documents.

## 6.16 Industrial Site, Australia

An industrial site in Australia was used for the manufacture of 1,2-dichloroethane in the 1960s. In 1969, a grassfire engulfed a drum store containing hundreds of drums of chlorinated hydrocarbon byproducts, resulting in contamination of a fractured basalt aquifer and a groundwater contaminant plume that is intercepted by a deep, leaky sewer approximately 2 km away. The groundwater is naturally saline (TDS >8,000 mg/L) and is not used for drinking, irrigation, or stock watering.

The fractured basalt aquifer is approximately 20 m thick and is underlain by a clay layer, a deeper basalt aquifer, and a series of deeper formations. Depth to the water table beneath the site is typically 8 to 9 m, and the estimated groundwater velocity at the site is 5-70 m/year. Monitoring shows that impacted groundwater does not discharge to any surface water bodies. The quantity of chlorinated hydrocarbons intercepted by the sewer is monitored by sampling and flow measurement at the inlet to the sewage treatment plant approximately 3 km from the groundwater plume.

The initial source area remedy included installation of a 45-m air sparge/soil vapor extraction (AS/SVE) boundary control system to limit off-site migration of chlorinated hydrocarbons in groundwater. Over 300 m of the basalt aquifer was blast-fractured to 19 m below ground surface, and the AS/SVE system was operated for seven years (2007 to 2014). When an active dechlorinating zone was discovered in the source area, microcosm trials, microbe surveys, and compound specific isotope analysis (CSIA) were conducted. The results of these studies allowed the AS/SVE system to be shut down and the source area remedy transitioned to enhanced in situ bioremediation (EISB) using propylene glycol (PG) as an electron donor.

### 6.16.1 Overview of Contaminants

The mixed chlorinated ethanes, ethenes, and methanes in source area groundwater include:

- 1,1,2,2-tetrachloroethane (1,1,2,2-TeCA)
- 1,1,2-trichloroethane (1,1,2-TCA)
- 1,2-dichloroethane (1,2-DCA)
- tetrachloroethene (PCE)
- trichloroethene (TCE)
- 1,1-dichloroethene (1,1-DCE)
- cis-1,2-dichloroethene (cis-1,2-DCE)
- trans-1,2-dichloroethene (trans-1,2-DCE)
- vinyl chloride (VC)
- chloroform (CF)
- dichloromethane (DCM)

BTEX, primarily toluene, is also present in the source area. Three DNAPL samples have been recovered from the basalt aquifer on site.

### 6.16.2 Overview of Site Complexities

Source area complexities include the following:

- a large source area, over 3 ha (approximately 300 m by 100m by 12 m thick), assumed to be middle stage, based on release timing (1969) and field data
- a highly heterogeneous basalt aquifer with permeable weathered zones, intermittent clay and sand lenses, variable columnar and horizontal fracturing and vesicular zones
- high dissolved-phase concentrations of mixed chlorinated organics with potential inhibitory effects including chloroform and competing electron acceptors (for example, 400-500 mg/L of $SO_4^{2-}$)
- high background salinity with additional salinity contributions from historical site operations
- a large DNAPL release during a 1969 grassfire, estimated at over 100 tonnes
- DNAPL in both the saturated and vadose zones
- transmissive and nontransmissive zones that are impractical to survey and map, except on a broad-scale

semiqualitative basis, using injection and pumping experience, bedrock core logging, and geophysical surveys

### 6.16.3 Technical Basis for Remedial Action

#### 6.16.3.1 Site Characterization

High resolution site characterization in the large, heterogeneous, fractured basalt source area (>3 ha) was considered impractical. Instead, it was more cost effective to conduct broader-scale site characterization, and then design, install, and operate a full-scale in situ bioremediation system with aggressive soluble amendment injections and groundwater recirculation. As intensive monitoring revealed various source zone characteristics, the EISB design and operation could be iteratively adapted and modified. This approach is consistent with the observational and adaptive approach recommended by NRC for fractured rock sites (NRC 2015).

Site characterization activities that were conducted included the following:

- installation of groundwater monitoring wells to broadly delineate dissolved-phase contamination
- coring basalt to visually characterize fractures and geology, as well as map the more continuous clay layer at the base of the basalt flow
- use of FLUTe liners in open boreholes to test for presence of residual DNAPL
- testing of basalt samples for density, TOC, porosity, and adsorption capacity
- testing of crushed basalt samples for VOCs after methanol extractions, and thermal desorption tests
- pilot air sparge and soil vapor extraction trials, before and after blast-fracturing
- laboratory microcosm trials to assess potential for natural attenuation (off-site) and bioremediation (in source area) and to evaluate PG versus emulsified vegetable oil (EVO) as an electron donor.
- in situ microcosm trials in source area wells, using biotraps to verify PG selection
- column trials using zero valent iron (ZVI) and ZVI plus organic carbon to evaluate the suitability of a permeable reactive barrier (PRB) remedial approach
- field trials to assess biodegradation of vinyl chloride in the vadose zone
- DNAPL recovery pumping tests
- pump tests to evaluate hydraulic conductivity and potential use of P&T for plume containment and recirculation of microbially active groundwater
- use of microbiological tools (MBTs) to characterize baseline microbe populations and to monitor and determine key process variables (KPVs) for EISB, as well as CSIA to assess degradation processes
- installation of eight long-screened monitoring wells across a 300 m transect located downgradient from the source area, and measurement of Darcy velocities using passive flux meters (PFMs) to enable estimated mass discharge to be used as a metric for assessing the effectiveness of source area remediation
- PFM surveys across two transects further downgradient in the off-site plume to estimate mass discharge across each transect, which was compared with chlorinated hydrocarbons captured by the leaky sewer system (Annable et al. 2014)

#### 6.16.3.2 Conceptual Site Model

Figure 68 shows typical preblast and postblast basalt cores in the main source area. Note that fractures appear to be predominantly near-horizontal, with some vertical fracturing, together with an underlying clay layer at the base of the basalt flow. Blast designs aimed to avoid disrupting this clay layer by leaving a 2-m buffer of nonblasted basalt above it, based on blasting experience at local basalt quarries. Effective porosity was assumed to be 1% for estimating pore volumes.

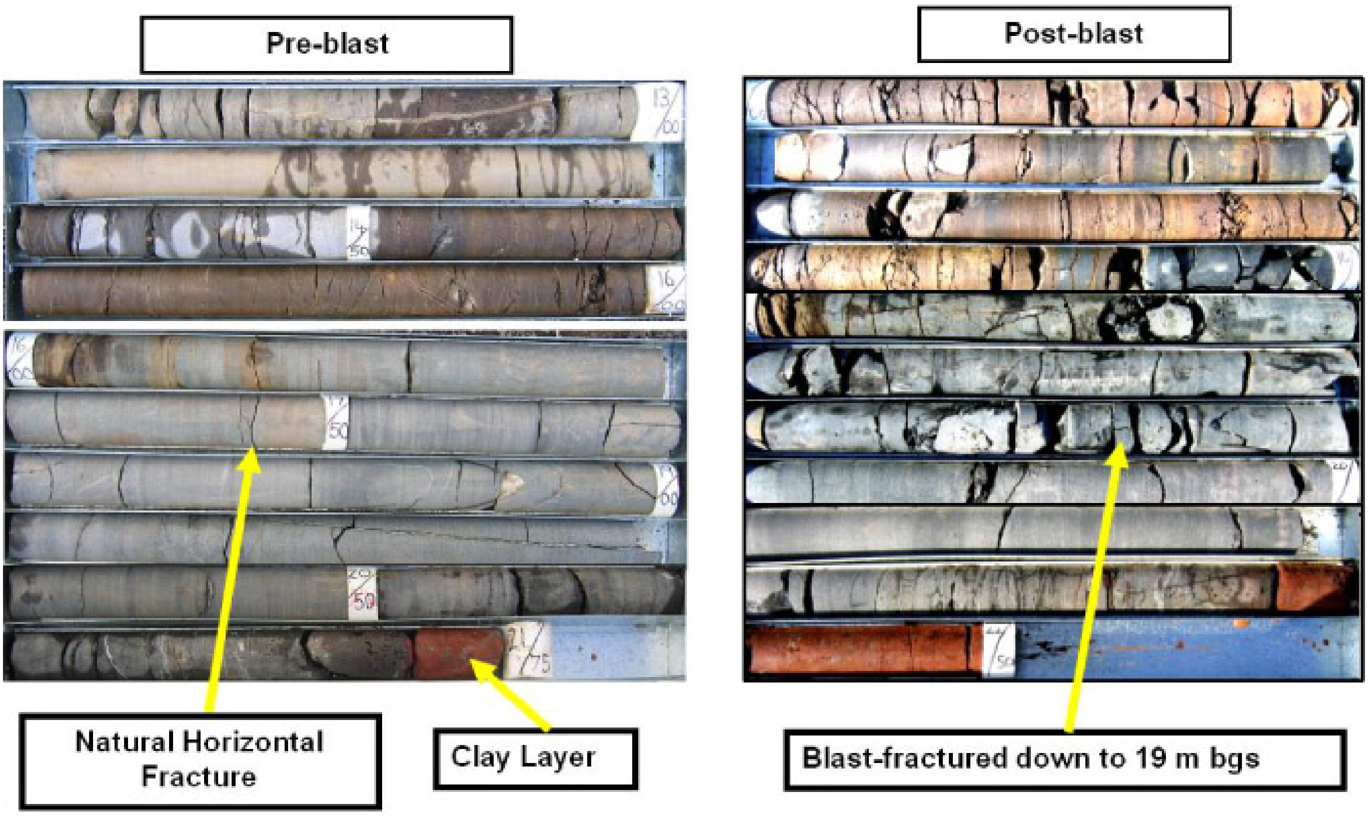


**Figure 68. Typical preblast and postblast basalt cores** (Goodwin et al. 2010)**.**

Figure 69 shows a 14-compartment model that summarizes the current CSM; see ITRC guidance (2011) for an explanation of the 14-compartment model. This model maps key areas where contaminant mass is located, and facilitates development and assessment of remedial alternatives. Figure 69 is based on the following assumptions for fractured basalt with low matrix porosity:

- Residual DNAPL is expected to be present in transmissive fractures in the source zone, probably mainly as ganglia. Dead end fractures in the source area may contain DNAPL, both above and below the water table. Thus, three zones in the source area have been classified as "high." Intermittent clay lenses and vesicles connected to transmissive fractures are also considered as part of low-permeability zones.
- The basalt matrix and clay samples had low TOC (average approximately 0.09%), and column tests confirmed that retardation of chlorinated solvents on basalt was minor, so the sorbed mass in off-site locations has been classified as "low."
- Equilibrium vapor concentrations in the vapor phase depend on aqueous concentrations at the water table. Field monitoring off site typically showed an order of magnitude (OOM) reduction below Henry's Law across the capillary fringe. Thus, the vapor phase in off-site plume areas has been represented as 1 OOM below equivalent aqueous concentrations in the groundwater.

| Phase/Zone | On-site Source Zones | | Off-site Proximal Plume Zone | | Off-site Distal Plume Zone | |
|---|---|---|---|---|---|---|
| | Low Permeability | Transmissive | Transmissive | Low Permeability | Transmissive | Low Permeability |
| Vapour | High | MODERATE | MODERATE | MODERATE | LOW | LOW |
| DNAPL | HIGH | HIGH | Not Applicable | Not Applicable | Not Applicable | Not Applicable |
| Groundwater | MODERATE | MODERATE | MODERATE | MODERATE | MODERATE | MODERATE |
| Sorbed | MODERATE | LOW | LOW | LOW | LOW | LOW |

**Key**

| | |
|---|---|
| | Equivalent aqueous conc. ~ 1000+ mg/L (OOM = 4) |
| | Equivalent aqueous conc. ~ 100+ mg/L (OOM = 3) |
| | Equivalent aqueous conc. ~ 10+ mg/L (OOM = 2) |
| | Equivalent aqueous conc. ~ 1+ mg/L (OOM = 1) |

**Figure 69. 14-Compartment model (middle stage)** (Confidential source 2017)**.**

Table 20 shows key results from testing three samples of DNAPL. Note the change in composition of DNAPL2A and DNAPL2B (sampled from the same well) over 16 years. The percent by weight (wt.%) of 1,2-DCA had decreased and the wt% of the least soluble compounds increased. Note also the theoretical predicted solubilities (from Raoult's Law) versus the range of dissolved-phase concentrations measured in the field. While the concentrations of 1,1,2-TCA, 1,1,2,2-TeCA, 1,2-DCA, PCE, TCE, and chloroform are consistent with DNAPL dissolution, the VC and ethene concentrations measured in the field indicate active biodegradation processes. The mean stable isotope d$^{13}$C (‰) values in the last column can be used to assess degradation processes.

**Table 20. Characterization of DNAPL samples** (Confidential source 2017)

| | **Mass Fraction (% w/w)** | | | **Predicted Solubility (mg/L)** | | **Measured in Field** | |
|---|---|---|---|---|---|---|---|
| **Compound** | **DNAPL 1 (2012)** | **DNAPL 2A (1998)** | **DNAPL 2B (2015)** | **DNAPL 1** | **DNAPL 2B** | **Concentration (mg/L)** | **Mean DNAPL $\delta^{13}$C ($^0/_{00}$)** |
| 1,1,2-TCA | 82.4 | 18.56 | 28 | 3,646 | 1,089 | <1 to >1,000 | -40.9 |
| 1,1,2,2 -TeCA | 10.46 | 2.67 | 3.11 | 248 | 62 | <1 to >140 | -28.3 |
| 1,2-DCA | 5.24 | 72.76 | 56.7 | 612 | 5,739 | <1 to >1,000 | -27.4 |
| PCE | 1.01 | 1.31 | 3.6 | 1.2 | 4 | <1 to ~20 | -40.7 |
| TCE | 0.634 | 1.75 | 4.41 | 7 | 43 | <1 to ~50 | -51.2 |
| VC | 0.013 | | 0.01 | 0.7 | 0.2 | <1 to ~500 | -29.4 |
| 1,1-DCE | 0.027 | 0.227 | 0.17 | 1 | 5 | <1 to ~25 | – |
| $CCl_4$ | – | 1.07 | 0.69 | – | 4 | – | -13.3 |
| Chloroform | 0.012 | 0.53 | 0.52 | 0.8 | 40 | <1 to ~30 | -34.3 |
| Ethene | – | – | – | – | – | <1 to~40 | – |

Figure 70 shows key microbial degradation pathways for the chlorinated ethanes, ethenes, and methanes identified at the site (Ogles et al. 2014, Ogles et al. 2015). The site assessment concluded that the high concentrations of VC measured in parts of the source area were due primarily to dichloroelimination of 1,1,2-TCA and the high ethene concentrations were due primarily to dichloroelimination of 1,2-DCA. Chloroform is a potential inhibitor for biodegradation of cis-1,2-DCE and VC.

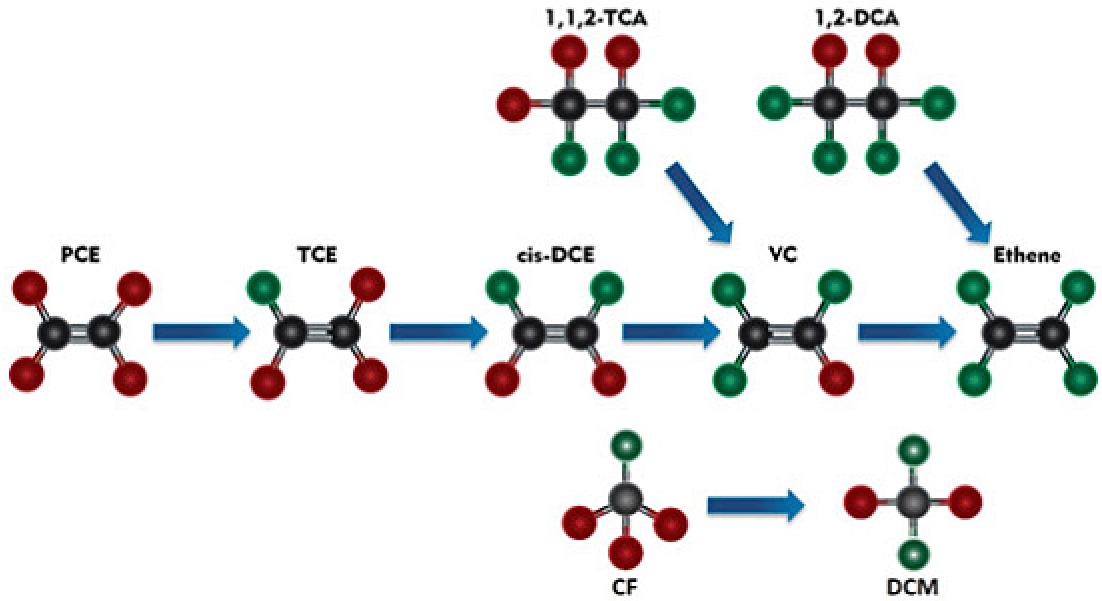


**Figure 70. Biodegradation pathways and potential chloroform inhibition at the site** (Ogles et al. 2014, Ogles et al. 2015)**.**

### 6.16.4 Regulatory and Stakeholder Involvement and Decisions

Following public notification of the groundwater problem in 1995, the environmental regulator facilitated development of a groundwater management plan (1995-1998) with input from a community advisory panel, consultants, city council, and other key stakeholders. Regular stakeholder consultations have continued for over 20 years, with annual progress reports to the Environmental Regulator and annual remediation reviews with a community environment monitoring team.

