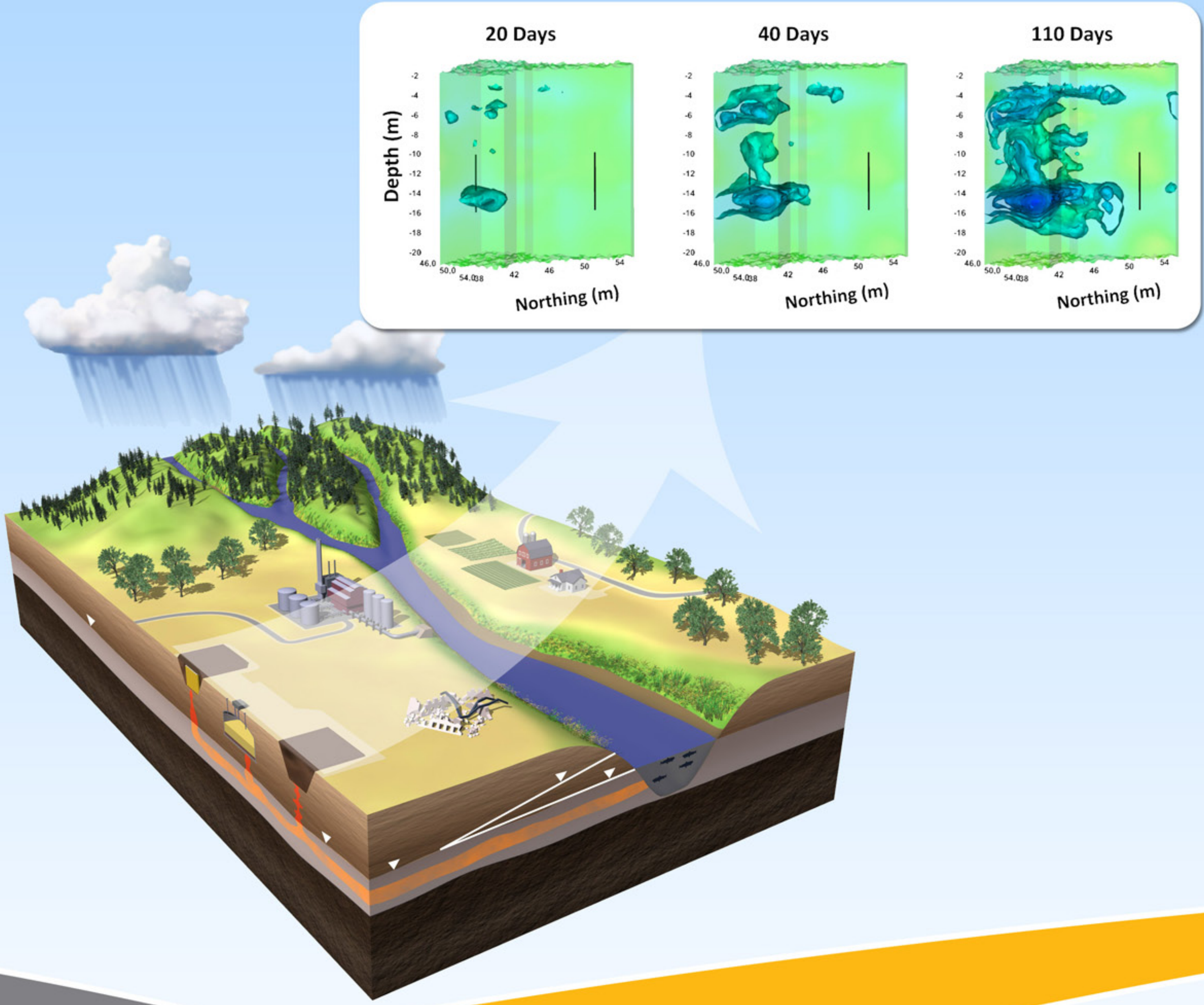
Scientific Opportunities for Monitoring at Environmental Remediation Sites (SOMERS)

Integrated Systems-Based Approaches to Monitoring



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Acknowledgements

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The authors are grateful to the members of the Interstate Technology and Regulatory Council Monitoring and Statistics Team, expert workshop participants, and other peer reviewers. Reviewers provided many suggestions and constructive comments on this document. Many comments have been addressed in this document; other comments are being taken into consideration in the development of two more follow-on documents: SOMERS Program Plan and SOMERS Guidance Document. In addition, the authors would like to acknowledge the assistance of Charles Castello and Luke Powell for literature reviews and organization of meetings during the early stages in document development.

The suggested citation for this document is as follows:

Bunn AL, DM Wellman, RA Deeb, EL Hawley, MJ Truex, M Peterson, MD Freshley, EM Pierce, J McCord, MH Young, TJ Gilmore, R Miller, AL Miracle, D Kaback, C Eddy-Dilek, J Rossabi, MH Lee, RP Bush, P Beam , GM Chamberlain, J Marble, L Whitehurst, KD Gerdes, and Y Collazo. 2012. *Scientific Opportunities for Monitoring at Environmental Remediation Sites (SOMERS): Integrated Systems-Based Approaches to Monitoring*. DOE/PNNL-21379. Prepared for Office of Soil and Groundwater Remediation, Office of Environmental Management, U.S. Department of Energy, Washington, D.C., by Pacific Northwest National Laboratory, Richland, WA.

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Acronyms and Abbreviations

ACL	Alternate Concentration Limit
ARAR	Applicable or Relevant and Appropriate Requirement
ASCEM	Advanced Scientific Computing for Environmental Management
CERCLA	Comprehensive Environmental Response, Compensation, and Liability Act
CSM	conceptual site model
DOE	U.S. Department of Energy
EM	U.S. Department of Energy Office of Environmental Management
EPA	United States Environmental Protection Agency
ITRC	Interstate Technology and Regulatory Council
LM	U.S. Department of Energy Office of Legacy Management
MCL	maximum contaminant level
MNA	monitored natural attenuation
OSWER	Office of Solid Waste and Emergency Response
RCRA	Resource Conservation and Recovery Act
SOMERS	Scientific Opportunities for Monitoring at Environmental Remediation Sites
TI	technical impracticability
USC	United State Code

Preface

The U.S. Department of Energy (DOE) has assembled a team of multidisciplinary technical experts from DOE Offices of Environmental Management (EM) and Legacy Management (LM), national laboratories, academia and consulting firms to work collaboratively to identify Scientific Opportunities for Monitoring at Environmental Remediation Sites (SOMERS). DOE currently maintains one of the largest environmental cleanup programs in the world. At some sites, monitoring networks include hundreds of locations within multiple media (e.g., vadose zone, surface water, sediments, groundwater), collectively costing millions of dollars per year. In addition, long-lived contaminants will be present for many decades or even centuries at approximately 100 sites, posing long-term monitoring challenges and opportunities.

This is the first of three peer-reviewed documents for DOE being prepared by the SOMERS team to state the vision and plan for monitoring and to provide guidance to DOE site managers. This first document presents DOE's vision for advancing monitoring through an integrated systems-based approach. This document identifies in detail scientific and technical challenges and opportunities associated with systems-based monitoring at DOE sites.

Specific opportunities include the following: 1) reliance on conceptual site models (CSM) and evolution of CSMs throughout the range of monitoring phases to improve understanding of the system as a whole and thereby improve monitoring design and interpretation; 2) promote lines-of-evidence approaches and flux-based approaches as alternatives to strict reliance on point measurements and to improve integration of monitoring information with remedy management and long-term site management; 3) develop and apply innovative monitoring tools, including surrogates, early indicator parameters, bioassessments, geophysics/remote sensing, predictive analyses/models, and information management that can reduce the cost of monitoring and associated site remediation and provide improved information to address risk management. These opportunities contribute to the design and implementation of monitoring programs that support long-term remedial objectives for site cleanup and closure.

Throughout the development of this document, team members and peer reviewers provided valuable technical input beyond identification of the scientific challenges and opportunities associated with monitoring. Therefore, two additional documents are being prepared by the SOMERS team: a SOMERS Program Plan and a SOMERS Guidance Document. The objectives of the Program Plan are to: 1) prioritize monitoring challenges and associated research needs at DOE sites; 2) correlate research priorities with the opportunities and challenges for an integrated systems-based monitoring approach; 3) identify potential collaborations with other Federal agencies, universities and other organizations; 4) identify opportunities to engage stakeholders, including regulatory agencies; and 5) pinpoint methods to enhance communication within and beyond DOE. The overall objective of the Guidance Document is to provide guidance to site managers on how to implement an integrated systems-based approach to monitoring at DOE sites. The Guidance Document will provide a number of case studies from DOE sites demonstrating the use of integrated systems-based monitoring approaches and highlighting the benefits from this approach. The Guidance Document will also provide recommendations for site managers to improve implementation of integrated systems-based monitoring.

This document is intended for a broad audience, including DOE leadership within EM (at Headquarters and the sites) and LM, as well as other Federal agencies that are facing similar monitoring challenges and opportunities. In addition, the document is intended to benefit site contractors by providing a broader, cross-disciplinary perspective of monitoring opportunities and challenges in different media, hydrogeologic settings, contaminant types, tools, and approaches.

Introduction

The U.S. Department of Energy (DOE) maintains the largest environmental remediation program in the world involving over a million acres in 13 states, 90 million gallons of radioactive waste stored in 230 tanks, 1.7 trillion gallons of contaminated groundwater, and 40 million cubic meters of contaminated soil and debris (DOE 2010a). DOE conducts monitoring in a range of environmental media, including surface water, groundwater, soils, sediment, air, flora and fauna (Figure 1). The purpose of monitoring ranges from initial site characterization to long-term protection of human health and the environment. Monitoring networks at some DOE sites may include tens to hundreds of sampling locations. Data collection, management, and interpretation may cost up to several million dollars per year at each facility (Reed and James 2010). In addition, long-lived contaminants will be present for many decades or even centuries at approximately 100 sites, posing long-term monitoring challenges and opportunities.

Previous DOE efforts to improve monitoring strategies have focused on the state of available monitoring technologies (DOE 2011) and/or optimization of long-term monitoring locations, analytes, and sample frequency. Efforts have been interdepartmental and cross-disciplinary. In 2009, DOE's Office of Environmental Management (EM) hosted a Long-Term Monitoring Technical Forum in Atlanta, Georgia, to discuss improvements in long-term monitoring (DOE 2009a). DOE's Office of Technology Innovation and Development supported the development of monitoring technologies through its mission of transforming science and innovation into practical solutions for environmental cleanup, and commissioned the Scientific Opportunities for Monitoring at Environmental Remediation Sites (SOMERS) documents. DOE's Office of

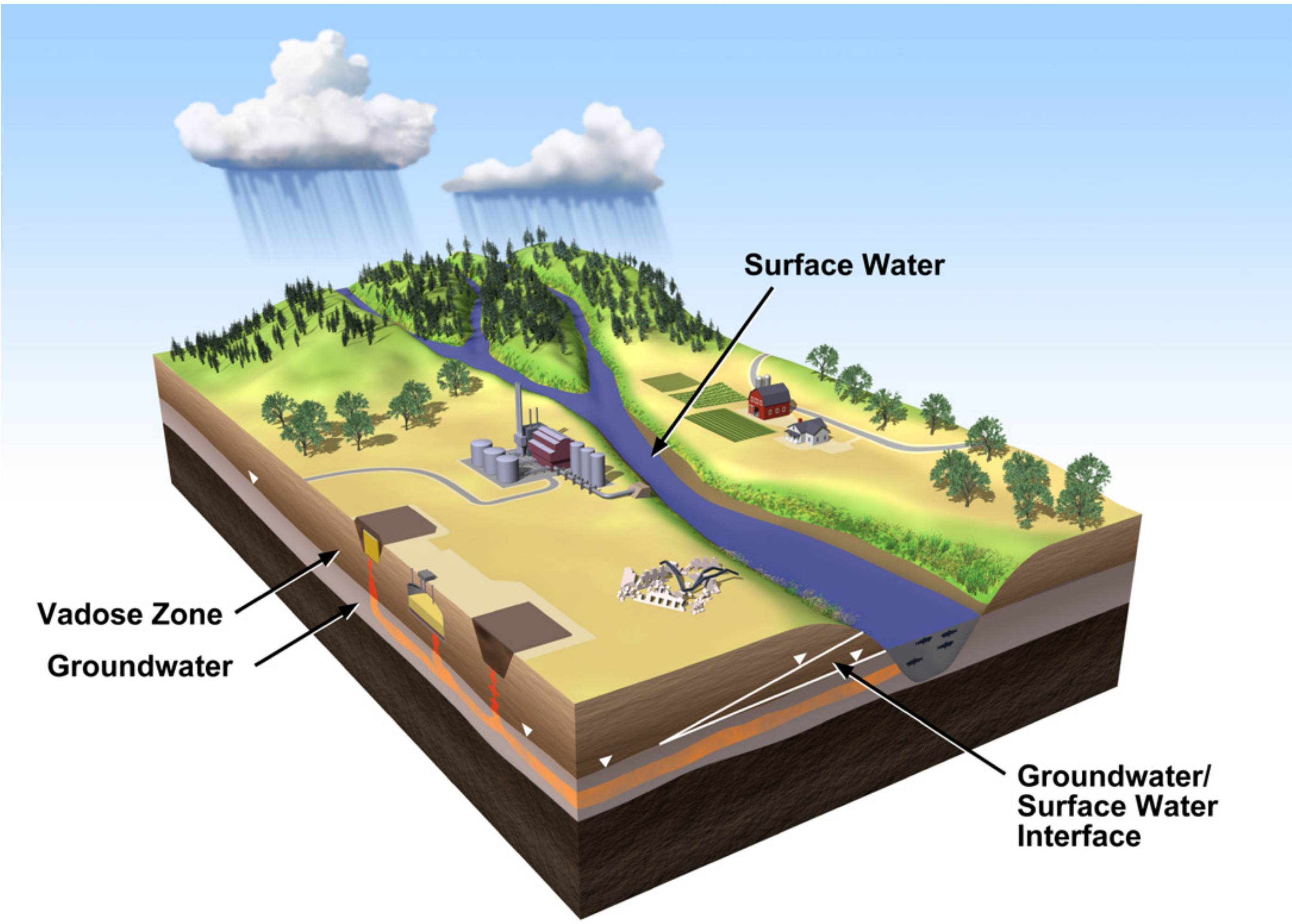

Figure 1. Monitoring at environmental remediation sites may include the vadose zone, groundwater, groundwater/surface water interface, and surface water as well as the receptors for protection of human health and the environment

Groundwater and Soil Remediation has developed some of these technologies for field implementation and transferred knowledge to site contractors (such as geophysical imaging [DOE 2011]).

This document builds on these accomplishments and takes the next step forward. By presenting a vision for monitoring at DOE sites, this document provides DOE with the foundation for implementing interdepartmental and cross-discipline monitoring activities in the near future, termed "integrated systems-based approaches for monitoring." For example, key questions for site remediation lead to the development of remedial objectives that are integral to the goals for accomplishing integrated, systems-based monitoring (Figure 2). This document is intended to be used by a variety of DOE offices to establish a path forward for making necessary investments throughout DOE. This document will also serve to communicate DOE's path forward on monitoring to potential partnering agencies, regulators and other stakeholders.

