Network of National Laboratories for

NNLEMS

Environmental Management and Stewardship

R&D Roadmap for Soil and Groundwater

September-2025

NNLEMS-2025-00003

U.S. DEPARTMENT OF ENERGY

DISCLAIMER

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Acknowledgements

Executive Summary

The Department of Energy Office of Environmental Management (DOE-EM) is responsible for soil and groundwater cleanup at the fifteen remaining DOE-EM sites. There are multiple groundwater plumes throughout the complex that are challenging, due to the presence of multiple contaminants, complex hydrogeological conditions, and possibly secondary contaminant sources. Despite a significant annual investment, this soil and groundwater cleanup mission is expected to extend until 2091 (EM Program Plan, 2022). The purpose of this Roadmap is to evaluate the current state of soil and groundwater remediation and to identify opportunities for reducing both the cost and the timeline of remediation by recommending innovative solutions to accelerate the cleanup and closure of these complex sites.

The DOE-EM leadership chartered the initiative by soliciting the Network of National Laboratories for Environmental Management and Stewardship (NNLEMS) to develop a Research and Development (R&D) Roadmap for supporting this objective. The team was comprised of 22 subject matter experts from 11 National Laboratories and one academic institution. The team members have extensive knowledge in soil and groundwater characterization, remediation, and monitoring with specific expertise in state-of-the-art tools, practices, and technologies of potential benefit to the overall cleanup mission of DOE-EM.

The EM Technology Operations Office and Laboratory Policy Office have previously supported initial work to lead the development of a Soil and Groundwater R&D Roadmap by investing in an updated Technical Targets document (SRNL-STI-2021-00502), site interviews regarding immediate site needs, and the development of end state visions for complex sites (NNLEMS-2024-00001). This information was used as a starting point to guide the team to develop investment recommendations. From the significant work already done, the Roadmap Team took the foundational principles and information to build upon to provide specific and actionable recommendations for DOE-EM Headquarters to consider for implementation, with the focus on schedule acceleration and cost savings.

To support the R&D Roadmap development, three topical teams were organized and led by members selected from the NNLEMS team: characterization, remediation, and monitoring. A series of sub-team meetings were organized first focused on each of those topics, the recommendations from which were then consolidated synergistically through overall discussions.

In addition to the three topical teams, a separate team, Enabling Technologies, was created to advocate for the five specific aspects important for the research priorities:

(1) **Artificial intelligence (AI) and machine learning (ML)** are rapidly becoming more essential in environmental cleanup as they can streamline standard/current practices, interpolate/extrapolate data with significant accuracy, and minimize spending and timeline projections.

(2) **Fate and transport modeling** offers predictive, quantitative, and process-based insights to enhance existing remedy selection. The development of the R&D Roadmap through the lens of implementing innovative modeling options is essential for providing strategies to help reduce costs and time.

(3) **Geophysical tools** are becoming increasingly essential for enabling high-resolution site characterization at lower costs than conventional methods. Integrating innovative geophysical tools to provide researchers with information to be used in parallel or replacing current methods can not only save money by being more efficient but can enhance current conceptual site models.

(4) **Standard robust data management** would be of great benefit to DOE-EM and LM by using standardized approaches for managing data, spanning from initial characterization, through remedy implementation, and then into the long-term stewardship of a site. A robust and standardized data management approach supports environmental remediation decision making to prioritize actions, eliminate redundancy, and focus investments where they deliver the greatest environmental and economic benefits. Development of a standardized framework for data management and sharing will facilitate FAIR (Findable, Accessible, Interoperable, and Reusable) data principles.

(5) **Unmanned Aviation Systems** (UAS) are used increasingly in various applications. As platforms for data acquisition, these technologies provide for (1) safe operation in hazardous areas and challenging terrain, (2) rapid and efficient data acquisition over large areas, (3) flyover 'birds-eye-view' surveys of areas inaccessible by foot or ground vehicle (e.g., caps and barriers), and (4) automation for repeat surveys. Once programmed, a drone mission is easily repeated with high precision, thus supporting cost-effective long-term monitoring.

Four overarching recommendations emerged from the R&D Roadmap development:

Shift active remedies to passive remediation – first priority for implementation by DOE-EM. By integrating enhanced attenuation (EA) practices in the near-term (e.g., bioremediation, constructed wetlands, in situ geochemical remediation), DOE could save between $450M and $850M per site on remediation costs. The team is recommending Moab, Hanford, and Paducah for piloting enhanced attenuation practices. Implementing enhanced attenuation practices will accelerate the schedule at these recommended pilot sites between 10 and 70+ years.

Implementing enhanced attenuation to shift from active to passive remediation has been successful at many sites already (e.g., Idaho National Laboratory (INL) and Savannah River Site (SRS)) and would benefit many sites. At the Savannah River Site for example, shifting from pump-and-treat to the funnel and gate with base injection concept, remedial costs went from $13M a year to $500K a year, an annual savings of $12.5M.

Improve plume monitoring through innovative geophysical tools, advanced monitoring techniques, and AI/ML – second priority for implementation by DOE-EM. AI-guided real-time monitoring – by coupling in situ sensors and geophysics data streams with change detection and regression algorithms – is recommended with a particular focus on measuring that "master" variables that govern plume movement (e.g., water table gradient, pH) and/or are proxy for contaminant concentrations (e.g., pore-water specific conductivity). Such real-time monitoring can enhance the site oversight, reduce sampling and cost, as well as serve as early warning in case of system changes. In particular, the application of passive in situ sensors should be expanded for monitoring difficult-to-access regions. In addition, the strategic application of AI/ML to guide monitoring strategies at different sites and to optimize groundwater monitoring. To enable such AI/ML applications across the DOE complexes, the standardized data management and analysis tool should be established by taking advantage of or expanding the existing tools such as the ERDMS (Electronic Records and Documents Management System), DOE-LM's Geospatial Environmental Mapping System (GEMS), DOE-EM's Tracking Restoration And Closure (TRAC) database. This recommendation promotes savings of $150M-$300M per site and can accelerate the schedule between 20 and 38 years by reducing the timeframes for comprehensive sampling and analysis of monitoring networks.

Refine conceptual site models through next-generation characterization tools, modeling, and AI/ML – third priority for implementation by DOE-EM. It is recommended for the long term that DOE-EM work with subcontractors, who house the flow and transport models, to integrate innovative tools (AI/ML, modeling, etc.) to optimize the site conceptual models. Hierarchical hydrostratigraphic models and geostatistical models play a critical role in improving the realism, accuracy, and utility of groundwater models for complex sites. By shifting to the recognition that contaminated groundwater environments are fundamentally three-dimensional and heterogeneous in nature, DOE-EM can enhance the flow and transport models to make better decisions on monitoring and remediation. This recommendation is expected to save $60M to $366M and accelerate the schedule by expediting a fully supportive CSM by 0-37 years.

Consider the use of testbeds to synergistically apply tools and technologies – recommended to be done concurrently with other recommendations*. The team recommends using testbeds to gather information and data concurrently at one particular site for demonstrating technologies. The implementation of testbeds will promote synergy, provide access to a site's existing information and infrastructure, address clear challenges and needs, support strategic challenges and programmatic improvements, provide effective support to its collaborator, and support a diverse portfolio of research. Successful testbeds in the DOE-EM complex have improved robustness and effectiveness of systems. By implementing one or more testbeds (Moab Testbed, In Situ Geochemical Remediation Testbed), DOE-EM can save between $70M and $200M per site and reduce the remediation timeframe by 0-19 years.

In summary, the four overarching recommendations can save between $830M and $2B over the lifecycle of soil and groundwater remediation and many recommendations are complex-wide options. To support the reduction of active cleanup time, the schedule can be accelerated 10 to 70 years if all recommendations are implemented at the three recommended pilot sites. To reduce the timeframe for comprehensive sampling and analysis of full monitoring well networks, timeframes can be reduced by 20 to 38 years. The addition of advanced characterization tools can support a schedule acceleration between 0 and 37 years. Finally, implementing testbeds to help support final regulatory actions by identifying data gaps can support a schedule acceleration timeframe between 0 and 19 years.

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Acronyms and Abbreviations

AI/ML	Artificial Intelligence/Machine Learning
ALTEMIS	Advanced Long-Term Environmental Monitoring Systems
ANL	Argonne National Laboratory
ARL	Adoption readiness level
ASM	Adaptive Site Management
BEC	Bulk electrical conductivity
CEC	Commission for Environmental Cooperation
CERCLA	Comprehensive Environmental Response, Compensation, and Liability Act
CSM	Conceptual site model
DFN	Discrete Fracture Network
DNAPL	Dense non-aqueous phase liquid
DOE	Department of Energy
EA	Enhanced attenuation
EM	Office of Environmental Management
EPA	Environmental Protection Agency
ERT	Electrical Resistivity Tomography
ETEC	Energy Technology Engineering Center
ETTP	East Tennessee Technology Park
FAIR	Findable, Accessible, Interoperable, and Reusable
FEHM	Finite Element Heat and Mass
FNAL	Fermi National Accelerator Laboratory
FRO	Future Research Opportunities
GAO	Government Accountability Office
GCAP	Groundwater Corrective Action Plan
GEMS	Geospatial Environmental Mapping System
HQ	Headquarters
INL	Idaho National Laboratory
ITRC	Interstate Technology Regulatory Council

LANL	Los Alamos National Laboratory
LBNL	Lawrence Berkeley National Laboratory
LLNL	Lawrence Livermore National Laboratory
LM	Office of Legacy Management
MESA	Mission and End State Accelerators
MIT	Massachusetts Institute of Technology
MNA	Monitored Natural Attenuation
NETL	National Energy Technology Laboratory
NNLEMS	Network of National Laboratories for Environmental Management and Stewardship
NNSA	National Nuclear Security Administration
NNSS	Nevada National Security Site
NRC	Nuclear Regulatory Commission
P&T	Pump-and-treat
PBT	Persistent, Bioaccumulative, and Toxic chemicals
PCB	Polychlorinated biphenyls
PFAS	Per- and polyfluoroalkyl substances
PNNL	Pacific Northwest National Laboratory
PRB	Permeable reactive barrier
R&D	Research & Development
RCRA	Resource Conservation and Recovery Act
RDX	Royal Demolition Explosive
ROM	rough order of magnitude; reduced-order modeling
SRNL	Savannah River National Laboratory
SRS	Savannah River Site
TB&D	Testbeds and Demonstrations
TDE	Technology and Data Enhancers
TOO	Technology Operations Office
TRAC	Tracking Restoration And Closure
TRL	Technology Readiness Level

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UAS	Unmanned Aircraft Systems
UMTRA	Uranium Mill Tailings Remedial Action
WVDP	West Valley Demonstration Project
LiDAR	Light Detection and Ranging
VTOL	Vertical Take-Off and Landing

Introduction

In a continuing effort to look for ways to complete the soil and groundwater cleanup mission safer, cheaper, and faster, the DOE-EM leadership has commissioned the NNLEMS to conduct an evaluation of the soil and groundwater approaches and technologies at the ten of the remaining 15 DOE-EM sites and produce an R&D Roadmap that identified opportunities for research and development investments.

Of the 15 remaining EM sites, ten sites house the most complex plumes for DOE-EM. These plumes are listed below in alphabetical order by site.

1. Energy Technology Engineering Center (ETEC) – Volatile organic compound plume
2. Hanford – Central Plateau and River Corridor
3. Idaho National Laboratory (INL) – Test Area North
4. Los Alamos National Laboratory (LANL) – Hexavalent chromium plume and RDX plume
5. Moab Uranium Mill Tailings Remedial Action (UMTRA) Project – Uranium and ammonium plumes
6. Oak Ridge – Dense non-aqueous phase liquids (DNAPL) plume at East Tennessee Technology Park (ETTP) and Mercury/DNAPL at Y-12
7. Paducah Gaseous Diffusion Plant – Technetium-99 and VOC plumes
8. Portsmouth Gaseous Diffusion Plant – Volatile organic compounds (VOC) plume
9. Savannah River Site (SRS) – F-Area and M-Area
10. West Valley Demonstration Project (WDVP)– Nuclear Regulatory Commission (NRC)-Licensed Disposal Area and North Plateau Groundwater Plume

These plumes are among the most challenging due to the presence of multiple radioactive and chemical contaminants that comingle in soil and groundwater, complex hydrogeologic conditions, possible secondary sources, and regulatory requirements that vary. The soil and groundwater cleanup missions throughout the EM complex are expected to extend until 2091 (EM Program Plan 2022) with significant annual investments for cleanup. While no plume was excluded based on complexity, DOE-EM has the largest liability with the above 12 plumes with the most complexity at ETEC, Hanford, LANL, Moab, Oak Ridge, SRS, and WVDP.

The Research and Development (R&D) Roadmap for Soil and Groundwater was developed by the NNLEMS team to guide innovation and investment in technologies and approaches that can address the complex and evolving challenges of contaminated site cleanup. It serves as a strategic framework for advancing remediation science by supporting cost-efficiency, reduction of remedy duration, and long-term site stewardship. The Roadmap is intended for DOE's consideration when setting technology development priorities in support of the soil and groundwater cleanup mission.

The scope and focus of this R&D Roadmap are to use previous work and recent surveying of sites as guidance for identifying critical research needs for the DOE-EM complex, focusing on reducing costs and timeline of selected remedies. The team focused on innovative, state-of-the-art technologies and approaches related to characterization, remediation, and monitoring, the three main areas of environmental cleanup; see Appendix A for the DOE Charter and Appendix B for the NNLEMS Proposal.

After issuance of the charter, the Federal Steering Committee notified NNLEMS to initiate the development of the Roadmap. The NNLEMS Team Lead organized the project team by soliciting volunteers from the 11 labs in NNLEMS, identifying team member expertise for placement into teams for 3 focus areas (characterization, remediation, and monitoring), and identifying team leads, and identifying

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additional expertise to select at least one representative for each Enabling Technology (Appendix C). The entire Roadmap team then met bimonthly to discuss status on background investigations and literature reviews, report development, and R&D recommendation development. The teams developed a questionnaire for the sites to receive more information about the current needs of the sites (Appendix D) and included a request for an update on scheduled items in EM Program Plan 2022 (DOE, 2022a). The focus area teams (characterization, remediation, and monitoring) met at various intervals throughout this process to work on the Roadmap as small teams, as did the R&D Roadmap lead and focus area leads. As a full team, the outline for the report was developed along with guidance parameters for prioritizing and ranking R&D recommendations.

The team focused on rough order of magnitude (ROM) cost estimates and timeline reduction as the main two factors for down selecting and prioritizing R&D recommendations. Technology readiness level (TRL), adoption readiness level (ARL), implementation cost and timeline, and applicable sites were used to further prioritize.

This R&D Roadmap includes:

- a description of previous work performed from 2021 to 2024,
- details of enabling technologies applicable to the three focus areas,
- expansion of the current state-of-science and applicability of characterization, remediation, and monitoring,
- specific R&D recommendations and descriptions of the categories the recommendations fall into,
- overarching recommendations for expediting closure with applicable R&D recommendations, and
- descriptions of R&D recommendations, including
  - short- and long-term recommendations
  - estimated cost savings
  - estimated timeline reduction

Previous Studies

In 2021, Savannah River National Laboratory (SRNL) led a three-phased NNLEMS groundwater closure study. Phase 1 revisited the 2002 Technical Targets, when a team identified critical technical issues required to expedite cleanup of DOE's complex plumes and develop an updated approach after 20 years of remedial activities. The team developed a framework and recommended a strategy for addressing the updated needs given the current state of remedial progress, developments in technical approaches, and lessons learned throughout the last 20 years of remediation efforts (Looney and Nyman, 2021). This team was comprised of 24 NNLEMS participants and was funded by DOE-EM Technology Development Office (currently known as Technology Operations Office [TOO]).

Phase 2 of the project was initiated by the EM Laboratory Policy Office following the completion of the updated Technical Targets document. The Phase 2 team is comprised of NNLEMS experts from Phase 1 and additional regulatory engagement experts. The team conducted interviews from May to August 2022 with each of the DOE-EM sites managing complex groundwater plumes: the Energy Technology Engineering Center (ETEC), the Hanford Central Plateau and River Corridor areas, Los Alamos National Laboratory (LANL), the Moab UMTRA Project, Oak Ridge, the Paducah Gaseous Diffusion Plant (Paducah), Portsmouth, the Savannah River Site (SRS) F- and M-Areas, and the West Valley Demonstration Project

(WVDP) (Eddy-Dilek, 2023). The goal of these interviews was to identify critical and high-priority challenges and assess common themes and best practices for groundwater site closure across the EM complex.

Finally, Phase 3 focused on the development of an integrated, complex-wide strategy to support groundwater closure, folding in the understanding of the technical needs (Technical Targets; Phase 1) and site-specific issues and challenges highlighted in Phase 2. The Team developed End State Vision matrices based on institutional knowledge and site interviews. A key component of this phase of the project was to provide metrics that could be used by DOE-EM to accelerate the cleanup of remaining contaminant plumes in a consistent manner and track progress. To this end, the team developed a set of four metrics for the End State Vision matrices as described below. Phase 3 was also funded by DOE-EM's Laboratory Policy Office, currently within the Office of Chief Technology Officer.

Technical Targets

Technical Targets were first developed in 2002 to guide and focus research efforts that would facilitate progress towards site closure (Looney and Nyman, 2021). After two decades of remedial activities at DOE sites, the current technical focus and needs have evolved.

Issues that have gained prominence since the original exercise include the need to address lower levels of contamination where active remediation is no longer cost effective and residual sources that are challenging to characterize, access, and remove.

The Technical Targets are the following:

Ensuring Environmental Stewardship
- Improving the Technical Basis for Environmental Stewardship Management
- Climate Resilience
- Emerging Contaminants
- Next Generation Modeling
- Methods to Verify and Validate Performance

Eliminating Contaminant Sources
- Source Zone Destruction, Stabilization, and Treatment
- Controlling Contaminants in the Vadose Zone

Isolating Contaminants
- Advanced Sustainable Containment Systems
- Integrated Contaminant-Treatment Concepts

Controlling Contaminant Plumes
- Effective and Sustainable Solutions for Plumes
- Overcoming Challenges to Achieving End States

Enabling DOE's Cleanup Efforts
- Subsurface Access and Delivery
- Next Generation Characterization Technologies (Tools)
- Biogeochemical Processes Determining Contaminant Fate
- Strongly Heterogeneous Systems

The 2021 Technical Targets report details each of the above Technical Targets and includes the status, data gaps, vital technical and scientific objectives, and key notes for future consideration when using the report as a guide for addressing specific site needs.

Site Interviews

The site interview phase began in 2022 with interviews at nine DOE-EM sites across the complex to identify critical challenges and assess common themes and best practices. This phase of the groundwater strategy development included experts in stakeholder interaction, regulatory engagement, risk assessment, and site management as well as representatives from the Technical Targets development team. The team of reviewers consisted of representatives from within Pacific Northwest National Laboratory (PNNL) and SRNL and outside participants from the Consortium for Risk Evaluation with Stakeholder Participation, Longenecker & Associates, and Geosyntec Consultants.

The nine sites participating in the Phase 2 interview process were:

- Energy Technology Engineering Center,
- Hanford,
- Los Alamos National Laboratory,
- Moab UMTRA Project,
- Oak Ridge (including Oak Ridge National Laboratory and the East Tennessee Technology Park),
- Paducah,
- Portsmouth,
- Savannah River Site, and
- West Valley Demonstration Project.

The sites completed questionnaires that identified some of the key challenges associated with groundwater cleanup at the sites, technical, regulatory, or otherwise, and metrics that are used to track progress.

Subsequently, the review team conducted a virtual interview between site representatives involved with groundwater cleanup and management. The sites presented an overview of the conceptual site model(s) and the scope of groundwater cleanup efforts. These site teams then fielded questions about the responses to the questionnaires. Following the interviews, the review team members provided input, and site summaries were prepared that distilled the reviewer team's recommendations, their overlap with Technical Targets, and links to other sites or broader themes.

End State Vision

Phase 3 focused on the development of an integrated, complex-wide strategy to support groundwater closure based on the information gained in the first two phases. End State Vision matrices were developed and then completed for the interviewed sites. The team developed a set of four metrics for the End State Vision matrices as described below.

End State. This metric measures whether an end state has been defined, including institutional and engineering controls. The ultimate success in this metric is that the end state has been defined, along with implemented institutional and engineering controls, and the end state has been appropriately incorporated into approved regulatory documents, e.g., orders, agreements, permits, Records of Decision,

Groundwater Compliance Action Plans (GCAP). Most sites have defined end state goals; some sites have a few areas that have reached final remediation with institutional and engineering controls.

Groundwater Plume Status. This metric measures the extent of groundwater plume control and regulatory approval of final groundwater remedies. The ultimate success in this metric is that the plume is stable or shrinking, regulatory acceptance has been obtained for final remedies, and remedies have shifted from active to passive. Most evaluated sites have groundwater plumes that are in the characterization stage and/or interim measure stage. Very few sites have a regulatorily approved final groundwater remedy in place that is active; fewer still have a final approved passive groundwater remedy. While active remediation and source control will be necessary at many plumes, the DOE goal is to remediate groundwater in support of the end state, ultimately using passive activities, such as monitored natural attenuation, that are approved in appropriate regulatory documents

Control of Exposure. This metric reflects whether any uncontrolled or unacceptable human exposure is occurring from DOE-sourced contamination either on-site or off-site. For most DOE sites, exposure risk should be controlled so that it is within acceptable risk ranges. However, this metric is a high-level way to track if there is any change in migration and exposure that requires action. This measure is also a good public-facing communications tool.

Engagement. This metric reflects the status and degree of regulatory, stakeholder, and Tribal Nation (if applicable) engagement. Currently, most DOE-EM sites have regular communication with decision-makers/stakeholders. Higher measurements of this metric reflect that the communication framework is sustainable, supports mission need schedules, and whether the communication framework extends up and down the management structures and across all key stakeholder groups.

The team evaluated the documents provided by the sites in the interview phase, the interview responses, and additional knowledge of the sites to determine whether they had low, medium-low, medium, medium-high, or high statuses in the categories listed above. The results can be found in NNLEMS-2024-00001.

In summary, these studies have set the stage for developing the Soil and Groundwater R&D Roadmap. These studies identified an end state goal for each of the complex plumes and identified key issues to facilitate closure. Most of these plumes will require remedial activities and monitoring for decades. The purpose of this Roadmap is to identify strategies to reduce costs and shorten the timeline to closure or transition to passive remedial strategies with improved monitoring of the residual contamination.

Introduction to Characterization, Remediation, and Monitoring

The three focus area teams, (1) Characterization, (2) Remediation, and (3) Monitoring – that were organized to support the roadmapping process are shown in Figure 1. The team-based organizational structure provided the opportunity to focus on the Roadmap brainstorming process and encouraged meaningful discussions with an appropriate level of detail and granularity. To maximize synergy and to assure that there was coordination and cross-fertilization among the three teams, the leads for each team participated in all three teams. The following paragraphs provide a summary of the vision (principles that were used to focus the work) for each team, followed by a more complete description. To support all three teams, a separate team of subject matter experts provided information on enabling technologies.

Figure 1. Summary of Team Structure Used for Soil and Groundwater Roadmap

The Characterization Team focuses on technologies and strategies to formulate or revise the conceptual site model (CSM). A conceptual site model identifies key operational history, contaminant source location/geometry and projected release mass flux, and key features in the environment that control the current and future distribution of contamination and govern the performance of potential remediation options. The CSM needs to identify the features governing plume dynamics (vadose zone thickness and aquitards, key heterogeneities, depositional facies and formations, and similar features). The technologies and strategies in the characterization portfolio need to contribute to a CSM that is robust and useable across multiple scales. Thus, the focus of technology application in the Characterization Team is on the intrinsic properties of the environmental system and the application of technologies/strategies often focuses on collecting, managing, and interpreting detailed depth discreet information. The conceptual site model is the primary basis for developing analytical and numerical models that are used to support and communicate DOE-EM decisions such as remedy selection, estimation of risk, and remediation timeframe.

The Remediation Team is focused on underutilized technologies and strategies that have realized significant success in the past and which might provide a step change in performance at many remaining DOE-EM sites. The focus of the team was to provide a path for DOE to better manage remediation as the site conditions evolve toward the remediation end state – moving from active to passive remedies along a clear, disciplined and well documented path. The team focused on matching technologies to conditions in space and time. The Remediation Team deliberations have forward and backward feedback loops to the other teams and connections to the central strategic EM decisions.

The Monitoring Team focuses on technologies and strategies that track changes over time and documents that the environmental system is behaving as expected based on the CSM and analytical or numerical models for the site. While many of the underlying technologies overlap between the Characterization and

Monitoring Teams, the core value of the Characterization Team is distinguishable from the Monitoring Team. The nature of technology application to monitoring can also be distinguished from the Characterization Team. For characterization, detailed information on structure and boundary conditions is needed to develop a robust CSM. For monitoring, more integrative metrics (i.e., different technologies or different configurations of a given technology) are needed since many DOE-EM endpoints (flux to a receptor, risks to human health and the environment, and the like) represent emergent system behaviors that integrate the many complexities and properties in the environment – one does not need to know all the fine details within the system if the emergent behavior is in control. Thus, monitoring technologies typically focuses less on detailed depth discrete information and more on high frequency measurements. If the monitoring data substantively diverge from the CSM, then the divergence becomes an important data input for DOE-EM and their contractor to cycle back to a focused characterization activity to refine the CSM. The forward and backward characterization and monitoring feedback loop is depicted in Figure 1 along with the other connections between the teams with all teams feeding into the central strategic Environmental Management responsibilities of DOE-EM.

For both the Characterization and Monitoring Teams, the participants focused on technologies that are sufficiently developed so that they can be deployed and provide significant value to DOE-EM during the next few years. The teams typically focused on ideas with a TRL of 6 or higher. In many cases, the teams recommended the use of existing technologies in new or innovative ways, technologies that have advanced rapidly and are ready for deployment (such as artificial intelligence and machine learning [AI/ML]) or focused on technologies that have proven useful, but which are not commonly deployed (underutilized technologies such as some types of geophysics). Several of the promising emerging technologies such as AI/ML were further developed by subject matter experts as part of the Enabling Technologies portion of the report. In the case of underutilized technology, there is an investment window of opportunity for DOE to accelerate progress/schedule, enhance their mission, or otherwise improve EM performance.

The core value and focus for each team were communicated to the Roadmap participants and are reflected in the listing of ideas and recommendations. In the next three sections below, the three team leads provide more detailed summaries of their core values and principles.

Characterization: A Cornerstone of Groundwater Remediation Strategy

Accurate and comprehensive characterization of contaminated subsurface environments is a critical precursor to effective remediation. Subsurface contamination at DOE-EM sites arises from a legacy of diverse and complex waste disposal practices that have resulted in persistent, spatially extensive plumes of radionuclides, metals, and industrial chemicals in saturated and unsaturated groundwater flow systems.

More specifically, such activities often addressed the collection and review of existing site data, including historical land use, previous site investigations, and regional hydrogeologic information. Field investigations were designed and implemented, often involving the installation of wells at strategic locations and depths to delineate the vertical and horizontal extents of groundwater contamination. Physical characterization focuses on determining the geological structure and properties of the subsurface, such as soil and rock types, porosity, permeability, and the presence of confining layers. This included mapping aquifer geometry, groundwater flow directions, hydraulic gradients, recharge and

discharge zones, and the boundaries of hydrogeologic units. Chemical characterization involved sampling groundwater and sometimes soil or soil gas to identify and quantify the types, concentrations, and distribution of contaminants. This process included laboratory analyses for a range of chemical constituents, such as volatile organic compounds (VOCs), metals, nutrients, and other site-specific compounds. In addition, traditional characterization sought to understand the fate and transport of contaminants by evaluating processes such as advection in groundwater, hydrodynamic dispersion, chemical sorption, and the potential for degradation and natural attenuation. This often requires the collection of site-specific geochemical groundwater data such as pH, redox potential, temperature, dissolved oxygen, and organic carbon content, all of which may influence contaminant mobility and persistence. The ultimate goal of traditional characterization was to develop a conceptual site model that integrates all available data to describe the sources, pathways, and receptors of contamination.

Over the past several decades, this approach has served as a strong foundation for risk assessment, remedial design, and long-term monitoring strategies, and it continues to do so. However, in the context of this report, characterization is being more broadly conceived as integrated within evolving concepts of monitoring and adaptive remediation technologies. Effective monitoring and remediation strategies depend and build on a sound understanding of the hydrogeologic and contaminant conditions established during characterization. Conversely, adaptive remediation technologies rely on continuous feedback loops made possible through integrated monitoring and a dynamic conceptual site model. Together, these three functions form a unified and iterative cycle that enables DOE-EM sites to reduce uncertainty, refine remedial designs, and adjust strategies in response to evolving site conditions or performance data. An effective characterization strategy must integrate advanced technologies and modeling frameworks that can reduce uncertainty, improve spatial and temporal resolution, and support predictive decision-making.

In this report, three principal themes are generally relevant to characterization of a contaminated groundwater system (Figure 2):

(1) Source term characterization is the process of identifying, quantifying, and understanding the nature of contaminant sources that release pollutants into groundwater or soil gas systems. It involves defining the location, chemical form, mass, and release mechanisms of contaminants in soils, wastes, or vadose zone materials, which is essential for predicting plume behavior, designing remediation strategies, and reducing long-term uncertainty in cleanup.

(2) Hydrogeologic conceptualization is the development of an integrated understanding of a site's geologic framework, hydrologic processes, and groundwater flow systems to explain how water moves through the subsurface. It provides the foundation for site characterization by linking stratigraphy, structure, and hydraulic properties into a conceptual site model that guides monitoring, modeling, and remediation decisions.

(3) Transport process conceptualization is the characterization of the physical, chemical, and biological processes that control how contaminants move, transform, and persist in the subsurface. It integrates hydrogeologic mechanisms such as advection, dispersion, diffusion, sorption, phase change, and reactions into the site conceptual model to explain plume behavior and support prediction and remediation planning.

In addition, following discussions with DOE site managers, both (4) vadose zone and (5) fractured rock characterization have emerged two critical cross-cutting themes that have relevance across the complex. In the vadose zone, contaminants can persist as deep, often inaccessible secondary sources that sustain groundwater plumes; characterizing their extent and release potential is critical to defining the source term. The vadose zone modulates recharge and infiltration, making it a key control in hydrogeologic conceptualization of groundwater flow systems. Vadose zone heterogeneity dictates preferential pathways, episodic infiltration, and overall contaminant residence times. Fracture geometry and connectivity are central to hydrogeologic conceptualization, while transport processes in fractured systems are dominated by dual-porosity behavior, matrix diffusion, and heterogeneous flows.

Figure 2. Major (1-3) and Cross-Cutting (4, 5) Themes Identified as Generally Relevant to Characterization of a Contaminated Groundwater System (Environmental Protection Agency, 1999)

Within this thematic discussion, eight specific topics have been identified as research priorities that merit future consideration for future site application (see Table 1). These are introduced briefly below (in bold) in the context of the themes and are described in more detail in a separate section of this report. Importantly, each of these topics can be mapped into individual technical targets identified in Looney and Nyman (2021). Linkages to these technical targets are also identified in the table.

Source Term Characterization

Understanding the location, form, persistence, and potentially dynamic nature of contaminant sources is essential to define appropriate remediation goals and evaluate remedy performance. At many DOE-EM sites, such as Hanford, Moab, LANL, and Paducah, complex source zones may include mobile and immobile contaminant phases, legacy infrastructure, or recalcitrant waste forms trapped within the vadose zone or low-permeability media. Accurately identifying and characterizing these source terms is particularly critical where long-term natural attenuation strategies are being considered.

Traditional methods for characterization often rely heavily on well-based sampling and generalized assumptions of source zone architecture. New characterization methods, used to varying extents at different DOE sites, can dramatically increase resolution and fidelity. Borehole flow logging techniques, including spinner, heat-pulse, nuclear magnetic resonance, and electromagnetic tools, can provide vertical profiles of hydraulic conductivity and help localize the vertical distribution of contaminant concentrations around open or screened boreholes. These measure profiles allow practitioners to infer stratigraphic variability in flow and pinpoint intervals contributing most to contaminant flux. This has important implications for source delineation and targeting in situ amendments or extraction wells.

Beyond direct sampling and logging, distributed sensing tools offer promising opportunities for embedding characterization into infrastructure. For instance, distributed fiber-optic sensing deployed alongside reactive barriers, or new wells, can detect thermal or acoustic signals correlated with subsurface flow changes. These systems allow for dense spatial and temporal data collection over long periods with minimal maintenance, reducing cost and providing a powerful tool for early, high-resolution detection of source behavior changes.

Tracer and isotopic characterization tools can be used to help identify, differentiate, and quantify contaminant sources, including differentiating between legacy and ongoing inputs. These tools can be used to fingerprint or differentiate contaminant waste streams, identify signatures of biodegradation, or identify groundwater ages and recharge source information.

Finally, integrating hierarchical hydrostratigraphic models into source zone analysis enables a more systematic delineation of lithologic and facies-level variability. Such models, which organize the subsurface into nested scales (e.g., region, formation, facies), can help characterize the spatial distribution of low-permeability units that may sequester contamination over long periods. This is particularly relevant to DOE sites like Hanford, where matrix diffusion from clay lenses sustains contaminant concentrations long after primary sources have been removed.