From 1998 to 2001, AS/SVE pilot trials at two source area locations concluded that while SVE was suitable for removing some DNAPL from the vadose zone, air injected under the water table would disperse uncontrollably with low sparge air recovery efficiency. Remediation by pumping and treating groundwater in an above ground air stripper was rejected because of the groundwater salinity and related water disposal issues. Microcosm studies investigated the natural attenuation potential; using radiolabeled carbon tetrachloride (CT) and TCE demonstrated intrinsic biodegradation of CT and CF, but results were inconclusive for TCE, PCE, and 1,1,2-TCA.

After another round of screening technology options, a pilot AS/SVE trial was conducted in a 15 m blast-fractured trench, designed to increase vertical fracturing and increase sparge air recovery efficiency. These trials demonstrated 90% reduction of total chlorinated hydrocarbons in the groundwater. Helium tracer tests showed practically 100% recovery of sparge air.

In 2003, the Environmental Regulator accepted a remediation action plan to install a full scale AS/SVE boundary control system (BCS) in the basalt aquifer with permeability enhanced by blast-fracturing, and issued a remediation notice requiring that the groundwater leaving the premises be cleaned up to the extent practicable (CUTEP). The groundwater remediation target, consistent with state environment protection policies, was to restore the potential beneficial use of groundwater for stock watering and to enable attenuation in the plume to occur naturally once mass discharge from the source had been reduced.

Following extensive stakeholder consultations, a 450 m long AS/SVE boundary control system was installed along the site boundary, with over 300 m of basalt being blast-fractured to depths of 19 m below ground surface. The system was operated from 2007 to 2014, recovering over 20 tonnes of chlorinated hydrocarbons which were destroyed in a catalytic oxidizer.

Before commissioning the BCS, a zone was discovered in the source area where active biodegradation of chlorinated hydrocarbons existed in an area where the groundwater contained volatile fatty acids (VFAs). Microcosm trials at University of New South Wales (2009-2010) showed that 1,1,2-TCA, 1,2-DCA and TCE could be biodegraded to ethene. PG was superior to EVO as an electron donor, because ethene conversions were higher and chloroform inhibition was less. In situ microcosm studies were conducted in the source area with PG and several other amendments to verify proposed use of PG. Microbe baseline surveys confirmed parts of the source area would require bioaugmentation by recirculating groundwater from biologically active zones, together with PG and pH buffer.

PFM surveys were conducted at three transects (2012-2014) and mass discharge from the site, as measured at Transect 1, was adopted as a key parameter for monitoring the combined effect of remedial measures in the source area (Annable et al. 2014, ITRC 2010b). Integrated monitoring found part of the source area where chloroform inhibition was limiting biodegradation. Regulatory approval was obtained to modify bioremediation operations, and bioaugmentation trials were initiated in 2014 using chloroform reducing cultures from University of New South Wales. Statistical analysis of key dechlorinating microbe populations was conducted to establish key operating parameters for the bioremediation system (Ogles et al. 2014, Ogles et al. 2015).

In 2014, the Environmental Regulator issued a new remediation notice requiring preparation of a new remediation plan, verified by an independent appointed environmental auditor, to remediate on- and off-site groundwater to the extent practicable. Annual progress reporting to the Environmental Regulator continues, with a revised, auditor-verified remediation plan required after five years.

## 6.16.5 Assessment of Implemented Remedial Alternatives

### 6.16.5.1 Air Sparge/Soil Vapor Extraction (AS/SVE) Boundary Control System (BCS)

The BCS achieved removal of >20 tonnes of chlorinated hydrocarbons over a seven-year period (2006-2014). However, the PFM survey of transect 1, located about 40 m downgradient from the site boundary, indicated that the BCS had probably bisected the original DNAPL source area, and 60% of mass discharge was occurring at depths consistent with bypassing beneath the AS curtain (Annable et al. 2014). By contrast, the EISB system provided a mechanism for ongoing degradation of chlorinated hydrocarbons beyond the site boundary and beneath the AS curtain.

### 6.16.5.2 Enhanced In Situ Bioremediation (EISB) System

Over a four-year period (2011-2015) more than 230 tonnes of PG, a 100% soluble amendment, was injected across and in the source area, and more than 14,000 $m^3$ of groundwater (about 4 pore volumes, based on 1% effective porosity) was recirculated around the source area to distribute amendment and microbes. Injection wells on the upgradient periphery of the source area were each injected annually, on a rotating basis, with 20 $m^3$ of PG solution buffered with potassium bicarbonate and chased with flush water. Chlorinated hydrocarbon, electron acceptor, ethene, methane, and VFA analysis was conducted together with QuantArray analysis to evaluate the potential for reductive dechlorination. CSIA was conducted on selected groundwater samples from the source area and downgradient plume to assess degradation pathways.

In the source area, following electron donor addition, increases in organohalide respiring bacteria were accompanied by decreases in parent compound concentrations, formation of degradation products, and stable isotope enrichment. One-way ANOVA revealed that for this source area, reaching total VFA concentrations greater than 1,000 mg/L and driving sulfate concentrations from 500 mg/L (background conditions) to below 50 mg/L were critical in consistently achieving *Dehalococcoides* populations greater than $10^4$ cells/mL. However, chloroform concentrations greater than 4 mg/L were inhibitory despite available electron donor and sulfate reducing or methanogenic conditions. After targeted recirculation and bioaugmentation in the inhibited area, *Dehalococcoides* populations were greater than $10^4$ cells/mL and vinyl chloride reductase gene copies increased by an average of three orders of magnitude in groundwater samples from nearly all monitoring wells. Chloroform reductase genes, which had not been detected prior to bioaugmentation, were also present.

Monitoring at Transect 1, (300 m wide and located approximately 100 m downgradient from the center of the source zone), continues to track performance of the source area EISB system. Figure 71 shows development of sulfate reducing conditions, from an initial background of 550 mg/L sulfate, while Figure 72 shows development of *Dehalococcoides,* and Figure 73 shows vinyl chloride reductase (vcrA) which indicates the potential for biodegradation of vinyl chloride to ethene. These charts track expansion of the biodegradation zone downgradient to Transect 1. Ongoing monitoring indicates that the biodegradation zone continues to expand down-hydraulic gradient, beyond Transect 1.

Amendment delivery to treatment zones is critical for in situ remediation systems. Figure 71 through Figure 73 indicate most wells across a 300 m wide transect met proposed operating targets for sulfate, *Dehalococcoides*, and vcrA by August 2015. The differing times required appear to be related to initial chloroform concentrations and differing VFA migration rates downgradient, consistent with the inherent heterogeneity of the basalt aquifer in and down-hydraulic gradient from the source zone.

Notably, the estimated mass discharge of total chlorinated VOCs from the source area, measured at eight groundwater monitoring wells over a 300 m wide transect, decreased by 80% over a two-year period, as shown in Figure 74. Mass discharge reductions for parent compounds 1,1,2-TCA and 1,2-DCA were even greater.

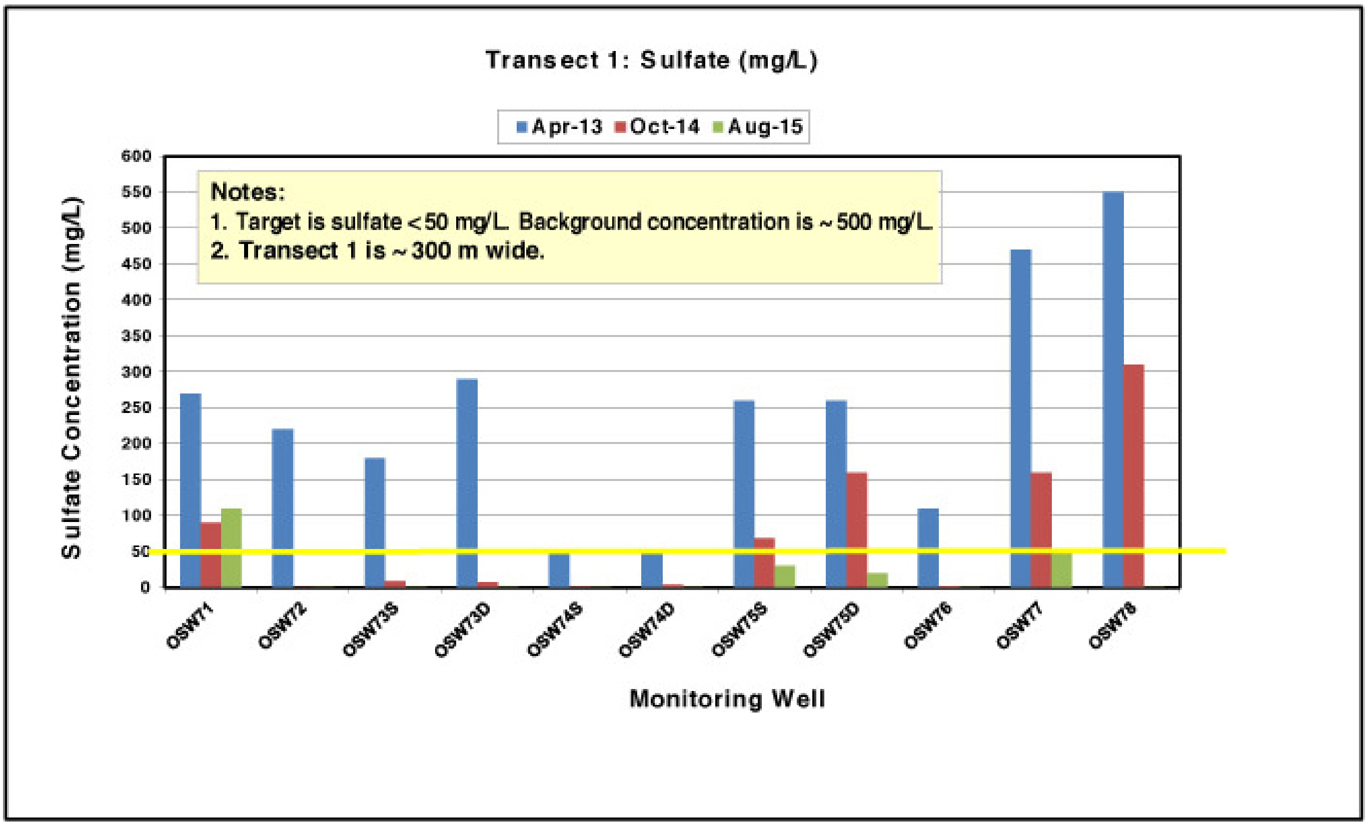


**Figure 71. Sulfate concentration across Transect 1 (immediately downgradient from source area)** (Confidential source 2017)**.**