The term "integrated systems-based approaches for monitoring" incorporates several concepts. One aspect of integrated systems-based approaches is the focus on designing monitoring programs with site remediation processes in mind, where monitoring is tailored to the needs and objectives of each phase in this process. To reach the long-term remedial objective(s), each site must transition through several characterization and remedial phases. The monitoring system configuration and monitoring objectives will evolve through these phases; monitoring data can be used to guide and inform the transition from one remedial phase to the next. Integrated systems-based approaches for monitoring therefore collect data to support, inform and develop the overall remedial approach. Details on monitoring phases and the remedial approach are provided in "Monitoring Program Objectives".

Monitoring programs must ultimately support long-term remedial objectives for site cleanup and closure. Several types of end states are possible at sites. The monitoring program should be designed to meet the unique needs of the end state, which may be very different for an unrestricted use scenario compared to an alternative designed to prevent exposure and protect a designated receptor. The most desirable end state at environmental remediation sites may be site closure with unrestricted use. However, at complex sites, unrestricted use may be unattainable. Exit strategies may be needed and may involve selecting risk-based, concentration limits for contaminants and regulatory approaches (as discussed in "End States") for end states other than unrestricted use, and these strategies may require long-term monitoring.

Another aspect of integrated systems-based monitoring programs is the iterative feedback nature of monitoring programs with the conceptual site model (CSM). In this approach, monitoring programs test or verify the CSM and provide insight into important transport processes and remediation system performance. As the CSM is refined, monitoring should also evolve with remedy adjustments, and help inform decision-makers during the development planning process for the next monitoring phase. Details are provided in "Conceptual Site Model".

Key questions	Objectives
Are the relevant processes identified in the conceptual site model occurring as intended to result in remediation and/or mitigation of contaminant fate and transport?	Demonstrate that the remedy is functioning and meeting remedial action objectives.
Have there been any perturbations in the relevant processes identified in the conceptual site model that could impact the remediation process and/or predicted contaminant fate and transport?	Detect changes in environmental conditions that may impact the remedy or contaminant fate and transport.
Are expected reaction products present or are there any reactions or biogeochemical processes occurring that produce problematic or unexpected products?	Demonstrate that relevant reaction processes are occurring and unexpected or unwanted processes are not occurring.
Is contaminant fate and transport occurring as expected?	Assess contaminant fate and transport and protection of potential receptors.

Goals for Integrated Systems-Based Approaches for Monitoring

- Identify scientific, technical and implementation challenges that currently impede informative, timely and cost-effective monitoring to support remediation actions.
- Provide prioritized science and technology strategies that meet current needs within the DOE complex for the most challenging environments.
- Develop a scientific and technical framework that combines regulatory drivers, point- and volume-averaged strategies and techniques into an advanced systems-based characterization and monitoring program that includes flux- and risk-informed approaches and transitions throughout the monitoring life of the facility.

Figure 2. Key questions, objectives and goals for integrated systems-based approaches for monitoring

A key aspect of integrated systems-based monitoring is a focus on understanding the system as a whole. Monitoring that provides an integrated measure of multiple processes within a system (e.g., flux-based approaches) can provide important system information. It is useful to design monitoring programs that provide information about controlling features, events, and processes that can be interpreted in terms of the system as a whole. The use of multiple "lines of evidence" approaches to support system-level understanding is an important aspect of integrated systems-based monitoring (as discussed in "Lines of Evidence: An Integrated Systems-Based Monitoring Approach").

Through discussions internally and with other experts, DOE has identified overall scientific and technical challenges and opportunities to advance integrated systems-based monitoring approaches (as discussed in "Scientific and Technical Challenges & Opportunities for Implementing Systems-Based Monitoring Approaches"). Ensuring a strong technical basis will enable regulatory acceptance of systems-based approaches that supplement contaminant concentration data at specified locations (e.g., monitoring wells).

Multiple tools and techniques can be used to support an integrated systems-based monitoring approach. Broad areas of opportunities that show promise for supporting integrated systems-based monitoring approaches are described in "Scientific and Technical Advancements that Support Systems-Based Monitoring Approaches," along with opportunities for technology advancement. These include the use of surrogates, indicators, geophysics, mass flux, predictive analysis, bioassessment, and integrated data management.

Integrated systems-based monitoring approaches have the potential to improve effectiveness, reduce risk, and reduce costs and labor associated with environmental monitoring at DOE sites, particularly at complex long-lived sites. Subsequent DOE monitoring documents will provide more information on integrated systems-based monitoring, including 1) a Program Plan where additional detail on the scientific and technical challenges and opportunities will be provided; and 2) a Guidance Document with more explanation of processes, procedures, and tools for sites to implement effective monitoring (as discussed in "Path Forward").

Monitoring Program Objectives

Monitoring objectives vary depending on the regulatory drivers for DOE site cleanup and the objectives of each phase of site remediation. Integrated systems-based monitoring programs recognize that the objectives of each phase of remediation influence the type of monitoring program that is needed. Each phase in the remediation process has specific objectives defined by the regulatory cleanup program. Environmental cleanup activities at DOE are conducted under the auspices of a number of federal regulations, most predominantly the *Comprehensive Environmental Response, Compensation, and Liability Act* (CERCLA) and the *Resource Conservation and Recovery Act* (RCRA). These cleanup regulations provide guidance for site characterization, risk assessment, remedy selection, remedy implementation, as well as for monitoring activities associated with the remedial phases. Potential threats posed by "uncontrolled" hazardous waste sites were addressed by the passage of CERCLA in 1980. Under CERCLA, the U.S. Environmental Protection Agency (EPA) has:

> "…authority to undertake monitoring to identify threats (42 USC §9604[b]), and defines removal and remedial actions as inclusive of any monitoring reasonably required to ensure that such actions protect the public health, welfare and the environment (42 USC §9601[23] and 42 USC §9601[24], respectively)" (EPA 2004a).

RCRA has similar provisions that establish monitoring programs at all U.S. hazardous waste treatment, storage and disposal facilities, solid waste landfills and other facilities.

As shown in Figure 3, each phase of monitoring under the RCRA and CERCLA processes has distinct objectives and approaches that influence the monitoring program. These objectives may or may not transition into the next phase of monitoring. During each phase, monitoring data may be collected for one or more purposes: screening or decision-making (Gilmore et al., 2006). Screening involves data collection to better understand site features or relevant processes such as contaminant loading or attenuation mechanisms. Screening data are used to develop the CSM and to determine what, if any, additional information is needed to fill data gaps. Decision-making involves using monitoring information and other data to determine the appropriate actions needed to move forward in the site cleanup and closure process (e.g., remedy selection, remediation, technology evaluation, site closeout). Each phase of monitoring is described below:

- **Characterization Monitoring**. The objective of characterization monitoring is to collect data to better understand the nature and extent of contamination in various media (e.g., air, water, soil) prior to remedy selection (Gilmore et al. 2006). The CSM is developed during characterization monitoring and refined as characterization activities progress.

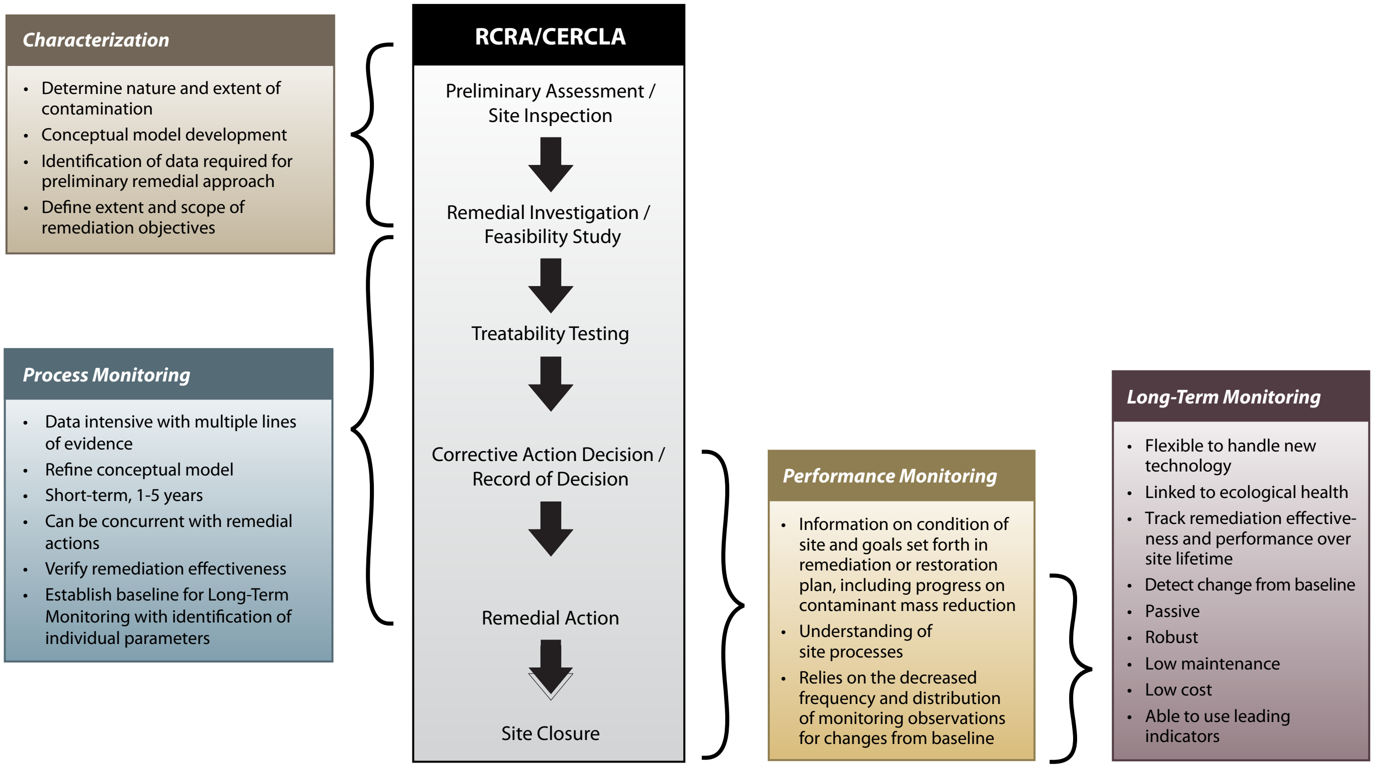

Figure 3. Monitoring stages and objectives within the context of the RCRA and CERCLA process

- **Process Monitoring.** Monitoring activity conducted during remedial design and remedial action is referred to in this document as process monitoring. The primary purpose of process monitoring is to verify remediation effectiveness. Process monitoring may track the delivery and distribution of remediation fluids, measure for breakdown products, or other indicators of the effectiveness of the remedial action. Process monitoring may integrate chemical, hydrological, physical, geological, and biological metrics (Gilmore et al. 2006). Typically, the tools used to collect process monitoring data are similar to those used during site characterization. However, the objective is very different. The process monitoring program is therefore distinct from characterization monitoring. A change in the monitoring program (e.g., locations, type of monitoring) when transitioning from characterization monitoring to process monitoring will likely expedite remedial progress (EPA 2004a; Looney et al. 2006).
- **Performance Monitoring.** Monitoring to assesses remedy effectiveness and short-term to mid-term remediation objectives is described as performance monitoring. Performance monitoring is conducted after the remedial action has been implemented. Performance monitoring provides information on the site condition relative to remedial goals. Performance monitoring can be data-intensive until the site reaches a stable state and begins to transition into long-term performance monitoring (EPA 2004b; Gilmore et al. 2006). Performance monitoring may include technology-specific considerations. For example, monitoring may be functionally different for active remedies versus passive remedies (e.g., in-situ chemical oxidation versus monitored natural attenuation [MNA]).
- **Long-Term Monitoring.** The overall objective of long-term monitoring—as defined in this document—is to confirm or assess contaminant stability, remedy stability, and site maintenance over the long term after long-term remedial actions have been completed. Other objectives include the following:
  - Confirm that remedial systems are functioning as intended. Long-term monitoring may include performance monitoring to ensure that all remedial systems are functioning within design parameters. Examples include periodic inspections, routine operations and maintenance requirements, and permit requirements. At sites where restoration is not expected to be completed for long time frames, active remediation or containment systems may still be in place to achieve nearer-term objectives. Natural attenuation processes may also require monitoring and documentation of their efficacy.

- Maintain protectiveness while contaminant concentrations at the site remain above cleanup objectives and that the contamination is stable or shrinking. Examples include monitoring contaminant concentrations in any nearby potable water supply wells or in sentinel wells to detect any concentration changes before water supply wells are impacted. This type of monitoring will be needed over the long-term at sites with long cleanup time frames.
- Verify whether final remedial objectives have been met. DOE's Office of Legacy Management (LM) conducts long-term monitoring at sites that are on schedule to meet long-term goals, yet will still require attention to ensure that remedial goals will be met.
- Detect relevant change in site conditions or baseline conditions that may affect the CSM (Gilmore et al. 2006). Long-term monitoring programs should ideally measure leading indicators of change in the system rather than lagging indicators. The frequency of data collection can be determined based on the time scale of anticipated changes at the site. This type of monitoring is especially needed at sites using a long-term management approach to residual contamination. Events that are relatively rare or uncertain (e.g., 100-year flood events, climate change) will need to be considered to ensure long-term management is sufficiently protective of human health and the environment.

The locations, type and frequency of monitoring may change throughout the lifetime of a long-term monitoring program to meet these objectives. Long-term monitoring will eventually lead to an end state, (e.g., site closure) but for some DOE sites with residual contamination, long-term monitoring and maintenance may be required for very long time frames.

In addition to the remediation phases shown on Figure 3, additional considerations for monitoring are programmatic transitions and end states.

- **Transitions.** It is important to differentiate between the various types and objectives of characterization and monitoring activities, and revise the monitoring program as needed whenever a site transitions from one phase of remediation to the next. Also, it is equally as important to revise the general concepts of each site as further information about the site is gained through each phase of the environmental remediation process. The transition from performance monitoring to long-term monitoring is particularly marked within DOE because site management moves from one office (EM) to another (LM). Aspects of this transition are described in the *EM/LM Site Transition Plan Guidance* (DOE 2004). For EM and LM, "the transition process is the passage from the phase during which engineered, near-term actions are taken to mitigate environmental and human health risk to the next phase where residual risks are maintained in a sustainable safe condition to allow beneficial use" (DOE 2009b). However, from the perspective of cost-effective and optimized monitoring, it is equally important to evaluate the effects of other cleanup transitions on the monitoring program. Because site conditions change in response to remediation activities, as well as natural variations in space and time, monitoring program objectives should be revisited and refined as necessary during the course of the monitoring program. Under CERCLA, these changes are reviewed every five years towards completion of the remedial action through site closure (EPA 2011a).
- **End State.** The end state for remediation is achieved when remedial goals have been met at the site. Unrestricted use is one potential end state. Depending on the regulatory program, unrestricted use may require meeting risk-informed concentrations, maximum contaminant levels (MCLs) and/or soil preliminary remediation goals. Another potential end state is future land use with restrictions (e.g., land use controls, water use restrictions, other institutional controls) to protect human health and the environment. These end states typically mark the end of long-term monitoring. At other sites, long-term monitoring may need to continue over decades or indefinitely for the foreseeable future. At these sites, an end state of environmental compliance monitoring and potentially other long-term maintenance activities can be reached. The ramifications of different end states on monitoring programs are described in the next section.