Hydrogeologic Conceptualization

A robust and defensible CSM is the backbone of all site cleanup decisions. Hydrogeologic heterogeneity, large domain sizes, and variable data density challenge the accuracy and utility of many current CSMs. Advances in computing and analytics now support a new generation of hydrogeologic conceptualization that integrates multiscale data into a coherent, flexible framework.

Hierarchical hydrostratigraphic modeling frameworks, including geostatistical techniques, are increasingly critical to this effort. These models incorporate structural geologic features, depositional history, and measured or inferred properties (e.g., porosity, permeability) across scales, from core to catchment. The incorporation of geophysical, hydrologic, and geochemical data sets into these frameworks allows modelers to better capture the complex relationships between stratigraphy, structure, and flow paths. At Los Alamos, such integration has been critical in reconciling legacy waste disposal patterns with deep groundwater transport mechanisms.

Machine learning (ML) and reduced-order modeling (ROM) approaches offer further enhancement. ML tools can rapidly evaluate large data sets to detect patterns, optimize parameter estimation, and prioritize data collection. They are particularly useful in assimilating disparate data types (e.g., historical records, geophysical logs, sensor outputs, tracer and isotope data) into a single model space. ROMs, on the other hand, can approximate complex models while preserving predictive power. This is valuable for real-time decision-making, optimization, scenario analysis, and stakeholder communication.

A properly developed CSM grounded in hierarchical and ML-informed models also enables better design and siting of remedies, optimization of monitoring networks, and effective uncertainty quantification. Importantly, the CSM must evolve as new data becomes available, necessitating iterative model updating, or "living CSMs." For long-term DOE sites where conditions can change over years to decades, it is necessary to maintain an up-to-date, technically robust conceptualization of hydrogeologic conditions.

Transport Process Identification

Transport process identification is essential for understanding how contaminants migrate through the subsurface, evolve over time, and interact with hydrogeologic features. Key processes include advection, dispersion, matrix diffusion, sorption, and degradation, each influenced by site-specific geology, chemistry, and hydrology.

Characterizing these processes requires tools capable of resolving temporal and spatial variability. Distributed fiber-optic sensing systems can provide nearly continuous measurements of temperature and pressure, which can be used to constrain flow and contaminant transport. High-resolution time-lapse geophysical surveys and tracer tests support the delineation of active flow paths and permit quantification of transport parameters. Similarly, advanced borehole flow logging techniques and distributed sensing tools can be used to identify changes in hydraulic conductivity and head over depth. Similarly, tracer and isotope techniques can directly quantify how contaminants move, react, and attenuate in the subsurface.

The use of ML models is also growing in transport monitoring efforts (see Monitoring Section on Page 36). These tools can detect subtle correlations in large, multivariate datasets, improving our ability to forecast plume behavior and optimize monitoring designs. This is especially helpful at sites with complex source terms, dynamic boundaries (e.g., seasonal river stage changes), and long remediation timelines.

Characterization of the Vadose Zone

The vadose zone is a critical and often under-characterized component of contaminant transport systems at many DOE sites. Vadose zone characterization is essential for understanding residual contaminant sources and their potential migration pathways. Contaminants in the vadose zone are often less mobile and less accessible to groundwater and can persist for longer periods as potential

groundwater contaminants. Many contaminants can volatilize into soil gases and vapors able to migrate separately and rapidly through soils and enter overlying buildings through cracks or utility conduits. In this sense they introduce added risk through additional human exposure pathways (such as inhalation) on top of those associated with groundwater alone. Gas phase contaminants are more challenging to detect and delineate compared to dissolved contaminants in groundwater (Figure 3). The vadose zone varies greatly in thickness and complexity, from shallow soils to deep, fractured geologic units extending more than 100 meters At sites like Hanford, LANL, and INL, deep vadose zones present a persistent source of groundwater contamination due to long travel times and slow release from contaminated low-permeability materials or fractured rock matrices. Furthermore, volatile contaminants can have extended source longevity in the vadose zone, acting as reservoirs that continue to emit vapors and recharge groundwater for decades or longer. Furthermore, dynamic variations in vadose zone thickness associated with changes in hydroclimate regimes (e.g., regional lowering of groundwater levels) and episodic events (e.g., storm-induced flooding and dam operations that result in increased groundwater levels) must be incorporated into CSM refinement and re-assessment activities.

Key challenges in vadose zone characterization include heterogeneity in soil texture and layering, difficulty accessing deep vadose zones for sampling, and complex flow behaviors such as preferential flow through fractures or high-permeability lenses. Capillary retention processes further complicate the movement and retention of liquid phase contaminants and/or their solution or exchange into percolating soil moisture, often trapping contaminants within soil pores or low permeability materials and delaying their migration to groundwater all while soil vapors continue to be released. Volatile contaminants add additional complexity due to rapid and sometimes unpredictable migration through the vadose zone, which can result in sudden changes in exposure risk and contaminant vapor distributions. Detection and characterization of these processes are inherently difficult, and the potential for contaminant rebound—where concentrations increase after remedial actions due to ongoing release from residual sources—requires careful long-term monitoring and adaptive management strategies. To address these challenges, DOE-EM is investing in high-resolution geophysical imaging, tracer studies, and long-term monitoring networks. Electrical resistivity tomography (ERT) and electromagnetic methods have been used to monitor infiltration processes at Hanford and elsewhere. These tools can help resolve subsurface structure, detect active transport pathways, and track contaminant persistence over time. Particular attention is needed to verify and validate vadose zone sources as they may act as secondary plumes that recharge groundwater for decades or longer.

Advanced vadose zone characterization is especially critical at Hanford's Central Plateau, LANL's Technical Area 16, and INL, where complex geologies such as fractured volcanic tuffs and interbedded basalt flows dominate. These sites require integrated approaches combining core sampling, geophysical surveys, and predictive modeling to identify transport hotspots and persistent sources. These efforts are essential to accurately forecast contaminant migration, evaluate attenuation potential, and guide long-term stewardship strategies.

Fractured Rock Characterization

At several DOE-EM sites, groundwater contamination occurs in fractured rock settings, where the transport of contaminants is governed by both fast advection through fractures and slow diffusion into the surrounding rock matrix. Fractured systems present dual-porosity behaviors that are fundamentally different from porous media and require specialized characterization approaches.

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Key components of fractured rock characterization include mapping fracture networks, evaluating fracture connectivity and aperture distributions, and modeling matrix diffusion processes. At LANL, for instance, high explosives such as Royal Demolition Explosive (RDX) have been shown to persist via diffusion into the volcanic tuff matrix, even as fracture water concentrations decline. Similar behaviors have been observed at INL and Hanford. Sophisticated discrete fracture network (DFN) models, calibrated through tracer tests and geophysical surveys, are now being applied to simulate these environments. These tools support risk assessments, remedy designs, and the development of robust long-term monitoring strategies.

Fractured rock and vadose zone characterization often intersect, especially in arid DOE-EM sites where fractures extend through the vadose zone. Integrating models of fracture flow with vadose zone transport and monitoring data is a critical need for predictive modeling and adaptive remediation planning. Tracer and isotope methods offer unique tools to understand transport behavior in the vadose zone and especially fractured rock environments. These dual challenges emphasize the need for flexible, multi-scale tools that span lithologic and hydrostratigraphic complexity.

Summary of Characterization Research Priorities

Table 1 summarizes eight advanced characterization concepts discussed in this Roadmap, their relationship to individual technical targets identified in Looney and Nyman (2021) and identifies representative DOE-EM sites where their use is applicable or known to be in use (or partially in use and under evaluation). They are described more fully in Appendix H. Their deployment at sites (either individually or in combination) can be used to refine conceptual site model, identify time-sensitive contamination risks, support predictive transport modeling, and enable adaptive remedy strategies tailored to local conditions. Their implementation may involve minimal to nominal impacts on schedule and cost at first, depending on the desired scope and extent of application, but the expectations are for longer term schedule and cost savings as noted in Table 1.

Broader Site Management Paradigm

Instead of existing as separate, up-front activities, the characterization technologies and priorities in Table 1 can be viewed as part of a broader site management paradigm in which characterization, remediation, and monitoring technologies are used in concert throughout the lifecycle of a cleanup program. In this sense, some characterization technologies may also be used as monitoring tools and as agents for developing and guiding adaptive remediation system designs over time. For example, characterization tools that serve to define the initial state of a contaminated system, such as a source term or spatial extent of a plume, are also in a position to monitor and define the evolving state of a contaminated system over time, which, in turn, can be used to update remediation strategies that have been implemented.

Establishing Testbeds and Cross-site Collaborations

Advanced characterization approaches have developed over the last thirty years and implemented at various sites across the across the DOE-EM complex. From resolving persistent source zones to refining hydrogeologic models and tracking dynamic transport processes, the emphasis must be on integration, innovation, and actionable insight. These efforts also feed directly into broader long term monitoring strategies and adaptive remediation frameworks. A properly characterized site allows for intelligent deployment of sensors, more targeted and efficient long-term monitoring, and more agile, data-informed adjustments to remediation strategies. These enable faster attainment of remediation goals,

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reduced costs, and greater confidence in long-term protectiveness. The Roadmap recommends prioritizing R&D investments that close technical gaps, reduce lifecycle monitoring costs, and improve remedy selection and performance confidence. Embracing these state-of-the-art characterization strategies will enable DOE-EM to meet its cleanup objectives faster, at lower cost, and with greater certainty.

Implementation of these innovative tools such as fiber-optic distributed sensing, groundwater age tracers, or machine learning-enhanced decision platforms may benefit from demonstration field testbeds where the installation and the performance of the tools can be evaluated. The existing implementations of these innovative technologies at DOE-EM sites may provide actionable information for implementation at other DOE-EM sites that have no experience in these technologies. In this sense, inter-site collaborations can be used to expedite technology transfer and reduce duplication of effort. An example of this would be potential lessons and benefits of fractured rock characterization activities conducted at the Nevada National Security Site (NNSS) as they may be applied at INL (see Appendix H). In addition, demonstrations and implementation of ERT at the Hanford site will expedite transfer to other sites including SRS and Moab.

Table 1. Summary of Potential Characterization Research Strategies and Site Relevance

Characterization Tool	Description	Example Applications / Relevant Sites (alphabetically)
Distributed Fiber-Optic Sensing	Passive/active sensing using fiber-optic cables to monitor subsurface flow and temperature at high resolution	• Applicable: Hanford, SRS • In partial use: Moab
Borehole Flow Logging	Tools to measure vertical hydraulic gradients and flow contribution along boreholes	• Applicable: LANL, Paducah, Hanford
Tracer and Isotopic techniques	Diagnostics to track groundwater movement, identify contaminant sources, quantify transport and attenuation, and improve subsurface characterization	• Applicable: All sites
Hierarchical Hydrostratigraphic Modeling	Multi-scale geologic modeling to structure subsurface heterogeneity	• Applicable: SRS, WVDP • In partial use: Hanford, NNSS
Machine Learning and Reduced Order Models	Data integration, model optimization, and uncertainty quantification using ML and simplified models	• Applicable: All sites
Targeted Temporal Characterization	High-frequency or event-triggered monitoring to capture plume dynamics	• Applicable: Paducah, LANL, Oak Ridge • In partial use: Moab
Vadose Zone Characterization	Characterization of unsaturated zones to identify long-term sources, preferential pathways, and groundwater recharge	• Applicable: Hanford, INL, LANL, Moab • In use: Hanford, INL, LANL
Fractured Rock Characterization	Mapping and modeling dual-porosity systems with fast fracture transport and slow matrix diffusion	• Applicable: LANL, Hanford, INL, NNSS, Yucca Mountain • In use: LANL, NNSS, Yucca Mountain

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Remediation: Removing Contaminant Sources and Containing Groundwater Plumes

The consensus framework for evaluating remediation strategies and technologies for the DOE-EM Soil and Groundwater Roadmap is discussed in this section. The framework is built on key technical principles to identify the most promising portfolio of activities for maximum impact. Rather than using contaminant class as the primary category for organizing the evaluation, the consensus framework is built upon key characteristics of robust and successful remediation technologies or strategies. Fundamental characteristics and classes of contaminants are explored as a secondary factor.

Remediation Related Technical Targets

Key EM technical targets focused on remediation research needs are annotated in Figure 3. Six of the overall fourteen targets focus on remediation: (1) effective and sustainable solutions for plumes, (2) source zone destruction, stabilization, and treatment, (3) controlling contaminants in the vadose zone, 4) advanced-sustainable containment systems, (5) integrated containment-treatment concepts, and (6) improving the technical basis for environmental stewardship management. Specific details that provide a deeper understanding of the remediation-centric targets are provided in the narratives in the full report. Notably, these narratives focus on topics of sustainability, transitioning to passive attenuation-based remedies, acceleration of progress, cost savings and similar metrics. There is a synergy among the remediation targets and with several of the other targets – such as biogeochemical processes determining contaminant fate, emerging contaminants, and others.

Relationship of Targets to Environmental Management Activities
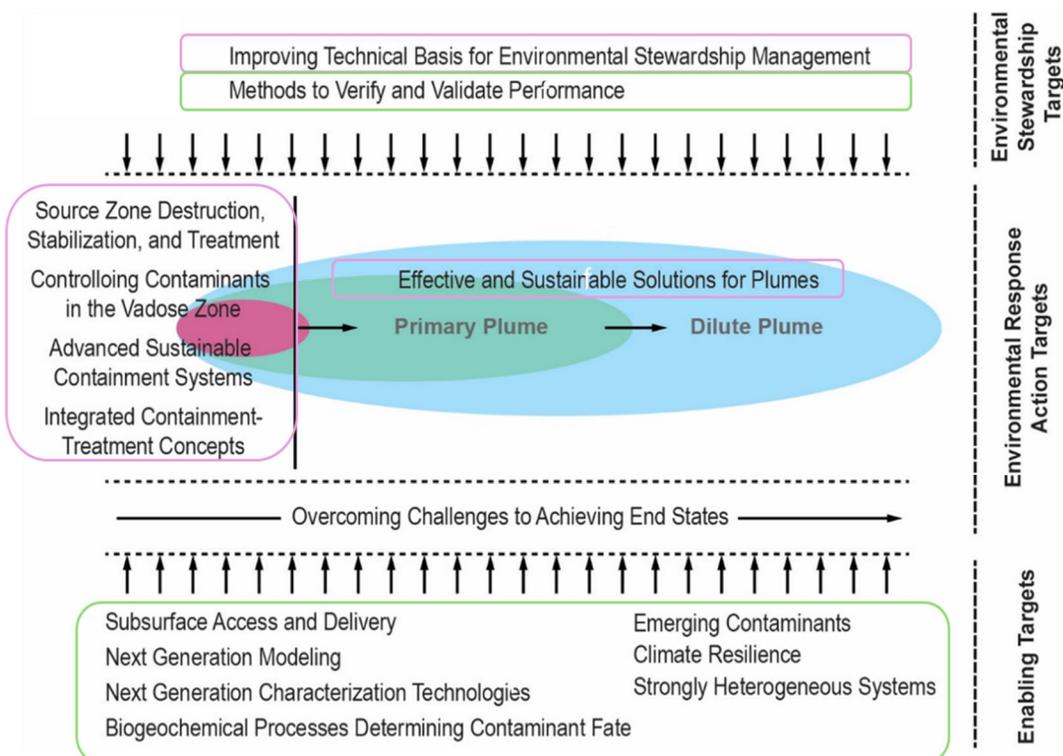
Figure 3. Summary Graphic of the 2021 Technical Targets – Remediation Targets are Annotated Using Fuchsia Color Boxes and Other Supporting Targets are Annotated Using Green Color Boxes

Techniques & Strategies for Addressing Technical Targets.

As a background for the framework several key historical technical strategies are highlighted: (1) persistent, bioaccumulative and toxic contaminants (PBTs), (2) Attenuation Based Remedies such as monitored natural attenuation (MNA) & enhanced attenuation (EA), (3) adaptive site management (ASM), and (4) DOE groundwater remediation status and forward-looking needs. To support the R&D Roadmap, core concepts from each of these historical strategies combined with DOE experience and the EM technical targets provide a powerful basis for the consensus remediation technical framework.

Persistent, Bioaccumulative and Toxic Chemicals

The US Environmental Protection Agency (EPA) and global governments have been working to develop a proactive framework to better identify potential contaminants that might pose significant and enduring environmental risks (Commission for Environmental Cooperation [CEC], 2009). The strategy focuses specifically on key categorical properties that control potential risks, such as a) lack of effective degradation or attenuation in environmental systems (persistent), b) the tendency to bioconcentrate or biomagnify in organisms (bioaccumulative), and c) causing dose-related harm to exposed humans or organisms (toxic). This framework has proven effective in identifying several historical and emerging contaminants. Historical PBTs include mercury, polychlorinated biphenyls (PCBs), dioxins/furans, benzo(a)pyrene, hexachlorobenzene, alkyl-lead, pesticides, Mirex, dieldrin/aldrin, chlordane, toxaphene, and octachlorostyrene. Other emerging compounds identified by EPA though the PBT framework include flame retardants, plasticizers, chemical additives and similar chemicals (such as decabromodiphenyl ether, phenol, isopropylated phosphate 3:1, 2,4,6-tris(tert-butyl)phenol, hexachlorobutadiene, and pentachlorothiophenol). Recently various perfluorinated compounds (e.g., per-and polyfluoroalkyl substances [PFAS]) have been identified as potential contaminants of concern.

The results and success of the PBT framework have been underrecognized and underutilized, particularly in providing information to make proactive decisions regarding potential emerging contaminants. The R&D Roadmap approaches that consider PBTs may provide value to DOE-EM, particularly related to emerging contaminants. While not an urgent activity, providing seed resources to implement an evaluation of potential PBT contaminants that were used within DOE might provide long-term benefits.

Attenuation Based Remedies and Enhanced Attenuation

Attenuation-based remedies such as MNA and EA focus on passive strategies that either eliminate the target contaminant(s) or reduce exposure and risk. MNA requires no human intervention, while EA involves up-front actions to supplement attenuation (Appendix E). The Interstate Technology Research Council (ITRC) has developed technical and regulatory guidance for EA to encourage implementing sustainable actions to transition sites unfavorable for MNA into an acceptable attenuation-based remedy (ITRC, 2008). Examples of acceptable EA mechanisms include accelerating in situ biological destruction, reducing contaminant toxicity, or reducing contaminant mobility by altering in situ biogeochemical conditions (reducing solubility, increasing sorption or forming solid phase minerals).

Over the past three decades, EA (and to a lesser extent, MNA) represents an area of significant success within DOE: EA has accelerated cleanup, reduced costs, and allowed sites to transition through the remediation process to meet end state goals. Despite this success, EA is significantly underutilized, and its

application could be expanded to more contaminants and more conditions with the use of more diverse contributing biogeochemical processes.

Adaptive Site Management

A key focus of the Remediation Team deliberations was related to the use Adaptive Site Management (ASM) (ITRC, 2004 and 2017; NRC, 2013). ASM has the potential to alter the remedial paradigm for addressing the complex site conditions that are typical of the remaining DOE challenges. The traditional regulatory implementation paradigm presumes that a reasonable technology (or technologies) can be identified to achieve remedial objectives in a single linear "study ➜ select ➜ design ➜ build ➜ monitor" process. While the traditional paradigm includes potential for contingency responses, the general presumption is that a period of study can support a reasonable and appropriate technology decision that will achieve the final remedial action objectives. Unfortunately, complex sites are poorly suited to the traditional linear process; the significant uncertainty inherent in environmental cleanup at complex sites has necessitated more flexible-iterative approaches such as adaptive site management.

Despite its name, adaptive site management is not a reactive strategy; instead, it is a proactive strategy that incorporates development of a phased remediation that will lead to achieving remedial goals. Each phase has clear achievable objectives. Selected technologies for each stage are based on meeting the focused objectives. Decisions on the later stages of remediation are determined at defined decision points based on ongoing characterization to fill data gaps. The data gaps and associated schedule/plan to address the uncertainties are defined in the adaptive site management plan to correspond to the timeframe of the phased decisions. With appropriate planning and coordination with regulators and stakeholders, adaptive site management can be effectively used within multiple regulatory frameworks, including RCRA, Comprehensive Environmental Response, Compensation, and Liability Act (CERCLA) and UMTRCA. Adaptive site management has been underutilized, and broadening its application has the potential to benefit DOE, reduce risks to humans and the environment, accelerate schedule, reduce costs, and improve regulator/stakeholder relationships. A more detailed description of adaptive site management is provided in Appendix F.

DOE Groundwater Remediation Status and Forward-Looking Needs

Based on the site surveys, source removal has been completed (or is ongoing/planned) at all DOE sites and an initial remedy is in place for soil and groundwater at most DOE sites. The current remediations have been planned, permitted, and implemented to meet regulatory requirements; however, the ability of some of the remedies to achieve final remedial objectives is not certain for several sites and facilities (e.g., Hanford 200 Area groundwater plumes). Nonetheless, DOE sites have many successes in meeting final objectives and are being monitored to support a transition to no further action. Some of the recently completed sites where both soil and groundwater required remediation include Mound OU1 and SRS T-Area. Both sites formally implemented EA and documented remedy performance using multiple lines of evidence. These successes indicate that broader use of adaptive site management and enhanced attenuation, along with improved characterization monitoring, have the potential to provide substantive benefits.

The core principles for evaluating remediation strategies and technologies for the Soil and Groundwater R&D Roadmap were:

- Technologies that accelerate progress and/or reduce costs,
- Technologies that increase robustness, resilience, sustainability,
- Technologies with sufficient maturity to advance DOE-EM performance over the short to medium term,
- Technologies (e.g., EA) that build on previous DOE successes,
- Geochemical and biogeochemical stabilization (in situ bioremediation and/or geochemical remediation),
- Optimization of Remedial Systems, including AI/ML,
- Combined Remedies and Treatment Trains (e.g., for PFAS because no individual technology has been demonstrated to be effective to date),
- Emphasis on testbeds to allow coordinated and synergistic development and demonstration of technologies,
- Emerging contaminants such as PFAS,
- Recommendations and team scoring performed in context with what is happening in other agencies (e.g., Strategic Environmental Research and Development Program (SERDP), the Environmental Security Technology Certification Program (ESTCP) through the Department of Defense, universities and industry), and
- Enabling technologies, such as methods to improve distribution of amendments for in situ remediation, and methods to address fractured rock etc. (which are important recurring challenges)

Summary of Remediation Research Priorities

The following table summarizes seven concepts discussed in this Roadmap and identifies representative DOE-EM sites where their application may be especially beneficial or already under evaluation.

Table 2. Summary of Remediation Research Priorities and Site Relevance

Remediation Priority Recommendations	Description	Example Applications / Relevant Sites (alphabetically)
Enhanced Attenuation (EA)	Use of engineered treatments and effective monitoring as a bridge to transition sites from active treatment into a passive attenuation-based remedy. This framework approach involves supporting the use of one or more central biological and/or geochemical remediation techniques. These are denoted with the Preface "EA" in the following rows of this table.	**Hanford**, **Moab,** SRS, and others
EA: In Situ Geochemical Remediation (MESA-3)	Use of geochemical processes to degrade or otherwise decrease the risks of contaminants. Bioremediation can result in contaminant destruction or act by decreasing the mobility, solubility and/or toxicity of contaminants in soil and groundwater.	**Hanford**, LANL, SRS, WVDP

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EA: Bioremediation (MESA-2)	Use of biological processes to degrade or otherwise decrease the risks of contaminants. Bioremediation can result in contaminant destruction or act by decreasing the mobility, solubility and/or toxicity of contaminants in soil and groundwater.	Hanford, LANL, Paducah, **SRS**
EA: Constructed Wetlands and Hyporheic Zones (MESA-4)	Use of the ecology in wetlands (bacteria, fungi, and plants) to degrade or otherwise decrease the risks of contaminants and to decrease the source mass flux to streams and other receptors.	Hanford, **Moab**, SRS
EA: Artificially Lithified Native Soils as Capping Material for Uranium Mill Tailings (TDE-1)	Use of surficial geochemical reagents to stabilize the surface and to alter infiltration. This can be used to provide a long-term sustainable alteration to infiltration boundary conditions to limit infiltration/flushing in targeted areas or to divert water and enhance infiltration/flushing. The ability to control hydrologic boundary conditions would supplement the performance of many other remediation methods.	**Moab** and other sites where infiltration control would be beneficial (at costs that are below traditional capping)
Modular, Synergistic Treatment Train Demonstration Test (TB&D-3)	Engineered use of multiple treatments for contaminant scenarios in which no single treatment has proven to be effective, such as perfluorinated compounds.	**SRS** and many other sites
E-Beam Accelerator (FRO-1)	Use of e-beam to treat soil and groundwater and to degrade recalcitrant contaminants such as perfluorinated compounds (ongoing/future research opportunity)	Ongoing and future research opportunity – consider use with modular treatment trains above

Monitoring: Validating the CSM and Confirming Remedial Performance

Environmental monitoring pertains to technologies and strategies that track changes over time to determine whether the environmental system is behaving as expected based on the conceptual site model or numerical models. While most systems primarily collect time series data at discrete points (e.g., concentrations from wells), key monitoring endpoints are often related to regulatory requirements (e.g., concentration limits) or eventually the risk that are best represented by integrated flux to a receptor location or a similar emergent system behavior. Compared to characterization, monitoring technologies typically focus less on detailed fine-scale, depth-discrete information and more on high-frequency measurements at locations determined to be indicators of potential exposure. If the monitoring data substantively diverges from the historical trend and/or CSM, this can signal the need for additional investigation (e.g., of anomalies, potential additional source terms, uncertainties in the hydrogeology, etc.) and to refine the CSM.

Traditionally, environmental monitoring has relied on periodic sampling using groundwater monitoring wells. The resulting data provides snapshots of the conditions at specific locations (i.e., individual points)

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scattered across a contaminated site. The collected information typically includes contaminant concentrations in a collected water sample, as determined by assay at an offsite laboratory, along with field measurements of key parameters, such as water level, pH, oxidation-reduction (redox) potential, temperature, and turbidity. The frequency of data collection depends on site status and conditions, as well as regulatory requirements, ranging from monthly to every few years, but quarterly, semiannually, or annually are typical. In some situations, special studies may dictate higher frequency (daily or weekly) to capture transient effects.

In the next several decades, DOE sites will continue to be remediated, and many sites are expected to transition from active remediation to passive treatment, such as MNA, or long-term stewardship. Robust long-term monitoring data is critical to provide assurance to the surrounding communities that residual contamination at sites undergoing remediation, or sites that are recovering through natural attenuation processes, do not pose a risk to human health and the environment.

The following sections provide context for assessment and recommendations for the monitoring focus area. Relevant technical targets are discussed, several examples of monitoring successes are described, and then site responses regarding monitoring challenges/needs are summarized. These lead to discussion of monitoring and specific recommendations for this Roadmap.

Monitoring-Related Technical Targets

Three of the DOE-EM Technical Targets previously identified in 2021 (Looney and Nyman, 2021) are potentially relevant to the monitoring focus area. The issues summarized for each of these three technical targets and the associated priority areas in the associated report are summarized below to provide context for this effort on the Roadmap Monitoring focus area.

Target: Methods to Verify and Validate Performance

A) Issue(s): Over the long term, remediation activities are dominated by issues, approaches, and costs associated with the verification and validation of performance, which is achieved through monitoring. The DOE sites would benefit from new methodologies for more efficient and cost-effective monitoring of contaminants over long time scales (decades and centuries).

B) Priority Area(s): The priority areas recommended for this technical target [Looney and Nyman, 2021] are directly relevant to the Roadmap Monitoring focus area. Development of new sensing technologies that can measure key "master" parameters, development and integration of new computational tools that leverage machine learning and artificial intelligence to design and refine monitoring approaches, and development of spatially integrative monitoring technologies, such as geophysics and unmanned aerial vehicles, were the priority areas for this technical target.

Target: Next Generation Characterization and Monitoring Technologies (Tools)

C) Issue(s): Next-generation characterization/monitoring tools are needed to provide data over multiple spatiotemporal scales to provide information on continuing contaminant sources, geologic and biogeochemical heterogeneities, and knowledge gaps related to amendment technologies and monitoring, as well as to achieve enhanced understanding of subsurface features in support of risk assessment and site cleanup.

D) Priority Area(s): The priority areas recommended for this technical target [Looney and Nyman, 2021] are directly relevant to the Roadmap Monitoring focus area. Priority areas for this target included development of frameworks involving existing and new/innovative monitoring tools (which could relate to new sensors, strategies, or data analysis, such as applying AI/ML or geostatistics), monitoring of inaccessible locations, data management and sharing framework, technologies for measuring indicator parameters, and broader application of existing technologies.

Target: Overcoming Challenges to Achieving End States

E) Issue(s): Remediation performance often decreases as active cleanup activities progress, and a site starts to approach cleanup objectives. This decrease in remedy efficiency inhibits timely remedy completion and can stall progress in meeting site closure objectives.

F) Priority Area(s): The priority areas recommended for this technical target [Looney and Nyman, 2021] are tangential to the Roadmap Monitoring focus area. That is, monitoring may support at least some of these priority areas. Consistently applying state-of-the-art practices for improved definition of end states, developing approaches to address/mitigate effects of matrix diffusion, taking action to limit contributions from secondary sources, applying mathematical functions and reduced-order models to inform end state decisions and remediation tools/techniques, and developing methods to inform transition to enhanced attenuation (EA) and MNA were the priority areas for this technical target.

Learning from Examples

Some examples of activities at DOE-EM/LM sites illustrate the importance of monitoring and introduce opportunities to more broadly incorporate alternative metrics and approaches.

Monitoring key indicator parameters, such as water levels, can be instrumental for understanding changes in groundwater plume behavior and for updating the CSM. At the Mound site, dewatering for a nearby (offsite) construction project caused a shift in the groundwater table and plume direction (DOE, 2019b). This same type of event was also seen at the Pinellas site in Florida in the 1990s. At several uranium mill tailing sites (e.g., Canonsburg), fluctuations in the stage of rivers adjacent to the sites have caused significant seasonal groundwater dynamics, surface flooding, and often increases in contaminant concentrations in the groundwater (Wainwright et al., 2023). Other sites exhibiting impacts from river stage fluctuations include Moab and Hanford. At Hanford, the river stage fluctuations not only impact hydraulic gradients and groundwater flow directions but also result in a "rewetted zone" where hexavalent chromium contamination can be introduced into the groundwater during high stage periods. Beyond river stage, other phenomena, such as extreme precipitation, droughts, and hydrological shifts associated with climate change, can impact groundwater flow direction and plume characteristics (e.g., distribution, concentrations, migration paths). This variety of hydrologically relevant phenomena are increasingly recognized as a potential risk (Libera et al., 2019; Xu et al., 2022). Thus, monitoring water levels, river stage, meteorological conditions, etc. can be important indicators for vadose zone and groundwater plume contamination behavior, and important for incorporating into the CSM. Note that measurement frequency is important to consider with these indicators (as with all monitoring). Temporally sparse data can make it difficult to promptly detect hydrologically induced changes and can

also make it more difficult to analyze concentration data anomalies (e.g., whether data are outliers or not) and trends.

A few specific examples of notable monitoring successes and promising developments over the past several years include:

- An early example (2009-2010) applied advanced geostatistical analysis with Bayesian probabilities to the monitoring results for in situ soil radionuclide concentrations obtained with high purity germanium detectors and in situ gamma ray spectroscopy (Eby, 2010). The baseline sampling network design was developed using historical approaches yielding over 300 sampling locations clustered near operating facilities in rugged terrain with restricted access over 890 square miles. A spatial declustering model that was applied included spatial dependence indicators and secondary surrogate environmental conditions and indicated that the number of sampling locations could be reduced by 60 percent (i.e., 150-180 fewer sampling locations). The sample collection effort for the revised sampling network was subsequently reduced significantly (by almost 0.25 FTE) (ESER, 2014).

- A few sites have formally incorporated alternative types of data into their monitoring database, such as soil gas monitoring wells at the LANL Site. For example, Material Disposal Areas C and L regularly sample volatile organic compounds (VOC) and tritium in the vadose zone to predict risk to groundwater (N3B, 2018; N3B, 2023).

- At a LANL VOC plume, advanced three dimensional (3D) multiphase simulations of soil vapor extraction and source leakage in the vadose zone were used to reduce sampling costs while still providing protection to the site. Seven sentry wells were identified for twice-yearly sampling while the full 28 wells at the site are now only sampled every other year (N3B, 2018).

- AI/ML approaches have shown promise in several applications. Researchers at the Savannah River Site have demonstrated using AI/ML for anomaly/outlier detections, spatiotemporal interpolation, and monitoring well optimization as part of the ALTEMIS (Advanced Long-Term Environmental Monitoring Systems) project (discussed in more detail in Appendix G). The algorithms – involving deep learning, Gaussian process regressions, and others – have been developed based on existing AI/ML libraries. The codes have been published as the open-source Python for Long-term Environmental Monitoring (PyLenM) python package (Meray et al., 2022; Siddiquee et al., 2024). Continuous monitoring via sensors/geophysics not only enables "immediate" detection of changes and anomalies but also allows interpretation of changes in data trends. Researchers at PNNL and other laboratories have applied AI/ML to optimize a diverse range of monitoring and remediation systems and decisions, such as monitoring and operating the 200 West Area pump-and-treat (P&T) system at Hanford.