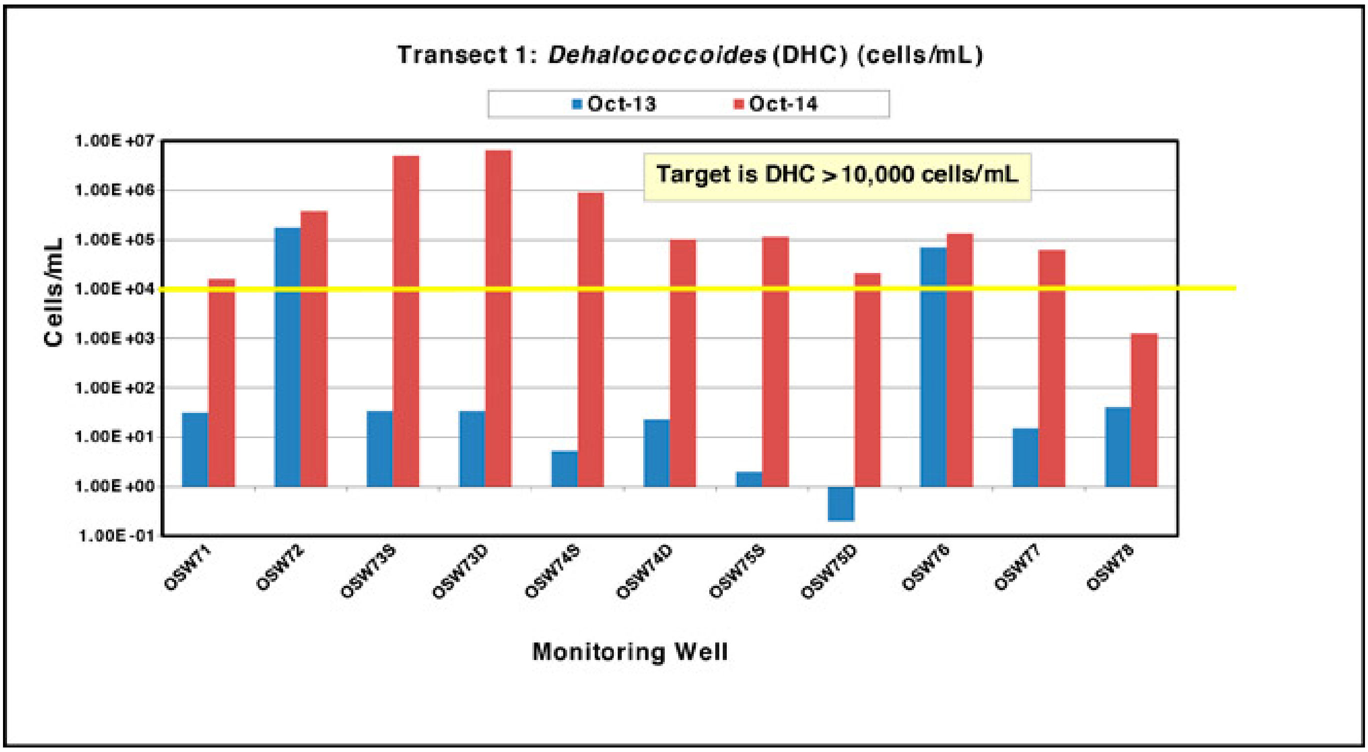


**Figure 72. *Dehalococcoides* (DHC) across Transect 1 (cells/mL)** (Confidential source 2017)**.**

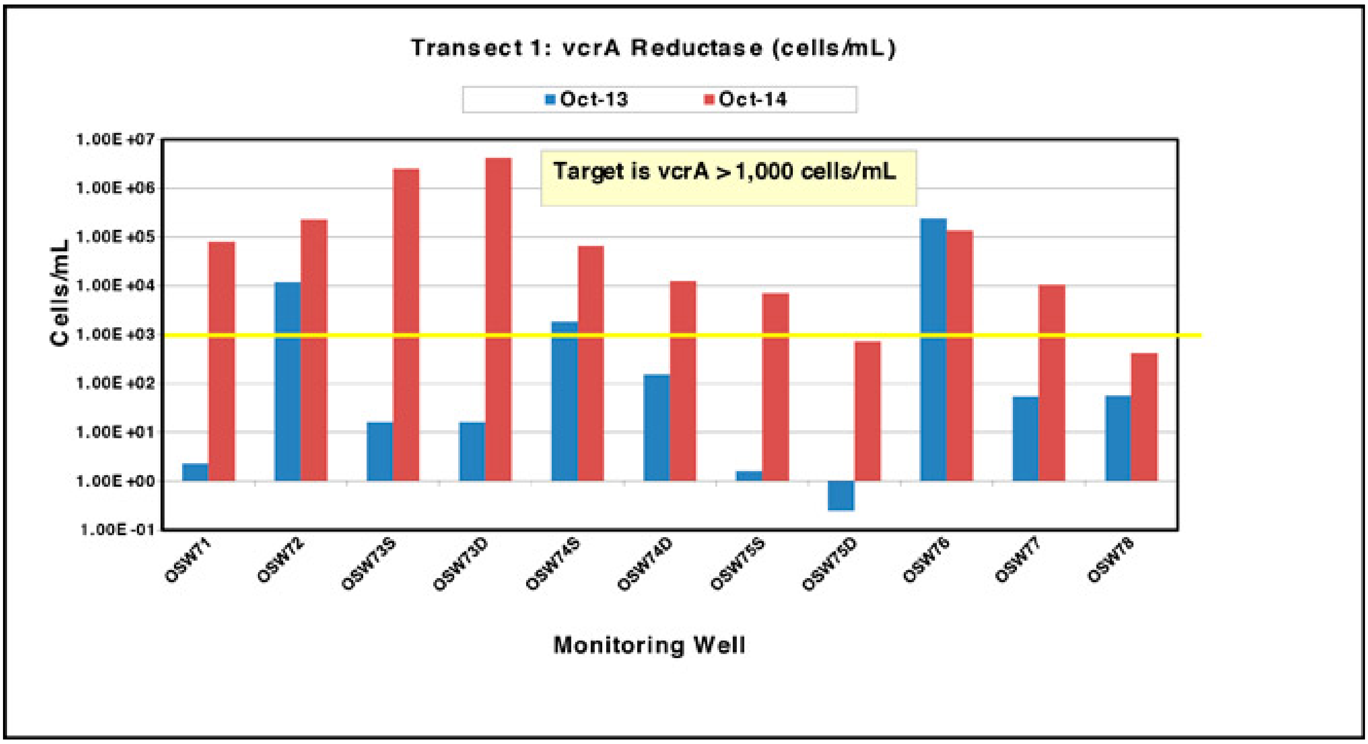


**Figure 73. Vinyl chloride reductase gene copies (vcrA) across Transect 1 (cells/mL)** (Confidential source 2017)**.**

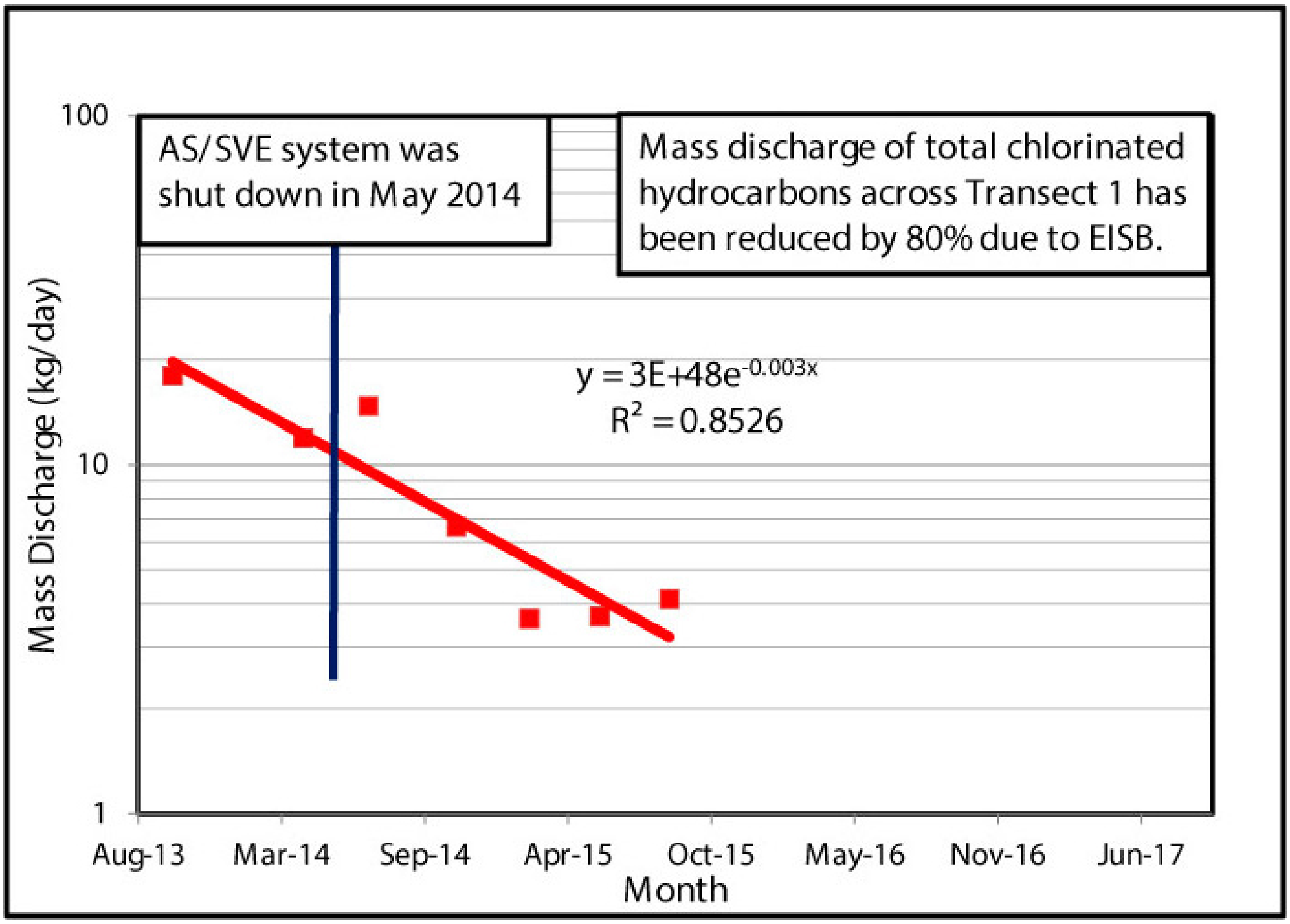

**Figure 74. Mass discharge of total chlorinated hydrocarbons (Transect 1)** (Baldwin et al. 2017)**.**

Overall, aggressive EISB with a soluble amendment and groundwater recirculation, in a large complex fractured basalt source zone, combined with comprehensive monitoring and adaptive site management, has substantially reduced contaminant mass discharge through transmissive zones. While the potential impact on residual DNAPL in dead end fractures, mass in weathered basalt areas, and the quantity of DNAPL remaining are unknown, this EISB approach may be an alternative for proactive long-term remediation and management of other large fractured rock source zones, with low matrix porosity, where costs associated with high resolution site characterization and DNAPL-focused remediation may be prohibitive.

As in this case study, long-term EISB operating requirements to minimize mass discharge from the source area should be established through a gradual process of optimization and monitoring. Once mass discharge has been reduced to the extent practicable, and active EISB is ceased, ongoing source treatment is likely to persist for years due to mechanisms such as endogenous decay and abiotic degradation from reactive minerals produced by sulfate reduction (Adamson and Newell 2009, Adamson et al. 2011).

This case study supports the observational and adaptive approach recommended by the NRC (2015) for fractured rock sites.

## 6.16.6 Costs and Risks

The installation and seven-year operating costs of the AS/SVE boundary control system totaled approximately A$10 million (installation 80%, operations 20%). Total installation and operating costs of the EISB system over six years were less than A$5 million. Operating costs for the EISB system were split between intensive monitoring, amendment makeup, and injection. Site operations personnel prepared and injected amendment and operated other site utility functions such as boilers. Groundwater sampling was performed by specialist environmental consultants. The requirements for intensive monitoring have declined as key operating variables have been identified, inhibited areas resolved, and more cost-effective methods implemented for mass-discharge monitoring.

Blast-fracturing the basalt for the AS/SVE BCS involved specialist blasting with multiple decks of explosives, and 20 ms delays between initiation of each charge to limit vibrations and avoid damage to petrochemical pipelines 25 m away. The blasting works were all conducted safely (Goodwin et al. 2010).

EISB can generate vinyl chloride, ethene, and methane in groundwater and the vadose zone. Site-specific monitoring and management plans are required. To date, methane generation using PG amendment is limited, while concentrations of about 1 to 10 mg/L chlorinated hydrocarbons persist in the groundwater.

## 6.16.7 Monitoring/Optimization

To characterize the operational performance of the EISB system, rather than attempting high resolution site characterization (which was considered impractical in this highly heterogeneous basalt aquifer), over 250 source area groundwater samples were analyzed by qPCR or QuantArray, and statistical analysis was conducted to identify and evaluate key process variables for operating the EISB system. Many groundwater samples from source and plume areas were also analyzed by CSIA to assess degradation and attenuation processes. This assessment allowed the key operating variables to be identified (total volatile fatty acids, sulfate, and chloroform concentrations) as shown in Figure 75 through Figure 77 below.

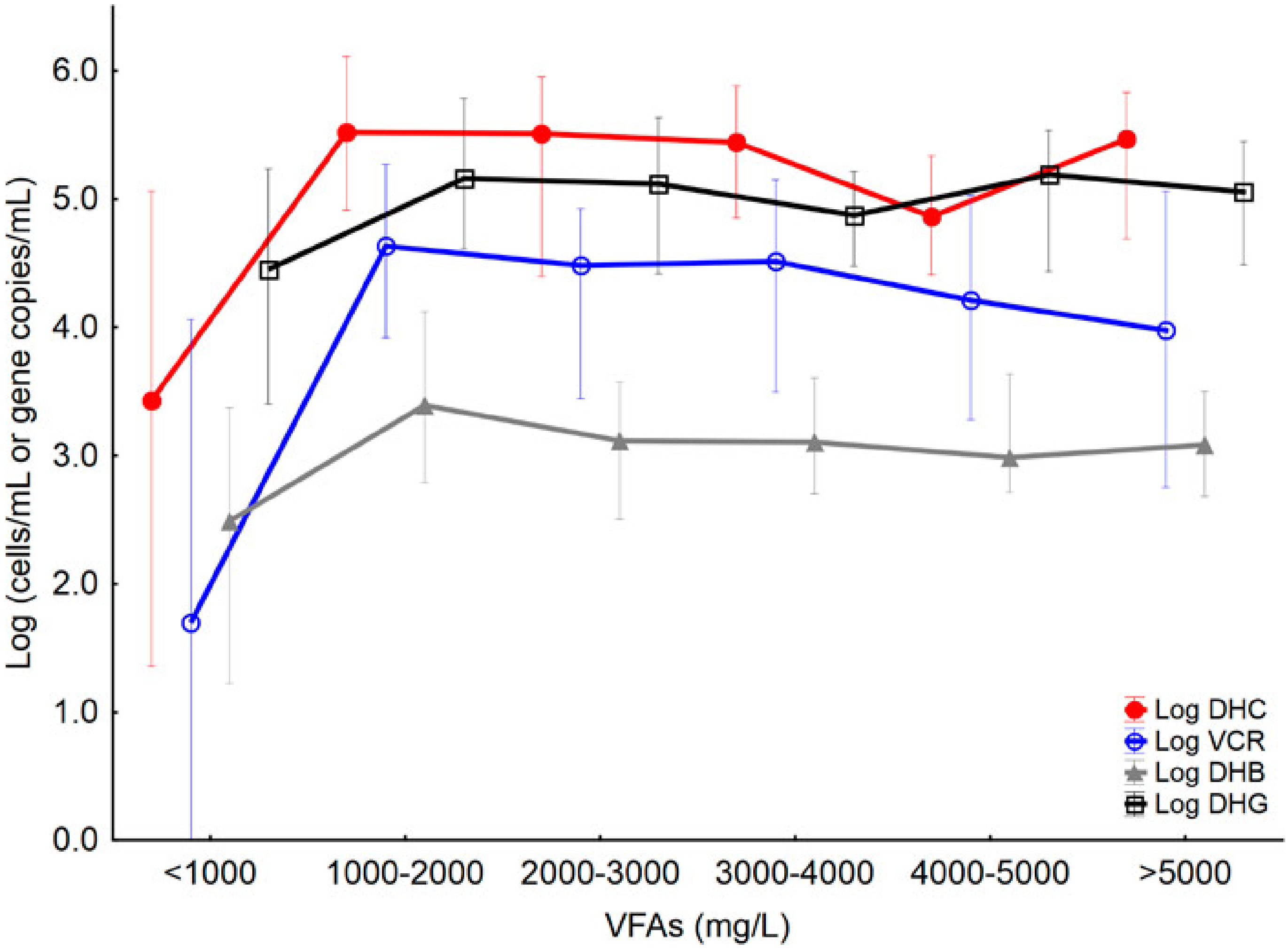


**Figure 75. Statistical analysis, key dechlorinating microbes (*Dehalococcoides* (DHC), *Dehalobacter* (DHB), *Dehalogenimonas* (DHG) spp. and vinyl chloride reductase (VCR)), versus total volatile fatty acids (VFAs)** (Baldwin et al. 2017)**.**

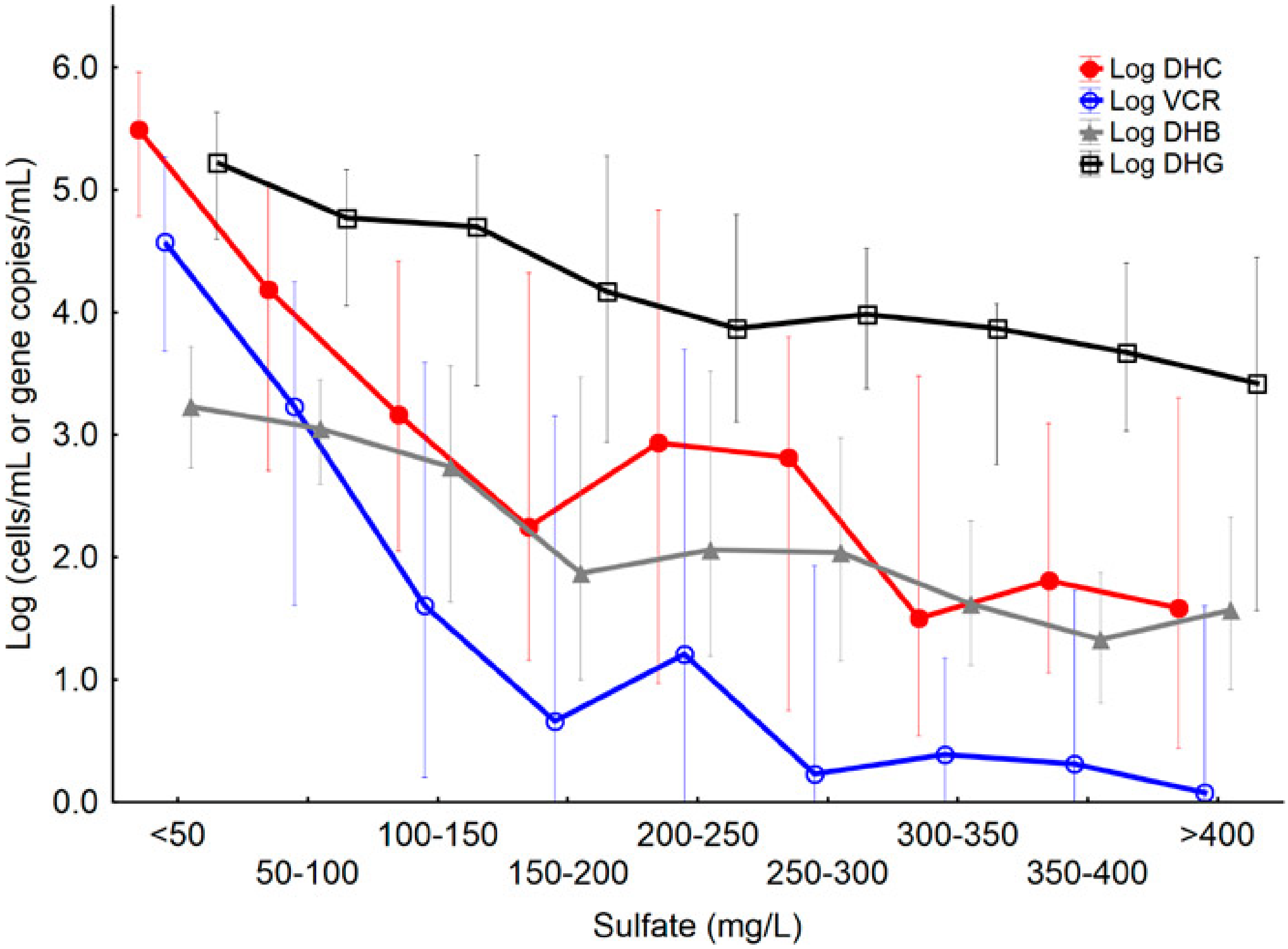


**Figure 76. Statistical analysis, key dechlorinating microbes (*Dehalococcoides* (DHC), *Dehalobacter* (DHB), *Dehalogenimonas (*DHG) spp. and vinyl chloride reductase (VCR)), versus sulfate** (Baldwin et al. 2017)**.**