End States

Remedial objectives are developed based on future land use, applicable regulatory standards, risk assessment, the site-specific CSM and/or other factors to protect human health and the environment. After remedial objectives have been met, remediation is complete and the site has reached its end state. Typically, the most desirable end state is unrestricted use (e.g., residential use). Other land use options can be considered (e.g., industrial or recreational use). The risk-based remedial objectives are derived based on protection of human health and the environment and on land use assumptions. Some complex sites require continued use restrictions (e.g., land use controls, water use restrictions or other institutional controls) after remediation is complete due to residual contamination left in place.

The appropriate end state and associated remedial objectives (endpoints) are typically determined as part of the site investigations and remedy selection processes (e.g., during the remedial investigation feasibility study and proposed plan processes at CERCLA sites) and prior to collecting process monitoring data. Factors that may be considered during this process include the feasibility of conducting complete restoration within a reasonable time frame; site-specific risk assessment; quality and ease of tracking, maintaining and enforcing land use restrictions and other institutional controls through existing programs; and zoning and plans for future land use at the site and adjacent properties.

The selected end state helps define the most appropriate monitoring approach. However, integrated systems-based monitoring approaches can also be used to inform and verify or refine the selection of appropriate end states. In parallel with remedy selection and implementation, integrated systems-based monitoring data can be used to predict remediation time frames and verify whether end state conditions have been achieved. In some cases, the end state is a long-lasting sustenance of a contaminant condition that must be verified. Especially under these latter conditions, unique approaches that avoid costly reliance on monitoring contaminant concentrations at specific locations should be considered and potentially integrated with the definition of the acceptable end state for the site.

PREDICTING THE TIME FRAME TO REACH AN END STATE

Monitoring data can be used to predict remedial time frames. Remedial time frames can be estimated using a variety of different methods depending on the CSM. Examples include the following:

- Groundwater trends extrapolated to predict remedial performance over time
- Dense nonaqueous phase liquid dissolution rates, which can limit remedy effectiveness and prolong cleanup time frames
- Matrix back-diffusion rates, which can limit remedy effectiveness and lengthen cleanup time frames in hydrogeologic settings with significant matrix porosity (e.g., in many deep vadose zones)
- Predictive modeling and analysis of one or more of the above processes.

Monitoring programs should collect the data needed for the above remedy time frame estimation techniques to support this aspect of remedy management. This information can justify options for remedial actions that can reduce the required remediation time but require significant cost and energy comsuption or relocation of the contamination at another site.

END OF LONG-TERM MONITORING

Monitoring data are collected to determine when remedial objectives have been met and when monitoring can be discontinued. Typical remedial objectives for groundwater include meeting MCLs in groundwater, background requirements, or risk-based cleanup levels. Risk-based cleanup criteria are frequently applied at sites under RCRA and voluntary cleanup programs, and may also be considered at CERCLA sites. Although objectives have typically been based on contaminant concentrations at defined locations, use of other metrics (e.g., mass flux, bioindicators) can be correlated with concentration goals or long-term remedial objectives such as protection of human health and the environment.

An alternative approach may need to be incorporated into the regulatory decision documents. At some CERCLA or RCRA sites where contaminated groundwater discharges to surface water, alternate concentration limits (ACLs) can be established as cleanup requirements. ACLs address the effect of dilution and mixing that occurs when groundwater discharges into surface water and can lead to higher cleanup goals for groundwater under specific circumstances. Concentrations can be measured in one location (e.g., in surface water) and used to demonstrate protectiveness in another location (e.g., groundwater). An EPA policy memorandum specified several factors to consider before establishing ACLs at CERCLA sites (EPA 2005). Several RCRA sites have used mixing zones and concepts similar to ACLs when developing cleanup criteria. Concentrations below ACLs can lead to an end of long-term monitoring.

A few cleanup programs have criteria for approving low-risk or low-threat closures and ceasing long-term monitoring before numerical cleanup criteria have been reached. For example, the San Francisco Bay Regional Water Quality Control Board has approved several low-threat closures at chlorinated solvent sites where contamination is expected to meet cleanup levels soon under natural conditions (SF RWQCB 2009). Colorado also has draft guidance for low-threat closure (CDPHE 2010). Several states have adopted similar practices for closing underground storage tank sites with petroleum hydrocarbons and other contaminants that are naturally biodegrading. Monitoring can be discontinued at these sites if data indicate that cleanup criteria will soon be reached under natural conditions.

With an integrated systems-based approach, monitoring data can be collected to support alternative paths towards the end of monitoring by demonstrating system behavior, understanding and documenting trends, and understanding relations between monitored variables, remedy performance, and remedial goals. For example, low mass flux measurements from a source area could be used as an indicator that downgradient contaminant concentrations are not likely to increase over time.

LONG-TERM MANAGEMENT

Monitoring is often used as a tool for long-term management at complex sites where residual contamination will remain in place for several decades, centuries, or even longer. At these sites where remedial goals were met for the selected end state, monitoring is needed to ensure that desired conditions are maintained and/or to verify the slow dissipation of a contaminant plume. To implement long-term management strategies, environmental remediation site decision-makers need to clearly define their expectations for remedy performance for the selected end state, minimize the risk of reopening the remedy at a later time, manage costs, and use resources effectively, while managing contamination over the long-term.

Complex sites with technical limitations to cleanup (e.g., nature and extent of contamination, hydrogeologic setting) and other challenges (e.g., life cycle costs, sustainability impacts, resource consumption) require decision-makers to select an end state and agree to risk-based concentration limits and time frames that are protective of human health and the environment for future use of the site. These are alternatives for end states other than unrestricted use but may allow other activities to continue or resume, e.g., industrial or recreational activities that do not alter the subsurface contamination. Alternative end states have been used at a variety of complex sites in different cleanup programs to address remediation goals for surface water, groundwater, soils and sediment contamination (Malcolm Pirnie 2011a). Examples of formal ways to acknowledge remedial time frames and implement long-term management approaches include the use of technical impracticability (TI) waivers, "greater risk" and other Applicable or Relevant and Appropriate Requirements (ARAR) waivers, and a variety of state designations for groundwater management/containment zones. The cleanup program and underlying reason for the long time frame are used to determine which long-term management approach is most appropriate (Malcolm Pirnie 2011a). Case studies provide examples of the type of site conditions that may lead to an evaluation of alternative risk-based concentration limits and time frames, as well as tools and analyses used in site-specific evaluations to demonstrate their appropriateness and gain stakeholder support for their use (Malcolm Pirnie 2011a).

> TI waivers waive specific ARARs within a defined area. TI waivers are appropriate at CERCLA sites where achieving ARARs is not technically practicable, from an engineering perspective, within a reasonable time frame.
>
> Contamination is typically contained within a "TI zone" and monitored to make sure that ARARs will be met at all areas outside of the TI zone. Sites must demonstrate remedy protectiveness of human health and environment and must prepare a TI evaluation report in accordance with EPA requirements (EPA 1993).
>
> As of November 2010, 77 environmentally-contaminanted sites have used TI waivers, but no sites within the DOE complex have been granted a TI waiver (Malcolm Pirnie 2011a).

Most highly complex sites have implemented active remediation technologies at some point, either at full-scale or pilot-scale, to meet the remediation goals for the designated end state or other near-term cleanup goal or objective. A review of case studies (Malcolm Pirnie 2011a) identified the use of excavation, free product recovery, thermal treatment, in-situ chemical oxidation, bioremediation and air sparging/soil vapor extraction in conjunction with different alternative risk-based concentration limits and time frames, including TI waivers. Such end states, including TI waivers, have been used in combination with passive remediation (such as MNA) and with long-term management and/or containment approaches. Thus, the choice by decision-makers for end states other than unrestricted use is not an option that avoids remediation.

Monitoring strategies that are effective for short-duration remedies may be inefficient and costly for long-term management. Alternative strategies for monitoring should be considered, including sentinel or contingency monitoring programs, monitoring programs that are intended to detect change from baseline conditions, and/or other management strategies such as land use controls and exposure controls. Within the long-term monitoring phase, several phases of monitoring may be needed (e.g., establishing baseline monitoring conditions, identifying key master variables and leading indicators of change in the system, and contingency monitoring programs in the event of some change).

In summary, end states—such as unrestricted use or site closure with land use controls—often drive the selection of appropriate remedial objectives. Remedial objectives in turn define the type of monitoring (process, performance and long-term monitoring) required to measure progress towards remedial objectives and site closure, predict remedial time frames, and inform long-term monitoring programs at complex sites.

Conceptual Site Model

Regardless of the monitoring phase or the end state planned for the remediation site, development and refinement of the CSM is key to achieving remedial action and monitoring objectives. Integrated systems-based monitoring approaches are based upon the framework of the CSM. An effective integrated systems-based approach to monitoring can be used to develop the CSM; continually test and refine the CSM throughout planning, design, and remedy implementation; and respond to changes in the CSM by making subsequent changes to the monitoring program.

Various EPA guidance documents have been published that describe the CSM (e.g., EPA 1996, 2003, 2011b). Aspects of CSMs include the following that emphasize the importance of integrating the CSM with remedy selection, implementation, and management:

- The CSM provides the "ability to efficiently access and interpret data [which] is essential to guiding project teams through the entire cleanup process, from project planning to site completion. [The] creation and revision of a CSM [is] a primary project planning and management tool" (EPA 2011b). Environmental remediation is advanced through the CSM.
- The CSM includes both qualitative and quantitative descriptions of site-specific information, including the release and dispersal of contaminant(s), relevant properties of the environment and how contaminant(s) interact with the environment, contaminant fate and transport processes, and potential routes of exposure and impacts of the contamination to plants, animals and humans. This information is compiled in a structured format designed to support subsequent analyses, evaluations and decisions, including remedy selection, implementation and monitoring. The CSM documents current site conditions and is supported by maps, cross sections, and site diagrams (EPA 1996).
- The CSM is a "living" framework that continually evolves as data are collected and synthesized and as the focus of the CSM, monitoring objectives, and key decisions change throughout characterization and remediation. EPA describes this as the CSM life cycle (EPA 2011b).

Similarly, in an integrated systems-based approach, monitoring is directly related to developing the CSM or informing changes in the CSM over time. Environmental systems inherently possess high degrees of spatial and temporal variability. Integration of monitoring and the CSM is essential to incorporate large and complex data sets in a statistically meaningful way (Ward et al. 1990). For example, monitoring results can be used to make inferences about subsurface vadose zone conditions and inherent variability (EPA 2003). Data can be used to identify significant processes that are occurring in the natural or engineered environments. The CSM is a framework for interpreting data and incorporating new data into a refined understanding of system.

An integrated systems-based monitoring approach is designed to address data gaps or key uncertainties in the CSM. In this approach, monitoring parameters are identified to help constrain or reduce the variability or uncertainty, or provide an additional line of evidence to differentiate between multiple potential processes. As monitoring data are collected, the data can be used to verify or refine the CSM.

The monitoring approach and the CSM are also integrated with the phases of the remedy processes (Bartram and Balance 1996). Concurrent monitoring and associated refinements to the CSM guide the development of subsequent monitoring program objectives and the collection of appropriate decision-making data throughout each remediation phase (Figure 4). An effective integrated system-based monitoring program promotes this dynamic and iterative interaction between the CSM, monitoring approach and objectives, and remedy decisions throughout remediation.

It is also important to recognize that the CSM can be linked to predictive analyses to project how the system is expected to function over time to meet the remedial action objectives. Predictive analyses can be numerical models or calculations (e.g., water balance, mass discharge or mass flux analysis). Together, the CSM and the predictive framework help interpret data to predict and verify remedy performance. The current development of the Advanced Scientific Computing for Environmental Management (ASCEM) is an example of advanced computational methods that integrate the CSM and remedial objectives with predictive modeling

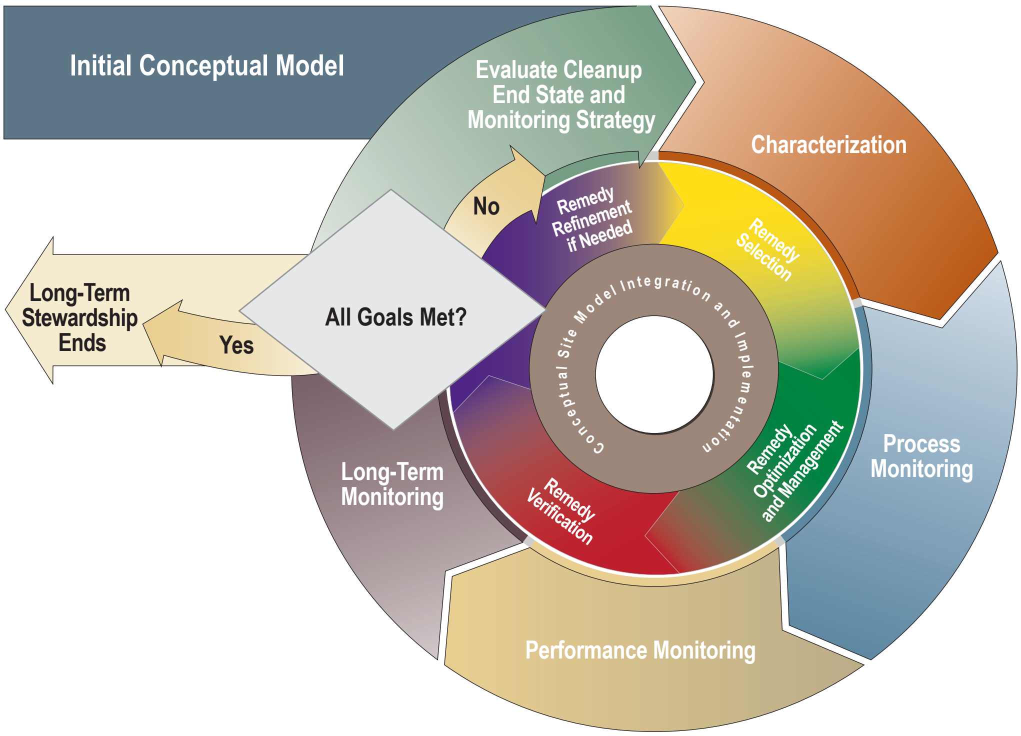

Figure 4. Systems-based monitoring framework integrating knowledge and process understanding provided through monitoring into the CSM and related remedy decisions

for subsurface fate and transport. Thus, integrated systems-based monitoring approaches also consider the data needs to conduct predictive analysis and evaluate remedy performance over time in relation to the predicted performance.

Lines of Evidence: An Integrated Systems-Based Monitoring Approach

Integrated systems-based monitoring approaches directly relate monitoring activities to key questions or objectives appropriate to each stage of remediation, as informed by the site-specific and evolving CSM. When approaching monitoring programs from this perspective, thinking in terms of lines of evidence can be useful for guiding data collection, making decisions, and refining the CSM and monitoring program accordingly.