Self-Identified DOE Site Needs

As discussed in the Introduction, DOE-EM sites were surveyed to understand their needs in the Roadmap focus areas. Responses included discussion of monitoring challenges, and several sites identified specific requests related to monitoring. A range of challenges pertained to the distribution of monitoring wells and improvement of the monitoring plan/approach. This includes a lack of monitoring points for complete coverage or to address multilevel aquifers (Moab, SRS, Hanford, and others), a need for additional monitoring wells to fill data gaps (Oak Ridge), a desire for a reduction in monitoring requirements (Hanford), and an interest in better spatial monitoring of specific conductivity and temperature (Moab). Shifting water tables and changing hydrological conditions were considered at some sites (Hanford and

INL Sites). Some sites have very deep aquifers (NNSS, LANL), which make sampling costly and challenging, while other sites expect to need well replacement or well deepening (INL). Sites can also face challenging requirements, such as low detection limits or issues trying to maintain temperature during sample shipment. Additionally, monitoring is projected to be a larger part of the budget over time, highlighting the need for advanced monitoring strategies and new technologies.

Assessment of Monitoring Technologies and Strategies

For the monitoring focus area, team members considered a range of technologies and strategies in the context of the technical targets, the site questionnaire responses, and information on the state of monitoring technologies. Recognizing the approach to vetting and evaluating priorities, as discussed in the R&D Roadmap section, recommendations that could provide significant benefit (in terms of cost reduction, efficiency, and effectiveness) and at a higher readiness level for deployment were of particular interest. Several key aspects that were assessed are discussed here, leading to recommendations that were evaluated based on a set of defined metrics, providing a set of research priorities. These aspects include the success of the ALTEMIS project, geophysics, drone/satellite-based remote sensing, water level monitoring, and key data management considerations.

The ALTEMIS project (discussed in more detail in Appendix G) has demonstrated usefulness in monitoring challenges and helped advance and improve future DOE-EM monitoring strategy in several aspects, though it is currently undergoing regulatory approval in 2025. The general goals of ALTEMIS include improving performance, reducing costs, incorporating state-of-the-art statistics/AI/ML, increasing use of sensor networks and geophysics in an optimized scheme, and generally diversifying the types of data and metrics that are collected. Reduction in cost is, in part, associated with reduced labor and improved worker safety. A specific objective of ALTEMIS is to encourage the development of leading indicators that provide actionable early-warning information so that DOE can respond and implement contingencies, if needed, in a timely fashion. In particular, ALTEMIS has focused on reducing the frequency of sampling at wells (reducing costs), while supplementing monitoring knowledge and responsiveness with other types of information (e.g., sensors or regular geophysical [ERT] surveys).

Other types of data have the potential to provide a more robust understanding of site conditions and how these are changing over time, or how the site is responding to remediation. These other types of data include geophysics (to identify geologic structure, moisture content, bulk conductivity, and potentially constituent distributions), drone/satellite-based remote sensing (multispectral, geophysical, radiological), meteorological data, stream/river stage measurements, and surrogate/indicator parameters (geochemical, water level, etc.). To date, it has been challenging to formally incorporate the entire breadth of possible data for monitoring at EM sites. Thus, the synergistic use of diverse and complementary data has been underutilized in monitoring of DOE-EM sites and other contaminated sites across the nation. Yet this other type of data has significant potential to be useful for understanding changes in plume or site conditions and/or in more effective monitoring at a reduced cost.

Water level monitoring with improved spatiotemporal interpolation algorithms is important for estimation of associated metrics such as hydraulic gradients and groundwater fluxes, which can impact remedies and the CSM if they change in unexpected ways. Vertically discrete monitoring in long-screened wells can be important for understanding the three-dimensional nature of contaminant plume distributions and should be considered through approaches such as packer isolation or pre-installed sensors/ports at the time of well construction (though care must be taken in interpretation of monitoring

data from packer-separated intervals and regulators may accept such data only for screening purposes, not for compliance).

Data management is a key aspect to effectively use monitoring data, encompassing data storage, access/findability, processing, quality assurance, interpretation, and integration across organizations (both internal and external). The current practice for DOE-EM results at each site with a different data management system and different methods in place to analyze the data (e.g., for anomaly identification, trend analysis, etc.). The adoption of standard and readily available technologies/strategies into the DOE-EM baseline, such as use of uniform or coordinated "Integrated Data Management Systems", could have benefits across the EM complex. Systems such as ERDMS (Electronic Records and Documents Management System) or DOE-LM's Geospatial Environmental Mapping System (GEMS) could be used to standardize high quality data management and anomaly detection and will allow the complex-wide monitoring and automated connection to DOE-EM's Tracking Restoration And Closure (TRAC) database and other services. Along with standardized data management, monitoring programs across the complex would benefit from more uniform guidelines to support anomaly detection and automated alerts. More information can be found in the Standardized Robust Data Management section in the Enabling Technologies section on page 54.

The assessment produced a set of recommendations (discussed below and in Appendix H). These recommendations included the use of existing technologies in new or innovative ways, technologies that have advanced rapidly and are ready for deployment (such as AI/ML), and incorporation of technologies that are underutilized (such as some types of sensors and geophysics). It was also recommended that demonstration/testing of monitoring technologies and associated data management approaches be incorporated into any DOE-EM testbeds to maximize the usefulness of the data and to provide effective case studies for use in communicating plans for improved monitoring to regulators and stakeholders.

Summary of Monitoring Research Priorities

Recommendations for the monitoring focus area are listed in Table 3 below and are described in more detail in Appendix H. The table below also lists the DOE-EM sites where the recommended research priorities align with site challenges/needs (described above) or are already under evaluation.

Table 3. Summary of Monitoring Research Priorities and Site Relevance

Monitoring Priority	Description	Example Applications / Relevant Sites (alphabetically)
Strategic Application of AI/ML for Groundwater Monitoring Optimization (MESA-1)	Expand the use of sensors and geophysics (allowing remote operation and adjustable measurement frequency) and use AI/ML approaches to determine an optimized monitoring network that will have improved efficiency (reduced costs) while still providing the information needed to support site management. ALTEMIS has been used at SRS to illustrate this.	Hanford, INL, Moab, Oak Ridge, SRS
AI-Guided Real-Time In Situ Monitoring: Actionable Information on Shifting Hydrological Conditions (MESA-6)	Expand the use of AI/ML in monitoring to assess parameter data (including indicator parameters such as hydrological information) for anomalies and changes in trends to support responsive plume/site management. ALTEMIS has been used at SRS to illustrate this.	Hanford, INL, SRS
Standardized Data Management and Analysis (see page 54 for more information)	Develop standardized approaches for managing data (including large amounts of "nonstandard" data from sensors/geophysics) and for analyzing data for implications on contaminant/plume behavior (making use of AI/ML where appropriate).	Hanford, INL, LANL, Moab, Oak Ridge, Paducah, Portsmouth, SRS
Expand the Application of Passive In Situ Sensors for Monitoring Difficult-to-Access Regions (MESA-5)	Expand the use of sensors to provide information on key parameters (e.g., biogeochemical conditions as leading indicators of change) for difficult-to-access areas. ALTEMIS has been used at SRS to illustrate this.	Hanford, INL, LANL, NNSS, SRS

Enabling Technologies

To guide the development of the R&D Roadmap, five factors were considered particularly useful in guiding the recommendations and supporting decision-making going forward. These technologies can be impactful to all aspects of soil and groundwater remediation.

Artificial Intelligence and Machine Learning

Artificial intelligence and machine learning have emerged as key enabling technologies that offer the potential to reduce costs, accelerate timelines, improve safety, and minimize waste footprints. While AI and ML are often grouped together, AI refers to the field of computer science aimed at developing systems that can perform tasks that typically require human intelligence, such as reasoning, decision making, and pattern recognition. AI is particularly useful for autonomous systems that integrate real-time control, multi-sensor data fusion, and adaptive task execution. ML, a subset of AI, enables computers to learn from

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data to perform specific functions such as prediction or classification without explicit programming. AI frameworks often combine rule-based logic with one or more ML techniques to support complex, data-driven decision-making.

Characterization, remediation, and monitoring of soil and groundwater systems across the DOE Complex present persistent challenges. These include heterogeneous subsurface conditions, multiphase contaminant transport, and sparse or intermittent data collection over long time scales. Traditional modeling approaches often struggle under these constraints, creating the need for more efficient and adaptive strategies to ensure resilience and control cost.

AI/ML offers transformative potential to:

- Accelerate site characterization via automated interpretation and fusion of geophysical, chemical, and hydrologic data (i.e., through high accuracy interpolation of subsurface characteristics, automation/enhancement of sample analysis, identification of sampling/characterization data gaps, etc.).
- Predict contaminant fate and transport to support proactive risk assessment.
- Optimize remedial design and monitoring by identifying high-value sampling locations and adaptive strategies.
- Integrate multi-source data – including remote sensing, in situ sensors, and historical records – into holistic site models.

While data sparsity remains a challenge, many DOE sites possess decades of historical data on environmental conditions and contaminant sources. By learning from this data, AI/ML can augment first-principles models with scalable, noise-tolerant, and adaptive tools. Additionally, generative AI – such as large language models – provides new capabilities in code generation, automated literature synthesis, and multi-modal data integration. These tools enhance accessibility to knowledge and technical skills, reducing evaluation and implementation costs by maximizing the use of data, rather than expensive deterministic model development.

The use of AI/ML in environmental remediation is an emerging but rapidly advancing field. A 2025 review article from Dhapre, et al. 2025 provides a comprehensive survey of machine learning for groundwater monitoring over the past 20 years. Supervised learning techniques – such as random forests, support vector machines, and neural networks – have been applied to both classification and regression tasks, including identification of contamination zones, proxy prediction/forecasting of contaminant concentrations, and estimation of soil properties (Soni et al., 2025; Alonso-Sarria et al., 2025. Unsupervised techniques, including clustering and principal component analysis, have aided in delineating subsurface hydrostratigraphic units and optimizing well locations for monitoring networks (Aribido et al., 2021, Meray et al., 2022). Deep learning techniques, including convolutional neural networks, transformers, and recurrent neural networks, are increasingly applied for spatio-temporal modeling (Song et al., 2023), image analysis, and pre-processing of large environmental datasets (Ganesan et al, 2004). Physics informed machine learning has been shown to further enhance predictive accuracy by incorporating physical constraints (e.g., boundary conditions) into data-driven models of subsurface flow and transport (Nilabh et al., 2023). Finally, generative AI is in the early stages of development for use cases such as knowledge management, data fusion, automating ML workflows, and technology transfer (de la Noval, 2025).

Several relevant case studies exist across the DOE Complex showing successful application of AI/ML technologies to monitoring, characterization, and remediation of contaminated soil and groundwater systems (see Table 4 for summary level information of AI/ML implementations across DOE). At the Hanford site, multiple studies have been executed that demonstrate the ability of ML algorithms to model the spatio-temporal dynamics of hexavalent chromium at the 100-Area. For example, tree-based approaches have proven effective at highlighting the importance of different wells in the network and the interplay between the aquifer and surface water (Soni et al., 2025). Additionally, recurrent neural networks have been applied at the Hanford 100-Area to forecast groundwater properties, including hexavalent chromium concentrations, conductivity, turbidity, pH, temperature, and redox potential, outperformance of regression/tree-based methods. These approaches demonstrate the potential for early detection of changes in plume migration, which can aid in automating remediation planning (Murphy et al., 2023). Similar techniques have been demonstrated at the Savannah River Site's F-Area as part of the Advanced Long-Term Environmental Monitoring Systems (ALTEMIS) project (SRNL - ALTEMIS, 2025).

At the Hanford 200-Area, deep learning models have been trained to predict future well performance in a pump-and-treat system based on historical well monitoring data that have been collected during pump-and-treat operations (Song et al., 2023). This system enables identification of characteristic patterns controlling extraction-well mass recovery and provides future mass recovery estimates for existing and candidate wells at any proposed location. Furthermore, the system can be used as a filtering tool to optimize the current pump-and-treat design by reducing the number of candidate well locations, ultimately ensuring resilience and reducing cost.

Several AI/ML development/incorporation opportunities remain with respect to soil and groundwater characterization, remediation, and monitoring activities. For example, regarding characterization, many respondents indicated a need to update their CSMs and hydrologic flow models because of site-specific condition changes that have caused changes in groundwater flow and recharge (e.g., Paducah/Portsmouth). The AI/ML approaches listed above may enable real-time updates or implementing these models in a shorter time span, without sacrificing accuracy or resolution. Additionally, the widespread adoption of AI/ML can enhance characterization activities across the complex by incorporating all relevant datasets and highlighting knowledge gaps, such that data collection can be optimized, ensuring more resilient monitoring systems and cleanup remedies. Such approaches may be especially useful for complex systems such as those that have fracture flow dynamics (e.g., LANL RDX plumes). Similar optimization techniques can be applied during monitoring and remediation. However, with the breadth of environmental challenges, the fusion of information from additional sensing technologies and the application of AI/ML in new environmental systems should continue to be explored for robustness. Continued adoption of generative AI approaches, such as large language models with the ability to reason, can augment DOE and its contractors' ability to vet candidate technologies and fuse multi-modal data streams in a more efficient manner, expediting technology transfer and implementation. Finally, as AI/ML adoption increases into the future, sites should be prepared to address model uncertainties and biases and communicate those appropriately to regulators.

It is important to note that the broad transferability of AI/ML techniques and approaches can be best realized with the development of appropriate model and data benchmarks. The performance of models developed for a particular site should be well documented with the contaminants, the system characteristics (e.g., hydrological, geochemical, etc.), and the datasets used during development. In this way, evaluation of model transferability for application at new sites can be performed more quickly and

with better understanding of the potential limitations. Finally, as data acquisition approaches are expanded to account for the use of AI/ML techniques (e.g., remote sensing), DOE-EM must consider secure data storage and model development, especially in cases where sensitive information may exist.

Table 4. Categorical Summary of AI Applications Across the DOE Complex

Application	Application and Benefit	Summary	Status	Challenges	Applicability
Remote sensing coupled with prediction or forecasting of contaminant concentrations	*Monitoring*; Potential reduction in the number of manually collected samples, resulting in cost reduction and early detection of plume anomalies	Real time monitoring of proxy variables and supervised ML for predicting concentration, forecasting plume migration, and anomaly detection	Field demonstration at SRS, exploratory phase at Moab (note: supervised ML approaches have been successfully trained on many historical groundwater datasets across the complex for predicting contaminant concentrations)	• Noisy historical data • Constrained by well installation (e.g., short versus long screens, locations, etc.) • Several remediation efforts (e.g., pump and treat, funnel-and-gate, base injections, etc.) implemented across time add complexity to the data	Complex wide at locations with active monitoring infrastructure (note: that the concept applies to a wide range of sensing technologies)
Semi-Supervised ML for contaminant source identification	*Characterization*; High quality characterization of plumes at reduced computational expense	Contaminant source identification of mixed groundwater plumes and the original geochemical concentration	Study performed at LANL	• Similarity in source geochemical signatures • Complex Chemical and geophysical systems (e.g., plume mixing influences transport)	Locations with overlapping groundwater plumes
Pump and Treat Optimization	*Remediation*; Reduced computational expense and real time guidance of optimized well networks for evolving systems	Optimization of pump and treat well network using ML prediction of groundwater plume migration under dynamic conditions	Study performed at Hanford 200-Area	• Large simulation suites required • Dynamic and complex systems	Locations with active pump and treat (note: techniques may be applicable to other remediation systems)

Fractured Flow and Transport	*Characterization*; Reduced uncertainty and computational expense for evaluating factured flow networks	Identification of preferential/dominant flow paths using a hybrid deterministic and supervised ML approach	Research study performed at LANL	• Highly complex system that is difficult to characterize • Computationally expensive problem to explore • High uncertainty	Locations with fractured flow and transport
Sediment grain size mapping	*Characterization*; Improved spatial characterization of grain size distribution of sediments that impacts groundwater/surface water exchange	Supervised machine learning to predict sediment grain size and distribution along large spatial regions of stream beds	Research study performed at Hanford	• High natural variability • Dynamic influences (e.g., water movement) • Unevenly distributed sample measurements	Areas where hydrologic exchange flows are a key controlling variable
Physics informed machine learning for parameter estimation and modeling	*Characterization*; Improved prediction of parameters (e.g., conductivity, hydraulic head, etc.) and/or lower computational expense in modeling plume migration	Stochastic models and observational data are used to estimate parameters from data or explore flow dynamics	Research study performed at Hanford	• High uncertainty due to natural variability • Noisy sampling data • Computationally expensive	Updates and/or verification of conceptual site models
Generative AI for Technology Transfer	*Multiple*; Enhanced knowledge management, information fusion, information discovery, and automated implementation and execution of computer based workflows (e.g.,	Knowledge management systems that fuses site specific data (e.g., groundwater well data) and open source data (e.g., publications, regulatory documents, etc.) to reduce the time for technology transfer,	Early prototyping applied to Moab	• Massive data environments • Uncertainty in generative AI model performance at tasks • Multi-modal data environments	Broad DOE-EM activities

	data analysis, machine learning, etc.)	remedyimplementation, end state recommendations, or monitoring system design			

Fate and Transport Modeling

Modeling is an essential technology in environmental remediation, offering predictive, quantitative and processes-based insights that can enhance the design, implementation, and optimization of remedial strategies. Physics-based models simulate the hydrogeological, geochemical, and biological processes governing contaminant fate and transport in subsurface environments; they typically bridge the gap between CSMs and risk assessment in support of remedy decision-making, enabling more efficient, cost-effective, and performance-driven remediation (e.g., performance-based P&T). These models allow practitioners to simulate complex environmental systems, predict contaminant behavior, assess risk, and support informed decisions under uncertainty.

Historically, modeling in the environmental remediation area progressed from basic analytical solutions toward highly integrated and predictive solutions, and more recently data-driven approaches. This evolution tracks advances in computational power as well as environmental monitoring and characterization, data science, and modeling techniques (e.g., ensemble approaches). Recent advances support more accurate, scalable, and decision-driven use of models in environmental remediation.

Enabling roles of modeling in environmental remediation include:

- Improved Conceptual Site Understanding: Models help refine and test alternative CSMs by integrating diverse site data (e.g., hydrogeological, geochemical, and geophysical) into a coherent framework. This can help identify dominant transport pathways, key source terms, and primary risk factors at a given site.

- Predictive Capability: Models enable the forecasting of contaminant and hydraulic behavior under various remediation scenarios (e.g., pump-and-treat, in-situ chemical oxidation, bioremediation), supporting adaptive management and long-term planning.

- Remedy Optimization and Design: By simulating alternative remediation strategies, physics-based models assist in screening and optimizing system configurations. For instance, they can be used to optimize well placement in P&T systems or to evaluate amendment delivery efficiency for in situ remedies. A critical example of such application has been demonstrated for Hanford 200 W P&T operations: Physics-based models were coupled to formal evolutionary algorithms in a performance-based management framework to assess optimized well network and capacity management strategies with the goal of minimizing the active pumping duration (Song et al., 2025).

- Mass Flux and Mass Discharge Quantification: Models are used to estimate the rate and direction of contaminant movement through soil and groundwater over time. This supports risk assessments, design of monitoring strategies, and evaluation of contaminant loading across environmental media. When integrated with geophysical monitoring data, models can also evaluate contaminant flux through the vadose zone and its discharge into underlying groundwater.

- Remedy Performance Assessment and Adaptive Management: Models function as decision-support tools during active remediation by evaluating whether implemented remedies are performing as intended. They help track changes over time, compare observed data with

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predicted outcomes, and support real-time adjustments to system operations—such as optimizing amendment injection strategies or modifying cleanup timelines.

- Integration with Monitoring and Data Assimilation: Advanced physics-based modeling can be combined with real-time monitoring and data assimilation techniques to continuously update predictions and refine strategies in near real-time.

Some modeling applications and tools that are widely used in the environmental remediation area include: MODFLOW and MT3DMS for groundwater flow and solute transport; STOMP, PFLOTRAN and TOUGH for multiphase flow and reactive transport modeling; and Finite Element Method- or Finite Volume Method-based platforms for site-specific custom modeling.

Although some of these codes have been around for some time, the computational resources and ability to run complex and more data-driven models have improved significantly over the past decades. As data becomes more available and computing more accessible, adaptive and predictive modeling—driven by AI, real-time monitoring, advanced data assimilation techniques, system optimization approaches, and ensemble and inverse learning—will become more important for understanding contaminant fate and transport under complex and changing environmental conditions, and support decision-making. Ways to improve on the standard for each capability are shown in Table 5 and a case study for remedial optimization through modeling can be found in Appendix G.

Table 5. Examples of Modeling Capabilities and Ways to Improve on the Current Standard.

Modeling Capabilities	Examples	How to Improve on the Standard
Improved Conceptual Site Understanding	MT3DMS, PFLOTRAN, Amanzi-ATS, SKUA GOCAD and Leapfrog	Examples and demonstrations to create and evaluate multiple CSMs in a consistent manner with established tools
Predictive Capability	MODFLOW, PFLOTRAN, Amanzi-ATS	Examples and demonstrations using the state-of-the art transport simulators (with complex reactions and geology) coupled with actual treatment scenarios
Remedy Optimization and Design	N/A	Tool development is needed to couple flow-and-transport simulators, monitoring data, and decision support tools
Mass Flux and Mass Discharge Quantification	PFLOTRAN	PFLOTRAN has been coupled with real-time geophysical data at the Hanford Site. More examples and demonstrations are needed in different geological and climatic conditions
Remedy Performance Assessment and Adaptive Management	N/A	Tool development is needed to couple flow-and-transport simulators, monitoring data, and decision support tools
Integration with Monitoring and Data Assimilation	Physics-informed machine learning, Neural operators for	AI-integration with simulation is an active area of research. Taking those technologies into the EM domain would be critical.

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	surrogate modeling (Meray et al, 2023)	

Geophysical Tools

Geophysical methods are used increasingly to enable high-resolution site characterization at lower cost than is possible with conventional methods. Compared to conventional methods of characterization, which comprise direct measurements (e.g., fluid or sediment sampling, hydraulic testing, drill core analyses), geophysical methods provide information about physical properties (e.g., electrical conductivity, seismic velocity) which are indirectly related to parameters of interest (e.g., permeability, porosity, concentration). Although indirect, geophysical surveys offer the advantages of being non- or minimally invasive and providing spatially dense information. Whereas direct measurements require wells or test holes and thus provide only spatially sparse information, geophysical surveys can provide spatially exhaustive data over large areas. Across the DOE complex, the National Laboratories have advanced and demonstrated a broad suite of geophysical methods in diverse geologic settings. Indeed, the National Laboratories have provided scientific leadership in the integration of geophysical methods into hydrologic investigations going back decades and helped to pioneer the new field of hydrogeophysics (Rubin and Hubbard, 2005; Hubbard et al., 2008). Today, the National Labs are using geophysical methods for both characterization of subsurface structure (e.g., Robinson et al., 2022) and for monitoring natural and engineered processes in the subsurface (e.g., Johnson et al., 2022a, b). Despite highly successful research, development, and field demonstrations, opportunities remain to more fully integrate geophysical characterization and monitoring into the closed-loop workflow of characterization, remediation, and monitoring.

Geophysical methods can be broadly categorized according to various criteria including (1) underlying physics (e.g., seismic reflection, electromagnetic induction, gravity, etc.), and (2) how measurements are collected (e.g., ground-based geophysical surveys, waterborne geophysical surveys, borehole logging, cross-well imaging). Measuring physics, instrument specifications, and survey design all play roles in determining resolving power and establishing the tradeoff between resolution and spatial coverage. Different methods provide different information and suitability in different geologic settings; hence selection of effective geophysical methods and survey design must consider study objectives and site conditions (Day-Lewis et al., 2011; Hammett et al., 2019; Thompson et al., 2021). Commonly multiple methods are used together to capitalize on the strengths of different methods, constrain interpretation of results, and reduce the uncertainty associated with interpreting a single data type. It should be stressed that geophysics is not a substitute for direct measurements, which are always needed for calibration and/or groundtruth; rather, geophysics serves to fill gaps in space (and possibly time) between sparsely distributed direct measurements.

An important challenge to recognize when planning or contracting geophysical investigations is the transfer of results to end users of geophysical information. End users commonly comprise modeling teams tasked with constructing, calibrating, and using predictive hydrogeological framework or fate and transport models to support the selection or optimization of remediation systems. For geophysical results to be useful, they must be accessible to non-geophysicists. This need commonly requires the transfer of interpreted results, either qualitative or quantitative, for assimilation into hydrogeologic framework models, models of contaminant source zones, or spatiotemporal models of injected tracers or

amendments. Qualitative interpretation amounts to geophysicists using subject-matter expertise to identify stratigraphic or lithologic boundaries which are then communicated to end users. This interpretation is best performed with the involvement of domain experts in geomorphology, structural geology, or stratigraphy. Quantitative interpretation involves conversion of geophysical property estimates to estimates of hydrologic properties. The conversion may involve petrophysical modeling, regression modeling based on empirical relations, geostatistics, or joint inversion (e.g., Linde 2006). Ultimately, geophysical information should be entered into geographic information systems or other software for managing framework models and constructing simulation models.

Today, geophysical methods are routinely integrated into site characterization efforts (e.g., Singha et al., 2022; Williams et al., 2023), particularly across the DOE complex, where there is a long and successful history of applications, including at Hanford (e.g., Robinson et al., 2024; Jaysaval et al., 2021; Truex et al., 2013; Wu et al., 2012), Rife (e.g., Chen et al., 2012; Williams et al., 2009), Savannah River (e.g., Denham et al., 2020), and Oak Ridge (e.g. Gasperikova et al., 2013). While geophysical surveying services are increasingly available from environmental contractors and geophysical firms, R&D at the National Laboratories and academic institutions continues to advance instrumentation, simulation methods and codes, and data analysis. Current trends include:

1) The use of artificial intelligence and machine learning (AI/ML) to accelerate data analysis (i.e., geophysical inversion) and to automate the interpretation of results (i.e., anomaly detection and classification) (e.g., Mudunuru et al., 2022), as detailed further under the AI/ML Enabling Technologies discussion and currently being investigated under ALTEMIS for the Savanna River F-Area.
2) Real-time monitoring of changes in fluid, rock, or soil conditions in the subsurface to understand changes associated with fluid injections, chemical reactions, and soil or groundwater remediation (e.g., Johnson et al., 2022a), as demonstrated at Hanford, Moab, and elsewhere. A brief case study is provided in Appendix G.
3) Development of mechanistic and empirical models to address the sensitivity of spectral induced polarization to chemical reactions and changes at the fluid/grain boundary, which is a focus of ongoing research at Hanford (e.g., Emerson et al., 2024).

The use of drones, particularly unmanned aircraft systems (UAS), as platforms for geophysical data collection, thereby accelerating data acquisition and expanding coverage compared to ground-based surveys, and improving resolution and reducing costs compared to conventional fixed-wing and helicopter surveys (e.g., Mangel et al., 2022). The use of drones for geophysical investigations complements other applications of drone technology (e.g., LIDAR).

Unmanned Aircraft Systems

UAS and other drone technologies (e.g., ground-based crawlers and quadrupeds) are used increasingly in research and practice. As platforms for data acquisition, these technologies provide (1) safe operation in hazardous areas and challenging terrain, (2) rapid and efficient data acquisition over large areas, (3) flyover 'birds-eye-view' surveys of areas inaccessible by foot or ground vehicle (e.g., caps and barriers), and (4) automation for repeat surveys (e.g., Mangel et al., 2022). Once programmed, a drone mission is easily repeated with high precision, thus supporting cost-effective long-term monitoring.

The National Laboratories have extensive capabilities developing and testing innovative sensors deployed using drone technology. This work spans the DOE mission space, with applications ranging from national

security to environmental and legacy management. Some recent and ongoing work supporting these DOE mission spaces includes detection of undocumented oil and gas wells (U.S. DOE, 2024), radiation mapping (Bunn et al., 2022), and assessments of mineral resources (e.g., Wu et al., 2024). The NNLEMS is currently developing a rolodex of the National Laboratories established and demonstrated drone capabilities with planned release date before the end of FY2025 and a high-level summary of laboratory capabilities is found in Table 6. Recognizing that DOE has extensive experience working with UAS contractors and using data collected from UAS, the topical team focused on the National Laboratories' unique capabilities and types of scientific investigations that are not yet commercially available or easily contracted as services.

Drone technologies and sensor payloads are advancing rapidly, and drone services are commercially available for many data types. Payloads relevant to EM and LM include sensors for radiation (e.g., gamma detectors), topography and cap/barrier integrity (e.g., Light Detection and Ranging (LiDAR)), surficial mapping and changes in caps/barriers (e.g., synthetic aperture radar), vegetation and changes in vegetation (e.g., multispectral), air quality (e.g., gas sampling), water quality and aqueous contamination (e.g., water sampling), subsurface structure (e.g., magnetics, electromagnetics, ground penetrating radar), leak detection (e.g., thermal infrared), and groundwater/surface-water exchange (e.g., thermal infrared). Many of these sensor payloads can be deployed from conventional, manned fixed-wing or helicopter platforms, but UAS surveys are less costly and offer enhanced resolution. With smaller physical footprints and the ability to fly at lower altitudes, UAS can achieve tighter line spacing and improved sensitivity.

Despite the clear benefits of drone technology for environmental characterization and monitoring, there are notable limitations. First, regulations (e.g., Federal Aviation Administration) and safety requirements commonly dictate that visual contact must be maintained between operators and the UAS, thus limiting surveys to line-of-sight and fair-weather conditions. Airspace compliance and no-fly zones must be observed, and operators require substantial training. Further, the datasets produced in drone-based data collection can be enormous and cumbersome to manage, visualize, and process without specialized software.

Table 6. UAS Capabilities at the National Laboratories

Laboratory	Sensor Capabilities	Platform types
Lawrence Berkeley National Laboratory	LiDAR, hyperspectral, magnetometer, EM sensor, infrared, RBG cameras	UAS
Lawrence Livermore National Laboratory	Magnetometer; ground penetrating radar; hyperspectral imaging; methane detection; spectrometers	UAS
Los Alamos National Laboratory	Gamma detection; magnetometer, air sampling; gas sampling; LiDAR, photogrammetry; ground penetrating radar; multispectral	UAS (including rotary, vertical take-off and landing (VTOL), and fixed wing)
Pacific Northwest National Laboratory	Radiation; LiDAR; electro-optical/infrared imaging; multi-spectral imaging; radiation mapping, radionuclide particulate detection/collection; gas sampling, water sampling; ground debris sampling; electromagnetic geophysical surveys	UAS (including rotary, jets, VTOL), ground robots

Sandia National Laboratories	Gamma detection; magnetometer, air sampling; gas sampling; LiDAR; photogrammetry; intelligence, surveillance and reconnaissance payloads	UAS (including rotary, jets, balloons, VTOL), ground (tracked, quadruped, wheeled)
Savannah River National Laboratory	LiDAR; sprayers (for herbicide)	UAS (rotary)

Standardized Robust Data Management

Effective use of environmental data collected at a site to support analysis, communication, and decision making depends on having robust data management practices, but this can be a challenge given that data comes from a wide range of activities and in many formats. Collection of observations is important across all stages of the remediation process, from characterization to monitoring performance during remedy implementation/optimization to routine overall monitoring to long-term monitoring. Observed data also takes many forms, spanning borehole logging, geophysics, analysis of individual soil/water samples, automated sensor data, airborne/spaceborne remote sensing data, etc. There are many formats for the resultant data; examples include tabular, structured/semi-structured, annotations, and proprietary formats, in written or electronic format. Robust data management facilitates the key attributes of data Visibility, Accessibility, Understandability, Interoperability, Trustworthiness, and Security (VAULTS) so that accurate, complete, current, and secure data is available to support decision making. Further, as AI becomes more integrated into environmental remediation (i.e., to design or optimize monitoring and remedies), it will be critical to manage data in a manner that is amenable to consumption by AI tools/models.

DOE-EM and LM would benefit from standardized approaches for managing data, spanning from initial characterization, through remedy implementation, and then into the long-term stewardship of a site. A robust and standardized data management approach supports environmental remediation decision making to prioritize actions, eliminate redundancy, and focus investments where they deliver the greatest environmental and economic benefits. Development of a standardized framework for data management and sharing will facilitate FAIR (Findable, Accessible, Interoperable, and Reusable) data principles. A data management framework would need to address data collection, processing, storage, quality assurance, traceability, interpretation, access, findability, and integration across organizations both internal and external.

Several key considerations are important for a standardized data management framework. First, as data collection transitions to better utilize sensor, geophysics, and remote sensing techniques to achieve effective monitoring while reducing costs, the data management framework needs to accommodate those types of data, which can be large in size and dependent on advanced data processing for interpretation. Second, and related, the environmental data that is collected must be available in a format that is readily consumed by AI tools/models, which are a rapidly evolving area with a lot of promise for streamlining monitoring and reducing costs. Finally, the data management framework needs to be able to accommodate changes over time, due to changes in technologies (for sensing, collection, telemetry, chemical analysis, data processing, etc.). Also, the data itself may have temporal effects (e.g., seasonal changes, dropping water tables resulting in lack of data, variations in measurement frequency, changes in site mission that may interfere with data collection, etc.) that need to be considered in the data management framework.

DOE-EM and LM have a variety of databases and data management approaches in place or being developed. DOE-LM probably has the best perspective on data management and governance, given that they are the long-term stewards for over 100 sites, which necessitates a consistent approach. The DOE-LM GEMS (https://gems.lm.doe.gov/) seeks to provide access to certain site information across the LM complex. Across the DOE-EM complex, data are typically stored in site-specific databases, including HEIS and PHOENIX (Hanford), EIM and IntellusNM (LANL), OREIS (Oak Ridge), and PEGASIS (Paducah and Portsmouth). The focus of these site-specific databases is mostly on discrete soil and groundwater sample data, with other types of datasets generally not accommodated. Hanford has ongoing work for the Hanford Environmental Data Index (HEDI) and the Hanford Environmental Data Management (HEDM) project, which are complementary efforts targeting cataloging environmental data of all types that have been collected for the Hanford Site, including adequate metadata to facilitate FAIR principles and understand the location of the data and the data pedigree. Another effort that originated with Hanford is the SOCRATES web application, which has expanded to application at other DOE-EM sites and which provides access, analysis, and visualization of a variety of dataset types. While there are not comprehensive data management frameworks, approaches such as LM's GEMS and SOCRATES could play a role in such a framework.