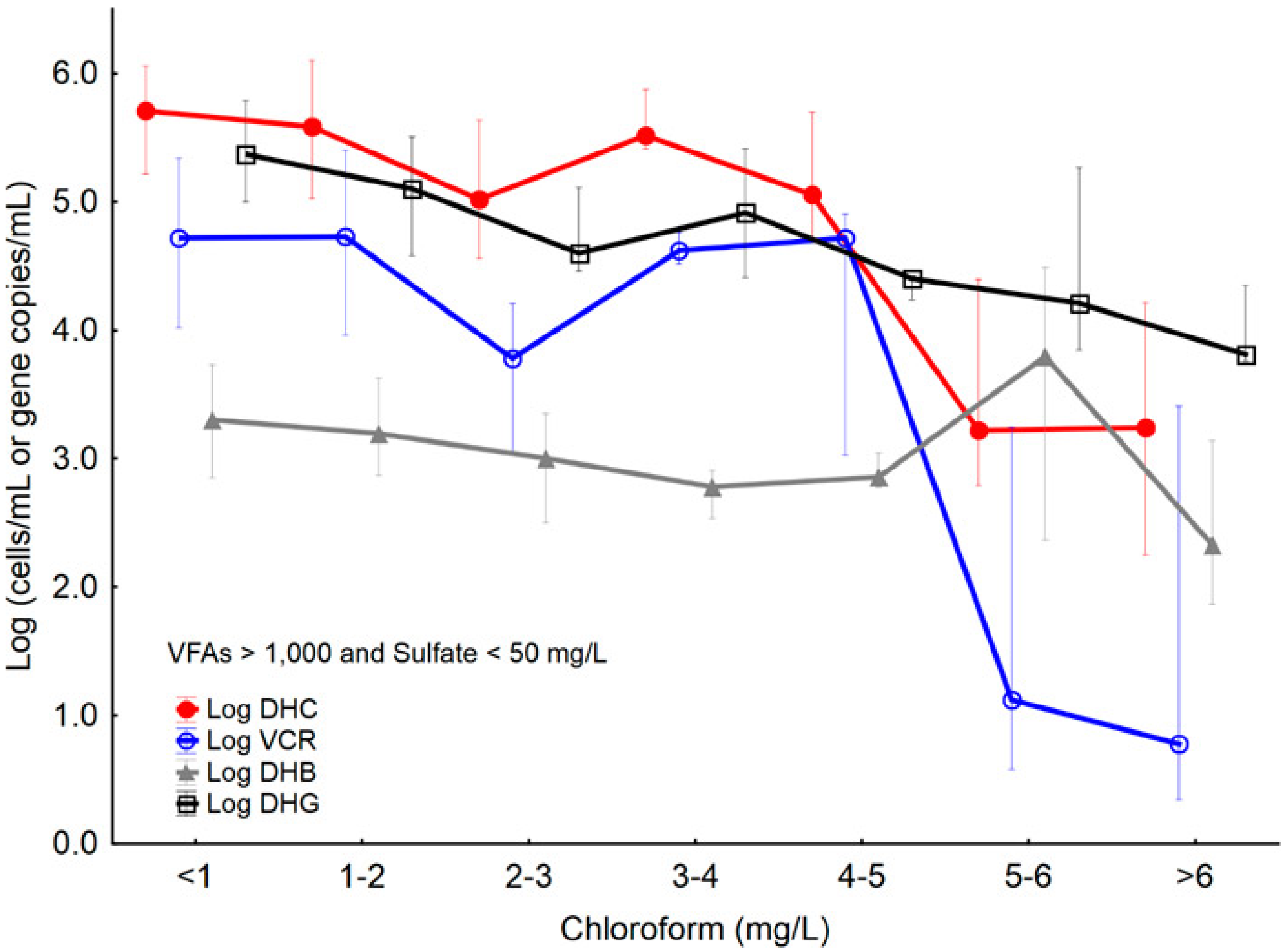


**Figure 77. Statistical analysis, key dechlorinating microbes (*Dehalococcoides* (DHC), *Dehalobacter* (DHB), *Dehalogenimonas* (DHG) spp. and vinyl chloride reductase (VCR)), versus chloroform** (Baldwin et al. 2017)**.**

Based on the statistical analysis of key dechlorinating microbes, for this particular EISB system, PG injections were effective when the total VFA concentration was >1,000 mg/L and sulfate concentration was <50 mg/L. Even with adequate electron donor and geochemical conditions, chloroform concentrations >4 mg/L inhibited growth of *Dehaloccoides* populations.

The EISB area continues to expand down and cross hydraulic gradient (as evidenced by migration of total VFAs, microbes, declining sulfate concentrations, and increased ethene concentrations) and a key objective is to achieve further mass discharge reductions from the source area. Once mass discharge across Transect 1 has been reduced to a minimum practical level, it is proposed to progressively modify/optimize operation of the source area EISB to sustain minimum mass discharge levels.

It is anticipated that after further years of operation of the EISB system, endogenous decay of biomass, reactive minerals formed by sulfate reduction processes, and possible electron donor diffusion from clay lenses may be able to maintain enhanced attenuation capacity in the source area for several years between further donor additions. Adamson and Newell 2009 and Adamson et al. (2011) provide a discussion of potential sustained treatment implications.

### 6.16.8 Summary of Alternatives

Ongoing review of remediation methods and efficacy has led to assessment of, and transition to, alternative remediation measures at the site. Remedial alternatives implemented in the source area include the following:

- AS/SVE in blast-fractured and non-blast-fractured basalt
- EISB in a large source area, using a soluble amendment and groundwater recirculation within the EISB
- biostimulation and bioaugmentation, including with the injection of chloroform reducing cultures
- P&T with groundwater reinjection for plume containment and treatment in EISB area

Potential alternatives under consideration for future source area proof-of-concept pilot trials include the following:

- radiofrequency heating of groundwater to accelerate DNAPL dissolution and degradation in a DNAPL source area
- remediation of the vadose zone in the main source area by soil vapor extraction
- potential use of existing air sparge wells for future PG injections to create a biobarrier
- permeable reactive barrier consisting of overlapping 1.2 m diameter holes drilled in basalt and backfilled with a ZVI/sand mixture

### 6.16.9 Conclusions

Contaminant occurrence, fate, and transport at this DNAPL-impacted site is inherently complex because of the scale of the original release (>100 tonnes of mixed chlorinated organics) and the variably weathered and fractured basalt aquifer. The original remedy, an AS/SVE boundary control system, recovered over 20 tonnes of chlorinated hydrocarbons during seven years of operation, but bisected the source area, and allowed bypassing under the sparge curtain. An EISB system, which uses a 100% soluble amendment (propylene glycol) with groundwater recirculation, has reduced mass discharge of chlorinated hydrocarbons from the source area by approximately 80%. The system has been developed iteratively by applying adaptive management with judicious use of site characterization tools including microbiological tools (QuantArray), passive flux meters, bioaugmentation, and CSIA. Investigations continue to optimize long-term EISB performance and to evaluate additional potential methods for accelerating DNAPL removal. This case study supports the observational and adaptive approach recommended by the NRC for fractured rock sites (NRC 2015).

# 7. Stakeholder Perspectives

Stakeholders are individuals and/or members of environmental organizations, community advocacy groups, or other citizens' groups that deal with environmental issues. Stakeholder perspectives incorporate cultural, historical, and other community-based values, as well as technological concerns. Contamination at complex sites damages resources that belong to both current and future generations, and stakeholders are usually concerned that it be remediated to the extent practicable.

The obligation to future generations is particularly strong among tribal stakeholders. Tribal stakeholders include Native American tribes, Alaska Natives, and Native Hawaiians. These stakeholders share many of the same concerns as other public stakeholders, but they also may have government-to-government relationships with federal, state, and local governments.

Engaging stakeholders early in the site decision-making process can benefit the management of a complex site. When they share in the decision-making process, public and tribal stakeholders are more likely to feel invested and involved in the site characterization and may be more likely to support the proposed cleanup. Some case studies also indicate that effective stakeholder engagement can help reduce the cost of remediation and long-term management.

## 7.1 General Stakeholder Expectations

Stakeholders—as individuals, members of environmental or community advocacy groups, and participants in official advisory bodies—are the ultimate beneficiaries of environmental remediation activities. Furthermore, tribal stakeholders have additional concerns as custodians of ancestral lands and shared resources. Complex sites often contain hazardous substances that pose a risk to health, a threat to property, and a danger to resources. While it may be impractical to remove or destroy all hazardous substances at complex sites, stakeholders generally expect the following:

- Responsible parties, regulators, and others who engage in the investigation and remediation of hazardous waste have an obligation to reduce the toxicity, mobility, and volume of waste to the extent practicable.
- As with initial remediation decisions, assessing when to transition to long-term management and a passive remedy should be based upon characterization using the latest applicable technologies.
- Innovative remedial technologies should be considered in all phases of the remediation process.
- All exposure pathways to hazardous substances that have been released into the environment should be eliminated.
- Decision-makers should include active components in every remedy, unless it can be shown that a passive remedy such as MNA or an engineered remedy such as permeable reactive barriers can achieve an equivalent reduction in contaminant concentrations in a similar time frame when compared to a more aggressive remedy.
- Remedies that operate for long time frames require a robust system of long-term management, and the cost and other challenges of long-term activity should be evaluated when considering initial remedies.
- Those who make remediation decisions should view public stakeholders and tribal representatives as partners in site remediation, from the initial identification of a contaminated site until the site is deemed fit for unlimited use and unrestricted exposure. In some circumstances, sites must be managed in perpetuity, and the role of public and tribal stakeholders should be incorporated into decisions about the site.
- Complex sites should be evaluated to determine whether the remedial design and objectives were based upon an adequate characterization and a valid conceptual site model. Finding and controlling sources reduces remediation time frames, as well as cost of remediation.
- Cost alone should not be the determining factor in classifying whether a site is complex or is subject to an alternative decision-making path.
- The remediation of complex sites should use sustainable, energy- and resource-efficient remedial technologies. Avoiding restoration of resources or delaying remedial goals due to cost or energy consumption is not acceptable, however, because restoring resources is a higher value component of sustainability. See the GSR-2 guidance (ITRC 2011a) for additional information on green and sustainable concepts.
- Long-term management strategies at complex sites must also remove institutional controls as remediation reduces risks, as well as return land and resources to community use. Short of complete cleanup, the remedial

goal is to restrict exposure hazards only to the source areas where continued site management operations occur.

## 7.2 Stakeholder Concerns

Contamination at complex sites not only threatens public health, but also creates stigma, undermines property values, restrains commerce, and endangers cultural practices. At these sites, stakeholders' overarching concern is preventing or mitigating damage to human health, resources, and culture. Specifically, stakeholder concerns can include the following:

- Adequacy of site characterization
- Removal of exposure pathways
- Adequacy of remedy
- Long-term management
- Cost

### 7.2.1 Adequacy of Site Characterization

Responsible parties and regulators may not have authority to reopen investigations at a site where remediation seems to have stalled or at a site that has already been closed, despite stakeholders' comments that their lives and property were affected by residual contamination. Additional characterization may be justified, however, because of emerging technology and new knowledge of contaminant transport in complex geological and hydrogeological environments. In some cases, stakeholder advocacy for renewed site investigation has resulted in better characterization, leading to modifications to the remedy.

For example, at the MEW Superfund Study Area in Mountain View, California, high-resolution instruments such as the membrane interface probe detected unexpected hotspots of TCE in groundwater two orders of magnitude above the results from conventional groundwater sampling. The detection of hotspots led to subsequent sampling events, pilot studies and the selection and implementation of a final remedy.

Sampling that better resolves geospatial heterogeneity makes it easier to focus new remedial strategies on the groundwater or soil where remediation is needed most or where innovative technologies can be used most effectively. Even where monitored natural attenuation is under consideration (common for complex sites), better characterization makes it possible to evaluate its suitability.

### 7.2.2 Removal of Exposure Pathways

Stakeholders generally insist on eliminating exposure pathways as the highest priority, before resources such as groundwater or soil are remediated. While parties may argue over acceptable exposure levels or remedies, they agree that without a pathway, there is no risk. For example, during remediation, the public and particularly remediation workers must be protected from hazardous substances. Homes and businesses should thus be provided with alternate water supplies, not just for drinking and cooking, but for showering and other activities likely to create exposures. The alternate water supply eliminates water from the site as an exposure pathway. Where vapor intrusion is likely, mitigation systems can also remove exposure pathways.

Regulators and responsible parties generally agree with stakeholders on this approach. For example, at the MEW plume, USEPA found that the groundwater remedy was not protective because in many buildings, the vapor intrusion pathway was complete. With community support, USEPA developed a separate ROD to prevent vapor intrusion exposures.

Stakeholders are also concerned, however, that the elimination of exposure pathways might be used as an excuse to slow or halt groundwater remediation. Often regulators agree. For example, at MEW, again with public support, USEPA required a reevaluation of groundwater remedies, and the responsible parties are replacing some of their long-operating P&T facilities with in situ technologies to accelerate treatment in many portions of the 1.5-mile plume. At the Lawrence Livermore National Laboratory (LLNL) Superfund Site, four treatability studies are underway that, if applied, will reduce the time needed to reach drinking water standards.

### 7.2.3 Adequacy of Remedy

Stakeholders are sometimes concerned that complex site attributes such as plume size or hydrogeologic features will constrain the choices for possible site remedies. When changes in the remedial process occur, stakeholders might suspect that, rather than solve complex problems, responsible parties and regulators are instead compromising environmental protections.

Required five-year reviews at superfund sites include the participation of the community to determine if the remedy initially selected remains protective of human health and the environment. If a remedy has failed or requires revision, public participation in remedy changes may be required. Many state environmental programs also have remedy review requirements that require community and stakeholder participation. Stakeholder participation in five-year reviews is documented in several case studies in this guidance (see NAS Jacksonville, Rocky Flats, Joliet Army Ammunition Plant, Tri-State Mining District and Industrial Site-Australia).

Five-Year Reviews and similar processes may lead to the use of innovative technologies when existing remedies are deemed unprotective, but stakeholders often want the parties to consider using new technologies where existing remedies are simply inefficient—that is, approaching asymptotic behavior in which risk reduction per dollar or unit of time is low—or because a better remedy may be available. Stakeholders are sometimes concerned that complex site attributes such as plume size or hydrogeologic features will constrain the choices for possible site remedies. When changes in the remedial process occur, stakeholders might suspect that, rather than solve complex problems, responsible parties and regulators are instead compromising environmental protections.

### 7.2.3.1 Remedy Selection

Stakeholders at complex sites may question tools or conclusions that indicate required cleanup cannot be achieved before the remedial responses are put in place. For example, conducting a remediation potential assessment in advance of any remedial action may cause concerns. Stakeholders may consider metrics such as "reasonable" time frames to be subjective or arbitrary, and be concerned that the use of such processes prior to adequate characterization and feasibility studies will fast-track sites directly to long-term management before the threats to human health and the environment are understood. This fast-track approach might result in unacceptable exposures or an over-reliance on institutional controls to prevent exposures, causing the long-term loss of property, resources, and community economic development.

Informed stakeholders acknowledge challenges such as the difficulty of drilling (for example, when developing a remedial design or selecting an advanced characterization technique), but may not consider such challenges enough reason to introduce new steps to the remedy selection process. Stakeholders are more likely to welcome new approaches, such as adaptive site management, where remedies are in place and their effectiveness appears to be diminishing. At most complex groundwater sites in the United States some form of remediation has already been implemented.

### 7.2.3.2 Passive Remedies

Stakeholders are often concerned about a passive (natural attenuation) remedy because it appears to be a "do-nothing" option and occurs over long time frames (NRC 2001). Passive remedies may win public support if site managers address stakeholder concerns by explaining the mechanisms of attenuation and using advanced monitoring technologies to confirm that exposure is not occurring. Passive remedies are frequently considered at complex sites where aggressive technologies may not yield better or faster results compared with passive remedies.

Despite initial skepticism, stakeholders may support the natural attenuation of metals and radionuclides (ITRC 2010a), particularly when incorporated into more complex treatment trains. Many stakeholders also recognize that natural degradation, in which organisms destroy contamination in the subsurface, is often superior to extraction, adsorption onto carbon filters, and combustion elsewhere. They may be concerned, however, that biodegradation will impair water quality because of bacterial metabolism that changes the geochemistry of the aquifer.

If contamination remains decades after releases first occurred at a complex site, however, stakeholders are likely to question the choice of natural attenuation as a primary remedial strategy. USEPA (1999b) notes that source control measures will be evaluated for all sites under consideration for any proposed remedy, progress will be monitored to determine if degradation is happening as predicted, and more active contingency measures will be implemented if natural attenuation does not meet performance goals.

### 7.2.3.3 Transition Assessments

USEPA and its state counterparts have policies that determine when transition to a different remedy is required. USEPA's latest document on the subject, *Groundwater Completion Strategy* (USEPA 2014b), states the following:

Modification of the remedy may involve the following activities as further described…

- Evaluate the groundwater's remediation potential.
- Evaluate if the current site objectives can be achieved with other technologies.
- Select an alternate remedial approach, and if necessary, modify the site objectives.
- Conduct technical impracticability (TI) evaluation.

If groundwater remediation or containment is still viable with a different technology or if the site objectives need to be changed, then the selected remedy may need modification.

Since USEPA policies do not include the term "transition assessment," stakeholders are likely to be more receptive to the concept if they hear how it fits into CERCLA or other regulatory frameworks. The National Research Council's section, "Has an asymptote been reached?" (NRC 2013) is a good start. Stakeholders generally agree that it is not worthwhile to spend time, money, and other resources doing little to reduce contamination and risk. They may be unwilling to support turning off even an ineffective remedy, however, if they believe that no effort will be made to replace it.

Stakeholders are generally unwilling to accept transition decisions that they believe are primarily designed to shift costs, in the broadest sense, from those responsible for cleanup to the community. This approach could take the form of institutional controls that restrict land use or long-term monitoring and maintenance that places burdens and risks on the community and its future generations. Where long-term management is slated to become the responsibility of state regulatory agencies, stakeholders may be concerned that the state lacks the will or resources to continue site management until completion.

At large complex sites, stakeholders are likely to question generalized findings that remediation is too difficult for the entire site based upon localized findings. Stakeholders may suggest that separate assessments be applied to different parts of sites, particularly where activity is focused on areas where exposure is most likely, reuse is under consideration, or contamination is greatest.