In addition to measuring contaminant concentrations at compliance locations, monitoring can be designed to track the controlling elements identified in the CSM that govern contaminant fate and transport, remedy processes and/or remedy impact on contaminant fate and transport. This type of approach can provide multiple lines of evidence about the controlling elements that can be interpreted in terms of whether or not the processes identified for meeting natural or active remedy goals are occurring as intended. Key questions may also include gathering information needed to refine the CSM based on process or technical uncertainties identified as important to understand and monitor with respect to remediation and contaminant fate and transport. Additionally, monitoring can be tailored as appropriate for specific remedies and remediation phase.

Data to supply the multiple lines of evidence can be gathered using several different technologies, tools, approaches, media or environments, and can be integrated over various scales—from pore-scale measurements to watershed-scale information. Figure 5 illustrates how a site with contaminated groundwater might use the following lines of evidence to transition to long-term monitoring.

As an example, a monitoring approach that uses multiple lines of evidence is already well established and widely applied for MNA remedies for contaminated groundwater. The MNA monitoring approach uses lines of evidence, along with compliance monitoring components, to address the objectives specified within the "Implementation" section of the EPA Office of Solid Waste and Emergency Response (OSWER) Directive

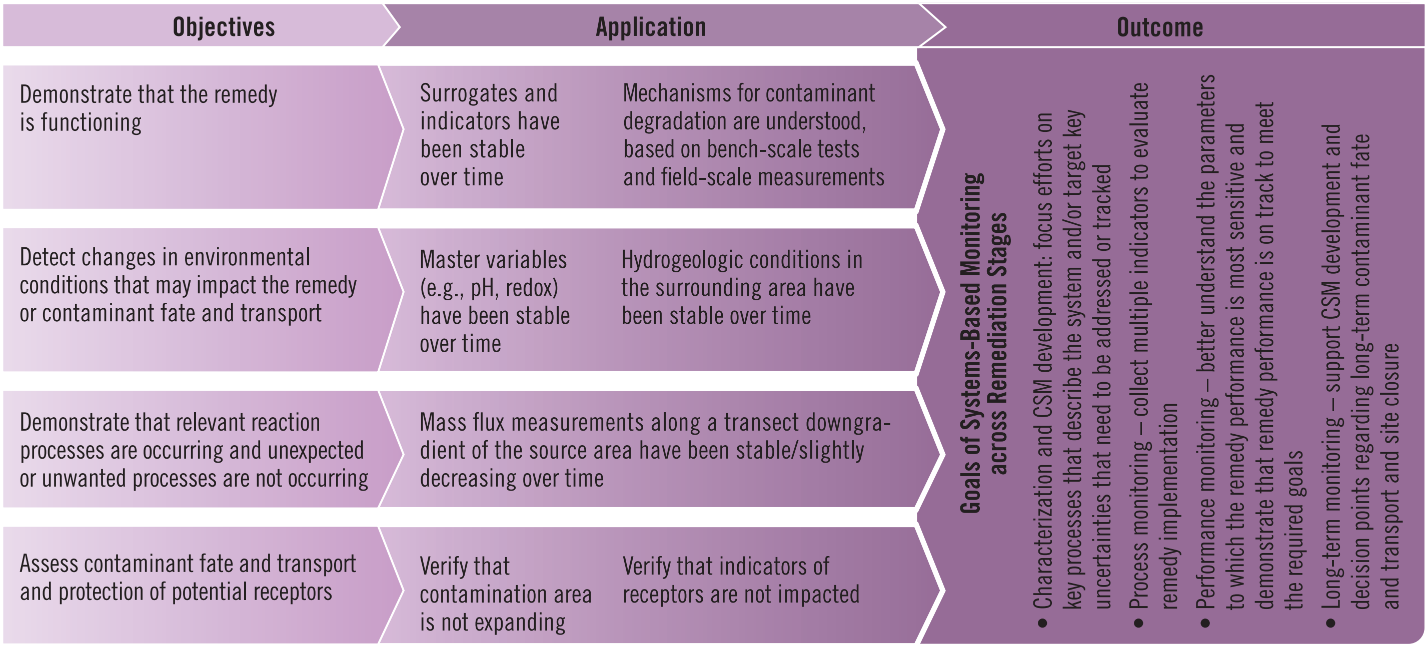

Figure 5. Example of lines of evidence for systems-based monitoring

9200.4-17P, "Use of Monitored Natural Attenuation at Superfund, RCRA Corrective Action, and Underground Storage Tank Sites" (EPA 1999). These objectives are extensions of the prescribed MNA remedy evaluation approach that is strongly based on CSM development and establishing appropriate attenuation process knowledge through multiple lines of evidence. Additional information related to implementing MNA and the associated monitoring programs have been developed and also follow a lines of evidence approach (EPA 1998, 2004b, 2007a, 2007b, 2010). The eight lines of evidence monitoring objectives specified in the OSWER directive are as follows:

1. Demonstrate that natural attenuation is occurring according to expectations
2. Detect changes in environmental conditions (e.g., hydrogeologic, geochemical, microbiological, or other changes) that may reduce the efficacy of any of the natural attenuation processes
3. Identify any potentially toxic and/or mobile transformation products
4. Verify that the plume(s) is not expanding (either downgradient, laterally or vertically)
5. Verify no unacceptable impact to downgradient receptor
6. Detect new releases of contaminants to the environment that could impact the effectiveness of the natural attenuation remedy
7. Demonstrate the efficacy of institutional controls that were put in place to protect potential receptors
8. Verify attainment of remediation objectives.

Lines of evidence can also be applied: 1) for remedies/technologies other than MNA; 2) for combinations of remedies/technologies, such as active remediation transitioning to MNA; and 3) to account for a broad range of hydrogeologic settings and media including vadose zone, groundwater, interfaces, and surface water systems. Regardless of the application, developing lines of evidence will enhance scientists' ability to view remedies as part of a bigger system and to define and evaluate overall performance with respect to remediation goals. In addition, when used as one of multiple lines of evidence, alternative indicators of system performance may be viable for remedy monitoring. Tools and technologies that can support a lines of evidence approach for various objectives, decision points, and environmental media are described in "Scientific and Technical Advancements that Support Systems-Based Monitoring Approaches".

Scientific and Technical Challenges and Opportunities for Implementing Systems-Based Monitoring Approaches

This section presents overall challenges and opportunities for advancing systems-based monitoring approaches within DOE. Monitoring configurations and approaches effective for long-term monitoring are a key opportunity for DOE to reduce overall environmental management costs. With many sites planning on use of remedies that leave waste in place, long-term monitoring will be required and it is important to adapt methods that make monitoring as effective and efficient as possible.

For an integrated systems-based monitoring approach, opportunities for monitoring were categorized for the four targeted monitoring segments (vadose zone, groundwater, groundwater/surface water interface, and surface water) based on the use of data in supporting the goals described in the previous sections and on the system characteristics for each segment. While the presentation of monitoring opportunities has been separated into different segments based on unique characteristics with respect to monitoring, a site monitoring program would holistically include all of the relevant segments as a total system.

CHALLENGES AND OPPORTUNITIES FOR VADOSE ZONE MONITORING

The vadose zone is the region of the subsurface between the land surface and the underlying water table. For this document, the remediation context for the vadose zone is for contaminants at depths below the limit of contact with surface receptors and is therefore based on exposure from transport of contaminants either to the surface (e.g., for vapor intrusion) or for groundwater protection. In this context, the vadose zone is a source zone and pathway for contaminant transport, upward to ground surface or downward to groundwater. Transport rates through the vadose zone depend on physical, chemical and biological properties of the vadose zone, contaminant properties, and on water flux conditions. As an example, a generalized depiction of the vadose zone is shown in Figure 6 for nonvolatile contaminants, where relative movement of water and contaminants (key targets for monitoring) are shown as functions of the type of interactions between contaminants and subsurface sediments. Monitoring the vadose zone may be applied for evaluating candidate waste disposal sites (i.e., before site activity commences) to evaluate remedy performance during implementation, or for understanding the effectiveness of remedies that leave contaminants in place (e.g., in situ vadose zone treatment, MNA, or use of surface barriers) and are implemented for long-term protection of groundwater (e.g., decades). For these applications, vadose-zone monitoring provides an opportunity to evaluate the remedy and verify performance before the media of concern (e.g., groundwater) are negatively impacted by contamination in the vadose zone.

Transport in the vadose zone is fundamentally different from groundwater transport and imposes monitoring challenges. For example, in the vadose zone: 1) oxidation state and reaction processes are affected by the presence of a gas phase, 2) there is a nonlinear relationship between water content and hydraulic conductivity that complicates water and contaminant flux, 3) subsurface interfaces can dramatically impact moisture and contaminant movement and distribution, and 4) preferred flow pathways can occur (e.g., dipping layers, vertical features or fractures). In addition, monitoring approaches commonly applied in the groundwater (e.g., water sampling from wells) are not possible in the vadose zone. Monitoring approaches must consider the unique features of the vadose zone and target configurations that take advantage of features and processes within the vadose zone.

Opportunities for New or Improved Vadose Zone Monitoring Techniques

Key targets for vadose zone monitoring techniques are to provide information that can: 1) quantify contaminant conditions as a leading indicator of potential future groundwater impact; 2) be interpreted in terms of a flux to groundwater; and 3) identify and monitor controlling features related to water and contaminant distribution, migration, and dissipation. In addition, monitoring of remedy processes may require information about moisture control, sequestration of contaminants, and contaminant transformation in addition to the above targets. Categories of potential monitoring technique efforts are listed in the following discussion.

- Recharge is a key parameter controlling water and contaminant flux to the groundwater. Advancements should consider use of remote sensing and threshold-based monitoring indicators for recharge over long time periods.
- The vertical and/or volumetric distribution of moisture and how it changes over time, or environmental parameters that affect moisture movement in the vadose zone are important for contaminant fate and transport. Advancements should consider: 1) configurations to target/identify controlling

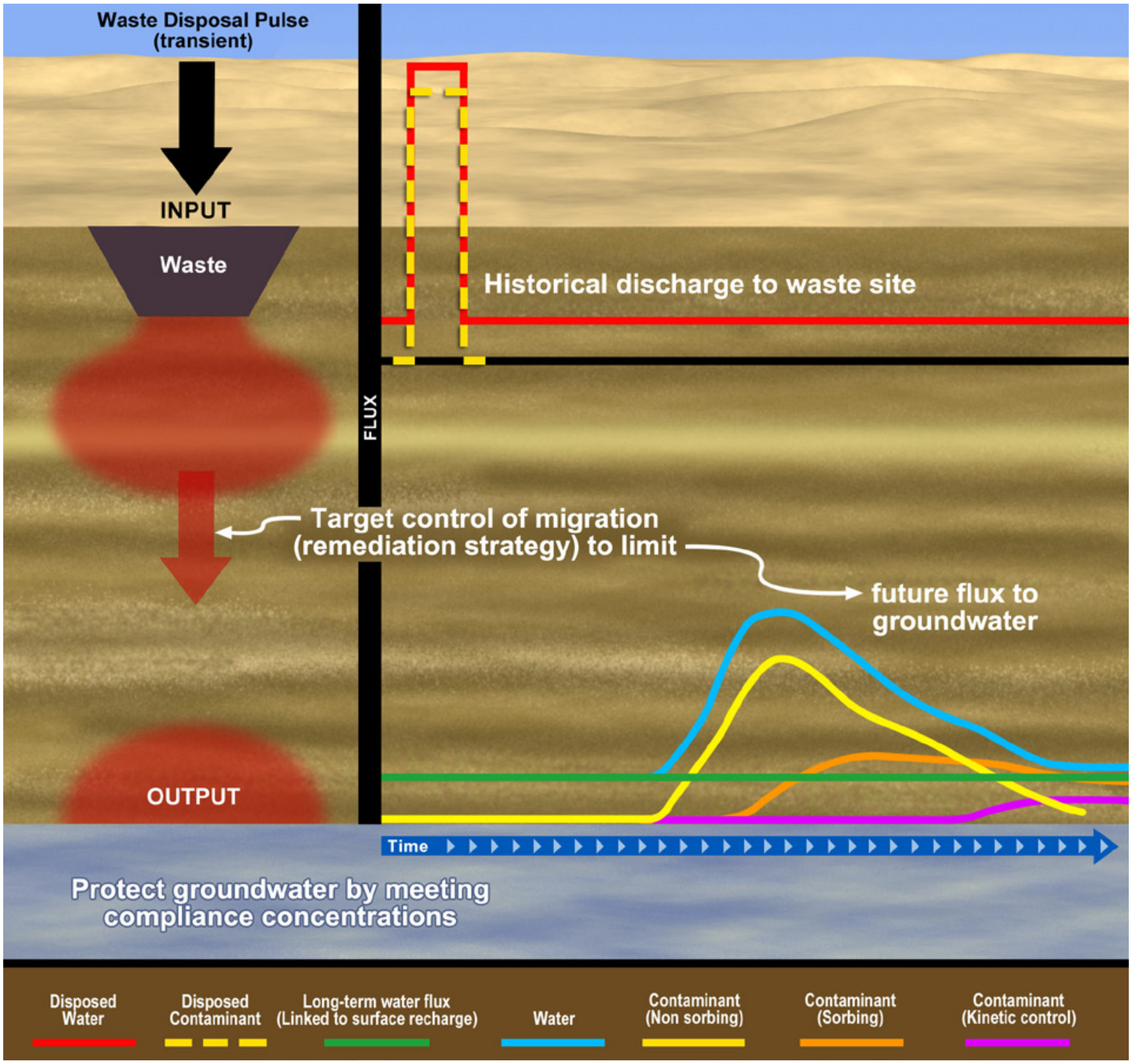

Figure 6. Generic depiction of the vadose zone for nonvolatile contaminants

features and moisture conditions across interfaces; 2) configurations and techniques that enable interpretation of geophysical monitoring data in terms of contaminant and/or water distribution and movement; and 3) identification of appropriate surrogate or indicators for contaminants (e.g., conductivity) that enable monitoring and interpretation in terms of contaminant distribution and flux.

- Biogeochemical conditions in the vadose zone that impact contaminant distribution and how it changes over time may be important to attenuation or mitigation approaches for contaminants. Monitoring of pore water chemistry and for interactions with sediments chemistry (e.g., changes associated with precipitation/dissolution processes) is relevant. Advancements should consider: 1) configurations that provide data for major pore water chemistry parameters; 2) use of biological monitoring systems/indicators; 3) configurations and techniques that enable interpretation of geophysical monitoring data in terms of pore water or sediment chemistry; and 4) techniques to monitor or interpret data for threshold changes in biogeochemical conditions relevant to contaminant flux to groundwater.
- Development of robust measurement approaches providing data that can be integrated to develop spatial information (e.g., flux and contaminant distribution).

