Scientific Opportunities for Monitoring of Environmental Remediation Sites (SOMERS) – 12224

Amoret L. Bunn[*], Dawn M. Wellman[*], Rula A. Deeb[**], Elisabeth L. Hawley[**], Michael J. Truex[*], Mark J. Peterson[***], Mark D. Freshley[*], Eric M. Pierce[***], John McCord[†], Michael H. Young[††], Tyler J. Gilmore[*], Rick Miller[†††], Ann L. Miracle[*], Dawn Kaback[#], Carol Eddy-Dilek[##], Joe Rossabi[###], M. Hope Lee[+], Richard Bush[++], Paul Beam[+++], Grover Chamberlain[+++], Kurt Gerdes[+++], and Yvette T. Collazo[+++]
[*]Pacific Northwest National Laboratory, Richland, WA 99352
[**]ARCADIS/Malcolm Pirnie, Emeryville, CA 94608
[***]Oak Ridge National Laboratory, Oak Ridge, TN 37831
[†]S.M. Stoller Corporation, Grand Junction, CO 81503
[††]University of Texas at Austin, Austin, TX 78705
[†††]University of Kansas, Kansas Geological Survey, Lawrence, KS 66047
[#]AMEC Geomatrix, Denver, CO 80222
[##]Savannah River National Laboratory, Aiken, SC 29808
[###]Redox Tech, LLC, Cary, NC 27513
[+]Idaho National Laboratory, Idaho Falls, ID 83415
[++]U.S. Department of Energy, Office of Legacy Management, Grand Junction, CO 81503
[+++]Development, Office of Groundwater and Soil Remediation Washington, DC 20585

ABSTRACT

The US Department of Energy (DOE) is responsible for risk reduction and cleanup of its nuclear weapons complex. DOE maintains the largest cleanup program in the world, currently spanning over a million acres in 13 states. The inventory of contaminated materials includes 90 million gallons of radioactive waste, 6.4 trillion liters of groundwater, and 40 million cubic meters of soil and debris. It is not feasible to completely restore many sites to predisposal conditions. Any contamination left in place will require monitoring, engineering controls and/or land use restrictions to protect human health and environment. Research and development efforts to date have focused on improving characterization and remediation. Yet, monitoring will result in the largest life-cycle costs and will be critical to improving performance and protection. Through an inter-disciplinary effort, DOE is addressing a need to advance monitoring approaches from sole reliance on cost- and labor-intensive point-source monitoring to integrated systems-based approaches such as flux-based approaches and the use of early indicator parameters. Key objectives include identifying current scientific, technical and implementation opportunities and challenges, prioritizing science and technology strategies to meet current needs within the DOE complex for the most challenging environments, and developing an integrated and risk-informed monitoring framework.

INTRODUCTION

Environmental remediation in the United States is a major undertaking. The National Research Council estimated costs ranging from approximately $500 billion to $1 trillion just to remediate contaminated groundwater [1]. Cleaning up the nation's nuclear weapons complex remains one of the most technologically challenging and financially costly problems. The Department of Energy (DOE) maintains the largest cleanup program in the world, currently involving over a million acres in 13 states [1]. Although DOE has made significant progress characterizing and remediating contaminated sites over the past 30 years, some of the most complex environmental restoration and remediation challenges remain. DOE conducts monitoring for a variety of purposes in a range of environmental media (e.g., surface water, groundwater, soils, sediment, air, and biota). Data collection, management, and interpretation may cost up to several million dollars per year at each facility [2]. Nearly all monitoring approaches being used at DOE sites are focused on point-source based characterization and compliance (i.e., concentration measurements at a given location and time), which are cost- and labor-intensive. Residual contamination is expected to remain at many DOE sites for tens to hundreds of years. Thus, there is a critical need and significant opportunity for DOE to advance monitoring approaches by moving away from point-source monitoring to systems-based monitoring strategies that utilize early indicator parameters and flux-based system understanding.