As noted in USEPA's *Groundwater Completion Strategy* and by the NRC (2013), decisions to waive or modify certain site objectives (termed "alternative cleanup levels") are allowed only after careful evaluation of risk and remediation potential. Where regulators propose to waive or modify site objectives, stakeholders generally support a robust public participation process. For example, at the Lower Duwamish Waterway Superfund Site near Seattle, the public, with the help of a Technical Assistance Grant, questioned a technical impracticability (TI) Waiver proposed by the responsible party. In response, USEPA instead required that the responsible parties continue cleanup for an interim period. USEPA promised the responsible party that it could later apply for a TI waiver if it were shown that cleanup standards could not be met after attempting remediation.

**Modifying Cleanup Levels: Duwamish Waterway Superfund Site**

*If long-term monitoring data and trends indicate that some ARARs-based cleanup levels selected in the ROD after public comment on this Proposed Plan are not met, a waiver of these ARARs could be considered by USEPA in a future decision document (ROD Amendment or ESD). For example, if monitoring shows such levels have reached Sediment Quality Standards (SQS) but have not reached the surface water Preliminary remediation goals (PRGs) or human health and natural background-based sediment PRGs, and USEPA were to conclude that no further action would practicably improve these levels, the ARARs that are not met would be eligible for a TI waiver. Because USEPA cannot know whether and to what extent ARARs for these various levels for different COCs will be achieved, consideration of the potential for such a waiver prior to the collection of monitoring data sufficient to inform any TI waiver decision(s) is neither warranted nor justifiable. (USEPA 2013c)*

### 7.2.4 Long-Term Management

Remedies that depend on long-term remediation require a robust system of long-term management. Costs and other challenges of long-term activity should be evaluated both when considering initial remedies and when conducting a transition assessment. Because complex sites will not achieve the unlimited use and unrestricted exposure end state for decades, long-term management is necessary for both active and passive remediation technologies to manage risk and maintain protectiveness.

Long-term remedies usually require institutional controls (ITRC 2016b). Affected stakeholders generally want the costs and uncertainties of proposed controls to be evaluated at the time of remedy selection or transition assessment, and they want to take part in that assessment. By definition, ICs limit the use of land, groundwater, or other resources, so stakeholders may be concerned that the cost of controls to the community outweigh the responsible parties' or government's cost of additional remediation. Furthermore, for tribal lands, restrictions may threaten the cultural traditions of the tribe or village. Stakeholders may question the practice of discounting costs over thirty years, because even after thirty years, someone is still responsible for managing sites that have not reached unlimited use and unrestricted exposure.

Stakeholders, including local governments, should be considered equal partners in the development of institutional controls because they are responsible for most future land-use decisions. Furthermore, community members and their local institutions may be the most important monitors of the efficacy of institutional controls, because they are likely to remain near the site long after regulators and responsible parties have ended site activities.

"Orphaned" sites are sites that no longer have a responsible party to pay for a remedy. Minimal financial resources are often used as a rationale for limiting characterization and only performing risk abatement (plume management, monitoring, institutional controls) while leaving large quantities of contamination behind with land use restrictions. Groundwater and surface water adjacent to these facilities may never return to an environmentally safe or usable level and indoor air may also need to be addressed. The public usually insists on stable funding sources to ensure that both institutional controls and engineering controls effectively protect the public in the long run. Where reuse is planned, stakeholders may ask that the parties redeveloping the property take such responsibility. Cities may require that state environmental review laws, such as the California Environmental Quality Act, be used to enforce such requirements (CPEO 2016b).

In some cases, responsible parties have claimed bankruptcy in the face of remediation or even characterization obligations. Regulators often must address these sites with limited budgets that do not allow proper characterization or a full understanding of site complexities. Some hazards, such as releases from undocumented underground tanks, unmeasured soil gas contamination, and unknown groundwater plumes are often only recognized long after bankruptcy settlements. Stakeholders may therefore ask that the court impose robust financial assurances during bankruptcy proceedings to reduce the public's financial exposure and to better protect human health and the environment.

### 7.2.5 Cost

Stakeholders recognize that satisfactory remediation cannot always be achieved in a reasonable time frame and generally do not support spending unreasonable amounts of time and money to achieve minimal contaminant (and thus risk) reduction. On the other hand, protective site objectives provide incentives for the development and use of innovative remediation technologies as well as the adoption of pollution prevention practices that protect resources.

Stakeholders care about effectiveness, efficiency, and long-term protection, and they want to be sure that cost-saving measures do not simply shift costs onto the public or onto future generations. When responsible parties and regulators work in good faith with community stakeholders to reduce risks and protect resources, while adapting site management using the latest and best remedial strategies and technologies, stakeholders are likely to accept new approaches regardless of the effect on costs.

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# Appendix A. Survey Results

To gauge state regulatory practices regarding site objectives, ITRC surveyed the ITRC state POCs. ITRC received responses from 40 of the 50 states. State representatives were asked the following two questions:

1. Does your state/tribal program allow the following as a primary means to meet RAOs?
2. Does your state/tribal program allow the following after the original selected remedy fails to reach the RAOs within the planned remedial time frame?

The term “RAOs” was used in the survey to encompass a broad range of state remediation program objectives (site objectives). Several methods of designating alternative points of compliance, contaminant management areas (areas subject to institutional controls, plume containment), criteria adjustment, schedule adjustment, technology adjustment, and other alternatives were then listed. Note that the second survey question referred to a “planned remedial time frame”; however, there is little evidence that states or tribes establish a planned remedial time frame during remedy selection. With this qualifier, the results of the survey are summarized in Table 21.

**Table 21. Summary of ITRC State Survey Results**

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A complete list of all the state survey questions and detailed responses is summarized here.

# Table 21. Summary of ITRC State Survey Results

| Theme | Technology or Process | Alabama | Alaska | Arizona | Arkansas | California | Colorado | Connecticut | DC | Delaware | Florida | Georgia | Hawaii | Illinois |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Alternative compliance points | Compliance demonstration via modeling | N : N | N : N | Y : Y | N : Y | Y : Y | Y : Y | N : N | Y : Y | n/a : Y | Y : Y | N : Y | N : Y | Y : Y |
| Alternative compliance points | Designated specific points of compliance | Y : Y | Y : Y | Y : Y | Y : Y | N : Y | Y : Y | N : N | Y : Y | n/a : Y | Y : Y | Y : Y | Y : Y | Y : Y |
| Alternative compliance points | Technical impracticability (TI) determination | N : N | Y : Y | N : n/a | N : Y | Y : Y | Y : Y | Y : Y | Y : n/a | n/a : Y | Y : Y | N : N | Y : Y | Y : Y |
| Contaminant Management Areas | Access restrictions (e.g., fence) | Y : Y | Y : Y | Y : Y | N : Y | Y : Y | Y : Y | N : N | Y : Y | n/a : Y | Y : Y | Y : Y | Y : Y | N : N |
| Contaminant Management Areas | Designated “contaminant” zones (residual zone) | N : N | Y : Y | Y : Y | Y : Y | N : N | Y : Y | N : N | Y : Y | n/a : Y | Y : N | N : N | Y : Y | N : N |
| Contaminant Management Areas | Engineered barriers (e.g., soil covers, asphalt cover, buildings) | Y : Y | Y : Y | Y : Y | N : Y | Y : Y | Y : Y | Y : Y | Y : Y | n/a : Y | Y : Y | Y : Y | Y : Y | Y : Y |
| Contaminant Management Areas | Groundwater Mixing Zones | N : N | N : N | Y : Y | Y : Y | N : N | N : N | N : N | N : N | n/a : Y | N : N | N : N | N : N | N : N |
| Contaminant Management Areas | Institutional controls (ICs) to manage exposure | Y : Y | Y : Y | Y : Y | N : Y | Y : Y | Y : Y | Y : Y | Y : Y | n/a : Y | Y : Y | Y : Y | Y : Y | Y : Y |
| Contaminant Management Areas | Land Use Controls (LUCs) | Y : Y | Y : Y | Y : Y | N : Y | Y : Y | Y : Y | Y : Y | Y : Y | n/a : Y | Y : Y | Y : Y | Y : Y | Y : Y |
| Contaminant Management Areas | Other: (please elaborate) | | Y : Y | | | n/a : n/a | n/a : n/a | n/a : n/a | | | | n/a : n/a | Y : Y | n/a : n/a |
| Contaminant Management Areas | Plume management zones (PMZ) | N : N | Y : Y | Y : Y | Y : Y | N : N | N : N | N : N | Y : Y | n/a : Y | Y : Y | N : N | Y : Y | N : N |
| Criteria Adjustment | Allowances for regional “background” concentrations | N : N | N : N | Y : Y | Y : n/a | Y : Y | Y : Y | Y : Y | Y : Y | n/a : Y | Y : Y | N : N | Y : Y | Y : Y |
| Criteria Adjustment | Alternate Concentration Limits (ACLs) | N : N | Y : Y | Y : Y | Y : Y | N : N | Y : Y | Y : Y | N : N | n/a : N | Y : Y | N : N | N : Y | N : N |
| Criteria Adjustment | Change remedial action objectives | Y : Y | Y : Y | Y : Y | N : Y | N : N | Y : Y | N : N | Y : Y | n/a : N | Y : Y | Y : Y | Y : Y | Y : Y |
| Criteria Adjustment | Demonstrate compliance with criteria by a statistical evaluation of the data | Y : Y | Y : Y | Y : Y | Y : Y | Y : Y | Y : Y | Y : Y | Y : Y | n/a : Y | Y : Y | Y : Y | Y : Y | Y : Y |
| Criteria Adjustment | Develop Site-Specific criteria based on a risk evaluation | Y : Y | Y : Y | Y : Y | Y : Y | Y : Y | Y : Y | Y : Y | Y : Y | n/a : Y | Y : Y | Y : Y | Y : Y | Y : Y |
| Criteria Adjustment | Interim/short-term cleanup goals or objectives | Y : Y | Y : Y | Y : Y | N : Y | N : Y | Y : Y | Y : Y | Y : Y | n/a : N | Y : Y | N : N | Y : Y | N : N |
| Criteria Adjustment | Low-threat site closure criteria | N : N | Y : Y | Y : Y | N : N | N : N | Y : Y | N : N | N : N | n/a : Y | Y : Y | N : N | Y : Y | N : N |
| Criteria Adjustment | Other: (please elaborate) | | n/a : n/a | | | n/a : n/a | n/a : n/a | n/a : n/a | | | | n/a : n/a | Y : Y | n/a : n/a |
| Criteria Adjustment | Technology-specific cleanup goals or objectives | N : N | Y : Y | N : N | N : N | Y : Y | N : N | N : N | Y : Y | n/a : Y | N : N | Y : Y | Y : Y | N : N |
| Other alternatives | Combination of alternatives depending on site characteristics (elaborate in the comments) | Y : Y | Y : Y | Y : Y | Y : Y | Y : Y | N : N | Y : Y | Y : n/a | n/a : Y | Y : Y | Y : Y | Y : Y | n/a : n/a |
| Other alternatives | Other: (please elaborate) | | | | | | | | | | | | | |
| Schedule Adjustment | Adjust time to complete objectives | Y : Y | Y : Y | Y : Y | Y : Y | Y : Y | Y : Y | Y : Y | Y : Y | n/a : Y | Y : Y | N : Y | N : Y | Y : Y |
| Schedule Adjustment | Long Term Monitoring (LTM) | Y : Y | Y : Y | Y : Y | Y : Y | Y : Y | Y : Y | Y : Y | Y : Y | n/a : Y | Y : Y | N : Y | Y : Y | N : N |
| Technology Adjustment | Applying technologies sequentially | Y : Y | Y : Y | Y : Y | Y : Y | Y : Y | Y : Y | Y : Y | Y : N | n/a : Y | Y : Y | Y : Y | Y : Y | Y : Y |
| Technology Adjustment | Changing active remedy or technology | Y : Y | Y : Y | Y : Y | Y : Y | Y : Y | Y : Y | Y : Y | Y : N | n/a : Y | Y : Y | Y : Y | N : Y | Y : Y |
| Technology Adjustment | Employing adaptive site management approaches | Y : Y | Y : Y | Y : Y | n/a : n/a | N : Y | n/a : n/a | Y : Y | Y : N | n/a : n/a | N : N | Y : Y | Y : Y | N : N |
| Technology Adjustment | Monitoring Natural Attenuation (MNA) | Y : Y | Y : Y | Y : Y | Y : Y | N : Y | Y : Y | Y : Y | Y : N | n/a : Y | Y : Y | Y : Y | Y : Y | N : N |
| Technology Adjustment | Other: (please elaborate) | | Y : Y | | | | | | | | | | | |

**Note:**

Responses to Questions 1 and 2 are separated by a colon

## Table 21. Summary of ITRC State Survey Results

| Theme | Technology or Process | Iowa | Kansas | Kentucky | Louisiana | Maryland | Minnesota | Mississippi | Missouri | Montana | Nebraska | Nevada | New Jersey |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Alternative compliance points | Compliance demonstration via modeling | Y : Y | Y : Y | N : N | Y : Y | N : N | N : Y | Y : Y | Y : Y | N : N | Y : Y | Y : Y | Y : Y |
| Alternative compliance points | Designated specific points of compliance | Y : Y | Y : Y | Y : Y | Y : Y | Y : n/a | Y : Y | Y : Y | Y : Y | N : N | Y : Y | Y : Y | N : N |
| Alternative compliance points | Technical impracticability (TI) determination | Y : Y | N : N | Y : Y | Y : Y | n/a : n/a | N : Y | N : N | Y : Y | N : Y | Y : Y | N : Y | Y : Y |
| Contaminant Management Areas | Access restrictions (e.g., fence) | Y : Y | Y : Y | Y : Y | N : N | Y : Y | Y : Y | N : Y | Y : Y | N : N | Y : Y | Y : Y | Y : Y |
| Contaminant Management Areas | Designated “contaminant” zones (residual zone) | Y : Y | Y : Y | N : N | N : N | n/a : n/a | Y : Y | N : N | Y : Y | N : N | N : N | N : Y | Y : Y |
| Contaminant Management Areas | Engineered barriers (e.g., soil covers, asphalt cover, buildings) | Y : Y | Y : Y | Y : Y | Y : Y | Y : Y | Y : Y | N : Y | Y : Y | Y : N | Y : Y | Y : Y | Y : Y |
| Contaminant Management Areas | Groundwater Mixing Zones | Y : Y | Y : n/a | N : N | N : N | N : N | Y : Y | N : N | Y : Y | N : N | N : N | Y : Y | Y : Y |
| Contaminant Management Areas | Institutional controls (ICs) to manage exposure | Y : Y | Y : Y | Y : Y | Y : Y | Y : Y | Y : Y | Y : Y | Y : Y | N : N | Y : Y | Y : Y | Y : Y |
| Contaminant Management Areas | Land Use Controls (LUCs) | Y : Y | Y : Y | Y : Y | Y : Y | Y : Y | Y : Y | N : Y | Y : Y | N : N | Y : Y | Y : Y | Y : Y |
| Contaminant Management Areas | Other: (please elaborate) | n/a : n/a | n/a : n/a | | | | | | n/a : n/a | n/a : n/a | n/a : n/a | | |
| Contaminant Management Areas | Plume management zones (PMZ) | Y : Y | Y : n/a | N : N | N : Y | n/a : n/a | Y : Y | N : N | Y : Y | N : N | N : N | N : N | Y : Y |
| Criteria Adjustment | Allowances for regional “background” concentrations | Y : Y | Y : Y | Y : Y | Y : Y | Y : Y | Y : Y | Y : Y | Y : Y | Y : N | Y : Y | Y : Y | Y : Y |
| Criteria Adjustment | Alternate Concentration Limits (ACLs) | Y : Y | Y : Y | Y : Y | Y : Y | Y : Y | Y : Y | n/a : n/a | Y : Y | N : N | Y : Y | N : N | Y : Y |
| Criteria Adjustment | Change remedial action objectives | Y : Y | n/a : Y | N : N | Y : Y | Y : Y | N : Y | n/a : n/a | Y : Y | N : N | N : N | Y : Y | Y : Y |
| Criteria Adjustment | Demonstrate compliance with criteria by a statistical evaluation of the data | Y : Y | Y : Y | Y : Y | Y : Y | Y : Y | Y : Y | Y : Y | Y : Y | Y : Y | Y : Y | N : Y | Y : Y |
| Criteria Adjustment | Develop Site-Specific criteria based on a risk evaluation | Y : Y | Y : Y | Y : Y | Y : Y | Y : Y | Y : Y | Y : Y | Y : Y | Y : N | Y : Y | Y : Y | N : N |
| Criteria Adjustment | Interim/short-term cleanup goals or objectives | Y : Y | Y : Y | Y : Y | N : N | Y : Y | N : n/a | Y : N | Y : Y | N : N | Y : Y | Y : Y | N : N |
| Criteria Adjustment | Low-threat site closure criteria | Y : Y | Y : n/a | Y : Y | N : N | n/a : n/a | Y : Y | Y : Y | N : N | Y : n/a | Y : Y | Y : Y | N : N |
| Criteria Adjustment | Other: (please elaborate) | Y : n/a | n/a : n/a | | | | | | n/a : n/a | n/a : n/a | n/a : n/a | | |
| Criteria Adjustment | Technology-specific cleanup goals or objectives | Y : Y | Y : Y | Y : Y | Y : Y | Y : Y | N : Y | N : N | N : N | N : N | Y : Y | N : N | N : N |
| Other alternatives | Combination of alternatives depending on site characteristics (elaborate in the comments) | Y : Y | Y : Y | Y : Y | Y : Y | Y : Y | Y : Y | Y : Y | Y : Y | Y : N | Y : Y | Y : Y | n/a : n/a |
| Other alternatives | Other: (please elaborate) | | | | | | | | | | | | |
| Schedule Adjustment | Adjust time to complete objectives | Y : Y | Y : Y | Y : Y | Y : Y | Y : Y | Y : Y | Y : Y | Y : Y | N : N | Y : Y | Y : Y | N : N |
| Schedule Adjustment | Long Term Monitoring (LTM) | Y : Y | Y : Y | Y : Y | N : N | Y : Y | Y : Y | Y : Y | Y : Y | N : N | Y : Y | N : Y | Y : Y |
| Technology Adjustment | Applying technologies sequentially | Y : Y | Y : Y | Y : Y | Y : Y | Y : Y | Y : Y | Y : Y | Y : Y | Y : Y | Y : Y | Y : Y | Y : Y |
| Technology Adjustment | Changing active remedy or technology | Y : Y | Y : Y | Y : Y | Y : Y | Y : Y | Y : Y | Y : Y | Y : Y | N : Y | Y : Y | Y : Y | Y : Y |
| Technology Adjustment | Employing adaptive site management approaches | Y : Y | Y : Y | Y : Y | N : Y | Y : Y | Y : Y | Y : Y | Y : Y | N : N | Y : Y | Y : Y | Y : Y |
| Technology Adjustment | Monitoring Natural Attenuation (MNA) | Y : Y | Y : Y | Y : Y | Y : Y | Y : Y | Y : Y | Y : Y | N : Y | N : N | Y : Y | Y : Y | Y : Y |
| Technology Adjustment | Other: (please elaborate) | | | | | | | | | | | | |