Opportunities for Systems-Based Approaches with Vadose Zone Monitoring

Key targets for applying a systems-based approach and supporting enhanced system understanding are to provide: 1) site-specific relations between driving forces (e.g., recharge) and water/contaminant migration; 2) integration with the CSM for system understanding targeting system elements where data can reduce uncertainty, refine the CSM, and improve system understanding; 3) information to support lines of evidence techniques for system understanding; and 4) integration with predictive modeling where modeling data needs are addressed through collection of monitoring data and monitoring data are used to evaluate whether actual trends or other metrics match model predictions over time (i.e., increase confidence in performance projections). Categories of potential opportunities are listed in the following discussion.

- Using predictive analyses in conjunction with a CSM enables prediction of contaminant transport and the impact of remediation for planning purposes. This type of predictive analysis sets the overall context for vadose zone monitoring; for example, by providing a site-specific estimate for the temporal-dependent water and contaminant fluxes. Using predictive analyses with the CSM can also quantify the role of specific features and processes that control transport and the range of parameter values that are significant.
- Monitoring at or within controlling features and interfaces, or at moisture fronts, may provide responses that are more readily observed and quantified and thus would be important when considering conceptual model updating.
- Monitoring should be tied to refinement of the CSM, leading to reduced monitoring as conceptual model uncertainties are decreased.
- Monitoring design could consider not only quantifying contaminant flux to groundwater, but demonstrating retention of material in the vadose zone as a line of evidence that flux to the groundwater is low.
- Apply adaptive management and decision-support processes for monitoring that also facilitates stakeholder communication.

Configurations for Long-Term Monitoring of the Vadose Zone

Key targets and opportunities for improving configurations of monitoring systems for long-term application in the vadose zone are listed in the following discussion.

- Install infrastructure that allows subsurface access, but which has no embedded sensors, utilizes offsite calibration, and allows new monitoring technologies to be included in future monitoring programs
- Incorporate elements that capitalize on the inherently more dynamic, near-surface responses so that environmental responses can be observed on shorter time scales
- Incorporate elements that take advantage of the inherently less dynamic response in the deeper vadose zone, particularly slower responses as distance from boundaries increase
- Install robust emplaced geophysics electrodes (e.g., for electrical resistivity tomography) that can be pulsed periodically
- Apply remote and threshold monitoring of system indicators
- Target controlling features and boundary conditions for monitoring of established thresholds or triggers that relate to contaminant flux
- Use surrogates for contaminants that can be more readily monitored with the above techniques.

CHALLENGES AND OPPORTUNITIES FOR GROUNDWATER MONITORING

The groundwater zone is typically defined as the water-saturated volume of the subsurface. Groundwater may be present in permeable (aquifers) or impermeable (confining or aquitard) formations and there may be multiple formations at a particular site. In addition, there may be smaller-scale impermeable layers or lenses within a generally permeable (aquifer) formation. Groundwater is a pathway for potential contaminant migration to receptors (e.g., surface water or downgradient wells) and may also be the compliance point for the remediation goal in terms of diminishing any existing plume. Contaminant migration and plume behavior depend on physical, chemical and biological properties of the saturated zone, contaminant properties, and on hydraulic conditions. As an example, a generalized depiction showing examples of contaminant migration and plume behavior scenarios that may need to be addressed by monitoring are shown in Figure 7. Monitoring may be applied to: 1) track contaminant movement, 2) quantify source flux into the downgradient plume, 3) assess remedy processes and performance, 4) provide information useful to enable prediction of future contaminant movement, or 5) verify subsurface conditions related to remediation or long-term plume behavior. For each application, monitoring typically needs to provide information to help demonstrate protection of receptors

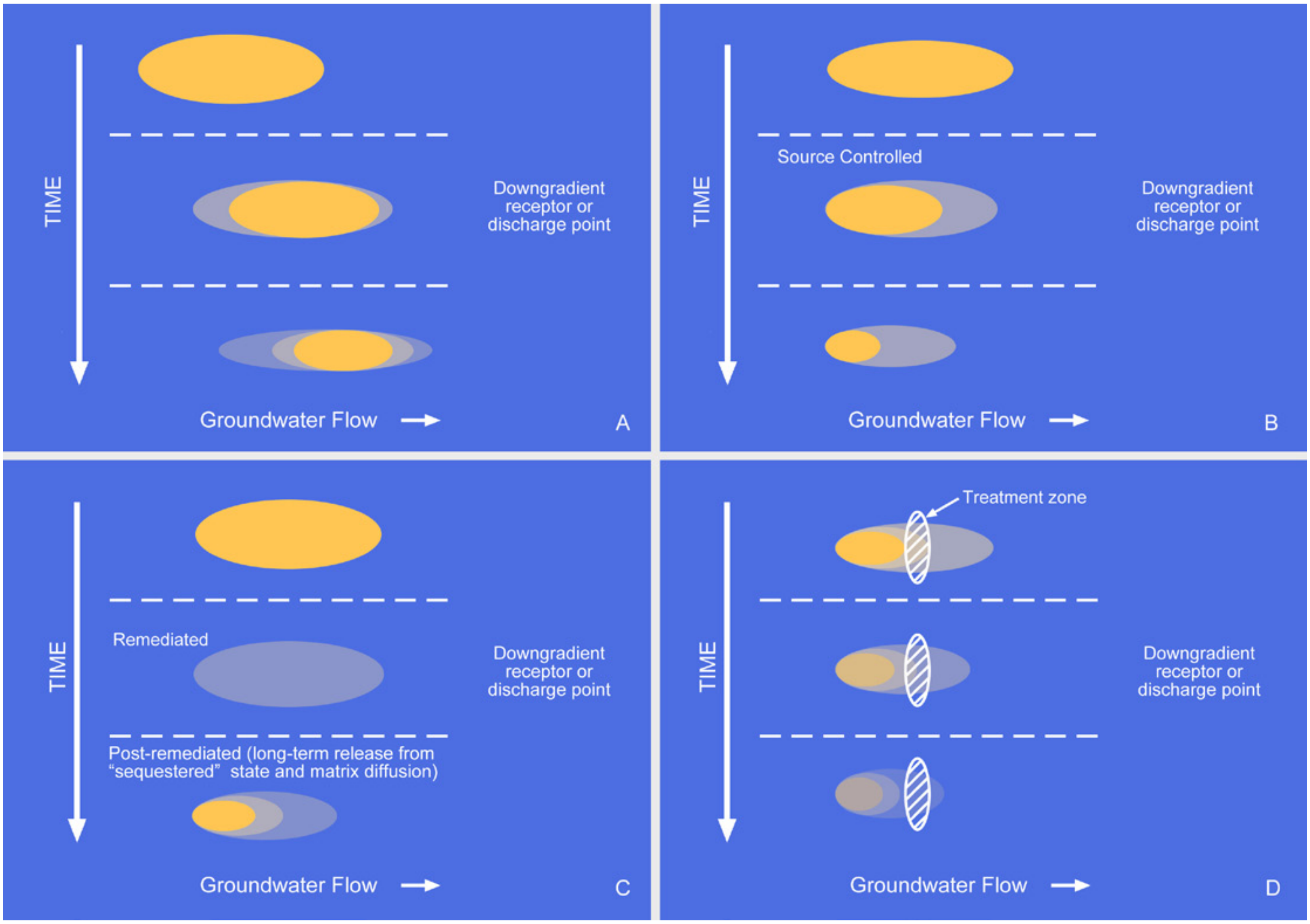

Figure 7. Conceptual top-view depiction of groundwater contaminant migration and plume behavior scenarios that may need to be addressed by monitoring. A) Natural attenuation diminishing a plume detached from a source. B) Plume diminishing from source reduction. C) Potential long-term plume behavior after remediation. D) Potential configuration for an active plume treatment

(e.g., contaminant migration and plume control) and confirm reaching goals associated with future beneficial use of the groundwater (e.g., plume dissipation).

Even within a single, hydraulically-connected groundwater zone, there is rarely a homogeneous distribution of groundwater flow. These variations in flow regimes and heterogeneity in physical and chemical processes that impact contaminant and/or remediation processes create challenges for monitoring, especially in translating information from a specific monitoring location to information about the spatial three-dimensional behavior of the contaminant or remediation process (e.g., fluxes and flux distribution). Additionally, reliance on standard monitoring well sampling and analysis for contaminant concentrations in groundwater may not be appropriate for all situations and may be costly, especially for long-term monitoring. However, use of monitoring wells is a traditional approach already established at most sites and efforts are needed to justify alternatives.

Opportunities for New or Improved Groundwater Monitoring Techniques

Key targets for groundwater monitoring techniques are to provide information that can: 1) provide leading indicators of potential contaminant migration; 2) be interpreted in terms of a flux for use in evaluating source or plume conditions and contaminant migration; and 3) identify and monitor controlling features related to contaminant distribution, migration, and dissipation and how these contribute to natural attenuation. Additionally, monitoring of remedy processes may require information about sequestration of contaminants, contaminant transformation, matrix diffusion, and hydraulic control in addition to the above targets. Categories of potential monitoring technique efforts are listed in the following discussion.

- Understanding the distribution of contaminants and how the distribution changes over time is a key monitoring goal. Advancements should consider: 1) configurations to target/identify controlling features and contaminant transport across interfaces (e.g., matrix diffusion); 2) configurations and techniques that enable interpretation of geophysical monitoring data in terms of contaminant distribution and movement and groundwater flow; and 3) identification of appropriate surrogate or indicators for contaminants (e.g., conductivity) that enable monitoring and interpretation in terms of contaminant distribution and flux.
- Biogeochemical conditions that impact the contaminant distribution and how it changes over time may be important to attenuation or mitigation approaches for contaminants. Monitoring for groundwater chemistry and for interactions with sediment chemistry (e.g., changes associated with precipitation/dissolution processes) is relevant. Advancements should consider: 1) configurations that provide data for "master variables" or the key variables that control the chemistry of the groundwater system; 2) use of biological monitoring systems/indicators; 3) configurations and techniques that enable interpretation of geophysical monitoring data in terms of groundwater or sediment chemistry; and 4) techniques to monitor or interpret data for threshold changes in biogeochemical conditions relevant to contaminant flux.
- Boundary conditions producing and controlling groundwater flow and biological-chemical distribution and transport can be a useful monitoring target. Temporal changes in boundary conditions can be linked to both the distribution of contaminants and groundwater flow.
- Integration of innovative measurements and approaches, such as boundary conditions and geochemical master variables with traditional monitoring well data into an overall systems-based monitoring approach with the goal of improving system understanding and reducing overall monitoring cost.
- Development of robust measurement approaches providing data that can be integrated to provide spatial information (e.g., flux and contaminant distribution) and evaluation of key remedy elements such as source control (e.g., managing the source flux into the downgradient plume).
- Development of statistical tools that can be used to optimize monitoring (blend data types and determine best value of information).

Opportunities for Systems-Based Approaches with Groundwater Monitoring

Key targets for applying a systems-based approach and supporting enhanced system understanding are to provide: 1) site-specific relations between driving forces (e.g., boundary conditions) and water/contaminant movement; 2) integration with the CSM for system understanding targeting system elements where data can reduce uncertainty, refine the CSM, and improve system understanding; 3) information to support lines of evidence techniques for system understanding; and 4) integration with predictive modeling where modeling data needs are addressed through collection of monitoring data to evaluate whether actual trends or other metrics match model predictions over time (i.e., increase confidence in performance projections). Categories of potential opportunities are listed in the following discussion.

- Using predictive analyses in conjunction with a CSM enables prediction of contaminant transport and the impact of remediation for planning purposes. This type of predictive analysis sets the overall context for groundwater monitoring; for example, by providing a site-specific estimate for the temporal-dependent groundwater and contaminant fluxes. Using predictive analyses with the CSM can also quantify the role of specific features and processes that control transport and the range of parameter values that are significant. Integrating monitoring with predictive analyses can be used to evaluate heterogeneity and complexity as well as natural attenuation capacity.
- Monitoring at or within controlling features and interfaces may provide responses that are more readily observed and quantified and thus would be important when considering conceptual model updating.
- Monitoring should be tied to refinement of the CSM, leading to reduced monitoring as conceptual model uncertainties are decreased.
- Applying adaptive management and decision-support processes for monitoring that also facilitates stakeholder communication.

Configurations for Long-Term Monitoring of Groundwater

Key targets and opportunities for improving configurations of monitoring systems for long-term application in the groundwater are listed in the following discussion.

- Install robust emplaced geophysics electrodes (e.g., for electrical resistivity tomography) that can be pulsed periodically.
- Apply remote and threshold monitoring of system indicators such as for boundary conditions.
- Target controlling features and boundary conditions for monitoring of established thresholds or triggers that relate to contaminant and/or source flux.
- Use surrogates for contaminants and target master variables that can be more readily monitored with the above techniques.

CHALLENGES AND OPPORTUNITIES FOR MONITORING GROUNDWATER/SURFACE WATER INTERFACES

The groundwater/surface water interface is the region of the subsurface beneath the bottom of a surface water body where conditions change from a groundwater dominated system to a surface water dominated system (Figure 8). The interface includes the entire region where spatial and temporal interchanges of groundwater and surface water occur, including hyporheic zones, where groundwater enters and mixes with the surface water and then reenters the groundwater. Bank storage occurs when surface water enters the subsurface and accumulates above the groundwater table. The groundwater/surface water interface typically is a complex region—chemically, physically, and biologically. The ecological importance of hyporheic zones was realized when studies in the 1990s