The overall goal of *Scientific Opportunities for Monitoring of Environmental Remediation Sites* (SOMERS) is to serve as a foundation document for DOE on monitoring. This paper summarizes the SOMERS document, which provides the scientific and technical basis to advance monitoring approaches beyond traditional point-source based monitoring approaches to whole system-based approaches (e.g., watershed, waste site, disposal facility, and ecosystem) necessary for monitoring complex sites. Monitoring data should be used to build, test or verify the conceptual site model, and the refined conceptual site model should in turn inform, develop, and refine monitoring plans.

Summarized here are the next steps that the SOMERS document is capturing to address the challenges associated with developing and implementing advanced cost-effective monitoring approaches that are aligned with site cleanup and closure goals. The objectives of the SOMERS document are:

- 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.

SOMERS is intended to be used by a variety of DOE agencies in establishing a path forward to support needed investments in monitoring technologies, tools and approaches. The document will also serve as a way to communicate DOE's path forward on monitoring to potential partnering agencies, regulators and other stakeholders. Finally, SOMERS is intended to be useful to practitioners by providing scenarios that illustrate how system-based monitoring approaches supported with scientific tools and can be used to develop a site-specific, systems-based monitoring program.

SYSTEMS-BASED MONITORING APPROACHES: CHALLENGES AND OPPORTUNITIES

Why Systems-Based Monitoring?

Environmental cleanup activities at DOE are conducted under the auspices of a number of federal regulations, predominantly under the Comprehensive Environmental Response, Compensation, and Liability Act (CERCLA) and Resource Conservation and Recovery Act (RCRA). Regulatory compliance is often determined from point-source measurements of contaminant concentrations collected from specific locations (e.g., monitoring wells) at a site.

For short-duration remedies such as contaminant removal, treatment and disposal, this approach has been successful. However, for long-term environmental management based on active in situ remedies, monitored natural attenuation (MNA) or other remedies that leave residual contamination in place (e.g., use of surface barriers), it is more challenging to demonstrate through monitoring and/or the use of predictive tools that contaminant levels at a site will remain below levels of concern in the future. Due to the nature of the contamination and environmental setting at DOE legacy waste sites, monitoring at complex sites will likely be needed over long timeframes and at significant scales where conventional monitoring approaches are not effective. Improved monitoring approaches are needed to scientifically and cost-effectively meet compliance requirements. Monitoring approaches need to be developed with a strong technical basis to enable acceptance by regulators as a viable alternative to approaches that rely heavily on point-source contaminant concentration monitoring. Systems-based monitoring approaches provide an opportunity to improve monitoring program cost and performance at DOE sites requiring long-term environmental management. Systems-based monitoring approaches can be used to inform or supplement compliance monitoring.

Importance of the Conceptual Site Model

The conceptual site model (CSM) provides the necessary description and understanding of the site into system components including the source zone, vadose zone, plume system, and receptors along with a detailed understanding of processes (i.e., physical, chemical, and biological) that occur in each component. This systems-based understanding is key to answering the questions of what, how, when, where and how long to monitor. Environmental systems inherently possess high degrees of spatial and temporal variability that require a robust strategy to integrate monitoring data into a CSM and use the CSM to guide subsequent monitoring efforts. The development of effective and efficient systems-based monitoring approaches is based on a detailed CSM integrated with an understanding of the objectives for each phase of monitoring.

Clearly-articulated objectives establish the intended use of the monitoring data, guide what additional data are needed to answer key questions, or indicate when the appropriate processes are occurring sufficiently to meet the remediation goals. Monitoring activities support decision points (e.g., assess whether a selected response action is or is not achieving its objectives). In addition, monitoring results are often used to make inferences about the subsurface conditions and inherent variabilities [5]. It is essential to have the ability to manage large and complex data sets, and to integrate these data into the CSM in a statistically meaningful way which accounts for temporal and spatial variability [6]. This process provides refinement to the CSM by tracking changes in site conditions through time.

The conceptual model can be linked to predictive analyses that project how the system is expected to function over time to meet the remedial action objectives. Predictive analyses can be numerical models or integrating calculations such as a water balance or evaluation of data as mass discharge or mass flux. Together, the conceptual model identifying the key elements of the system and the predictive framework enable interpretation of monitoring data. Guided by the site-specific CSM, data to evaluate the feasibility and timeframe for remediation and restoration need to be collected in order to evaluate achievable alternative endpoints. Long-term monitoring data are incorporated in an iterative manner into site conceptual and numerical/predictive models for data interpretation and feedback.