**Note:**
Responses to Questions 1 and 2 are separated by a colon

## Table 21. Summary of ITRC State Survey Results

| Theme | Technology or Process | New Mexico | New York | North Carolina | Oregon | Pennsylvania | Puerto Rico | Rhode Island | South Carolina | South Dakota |
|---|---|---|---|---|---|---|---|---|---|---|
| Alternative compliance points | Compliance demonstration via modeling | Y : Y | N : N | Y : n/a | Y : Y | Y : n/a | Y : Y | N : N | Y : Y | Y : Y |
| Alternative compliance points | Designated specific points of compliance | N : N | N : N | Y : n/a | Y : Y | Y : n/a | Y : Y | Y : Y | Y : Y | Y : Y |
| Alternative compliance points | Technical impracticability (TI) determination | Y : Y | n/a : n/a | Y : n/a | N : N | Y : n/a | N : Y | N : Y | n/a : n/a | Y : Y |
| Contaminant Management Areas | Access restrictions (e.g., fence) | Y : Y | n/a : n/a | Y : Y | Y : Y | Y : n/a | n/a : Y | N : N | Y : Y | n/a : n/a |
| Contaminant Management Areas | Designated “contaminant” zones (residual zone) | Y : Y | n/a : n/a | Y : Y | Y : Y | Y : n/a | N : N | N : Y | n/a : n/a | Y : Y |
| Contaminant Management Areas | Engineered barriers (e.g., soil covers, asphalt cover, buildings) | Y : Y | n/a : n/a | Y : Y | Y : Y | Y : n/a | N : Y | Y : Y | Y : Y | Y : Y |
| Contaminant Management Areas | Groundwater Mixing Zones | N : N | n/a : n/a | N : N | N : N | Y : n/a | N : Y | N : N | Y : Y | n/a : n/a |
| Contaminant Management Areas | Institutional controls (ICs) to manage exposure | Y : Y | Y : Y | Y : Y | Y : Y | Y : n/a | N : Y | Y : Y | Y : Y | Y : Y |
| Contaminant Management Areas | Land Use Controls (LUCs) | Y : Y | n/a : n/a | Y : Y | Y : Y | Y : n/a | N : Y | Y : Y | Y : Y | Y : Y |
| Contaminant Management Areas | Other: (please elaborate) | n/a : n/a | n/a : n/a | n/a : n/a | n/a : n/a | | n/a : n/a | n/a : n/a | n/a : n/a | |
| Contaminant Management Areas | Plume management zones (PMZ) | Y : n/a | n/a : n/a | Y : Y | Y : Y | Y : n/a | Y : Y | N : Y | n/a : n/a | Y : Y |
| Criteria Adjustment | Allowances for regional “background” concentrations | Y : Y | Y : Y | N : N | Y : Y | Y : n/a | Y : Y | Y : Y | n/a : n/a | n/a : n/a |
| Criteria Adjustment | Alternate Concentration Limits (ACLs) | Y : Y | n/a : n/a | Y : n/a | N : Y | N : n/a | Y : Y | N : N | Y : Y | Y : Y |
| Criteria Adjustment | Change remedial action objectives | Y : Y | n/a : n/a | N : n/a | Y : Y | n/a : n/a | N : N | N : Y | n/a : n/a | Y : Y |
| Criteria Adjustment | Demonstrate compliance with criteria by a statistical evaluation of the data | Y : Y | N : N | N : n/a | Y : Y | Y : n/a | N : Y | Y : Y | n/a : n/a | Y : Y |
| Criteria Adjustment | Develop Site-Specific criteria based on a risk evaluation | Y : Y | n/a : n/a | Y : n/a | Y : Y | Y : n/a | Y : Y | Y : Y | Y : Y | Y : Y |
| Criteria Adjustment | Interim/short-term cleanup goals or objectives | Y : Y | n/a : n/a | Y : n/a | Y : Y | Y : n/a | N : Y | Y : Y | Y : Y | Y : Y |
| Criteria Adjustment | Low-threat site closure criteria | N : N | n/a : n/a | Y : n/a | N : N | N : n/a | Y : Y | N : N | n/a : n/a | Y : Y |
| Criteria Adjustment | Other: (please elaborate) | n/a : n/a | n/a : n/a | n/a : n/a | n/a : n/a | | n/a : n/a | n/a : n/a | n/a : n/a | |
| Criteria Adjustment | Technology-specific cleanup goals or objectives | Y : Y | n/a : n/a | Y : n/a | Y : Y | N : n/a | N : N | N : N | n/a : n/a | Y : Y |
| Other alternatives | Combination of alternatives depending on site characteristics (elaborate in the comments) | n/a : n/a | n/a : n/a | Y : n/a | Y : Y | Y : n/a | Y : Y | Y : Y | Y : Y | Y : Y |
| Other alternatives | Other: (please elaborate) | | | n/a : n/a | | | | | | n/a : n/a |
| Schedule Adjustment | Adjust time to complete objectives | Y : Y | n/a : n/a | Y : n/a | Y : Y | Y : n/a | Y : Y | Y : Y | Y : Y | Y : Y |
| Schedule Adjustment | Long Term Monitoring (LTM) | Y : Y | n/a : n/a | Y : n/a | Y : Y | Y : n/a | N : Y | Y : Y | Y : Y | Y : Y |
| Technology Adjustment | Applying technologies sequentially | Y : Y | n/a : n/a | Y : n/a | Y : Y | N : n/a | Y : Y | Y : Y | Y : Y | Y : Y |
| Technology Adjustment | Changing active remedy or technology | Y : Y | n/a : n/a | Y : n/a | Y : Y | Y : n/a | Y : Y | Y : Y | Y : Y | Y : Y |
| Technology Adjustment | Employing adaptive site management approaches | Y : Y | n/a : n/a | Y : n/a | Y : Y | Y : n/a | N : Y | N : N | n/a : n/a | Y : Y |
| Technology Adjustment | Monitoring Natural Attenuation (MNA) | Y : Y | n/a : n/a | Y : n/a | Y : Y | Y : n/a | N : Y | Y : Y | Y : Y | Y : Y |
| Technology Adjustment | Other: (please elaborate) | | | | | | | | | |

**Note:**

Responses to Questions 1 and 2 are separated by a colon

## Table 21. Summary of ITRC State Survey Results

| Theme | Technology or Process | Tennessee | Texas | Utah CERCLA | Utah UST LUST | Vermont | Virginia | Wisconsin |
|---|---|---|---|---|---|---|---|---|
| Alternative compliance points | Compliance demonstration via modeling | N : n/a | Y : Y | N : Y | N : Y | Y : Y | Y : Y | Y : Y |
| Alternative compliance points | Designated specific points of compliance | Y : Y | Y : Y | Y : Y | Y : Y | Y : Y | Y : Y | Y : Y |
| Alternative compliance points | Technical impracticability (TI) determination | n/a : n/a | N : Y | N : Y | N : N | Y : Y | Y : Y | N : N |
| Contaminant Management Areas | Access restrictions (e.g., fence) | Y : Y | Y : Y | Y : Y | N : N | Y : Y | Y : Y | Y : Y |
| Contaminant Management Areas | Designated "contaminant" zones (residual zone) | n/a : n/a | Y : Y | Y : Y | N : N | N : Y | Y : Y | Y : Y |
| Contaminant Management Areas | Engineered barriers (e.g., soil covers, asphalt cover, buildings) | Y : Y | Y : Y | Y : Y | N : Y | Y : Y | Y : Y | Y : Y |
| Contaminant Management Areas | Groundwater Mixing Zones | n/a : n/a | Y : Y | N : Y | N : N | N : N | Y : Y | N : N |
| Contaminant Management Areas | Institutional controls (ICs) to manage exposure | Y : Y | Y : Y | Y : Y | N : Y | Y : Y | Y : Y | Y : Y |
| Contaminant Management Areas | Land Use Controls (LUCs) | Y : Y | n/a : n/a | Y : Y | N : Y | Y : Y | Y : Y | Y : Y |
| Contaminant Management Areas | Other: (please elaborate) | n/a : n/a | n/a : n/a | n/a : n/a | N : Y | n/a : n/a | n/a : n/a | Y : n/a |
| Contaminant Management Areas | Plume management zones (PMZ) | n/a : n/a | Y : Y | Y : Y | N : N | N : N | Y : Y | N : N |
| Criteria Adjustment | Allowances for regional "background" concentrations | n/a : n/a | Y : Y | Y : Y | Y : Y | Y : Y | Y : Y | Y : Y |
| Criteria Adjustment | Alternate Concentration Limits (ACLs) | N : N | Y : Y | Y : Y | n/a : n/a | N : N | Y : Y | N : N |
| Criteria Adjustment | Change remedial action objectives | Y : Y | Y : Y | N : Y | N : Y | N : N | Y : Y | N : N |
| Criteria Adjustment | Demonstrate compliance with criteria by a statistical evaluation of the data | Y : n/a | Y : N | N : Y | N : N | Y : Y | Y : Y | N : N |
| Criteria Adjustment | Develop Site-Specific criteria based on a risk evaluation | Y : Y | Y : Y | Y : Y | Y : Y | Y : Y | Y : Y | Y : Y |
| Criteria Adjustment | Interim/short-term cleanup goals or objectives | Y : Y | Y : Y | N : Y | N : N | N : N | Y : Y | N : N |
| Criteria Adjustment | Low-threat site closure criteria | n/a : n/a | Y : N | N : N | N : N | Y : Y | Y : Y | N : N |
| Criteria Adjustment | Other: (please elaborate) | n/a : n/a | n/a : n/a | n/a : n/a | n/a : n/a | n/a : n/a | n/a : n/a | n/a : n/a |
| Criteria Adjustment | Technology-specific cleanup goals or objectives | Y : n/a | Y : Y | Y : Y | N : Y | N : N | Y : Y | N : N |
| Other alternatives | Combination of alternatives depending on site characteristics (elaborate in the comments) | Y : Y | Y : Y | Y : Y | Y : Y | Y : Y | Y : Y | n/a : n/a |
| Other alternatives | Other: (please elaborate) | | | | | | | |
| Schedule Adjustment | Adjust time to complete objectives | Y : Y | Y : Y | Y : Y | Y : Y | Y : Y | Y : Y | Y : Y |
| Schedule Adjustment | Long Term Monitoring (LTM) | Y : Y | Y : Y | Y : Y | N : Y | Y : Y | Y : Y | Y : Y |
| Technology Adjustment | Applying technologies sequentially | Y : n/a | Y : Y | Y : Y | Y : Y | Y : Y | Y : Y | N : N |
| Technology Adjustment | Changing active remedy or technology | Y : Y | Y : Y | Y : Y | Y : Y | Y : Y | Y : Y | Y : Y |
| Technology Adjustment | Employing adaptive site management approaches | Y : n/a | n/a : n/a | Y : Y | n/a : n/a | Y : Y | Y : Y | n/a : n/a |
| Technology Adjustment | Monitoring Natural Attenuation (MNA) | n/a : n/a | Y : Y | N : Y | Y : Y | Y : Y | Y : Y | Y : Y |
| Technology Adjustment | Other: (please elaborate) | | | | | | | |

**Note:**
Responses to Questions 1 and 2 are separated by a colon

# Appendix B. Summary of Tools For Site Characterization

Table 22 summarizes potential tools to support site characterization and evaluation. Only limited number of characterization tools are provided in Table 22 because these have been compiled in other ITRC resources. Relevant tools for characterization and evaluation information can be found in the following ITRC documents (itrcweb.org). In particular, the *Integrated DNAPL Site Characterization and Tools Selection* (ITRC 2015b) provides a useful compilation of relevant tools and is a recommended resource for characterization tools. Table 22 provides additional information for evaluation tools compiled from team input.

- *Integrated DNAPL Site Characterization and Tools Selection (ISC-1)*
- *Use and Measurement of Mass Flux and Mass Discharge (MASSFLUX-1)*
- *The Use of Direct-push Well Technology for Long-term Environmental Monitoring in Groundwater Investigations (SCM-2)*
- *Environmental Molecular Diagnostics Fact Sheets (EMD-1)*
- *EMD – New Site Characterization and Remediation Enhancement Tools (EMD-2)*
- *Groundwater Statistics and Monitoring Compliance Website (GSMC-1)*
- *Incremental Sampling Methodology (ISM-1)*
- *User's Guide for Polyethylene-Based Passive Diffusion Bag Samplers to Obtain Volatile Organic Compound Concentrations in Wells (DSP-1)*
- *Technical and Regulatory Guidance for Using Polyethylene Diffusion Bag Samplers to Monitor Volatile Organic Compounds in Groundwater (DSP-3)*
- *Technology Overview of Passive Sampler Technologies (DSP-4*
- *Protocol for Use of Five Passive Samplers to Sample for a Variety of Contaminants in Groundwater (DSP-5)*
- *Decision Making at Contaminated Sites: Issues and Options in Human Health Risk Assessment (RISK-3)*
- *Incorporating Bioavailability Considerations into the Evaluation of Contaminated Sediment Sites Website (CS-1)*
- *Technical and Regulatory Guidance for the Triad Approach: A New Paradigm for Environmental Project Management (SCM-1)*
- *Triad Implementation Guide (SCM-3)*
- *Vapor Intrusion Pathway: A Practical Guideline (VI-1)*
- *Vapor Intrusion Pathway: Investigative Approaches for Typical Scenarios (A Supplement to VI-1)*