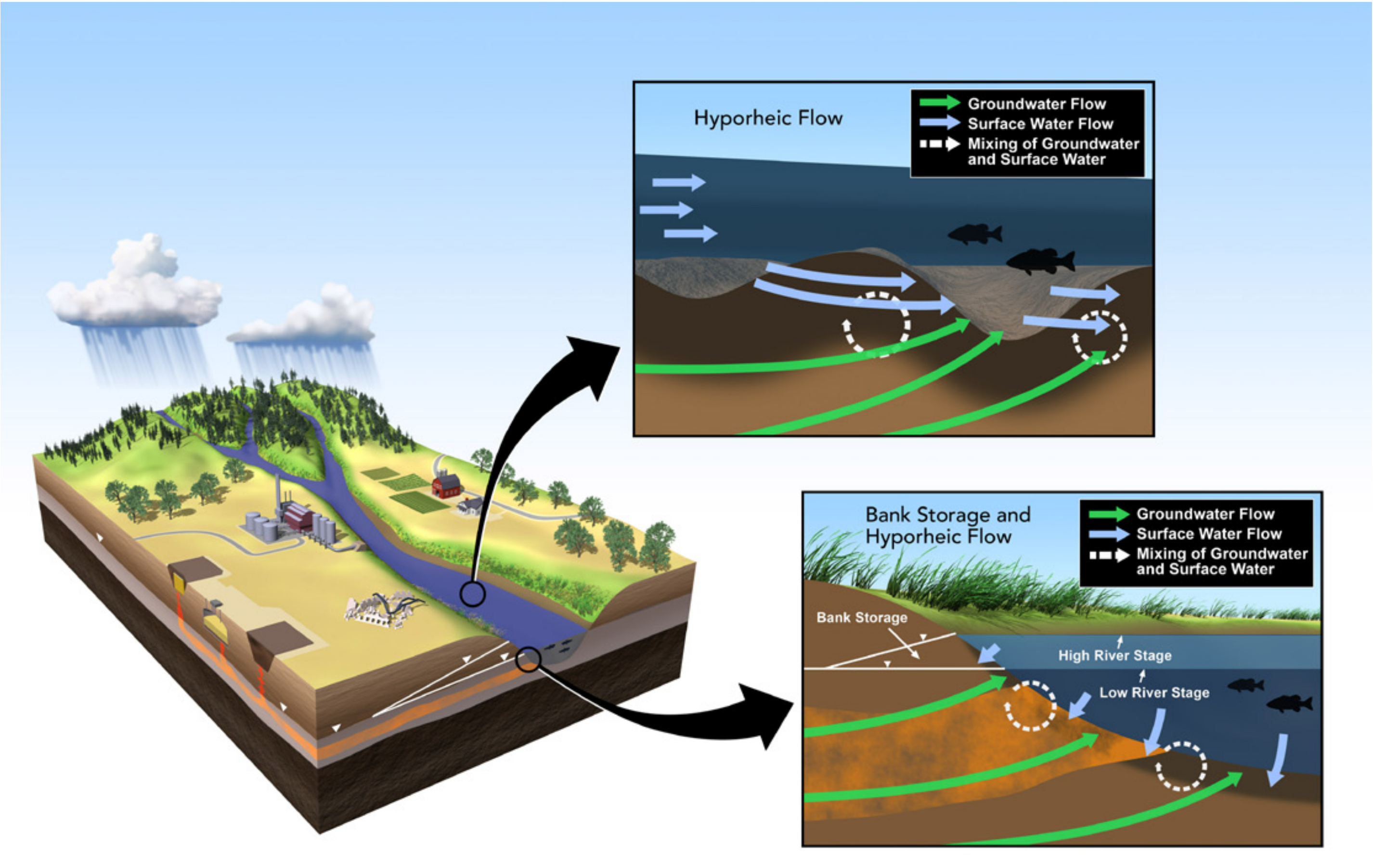

Figure 8. Groundwater/surface water interface can be highly variable through a watershed and can include hyporheic zones as well as bank storage

demonstrated that salmonoid species seek out hyporheic regions in rivers for construction of their redds, ensuring their eggs and alevin develop in nutrient – and oxygen-rich substrate (Geist and Dauble 1998). The groundwater/surface water interface is a dynamic pathway for contaminant transport for both groundwater and surface water. Transport of contaminants at the groundwater/surface water interface can also impact the vadose zone. For example, contaminants in groundwater or surface water can be spread in the vadose zone near a fluctuating river due to bank storage.

Monitoring of the groundwater/surface water interface is challenging, primarily due to the potential for highly dynamic hydraulic conditions and wide variability in biogeochemical conditions. Both the hydraulic gradients of the groundwater and surface water influence the interface zone and need to be interpreted in conjunction with an understanding of the temporal and spatial variability of the region. Geochemical conditions in the groundwater and surface water, and associated impacts on contaminants, may change dramatically as water passes through regions of varying dissolved oxygen, reduction-oxidation conditions, and organic matter. Geomorphic features in the region may influence hydraulic conditions (e.g., creating hyporheic zones) and increase or decrease mixing of the groundwater and surface water. The importance of the groundwater/surface water interface may depend on the phase of monitoring, the need for completeness of the CSM, and the relationship of the region to the remedial action and remedy goals.

Opportunities for New or Improved Monitoring Techniques in the Groundwater/Surface Water Interface

Key targets for groundwater/surface water interface monitoring techniques are to provide information that can: 1) provide indicators of potential contaminant discharge; 2) be interpreted in terms of a flux for use in evaluating contaminants fate and transport within and/or across the interface; and 3) identify and monitor controlling features related to contaminant distribution, migration, and dissipation and how these contribute to natural attenuation. In addition, monitoring of remedy processes may require information about sequestration of contaminants, contaminant transformation, matrix diffusion, and hydraulic control in addition to the above targets. Consideration of these key targets is depend on the type of groundwater/surface water, particularly in dynamic regions (e.g., frequently fluctuating surface water regions). Categories of potential monitoring technique efforts are listed below.

- Hydraulic gradient is a key parameter controlling water and contaminant flux in the groundwater/surface water interface. Advancements should consider use of tools for measuring the hydraulic gradient across wider areas of the interface and over time.
- Biogeochemical conditions of the groundwater/surface water interface are dynamic and impact contaminant distribution and how it changes over time. Advancements should consider: 1) configurations that provide data for "master variables" or the key variables that control the chemistry of the groundwater system; 2) use of biological monitoring systems/indicators; 3) configurations and techniques that enable interpretation of geophysical monitoring data (or remote sensing tools) in terms of groundwater and/or surface water chemistry; and 4) techniques to monitor or interpret data for threshold changes in biogeochemical conditions relevant to contaminant flux.
- Boundary conditions producing and controlling flow in the interface and biological-chemical distribution and transport can be a useful monitoring target. Temporal changes in boundary conditions can be linked to both the distribution of contaminants as well as groundwater and surface water flow.
- Development of robust measurement approaches providing data that can be integrated to provide spatial information (e.g., flux and contaminant distribution).
- Development of statistical tools that can be used to optimize monitoring (blend data types and determine best value of information).

Opportunities for Systems-Based Approaches with Monitoring the Groundwater/Surface Water Interface

Key targets for applying a systems-based approach and supporting enhanced system understanding to the groundwater/surface water interface are to provide: 1) site-specific relations between driving forces (e.g., boundary conditions) and water/contaminant movement; 2) integration with the CSM for system understanding targeting system elements where data can reduce uncertainty, refine the CSM, and improve system understanding; 3) information to support lines of evidence techniques for system understanding; and 4) integration with predictive modeling where modeling data needs are addressed through collection of monitoring data that are used to evaluate whether actual trends or other metrics match model predictions over time (increase confidence in performance projections). Categories of potential opportunities are listed in the following discussion.

- Using predictive analyses in conjunction with a CSM enables prediction of contaminant transport and the impact of remediation for planning purposes. This type of predictive analysis sets the overall context for groundwater/surface water interface monitoring; for example, by providing a site-specific estimate for the temporal-dependent groundwater and/or surface water monitoring, and contaminant fluxes. Using predictive analyses with the CSM can also quantify the role of specific features and processes that control transport and the range of parameter values that are significant. Integrating monitoring with predictive analyses can be used to evaluate heterogeneity and complexity across the spatial and temporal boundaries of the affected area.
- Monitoring at or within controlling features and interfaces may provide responses that are more readily observed and quantified and thus would be important when considering conceptual model updating.
- Monitoring should be tied to refinement of the CSM, leading to reduced monitoring as conceptual model uncertainties are decreased.
- Applying adaptive management and decision-support processes for monitoring that also facilitates stakeholder communication.

Configurations for Long-Term Monitoring of the Groundwater/Surface Water Interface

Key targets and opportunities for improving configurations of monitoring systems for long-term application in the groundwater and surface water interface are listed in the following discussion.

- Target controlling features of the groundwater/surface water interface that are appropriate for the remedial decisions and cannot be evaluated in regions outside of the interface.
- Select tools appropriate for the groundwater/surface water interface that target controlling features of the interface. Consider tools that are appropriate for the flows of the system (e.g., in fast flowing regions, remote sensing tools may be only option for longevity and safety).

CHALLENGES AND OPPORTUNITIES FOR SURFACE WATER MONITORING

The surface water system near many environmentally contaminated sites can cover large geographic areas with contaminant-related impacts in surface waters extending far from the original contaminant source areas (Figure 9). Contaminants commonly enter surface water systems via facility effluent discharges, storm drains, soil runoff, groundwater seeps, or hyporheic flows. After a contaminant enters the stream or other water body, surface water flow becomes an important contaminant transport pathway to more downstream environments and media, including stream and reservoir sediments, bank soils, and floodplains. Contaminant distribution is thus multifaceted and dynamic, and the form, fate, and human and ecological risks of contaminants can vary dramatically from one site to the next depending on in-stream controlling variables. Biological controls are important aspects of surface water systems: microbial communities can enhance bioavailability or convert contaminants to more toxic forms (e.g., generation of methylmercury), and aquatic organisms can bioaccumulate and biomagnify contaminants that can negatively impact human and terrestrial wildlife receptors.

The challenge of surface water monitoring programs is to adequately capture the complexities of DOE contaminant related impacts in the context of potentially large-scale, highly variable, and complex surface water systems. Some of the challenges for monitoring surface water systems include: 1) developing conceptual and quantitative models that adequately consider contaminant concentration, flux, and resultant risks across large and complex spatial gradients; 2) quantifying surface water contaminant flux in industrial subsurface transport pathways or lotic systems affected by high storm flow (without building weirs or dams); 3) determining clear causes of surface water impacts (i.e., source attribution) and the role of in-stream mechanisms and variables affecting water quality or bioaccumulation; 4) using appropriate, time averaged and cost-effective monitoring tools to assess human and ecological health, biological criteria, and nonpoint source problems (erosion, siltation, habitat effects); and 5) considering and enhancing regulatory and stakeholder communications for effective remedial decision-making.

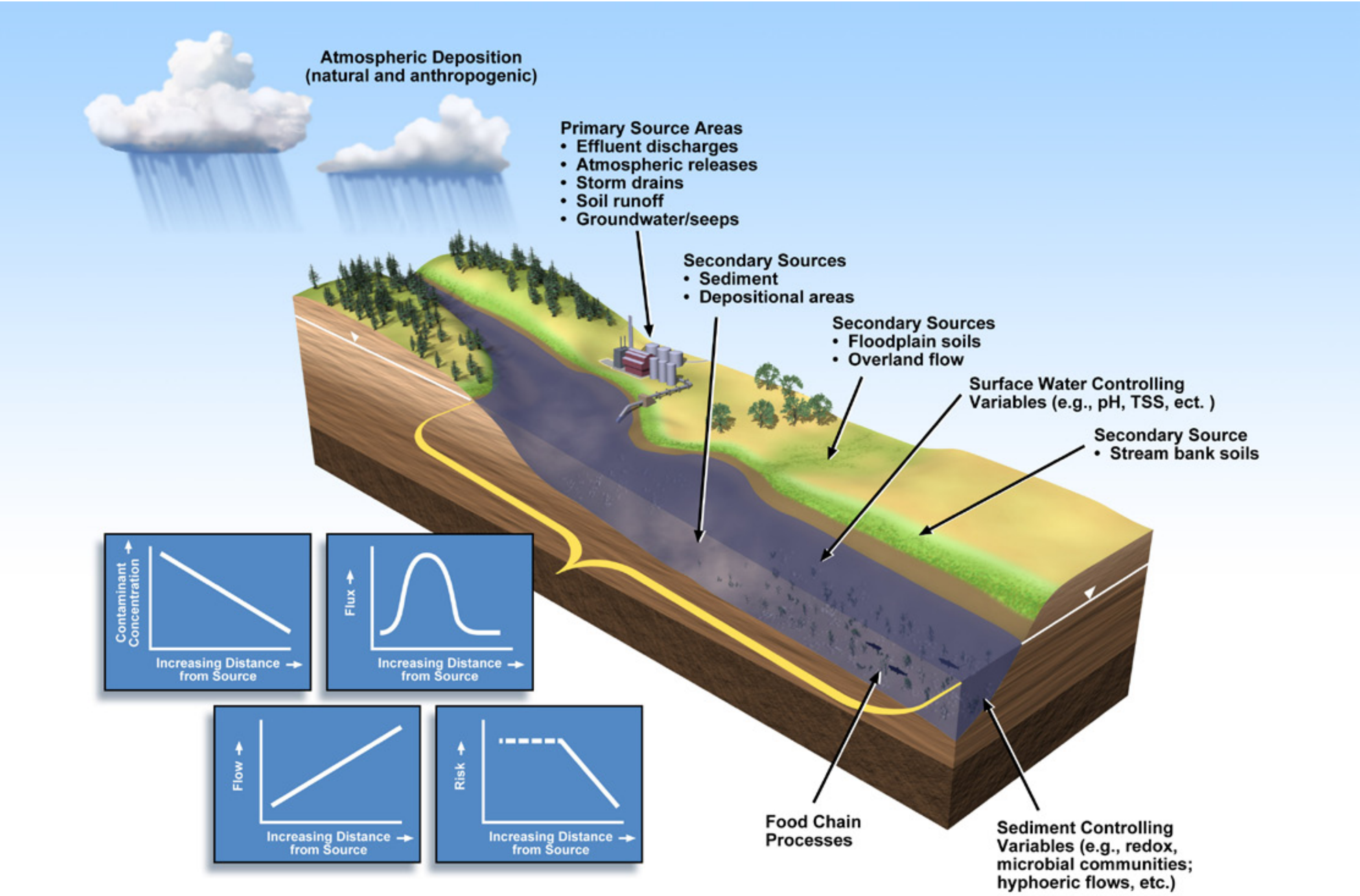

Figure 9. Spatial connectivity of major contaminant source areas, transport pathways, and in/stream processes in surface water systems

Opportunities for New or Improved Surface Water Monitoring Techniques

The most effective monitoring programs and techniques are those that are applicable to the contaminant source or remedial actions undertaken, maintain consistency in methods while also incorporating new knowledge or research, and are flexible and adaptable in design such that actionable monitoring information is available to make any prudent changes to environmental management and remediation strategies. The selection of some monitoring tools to characterize the system's contaminant distribution, migration, and dissipation can include consideration of staff's time for monitoring activities or cost needs (e.g., flux measurement tools, remote sensing). Other tools may be especially valuable in understanding remedy processes and performance (e.g., time-averaged biological metrics). Because of the complexities of surface water systems, surface water monitoring frameworks with the most interpretive power are those that use multiple lines of evidence approaches.

New tools, technologies, or strategies that were highlighted previously and considered most applicable to surface water include the following:

- Biomarkers
- Remote sensing
- Flux measurement tools
- Data management and modeling.

Opportunities for Systems-Based Approaches with Surface Water Monitoring

There are numerous surface water monitoring approaches and decision support strategies presented in the scientific literature. Clearly, there is not a "one size fits all" approach to surface water monitoring in part because of the highly variable and complex nature of surface water systems, and also because of the different site-specific goals and needs of each monitoring program. There are, however, key aspects of a surface water monitoring framework that should be considered in all approaches, and potential opportunities for improving those frameworks. Categories of potential opportunities include the following:

- A good surface water monitoring program should start with planning and defining clear goals. Potential monitoring goals specific to surface water could include evaluating the achievement of surface water regulatory standards; conducting remedial performance assessment or evaluating the recovery; or identifying impairment. Early planning should include the use of conceptual or quantitative predictive models, and a framework for future decision-making.
- Monitoring design should move away from short-term, point source evaluations to longer-term, watershed sampling at key integration points. A systems-based approach to surface water could reduce the number and cost of samples while still maintaining statistical or interpretive power.
- The results of surface water monitoring are routinely fed into a data evaluation process, ideally defined in the planning phase. The ability to discern long-term monitoring trends is strengthened by a well-designed spatial and temporal strategy using multiple monitoring tools and lines of evidence.
- Surface water monitoring programs need to be integrated across media types, monitoring programs, watershed facilities and organizations, and stakeholders. Perhaps more than any other system, a coordinated program and effective stakeholder communication strategy is needed for remedial prioritization and decision-making.
- An adaptive management approach is advocated such that monitoring results feed into two potential management outcomes: 1) monitoring is continued, revised, or ended, consistent with an adaptive management approach; or 2) a management action is conducted (e.g., the source or problem is eliminated or controlled).