Ultimately, a robust and standardized data management framework facilitates the transformation of raw environmental data into actionable insights that lead to streamlining workflows, enhancing collaboration, identifying high-priority remediation areas, optimizing resource allocation, and leveraging interoperable systems to link datasets and improve transparency. Existing best practice guidance (e.g., ITRC, 2022; DoD, 2020), along with commercial approaches (e.g., EQuIS by EarthSoft or ESdat by EarthScience Information Systems) can provide elements of a good foundation for a standardized and robust data management framework.

R&D Roadmap

The team reviewed documentation from the previous work (Technical Targets, 2022 Site Interviews, and End State Vision) and discussed pressing needs and future strategies together in semi-monthly meetings. The Team used this information and developed site-specific and complex-wide recommendations for advancing soil and groundwater cleanup for DOE-EM headquarters (HQ) to consider for expediting closure. The recommendations were first sorted into the following categories: Mission and End State Accelerators (MESA), Technology and Data Enhancers (TDE), Testbeds and Demonstrations (TB&D), and Future Research Opportunities (FRO) (Figure 4).
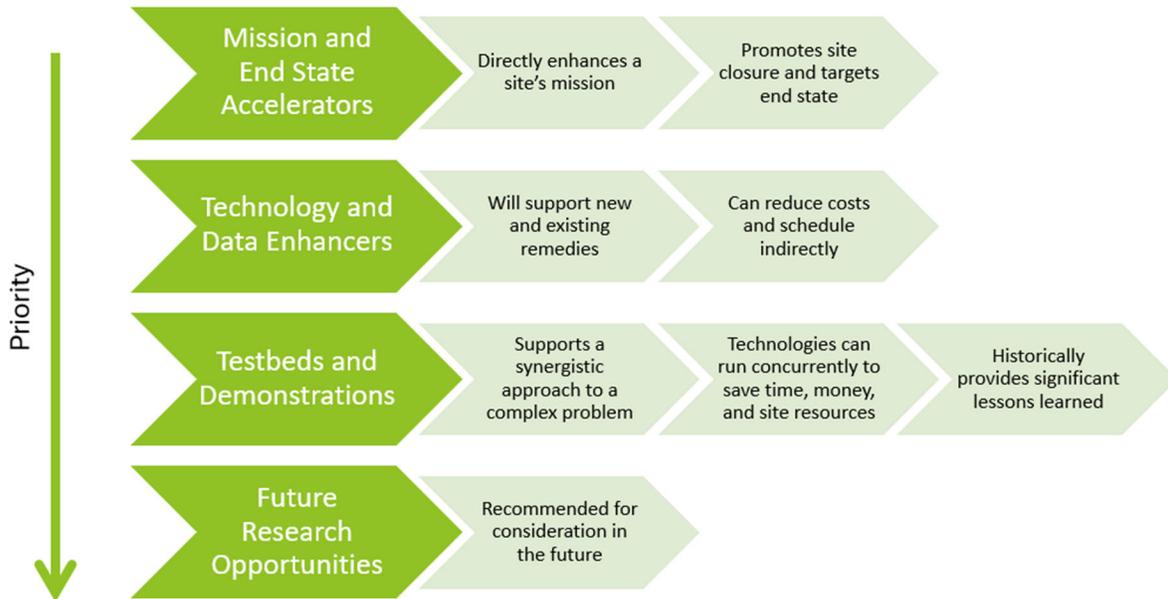
Figure 4. Priority of Categories for Recommendations with Description

Mission and End State Accelerators are mission and/or end state-focused, specifically focused on acceleration of closure through either a significant reduction of required funding or remediation timeline that are likely to enhance site or parcel closure or transfer. Many of these recommendations are focused on the shifting from active to passive remedial strategies. Typically, the transition to enhanced attenuation results in very significant operation cost savings.

Technology and Data Enhancers are recommendations that will greatly benefit the overall mission of existing activities. They can increase data confidence or provide site personnel with additional information (particularly for characterization) that can be used to enhance data input into conceptual site models, flow and transport models, etc. They directly support mission-critical activities. TDEs can also increase stakeholder and regulatory confidence. The team has developed eight recommendations to enhance the current state of science and existing data retrieval methods which are described below.

Testbeds and demonstrations serve an important and crucial role in demonstrating and evaluating new technologies and integrating them into effective and efficient environmental management; furthermore, TB&D expedite technology transfer and directly support characterization, remediation and monitoring aimed at the site's mission and end state. By addressing site-specific challenges and identifying site-specific—yet transferable—solutions, TB&D can directly reduce costs at the test sites while indirectly

reducing longer-term costs at sites to which technologies are transferred. In identifying sites for TB&D, it is important to focus on clear and identifiable problems shared by multiple sites, and to strategically plan for sharing lessons learned to other sites through expansion.

Future research opportunities are recommendations that are not presently achievable or not currently needed but could be considered in the future as a need arises and/or technological advances enable research in that area.

After categorizing recommendations, the rough order of magnitude (ROM) cost savings and range of schedule acceleration were determined. These ranges were determined by using successes within DOE-EM and DOE-LM and are the Team's best estimation given the turnaround time for the Roadmap. These ranges are for the lifetime of the remedy compared to current practices. The team also assessed the following metrics to further prioritize the recommendations:

- Cost of implementation,
- Technology readiness level,
- Adoption readiness level, and
- Implementation timeframe.

Within each category, the recommendations were ranked based on both ROM cost savings and estimated schedule acceleration as the deciding factor for prioritization. For example, TDE-3 and TDE-4 are both expected savings between $10M and $50M, but the schedule reduction for TDE-3 is more impactful than TDE-4, so TDE-3 is ranked higher. The Team further delineated the rankings when cost savings and schedule acceleration are similar by incorporating cost of implementation, TRL (Figure 5), ARL, and implementation timeframe. It is important to note that cost of implementation, TRL, ARL, and implementation timeline were not considered as reasons to reject a recommendation and were used to help prioritize rankings after ROM cost savings and schedule acceleration were considered first. The cost of implementation does not consider annual costs for multi-year projects and are for the initial cost to begin. Implementation timeframe does not consider potential regulatory and stakeholder hurdles that could impact adoption, but a higher ARL suggests that regulatory and stakeholders are more likely to be amenable to the recommendation.

Figure 5. Technology Readiness Level (TRL) Rubric (Iowa Technology Institute, 2025)

Table 7 provides a summary of the twenty priorities that were evaluated. Specific details of each of the recommendations can be found in Appendix H. Sites that are bolded and listed first are the Team's recommendations for initial deployment. The other applicable sites are listed after the recommended site in alphabetical order.

Table 7. Summary of R&D Priorities

Category	Concept	Recommended Pilot Site(s)	Other Applicable Site(s)	ROM Lifecycle Cost Savings Per Site	Estimated Schedule Acceleration Per Site	Cost to Implement	TRL	ARL	Timeframe to Implement
MESA-1	Strategic Applications of AI/ML for Complex-wide Groundwater Monitoring Optimization	**Hanford** – largest site with the greatest number of wells	INL, Moab, Oak Ridge	$100M-$300M	10-19 years	$500K-$1M per site to implement; $200K/year to maintain	4-5	4-6	6-18 months
MESA-2	EA: Bioremediation	**Paducah** – accessible VOC contamination in a plume that impacts offsite receptors **SRS -** accessible VOC contamination in a wide range of conditions	Hanford, INL, Moab	$100M-$200M	10-30 years	0.5 to 5x baseline (P&T)	3-9*	2-9*	6-18 months
MESA-3	EA: In Situ Geochemical Remediation	**Hanford** – accessible vadose zone contamination source mitigation opportunities **Moab** – residual contamination in shallow soil and groundwater	SRS	$50M-$100M	20-50 years	0.5 to 5x baseline (P&T)	3-8*	2-9*	6-18 months
MESA-4	EA: Constructed Wetlands and Hyporheic Zones	**Moab –** accessible ammonium plume impacting Colorado River	Hanford, SRS	$50M-$100M	20-50 years	0.5 to 5x baseline (P&T)	3-7*	2-8*	12-24 months

MESA-5	Expanding the Applications of Passive In Situ Sensors for Difficult -to-Access Regions	INL – INL has a deep vadose zone and could benefit from in situ sensors to support water table issues	Hanford, LANL, NNSS	$50M-$100M	10-19 years	$500K-$800K per site	4-5	4-6	6-18 months
MESA-6	AI-Guided In Real-Time Situ Monitoring: Actionable Information on Shifting Hydrological Conditions	**Hanford INL**	‡	$50M-$100M	10-19 years	$500K-$800K per site	4-5	4-6	6-18 months
TDE-1	EA: Artificially Lithified Native Soils as Capping Material for Uranium Mill Tailings	**Moab** – areas of opportunity to control erosion, infiltration, and source release	‡	$50M	0-9 years	0.2x to 1.5x of baseline (capping)	4-5	5	6-18 months
TDE-2	Fractured Rock Characterization	**INL** – significant fractured rock systems present	Hanford, NNSS, Oak Ridge	$10M-$50M	10-19 years	$500K-$700K	8-9	9	6-18 months
TDE-3	Targeted Temporal Characterization for Refining Site Behavior and Long-Term Regulatory Compliance	**Moab** – seasonal changes control plume migration	Hanford, Paducah, SRS	$10M-$50M	10-19 years	< $500K	8	7	6-18 months
TDE-4	Vadose Zone Characterization	**Hanford** – has one of the most complex vadose zones in the DOE-EM complex	INL, NNSS	$10M-$50M	0-9 years	$500K-$700K	6-7	6	6-18 months
TDE-5	On the Use of Machine Learning Techniques to Advance Specific	**Hanford, SRS, LANL**	INL, Moab, Paducah	$10M-$50M	0-9 years	$500K-$700K per site	3-5	3	6-18 months

	Groundwater Flow and Transport Model Applications	The three recommended pilot sites all have existing numerical models that are in a position to benefit from the addition of AI/ML							
TDE-6	Hierarchical Hydrostratigraphic and Geostatistical Models	**LANL –** large-complex interrelated hydrologic system	Hanford, INL, Moab, Paducah, SRS	< $10M	0-9 years	$250K-$750K per site	8	7	6-18 months
TDE-7	Flow Logging	**Hanford –** has complex depth-discrete flow within the groundwater	LANL, Moab	<$10M	0-9 years	$100K-$500K	6-7	6	< 6 months
TDE-8	Distributed Fiber-Optic Sensing	**Moab –** GCAP will require seasonality and spatial variability of the fluxes to the Colorado river	Hanford, Paducah, SRS	< $10M	0-9 years	$200K-$500K	7	6	6-18 months
TDE-9	Biogeochemical Tracers and Isotope Measurements	**Moab –** presence of a stratified aquifer system requiring knowledge of complex flow patterns	‡	< $10M	0-9 years	$400K	6-7	5	6-18 months
TB&D-1	Moab Testbed	**Moab –** regulatory decisions will be made in the next few years and will likely have outstanding data gaps	‡	$10M-$50M	0-9 years	$1.5M-$2M	N/A	8	6-18 months
TB&D-2	In Situ Geochemical Remediation Testbed	**Hanford -** accessible vadose zone contamination	Moab, Paducah, SRS	$50M-$100M	10-19 years	$5M-$10M	N/A	7-9	< 6 months

		source mitigation opportunities							
TB&D-3	Modular, Synergistic Treatment Train Demonstration Test	**SRS –** presence of diverse, complex, recalcitrant contaminant challenges	Hanford, Paducah	$10M-$50M	10-19 years	$1M-$3M	5-6	4-6	6-18 months
FRO-1	E-Beam Accelerator	**N/A**	DOE-Legacy Management (LM) sites; SRS, LANL, Hanford	$10M-$50M	10-19 years	$10M-$20M	4-5	5	18-24 months

Bolded sites are the recommended pilot location.

*Various types of enhanced attenuation have differing TRL and ARL levels; a broad range reflects the minimum and maximum.

‡ indicates a cell was deliberately left blank.

Note: Schedule acceleration and cost savings may not be cumulative given each remediation action will have to be implemented on its own and can downstream impacts on other processes due to funding constraints or regulatory decisions.

Summary of R&D Recommendations

This report identified a variety of strategies to address the remediation of DOE's complex groundwater plumes. Cleanup activities to remediate these plumes have been ongoing for three to four decades, yet reaching closure by meeting regulatory standards will require many more decades of treatment and monitoring. Many of the complex plumes are well characterized and contaminant migration is well understood, while at other sites, this is not true. The team recommends that DOE should focus efforts at sites where active remediation is ongoing and to facilitate transition to passive methods. For the sites that have been transitioned to passive methods, the focus should be on effective and efficient monitoring that allows for early identification of anomalies where plume direction or concentration changes so deviations can be addressed quickly. Other soil and groundwater sites have proven difficult to characterize, and standard methods focused on installation and monitoring of groundwater wells are not effective or extremely expensive. At these sites, innovative strategies using geophysical or other tools need to be identified and evaluated for innovative characterization or monitoring.

The NNLEMS Team recommends the following overarching recommendations to support the cleanup of these complex soil and groundwater plumes:

1. ## Shift Active Remedies to Passive Remediation

Shifting from active to passive remediation is an essential component of successful environmental remediation and should be the **first priority for implementation**. Recommendations that fit this overarching recommendation are found in Table 8.

Active remediation, e.g., P&T or soil vapor extraction, are implemented in the early stages of remediation to reduce the size of larger and highly contaminated plumes. These methods are effective for rapidly reducing high contaminant levels, controlling the plume hydraulically, and reducing the plume source by reducing risks to human health and the environment. Unfortunately, these techniques are energy-intensive, very costly for long-term remediation, and become less efficient as the plume evolves and dilutes.

As sites transition toward lower levels of contamination, passive remedial approaches become increasingly important. Passive techniques, e.g., MNA, bioremediation, permeable reactive barriers (PRBs), rely on natural processes which have significantly lower maintenance and operational costs, and are more sustainable. These passive systems allow for better integration to the end state.

The shift to passive remediation also reflects a more holistic understanding of the site-specific geochemical conditions and long-term contaminant behavior. Rather than forcing short-term removal through active remediation, passive strategies focus on stabilizing contaminants, enhancing natural degradation, and prevention of further migration. This practice not only is cost-effective and promotes better resilience, but it also is essential for managing aging infrastructure and the overall mission of reducing cost and facilitating site transfer.

Currently, the Hanford site treats 2.5 billion gallons of contaminated groundwater annually at their P&T facilities at the cost of 1.31 cents per gallon, totaling $32.75M yearly (DOE, 2019a). In the Hanford Strategic Vision for 2023-2033, P&T activities will continue at least through 2033 (DOE, 2023b). Based on projected concentrations and performance data, the groundwater will not meet remedial objectives at that time and P&T may need to operate substantially longer, perhaps for decades, to meet

regulator/stakeholder requirements and expectations. It is recommended that during the next seven years (2026-2033), DOE-EM focus on continuing to identify sustainable and reasonable solutions to shift from active to passive remediation.

Enhanced attenuation has been successful at many sites already (e.g., Mound, SRS, Hanford and others) and continuation and expansion would benefit sites like Moab, Hanford, Paducah, and SRS. The technology readiness level for these types of systems is between 8 and 9. Not only does EA support many of the technical targets, but it has been successful already throughout the DOE-EM complex (INL, SRS) and numerous DOE-Legacy Management sites. At the Savannah River Site, for example, shifting from pump-and-treat to the funnel and gate with base injection concept, remedial costs went from $13M a year to $500K a year, an annual savings of $12.5M. DOE can save significantly by shifting from active to passive remediation where possible.
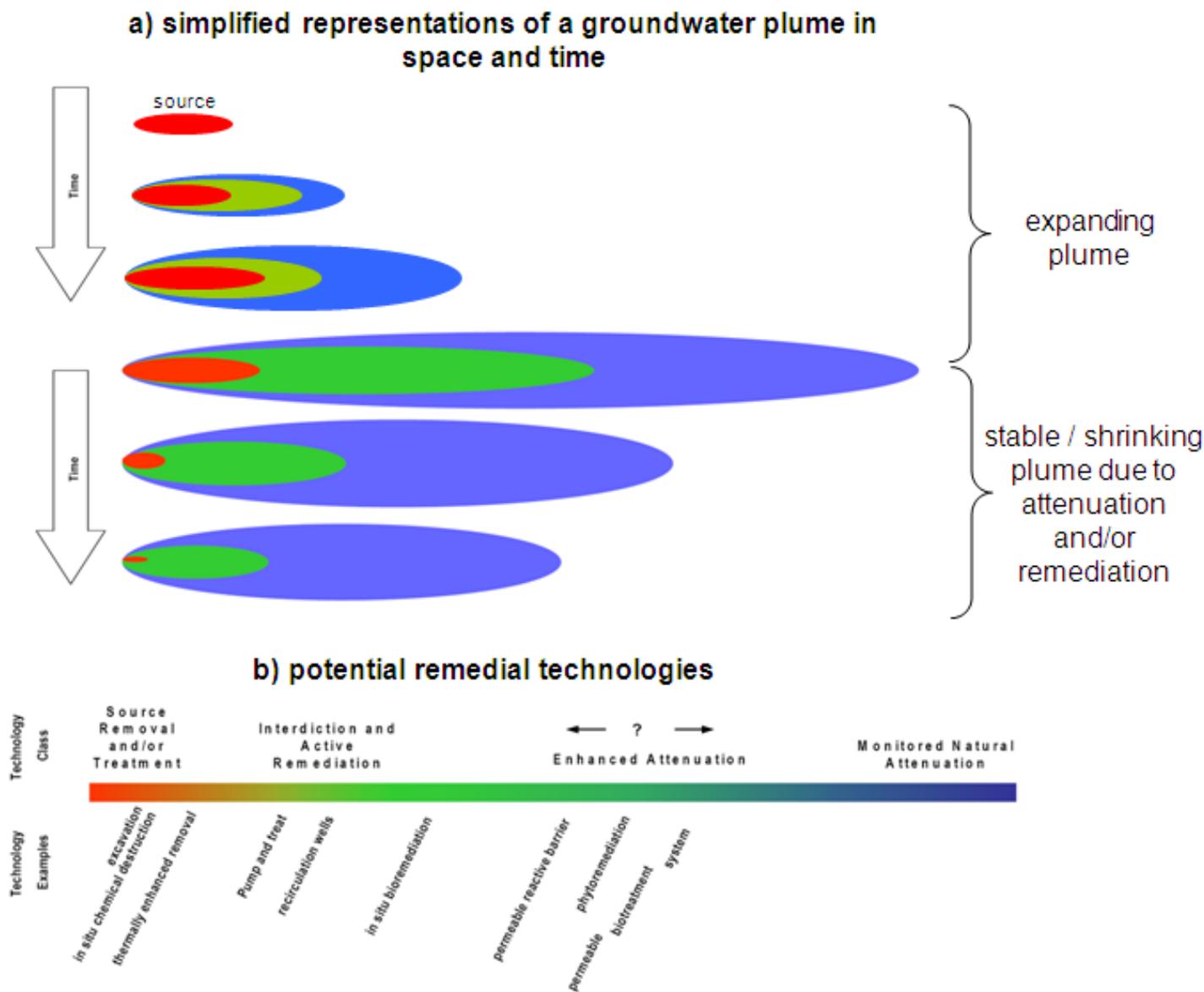
Figure 6. Progression of a plume with associated recommended remedial strategies.

Table 8. R&D Recommendations that Support Shifting Active Remedies to Passive

Category	Concept	Recommended Pilot Site(s)	Other Applicable Site(s)
MESA-2	EA: Bioremediation	Paducah, SRS	Hanford, INL, Moab
MESA-3	EA: In Situ Geochemical Remediation	Hanford, Moab	SRS
MESA-4	EA: Constructed Wetlands and Hyporheic Zones	Moab	Hanford, SRS
TDE-1	EA: Artificially Lithified Native Soils as Capping Materials	Moab	‡
TB&D-2	In Situ Geochemical Characterization Testbed	Hanford	Moab, Paducah, SRS

‡ indicates a cell was deliberately left blank

Specific Recommendations from NNLEMS Roadmap Team

The NNLEMS Team recommends that DOE apply enhanced attenuation practices at applicable sites to reduce costs of active remediation.

Implementing EA strategies, when appropriate, is critical for shifting from active remediation to passive. Previous implementations of EA have resulted in schedule acceleration, cost savings, risk reduction and EM mission enhancement. While EA concepts are portable and can be applied to any type of contaminant, most of the past EA implementations in DOE have focused on organic solvents except for SRS F-area. A key next step is the application of EA to other contaminant classes such as other radionuclides and metals. Such an implementation would be based on sustainably altering/controlling the mass balance (of source mass flux and attenuation) in the subsurface and using the EA flowchart principles developed by ITRC. The EA efforts could include in situ geochemical remedies, bioremediation, wetland/hyporheic processes, and soil lithification or a combination of these strategies in different areas of a site. EA could be central to DOE-EM testbeds with related MESA and TDE activities incorporated as appropriate to provide synergistic opportunities (see below).

The team recommends the process below.

1. Inventory groundwater remediation strategies in the DOE-EM complex
2. Identify active remedies, and perform review of efficacy
3. Evaluate where passive remedies potentially can be initiated and remaining uncertainties
4. Review successes at DOE sites for lessons learned
5. Develop path forward for full or partial transition to passive remediation

Cost Savings and Schedule Acceleration

The Team has estimated that implementing the recommendations at pilot sites will save a combined $450M to $850M over the lifetime of the remedy. Individually, the four sites can accelerate their timeframe for active remediation activities between 10 and 70 years.

Table 9. Cost Savings and Schedule Acceleration at Recommended Pilot Sites for Shifting Active Remedies to Passive Remediation

Recommended Pilot Site	Recommendation	Cost Savings	Schedule Acceleration
Hanford	MESA-3, TB&D-2	$100M-$200M	30-69 years
Moab	MESA-3, MESA-4, TDE-1	$150M-$250M	40-70+ years
Paducah	MESA-2	$100M-$200M	10-30 years
SRS	MESA-2	$100M-$200M	10-30 years

It is important to note that there are additional sites where implementation would be beneficial. If implemented beyond the recommended pilot sites, DOE can be expected to save costs and accelerate the schedule in a similar manner to the pilot sites. See Table 8 for additional applicable sites.

2. Use Innovative Geophysical Tools, Advanced Monitoring Techniques, and AI/ML to Better Monitor Plumes

Effective long-term stewardship of contaminated groundwater at DOE sites requires robust, adaptive monitoring frameworks that go beyond incremental well-based sampling. The integration of innovative geophysical tools, advanced subsurface characterization, and AI/ML is important for understanding the changing spatial and temporal resolution of plume dynamics and improving predictive capabilities and should be **considered for implementation second**, after evaluation of shifting from active to passive remediation. Advanced geophysical tools and characterization techniques (e.g., ERT – see case study in Appendix G) are valuable in understanding the true nature of the plume. In addition, making use of AI/ML technologies to predict these shifts in advance can meld with advanced geophysical tools and characterization techniques. Recommendations that fit this overarching recommendation are found in Table 10.

DOE-EM began plume characterization, installation of monitoring wells, and development of agreements with regulatory bodies three decades ago. It is critical that sites ensure the plumes are still being efficiently captured with the existing monitoring wells by revisiting the plume dynamics through geophysical tools, advanced characterization techniques, and advances in AI/ML. The need for reevaluation of monitoring well locations and depths to actively monitor the plume have been reported specifically by INL, Oak Ridge, and LANL.

Implementing expansion of innovative approaches such as Passive In Situ Sensors, use of AI/ML for Complex-wide Groundwater Monitoring Optimization and Real-Time In Situ Monitoring: on Shifting Hydrological Conditions would support monitoring well optimization (applicable at many DOE-EM sites, potentially saving 50-80% in monitoring costs), guide accurate well depth and locations for sites with hard-to-access locations (INL, LANL, Oak Ridge), and provide sites with the knowledge of the best location for monitoring wells based on current and future groundwater conditions where drilling monitoring wells is expensive (INL, LANL). This has been done successfully at SRS and will be implemented at Moab.

Site Specific Examples include:

- LANL: Drilling monitoring wells (particularly regional groundwater wells) at LANL is expensive and a regulatory challenge. Source evaluation is limited to general regional drip points.
- LANL: challenges for monitoring include difficulties in access.

- INL: Fractured rock aquifer complicates local groundwater flow, distribution of contaminants, and remedial actions.
- INL: The primary challenge for groundwater monitoring is decreasing water levels or the increasing depth to water at the INL site and corresponding increases in vadose zone thickness
- Oak Ridge: In areas with ongoing missions, contaminated media and sources are considered inaccessible due to the presence of active facilities and infrastructure.

Table 10. R&D Recommendations Supporting the Use of Innovative Geophysical Tools, Advanced Monitoring Techniques, and AI/ML to Better Monitor the Plumes

Category	Concept	Recommended Pilot Site(s)	Other Applicable Site(s)
MESA-1	Strategic Applications of AI/ML for Complex-Wide Groundwater Monitoring Optimization	Hanford	INL, Moab, Oak Ridge
MESA-5	Expanding the Applications of Passive In Situ Sensors for Difficult-to-Access Regions	INL	Hanford, LANL, NNSS
MESA-6	AI-Guided Real-Time In Situ Monitoring: Actionable Information on Shifting Hydrological Conditions	Hanford, INL	‡

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Using lessons learned at the SRS F-Area demo and current expansion to the Moab Site, a near-term recommendation is for DOE-EM to focus in situ sensor installation at difficult-to-access locations. The Nevada National Security Site reported difficulty with monitoring deep groundwater plumes. Los Alamos also has very deep groundwater and should also be considered a difficult-to-access region. INL reported the lowering of the water table, resulting in the likelihood of requiring deepening or replacement of wells. Three sites have been identified as having hydrogeologic conditions that implementing in situ sensors coupled with artificial intelligence and machine learning (AI/ML) and advanced modeling would be beneficial. These advancements in monitoring can support strategic decisions about well placement and plume anomalies. More remote monitoring would cut down on analytical monitoring costs, worker effort and hazards, and provide real-time data. In addition, it is recommended to implement this complex-wide, even if traditional groundwater sampling is not particularly difficult. This framework is expected to save 60%-80% on monitoring.

Specific Recommendations from NNLEMS Roadmap Team

(1) Use Known Successes at the F-Area Testbed to Expand to Sites that Have Difficulties with Accessibility

The Roadmap Team recommends using AI/ML and advanced modeling implementation to better monitor plumes in difficult-to-access regions. INL and NNSS reported difficulty with deep groundwater monitoring due to sampling or pumping issues, as more powerful pumps are needed for operating at greater depths, particularly for larger diameter wells. This need also highlights the difficulty and high cost associated with purging wells prior to sampling. In situ sensors have shown great technological advancements for monitoring groundwater metrics such as temperature, water table, pH, dissolved oxygen, and electrical conductivity. These variables are often proxies for contaminant concentration or mobility changes. It

would be advantageous for DOE-EM to consider piloting a deep groundwater in situ monitoring system at INL or NNSS, or even potentially LANL. This approach is estimated to save 60%-80% of monitoring costs, and with the high cost of monitoring deep groundwater at these sites, it would be advantageous to implement. More information on cost savings can be found in the AI/ML case study in Appendix G.

(2) Expand In Situ Groundwater Sensors Complex-Wide

It would be to DOE-EM's benefit to use in situ sensors for monitoring all groundwater plumes and to continue researching these technologies to address data gaps (see Monitoring section). Beginning this process with difficult-to-access sites would optimize cost savings (MESA-5) with the recommendation to expand to all sites (MESA-1).

The team recommends the process below.

1. Evaluate whether current methods primarily focused on well monitoring are accurate and cost efficient at DOE-EM sites
2. Perform AI-based analyses at sites where monitoring could be of benefit to determine if integration of in situ sensors/innovative strategies will be advantageous
3. Provide guidance for the implementation of innovative methods and in situ sensors where appropriate

Cost Savings and Schedule Acceleration

The Team estimates that implementing the recommendations at both pilot sites will save a combined $250M to $600M over the lifetime of the remedy. Individually, the four sites can support a reduction in timeframe for comprehensive sampling and analysis of full monitoring well network by 20 and 38 years.

Table 11. Cost Savings and Schedule Acceleration at Recommended Pilot Sites for Using Innovative Geophysical Tools, Advanced Monitoring Techniques, and AI/ML to Better Monitor Plumes

Recommended Pilot Site	Recommendation	Cost Savings	Schedule Acceleration
Hanford	MESA-1, MESA-6	$150M-$400M	20-38 years
INL	MESA-5, MESA-6	$100M-$200M	20-38 years

It is important to note that there are additional sites where implementation would be beneficial (Moab, LANL, Oak Ridge, NNSS). If implemented beyond the recommended pilot sites, DOE can be expected to save costs and accelerate the schedule in a similar manner to the pilot sites. See Table 10 for additional applicable sites.

3. Refine Conceptual Site Models through Next Generation Characterization Tools, Modeling, and AI/ML

Up-to-date conceptual site models are integral to providing site personnel and DOE-EM with the most accurate information regarding clean up and managing contaminated sites. Refinements to the CSMs should be **considered for implementation third**. Advancements in groundwater modeling, data analysis, and AI/ML now allow for a much better understanding of how specific contaminants behave over time. LANL reported needing an updated CSM and INL reported that the refinement of the CSM for Test Area

North would be advantageous. Recommendations that fit this overarching recommendation are found in Table 12.

For updating models, LANL reported that the Independent Review Team has recommended transition from the Finite Element Heat and Mass Transfer Code numerical modeling platform to MODFLOW. If DOE-EM decides to pursue this, focused technical assistance or designated funding for such an effort could be valuable. TDE-5 (On the use of machine learning techniques to advance specific groundwater flow and transport model applications) and TDE-6 (Hierarchical Hydrostratigraphic and Geostatistical Models) are two recommendations that can support this need.

Advanced characterization techniques such as TDE-2 – Fractured Rock Characterization, TDE-3 – Targeted Temporal Characterization for Refining Site Behavior and Long-Term Regulatory Compliance, and TDE-4 – Vadose Zone Characterization can be implemented to better understand local groundwater flow, distribution of contaminants, and distribution of amendments at sites with fractured rock (INL) and sites needing better vadose zone characterization (LANL) which can feed into CSM refinement.

Table 12. R&D Recommendations that Support Refining Conceptual Site Models through Next Generation Characterization Tools, Modeling, and AI/ML

Category	Concept	Recommended Pilot Site(s)	Other Applicable Site(s)
TDE-2	Fractured Rock Characterization	INL	Hanford, NNSS
TDE-3	Targeted Temporal Characterization for Refining Site Behavior and Long-Term Regulatory Compliance	Moab	Hanford, Paducah, SRS
TDE-4	Vadose Zone Characterization	Hanford	INL, NNSS
TDE-5	On the Use of Machine Learning Techniques to Advance Specific Groundwater Flow and Transport Model Applications	Hanford, SRS, LANL	INL, Moab, Paducah
TDE-6	Hierarchical Hydrostratigraphic and Geostatistical Models	LANL	Hanford, INL, Moab, Paducah, SRS
TDE-7	Flow Logging	Hanford	LANL, Moab
TDE-8	Distributed Fiber-Optic Sensing	Moab	Hanford, Paducah, SRS
TDE-9	Biogeochemical Tracers and Isotope Measurements	Moab	‡

‡ indicates a cell was deliberately left blank

Specific Recommendations from NNLEMS Roadmap Team
The NNLEMS Roadmap Team recommends using AI/ML for Flow and Transport Models to Inform CSMs.

Reliable site decisions rely on a strong CSM. However, it's often difficult to get accurate CSMs due to complex ground conditions and uneven data. New technology helps by combining data from different scales into a clear model. Advanced models consider geological features and other properties to better understand the site. Machine learning and simplified models help process large data sets and make real-time decisions easier. Updating the CSM regularly as new data becomes available is crucial, especially for long-term projects.

ML Techniques to Advance Specific Groundwater Flow and Transport Model Applications (TDE-5) and Hierarchical Hydrostratigraphic and Geostatistical Models (TDE-6) should be applied at applicable sites to support the further refinement of CSMs. Applying these recommendations can save $10M to $60M while supporting more informed decisions by both site personnel and HQ. These two recommendations can accelerate the schedule by 0 to 18 years.

The team recommends the process below.

1. Support LANL with transitioning to FEHM to MODFLOW to align with regulatory direction
2. Support INL for characterization of fractured rock by implementing advanced characterization tools
3. Evaluate the site needs for updated CSMs and support those updates with advanced characterization tools

Cost Savings and Schedule Acceleration

The Team estimates that implementing the recommendations at both pilot sites will save a combined $60M to $340M over the lifetime of the remedy. Individually, the pilot sites can support a reduction in timeframe for a fully supportive CSM by 0 and 37 years.