**Table 22. Compilation of Potential Tools to Support Site Characterization and Evaluation**

| Tool | Description | Link/Reference |
|---|---|---|
| | | **Characterization Tools** |
| High Resolution Characterization | Multiple characterization tools | https://www.serdp-estcp.org/Tools-and-Training/Environmental-Restoration |
| MAROS | Tool to assist in monitoring network optimization | http://www.gsi-net.com/en/software/free-software.html |
| 3TMO | The 3-Tiered Monitoring Optimization Tool (3TMO) is a long-term monitoring optimization (LTMO) decision support tool. | Nobel, C. and Anthony, J.A. 2004. "Three-Tiered Approach to Long-Term Monitoring Program Optimization." *Bioremediation Journal* 8 (3-4): 147-165. |
| Visual Sampling Plan (VSP) | Tool for guiding sampling design with consideration of statistical analyses. | http://vsp.pnnl.gov/ |
| | | **Evaluation Tools** |
| ***Risk*** | | |
| GOLDSIM | GoldSim simulation software allows you to model complex, real-world multimedia environmental systems and assess the risk of those environmental systems. | http://www.goldsim.com/Home/ |
| RESRAD | The RESRAD has been widely used in the US and internationally for calculating doses and risks from exposure to radioactively contaminated soils. | http://web.evs.anl.gov/resrad/ |
| GWSCREEN | GWSCREEN was developed for assessment of the groundwater pathway from leaching of radioactive and nonradioactive substances from surface or buried sources and release to percolation ponds. | https://www.osti.gov/scitech/servlets/purl/10176916<br>Rood, AS. 2003. *GWSCREEN: A Semi-Analytical Model for Assessment of the Groundwater Pathway from Surface or Buried Contamination, Theory and User's Manual, Version 2.5*. INEEL/EXT-98-00750 Rev 1b, Idaho National Laboratory. |

| Tool | Description | Link/Reference |
| --- | --- | --- |
| CAP88 | The CAP88 (Clean Air Act Assessment Package – 1988) computer model is a set of computer programs, databases and associated utility programs for estimation of dose and risk from radionuclide emissions to air. | http://www.epa.gov/rpdweb00/assessment/CAP88/ |
| @RISK | @RISK is a spreadsheet based tool to perform risk analysis using Monte Carlo Simulation. It also has optimization tools. It is designed to analyze risk and uncertainty in a wide variety of industries, including groundwater remediation. | http://www.palisade.com/risk/<br>Byrd III, Daniel and C. Richard Cothern, "Introduction to Risk Analysis: A Systematic Approach to Science Based Decision Making, "Government Institutes Publishing, August 2000 (ISBN 0865876967) |
| ***Flow and Transport Models*** | | |
| MODFLOW | MODFLOW is a three-dimensional (3D) finite-difference groundwater flow model. MODFLOW is considered an international standard for simulating and predicting groundwater conditions and groundwater/surface-water interactions. | http://water.usgs.gov/ogw/modflow/<br>http://pubs.usgs.gov/tm/2005/tm6A16/PDF/TM6A16.pdf |
| MT3D codes | Numerical modeling tool for transport assessment using MODFLOW for the groundwater flow component. There are a number of subsidiary codes (such as RT3D, SEAM3D, PHT3D, and SEAWAT) and graphical user interfaces available. | https://water.usgs.gov/ogw/modflow/index.html<br>http://bioprocess.pnnl.gov/<br>https://water.usgs.gov/ogw/mt3d-usgs/<br>https://water.usgs.gov/ogw/seawat/ |
| RT3D guides and RTFlux | Numerical modeling tool that enables customized reaction processes. Includes a tool to extract flux data from the numerical simulations. Primarily targeted at chlorinated solvent sites, but applicable to other contaminants. | http://bioprocess.pnnl.gov/ |
| REMCHLOR, BIOCHLOR, BIOSCREEN, FOOTPRINT, REMFUEL | Screening-level transport models | https://www.epa.gov/water-research/remediation-evaluation-model-chlorinated-solvents-remchlor<br>https://www.epa.gov/water-research/biochlor-natural-attenuation-decision-support-system<br>https://www.epa.gov/water-research/bioscreen-natural-attenuation-decision-support-system<br>https://www.epa.gov/water-research/footprint-screening-model-estimating-area-plume-produced-gasoline-containing-ethanol<br>https://www.epa.gov/water-research/remediation-evaluation-model-fuel-hydrocarbons-remfuel |
| PREMChlor | PREMChlor is developed by linking the analytical model REMChlor to a Monte Carlo modeling package GoldSimTM via a FORTRAN Dynamic Link Library (DLL) application. REMChlor, or Remediation Evaluation Model for Chlorinated Solvents, is an analytical solution for simulating the transient effects of groundwater source and plume remediation. In the analytical method, the contaminant source model is based on a power-function relationship between source mass and source discharge, and it can consider partial source remediation at any time after the initial release. The source model serves as a time dependent, mass-flux boundary condition to the analytical plume model, where flow is assumed to be one dimensional. The plume model simulates first-order sequential decay and production of several species, and the decay rates and parent/daughter yield coefficients are variable functions of time and distance. This approach allows for flexible simulation of enhanced plume degradation that may be temporary, limited in space, and have different effects on different contaminant species in the decay chain. Health risks posed by carcinogenic species in the plume are calculated that the contaminated water is used in a house for drinking, bathing, and other household activities. | https://www.serdp-estcp.org/Program-Areas/Environmental-Restoration/Contaminated-Groundwater/Persistent-Contamination/ER-200704 |
| STOMP | STOMP is a multiphase computer model with capabilities to address a variety of subsurface environments, including nonisothermal conditions, fractured media, multiplephase systems, nonwetting fluid entrapment, soil freezing conditions, nonaqueous phase liquids, first-order chemical reactions, radioactive decay, solute transport, dense brines, non-equilibrium dissolution, and surfactant-enhanced dissolution and mobilization of organics | http://stomp.pnnl.gov/ |
| TOUGH | The TOUGH ("Transport of Unsaturated Groundwater and Heat") suite of software codes are multidimensional numerical models for simulating the coupled transport of water, vapor, noncondensible gas, and heat in porous and fractured media. Has been used for applications to nuclear waste disposal, environmental remediation problems, energy production from geothermal, oil and gas reservoirs as well as gas hydrate deposits, geological carbon sequestration, vadose zone hydrology, and other uses that involve coupled thermal, hydrological, geochemical, and mechanical processes in permeable media. | http://esd.lbl.gov/research/projects/tough/ |
| HYDRUS | HYDRUS is a Microsoft Windows based modeling environment for the analysis of water flow and solute transport in variably saturated porous media. | http://www.pc-progress.com/en/Default.aspx?h3d-ver2 |

| Tool | Description | Link/Reference |
|---|---|---|
| PORFLOW | PORFLOW is a comprehensive tool to accurately solve problems involving transient or steady state fluid flow, heat, salinity and mass transport in multiphase, variably saturated, porous or fractured media with dynamic phase change. The porous/fractured media may be anisotropic and heterogeneous, arbitrary sources (injection or pumping wells) may be present and, chemical reactions or radioactive decay may take place. It accommodates alternate fluid and media property relations and complex and arbitrary boundary conditions. The geometry may be 2D or 3D, Cartesian or Cylindrical and the mesh may be structured or unstructured, giving maximum flexibility to the user | http://www.acricfd.com/software/porflow/ |
| FEHM | The primary use of FEHM over several years was to assist in the understanding of flow fields and mass transport in the saturated and unsaturated zones below the potential Yucca Mountain repository. Today FEHM is used to simulate groundwater and contaminant flow and transport in deep and shallow, fractured and un-fractured porous media throughout the US DOE complex. The numerical method used in FEHM is the control volume method (CV) for fluid flow and heat transfer equations which allows FEHM to exactly enforce energy/mass conservation; while an option is available to use the finite element (FE) method for displacement equations to obtain more accurate stress calculations. In addition to these standard methods, an option to use FE for flow is available, as well as a simple Finite Difference scheme. | https://fehm.lanl.gov/pdfs/fehm_umV3.pdf |
| Advanced Simulation Capability for Environmental Management (ASCEM) | Department of Energy simulator/toolset and user interface. It includes a set of tools to support decision making including: data management and analysis, model setup, simulation and evaluation and visualization of results and decision support. | http://esd.lbl.gov/research/projects/ascem/ascemdoe.org |
| ***Uncertainty*** | | |
| R | R provides a wide variety of statistical (linear and nonlinear modelling, classical statistical tests, time-series analysis, classification, clustering) and graphical techniques, and is highly extensible. The S language is often the vehicle of choice for research in statistical methodology, and R provides an Open Source route to participation in that activity. | |
| PSUADE | PSUADE is an acronym for Problem Solving Environment for Uncertainty Analysis and Design Exploration. It is a software toolkit to facilitate Uncertainty Quantification. PSUADE has a rich set of tools for performing uncertainty analysis, global sensitivity analysis, design optimization, model calibration, etc. PSUADE supports a global sensitivity methodology for models with large number of parameters and complex constraints. PSUADE includes sampling methods, a simulator execution environment, and many different statistical analysis tools. | http://computation.llnl.gov/casc/uncertainty_quantification/ |
| DAKOTA | The DAKOTA (Design Analysis Kit for Optimization and Terascale Applications) toolkit provides a flexible, extensible interface between analysis codes and iterative systems analysis methods. DAKOTA contains algorithms for:<br>• optimization with gradient and non-gradient-based methods;<br>• uncertainty quantification with sampling, reliability, stochastic expansion, and epistemic methods;<br>• parameter estimation with nonlinear least squares methods; and<br>• sensitivity/variance analysis with design of experiments and parameter study methods.<br><br>These capabilities may be used on their own or as components within advanced strategies such as hybrid optimization, surrogate-based optimization, mixed integer nonlinear programming, or optimization under uncertainty. | https://dakota.sandia.gov/ |

| Tool | Description | Link/Reference |
|---|---|---|
| PEST | PEST implements parameter estimation based on the use of only a few parameters, as well as highly parameterized, regularized inversion based on the use of hundreds (or even thousands) of parameters. It implements both linear and nonlinear uncertainty analysis, including its unique, efficient and powerful “null-space Monte Carlo” methodology for rapid generation of many different calibration-constrained parameter fields.<br>PEST provides three options for nonlinear uncertainty analysis:<br>1. Predictive maximization/minimization<br>2. “Predictive calibration”<br>3. Calibration-constrained Monte-Carlo analysis.<br>The last of these is achieved through PEST’s unique, and extremely powerful, null space Monte Carlo technique. | http://www.pesthomepage.org/Home.php |
| UCODE | UCODE_2005 and six post-processors are included. These programs can be used with existing process models to perform sensitivity analysis, data needs assessment, calibration, prediction, and uncertainty analysis. Any process model or set of models can be used; the only requirements are that models have numerical (ASCII or text only) input and output files, that the numbers in these files have sufficient significant digits, that all required models can be run from a single batch file or script, and that simulated values are continuous functions of the parameter values. | http://igwmc.mines.edu/freeware/ucode/?CMSPAGE=igwmc/freeware/ucode/ |
| ***Visualization*** | | |
| ParaView | ParaView is an open-source, multiplatform data analysis and visualization application. ParaView users can quickly build visualizations to analyze their data using qualitative and quantitative techniques. The data exploration can be done interactively in 3D or programmatically using ParaView’s batch processing capabilities.<br>ParaView was developed to analyze extremely large data sets using distributed memory computing resources. It can be run on supercomputers to analyze data sets of exascale size as well as on laptops for smaller data. | http://www.paraview.org/ |
| VisIt | VisIt is an open source, interactive, scalable, visualization, animation and analysis tool. From Unix, Windows or Mac workstations, users can interactively visualize and analyze data ranging in scale from small (<101 core) desktop-sized projects to large (>105 core) leadership-class computing facility simulation campaigns. Users can quickly generate visualizations, animate them through time, manipulate them with a variety of operators and mathematical expressions, and save the resulting images and animations for presentations. VisIt contains a rich set of visualization features to enable users to view a wide variety of data including scalar and vector fields defined on two- and three-dimensional (2D and 3D) structured, adaptive and unstructured meshes. Owing to its customizable plugin design, VisIt is capable of visualizing data from over 120 different scientific data formats. | https://wci.llnl.gov/simulation/computer-codes/visit |
| Tecplot | Tecplot 360 is numerical simulation software package used in post-processing and visualization of simulation results. Capabilities include calculating grid quantities (such as aspect ratios, skewness, orthogonality, and stretch factors), normalizing data, verifying solution convergence, interactively exploring data through cut planes, iso-surfaces, and particle paths. Tecplot also supports data import from a wide variety of data formats. | http://www.tecplot.com/ |

| Tool | Description | Link/Reference |
|---|---|---|
| Grapher, Surfer and other tools | Grapher is a multipurpose visualization tool capable of producing more than 60 types of graphs. Create 2D or 3D line, scatter, function, class scatter, bubble, step, vector, bar charts, and floating bar chart graphs. Create line, scatter, class scatter, vector, bar, rose, wind, and radar polar plots. Create line, scatter, class scatter, or bubble ternary diagrams. Display high-low-close, candlestick, or stiff diagram specialty plots. Create statistical graphs including box-whisker plots, 2D and 3D histograms, 2D and 3D pie charts, 2D and 3D doughnut plots, Q-Q plots, and normal Q-Q plots. Alter any portion of the graph, axes, or plot for complete control of your display.<br>Surfer is a full-function 3D visualization, contouring and surface modeling package that runs under Microsoft Windows. Surfer is used extensively for terrain modeling, bathymetric modeling, landscape visualization, surface analysis, contour mapping, watershed and 3D surface mapping, gridding, volumetrics, and much more.<br>Golden Software also produces other visualization tools that are described in the brochure at the link below. | http://www.goldensoftware.com/ |

# Team Members and Contact Information

This appendix provides full contact information for ITRC Team Leaders and the ITRC Program Advisor as well as a complete list of registered ITRC team members.

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## Team Members

Team members are listed alphabetically by organization. Due to the large size of the team (over 400 participants) contact information is not included for each team member. Note that the ITRC team was active over several years (2015-2017); not all team members were part of the team for the full duration.

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# Glossary

## A

**adaptive remedial strategy**

A strategy that is designed to achieve interim objectives within a prescribed timeframe at a site. The selected strategy might include a mix of engineered/constructed remedies, natural attenuation, or institutional controls applied to specific media or site segments over time to stabilize and improve site conditions.

**adaptive site management**

An approach to resource management in which policies are implemented with the express recognition that the response of the system is uncertain, but with the intent that this response will be monitored, interpreted, and used to adjust programs in an iterative manner, leading to ongoing improvements in knowledge and performance (NRC 2003).

**alternate concentration limits (ACLs)**

Limits for a hazardous constituent as allowed by 40 CFR 264.94(a)(3) where the constituent will not pose a substantial present or potential hazard to human health or the environment as long as the alternate concentration limit is not exceeded. Factors to consider in developing an ACL are listed in §40 CFR264.94 (b).

For purposes of groundwater monitoring, hazardous constituent limits established by the USEPA Regional Administrator that are allowed to be present in groundwater (USEPA 2014c).

**Applicable or Relevant and Appropriate Requirements (ARARs)**

As defined in the NCP (40 CFR §300.5), the term "applicable requirements" means those site objectives, standards of control, and other substantive requirements, criteria, or limitations promulgated under federal environmental or state environmental or facility siting laws that specifically address a hazardous substance, pollutant, contaminant, remedial action, location, or other circumstance found at a CERCLA site. Only those state standards that are identified by a state in a timely manner and that are more stringent than federal requirements may be applicable. The term "relevant and appropriate requirements" means those site objectives, standards of control, and other substantive requirements, criteria, or limitations promulgated under federal environmental or state environmental or facility siting laws that, while not 'applicable' to a hazardous substance, pollutant, contaminant, remedial action, location, or other circumstance at a CERCLA site, address problems or situations sufficiently similar to those encountered at the CERCLA site that their use is well suited to the particular site. Only those state standards that are identified in a timely manner and are more stringent than federal requirements may be relevant and appropriate.

**asymptotic**

A line that is the limit to a curve. As the curve approaches the asymptote, the distance separating the curve and the asymptote continues to decrease, but the curve never actually intersects the asymptote (USEPA 2004c).

## B

**background levels**

An amount of a substance that occurs naturally in the environment (Agency for Toxic Substances and Disease Registry 2016).

**baseline site conditions**

Needed initial analytical data that have been measured at a site and serve as the basis or points of comparison for assessing or predicting remedy performance.

## C

**closure**

See definition of "site closure"

**comingled plumes**

Two or more plumes of contaminated groundwater from different sources that have blended together (Enviroforensics 2014).

**complex site**

A site where remedial approaches are not anticipated to bring the site to closure or facilitate transitioning to sustainable long-term management within a reasonable time frame. The National Research Council describes complex sites as follows: "Although progress has been made in remediating many hazardous waste sites, there remains a sizeable population of complex sites, where restoration is likely not achievable in the next 50-100 years. Although there is no formal definition of complexity, most remediation professionals agree that attributes include areally extensive groundwater contamination, heterogeneous geology, large releases and/or source zones, multiple and/or recalcitrant contaminants, heterogeneous contaminant distribution in the subsurface, and long time frames since releases occurred. Additional factors that contribute to complexity include restrictions on the physical placement or operation of remedial technologies and challenging expectations (e.g., regulatory requirements, cleanup goals, community expectations). The complexity of a site increases with the number of these characteristics present" (NRC 2013).

**Comprehensive Environmental Response Compensation and Liability Act (CERCLA)**

An Act of Congress passed in 1980 and amended by the Superfund Amendments and Reauthorization Act of 1986, to authorize the assessment and remediation of hazardous substances, pollutants, or contaminants that have been released into the environment.

**conceptual site model (CSM)**

"An iterative, 'living representation' of a site that summarizes and helps project teams visualize and understand available information" (USEPA 2011a).

**construction completion**

A Superfund program milestone that indicates that all physical construction of all remedial actions for a site are complete, including actions to address all immediate threats and to bring all long-term threats under control (USEPA 2011b).

**contaminants of concern (COCs)**

Contaminants in an ecosystem that may have an effect on that or other environments. These may consist of chemicals, biota, natural features or any other thing that could affect the area of concern.

**contingency remedy**

A remedy that has been prepared as a contingency plan, to be implemented if the contingency criteria occur.

**criteria adjustment**

A change in remediation standards as deemed necessary by site conditions.