The CSM informs the purpose of monitoring and monitoring objectives, which may change over time with each stage of remediation [3, 4]. Each phase in the remediation process has specific objectives that are defined by the regulatory cleanup program, and the objectives of each phase of remediation influence the type of monitoring program and the appropriateness of point-source based or system-based approaches. As shown in Figure 1, each phase of monitoring has distinct objectives and approaches that influence the monitoring program. These objectives may or may not transition into the next phase of monitoring.

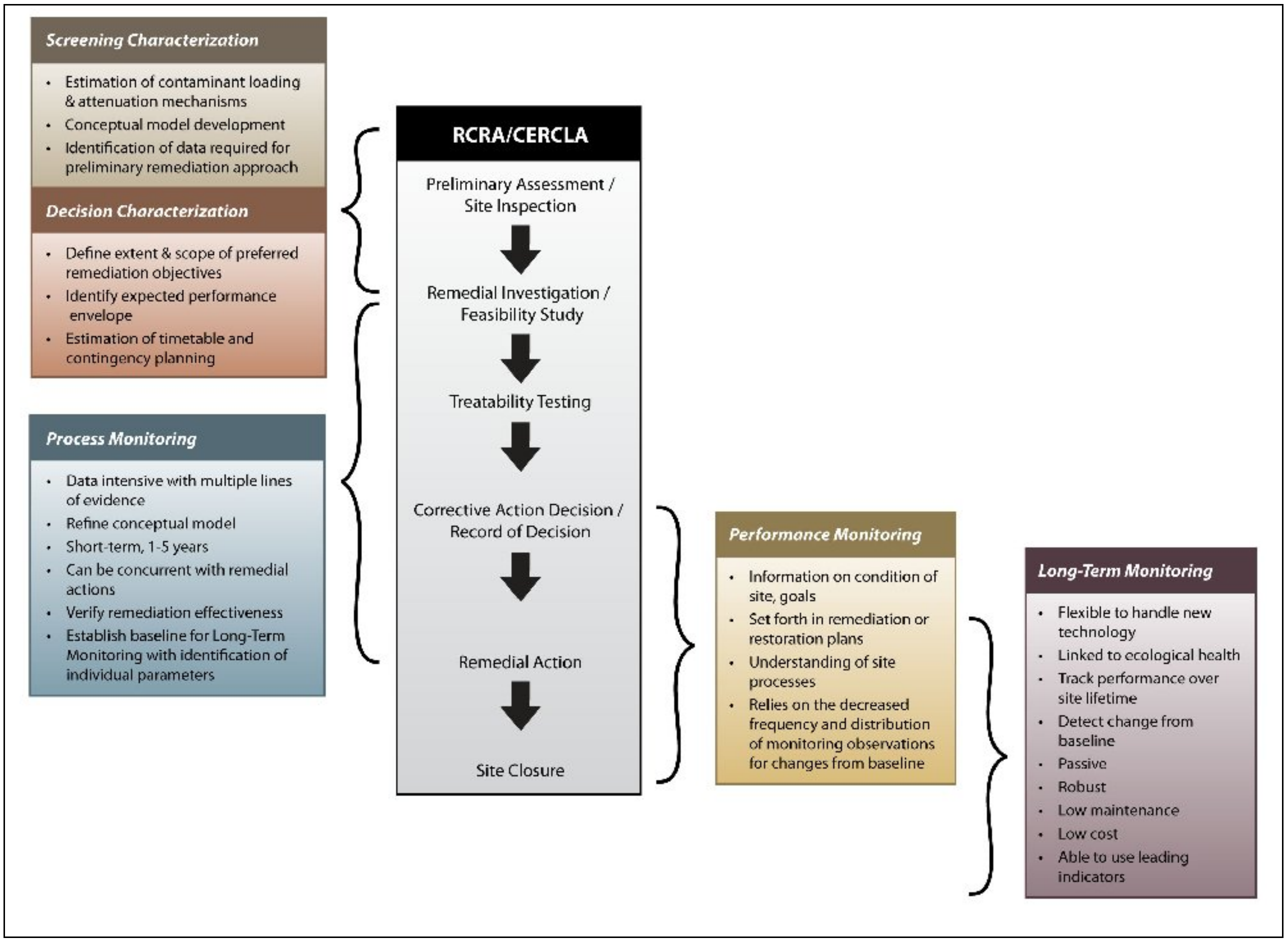

Fig. 1. Information and understanding provided through the monitoring stages within the context of the RCRA and CERCLA processes