Table 13. Cost Savings and Schedule Acceleration at Recommended Pilot Sites for Refining Conceptual Site Models through Next Generation Characterization Tools, Modeling, and AI/ML

Recommended Pilot Site	Recommendation	Cost Savings	Schedule Acceleration
Hanford	TDE-4, TDE-5, TDE-7	$20M-$110M	0-27 years
INL	TDE-2	$10M-$50M	10-19 years
LANL	TDE-5, TDE-6	$10M-$60M	0-18 years
Moab	TDE-3, TDE-8, TDE-9	$10M-$70M	10-37 years
SRS	TDE-5	$10M-$50M	0-9 years

It is important to note that there are additional sites where implementation would be beneficial (Table 12)Table 12Table 10. If implemented beyond the recommended pilot sites, DOE can be expected to save costs and accelerate the schedule in a similar manner to the pilot sites. Estimated cost savings and schedule acceleration can be found delineated in Table 7.

4. Consider the Use of Testbeds to Synergistically Apply Tools and Technologies

DOE-EM has made considerable progress in reducing the risk from environmental contaminants, yet major remediation challenges remain, some of which are present at multiple sites. One challenge that often limits the adoption of new technologies is the lack of information about their performance at specific sites in comparison to standard approaches. This is particularly true regarding the radiological and chemical environments found at many DOE-EM sites. Historically, DOE-EM has funded the development of testbeds for several sites, and funding additional testbeds can provide the following benefits as testbeds can:

1. Provide opportunities for synergy between multiple remedial options
2. Be easily accessible and support leveraging of existing information and infrastructure,

3. Address clear and identified challenges and needs,
4. Support EM strategic challenges and programmatic improvements,
5. Provide efficient and effective support to its collaborator, and
6. Support a diverse portfolio of research.

The impact that the use of testbeds and demonstrations can have is multi-faceted and should be considered for implementation in concurrence with the three above recommendations. First, field-based evaluation and implementation of monitoring and remedial technologies/strategies have been shown to save money, time, and site resources. They have demonstrated success in working with both research and commercial entities. Additionally, associated regulatory framework that facilitates acceptance of non-traditional approaches at real-world sites. Successes and lessons learned can be applied to the broader DOE-EM complex.

There are multiple promising physical sites:
- Energy Technology Engineering Center
- Hanford Vadose Zone
- Los Alamos groundwater
- Moab UMTRA Site
- Paducah Gaseous Diffusion Plant
- West Valley Demonstration Project

Two testbeds were recommended for early consideration (Table 14): Results from the Moab Testbed (TB&D-1) and In Situ Geochemical Remediation Testbed (TB&D-2) would be applicable to multiple sites with significant benefits to DOE-EM. These testbeds would be built around a central activity (such as an EA strategy or a combined remedy) and other MESA, TDE, and FRO activities would be incorporated synergistically. In all testbed cases, AI/ML (MESA-1) would be applied to provide knowledge on the potential value and power of this key emerging technology as DOE-EM plans for future work. Complex-wide pilot or seed studies of some of the MESA, TDE and FRO topics were also discussed during the roadmap development and may be a useful adjunct to augment the value of selected-specific testbeds.

Table 14. R&D Recommendations that Support Implementing One or More Testbeds to Synergistically Apply Tools and Technologies

Category	Concept	Recommended Pilot Site(s)	Other Applicable Site(s)
TB&D-1	Moab Testbed	Moab	‡
TB&D-2	In Situ Geochemical Remediation Testbed	Hanford	Moab, Paducah, SRS
TB&D-3	Modular, Synergistic Treatment Train Demonstration Test	SRS	Hanford, Paducah

‡ indicates a cell was deliberately left blank

Specific Recommendations from NNLEMS Roadmap Team
The NNLEMS team recommends DOE to Implement One or More Testbeds.

A strategic recommendation would be to implement one or more testbeds **concurrently with the other three recommendations**. The Moab Testbed recommendation would be advantageous as significant preliminary work has been done by LBNL, PNNL, and SRNL. The Moab Site is an arid site with a key

challenge to monitor the seasonal plume flow into of the Colorado river. The Moab Site is nearing completion of tailings removal and relocation and has a date to transfer from DOE-EM to DOE-LM in 2029. A GCAP is currently being developed to support the transfer and to determine a strategy to contain the spread of contaminants to the groundwater and surface water, and to mitigate the threat to public health and the environment. Moab is an ideal test site due to location and accessible soil and groundwater.

A notional EA remedy has been proposed for the site includes in situ geochemical or biogeochemical stabilization in the former source area(s) (furthest from the Colorado River, soil lithification to direct or alter areas of infiltration, flushing of contaminants from the soil and groundwater in a corridor along the river, and actions to protect sensitive fish species in spawning areas of the Colorado River. Seasonal flooding of the river impacts groundwater hydrology. Based on the site conditions, Moab is ideally suited to serve as a testbed in which EA is a central activity with supporting AI/ML, geophysics, and other advanced/innovative characterization techniques, such as tracers and isotope analysis, and distributed sensing techniques such as fiber-optics. This approach would combine innovative characterization and geophysical techniques within a framework and ultimately would be beneficial in facilitating the transfer of the site to LM.

A Moab Site testbed is estimated to save between $10M and $50M with a cost between $1.5M and $2M. With the estimated transfer year of 2029, it can ensure data gaps and other unknowns have been addressed to build confidence with the Nuclear Regulatory Commission (NRC) to approve a GCAP and stay on the schedule of the 2029 transfer. Finally, by encouraging an EA strategy a testbed would facilitate orderly transition to a passive remedy and substantially reduce the remediation timeframe. This is expected to reduce the schedule at Moab by 0 to 9 years by identifying data gaps to support final regulatory actions.

A second in situ geochemical testbed (also EA) addressing an alternative scenario is also recommended. Various candidate sites were identified, notably the Hanford vadose zone. Using chemical amendments to enhance natural processes to immobilize, transform, or degrade contaminants into less toxic or less mobile forms would not only be beneficial to the applicable sites, but for regulators and stakeholders. Ultimately, this is expected to reduce costs by $50M-$100M per site with the infusion of $5M-$10M to implement. This task, at the recommended pilot location, will reduce the schedule by identifying data gaps by 10 to 19 years.

The team recommends the process below.

1. Evaluate ETEC, Hanford vadose zone, Los Alamos, Moab, Paducah, and WVDP for prioritization of implementing a testbed process
2. Solicit the NNLEMS for testbed proposals
3. Implement a testbed at Moab due to short transition period to LM for an approved GCAP and one other site

Cost Savings and Schedule Acceleration

The Team estimates that implementing the recommendations at both pilot sites will save a combined $70M to $200M over the lifetime of the remedy. Individually, the pilot sites can support a reduction in timeframe to fill data gaps to support final regulatory actions by 0 and 19 years.

Table 15. Cost Savings and Schedule Acceleration at Recommended Pilot Sites for Considering the Use of Testbeds to Synergistically Apply Tools and Technologies

Recommended Pilot Site	Recommendation	Cost Savings	Schedule Acceleration
Hanford	TB&D-2	$10M-$50M	0-9 years
Moab	TB&D-1	$50M-$100M	10-19 years
SRS	TB&D-3	$10M-$50M	10-19 years

It is important to note that there are additional sites where implementation would be beneficial (Table 14)Table 12Table 10. If implemented beyond the recommended pilot sites, DOE can be expected to save costs and accelerate the schedule in a similar manner to the pilot sites. Estimated cost savings and schedule acceleration can be found delineated in Table 7.

Conclusion:

The four overarching recommendations can save between $830M and $2B over the lifecycle of soil and groundwater remediation and many recommendations are complex-wide options. Piloting these recommendations can accelerate the schedule in various ways and can be reflected in the reduction in timeframes for: (1) active cleanup time, (2) comprehensive sampling and analysis of full monitoring well networks, (3) developing or finalizing fully supportive CSMs, and (4) filling data gaps to support final regulatory actions. On an individual site level, these timeframes can be reduced at variable lengths. To support the reduction of active cleanup time, it can be reduced by 10 to 70 years if all recommendations are implemented at the three recommended pilot sites. To reduce the timeframe for comprehensive sampling and analysis of full monitoring well networks, timeframes can be reduced by 20 to 38 years. The addition of advanced characterization tools can support a schedule acceleration between 0 and 37 years. Finally, implementing testbeds to help support final regulatory actions by identifying data gaps can support a schedule acceleration timeframe between 0 and 19 years.

It is important to note that reaching regulatory standards will surpass the 2091 estimated date. At SRS M-Area for example, calculations have been done that indicate that active remedies have reduced the timeline by hundreds of years but to reach regulatory standards, more than 200 years will be required. DOE-EM can multiply these cost savings and schedule acceleration benefits by expanding past the recommended pilot sites to other applicable sites by using lessons learned from those activities.

By focusing on shifting to active to passive remedies, DOE-EM will move towards the desired end state at each site. Using state-of-the-art tools and technologies for monitoring, DOE-EM can streamline monitoring needs and regulatory requirements to make more informed decisions on paths forward. Refining CSMs where needed using advanced techniques will inform researchers and DOE-EM HQ on plume changes, anomalies, and promote adaptive site management. Implementing testbeds and demonstrations can combine multiple tools and technologies, reduce the burden on site personnel, and provide lessons learned for complex-wide implementation.

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Appendices

Appendix A: DOE Charter

Appendix B: NNLEMS Proposal

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Appendix E: Enhanced Attenuation

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Appendix A: Charter

U.S. DEPARTMENT OF ENERGY

Charter for Developing the Research and Development Roadmap for Accelerating the Soil and Groundwater Cleanup Mission

1. Purpose

The Department of Energy (DOE) Office of Environmental Management (EM) is responsible for the cleanup of soil and groundwater contamination at 13 of the remaining 15 EM sites, including Energy Technology Engineering Center (ETEC), Hanford, Idaho, Lawrence Livermore National Laboratory, Los Alamos National Laboratory (LANL), Moab, Nevada Nuclear Security Site, Oak Ridge, Paducah, Portsmouth, Sandia National Laboratories, Savannah River, and West Valley Demonstration Project. Ten of these remaining sites - ETEC, Hanford, Idaho, LANL, Moab, Oak Ridge, Paducah, Portsmouth, Savannah River, and West Valley Demonstration Project - are among the most challenging sites due to the presence of multiple radioactive and chemical contaminants comingling in groundwater and soil, complex hydrogeologic conditions, possible secondary contaminant sources, and regulatory requirements that vary by location. The estimated environmental liability for completing the legacy cleanup mission, including tank waste, spent nuclear fuel, nuclear materials, transuranic waste, depleted uranium, low level and mixed waste, soil and groundwater, and excess facilities deactivation and decommissioning, exceeds $530 billion. Despite an annual investment of $540 million in soil and groundwater remediation, the soil and groundwater mission is expected to extend until 2091 (EM Program Plan 2022). In order to shorten the cleanup lifecycle and reduce cost to the taxpayer, EM must continually evaluate research and development (R&D) opportunities in the remediation sector, with a particular focus on technologies that can improve efficiency, accelerate cleanup timeline, and optimize financial investment.

To that end the EM Associate Principal Deputy Assistant Secretary for Field Operations (EM-3) will commission the Network of National Laboratories for Environmental Management and Stewardship (NNLEMS) to conduct an evaluation of the soil and groundwater remediation approaches and technologies at the ten remaining EM sites and produce an R&D Roadmap that identifies opportunities for applied research and technology development investments. This R&D Roadmap is estimated to be completed in the first quarter of 2025 and will be used to inform decisions for technology development investments in the EM budget request for fiscal year (FY) 2027.

2. Roles and Responsibilities

2.1   Federal Stewardship

Development of the R&D Roadmap will be managed, approved, and maintained by a Federal Steering Committee that reports to EM-3. The EM Senior Advisor for Laboratory Policy will be responsible for leading the Federal Steering Committee. Members of Federal Steering Committee include the Director of Subsurface Closure Office; the Director of the EM Technology Operations Office; the Deputy Assistant Secretary for Resource Management; and representatives from the Energy Technology Engineering Center, Hanford, Los Alamos, Moab, Oak Ridge, Savannah River, and West Valley Sites.

The Senior Advisor for Laboratory Policy and the Director of the EM Technology Operations Office will provide input to the Chief Technology Officer to ensure the proposed Roadmap is consistent with and will complement the integrated technology development program for the EM complex.

Site office representatives will be responsible for supplying site data and other information that the NNLEMS Team may request, as well as review of the draft Roadmap. Site representatives will consider site-directed R&D activities when evaluating roadmap recommendations. For external communications about the roadmap work, the applicable sites will be notified in advance and be included in the review and release process.

The Federal Steering Committee will coordinate with representatives from EM site offices and other DOE and Federal organizations [e.g., the Office of Legacy Management, Office of Science and Advanced Research Projects Agency-Energy (ARPA-E)], as necessary, during the development and implementation of the Roadmap to ensure that the Roadmap is consistent with current and planned basic research and innovation initiatives sponsored by other DOE programs or other Federal agencies.

Any update to the leadership and membership of the Federal Steering Committee will be approved by EM-3.

2.2   NNLEMS Team

The NNLEMS Team will include, but not be limited to, the Savannah River National Laboratory (SRNL), Pacific Northwest National Laboratory (PNNL), Argonne National Laboratory, Lawrence Berkeley National Laboratory, Idaho National Laboratory, Los Alamos National Laboratory, National Energy Technology Laboratory, Oak Ridge National Laboratory, Sandia National Laboratories, and Fermi National Accelerator Laboratory. The NNLEMS Team will be led by SRNL. The NNLEMS Team may consult with subject matter experts in industry, academia, or other stakeholders as necessary. DOE will have no role in the selection of such experts to work with the NNLEMS Team, and DOE will not exercise management control of any groups of

experts created by the NNLEMS Team. The NNLEMS Team will not engage EM site stakeholders except through the local DOE site team, as needed.

In accordance with applicable laws, pre-decisional documents from the DOE National Laboratories can be shared with technical experts. Members of the NNLEMS Team will be required to sign a Non-Disclosure Agreement before viewing DOE pre-decisional documents. NNLEMS will follow their own processes and procedures to manage access to such documents by any non-DOE Laboratory participants. Participation of industry experts in consultations with the NNLEMS Team does not disqualify their company from participating in future procurement activities at the EM sites.

3. Scope of Work

Over the next six (6) months beginning with the approval of this Charter, the NNLEMS Team will review key documents that were previously developed, including:
- *Technical Targets 2021 -A Tool to Support Strategic Planning in the United States Department of Energy (DOE)*, SRNL-STI-2021-00502, Revision 0,
- *Development of Science Based Solutions to Address DOE-EM's Challenging Soil and Groundwater Problems*, and
- *Closure Strategy Plan for DOE-EM Complex's Groundwater Plumes.*

To develop R&D focus areas the NNLEMS Team will evaluate existing technologies and best practices used in EM Sites' soil and groundwater programs, previously identified challenges to completing soil and groundwater remediation, as well as emerging and alternative technologies and past proposals for program acceleration. Alternative approaches must align with regulatory requirements and agreements. however, the focus of this evaluation will be on advancing science and technologies to provide the technical underpinning for addressing challenges in meeting regulatory objectives.

The evaluation will consider, but is not limited to, the following main technical areas as outlined in SRNL-STI-2021-00502, Revision 0:

- Ensuring Environmental Stewardship
    - Improving Technical Basis for Environmental Stewardship Management
    - Climate Resilience
    - Emerging Contaminants
    - Next Generation Modeling
    - Methods to Verify and Validate Performance
- Eliminating Contaminant Sources
    - Source Zone Destruction, Stabilization, and Treatment
    - Controlling Contaminants in the Vadose Zone
- Isolating Contaminants
    - Advanced Sustainable Containment Systems

- o   Integrated Containment-Treatment Concepts
- Controlling Contaminant Plumes
  - o   Effective and Sustainable Solutions for Plumes
  - o   Overcoming Challenges to Achieving End States
- Enabling Soil and Groundwater Remediation Efforts
  - o   Subsurface Access and Delivery
  - o   Next Generation Characterization and Monitoring Technologies (Tools)
  - o   Biogeochemical Processes Determining Contaminant Fate
  - o   Strongly Heterogeneous Systems

The evaluation shall also consider sequencing and timing of mission activities and planned site end states. In addition, the evaluation will track the progress and status of other DOE research programs, such as the Energy Frontier Research Centers and ARPA-E programs, to ensure that applicable advancements are incorporated into this Roadmap.

Based on the evaluation, the NNLEMS Team will provide a draft Roadmap to EM for consideration. The roadmap will recommend R&D focus areas developed during the evaluation, identify methods or approaches for accelerating soil and groundwater remediation, and include a preliminary risk assessment and cost/benefit analysis. Laying out the technical recommendations and opportunities through this Roadmap will help guide DOE investments to expedite the cleanup of soil and groundwater contamination and support closure of the EM sites. A graded approach, considering the varying degrees of site complexities, will be used to develop the recommendations.

NNLEMS will incorporate input from DOE, the Environmental Management Advisory Board (EMAB) on "Best Practices for Implementing EM's Groundwater Closure Strategy and Long-Term Monitoring Paradigm" and additional EMAB reviews, as well as potentially the Government Accountability Office, to finalize the Soil and Groundwater R&D Roadmap.

In the near term, the draft Roadmap will be used to inform the EM budget request for FY2027. NNLEMS will support periodic updates to the Roadmap based on technology development and management directives. Longer term, the Roadmap will be used by DOE to guide the investment in breakthrough technologies to improve efficiencies in the EM soil and groundwater cleanup mission. Finally, a soil and groundwater R&D program like the Hanford Tank Waste R&D Program ([Hanford Tank Waste Research and Development | Department of Energy](#)) may be developed for implementation after completion of this Roadmap.

4. Funding

Funding for the NNLEMS Team development of the roadmap will be allocated to each of the participating National Laboratories by the EM Laboratory Policy Office, in consultation with the Steering Committee, and approved by EM-3. Implementation of the roadmap will be subject to availability of congressional appropriations.

5. Reporting and Documentation

The Federal Steering Committee and the NNLEMS Team will provide quarterly and as needed briefings to EM senior leadership on the status of the Roadmap. Key schedule milestones include:

- NNLEMS proposal due to DOE by February 15, 2025.
- Draft R&D Roadmap due to DOE by July 15, 2025.
- Final R&D Roadmap due for public release by September 30, 2025.

Additional interim milestones/deliverables will be developed and identified in the NNLEMS Team proposal.

Development of the R&D Roadmap will be documented in a DOE SharePoint site for transparency and traceability.

Concurrence:

MING ZHU   Digitally signed by MING ZHU
Date: 2025.01.21 16:03:08 -05'00'

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Ming Zhu, Senior Advisor for Laboratory Policy, Laboratory Policy Office   Date

ROBERT SEIFERT   Digitally signed by ROBERT SEIFERT
Date: 2025.01.28 13:11:07 -05'00'

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Robert Seifert, Director, Infrastructure, Disposition and Regulatory Policy   Date

Rodrigo V. Rimando   Digitally signed by Rodrigo V. Rimando
Date: 2025.01.28 09:45:35 -05'00'

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Rodrigo Rimando, Director, Office of Technology Operations   Date

CHARLES TRISCHMAN   Digitally signed by CHARLES TRISCHMAN
Date: 2025.01.30 18:53:32 -05'00'

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Steve Trischman, Deputy Assistant Secretary, Resource Management   Date

JOHN MARRA   Digitally signed by JOHN MARRA
Date: 2025.01.28 10:07:03 -05'00'

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John Marra, Chief Technology Officer   Date
  Office of Chief Technology Officer

Approval:

GREGORY SOSSON   Digitally signed by GREGORY SOSSON
                 Date: 2025.01.31 06:01:58 -05'00'

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Gregory Sosson, Associate Principal Deputy Assistant Secretary   Date
  for Field Operations

Appendix B: Proposal

NNLEMS Soil and Groundwater Roadmap Proposal

Proposal

The Department of Energy (DOE) Office of Environmental Management (EM) requests the Savannah River National Laboratory (SRNL) lead a team from the Network of National Laboratories for Environmental Management and Stewardship (NNLEMS), industry, and academia to develop an R&D Roadmap for the remediation of soil and groundwater, DOE-EM's largest long-term fiscal responsibility.

This Roadmap will focus on R&D opportunities to address overarching and site-specific soil and groundwater technical needs. Recommendations will be taken from, but not limited to, the previous Groundwater Closure Strategy with an emphasis on technical investments to expedite closure of EM's complex groundwater sites. To develop an integrated roadmap, there will be a focus on identifying innovative technical approaches and state-of-the-art technologies for development with EM. While the general technology areas have been identified, priority will be assigned based on potential return on investment that aims at lifecycle cost reduction and schedule acceleration of the soil and groundwater cleanup mission.

The objectives of the roadmap are to inform DOE-EM's FY2027 budget request, guide technology investments in soil and groundwater, and prioritize recommended technologies based on personnel resources, cost/benefit, and research areas. The R&D Roadmap for Hanford Tank Waste Mission Acceleration (NNLEMS-2022-00005, Rev. 0) will serve as a reference point when completing this R&D Roadmap. The NNLEMS Team will meet regularly and keep the DOE Steering Committee updated with status reports to ensure a robust final product.

Background

Cleanup and long-term monitoring/stewardship is a necessity at DOE-EM sites to protect human health and the environment. DOE estimates over $544B in continuing environmental liabilities associated with the cleanup of DOE sites (DOE Agency Financial Report Fiscal Year 2024). It is critical to prioritize remediation efforts and structure investments to make technically defensible decisions that expedite progress towards site closures.

Since 2021, three NNLEMS Teams have identified a pathway to expedite closure of DOE's complex groundwater plumes by developing much of the information needed to make complex-wide and site-specific recommendations for technical and other needs.

Phase 1: Technical Targets Document (November 2021) → Phase 2: Site Interviews (August 31, 2022) → Phase 3: Expedited Site Closure Strategy Document (March 2024)

Phase 1. The first of these activities, funded by the EM Technology Development Office, was an update of the 2002 Technical Targets document, which acts as a pathway for identifying key technologies and strategies for addressing specific soil and groundwater needs after 25 years of active remediation. This Technical Targets document was completed at the end of FY21 and included subject matter experts from Argonne National Laboratory, Lawrence Berkeley National Laboratory, Los Alamos National Laboratory, National Energy Technology Laboratory, Pacific Northwest National Laboratory (PNNL), Sandia National Laboratories, SLAC National Accelerator Laboratory, SRNL, and Geosyntec Consultants, Inc.

Phase 2. Following the updates to the Technical Targets document, SRNL led the next phase of the overarching strategy to enhance and achieve soil and groundwater cleanup. Funded by the EM Laboratory Policy Office, this phase consisted of interviews with subject matter experts (SMEs) at DOE-EM sites with complex groundwater plumes. To identify the current challenges in achieving final groundwater closure, the team reviewed site documents and devised a standardized questionnaire. This questionnaire categorized the sites' remediation status, proposed end state, residual stakeholder risk, schedule, etc., as well as identified three main challenges each site faces in executing technical, regulatory, and stakeholder projects/needs.

Phase 3. Once the needs of the sites were identified, a smaller team including SRNL, PNNL, Longenecker and Associates, Oregon State University, and Geosyntec, worked with DOE-EM HQ to classify the status of each site's progress toward regulatory closure. This revolved around developing a standard matrix used for each site, ranking each site from low to high in the areas of current exposure control, groundwater plume control, end state progress, and regulatory, stakeholder, and Tribal engagement.

While this three-phased process created an overarching strategy for groundwater closure, a roadmap is needed to identify and prioritize key technical and regulatory needs to expedite site closure at the individual sites.

Approach

Three Focus Areas have been established: Characterization, Modeling, and Remediation. The scope of these Focus Areas encompasses the primary R&D needs in the EM complex and will be evaluated using the categories developed in the updated Technical Targets document, specifically addressing the needs to:

- Ensure Environmental Stewardship
    - Improving Technical Basis for Environmental Stewardship Management
    - Climate Resilience
    - Emerging Contaminants
    - Next Generation Modeling
    - Methods to Verify and Validate Performance
- Eliminate Contaminant Sources
    - Source Zone Destruction, Stabilization, and Treatment
    - Controlling Contaminants in the Vadose Zone
- Isolate Contaminants
    - Advanced Sustainable Containment Systems
    - Integrated Containment-Treatment Concepts
- Control Contaminant Plumes

- o Effective and Sustainable Solutions for Plumes
- o Overcoming Challenges to Achieving End States
- Enable Soil and Groundwater Remediation Efforts
  - o Subsurface Access and Delivery
  - o Next Generation Characterization Technologies (Tools)
  - o Biogeochemical Processes Determining Contaminant Fate
  - o Strongly Heterogeneous Systems

The team will revisit the previous documents performed by the NNLEMS, academia, and industry to identify R&D needs in soil and groundwater throughout the DOE-EM complex; see references 1-5 below.

Each Focus Area team will review these documents and identify specific R&D needs facing the DOE-EM complex. Together, the Roadmap team will categorize them into groupings of "quick wins", critical needs, high priority, or useful to guide prioritization EM; definitions will be determined by the team during the Roadmap development process. R&D prioritization will be based on mission-criticality, cost/benefit analyses, and implementation timeframe and impact (i.e., return on investment).

To ensure immediate site needs are being identified and described for the Roadmap, the previously used questionnaire (SRNL-L3200-2023-00004, Rev. 1) will be resent to the sites, requesting them be updated and more focused on technology needs. Follow-up meetings with the sites will be scheduled if more information is required.

Team Members and Team Structure
Emily Fabricatore from SRNL will act as the project lead for the R&D Roadmap Team. SRNL will be responsible for coordinating, directing the team activities, and providing updates to DOE-EM HQ at NNLEMS meetings and the Technology Program Portal.

Andy Tompson (Lawrence Livermore National Laboratory (LLNL)), Chris Johnson (PNNL), and Brian Looney (SRNL) will lead the three Focus Area groups. Enabling technologies encompasses key considerations in the characterization, remediation, and monitoring R&D needs. One team member will be a representative in each topic of enabling technologies to ensure its visibility and consideration throughout the roadmap and between Focus Area teams if the need arises. Remaining team members have been distributed into those groups based on their expertise and a full list of team members by laboratory/affiliation is in Table 1.

Additional team members can be added as need arises if funding is available.
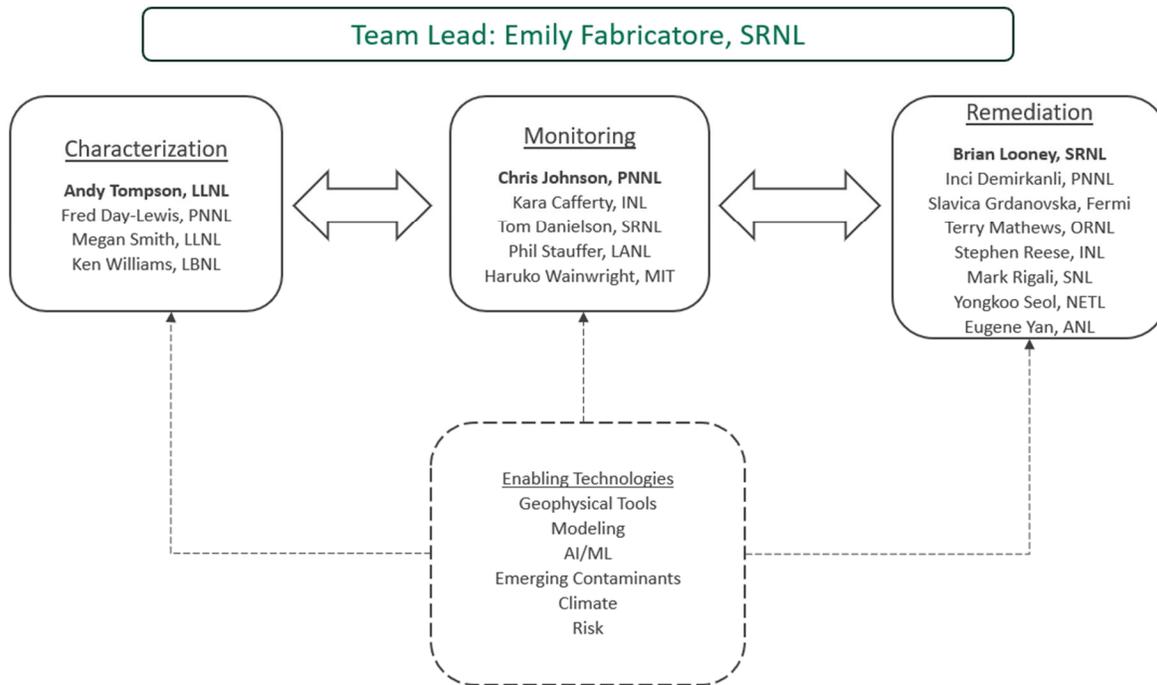
Figure 1. Focus Areas, Leads (bolded), and Team Members.

Table 1: Proposed NNLEMS Team Members

Argonne National Laboratory	Eugene Yan
Fermi Laboratory	Slavica Grdanovska
Idaho National Laboratory	Kara Cafferty Stephen Reese
Los Alamos National Laboratory	Philip Stauffer
Lawrence Berkeley National Laboratory	Kenneth Williams
Lawrence Livermore National Laboratory	Megan Smith Andrew Tompson
National Energy Technology Laboratory	Yongkoo Seol
Oak Ridge National Laboratory	Teresa Mathews
Pacific Northwest National Laboratory	Inci Demirkanli Christian Johnson Fred Day-Lewis
Sandia National Laboratories	Mark Rigali
Savannah River National Laboratory	Thomas Danielson Carol Eddy-Dilek* Emily Fabricatore Brian Looney Brooke Stagich[‡] Alejandro de la Noval[‡]
Massachusetts Institute of Technology	Haruko Wainwright

*Team members supporting the overall project as a consultant; not on Focus Area team

‡ Team members supporting specific enabling technologies; not on Focus Area team

Meeting Structure

Recurring semimonthly meetings will be established and hosted on Microsoft Teams. The meetings will be scheduled for 90 minutes with equal time for each Focus Area to drive the discussion on assignment findings, led by the Focus Area leads. Having full meetings rather than weekly meetings for Focus Areas will facilitate robust conversations, identify overlap between Focus Areas, and promote collaboration. The framework for the semimonthly meetings will consist of:

- 5 minutes: Opening comments by Emily Fabricatore
- 15 to 25 minutes each: Focus Area teams to present assignments, request feedback from full team, etc.
- 5 minutes: Final thoughts or questions by any of the team members
- 5 minutes: Closing comments by Emily Fabricatore, including next assignment for next meeting

Timeline

The Charter contains three deliverables shown in bolded type in Table 2. Key dates and actions have been added that reflect intermediate tasks to ensure deliverables are met in a timely fashion. Additional delineation of the intermediate milestones and additional target dates may be developed by the team as needed.

Table 2: Proposed Timeline

Charter finalized	January 30, 2025
Proposal submitted to the DOE Steering Committee	**February 15, 2025**
Team Kick-Off Meeting	February 20, 2025
Kick-Off Meeting with DOE	February 25, 2025
Full Team Meetings – semimonthly	through July 15, 2025
Focus Area Meetings	As scheduled by Focus Area Leads
Finalize draft roadmap for team review	June 30, 2025
Receive team comments	July 7, 2025
Incorporate edits/comments from team members	July 14, 2025
Submit draft roadmap to the DOE Steering Committee	**July 15, 2025**
Meetings with DOE/updates to roadmap based on DOE's and potentially EM Advisory Board's input	July 16 to September 30, 2025, as needed
Submit final R&D Roadmap to the DOE Steering Committee for public release	**September 30, 2025, DOE-EM HQ**

Note: Deliverable dates are subject to be extended if funding has been spent out for significant contributors.

References

(1) Eddy-Dilek, C. 2023. *Summary of Groundwater Closure Strategy Phase 2 Site Interviews.* SNRL-L3200-2023-00004, Rev. 1.

(2) Eddy-Dilek, C., Fabricatore, E. 2023. *Development of Science Based Solutions to Address DOE-EM's Challenging Soil and Groundwater Problems.* SRNL-STI-2023-00234, Rev. 0.

(3) Eddy-Dilek, C., Fabricatore, E., Wilson, S., Nyman, J., Bender, W. 2024. *Closure Strategy Plan for DOE-EM Complex's Groundwater Plume.* NNLEMS-2024-00001.

(4) Environmental Management Advisory Board. 2024. *Best Practices for Implementing EM's Groundwater Closure Strategy and Long-Term Monitoring Paradigm.*

(5) Looney, B., Nyman, J. 2021. *Technical Targets 2021 – A Tool to Support Strategic Planning in the United States Department of Energy (DOE).* SRNL-STI-2021-00502.

(6) NNLEMS. 2022. *R&D Roadmap for Hanford Tank Waste Mission Acceleration.* NNLEMS-2022-00005, Rev. 0.

Appendix C: Team Structure

Team Lead
Emily Fabricatore, SRNL

Characterization

Andy Tompson, LLNL
Fred Day-Lewis, PNNL
Megan Smith, LLNL
Ken Williams, LBNL
Kris Kuhlman, SNL

Monitoring

Chris Johnson, PNNL
Kara Cafferty, INL
Tom Danielson, SRNL
Phil Stauffer, LANL
Haruko Wainwright, MIT

Remediation

Brian Looney, SRNL
Inci Demirkanli, PNNL
Slavica Grdanovska, Fermi
Terry Mathews, ORNL
Stephen Reese, INL
Mark Rigali, SNL
Yongkoo Seol, NETL
Eugene Yan, ANL

Geophysical Tools - Fred Day-Lewis
Modeling - Inci Demirkanli
AI/ML - Tom Danielson
Emerging Contaminants - Eugene Yan
Remedy Resilience - Ken Williams
Risk - Brooke Stagich

Appendix D: Site Questionnaire Responses

Please see Attachment D in email form. This attachment will be added when put in final PDF format.