Configurations for Long-Term Monitoring of Surface Water

The surface water monitoring configuration of the future may include a number of valuable elements and characteristics consistent with the systems-based approach.

- Key characteristics of an optimized surface water monitoring framework include being watershed based, spatially and temporally explicit, consistent and repeatable, quantitative, and multidisciplinary.
- Future configurations must balance consistency of methods with the need to incorporate new tools and strategies that might provide more useful information at less cost.
- Future monitoring systems need to include assessments of contaminant flux along with concentrations to define point source and downstream boundary conditions, and to better define relative source loading.
- Remote technologies may offer new ways to evaluate aquatic impacts and provide opportunities for real time monitoring results at less cost.
- Given the multiple and complex stressors affecting surface water systems, causal tools such as biomarkers may provide an opportunity to separate out DOE-related anthropogenic sources from other watershed sources or stressors, or natural variation.

Substantial improvements to long-term monitoring configurations can be attained with improved planning and conceptual model approaches, predictive and statistical approaches to data evaluation, and stronger regulator and stakeholder communication strategies and remedial decision support tools.

Scientific and Technical Advancements that Support Systems-Based Monitoring Approaches

A variety of existing monitoring approaches, methodologies, and tools can be used to support systems-based monitoring. Through the process of developing this document, the interdisciplinary group of authors and contributors developed a list of approaches that can be used to support systems-based monitoring and afford the opportunity for additional scientific and technical advancements:

- Surrogates and indicators, including biological, chemical and physical-based measurements
- Geophysical assessment
- Predictive analysis tools, ranging from parametric analyses to detailed analytical and numerical models
- Mass flux/mass discharge measurements
- Bioassessment
- Information management tools, including analytical and geospatial database systems

SURROGATES AND INDICATORS

Surrogates are parameters or analytes that are measured in place of target compounds, due to their correlation with target compounds, such as similar distribution and behavior. For example, if specific conductance is well correlated to contaminant concentration or presence, specific conductance can be monitored as a surrogate for the contaminants. Indicator parameters are physical, biological or geochemical conditions that are measured to provide information about remedy performance, contaminant transport, or some other topic of interest. For example, pH or oxidation-reduction potential may be indicators of remedy performance for in-situ biodegradation. Remote imaging of watershed vegetation leaf area or stream gauge data may be used as an indicator of rainfall measurements. It is typically easier or less costly to monitor surrogate parameters or analytes compared with target parameters or analytes. In addition, surrogates and indicators may provide leading indicators of remedy performance that can be used to predict contaminant migration and trigger action to prevent migration from occurring. In contrast, measuring contaminant concentrations is always a lagging indicator of remedy performance because migration is already occurring when the contaminant is first detected.

Surrogates and indicators can provide potential opportunities for use in an integrated systems-based monitoring program (Gilmore et al. 2006), as a tool to directly support monitoring objectives, verify or refine the CSM, or as a line of evidence for characterization and/or decision making. Examples of ways that surrogates and indicators can be used as one component in an integrated systems-based approach include the following:

- Replace or reduce the frequency of monitoring for more expensive parameters (e.g., specific conductance instead of a suite of parameters).
- Serve as leading indicators (i.e., sentinels) for contaminant fate and transport or remedy processes (e.g., changes in pH or redox potential).

SURROGATES AND INDICATORS

Desired Capability: Surrogates and indicators are monitored in place of target parameters to provide cost-effective information on contaminant distribution and migration, environmental conditions affecting fate and transport, and/or remedy performance. Monitoring surrogates/indicators are used to detect changes in the environment or provide leading indicators that predict future contaminant fate and transport.

Current Approach: Surrogates/indicators such as pH, dissolved oxygen, temperature, geochemical parameters (e.g., ferrous iron), specific conductivity, and total organic carbon are measured at monitoring wells and used to interpret local subsurface conditions. Additionally, introduced tracer compounds or isotopic tracers are used as part of specific tests to evaluate flow or reaction conditions, typically interpreted for characterization, not monitoring purposes.

	Targeted Advancements
System-Based Capabilities	Develop methods to interpret monitoring results for surrogates/indicators in terms of remedy performance, contaminant distribution and migration, as a line of evidence, and/or in conjunction with predictive analyses to support remedy or monitoring decisions.
	Demonstrate use of surrogates/indicators for system-based monitoring to support regulatory acceptance and technology transfer.
Applied Capabilities	Establish a functional relationship between surrogate/indicator response and the target analyte or system parameter.
	Identify the threshold and resolution for measuring surrogate/indicator responses with respect to relevant change(s) in system parameters.
	Develop and validate monitoring techniques and configurations to measure the surrogate/indicator at reduced cost or with improved temporal or spatial information compared to the baseline approach for the target analyte or system parameter.
Fundamental Capabilities	Identify new surrogates/indicators and associated monitoring processes for important target analytes and system parameters.

Figure 10. Current approaches and capabilities for surrogates and indicators

- Detect changes from baseline or desired conditions and triggering actions should these changes occur (e.g., if rainfall is above an acceptable range, inspections will be conducted).
- Serve as a line of evidence for contaminant fate and transport or in-situ remedy performance (e.g., biological techniques that quantify microbial presence, species and functional genes; changes in geochemical parameters).
- Track the progress of processes that are difficult to measure. For example, ammonia gas can be added to the vadose zone to temporarily increase the pH of pore water, dissolve existing precipitates and minerals, and form new precipitates that sequester contaminants as the pH declines. Geophysics has been applied to measure the associated changes in conductivity and chargeability that occur during this process.
- Provide data that can guide other elements of the characterization or monitoring program. For example, geophysical surveys can provide information on the distribution of contaminants, moisture, or hydrogeologic properties.
- Address monitoring objectives that are related to large-scale issues or factors that can impact site conditions. For example, remote sensing for vegetation leaf area or watershed stream gauge data can be an indication of rainfall.

Several types of surrogates/indicators have been applied or are being developed and offer potential for continued use and development as part of applying a systems-based monitoring program. An example of the current and desired approach for systems-based monitoring with surrogates and indicators is discussed in Figure 10.

GEOPHYSICAL ASSESSMENT TOOLS

The overall objective of geophysical assessment tools is to provide spatial subsurface information (Figure 11). These tools and techniques can be used for a wide range of environmental site characterization and remediation applications. Geophysical measurements can be collected using airborne, surface, and/or downhole tools and techniques. Geophysical measurements provide a more thorough understanding of the interplay and continuity of various subsurface materials and how these materials collectively influence contaminant fate and transport in the environment (e.g., lithologic contacts, hydrologic boundaries, structural irregularities, and localized anomalies).

Geophysical measurements are indirect, and therefore rarely produce specific tactile measurements. Although not as precise or detailed as invasive borehole sampling, most geophysical and remote sensing methods are solidly grounded in theory and have empirically proven to be useful and effective in identifying where changes in subsurface properties (indicative or natural or engineered processes) are occurring. These methods are commonly used in conjunction with invasive borehole measurements, either to identify where invasive samples are needed or to get more information about spatially undersampled zones typically found between widely spaced or gridded boreholes. Most applications use invasive borehole studies to identify specific subsurface characteristics at a catchment or smaller site.

There may be several plausible ways to interpret or characterize the subsurface from any single geophysical or remote sensing data set (“nonuniqueness”). Joint analysis of data from several methods or sources (geophysics, remote sensing, invasive sampling, physical or numerical models, etc.) can help reduce the range of possibilities of subsurface conditions and thereby improve the accuracy of well-to-well correlations.

Geophysical assessment tools can be used in a systems-based approach to characterization monitoring, process monitoring, performance monitoring, or long-term monitoring. When used during characterization monitoring, geophysical assessment tools are used to detect and quantify some physical property, whereas their use during process monitoring would likely focus on detecting and quantifying change. Geophysical assessments can provide subsurface information over a regional scale at a relatively low cost. Geophysical assessments can be used to test or verify a CSM, primarily with regard to the fate and transport of aqueous-phase contamination (surface, vadose, and aquifer). When used in conjunction with other monitoring methods, geophysical assessments can provide a line of evidence in support of the conceptual understanding of remedial processes and contaminant behavior, fate and transport in the environment.

GEOPHYSICAL ASSESSMENTS

Desired Capability: Geophysical monitoring data are used directly or as a line of evidence to estimate contaminant movement and/or remedy performance to inform remediation and monitoring decisions. Geophysical monitoring data provide system-level information that can be interpreted in terms of maintaining the conditions necessary to remediation goals.

Current Approach: Geophysical measurements have been applied for subsurface characterization of site conditions or contaminant extent. Limited applications for monitoring of injected remediation amendments and to track remediation progress have been demonstrated. Most typical applications of geophysical methods are for identifying anomalies that correspond to buried or surface physical waste items. Remote imaging has been applied at large scale for mapping of large scale features of interest.

	Targeted Advancements
System-Based Capabilities	Demonstrate the ability to interpret geophysical data for different scales of data and resolution.
	Develop framework/process to integrate geophysical data as a line of evidence and/or in conjunction with predictive analyses to support remedy or monitoring decisions.
	Develop and demonstrate application of geophysical methods at the watershed/system scale.
	Develop and demonstrate improved approaches to collect and use time-lapse geophysical data to support monitoring remedy performance.
Applied Capabilities	Establish correlations between geophysical response and the target analyte or system parameter and enable use for estimating the field-scale spatial distribution for parameters of interest.
	Identify the thresholds, resolution, and uncertainties that impact application of geophysical measurements and analyses with respect to relevant change(s) in system parameters.
	Develop and validate monitoring techniques and configurations to apply geophysical monitoring at reduced cost or with improved temporal or spatial information compared to the baseline approach for the target analyte or system parameter.
	Develop methods to apply geophysical methods for mass flux/discharge measurement.
	Integrate remote sensing techniques with analyses relevant to system behavior/conditions.
	Develop and demonstrate methods to apply geophysics to monitor at critical interfaces between subsurface or surface zones.
	Refine the ability to integrate geophysical data with predictive analysis tools.
Fundamental Capabilities	Provide methods to asses data fitness, uncertainty, accuracy, resolution, and collection approaches to improve application and interpretation of geophysical methods.
	Develop improved geophysical approaches for monitoring dilute concentrations of contaminants or other target analytes.

Figure 11. Current approaches and capabilities for geophysical assessment tools

PREDICTIVE ANALYSES

Predictive analyses integrate scientific data and monitoring results from environmental systems into a common framework to inform or test the CSM, project how a system is expected to function over time to meet remedial objectives, and inform decision-makers. Predictive analyses can range from parametric analyses (e.g., statistical evaluation of monitoring data) to detailed analytical and numerical models. Predictive analyses can be used for the following purposes (Neuman and Wierenga 2003):

- Integrate data to construct a valid CSM
- Test alternative CSMs
- Use inverse methods to calibrate the alternative conceptual and numerical models
- Estimate contaminant behavior over time
- Use model results to inform monitoring programs and vice versa.

Analytical and numerical models are closely linked to the CSM and can be effective tools to integrate site knowledge and data to evaluate uncertainties. Using predictive analyses in conjunction with a CSM enables assessments of contaminant transport and the impact of remediation for planning purposes. Predictive analyses can also be effective in establishing the context and goals of monitoring, and may help quantify the role of key site-specific features and processes or identify the significance of a range of parameter values. Predictive analyses can provide important information for selecting an appropriate monitoring approach and associated instruments/techniques that match monitoring capability (e.g., instrument sensitivity and resolution) to the magnitude of the relevant response in the monitoring target. Future monitoring program development and design can benefit from predictions of transport rates for representative ranges of scenarios. These efforts would help address a current challenge in monitoring—understanding how monitoring data provided by a particular system (e.g., the type of data provided, sensitivity, and resolution) can be used for interpreting contaminant fate and transport.

PREDICTIVE ANALYSES

Desired Capability: A toolset will be available to facilitate the process of building models from a CSM while maintaining quality control. An interactive and graded approach is needed, starting with a CSM that is as simple as may be warranted by the problem being addressed and adding complexity, available data and more detailed processes in an iterative manner. The ability to implement a systematic and comprehensive approach that includes site characterization, translation to mathematical model descriptions, parameter estimation/model calibration using monitoring data, and assessing uncertainty is a desired outcome.

Current Approach: The process of predictive model construction from a CSM is time consuming and labor intensive and is not done in a consistent way across DOE EM. CSMs and predictive models are ineffective if they do not capture sufficient understanding of the system to be able to represent contaminant transport. CSM development typically is not viewed as an important activity for setting up monitoring systems.

	Targeted Advancements
System-Based Capabilities	Provide toolsets for CSM development and assessment of alternatives; identify data that will be required for CSMs to support different monitoring methods and systems.
	Develop tools that enable data management, visualization, uncertainty analysis, and decision support for monitoring.
Applied Capabilities	Apply research and development versions of predictive analysis tools (including ASCEM) to demonstrate effectiveness at environmental remediation sites.
	Expand existing predictive assessment capabilities (including ASCEM) and apply to EM monitoring designs.
	Engage regulatory and end user communities with implementation of integrated predictive models for monitoring environmental remediation sites.
Fundamental Capabilities	Incorporate developments in biogeochemical reactive transport into CSM and numerical modeling toolsets.
	Capitalize on advancements in computing resources (high-performance computing) to enable CSM evaluation and monitoring system design.

Figure 12. Current approaches and capabilities for predictive analysis tools

Predictive analyses can be used to identify data gaps and inform the design of monitoring systems to reduce uncertainty and improve the effectiveness of environmental remediation and management. The CSM is the primary consideration in selecting and assembling technologies and approaches for near- and long-term monitoring (Figure 12). Predictive analyses are particularly useful for evaluating CSMs at challenging sites that are complex and where contaminant transport time frames are projected to be centuries or longer. After site models have been calibrated using performance monitoring data, they can be used to predict long-term system behavior. Predictive analyses, analytical solutions, and numerical models are useful for testing alternative CSMs and are compared with performance monitoring data and are adjusted (calibrated) to provide a technical foundation for long-term monitoring. DOE monitoring efforts are shifting from point-based to systems-based approaches (i.e., ecosystem monitoring, biological monitoring, and flux monitoring). Methods such as flux monitoring require the use of analytical or numerical models for integration of data and assessment of monitoring data. The active use of decision support tools and models will be needed to interpret data and inform monitoring program design. An iterative approach to modeling and data collection can provide powerful insights into the behavior of an environmental system, and the basis for optimizing current monitoring programs and designing monitoring programs for the next phase of the remediation process. Long-term monitoring data are incorporated in an iterative manner into the CSM and numerical models for data interpretation and feedback.

One example where predictive analysis tools are being applied for EM is with the ASCEM initiative. The DOE Office of Science has made a considerable investment to develop subsurface fate and transport models and supporting data (DOE 2010b). These advancements are being applied through ASCEM within EM. ASCEM is a state-of-the-art scientific tool and approach for understanding and predicting contaminant fate and transport in natural and engineered systems. ASCEM is intended to address the opportunities and challenges in Figure 12 and facilitate application of long-term monitoring programs and systems based monitoring approaches (e.g., flux-based monitoring, other integrated measurements).