## D

**data quality objectives (DQOs)**

Needed performance and acceptance criteria, which serve as the basis for designing a plan for collecting data of sufficient quality and quantity to support the goals of the study. (USEPA 2006a).

**decision document**

A public site-specific document that outlines the course of action for remediation. Examples include a CERCLA Record of Decision, RCRA permit modification, or equivalent documentation.

**designated points of compliance**

The locations where enforcement limits for contaminants of concern have been set and are not to be exceeded.

## F

**Feasibility Study (FS)**

As defined in the NCP (40 CFR §300.5): An FS means a study undertaken by the lead agency to develop and evaluate options for remedial action. The FS emphasizes data analysis and is generally performed concurrently and in an interactive fashion with the remedial investigation (RI), using data gathered during the RI. The RI data are used to define the objectives of the remedial action, to develop remedial action alternatives, and to undertake an initial screening, and detailed analysis of the alternatives. The term also refers to a report that describes the results of the study.

**Five-Year Reviews**

Five-Year Reviews generally are required by CERCLA or program policy when hazardous substances remain on site above levels which allow for UU/UE. Five-year reviews provide an opportunity to evaluate the implementation and performance of a remedy to determine whether it remains protective of human health and the environment. Generally, reviews are performed five years following the initiation of a CERCLA remedial action, and are repeated every five years so long as future uses remain restricted. Five-year reviews can be performed by USEPA or the lead agency for a site, but USEPA retains responsibility for determining the protectiveness of the remedy (USEPA 2001b).

**Focused Feasibility Study (FFS)**

A feasibility study "under which fewer alternative options would be studied…consistent with the NCP (see § 300.430(e)(1))" (NCP 1990).

**front end**

In relations to the site remediation process, "front end" is defined as before a final remedy has been identified and implemented (USEPA 1993).

## G

**Groundwater Remedy Completion Strategy**

A recommended site-specific course of actions and decision-making processes to achieve site objectives for groundwater and associated remediation objectives using an updated CSM, performance metrics and data derived from site-specific remedy evaluations (USEPA 2014b).

## I

**institutional controls (ICs)**

Nonengineered instruments, such as administrative and legal controls, to help minimize the potential for human exposure to contamination and/or protect the integrity of a remedial action. They are typically used in conjunction with, or as a supplement to, other measures, such as waste treatment or containment. There are generally four categories of ICs: governmental controls; proprietary controls; enforcement and permit tools with IC components; and information devices (USEPA 2012a).

**integrated site characterization (ISC)**

A process for improving the efficiency and effectiveness of characterization efforts at a site. The specific steps in an ISC process are as follows: (1) Define the problem and uncertainties in the CSM. (2) Identify the data gaps and spatial resolution required in the investigation. (3) Establish the data collection objectives. (4) Design the data collection process. (5) Select the appropriate investigative tools. (6) Manage, evaluate, and interpret the data (ITRC 2015b).

**interim measures**

Measures used to address risks to human health or the environment in advance of final remedy selection. Interim measures control, minimize or eliminate releases that pose actual or potential threats to human health and the environment.

**interim objective**

Intermediary goals that guide progress towards achieving site objectives.

## L

**long time frame**

This is a general term that does not have a specific definition or legal meaning. The maximum assumed remediation time frame is typically 30 years for cost estimating purposes. At complex sites, remediation time frame estimates may exceed 100 years. When used in the context of remediation technologies, a long time frame may be relative; one technology may require more time compared to another technology.

**long-term management**

A phase in remediation programs that typically includes post-construction phases of remediation management, monitoring and evaluation of remedy protectiveness.

**long-term management plan**

A living document outlining the remedy components, interim objectives, performance metrics, basis for predicting performance and decision criteria, schedule and basis for periodic evaluations and decision logic for remedy evaluation, optimization, modification or transition. The plan can be revised based on periodic performance evaluations.

## M

**maximum contaminant level (MCL)**

Drinking water standards established under the Safe Drinking Water Act which as ARARs typically represent remediation objectives at CERCLA sites. "MCLs are set at levels that are protective of human health, and are set as close to MCLGs as is feasible taking into account available treatment technologies and the costs to large public water systems." Consistent with CERCLA and the NCP, MCLs typically are relevant and appropriate when establishing remediation objectives for contaminated groundwater that is or may be used as drinking water (USEPA 1988).

**maximum contaminant level goals (MCLG)**

"Strictly health-based levels established under the Safe Drinking Water Act that do not take cost or feasibility into account. As health goals, MCLGs are established at levels at which no known or anticipated adverse effects on the health of persons occur and which allow an adequate margin of safety" (USEPA 1988).

**milestone**

An action or event marking a significant change or stage in development of a project.

**monitored natural attenuation (MNA)**

Typically, physical or biological processes (unassisted by human intervention) that will "attain cleanup levels (or other site objectives) in a timeframe that is reasonable when compared to the remediation timeframes of the other alternatives and when compared to the timeframe of the anticipated resource use" (USEPA 1999b).

## N

**National Priorities List (NPL)**

The NPL means the list, compiled by USEPA pursuant to CERCLA section 105, of uncontrolled hazardous substance releases in the US that are priorities for long-term remedial evaluation and response (40 CFR 300.5).

## O

**operation and maintenance (O&M)**

"Activities required to maintain the effectiveness and integrity of a remedy; in the case of Fund-financed measures to restore groundwater or surface water, O&M refers to the continued operation of such measures beyond the LTRA (long-term response action) period until cleanup levels are achieved" (USEPA 2011b).

**optimization**

"Efforts at any phase of the removal or remedial response to identify and implement specific actions that improve the effectiveness and cost-efficiency of that phase" (USEPA 2012c).

**optimization review**

An optimization review considers the goals of the remedy, available site data, the conceptual site model (CSM), remedy performance and exit strategy. Optimization review activities include: examining site documents, interviewing site stakeholders, potentially visiting the site, evaluating site data, developing findings and recommendations and compiling a report for the purposes of project documentation and technology transfer (USEPA 2013e).

## P

**partial cleanup**

A cleanup remediation in which current conditions meet adequate standards to protect human health and the environment where groundwater contamination is either not present, or is present at concentrations where further groundwater cleanup remediation is unnecessary at this time to be protective.

**performance metrics**
Site-specific remedy performance criteria typically used to evaluate remedy performance and measure progress towards achieving interim objectives (such as effluent discharge concentrations, contaminant concentrations trends, and hydrogeologic parameters).

**performance model**
A predictive graphic model or other predictive software model or tool (such as statistical application and numeric/analytical software models) that describes the expected performance of the remedial approach over time. Performance models are used to project future progress towards the attainment of the interim and site objectives. Performance models/prediction tools demonstrate, quantify, track, and support the evaluation of remedy progress.

**periodic evaluation**
A scheduled evaluation of remedy performance where actual performance is compared with predicted performance towards meeting interim objectives.

**point of compliance**
For groundwater, the point of compliance represents where a facility should achieve specified groundwater quality criteria to satisfy facility-specific cleanup goals (Adapted from USEPA 1996).

**postremedy implementation**
Implementation of a remediation management tool or approach (for example, technical impracticability waiver, or remediation potential assessment) after a remedy has already been selected, as during long-term management phase of site operations.

**practicable**
Capable of being accomplished. In remediation, often used to describe the limitations of proven remediation technology performance and the current state of practice.

**prevent**
A term that may be used in site or interim objectives to describe stopping the release of hazardous substances, pollutants or contaminants so that they do not migrate to cause substantial danger to present or future public health or welfare or the environment (from CERCLA Section 101(24)).

**pump-and-treat (P&T) systems**
Groundwater remedies consisting of groundwater extraction, above ground treatment, disposal of treated water, groundwater monitoring in the subsurface to determine if remediation objectives are decreasing or have been achieved, and process monitoring of the treatment plant (USEPA 2002a).

## R

**reasonable time frame**
The amount of time which is necessary to restore resources to beneficial use, as circumstances permit. This term is used in the NCP and is subject to legal interpretation: "EPA expects to return usable ground waters to their beneficial uses wherever practicable, **within a timeframe that is reasonable**, given the particular circumstances of the site" (40 CFR 300.430(a)(1)(iii)(F)). The amount of time that is considered reasonable depends on the particular circumstances of the site and the remediation method employed. The NCP also stated: "For groundwater response actions, the lead agency shall develop a limited number of remedial alternatives that attain site-specific remediation goals within different remediation periods utilizing one or more different technologies." Thus, a comparison of remediation alternatives from most aggressive to passive (natural attenuation) will provide information concerning the approximate range of time periods needed to attain groundwater remediation objectives. Although remediation timeframe is an important consideration, no single time period can be specified which would be considered excessively long for all site conditions (USEPA 1993).

**Record of Decision (ROD)**
As described in USEPA's 1999 ROD guidance: "The ROD documents the remedial action plan for a site or operable unit and serves the following three basic functions: (1) it certifies that the remedy selection process was carried out

in accordance with CERCLA and, to the extent practicable, with the NCP; (2) it describes the technical parameters of the remedy, specifying the methods selected to protect human health and the environment including treatment, engineering, and ICs components, as well as remediation objectives; and (3) it provides the public with a consolidated summary of information about the site and the chosen remedy, including the rationale behind the selection" (USEPA 1999a).

**remedial action**
RA means those actions consistent with permanent remedy taken instead of, or in addition to, removal action in the event of a release or threatened release of a hazardous substance into the environment, to prevent or minimize the release of hazardous substances so that they do not migrate to cause substantial danger to present or future public health and welfare, or the environment (40 CFR 300.50).

**remedial action objectives (RAOs)**
For CERCLA sites, RAOs specify "contaminants and media of concern, potential exposure pathways, and site objectives" (40 CFR 300.430(e)(2)(i)). Consistent with the NCP, "RAOs are designed to provide a general description of what the cleanup will accomplish (e.g., remediation of groundwater to drinking water levels)" (USEPA 1999a).

Specific goals for protecting human health and the environment. RAOs are developed by evaluating Applicable or relevant and Appropriate Requirements (ARARs) that are protective of human health and the environment and the results of the remedial investigations, including the human and ecological risk assessments.

Cleanup goals for a selected remedial action. Preliminary RAOs are often developed during the Preliminary Assessment/Site Investigation phase of a munitions response, and are refined into definitive RAOs during the course of the Remedial Investigation/Feasibility Study process. Final RAOs are documented in the Record of Decision or Decision Document. Remediation efforts are considered complete upon attainment of the RAOs.

**remedial alternatives**
Solutions used in place of original remediation strategies to ensure that site cleanup objectives are met.

**remedial approach**
A combination of remedial technologies and other approaches to remediate a site and ultimately achieve site objectives.

**remedial design**
The technical analysis and procedures which follow the selection of remedy for a site and result in a detailed set of plans and specifications for implementation of the remedial action (40 CFR 300.5).

**remedial investigation (RI)**
The RI is a process undertaken by the lead agency to determine the nature and extent of the problem presented by the release. The RI emphasizes data collection and site characterization, and is generally performed concurrently and in an interactive fashion with the FS. The RI includes sampling and monitoring, as necessary, and includes the gathering of sufficient information to determine the necessity for remedial action and to support the evaluation of remedial alternatives (40 CFR 300.5).

**remediation**
The act or process of abating, cleaning up, containing, or removing a substance (usually hazardous or infectious) from an environment.

**remediation management**
The process of managing site remediation to ultimately achieve site objectives while protecting human health and the environment. Remediation management occurs at all stages of the remedial process and includes but is not limited to, evaluating, selecting, and implementing a site-specific remedial approach and overseeing remedy operation and maintenance, monitoring programs, and remedy adjustments during long-term management.

**remediation potential**
The possibilities that exist of using technology to remove or clean up hazardous constituents that have been released into the environment.

**remediation potential assessment**

A tool used to identify a site's remediation potential and to help evaluate whether adaptive site management is needed.

**remediation time frame**

The time between implementing a final remedy and achieving all site objectives.

**remediation time frame analysis**

A study of the amount time required to meet site cleanup goals.

**remedy completion strategy**

A recommended site-specific course of action(s) and decision-making process(es) to achieve site objectives for groundwater and associated cleanup levels using an updated conceptual site model, performance metrics and data derived from site-specific remedy evaluations (USEPA 2014b).

**remedy component**

A technology or other approach such as deed restrictions that is used as part of the overall site remedy to remediate a site and maintain protection of human health and environment.

**remedy performance**

How well a selected technology is progressing to meet site cleanup goals.

**restoration**

Generally speaking, the process of returning resources to beneficial uses and the reduction of contaminant concentrations to levels that ensure protectiveness of human health and the environment, consistent with Superfund or RCRA Corrective Action programs. For groundwater, a term is used to describe "returning usable ground waters to their beneficial uses wherever practicable, within a timeframe that is reasonable given the particular circumstances of the site" (40 CFR 300.430(a)(1)(iii)(F)). For groundwater currently or potentially used for drinking water purposes, these levels may be MCLs or non-zero MCLGs established under the SDWA; state MCLs or other cleanup requirements; or risk- based levels for compounds not covered by specific state or federal MCLs or MCLGs. Other remediation objectives may be appropriate for groundwater used or potentially used for non-drinking purposes (USEPA 1993).

**risk assessment**

An organized process used to describe and estimate the likelihood of adverse health outcomes from environmental exposures to chemicals. The four steps are hazard identification, dose-response assessment, exposure assessment, and risk characterization (The Presidential/Congressional Commission on Risk Assessment and Risk Management 1997a).

The risk assessment is the evaluation of the human health and environmental risks presented by the release and potential release of hazardous substances from a site. The risk assessment (1) provides an analysis of baseline risks and helps determine the need for action; (2) provides a basis for determining levels of chemicals that can remain on site and still be adequately protective of public health and the environment; (3) provides a basis for comparing potential health and environmental impacts of various remedial alternatives; and (4) provides a consistent process for evaluating and documenting public health and environmental threats (USEPA 1989b).

**risk-based criteria**

Site-specific clean up objectives that have been derived from human health or ecological risk based data.

## S

**schedule adjustment**

For this document, changes allowed in a schedule to meet site objectives.

**site closure**

Generally, closing sites under RCRA corrective action or under CERCLA will satisfy requirements of both programs. At many complex sites, both regulatory programs will be coordinated and jointly applied.

Under CERCLA, site completion typically occurs when it is determined that no further response is required at the site, all cleanup levels have been achieved, appropriate controls are in place and the site is deemed protective of human health and the environment (USEPA 2011b, e).

When closing units or facilities under RCRA, two approaches are possible: (1) clean closure, where owners remove all wastes from the unit and decontaminate or remove all equipment, structures, and surrounding soils; or (2) closing with the waste in place (“closure as a landfill”), which is the required closure method for hazardous waste management units that cannot meet the clean closure requirements (USEPA 2017a).

**site objective**
The overall expectations for a site, inclusive of protecting human health and the environment. Site objectives may include meeting applicable or relevant and appropriate Federal and State requirements or standards (ARARs), achieving target risk levels, or other objectives to protect human health and the environment.

**site segment**
Where a whole site or plume is divided into discrete subsets that are candidates for different remediation management strategies.

**stakeholders**
Public stakeholders may include citizens, community, or environmental advocacy members, or members of the affected public. Tribal stakeholders may include Native Americans, Alaska natives, Native Hawaiians, or persons affiliated with or are employees of Native American tribes. USEPA defines the term stakeholders to include “people or communities who are affected by an agency’s work, who have influence or power over it, or have an interest in its successful or unsuccessful conclusion. This includes people and communities with the power to either to block or advance an agency’s work (USEPA 2016d). In general, the term includes anyone who has a “stake” in the development, outcome or decisions made as a result of a risk assessment. A stakeholder can be a person, group or an organization that is either affected, potentially affected, or has any interest in the project or in the project’s outcome, either directly or indirectly (The Presidential/Congressional Commission on Risk Assessment and Risk Management 1997a, b, NRC 1996).

## T

**technical impracticability (TI)**
An ARAR waiver that may be authorized under CERCLA. The TI waiver may be appropriate when compliance with an ARAR specified in a ROD “is technically impracticable from an engineering perspective” (40 CFR 300.430(f)(2)(ii)(C)(3)).

**technology adjustment**
For this document, changes in technology to meet site objectives.

**TI determination**
Specific guidance established by USEPA for evaluating the technical impracticability of attaining groundwater clean-up criteria and establishing alternative, protective remedial strategies where restoration to a criterion is not practicable. Impracticability of achieving the criterion may be demonstrated through factors such as hydrogeologic, contaminant-related, remedial technology limitations, or others (USEPA 1993).

**time-bound**
Criteria or standards that have a time constraint.

**transition assessment**
An analysis similar to a focused feasibility study that considers alternatives for site management—choosing a new remedy or transitioning to long-term management (such as monitored natural attenuation) or the other alternative approaches (NRC 2013).

**treatment train**
A sequence of independent treatment technologies designed to collectively address different aspects of site contamination.

## U

**unlimited use/unrestricted exposure (UU/UE)**
No restrictions on the potential use of land or other natural resources (40 CFR 300.430.4.ii). Such restrictions may be temporarily (over the short-term or long-term) placed on land or resources to protect human health and environment.

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