Appendix E: Attenuation-Based Remedies

Attenuation-based remedies such as Monitored Natural Attenuation and Enhanced Attenuation (EA) either destroy the target contaminant(s) (preferred) or reduce exposure and risk. MNA works without human intervention while EA involves up front actions to supplement and enhance attenuation. ITRC has developed technical and regulatory guidance for EA to encourage implementing sustainable actions to transition sites that do not meet all the requirements for MNA into an acceptable attenuation-based remedy. Examples of acceptable EA enhancements include accelerating in situ biological destruction, reducing contaminant toxicity, or reducing contaminant mobility by altering in situ biogeochemical conditions (reducing solubility, increasing sorption or forming solid phase minerals). Over the past three decades EA (and to a lesser extent MNA) represent an area of significant success within DOE – EA has accelerated cleanup, reduced costs, and allowed sites to transition through the remediation process to meet end state goals. Despite this success, EA is significantly underutilized, and its application could be expanded to more contaminants and more conditions with the use of more diverse contributing biogeochemical processes. Thus, the Soil and Groundwater Roadmap concepts that build on the conceptual approach of EA may be appropriate for consideration.

MNA is an important environmental management strategy that recognizes the effects of natural mechanisms in the subsurface which stabilize or shrink a contaminant plume. During the past 30 years, MNA for chlorinated organics has advanced rapidly, supported by improved scientific information and clear policy developments. EPA formally recognized the use of natural attenuation and the use of the term "MNA" with issuance of two documents, a protocol (EPA, 1998) and a directive (EPA, 1999) and later documents extending the approach to other contaminants such as metals and radionuclides. EPA encouraged the use of MNA, in combination with other actions, to achieve remediation goals. According to EPA (1999), the processes that contribute to MNA include "a variety of physical, chemical, or biological processes that under favorable conditions, act without human intervention to reduce mass, toxicity, mobility, volume, or concentration of contaminants in soil or groundwater." EPA guidance for MNA typically relies on multiple lines of evidence (MLE). In summary, the requirements for environmental strategies that rely on natural attenuation include the following:

- Documenting that the plume poses minimal risk
- Documenting that the plume is stable or shrinking
- Monitoring to ensure environmental protection
- Triggers to implement contingency plans as needed

MNA is a remedial strategy that specifies no human intervention. It has been described as "watchful waiting"; however, MNA remedies are intended to move toward remediation goals that minimize risks at an acceptable rate. There are a variety of issues and challenges to broader implementation of MNA, including:

- Limited understanding of site-specific natural attenuation processes
- Limited characterization, including site-specific geochemical conditions
- Unreasonably long remediation time frames
- Insufficient natural attenuation rates relative to the mass loading entering the plume from the source area(s)

- Inability to collect information due to ongoing operations of an active remedy such as pump-and-treat (note that this challenge is a primary basis for the development of EA as a technically defensible bridge between active and passive remedies).

A typical timeframe for MNA is 10 to 50+ years. In cases where natural attenuation mechanisms are not sufficient to achieve remediation goals— because of risk/exposure to receptors, plume growth, or long time-frames — additional actions are required. Targeted approaches are necessary to overcome the conditions(s) that cause MNA alone to be inadequate for site remediation. Such actions can include active treatments or EA.

EA is an engineered treatment that uses an engineering action (such as biogeochemical or hydrologic manipulation, biostimulation or/and bioaugmentation, or similar) to sustainably alter site conditions to destroy or transform contaminants and beneficially alter the plume mass balance such that the remedial objectives are met in a reasonable timeframe.

Note that DOE led in developing the principles of enhanced attenuation (EA) and developed the technical basis for this design strategy – in collaboration with scientists from multiple Federal Agencies, various university, industry and with an interagency and State/Federal regulators. DOE supported the Interstate Technology and Regulatory Council (ITRC) as they developed comprehensive technical guidance through the "Enhanced Attenuation Chlorinated Organics (EACO)" team (Figure 7). Selection of enhanced attenuation is based on a mass flux analysis. EA relies on sustainable enhancements to bridge between active treatment and a monitored natural attenuation (MNA) remedy. The design basis for EA applications is different from conventional active bioremediation because EA is built on the principles of sustainability and mass balance – beneficially altering the relationship between mass loading from the source area(s) and the rate of mass attenuation (attenuation capacity) in the plume. The mass balance relationship defines the emergent plume behavior (i.e., expanding, stable or shrinking).

Providing sustainable conditions for a stable or shrinking plume based on a mass balance evaluation is the fundamental design basis and outcome of a successful EA. Sustainability is defined as the ability of a groundwater system to maintain the attenuation mechanisms that destroy or immobilize contaminants for a sufficient time and rate to meet remedial objectives until the source mass flux is depleted. When properly designed, EA shifts the site conditions to meet the requirements of MNA. Sustainability is affected by the rate at which the contaminants are transferred from the source area and whether the protective processes are robust and renewed due to the long-term resilience of the microbial community. The core requirement of sustainability, i.e., shifting the site in a technically defensible, enduring and sustainable manner, typically requires use of longer lasting amendments and more focus on the structure and function of the subsurface microbial ecosystem. A typical performance timeframe for EA is 5 to 30 years.
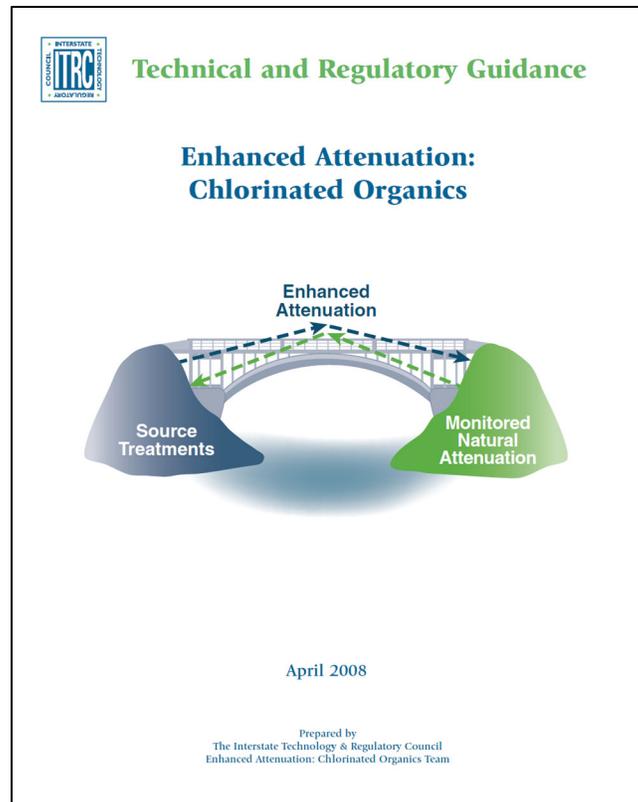
Figure 7. ITRC Technical Guidance on Enhanced Attenuation for Chlorinated Organics -- Enhanced attenuation provides a "bridge" between active treatment and MNA.

To facilitate implementation of EA, the ITRC developed technical and regulatory guidance that is built around an implementation flowchart. The flowchart provides an important rubric for decision making (Figure 8 and Figure 9). This flowchart was based on existing regulatory guidance documents and protocols. The initial efforts at a contaminated site (blue boxes I and II in Figure 8 and Figure 9) represent the initial discovery, characterization, source treatment, and active remediation. These activities result in a range of characterization data as well as decision-making information related to risk, technology performance, treatment time, and treatment cost (green circles). These criteria, in turn, are inputs to a series of questions related to the viability of MNA (yellow diamonds). This portion of the process encourages implementation of MNA according to the existing regulatory protocols with added emphasis on mass balance-based assessment of plume stability and with documentation of treatment sustainability. This ITRC specified sustainability requirement, represents an additional level of documentation and rigor compared to prior MNA protocols.

As a site is approaching MNA but does not meet the requirements of MNA, (i.e., it does not pass the yellow diamond gantlet of requirements), the decision flowchart provides an additional potential option of EA (orange assessment-implementation process). The EA path provides specific requirements to be considered in evaluating the mass balance to optimize long-term plume stability/reduction (shrinking) and in selecting and designing an EA treatment. In this case, the scientist/engineer determines whether there is a sustainable action that will modify the risk, plume stability, or remediation time frame and allow for implementation of that action. The types of enhancement evaluated, and the objectives of the

enhancements are developed based on the specific issues identified in the MNA questions. For example, if the remediation time frame is determined to be too long, then enhancements that increase degradation rates will be identified; if conditions are not sustainable then enhancements to further sustain the attenuation process will be identified and evaluated. If enhancements are not viable, then traditional treatment continues. If enhancement is viable and has the potential to be more effective than the current treatment, then it is implemented and monitored to document that the desired change was achieved so that the site can transition to MNA or to identify that the desired change was not achieved such that further enhanced treatment is required. The ITRC (2008) technical guidance document provides detailed descriptions and documentation for each step in the flowchart process.

Remediation Topical Team consensus was that DOE-EM would benefit from emphasizing strategies that facilitate the transition of remediations from active toward passive remediation. EA is an overarching framework for that transition. EA relies on innovative applications of in situ bioremediation and in situ geochemical remediation methods along with multiple lines of evidence (metrics) that efficiently document EA performance and sustainability.
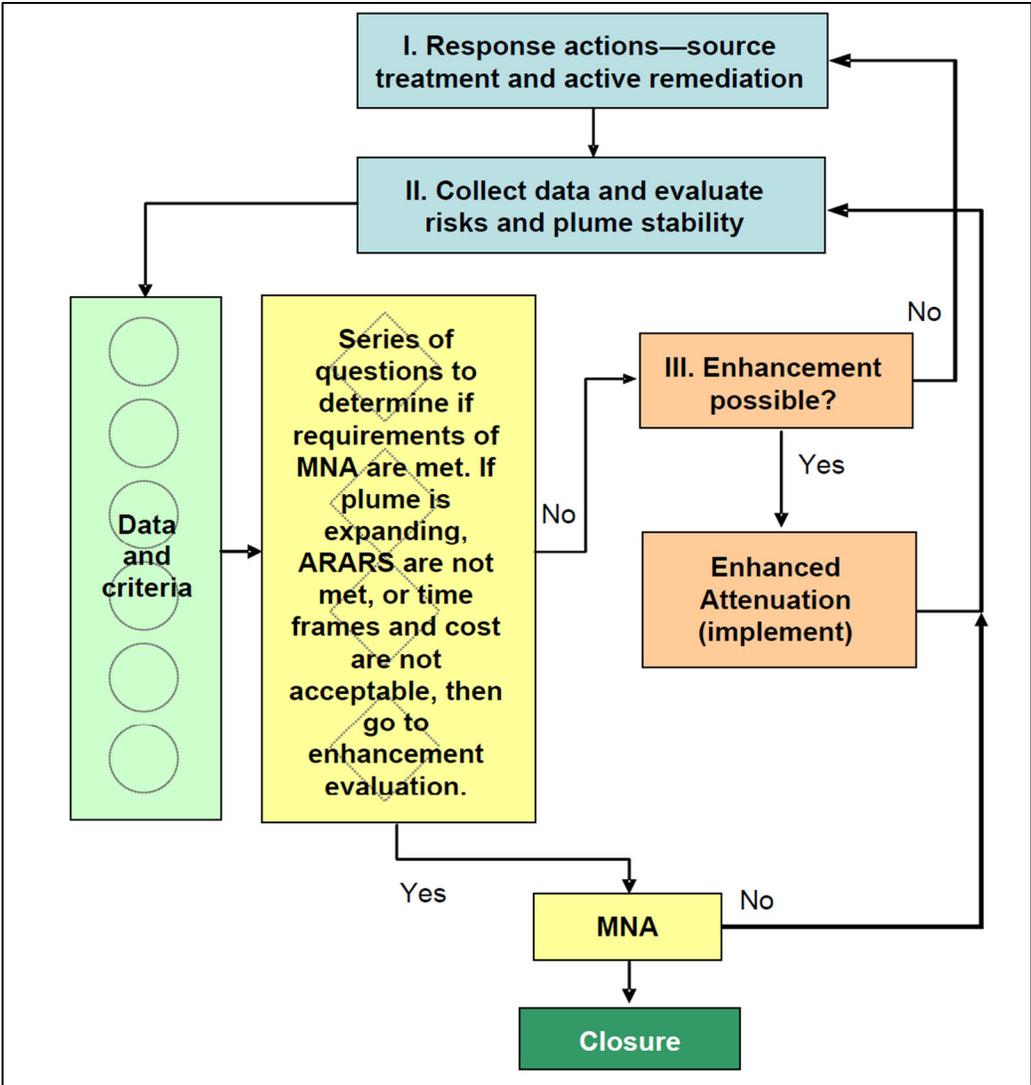
Figure 8. General Structure of ITRC MNA/EA Decision Flowchart (ITRC, 2008).
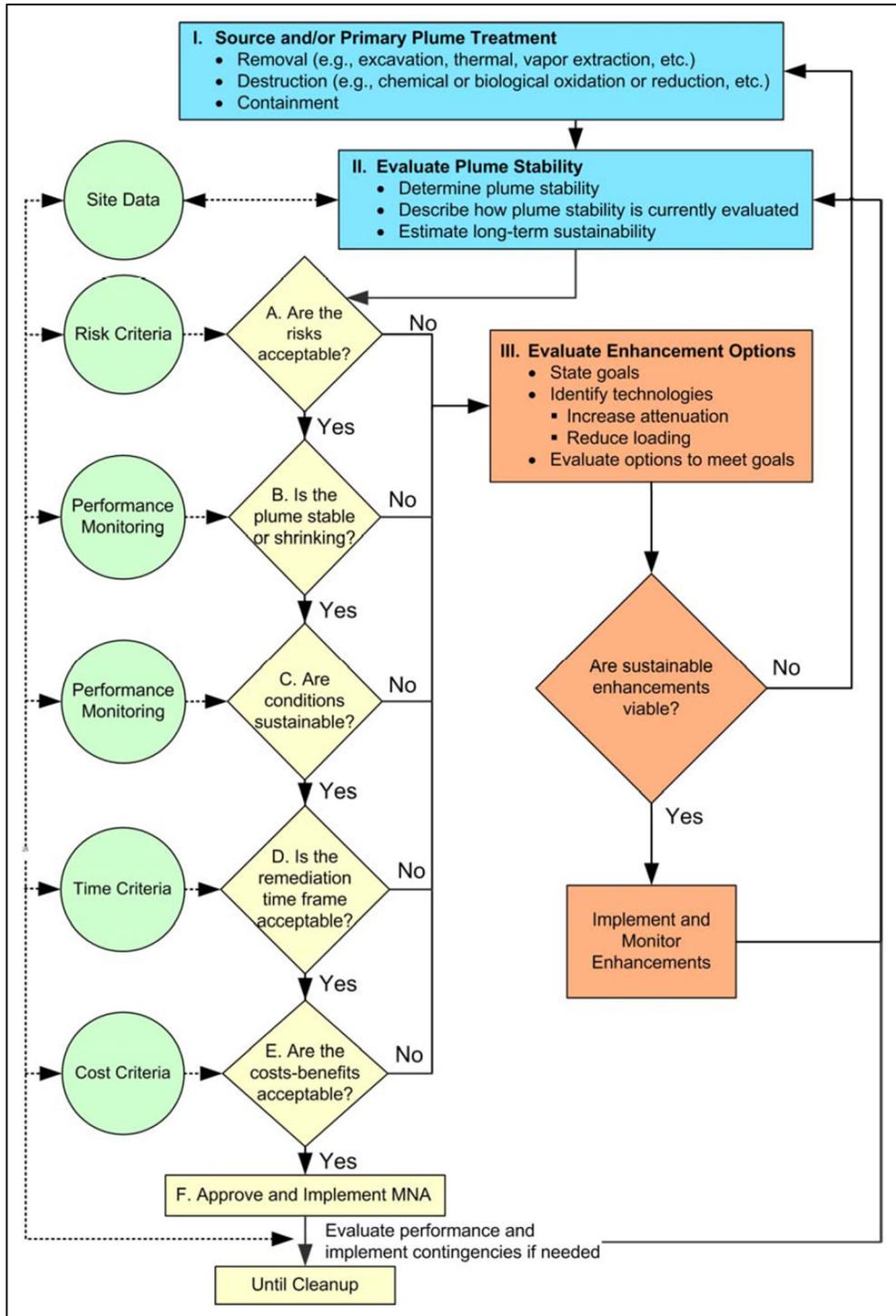
Figure 9. Expanded ITRC MNA/EA Decision Flowchart (ITRC, 2008).

Appendix F: Adaptive Site Management a Central Theme to Optimize Remediation at Complex Sites

A key focus of the Soil and Groundwater Roadmap Remediation Team deliberations related to a potential opportunity to alter the remedial paradigm to address the complex site conditions that are typical of the remaining DOE challenges. The emerging complex site paradigm is broadly accepted and has been inclusive in its development process, including key federal and state regulators. The complex site paradigm is emerging as an important tool in addressing the nation's most significant environmental challenges; several guidance documents are available to support both the general approach and site-specific applications (ITRC, 2004 and 2017; NRC, 2013). Likewise, the U.S. EPA Superfund Task Force has recommended broadening the use of adaptive management for complex sites and is currently running select pilots (EPA, 2018).

Framework for Complex Site Remediation

The traditional regulatory implementation paradigm presumes that a reasonable technology (or technologies) can be identified to achieve remedial objectives. In this scenario, the default strategy is a basic "study ➔ select ➔ design ➔build ➔ monitor" linear process. While the traditional paradigm includes a contingency process, the general presumption is that a period of study can support a reasonable and appropriate technology decision that will achieve the final remedial action objectives. For example, under the Resource Conservation and Recovery Act (RCRA), there is a corrective measures study, followed by corrective measures selection based on a set of screening criteria. Unfortunately, complex sites are poorly suited to the traditional linear process; the significant uncertainty inherent in environmental cleanup at complex sites has necessitated more flexible-iterative approaches. Over the past two decades, remediation of complex sites has achieved progress and success by focusing on developing and achieving interim goals (steps toward final remedial objectives) and using the information obtained during each step to resolve uncertainties and to improve and refine the technology decision for later stages of the remediation.

Despite its name, adaptive site management is not a reactive strategy, instead, it is a proactive strategy that encourages development of a phased remediation that will lead to achieving remedial goals. Each phase has clear achievable objectives. Selected technologies for each stage are based on meeting the focused objectives. Decisions on the later stages of remediation are determined at defined decision points based on ongoing characterization to fill data gaps. The data gaps and associated schedule/plan to address the uncertainties is defined in the adaptive site management planning to correspond to the timeframe of the phased decisions.

According to the National Research Council (NRC, 2013), "limitations of currently available remedial technologies … make achievement of MCLs throughout the aquifer unlikely at most complex groundwater sites in a time frame of 50-100 years." The Interstate Technology and Regulatory Council (ITRC, 2004) further notes that "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…. At some sites, complex site-specific conditions make it difficult to fully remediate environmental contamination using proven remediation approaches." The ITRC guidance lays out a recommended process for identifying complex sites and then for remediation management, termed "adaptive site management." Adaptive site management is useful for sites with significant uncertainty. This approach allows for advancing the remediation despite uncertainties, by using an iterative process that includes

periodic evaluations, by updating and refining the conceptual site model over time, setting and tracking interim objectives, and implementing new technologies supporting ultimate objectives.

NRC (2013) provides information on identifying challenging remediation sites and determining if a site could benefit from applying the complex site framework. Specifically, the guidance documents define several factors, including geologic conditions, hydrogeologic conditions, geochemical conditions, contaminant related factors, scale, site remedial objectives, expected changes over time, overlapping responsibilities, institutional controls, land use, funding, and regulators/stakeholder concerns. Within each category, the guidance documents provide specific examples of the types of conditions that would result in determining if a site could/should be considered a complex site. Further, the documents indicate that if a site is considered positive for one or more of the categories, it is a candidate for management as a complex site benefiting from the adaptive iterative approach. This process has been applied to several DOE-EM sites such as the Los Alamos chromium plume.

Common Collateral Impacts of the Traditional Paradigm when Applied to Complex Sites
There are several adverse collateral effects that often result from applying the traditional linear "deterministic" management strategy versus a preplanned adaptive iterative management strategy. Importantly, the traditional strategy presumes that the process will result in a technology, or a portfolio of technologies, that will achieve the final remedial action objectives. For the site owner, this can provide a sense of certainty -- "…if I follow this remedial plan, at the end I will be done…"; however, if the remediation underperforms and contingencies are needed, this initial perceived certainty can lead to assessments of failure, resistance to taking further action, and a desire to jump directly to technically impractical solutions. For the regulator and stakeholder, the paradigm that the selected technology (or technology portfolio) needs to have a high potential to successfully achieve final remedial objectives can lead to intractable requests for data and analysis and/or requirements to grossly overdesign remediation systems leading to higher costs and inefficiencies (e.g., using a source treatment for a dissolved plume or if pump-and-treat will effectively remediate a source zone). Finally, the traditional paradigm encourages a focus on filling in data gaps and resolving uncertainties prior to taking action; thus, the attention of both site staff and regulators is on what is not known, and less focus is put on what is known. While the traditional approach does provide a pathway for responding to contingencies, for example through ongoing-periodic "5 year" reviews, the composite collateral impacts of the traditional deterministic approach can impede progress on remediation.

Principal Benefits of Adaptive Management Paradigm
Managing complex sites relies on an iterative-adaptive paradigm that explicitly recognizes that it is difficult, or intractable, to generate advanced knowledge that is sufficient to provide a technically defensible basis for the final remediation decision, design, and implementation. The adaptive management strategy encourages a focus on what can be done now with the information that is known, what can be done now to stabilize the contamination, and what achievable interim objective can be set that will allow success for all parties. Technologies can be optimally implemented in a manner that is targeted in space, time, and goal. Finally, implementation of the technologies can, and should, be done in such a manner that the system response to each action provides meaningful data to help resolve uncertainties and inform the next stage of remediation decisions and design.

A key to the adaptive management strategy is that the stages of the remediation need to be planned to play out for timeframes that provide stability and certainty for the site owner, that provide data over

representative time scales for the particular site (often 5 to 10 years), and that allow time for additional data collection and follow-on technology decision evaluation and regulatory approvals. As described, the adaptive process requires trust and collaboration among all parties. The optimal collaboration requires the various parties to recognize the perspectives and risks of those across the table. For example, in this scenario, site owners are proceeding without the certainty of the total future scope and need, or regulators may need to provide space for nonstandard or innovative approaches. Ultimately, all parties are taking risks with the caveat that one or more actions could underperform. The potential benefit of the collaboration is significant with the potential to facilitate steady progress toward remedial objectives.

Typical Adaptive Management Phases and Actions

The phases and actions in the adaptive management paradigm are defined by clear-limited objectives. For example, a pump-and-treat system is often put in place to control or limit the spread of the plume. The system is designed to meet that objective and there is no attempt to fully remediate residual sources or fully remediate the plume to remedial objectives. The limited design objectives avoid overdesigning the pump-and-treat in an inefficient attempt to achieve goals that this system will not be able to meet (and a potential future assessment that the pump-and-treat was a failure). In the adaptive management paradigm, the pump-and-treat can be efficiently designed to meet an achievable objective, can be implemented quickly even with typical data gaps, can provide information to resolve data gaps, and can reduce the sense of urgency while allowing future tests of technology in or near the residual source areas. The pumping can also provide some mass removal and help resolve where residual subsurface sources are located. At other DOE sites, the protections provided by an initial pump-and-treat system in an adaptive management paradigm encouraged testing innovative technologies that would otherwise have been difficult to test because of the potential to spread contamination. The stages of an adaptive management paradigm are often focused on spatial zones in the subsurface but can also be focused on particular geochemical species or conditions, interfaces, flux boundaries, and/or areas for enhanced attenuation or passive/active interception.

Figure 10 exemplifies the spatial framework and some of the associated factors that inform adaptive management. This figure was originally developed in the early 1990s to communicate the approaches DOE was using to manage complex groundwater remediation at the Savannah River Site (SRS). Efficient and effective environmental cleanup requires matching the character of remediation and stabilization methods to the nature of the target zone of contamination, as the nature of the target zone evolves through the life of the remedial project. Figure 12 shows the different areas of a generalized contaminant plume, i.e., the disturbed zone, the impact zone, and the transitional zone, and describes the general characteristics of each zone. Thus, physical and chemical methods (e.g., trapping, immobilization, destruction, or isolation) that directly address the source contaminants are often appropriate for the disturbed zone during the remedial process. A variety of methods that include both active treatments (e.g., pump-and-treat or active bioremediation) and enhanced attenuation technologies (e.g., geochemical manipulation or reactive barriers) are often suitable for the primary contamination zone or impact zone. Various strategies based on natural attenuation processes may be applicable to the primary contamination zone and these passive methods are well suited to the transition or baseline portions of the plume. This spatial conceptual framework, based on matching technology attributes to site-specific conditions and needs, has proven to be effective in supporting environmental management decisions. Key factors in selecting rational and optimal remedies are captured in existing regulatory decision guidelines and include ability to implement, expected performance, uncertainties/risks, and costs for actions as they

apply to the various target zones. In addition to the traditional factors, emphasis is increasingly placed on sustainability and metrics for evaluating remedial actions and balancing benefits against the associated environmental burdens and collateral damages.
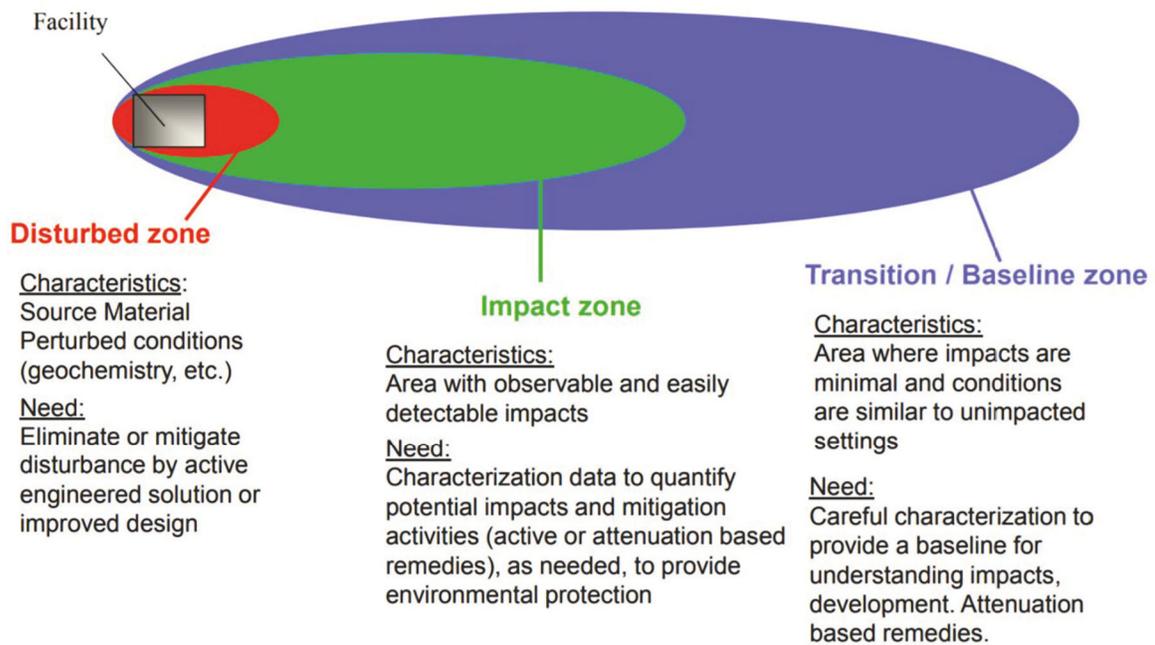
Figure 10. Simplified conceptualization of an example spatial framework at a contaminated groundwater site. At LANL, the >300m thick vadose zone would be added above the red oval and the complex geometry of the transport pathway emphasized.

## Appendix G: Enabling Technologies Case Studies

Artificial Intelligence and Machine Learning – F-Area Cost Savings Case Study

The current standard of monitoring at DOE-EM and DOE-LM sites is to sample monitoring wells at a predetermined frequency (e.g. quarterly, annuary) in accordance with appropriate regulatory bodies. Over 13,000 monitoring wells are estimated to exist in the DOE-EM complex with roughly 6,000 wells being actively monitored. The current method of well monitoring entails an individual, or more likely a team of individuals, manually taking groundwater samples, an event known as sampling campaigns, that can oftentimes have hundreds of wells to sample depending on site size. These samples are then sent to an offsite lab for analysis, where long turn-around times can be incurred. Based on the results received, certain actions will then take place as needed. This traditional process has multiple downsides including (1) increased risks to worker safety, (2) increased long-term costs, and (3) delayed data reception (the lab analysis takes a few days to weeks). It often fails to respond to changes in plume dynamics in a timely manner. A more proactive approach to monitoring is needed that minimizes both associated costs and data availability time frames.

The ALTEMIS project focuses on addressing these challenges and developing innovative solutions, using the SRS F-Area as a testbed. Current sampling at F-Area includes quarterly sampling of 87 wells, semi-annual sampling at 54 wells, an annual sampling of 99 wells (most of the annual and semi-annual sampling can be done during quarterly sampling). This results in a total of 356 sampling events. The approximate cost of sampling (worker effort and laboratory analysis) is $4,000 per sample. This totals $1.4M per year for sampling at just a subset of SRS.

The overarching goal of ALTEMIS is to integrate AI/ML, in situ sensors and regulatory interactions/discussion to support the reduction in sampling frequency and cost. ALTEMIS has identified leading in situ-measurable groundwater parameters that correlate with contaminant concentration changes. Monitoring these parameters with field-based sensors can then potentially be used in place of traditional sample collection-based techniques at the majority of groundwater monitoring wells. Not only is this cost effective, which will be explored in this report, but it will allow for real-time plume monitoring, which enhances the site oversight. Real-time plume monitoring offers a significant advantage in terms of timely feedback and ability to evaluate any necessary response or optimization actions.

In addition, new approaches are being developed to reduce the number of wells and well monitoring frequencies, using AI/ML techniques. The ALTEMIS team developed AI techniques to determine a set of wells to capture the heterogeneity of contamination concentrations and groundwater dynamics with a minimal number of wells. The results were then further refined using an algorithm to optimize the selection process (Figure 11). This resulted in a list of 20 wells, which were then used to install the sensor network at the F-Area.
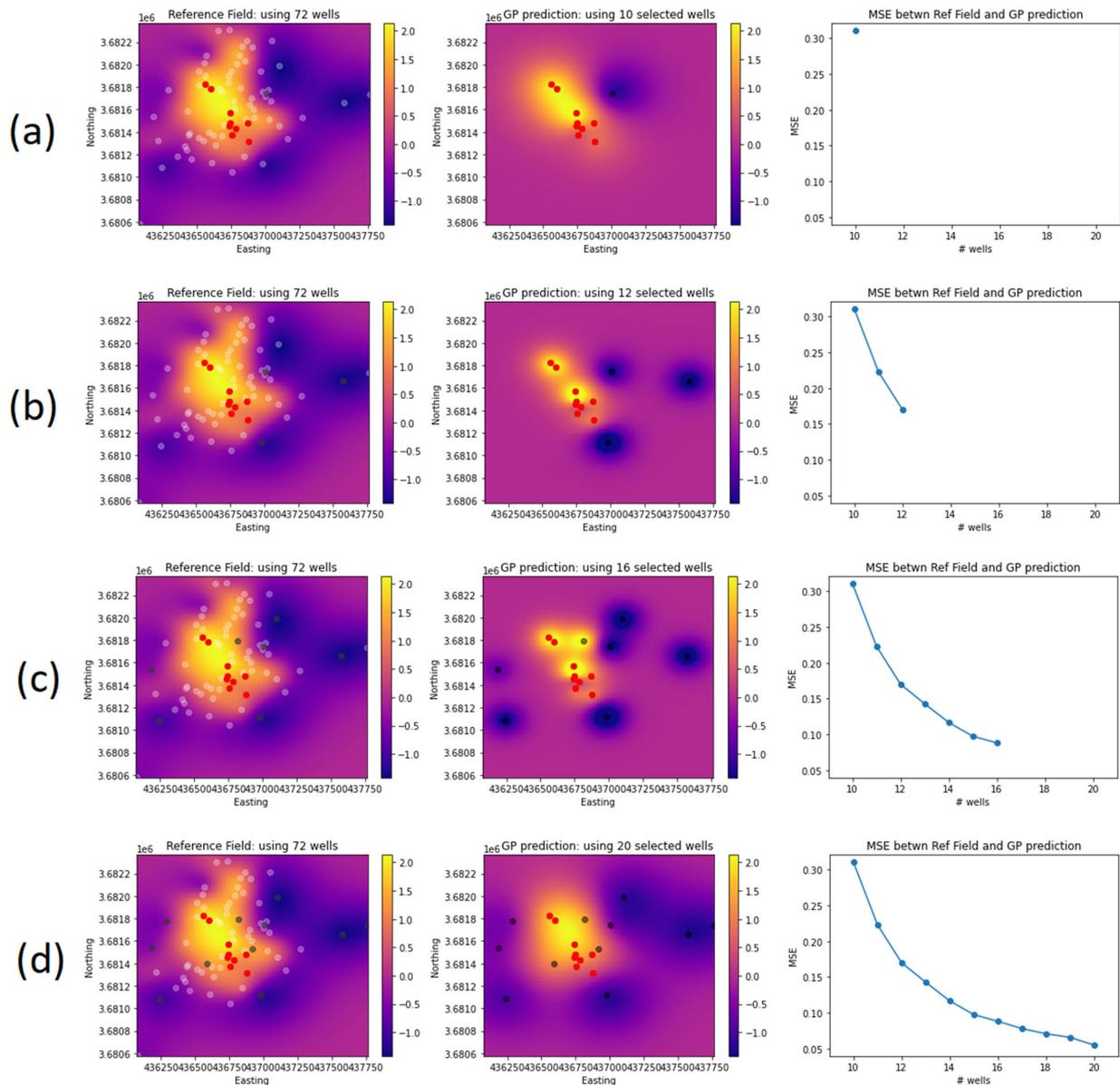
Figure 11. Well Reduction Algorithm Steps (performed by LBNL)

AquaTroll in situ sensors were then placed in 25 critical wells to monitor for controlling variables which have been identified as those which indicate plume variation in real time. The benefit of implementing in situ sensors is not only to reduce costs, but to also alert site personnel to plume changes as they happen, rather than 3 months in the future. This allows a more nuanced response if needed.