MASS FLUX/MASS DISCHARGE MEASUREMENTS

"Mass flux" is a term used to describe the mass of contaminants moving through a unit cross sectional area per unit time (e.g., grams per square foot per year). It is typically used to characterize contaminant transport in groundwater, but may also be measured in surface water, soil vapors, or at an interface (e.g., vadose zone/groundwater, groundwater/surface water, or sediment/surface water interface). "Mass discharge" is a measurement of the total mass of contaminants per unit time passing through the cross-sectional area of interest (e.g., grams per year). Thus, mass flux/discharge provides a way to describe contaminant mobility at a selected location (Figure 13).

Mass flux is typically thought of as a tool for evaluating source treatment technologies. However, mass flux can be used for a variety of different cleanup decisions (ITRC 2010; Malcolm Pirnie 2011b). A recent overview report on mass flux (ITRC 2010) documented applications at 65 different sites, illustrating that mass flux measurements are being used more frequently and gaining more widespread acceptance, including from state regulators and other Interstate Technology and Regulatory Council (ITRC) members. The most common methods include synoptic point sampling (nine sites), passive flux meters (five sites), and integral pump tests (two sites). In addition, mass flux has been designated as a performance metric in a Record of Decision for at least one site (EPA 2009).

Mass flux measurements can be used to improve a variety of decisions associated with environmental remediation. Some of the benefits and potential uses of mass flux measurements include the following:

- Shifts the focus from compliance with point-based concentration measurements to contaminant migration potential.
- Captures an average mass loading rate that can be used to evaluate and track potential risks to downgradient receptors and estimate potential exposure.
- Can be measured at multiple source areas and used to assign remedial priority within a cleanup program.

MASS FLUX/MASS DISCHARGE MEASUREMENTS

Desired Capability: Mass flux/mass discharge and/or changes in mass flux/mass discharge are used to inform a variety of decisions including remediation of source areas, potential risks to receptors, remedial performance, duration of treatment system operation and/or transition to another remedial approach or phase to the next. Mass flux/mass discharge measurements supplement or replace point-based contaminant concentrations as a metric for remediation objectives.

Current Approach: Mass flux/mass discharge monitoring techniques are typically applied in groundwater using monitoring wells located along transects and with either accumulation devices or pumping methods. In surface water and at the groundwater/surface water interface, mass discharge is estimated using stream, river, or lake inlet/outlet samples. Mass flux measurements are less common in vadose zone environments, typically applied as part of soil vapor extraction performance analysis.

	Targeted Advancements
System-Based Capabilities	Develop strategies to enable a transition to use of mass flux/mass discharge as a measure of remedy performance, as a line of evidence, and/or in conjunction with predictive analyses to support remedy or monitoring decisions and as a metric for remediation objectives.
	Develop analysis methods to use mass flux/mass discharge analysis for remedy management and optimization.
	Demonstrate use of mass flux/mass discharge for system-based monitoring to support regulatory acceptance and technology transfer.
Applied Capabilities	Develop and refine field measurement techniques to collect data that can be interpreted in terms of mass flux/mass discharge.
	Identify the thresholds, resolution, and uncertainties that impact application of mass flux/mass discharge measurements and analyses with respect to relevant change(s) in system parameters.
	Develop and validate monitoring techniques and configurations to measure mass flux/mass discharge at reduced cost or with improved temporal or spatial information compared to baseline monitoring well approaches.
Fundamental Capabilities	Identify mass flux/mass discharge approaches that can be used for applications other than in groundwater and at critical interfaces between subsurface or surface zones.
	Identify new tools and techniques to collect data that can be interpreted in terms of mass flux/mass discharge.

Figure 13. Current approaches and capabilities for mass flux/mass discharge measurements

- Can be used to guide remedy design by identifying areas where remediation provides the most benefit.
- As a measure of source strength, mass flux may provide insights to the age of various sources and impact of natural attenuation processes over time.
- As a performance metric, with changes in mass flux used to track the efficacy of the remedial action. Mass flux can provide a meaningful way to identify contaminant trends and their implications, express average concentration reductions across a plume, calculate attenuation rates and support conclusions regarding treatment efficacy.
- Mass flux may be designated as a near-term remedial objective or technology objective (i.e., when mass flux concentrations fall below some threshold value).

BIOASSESSMENT MONITORING

Changes in the composition and function of a biological community (e.g., in response to remediation) can be identified and tracked to better understand, predict, and assess the efficacy of remediation strategies. Microorganisms, invertebrates, vertebrates and plants almost never exist as individual species in nature, but as integrated communities. Changes to environmental conditions affect these communities and vice versa. For example, characterization of baseline biological conditions within an environment (diversity or probable metabolic potential) can be used to develop CSMs. Microbes may be used for soil and groundwater remediation (e.g., bioaugmentation, biostimulation, MNA). Invertebrates, vertebrates, and plants can uptake or sequester specific

BIOASSESSMENT TOOLS

Desired Capability: Bioassessment tools would provide more accurate, precise, and cost-effective metrics which would replace existing out-dated, expensive and/or time-consuming monitoring/assessment strategies. They would act as leading indicators and supplement or synergize with other measures to provide more holistic line of evidence determinations. State-of-the-art bioassessment tools would lead to lower costs and more useful/accurate data in monitoring environmental conditions affecting fate and transport and/or remedy performance.

Current Approach: Current bioassessment approaches, if they are used at all, use generalized, inferred, or vague measures, such as indirect chemical, biological, and/or physical conditions that do not capture complex biological interactions/responses. Current bioassessment strategies include cultivating, collecting organisms for further study/identification, or broad growth, reproduction or viability metrics that only provide limited information on the 'driving force' for change or master variables.

	Targeted Advancements
System-Based Capabilities	Demonstrate bioassessment tools as early-indicators of system changes to support remedy or monitoring decisions.
	Develop framework/process for using bioassessment tools as line of evidence and/or in conjunction with predictive analyses to support remedy or monitoring decisions.
	Demonstrate use of bioassessment tools for systems-based monitoring to support regulatory acceptance and technology transfer.
Applied Capabilities	Establish functional relationships (e.g., dose-response) between novel bioassessment tools and target analytes or system parameter.
	Technology demonstrations and technology transfer of bioassessment tools as indicators of remedy performance (similar to guidance for MNA).
Fundamental Capabilities	Develop and discover new, more accurate and informative bioassessment tools, including innovative uses from other disciplines and application in new environments (e.g., vadose zone).
	Identify bioassessment metrics and collection systems that are robust in challenging environments.

Figure 14. Current approaches and capabilities for bioassessment tools

contaminants (e.g., phytoremediation) or serve as indicators of contaminant flux and environmental toxicity (ITRC 2011a).

Bioassessment monitoring can be used to develop or verify CSMs, provide additional information on contaminant fate and transport, predict contaminant and receptor interactions, and serve as long-term monitoring metrics for characterization and remediation (Figure 14). Biological indicators that can be measured before an adverse effect occurs as leading indicators of change are particularly useful. Bioassessment data can be integrated with other information as a line of evidence to describe the CSM. Bioassessment tools can be used during characterization, process monitoring, performance monitoring or long-term monitoring phases (ITRC 2011b).

INFORMATION MANAGEMENT TOOLS

Information management is central to the task of designing and implementing effective monitoring programs and long-term environmental care at DOE sites. The goal of information management at environmental remediation sites is not only to collect, organize, analyze, and archive data but also to synthesize data into meaningful information that can be easily recognized and communicated. Another key goal of information management at DOE sites is to engage and inform both site-specific and national stakeholders. Over the long term, environmental monitoring data at each site needs to be synthesized to determine the protectiveness and performance of the environmental remedy and confirm that site conditions do not pose a threat to human health or ecological receptors.

Prior DOE workshops and reviews have identified a number of broad challenges and opportunities for improving information management of environmental monitoring data (DOE 2009a). Examples include the following:

- Efficiently managing large, diverse data sets
- Maintaining data consistency and comparability
- Incorporating accurate historical information into the information management system
- Ensuring that relevant data are accessible to stakeholders in a timely fashion
- Interpreting, synthesizing and visualizing information
- Linking data to site management objectives and criteria for transitioning from one phase of remediation to the next
- Leveraging data management system to forge consensus among stakeholders during transition periods or other key decision-making time frames.

Details on each of these challenge areas are provided in the *DOE-EM Long-Term Monitoring Technical Forum* (DOE 2009a).

Specific areas for improving information management tools include analysis methods such as data mining, pattern recognition, and other methods to determine the value of data. Data mining is the process of extracting patterns from large data sets by combining methods from statistical and artificial intelligence with database management. Pattern recognition will become more important in monitoring as systems-based approaches become more commonly used. Pattern recognition has been performed for years manually via regression analysis and other statistical methods. As the size and complexity of data sets increase, data analysis has been augmented by indirect, automatic data processing and other computer science advances. Examples include neural networks, clustering, and other statistical analyses.

During the 2009 workshop, the following three items were identified as priority for continued DOE investments (DOE 2009a):

1. Identify and build on existing information management infrastructure.
2. Review and revise DOE orders governing these systems that are related to information management.
3. Develop a distributed data search engine with comprehensive coverage of DOE complex environmental information and relevant sources outside of DOE (e.g., EPA, National Oceanic and Atmospheric Administration, National Aeronautics and Space Administration). Data and content from the network should be processed for use by "middleware" interfaces that facilitate data review and the analysis of resources.

Environmental information management challenges at DOE center around communication between and within several DOE agencies, including the challenge of effective technology transfer for sites entering long-term monitoring. DOE has established database systems that can accommodate large quantities of diverse data in evolving formats. Additional challenges include providing useful user interfaces and analysis options to distill monitoring output to a level that can be interpreted by and communicated easily to stakeholders. Tools to analyze and distill data must be flexible enough to adapt to change in data input and evolving environmental support objectives (DOE 2009a). DOE has established a 5-year vision for addressing these challenges that aim to leverage existing cyber infrastructure, provide guidance for addressing management and communication deficiencies, and establish data management tools to integrate various existing environmental operations.

Current approaches and advancements are increasing communication of environmental monitoring to the public and other stakeholders. Programs now allow users to map and visualize spatial data collected under DOE's environmental remediation and long-term surveillance and maintenance programs. DOE LM established the Geospatial Environmental Mapping System (GEMS) in 2002. GEMS has evolved and been enhanced, and information from 58 LM sites is now available online (see http://gems.LM.doe.gov). The users can also query and/or export environmental data, including analytical monitoring results, sampling locations, well construction details, and photographs. EM is investing in similar mapping and visualization tools (e.g., PHOENIX for the Hanford site). Additional options are becoming available, such as a query tool to demonstrate compliance with remedial action goals and groundwater monitoring criteria. These tools play an increasingly valuable function in assisting site managers and regulators evaluate large amounts of data and make decisions on remediation and monitoring progress.

Path Forward

The overall value of systems-based monitoring is the opportunity for DOE and other environmental remediation site owners to establish and improve monitoring programs and address key cleanup objectives and goals, including cost and schedule, and continuing to ensure protection of human health and the environment. Through the development of this document, the contributions of national experts have identified a framework for systems-based monitoring in a variety of different media/different types of sites. In addition, the approach for systems-based monitoring has unfolded from workshop recommendations from participants at a DOE expert workshop held in conjunction with the ITRC 2011 Fall Meeting in Denver, Colorado. The path forward for the ideas, plans and guidance for implementation will be addressed in further documents: a SOMERS Program Plan and a SOMERS Guidance Document.

SOMERS Program Plan objectives are as follows: 1) to prioritize monitoring challenges and associated research needs at DOE sites; 2) correlate research priorities with the opportunities and challenges for an integrated systems-based monitoring approach; 3) identify potential collaborations with other Federal agencies, universities and other organizations; 4) identify opportunities to engage stakeholders, including regulatory agencies; and 5) pinpoint methods to enhance communication within and beyond DOE.

The SOMERS Guidance Document objective is to provide guidance to site managers on how to implement an integrated systems-based approach to monitoring at DOE sites. The Guidance Document will provide a number of case studies from DOE sites demonstrating the use of integrated systems-based monitoring approaches and highlighting the benefits from this approach. The Guidance Document will also provide recommendations for site managers to improve the implementation of integrated systems-based monitoring.

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APPENDIX

ITRC Expert Workshop on SOMERS

Appendix: ITRC Expert Workshop on SOMERS

In coordination with the Interstate Technology and Regulatory Council (ITRC), the authors of this document held two meetings on SOMERS to illicit their ideas on systems-based approaches to monitoring. Participants provided many suggestions and constructive comments on a draft version of this document. Many comments have been addressed in this document; other comments are being taken into consideration in the development of the SOMERS Program Plan and SOMERS Guidance Document.

The authors are grateful to the following members of the ITRC Monitoring and Statistics Team, expert workshop participants and other peer-reviewers:

- Buddy Bealer, Shell Global
- Cara Patton, designated SERDP/ ESTCP representative
- Carl Spreng, Colorado Department of Public Health and Environment
- Chris Stubbs, ENVIRON
- Craig Benson, University of Wisconsin/Consortium for Risk Evaluation with Stakeholder Participation
- Dan Powell, EPA
- Dave Smit, Mountain Area Land Trust Stakeholder
- Dib Goswami, Nuclear Waste Program, Washington State Department of Ecology
- Ernest Ashley, CDM
- Fred Payne, ARCADIS
- Gail Lipfert, Maine Department of Environmental Protection
- Greg Gervais, EPA
- Harold Tempin, Indiana Department of Environmental Management
- Helen McKenzie, Sellafield Ltd. (United Kingdom)
- Joel Hubbell, Idaho National Laboratory
- John McCord, Stoller & Associates
- Katie Walton-Day, U.S. Geological Survey
- Kimberly Wilson, South Carolina
- Kirby Biggs, EPA
- Kirk Cameron, MacStat Consulting (designated AFCEE representative)
- Leslie Hay-Wilson, Sage Risk Solutions
- Liz Simmons, Kleinfelder
- Mavis Kent, Plateau Geoscience Group LLC
- Michelle Crimi, Clarkson University
- Ning-Wu Chang, California Department of Toxic Substances Control
- Paul Hadley, California Department of Toxic Substances Control
- Prashanth Khambhammettu, S.S. Papadopulos & Associates
- Randall Ryti, Neptune and Company
- Robert Storms, Tennessee Department of Environmental Conservation
- Ryan Wymore, CDM
- Sandy Britt, ProHydro
- Sarah Libeau, ENVIRON
- Scott R. Surouchak, DOE Office of Legacy Management
- Stephen Johnson, Delaware Department of Natural Resources and Environmental Control
- Tamzen Macbeth, CDM
- Tanwir Chaudhry, U.S. Navy
- Todd Mullins, Kentucky Division of Waste Management
- Tom Georgian, U.S. Army Corps of Engineers
- Tom McHugh, GSI Environmental
- Tom O'Neill, New Jersey Department of Environmental Protection

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May 2012

U.S. DEPARTMENT OF ENERGY | Office of Environmental Management