The current stage of fully implementing the ALTEMIS approach to F-Area is to inform South Carolina Department of Environmental Services (SCDES) of the technical basis for requesting a reduction in frequency of sampling. Two options are currently proposed, both include monitoring point of compliance, background, and plume assessment wells every two years. Option 1 includes monitoring the wells with the 25 in situ sensors manually every quarter and option 2 monitors the wells with in situ sensors semi-

annually. This would result in an annual cost for monitoring of $550K for option 1 and $300K for option 2. Compared to the current cost of $1.4M, this would reduce the cost of monitoring by 60% to 80% (Fabricatore, 2024).

The goal of this project was to use F-Area as a testbed and expand to other sites. Currently, the Moab Site is undergoing the same AI/ML process to identify the optimal wells for monitoring and install in situ sensors similar to the success had at F-Area. It would be advantageous to reduce the cost of monitoring by 60%-80% by streamlining this process and making it more autonomous for expanding throughout the DOE-EM complex. Sensors cost less than $1K and serve as a cost-effective system for autonomous monitoring.

Geophysical Tools – ERT Case Study

Engineered multi-layer covers (i.e., caps and barriers) are utilized at numerous sites within the Department of Energy complex to prevent or control downward transport of contaminants through unsaturated soils. Multi-layer covers reduce infiltration, thus decreasing contaminant flux to the water table and downgradient biological receptors. Long-term monitoring is necessary to ensure that the covers provide the intended protection of human health and the environment. However, the spatial and temporal scales required to comprehensively assess barrier performance pose technical and financial challenges to conventional point-based sampling and/or non-automated monitoring. Electrical resistivity tomography has been demonstrated as a strategy to address these challenges by providing remote, autonomous, and spatially comprehensive long-term monitoring of cover performance (Johnson et al., 2022).

Under ALTEMIS, ERT is being evaluated as a remote, autonomous monitoring tool for barrier integrity. To this end, an ERT array was installed in August of 2022 (Figure 12). The ERT array comprises a total of 128 electrodes on a 5 m × 5 m grid. The electrodes were buried in shallow (~15-cm-deep) trenches to protect electrodes from disturbance. Materials above the cap include a drainage layer of (coarse-grained) sand, common fill, and topsoil. Materials below the cap include contaminated landfill waste overlain by foundation materials.

The ERT array autonomously monitors changes in bulk electrical conductivity (BEC) beneath the clay cap to detect diagnostic indications of cap failure. Decreases and increases in water content beneath the cap will cause decreases and increases in BEC. The location and timing of increases in BEC beneath the cap are diagnostic of when and where the cap has allowed moisture to pass into the waste zone. Because there are no other processes expected to cause changes in BEC beneath the cap, increases in BEC provide a unique metric for diagnosing cap failure. Apart from downtime resulting from equipment issues, the ERT system runs autonomously, collecting ERT surveys every six hours (with the capability to collect hourly surveys). ERT survey data are autonomously transferred to offsite computing resources where they are filtered, processed to produce ERT images, and archived for inspection.
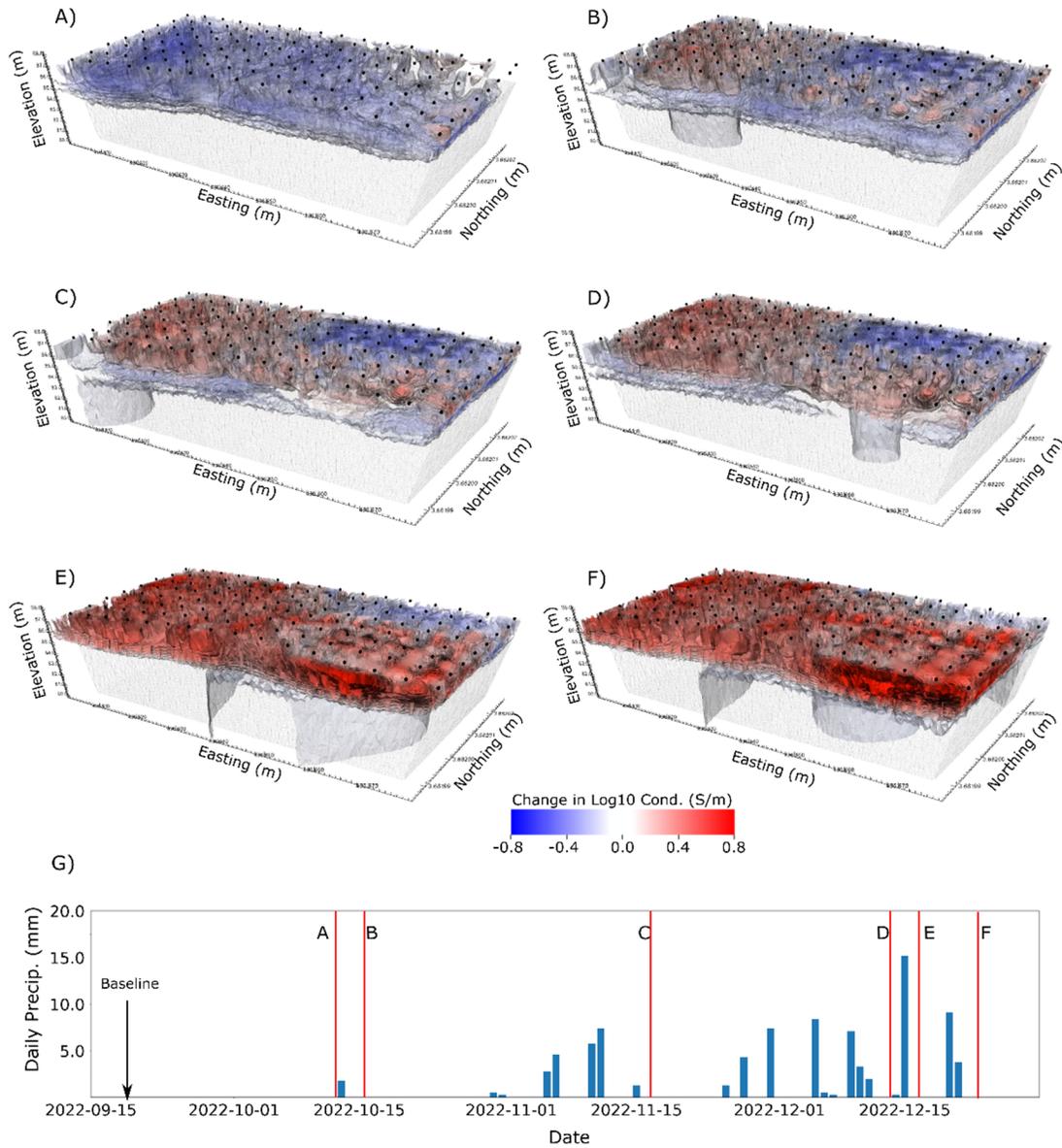
Figure 12. A-F) ERT-derived 3D changes in bulk conductivity with the F-Area Basin 3 landfill cover, from baseline conditions on Sept. 27ᵗʰ, 2022.

Decreases and increases in bulk conductivity are caused by corresponding decreases and increase in water content, driven primarily by precipitation events (G), or a lack thereof. For example, A) shows a consistent decrease in bulk conductivity (water content) above the landfill's clay boundary layer after sustained dry period. Conversely, F) shows a consistent increase in bulk conductivity above the clay boundary layer after a series of large precipitation events. Increase in bulk conductivity does not occur beneath the clay boundary layer, suggesting that moisture is not penetrating the boundary, and the cap is operating as designed.

Modeling – Performance-Based Management of Hanford 200 West Pump-and-treat Case Study

Pump-and-treat systems are among the most commonly used methods for the hydraulic containment and treatment of contaminated groundwater. While P&T operations can be effective for groundwater remediation, maintaining their performance over time poses significant challenges at many sites due to site complexities such as heterogeneous geology, large capture zones requiring multiple pore volume flushes, the presence of source zones, diffusion-limited mass transfer, co-located and/or recalcitrant contaminants, or dispersed contaminant distributions (NRC, 2013). Furthermore, at many contaminated sites using P&T, short-term response actions at the startup are typically based on limited understanding of system performance and focus on mitigating immediate risks. As a result, the initial design of P&T systems is often focused on large-scale containment and bulk treatment rather than on an optimized system to maximize contaminant removal for the purpose of achieving a certain end state in fastest cleanup timeframe. This initial focus may contribute to plume persistence and limited effectiveness of the P&T systems as the remedy progresses.

Performance-based optimization and/or management of P&T remedies is a critical strategy for maintaining the effectiveness of contaminant removal throughout the remedy's lifetime and managing systems toward a specific end-state for site completion or remedy transition (Figure 13) (ITRC, 2023).

The 200 West P&T system is the primary selected groundwater remedy for treating multiple, co-mingled plumes and contaminants in the Central Plateau of the Hanford Site (Figure 14). This region is characterized by shallow source zones, persistent deep vadose zone contamination, large-scale and co-mingled groundwater plumes, and considerable subsurface heterogeneity (Demirkanli & Freedman, 2021). Therefore, it illustrates both the challenges and opportunities associated with managing large-scale, long-term P&T systems.

The 200 West P&T system, operational since 2012, was installed to address large plumes of carbon tetrachloride, technetium-99, uranium, nitrate, and other contaminants. With the initial design treatment capacity of approximately 2,500 gallons per minute (gpm) and current increased capacity of 3,400 gpm and more than 70 extraction and injection wells, it is one of the largest P&T systems in the DOE complex.

Since its initiation, the system has successfully maintained hydraulic containment and removed significant contaminant mass. Annual evaluations indicate that system-wide flow rates and mass recovery have generally met the design target (DOE/RL-2008-78, 2009). However, challenges remain for meeting cleanup goals within the regulatorily determined timeframes, potentially requiring longer operational timeframes.

A comprehensive remedy optimization study was designed and initiated in 2019 and currently ongoing to address some of the technical challenges associated with the remedy for achieving the remedial action objectives (RAOs) for carbon tetrachloride (DOE, 2019c). Some of these challenges include more contaminant mass in the aquifer than what was estimated during the feasibility study and new degradation rates for carbon tetrachloride that are an order of magnitude slower than those estimated previously. The primary objectives of the optimization study include (1) increasing the treatment capacity for carbon tetrachloride, (2) evaluating transition to monitored natural attenuation for nitrate consistent with RAOs, and (3) ensuring that any modified remedy configuration will also achieve the cleanup goals for all other contaminants.

A performance-based optimization framework for maintaining the effectiveness of the P&T remedy and achieving cost efficiency throughout its lifetime has been developed and implemented into a computational tool, OPTIMA (Optimization for Pump-and-Treat Implementations: Management & Assessment) (Figure 15). The tool consists of three fully coupled components: (1) optimization setup, allowing users to select optimization objectives (e.g., mass recovery targets), end-state criteria (e.g., cleanup concentrations), and other constraints (e.g., total capacity); (2) evolutionary algorithm, being used for evaluations of thousands of injection/extraction strategies; and (3) fate and transport or deep-learning models, for simulation of dynamic subsurface responses.

Applied to the carbon tetrachloride plume in the Central Plateau, this performance-based optimization tool demonstrated that, with the aid of computational approaches, it is possible to accelerate the cleanup and minimize the active pumping timeframes to achieve certain end-states with dynamic management of the P&T total capacity and more importantly the injection and extraction well network, ultimately providing significant reductions in the total cost of the remedy lifecycle (Song, et al., 2025). These evaluations also presented the power of scenario-based assessments for developing the site-specific management strategies for P&T remedies; for example, determining the appropriate optimization goals, such as maximizing contaminant mass removal or minimizing active pumping timeframe, or conducting multi-objective optimization evaluations (e.g., minimizing active pumping timeframe and maintaining aquifer water levels/pumping capacity) found to be critically important for acceleration strategies.
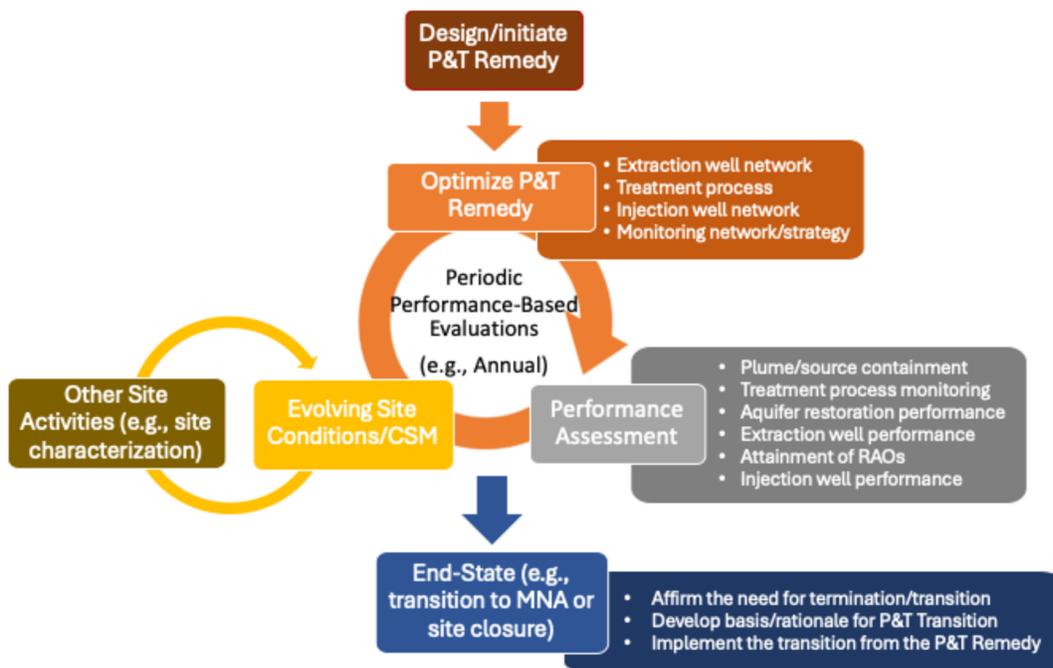

Figure 13. Schematic representation of performance-based management of P&T remedies (ITRC, 2023).
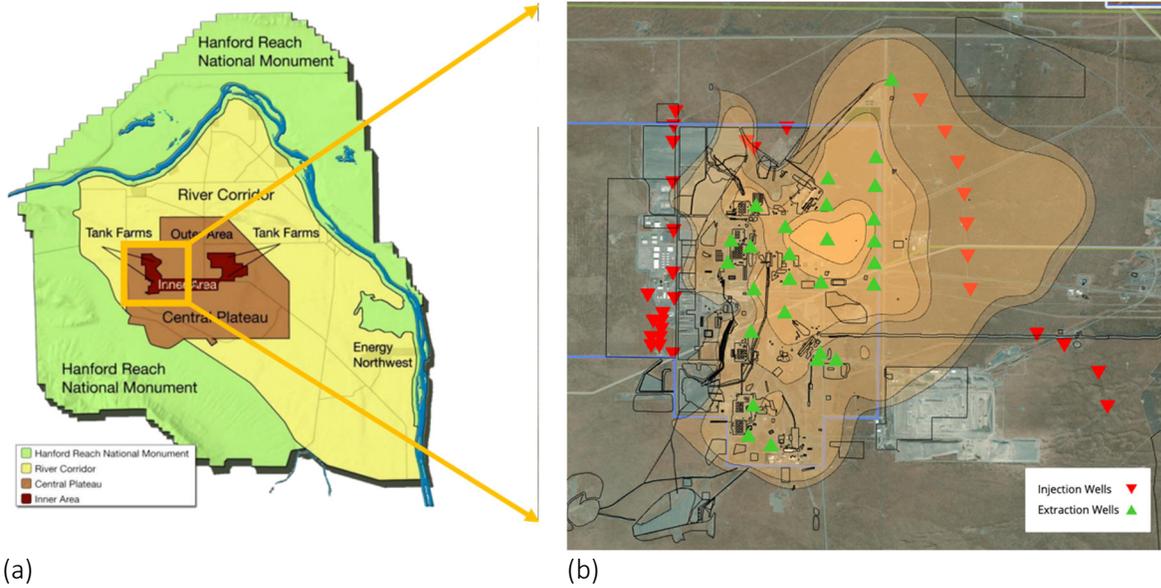
Figure 14. (a) Hanford Site Central Plateau and 200 West Area location, and (b) Carbon tetrachloride plume distribution and the 200 West P&T well network in 2023.
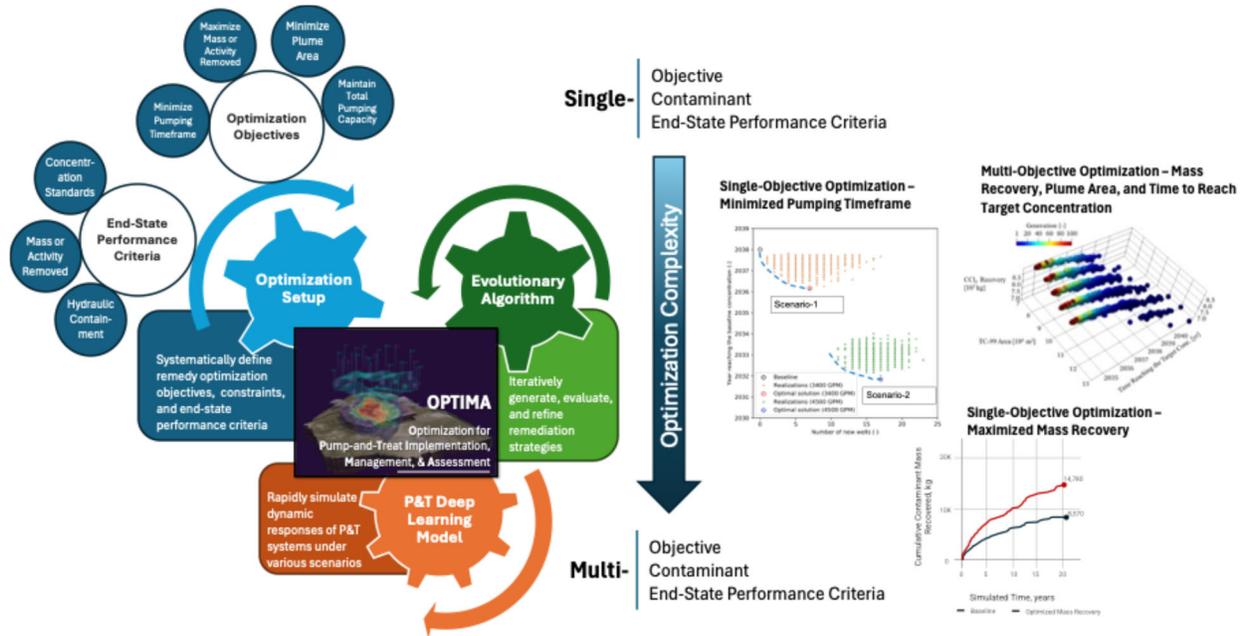

Figure 15. Performance-based P&T optimization tool framework

Appendix H: Recommendations Expanded

Mission and End State Accelerators

MESA-1: Strategic Applications of AI/ML for Complex-wide Groundwater Monitoring Optimization

Groundwater monitoring optimization has tremendous potential to reduce monitoring costs by identifying key wells and/or defining the minimum-but-sufficient number of wells. Comprehensive and strategic monitoring optimization across the DOE-EM complexes will have a tremendous opportunity to transfer lessons learned and effective strategies. In addition to the existing algorithms, further advancements can be made by adopting the state-of-the-art AI and ML methods.

The site survey has reported the challenges associated with a lack of monitoring points and coverage, particularly accounting for deep subsurface, specific landcover types and strategic areas (Moab, Oak Ridge). In addition, several sites reported the difficulty of effectively reducing monitoring requirements (Hanford), strategically replacing wells (INL) and defining additional wells for filling gaps (Oak Ridge).

There have been monitoring optimization algorithms developed for groundwater monitoring (e.g., Meray et al., 2022; Siddiquee et al., 2024). In parallel, the complex-wide understanding of groundwater plumes and databases are being developed such as PNNL's TRAC database. Given the advancement in AI, there are tremendous opportunities to improve algorithms. Further, there is an opportunity to standardize monitoring optimization across the sites such that effective strategies can be transferred across the sites.

Previous funding for piloting has been received, and work has been done through the ALTEMIS project.

Relevant Technical Targets: next generation modeling, improving the technical basis for environmental stewardship management, methods to verify and validate performance

Recommended sites: **Hanford**, INL, Moab, Oak Ridge

Recommended by: Haruko Wainwright, MIT

Enhanced Attenuation: MESA-2, MESA-3, MESA-4, TDE-1

EA is an intermediate type of action that serves as a bridge between active treatments (like pump-and-treat, in situ destruction/detoxification, and/or bulk removal actions) and MNA (which by rule can have no human intervention). DOE facilitated national development of the EA paradigm – including working with ITRC in developing technical and regulatory guidance for EA of chlorinated organic contaminants. EA applications have been highly successful and extension of the paradigm to other contaminant classes would provide significant benefits in accelerating and improving the performance of the DOE-EM soil and groundwater remediation activities. Further, several related DOE technology concepts – such as the hydroxyapatite treatments for uranium – could be designed and performed using an EA strategy and this might aid in regulatory and stakeholder acceptance. This is a strategy that is potentially transformational for the DOE-EM program.

The presents an opportunity to overcome barriers to transition sites to passive remedies and end states.

Significant historical funding for possible/contributing remediation technologies such as bioremediation and in situ geochemical stabilization. Some seed funding exists at Moab and other sites for regulatory strategy development.

MESA-2: EA – Bioremediation

Bioremediation offers a suite of promising opportunities for restoring contaminated sites using natural or engineered biological processes. Key opportunities and approaches include:

Table 16. Examples of Key Opportunities and Approaches for Bioremediation throughout the DOE-EM Complex

Strategy	Mechanism	Applications	Example EM Sites Where Strategies Can Be Deployed	TRL	ARL
Microbial Bioremediation via bioaugmentation and/or biostimulation	Use of native or introduced microbes to degrade or transform contaminants	Petroleum hydrocarbons, chlorinated solvents, heavy metals, PCBs	**Hanford:** Reductive dechlorination of carbon tetrachloride **Portsmouth:** Bioaugmentation for TCE **SRS:** Bioreduction of VOCs, uranium, and metals using acetate-stimulated microbes	8-9	8-9
Phytoremediation	Use of plants to extract, degrade, or stabilize pollutants	Metals (Pb, Cd, Zn), radionuclides, organics (TNT, PAHs)	**ORNL**: native plants stabilized PCBs in contaminated sediments	6-8	7-8
Constructed Wetlands	Engineered ecosystems that support microbial and plant-based treatment	Acid mine drainage, nutrient-rich runoff, VOCs, trace metals	**Moab:** ammonium remediation near Colorado River	8-9	9
Mycoremediation	Use of fungi to break down organic contaminants or absorb metals	PAHs, PCBs, heavy metals	Should be considered for incorporation where microbial bioremediation is deployed	3-5	2-4
Rhizoremediation	Plant root zone (rhizosphere) enhancement of microbial degradation	Hydrocarbons, pesticides, nitrates	**SRS**: A/M-Area plume near Tims Branch	5-6	5-6
Synthetic biology	Genetically engineered microbes for enhanced (microbial) degradation (and monitoring)	Chlorinated solvents, heavy metals, organics (PAH's PCBs), dioxins, hydrocarbons	Future research opportunity for emerging contaminants (e.g., per- and polyfluoroalkyl substances (PFAS))	3-5	2-3

Additionally, synthetic biology represents one of the most innovative and rapidly evolving frontiers in bioremediation. Genetically modified microbes that are designed to express or enhance specific traits such as degradation enzymes, metal-binding proteins, or stress tolerance may offer enhanced capabilities for degrading, transforming, or immobilizing contaminants that natural microbes may not handle efficiently. The ARL of genetically modified microbes may be low because of risks of horizontal gene transfer or unintended environmental consequences but this technology may be suitable for closed environments (e.g. bioreactors) or reactive barriers. Genetically modified microbes could be combined with biosensors to not only remediate contaminants but also report contamination levels in real-time (e.g., fluorescence or electrochemical signals).

Relevant Technical Targets: overcoming challenges to achieving end states, improving the technical basis for environmental stewardship management, effective and sustainable solutions for plumes

Recommended sites: **Paducah, SRS**, Hanford, INL, Moab

Recommended by: Teresa Mathews, ORNL

MESA-3: EA – In Situ Geochemical Remediation

In-situ geochemical remediation technologies are environmental cleanup methods that treat contaminated soil or groundwater directly in place (i.e., without excavation or extraction) for source or plume control. These technologies use chemical amendments to enhance natural processes to immobilize, transform, or degrade contaminants into less toxic or less mobile forms.

They are widely used for a variety of contaminants, including heavy metals, radionuclides, and chlorinated solvents. They typically involve reductive strategies for redox sensitive contaminants such as technetium-99, uranium, or chromium, while followed by a mineral precipitation step, through injection of amendments like phosphate-based solutions (e.g., apatite), to ensure long-term stabilization. The amendments could be in gas form for some direct vadose zone treatment, or particulate and liquid forms for saturated zone treatments. The subsurface application approaches may involve direct injection into plume and/or use of these amendments in a reactive barrier form for the saturated zone treatments.

Important benefits of these technologies include cost-effectiveness, especially for large groundwater plumes and long-term stabilization of source reducing impacts to groundwater—reducing the timeframes of groundwater remedies. However, they also require significant site characterization, effective amendment delivery approaches, and long-term monitoring to ensure effectiveness.

See TB&D-2 for examples of successes throughout the DOE complexes and recommendation for integration into a testbed.

Relevant Technical Targets: overcoming challenges to achieving end states, improving the technical basis for environmental stewardship management, effective and sustainable solutions for plumes

Recommended sites: **Moab, Hanford**, SRS

Recommended by: Inci Demirkanli, PNNL

MESA-4: EA – Constructed Wetlands and Hyporheic Zones

Constructed wetlands and use of hyporheic zones are essential in enhanced remediation as they use the ecology in wetlands (bacteria, fungi, and plants) to degrade or otherwise decrease the risks of contaminants and to decrease the source mass flux to streams and other receptors. In particular, setting up constructed wetlands and hyporheic zones improve water quality by filtering and removing pollutants (heavy metals and nutrients) through natural processes by using plants, soil, and microbial communities to filter and purify water. In addition to water quality improvements, constructed wetlands support biodiversity, promote the cycling of nutrients and other materials, and enhance carbon sequestration. The treatment of contaminated water can be a low-case and low-energy process and does not require significant oversight once implemented.

Relevant Technical Targets: overcoming challenges to achieving end states, improving the technical basis for environmental stewardship management, effective and sustainable solutions for plumes

Recommended sites: **Moab,** Hanford, SRS

Recommended by: Brian Looney, SRNL

MESA-5: Expanding the Applications of Passive In Situ Sensors for Difficult-to-Access Regions
The enhanced uses of sensor-based passive monitoring (such as specific conductance, pH) are important across the DOE-EM site complex; particularly for sites/wells at which pumping is difficult. Sensor-based monitoring reduces the need and frequency of expensive pumping-based groundwater monitoring.

The site survey has reported the difficulty of deep groundwater monitoring due to sampling/pumping issues (NNSS). More powerful pumps are needed for operating at greater depths, particularly for larger diameter wells. In addition, it is logistically difficult and expensive to purge wells prior to sampling. At the same time, the SRS F-Area site monitoring study has indicated that pumping/sampling-based monitoring is prone to errors and outliers, since the pumping/sampling locations could change from time to time and the concentration could be stratified across the depth.

Recently, there have been rapid advances in in situ sensors for groundwater such as temperature, water table, pH, dissolved oxygen and electrical conductivity, which are often proxies for contaminant concentrations or mobility changes (Schmidt et al., 2018; Meray et al., 2022). Many sensors are commercially available at a relatively low cost of several hundred dollars per sensor. There are also more sophisticated sensors under development such as optical sensors for nitrate and organic matter. These sensors are typically placed inside wells to monitor groundwater or surface water continuously without any active pumping requirements. In addition, such wireless sensor networks can monitor dozens or hundreds of sensors and characterize spatially heterogeneous properties. Such a passive sensor-based monitoring is considered particularly powerful for the sites that have a strong gradient in groundwater geochemical conditions (e.g., salinity, pH, dissolved oxygen) such as the Moab, SRS, and other sites located in riparian zones adjacent to rivers.

In parallel to the sensor installation, associated AI/ML algorithms are important for anomaly detection and spatiotemporal interpolations. The site survey has noted that data anomalies are still flagged and corrected (if possible) manually, and that more automated and effective approaches are necessary.

Previous funding for piloting has been received, and work has been done through the ALTEMIS project.

Relevant Technical Targets: next generation modeling, improving the technical basis for environmental stewardship management, methods to verify and validate performance

Recommended sites: **INL**, Hanford, LANL, NNSS

Recommended by: Haruko Wainwright, MIT

MESA-6: AI-Guided Real-Time In Situ Monitoring: Actionable Information on Shifting Hydrological Conditions

Combining in situ real-time water table monitoring coupled with various AI/ML algorithms, such as anomaly detection, and improved spatiotemporal interpolation algorithms would substantially enhance the understanding of hydrological conditions in the subsurface. The combined approach will also facilitate estimation of associated metrics such as hydraulic gradients, groundwater fluxes, plume speed/direction, and the stability of residual contaminants.

The site survey has reported the challenge associated with shifting water tables and hydrological conditions at multiple sites, particularly the Hanford Site and INL. In addition, in situ water table monitoring was useful at the LANL site, understanding the contaminant plume direction and its change associated with the pump-and-treat system. In parallel, over the past decades, there have been emerging concerns associated with changing hydrological conditions.

At the US Department of Energy (DOE)'s Mound site, for example, dewatering activities at the adjacent construction site impacted the aquifer, causing a change in the groundwater table and a shift in the plume direction. At several uranium mill tailing sites (e.g., Canonsburg), river stage fluctuations adjacent to the sites have caused significant seasonal groundwater dynamics, surface flooding, and often increases in contaminant concentrations in the groundwater. However, temporally sparse data often make it difficult to detect such changes immediately and to analyze concentration data anomalies (e.g., outliers or not). Furthermore, extreme precipitation, droughts, and hydrological shifts associated with climate change are expected to impact residual contaminants, which are increasingly recognized as a potential risk (e.g., Libera et al., 2019; Xu et al., 2022). At the same time, there are additional pieces of information we can extract from the groundwater table measurements including the groundwater gradient, fluxes, contaminant plume directions and speed. To pilot the development of an AI/ML-based model, the model should be trained on data from a well characterized site. Once trained the model can be applied to sites where sparse data and anomalies need to be addressed.

Previous funding for piloting has been received, and work has been done through the ALTEMIS project.

Relevant Technical Targets: next generation modeling, improving the technical basis for environmental stewardship management, methods to verify and validate performance

Recommended sites: **Hanford** and **INL**

Recommended by: Haruko Wainwright, MIT

Technology and Data Enhancers

TDE-1: EA: Artificially Lithified Native Soils as Capping Material for Uranium Mill Tailings

Lithified Technologies, LLC. (a small business located in Santa Fe in New Mexico) has spent several years working with LANL scientists to develop their Rad-Barrier Capping System, based on lessons learned from developing formulations used in road construction. Their technology utilizes an accelerated lithification

process to turn road base materials and native soils into a structural pavement core. Recognizing that a capping material for uranium daughter bearing waste must: 1) resist erosion and the distribution of particles by wind, 2) control water infiltration to prevent the mobilization of soluble radionuclides by rain/groundwater, and 3) prevent significant emanation of radon gas, the artificially lithified material is potentially an ideal material for the capping and closure of sites contaminated with uranium mine waste or mill tailings. The primary advantage of this material is the possibility of reducing capping barrier thickness by significant amounts if the performance of the material can be demonstrated.

Radon diffusion measurements and preliminary hydrologic modeling exercises are funded through the New Mexico Small Business Assistance program.

Relevant Technical Targets: overcoming challenges to achieving end states, improving the technical basis for environmental stewardship management

Recommended site: **Moab**

Recommended by: Phil Stauffer, LANL

TDE-2: Fractured Rock Characterization

At several DOE sites, including Hanford, LANL, and INL groundwater contamination occurs in fractured geologic media. Characterizing these fractured rock systems is essential for building accurate multi-scale conceptual models of groundwater flow and contaminant transport, and for designing effective remediation strategies. Unlike porous media, fractured rock presents unique challenges due to its dual-porosity nature: fast advective transport occurs through connected fracture networks, while slower diffusion and retention occur in the surrounding rock matrix.

Fracture Characterization - Multi-Scale and Multi-Process: Fracture flow and transport must be conceptualized across multiple spatial scales—from micro-scale fracture apertures to site-wide structural features—and time scales ranging from minutes (in tracer tests) to decades (in long-term monitoring). At LANL, for example, high explosives such as RDX have been observed to migrate through volcanic tuff fractures, with diffusion into the rock matrix leading to long-term persistence even as fracture water concentrations decline. Similarly, at INL, basalt flows interbedded with sediments require detailed fracture and matrix characterization to assess contaminant migration through vertical and lateral pathways. Matrix diffusion plays a dominant role in contaminant attenuation and long-term plume behavior in fractured systems. It serves as both a sink—retarding contaminant movement—and a long-term source—slowly releasing previously absorbed mass. At Hanford, this dual role is critical for understanding the persistence of contaminants like uranium and technetium-99 in the vadose and saturated zones.

Modeling Fractured Systems - Tools and Applications: A wide range of models has been developed to simulate fractured rock systems, from simplified dual-porosity analytical solutions to sophisticated 3D DFN models. At LANL's Technical Area 16, for instance, both flow and transport were modeled using coupled fracture-matrix approaches calibrated against tracer tests and geophysical surveys. These models account for advection in fractures, matrix diffusion, and sorption, providing a robust framework for risk assessment and remedy evaluation.

Lessons and Benefits from Other DOE Sites: It is fortuitous that EM activities at the Nevada National Security Site (NNSS) and within the Yucca Mountain Project can serve as a natural laboratory for fracture

flow and transport studies. At the NNSS, field-scale tracer tests and integrated fracture-matrix modeling have enabled model-based predictions of groundwater flow and radionuclide contaminant migration in saturated and unsaturated volcanic tuffs and alluvial formations in model domains spanning 10s of kilometers in length. These efforts have demonstrated the utility of characterizing fracture connectivity and matrix properties for evaluating contaminant fate and developing defensible long-term monitoring strategies. Similarly, the Yucca Mountain Project produced one of the most comprehensive datasets on fracture flow and matrix interaction in tuffaceous units. This work led to improved understanding of episodic flow, fracture-matrix exchange, and scaling behaviors that are directly applicable to other DOE sites with volcanic or layered fractured media. In fractured rock, for example, water and contaminants move rapidly and unevenly through variably-connected, low porosity fracture networks, often bypassing much of the rock, while in unconsolidated porous media, flow and transport occur more uniformly through all the rock in smaller, well-connected pore networks. Additionally, fractured rocks exhibit significant matrix diffusion, causing contaminants to be stored and slowly released from the rock matrix, often as a delayed source term, making prediction and modeling more complex compared to unconsolidated media.

In summary, fractured rock characterization is essential for accurate conceptual site characterization, model development, and long-term management of contaminated groundwater at complex DOE sites. Understanding matrix diffusion, fracture-matrix interactions, and multi-scale transport is key to predicting plume evolution and designing sustainable remediation strategies. Leveraging advanced modeling tools and lessons from other sites, notably NNSS and Yucca Mountain, can improve outcomes across the DOE complex.

Relevant Technical Targets: strongly heterogeneous systems, next generation characterization technologies (tools), methods to verify and validate performance, overcoming challenges to achieving end states

Recommended sites: **INL**, Hanford, NNSS

Recommended by: Andy Tompson, LLNL

TDE-3: Targeted Temporal Characterization for Refining Site Behavior and Long-Term Regulatory Compliance

Increased temporal sampling is critically important for groundwater characterization activities at many contaminated sites operated by the U.S. Department of Energy Office of Environmental Management (DOE-EM) due to the dynamic nature of contaminant plumes and hydrogeological conditions. This is especially the case for those DOE-EM sites adjoining or proximal to inland waterways where dynamic hydrologic changes (e.g. large excursions in stream discharge and/or groundwater levels) occur both seasonally and episodically. Traditional, infrequent sampling activities for site wide characterization provide only limited temporal information, potentially missing crucial information about contaminant fluctuations, the arrival of new contaminant fronts associated with intermittent hydrologic connectivity, or the impact of seasonal variations on groundwater flow and contaminant transport. Incorporation of limited-but-targeted increased temporal sampling for site characterization allows for the observation of transient events, provides a more accurate representation of contaminant concentrations over time, and enables a better understanding of the processes controlling plume migration and attenuation. This improved temporal resolution is essential for developing more robust conceptual site models, optimizing

remediation strategies, and making more informed decisions regarding long-term stewardship and risk management at these complex and often challenging sites.

Important considerations regarding this technology include:

Dynamic Conceptual Site Model Development and Re-Assessment: Existing conceptual site models and/or flow and transport models should be used to identify locations where increased temporal sampling as part of characterization activities is most likely to address gaps in the long-term understanding of contaminant behavior and the extent to which dynamic hydrologic events may impact attenuation (both natural and enhanced) and regulatory compliance. Increased temporal sampling for characterization is distinct from long-term monitoring activities, which are already in place at most/all DOE-EM sites. Rather, this technology idea or concept is focused on ensuring that long-term approaches to attenuation and regulatory compliance honor dynamic changes in coupled contaminant-hydrologic behavior. Coupling targeted temporal sampling to characterization efforts also provides a mechanism for re-assessing and refining existing CSMs that rely on limited (or no) temporal characterization data.

Refining long-term monitoring activities: Incorporation of targeted temporal sampling activities at DOE-EM sites where existing (or needed) conceptual site models are failing to account for observed system behavior is valuable beyond simply improving a given CSM. Rather, targeted characterization efforts are invaluable for guiding long-term monitoring strategies that are informed by identified temporally dynamic processes, such as surface water-groundwater interactions, temporally variable changes in vadose zone thickness, etc.

Addressing regulatory compliance: Temporally-appropriate characterization approaches are integral to DOE's forward-looking remediation strategies, including natural and enhanced attenuation, and central to addressing long-term regulatory compliance issues including the development of viable, site-appropriate groundwater compliance action plans, where applicable.

Targeted Temporal sampling is potentially relevant to needs at Hanford, Moab, Savannah River, and Paducah sites. It is also relevant for monitoring and remedial design optimization, conceptual site model refinement, uncertainty quantification, and stakeholder engagement and risk communication.

Relevant Technical Targets: next generation characterization technologies (tools), methods to verify and validate performance

Recommended sites: **Moab**, Hanford, Paducah, SRS

Recommended by: Ken Williams, LBNL

TDE-4: Vadose Zone Characterization

The vadose zone, the unsaturated region between the land surface and the water table—plays a critical role in the transport and fate of contaminants at DOE sites. Characterizing this zone is essential for identifying residual contaminant sources, understanding migration pathways, and informing remediation strategies. This is especially important at western sites with deeper vadose zones (extending >100 meters), such as Hanford, LANL, and INL, where complex geologic and hydrologic conditions drive long-term risk.

Primary Source Identification: At many DOE sites, historical operations left contaminant sources in the vadose zone that continue to leach into groundwater. At Hanford, for instance, inventories of uranium,

technetium-99, and nitrate exist in the deep vadose zone that remain a long-term source to the saturated zone. In shallow systems, such as those near wetlands at the Savannah River Site (SRS), sources are more accessible and remediation approaches like excavation or capping have proven effective.

Transport Pathways in Heterogeneous Systems: Heterogeneity—caused by variations in soil texture, stratigraphy, and fractures—controls contaminant migration. In deep vadose zones like those at Hanford's Central Plateau or INL's basalt flows, preferential flow through fractures or high-permeability layers can result in rapid, localized contaminant transport, bypassing attenuation zones and challenging traditional plume management assumptions. In contrast, shallow systems dominated by finer-grained sediments may exhibit more predictable, diffuse transport.

Time and Scale of Contaminant Migration: Deep vadose zones introduce a temporal disconnect between release and groundwater impact: contaminants may take decades to centuries to reach groundwater, as seen at LANL where high explosives such as RDX have migrated slowly through fractured volcanic tuffs. Shallow systems often present more immediate risks and shorter feedback loops for remediation performance evaluation.

Monitoring and Remediation Challenges: Deep vadose zones are inherently more difficult and expensive to monitor and treat. Installing boreholes to depths of 100 meters or more is costly and spatially limited, leading to gaps in data and increased reliance on indirect methods like geophysics or tracer tests. At INL, this complexity is exacerbated by the interbedding of basalt and sediment layers, which require integrated monitoring systems to track potential fast pathways. In contrast, shallow systems allow for denser monitoring networks and wider use of in situ sensors and real-time monitoring technologies.

Persistent Sources and Long-Term Stewardship: Deep vadose zones often contain persistent contaminant sources that can act as "secondary plumes," slowly recharging groundwater for decades. This long-term risk has been recognized in DOE's Technical Targets document, which emphasize the need for tools to verify and validate residual source behavior in the vadose zone, especially in areas where source removal is impractical.

DOE's Technical Targets and complex-wide groundwater closure strategy emphasize "Controlling Contaminants in the Vadose Zone" and "Next Generation Characterization and Monitoring Tools" as essential investment areas. Understanding deep vadose zone behavior is especially critical for informing end-state visions, risk assessments, and sustainable remediation strategies. Coupling vadose zone and groundwater monitoring, improving fracture flow models, and deploying high-resolution geophysical tools are among the recommended approaches for deep systems.

Four particular relevant sites include:

(1) Hanford: The vadose zone beneath the Central Plateau is over 100 meters thick in some areas, and waste releases from tanks and cribs have led to extensive contamination of this zone. Deep vadose zone transport through fractured and stratified sediments continues to pose a threat to groundwater and the Columbia River. Characterization and modeling efforts are ongoing to refine source terms and prioritize targeted remediation.

(2) LANL: RDX and other high explosives have migrated through fractured volcanic tuff beneath Technical Area 16, with transport potentially spanning decades. The deep vadose zone and its complex geochemistry and fracture flow regimes necessitate detailed modeling and tracer tests. Biogeochemical

conditions in the deep vadose zone may also limit natural attenuation, making characterization essential for understanding long-term risks.

(3) INL: Characterization of the deep vadose zone is critical due to the site's thick unsaturated basalt layers and interbedded sediments, which complicate transport prediction. Past disposal at surface pits and injection wells has left legacy contaminants, including radionuclides and solvents, that require long-term monitoring and modeling to assess their mobility and threat to underlying aquifers.

(4) Moab: Albeit shallower, the vadose zone at Moab is a critical transport pathway for uranium and ammonia contaminants that have leached from mining tailings amassed on the ground surface and are moving toward the water table and close-by Colorado River. Additionally, strong seasonal variations in vadose zone thickness occur as a result of annual excursions in Colorado River discharge that temporally impact groundwater elevations at the site.

Relevant Technical Targets: next generation characterization technologies (tools), methods to validate and verify performance, overcoming challenges to achieving end states

Recommended sites: **Hanford**, INL, NNSS

Recommended by: Andy Tompson and Characterization Team

TDE-5: On the Use of Machine Learning Techniques to Advance Specific Groundwater Flow and Transport Model Applications
Trained "Machine Learning" and related "Reduced Order (or Surrogate) Modeling" (ML/ROM) paradigms offer ways to develop fast, accurate, and repeatable simulations that can allow improved system characterization, assessments of model or monitoring optimization, remedial design, source identification, disparate data assimilation, hydraulic test interpretation, complex system behavior, and uncertainty quantification, all in support of improving remediation confidence, costs, and time-lines. Increasingly sophisticated versions are based upon approaches that naturally incorporate the physics and physical observations of system behavior.

In the context of groundwater contamination problems, flow and transport models are used to characterize and quantify the rates and movement of groundwater through saturated and unsaturated formations and the associated transport, reaction, and dispersion of contaminants away from source zones. They are routinely used to design and optimize the capture and removal of contaminants in pump-and-treat systems, assess levels of dispersion and concentration reduction as they relate to closure decisions or shifting modes remediation (e.g., active to passive), or characterize the nature of source zones through inverse modeling algorithms. Models can be powerful tools for improving remediation efficiency and evaluating its effectiveness with improved confidence, but their utility can be plagued by costs (e.g., to develop and run increasingly complex models) and uncertainty (e.g., in the underlying conceptual and mathematical models, physical and chemical parameters, or sheer numbers of simulations required for an assessment).

Machine Learning and Reduced Order Model activities are integral to DOE's forward-looking remediation strategies. These tools are recommended to enhance predictive capability, reduce long-term monitoring costs, and support transition from active to passive remediation while improving stakeholder confidence.

Funding is potentially in projects that currently incorporate modeling activities.

Relevant Technical Targets: next generation computational technologies (tools), methods to verify/ validate, predict, and optimize performance, overcoming challenges to achieving end states

Recommended sites: **Hanford, SRS, LANL**, INL, Moab, Paducah

Recommended by: Andy Tompson, LLNL

TDE-6: Hierarchical Hydrostratigraphic and Geostatistical Models

The concept is one that recognizes that contaminated groundwater environments are fundamentally three-dimensional and heterogeneous in nature. The recommendation is to consider a more systematic incorporation of hierarchical hydrostratigraphy and geostatistics in overall conceptual hydrogeologic model development and to marry this framework into groundwater flow and transport models, ML/ROM development, remediation design and optimization, monitoring design, and other activities related to delineation and quantification of uncertainty, as needs dictate.

Hierarchical hydrostratigraphic and geostatistical models play a critical role in improving the realism, accuracy, and utility of groundwater models, particularly for complex contaminated sites. Their integration enhances both the understanding of subsurface heterogeneity and the prediction of contaminant transport, which are key to effective groundwater remediation. Hierarchical hydrostratigraphy refers to the organization of geologic units into a three-dimensional, multi-level system based on their hydrologic properties. These models organize the subsurface into nested scales (e.g., region, formation, facies, lithologic units) and reflect the inherent structural and depositional hierarchies and heterogeneity in geologic media. They compel a three-dimensional perspective and are designed to honor all geologic structural data. In groundwater models, they provide a geologically reasonable framework that defines hydraulic conductivity contrasts, preferential flow paths, and barriers to flow. By delineating confining layers or aquifers, they help specify no-flow or transmissive zones correctly. They guide placement of contamination sources and better represent the vertical and lateral heterogeneity. In remediation, they may be used to guide well placement (e.g., targeting high-permeability zones), used to support design of hydraulic barriers, PRBs, or in situ treatment zones, and better forecast contaminant fate.

Geostatistical models use spatial statistics to simulate the distribution of materials (e.g., sands, silt, gravels, and cays) or material properties (e.g., permeability, porosity), generally within in the smallest scale lithologic units identified in a domain. In groundwater models, they are used to better quantify uncertainty (e.g., in providing a range plausible realizations of the subsurface to evaluate how uncertainty affects flow and transport predictions), capture spatial variability in key properties that govern important processes (e.g., preferential flow and matrix diffusion), and in roles that support Machine Learning and Reduced Order Model (ML/ROM) development by identifying influential features or parameters. In remediation, they may be used to predict worst-case plume migration scenarios, identify optimal locations for monitoring wells, treatment systems, or reactive barriers, and assess robustness of remedial designs across a range of hydrogeologic conditions.

The use of hierarchical hydrostratigraphic and geostatistical models is not only relevant but essential for effective remediation across the DOE complex – especially at large, heterogeneous, and long-lived contaminated sites. These models underpin several of the key technical targets and strategy documents developed by DOE, including the 2021 Technical Targets report, the Groundwater Closure Strategy (2024),

and site-specific review documents such as those for the Hanford, Los Alamos, Savannah River, and Paducah sites.

Potentially relevant to all projects that currently incorporate modeling activities, but especially to the Hanford, Savannah River, Los Alamos, Moab, INL, and Paducah sites.

Relevant Technical Targets: strongly heterogeneous systems, next generation modeling, methods to verify and validate performance, next generation characterization technologies (tools)

Recommended sites: **LANL**, Hanford, INL, Paducah, SRS

Recommended by: Andy Tompson, LLNL

TDE-7: Flow Logging

A variety of technologies and experimental approaches exist for flow logging. Direct measurements of vertical flow in wells can be made using heat-pulse, spinner, or electromagnetic borehole flowmeters. Various types of single-well tracer tests constitute indirect methods of characterization, including dilution logging, hydrophysical logging, fluid electrical conductivity logging, stacked-dynamic profiling, and thermal profiling during active heating experiments. The concept is to characterize vertical flow in boreholes and from this information characterize profiles of hydraulic conductivity (or transmissivity associated with fractures) and vertical hydraulic gradients. Using this information alongside sampling results, contaminant concentration profiles may also be estimated. This information could lead to the design of more effective well construction (i.e., placement and length of screens) for more efficient remediation, where high-concentration intervals of an aquifer are targeted for extraction or treatment.

Characterization of borehole flow under stressed (pumping/injection) and ambient hydraulic conditions can provide insight into aquifer heterogeneity (i.e., the vertical profile of hydraulic conductivity) and vertical hydraulic gradients. In fractured rock, flow logging can be used to characterize the transmissivity and heads of individual fractures identified using other logging methods (e.g., televiewer). Flow logging in one well during pumping in another well (crosshole flow logging) provides insight into the hydraulic properties and connectivity of preferential pathways. Integration of flow logs with sampling data allows for inference of the vertical distribution of contamination, which is difficult to characterize in long-screened wells and open boreholes.

The use flow logging supports technical targets and strategy documents developed by DOE, including the 2021 Technical Targets Report, the Groundwater Closure Strategy (2024), and site-specific review documents such as those for the Hanford and Los Alamos sites.

Potentially relevant to all projects with groundwater contamination spread over a large vertical extent of the aquifer, but especially to the Hanford, Los Alamos, Moab, and National Nuclear Security Administration sites.

Relevant Technical Targets: next generation characterization technologies (tools), methods to verify and validate performance, controlling contaminants in the vadose zone, strongly heterogeneous systems

Recommended sites: **Hanford,** LANL, Moab

Recommended by: Fred Day-Lewis, PNNL

TDE-8: Distributed Fiber-Optic Sensing

The concept is to consider an integrated approach to characterization and monitoring and capitalize on construction of new site infrastructure to integrate fiber-optic cables into designs.

Fiber-optic distributing sensing technologies offer solutions for characterization and long-term monitoring of hydrologic and geotechnical conditions with unprecedented resolution in space and time. Temperature and acoustic sensing are increasingly used in hydrologic and engineering applications to characterize properties and monitor processes related to flow, transport, and ground movement. Construction of new wells, reactive barriers, engineered landfills, storage tanks, pipelines, impounds, etc., provide opportunities for cost-effective installation of fiber-optic cables for permanent deployments. In addition to characterization, there are applications to leak detection, groundwater/surface-water exchange, and measurement of borehole flow.

Potentially relevant to all projects that could benefit from characterization and monitoring related to groundwater/surface-water exchange, borehole flow, leak detection, barrier performance, etc., but especially to the Hanford, Savannah River, Moab, and Paducah sites.

The use fiber-optic sensing supports technical targets and strategy documents developed by DOE, including the 2021 Technical Targets Report, the Groundwater Closure Strategy (2024), and site-specific review documents such as those for the Hanford, LANL, Savannah River, and Paducah sites.

Relevant Technical Targets: next generation characterization technologies (tools), methods to verify and validate performance, overcoming challenges to achieving end states, next generation modeling

Recommended sites: **Moab,** Hanford, Paducah, SRS

Recommended by: Fred Day-Lewis, PNNL

TDE-9: Biogeochemical Tracers and Isotope Measurements

Tracer and isotope techniques represent a powerful but underutilized class of tools for advancing groundwater cleanup at complex DOE sites. These tools are especially valuable for improving conceptual site models (CSMs), filling persistent data gaps, and supporting remedy optimization in geologically and hydrologically heterogeneous environments. Their broader deployment would directly support DOE's goals of reducing cleanup timeframes, costs, and uncertainties—particularly as sites transition from active remediation to long-term monitoring and closure. Tracer and isotope approaches can uniquely address several high-priority technical challenges:

Source Term Characterization: These tools help identify, differentiate, and quantify contaminant sources, including legacy versus ongoing inputs. For example, Isotope fingerprinting (e.g., U-series, Cl-36, Sr, $\delta^{15}N$, $\delta^{13}C$) allows differentiation between multiple waste stream signatures or between natural and anthropogenic sources. Compound-specific isotope analysis (CSIA) for contaminants like RDX, TCE, or perchlorate can indicate whether biodegradation is actively reducing source mass, and at what rate. Groundwater age-dating using tritium/helium, S and Na isotopes, or CFC-based techniques can constrain contaminant release timing and link it to historical operations, helping refine source attribution and plume origin.

Hydrogeologic Conceptualization: Tracers and isotopes provide critical insight into flow systems—particularly where conventional monitoring is insufficient. Stable isotopes of water (δ^2H, $\delta^{18}O$),

tritium/helium, CFCs, SF_6, and noble gases can delineate recharge zones, track water origin and residence time distributions including groundwater age and quantify mixing (or lack thereof) between shallow and deep groundwater. Isotope and geochemical tracers can identify lateral and vertical flow paths, aquifer connectivity, and interactions with surface water. Fracture flow vs. matrix flow distinctions can be resolved using injected tracers or natural geochemical signatures.

Transport Process Identification and Monitoring: Tracer techniques can directly quantify how contaminants move and attenuate in the subsurface. Conservative tracers, for instance, track advection and dispersion while reactive tracers can assess sorption, degradation, or redox interactions. Injected tracers can quantify mass flux, estimate travel times, or validate remediation system capture zones. Natural tracers (e.g., δ^{13}C-DIC, nitrate isotopes) can verify whether monitored natural attenuation is occurring and assess contaminant stability. For example, at WVDP, a permeable treatment wall was installed to treat Sr-90. Tracer testing could verify long-term performance and detect bypass or declining treatment efficacy before it becomes a risk.

Vadose Zone and Fractured Rock Characterization: These environments present some of the greatest characterization and modeling challenges in the DOE complex. Tracer and isotope methods offer rare tools to understand them: Gas-phase tracers (e.g., SF_6, noble gases) help define vapor-phase transport and recharge in unsaturated zones. Dye, heat, or ionic tracers can delineate preferential pathways and fracture networks in hard rock. Isotopic methods can reveal fracture-matrix exchange and assess retention processes that affect long-term plume behavior.

The 2021 Technical Targets and NNLEMS Closure Strategy both prioritized advanced monitoring and modeling in the deep vadose zone and fractured media, where legacy waste sites often lack clear performance metrics or conceptual clarity. Tracer and Isotopic techniques have been employed at a number of DOE sites. At LANL, tracer testing and isotopic analysis helped determine whether regional aquifer contamination was from historical discharges versus active sources, informing remediation priorities. At Moab, where seasonal river stage fluctuations and underlying brines complicate flow direction, isotopic tools could clarify interactions between the freshwater aquifer, brine interface, and surface water, supporting defensible transition to natural flushing. At the Nevada National Security Site (NNSS), Pu isotope fingerprinting confirmed the source of a radiologic contaminant, the mechanism of its migration, and generated new understanding of source term transport dynamics. Within the Yucca Mountain Project (YMP), identification of Cl-36 in groundwater led to a revision of how contaminant transport occurs in fractured rock. At WVDP, a permeable treatment wall was installed to treat Sr-90. Tracer testing could verify long-term performance and detect bypass or declining treatment efficacy before it becomes a risk

Tracer methods align directly with DOE's Technical Targets framework and support high-impact goals such as: Developing exit strategies for pump-and-treat systems; quantifying long-term attenuation and remedy stability; validating site closure metrics and enhancing regulatory and stakeholder confidence through defensible science. Efforts like ALTEMIS and the TRAC system are laying the groundwork for integrating tracer-based insights into long-term monitoring and site tracking systems.

Tracer and isotope tools are not only scientifically robust—they are strategically necessary. They enhance understanding of contaminant behavior, validate remedy performance, and reduce uncertainty at every stage of the remediation lifecycle. DOE should prioritize their broader deployment, especially in support of complex plume closure, remedy transition, and long-term stewardship.

Relevant Technical Targets: next generation characterization technologies (tools), methods to validate and verify performance, overcoming challenges to achieving end states

Recommended site: **Moab**

Recommended by: Andy Tompson, LLNL

Testbeds and Demonstrations

TB&D-1: Moab Testbed

The Moab Site is nearing completion of tailings removal and relocation and is scheduled to transition to final groundwater and soil cleanup in the next 4 years. The site is accessible for field studies, and the scale of the plume allows for multi-scale characterization and monitoring using a variety of approaches. The site has high visibility and stakeholder engagement given its location relative to national and state parks and the Colorado River.

The ALTEMIS team is applying the sensor network paradigm developed for SRNL and numerical AI/ML algorithms to design an innovative sensor system for the Moab Site. It will be effective at monitoring evolving environmental conditions and plume migration. The Python package PyLEnM, Python for Long-term Environmental Monitoring, has been applied to multiple sites, including DOE's Rifle and LANL sites and UK's Sellafield site. In these applications, this package, developed using the SRS F-Area data, will be used to identify dominant controlling variables (e.g., water table fluctuations, specific conductance, etc.) in the system that can be used as proxies to predict contaminant concentrations and plume migration. Additionally, the framework has been used for spatiotemporal optimization of sensor locations for designing a robust monitoring system. The team will apply the ALTEMIS spatiotemporal data-driven AI/ML approach to optimize a monitoring network for the Moab Site based on the key controlling variables. This activity will provide a specific recommendation for a sensor network for regulatory approval that can be used in real-time to cost effectively and efficiently monitor contaminant plume migration and thus take timely action to avoid impacts on endangered species. Additionally, the team will document findings related to the plume dynamics that are identified in the historical data.

The Moab testbed is a straightforward opportunity for the synergistic demonstration of multiple technologies.

Seed funding is in place to plan coordinated activities at Moab.

Relevant Technical Targets: next generation characterization technologies (tools), methods to verify and validate performance, improving the technical basis for environmental stewardship management

Recommended site: **Moab**

Recommended by: Brian Looney, SRNL

TB&D-2: In Situ Geochemical Remediation Testbed for In-situ Attenuation of Contaminants

In-situ geochemical remediation technologies are environmental cleanup methods that treat contaminated soil or groundwater directly in place (i.e., without excavation or extraction) for source or plume control. These technologies use chemical amendments to enhance natural processes to immobilize, transform, or degrade contaminants into less toxic or less mobile forms.

They are widely used for a variety of contaminants, including heavy metals, radionuclides, and chlorinated solvents. They typically involve reductive strategies for redox sensitive contaminants such as technetium-99, uranium, or chromium, while followed by a mineral precipitation step, through injection of amendments like phosphate-based solutions (e.g., apatite), to ensure long-term stabilization. The amendments could be in gas form for some direct vadose zone treatment, or particulate and liquid forms for saturated zone treatments. The subsurface application approaches may involve direct injection into plume and/or use of these amendments in a reactive barrier form for the saturated zone treatments.

Important benefits of these technologies include cost-effectiveness, especially for large groundwater plumes and long-term stabilization of source reducing impacts to groundwater—reducing the timeframes of groundwater remedies. However, they also require significant site characterization, effective amendment delivery approaches, and long-term monitoring to ensure effectiveness.

These technologies have been successfully tested at various DOE sites, see Table 17 for some examples.

Table 17. Examples of In Situ Geochemical Remedy Applications Across the DOE Complex

Site & Location	Technology	Target Contaminant(s)
Hanford DV-1 Source OU	Laboratory treatability testing of five geochemical technologies for the saturated zone treatment: • Stannous apatite for sequestration • Sulfur-modified iron (SMI) for reduction and polyphosphate for sequestration • Bismuth subnitrate for sequestration • Citrate phosphate for sequestration • Calcium polysulfide for reduction and polyphosphate for sequestration	Uranium and Technetium-99[*]
Hanford 100-N & 300 Areas	Treatability testing and remedy implementation of Calcium-citrate-phosphate and polyphosphate	Uranium and Strontium-90
Moab, UT	Field validation of calcium-citrate-phosphate induced hydroxyapatite precipitation	Uranium
Moab, UT	Expansion of above with inclusion of additional mineral phases to develop more effective remedies, including those with ammonium	Uranium and ammonium
Old Rifle Site, CO	Laboratory and field validation of calcium-citrate-phosphate induced hydroxyapatite precipitation	Uranium, vanadium
SRS P-Area	Zero valent iron permeable reactive barrier (ZVI-PRB)	cVOCs
SRS H-Canyon National Pollutant Discharge Elimination System (NPDES) H-12	Humic acid (Borregro HA-1)	Copper
SRS F-Area Seepage Basins	Potassium humate (Huma K)	Uranium
SRS F-Area	Silver chloride	I-129
SRS F-Area	Base/alkaline solution	Uranium and strontium-90

[*]The treatability testing also includes evaluation of co-contaminants such as strontium-90, chromium, iodine-129, and nitrate.

The recommendation for furthering these technologies is to conduct a comprehensive field-scale treatability testing of the select amendments, which could be achieved as part of a feasibility study at Hanford (200-DV-1 OU), Moab, or Paducah in the form of a testbed.

Relevant Technical Targets: next generation characterization technologies (tools), methods to verify and validate performance, improving the technical basis for environmental stewardship management

Recommended sites: **Hanford**, Moab, Paducah, SRS

Recommended by: Inci Demirkanli, PNNL

TB&D-3: Modular, Synergistic Treatment Train Demonstration Tests

This concept is to leverage multiple remediation technologies in series or parallel to address recalcitrant contaminants or mixtures of contaminants comprehensively and intelligently. Active remediation often faces challenges: (1) single treatment technology could fail to address chemically diverse contaminants (e.g. PFAS, VOCs, and ionic metals) at different concentration levels (e.g. ppt, ppb, and ppm) in a cost-effective way; (2) co-occurring contaminants might reduce treatment efficiency (e.g. presence of organic matter interferes with PFAS treatment); (3) energy-intensive technologies (e.g. RO, electrochemical oxidation, plasma) are costly for large-scale, low-concentration sites; and (4) scalability is limited to many advanced technologies (e.g. plasma, sonochemical destruction) that can powerfully facilitate complete mineralization of persistent and recalcitrant contaminants (e.g. PFAS).

The "modular" aspect allows flexibility to adapt the system to site-specific conditions, such as types of target contaminants (e.g., long-chain like PFOA/PFOS or short-chain like PFBS), concentration levels, and co-contaminants (e.g., organic matter, metals). Each module targets specific aspects of contaminant separation, concentrating, or destruction. The train as a synergistic combination is optimized for maximum efficiency and cost-effectiveness. The key components of modular, synergistic treatment train may include, but not limited to, separation technologies, destruction technologies, and in-situ, real-time sensor monitoring technologies. For PFAS treatment as an example, it may include *separation technology*: nanofiltration, ion-exchanges resins, GAC, electrochemical separation, etc.; *destruction technologies*: electrochemical anodic oxidation, sonochemical destruction, plasma-based destruction, etc.; and *real-time monitoring technologies*: in-situ sensors for monitoring influent, intermedia flow, and effluent, and AI-assisted data analysis for operational optimization.

This approach offers key benefits including:

Flexibility and Selectivity: Modules can be tailored to site-specific contaminants and/or mixture of contaminants, concentrations, and media (e.g., drinking water, groundwater, surface water, and soil).

Synergy: Combining separation and destruction technologies enhances overall efficiency, minimizing co-occurring contaminants interference, and addressing chemical-specific separation and mineralization.

Cost-Effectiveness: Modular designs allow optimization of each stage, reducing energy and operational costs compared to standalone methods and train system with real-time monitoring offers multi-modular optimization for the best system outcomes.

Scalability: Systems can be scaled up or down based on contamination levels, treatment volume and rate, and treatment goals.

Technology adoption, adaptation, and growth: The treatment train provides a platform that promotes new technology adoption and adaptation at a modular scale for pilot testing and optimization at early development stage.

Many individual technologies to build the modules and initial prototype of treatment train have been tested (or testing) through the existing fundings. New seed funding may support a platform for deployment and demonstration at EM sites; Paducah, SRS, and Hanford would benefit from this demonstration.

Relevant Technical Targets: improving the technical basis for environmental stewardship management, effective and sustainable solutions for plumes, emerging contaminants overcoming challenges to achieving end states

Recommended sites: **SRS**, Hanford, Paducah

Recommended by: Eugene Yan, ANL

Future Research Opportunities

FRO-1: Fermilab SRF E-Beam Accelerator

This concept leverages Fermilab's compact SRF accelerator to deliver 10 MeV electrons to contaminated media. The resulting ionizing radiation initiates radiolysis of water, forming reactive species capable of degrading persistent organic pollutants. The system is designed for mobile deployment, allowing on-site treatment with minimal infrastructure.

Many DOE sites face persistent challenges in addressing widespread contamination in complex hydrogeologic settings. Traditional pump-and-treat or excavation methods are costly, disruptive, and often ineffective for highly stable compounds like PFAS. This technology addresses a major gap by providing a high-penetration, reagent-free, scalable solution for in situ destruction of contaminants. Potential application sites include Formerly Utilized Sites Remedial Action Program locations and legacy waste sites managed by EM and LM.

Initial development funded through internal Fermilab R&D and limited support from DOE-EM-aligned work. Seeking new funding for scaled-up deployment and demonstration in environmental remediation contexts.

Relevant Technical Targets: emerging contaminants, overcoming challenges to achieving end states

Recommended sites: DOE-LM sites; Hanford, LANL, SRS

Recommended by: Slavica Grdanovska, FNAL