For system-based monitoring, objectives for the remedy and a CSM (i.e., description of the physical/geochemical system) are needed to provide a basis for the monitoring approach and for data interpretation. Together, these can be described as a monitoring framework. The systems-based monitoring approach should also elucidate key properties that need to be quantified or estimated as part of data interpretation (or supporting predictive analyses). Thus, the monitoring approach, design, and implementation are based on and linked to refinement of the CSM. The CSM will have key uncertainties and variables that affect the predictability of contaminant impact. The monitoring program should identify parameters (characteristics, locations, distribution) that can be measured that help constrain or reduce the variability or uncertainty of the predictions leading to a refinement and verification of the CSM.

The configuration of the monitoring system must evolve in response to the changing conditions as a site transitions though the phases of monitoring (i.e., process, performance and long-term monitoring). In doing so, a detailed understanding of the system components and monitoring objectives of each phase provides opportunities for the development of innovative and optimized monitoring configurations that can advance from reactive point source-based analyses to proactive systems-based monitoring approaches. Examples of systems-based monitoring approaches include lines of evidence and mass flux/mass discharge measurement.

Lines of Evidence: A Systems-Based Approach.

The approach for lines of evidence monitoring is based on collecting data to meet specific objectives and answer key questions related to the performance of the remedy and indications that the appropriate processes are occurring sufficiently to meet the remediation goals. Examples of monitoring objectives and general questions that are addressed through lines of evidence monitoring are listed below. These general lines of evidence objectives can be refined using the CSM based on the key processes or key technical uncertainties identified as important to understand and monitor with respect to remediation and contaminant fate and transport. The objectives for lines-of-evidence modeling should include: demonstrating that the remedy is functioning; detecting changes in environmental conditions that may impact the remedy or contaminant fate and transport; demonstrating that relevant reaction processes are occurring and unexpected or unwanted processes are not occurring; and assessing contaminant fate and transport and protection of potential receptors.

A monitoring approach using multiple lines of evidence is already well established and widely applied for MNA remedies for contaminated groundwater [8]. The specific objectives defined in the implementation of MNA are extensions of the prescribed MNA remedy evaluation approach that is strongly based on conceptual model development and establishing appropriate attenuation process knowledge through multiple lines of evidence [5, 7, 8, 9, 10, 11]. For MNA, lines-of-evidence monitoring primarily occurs within the contaminated zone to examine attenuation conditions and verify that they are acceptable, or to identify changes that may become problematic, in terms of achieving and maintaining compliance goals. Flux-based monitoring techniques and mass-balance approaches to monitoring design are examples of alternatives for lines of evidence monitoring and were developed and investigated with respect to chlorinated solvent MNA through recent DOE programs [12, 13].

A challenge for environmental monitoring is to build on the success of the established MNA monitoring approach and develop a lines-of-evidence monitoring approach that is relevant: to other remedies (e.g., where different factors are important); for multi-component remedies (e.g., an active remedy combined with MNA); and to a broad range of hydrogeologic settings (e.g., vadose zone contamination and surface water systems). To use this type of approach, a means to interpret the lines-of-evidence monitoring data is needed in terms of the processes of interest and to integrate this interpretation with compliance requirements. The MNA approach has been successful because it provides this type of interpretation framework.

To meet the challenge of applying lines of evidence monitoring approaches for a variety of remediation applications, a systems-based structure is needed using a conceptual model of the site and relevant controlling processes. The conceptual model can be linked to predictive analyses that project how the system is expected to function over time to meet the remedial action objectives. Successful, cost-effective lines-of-evidence implementation will benefit from development of monitoring tools and approaches that provide appropriate information about components of the system or that monitor the integrated system and thereby aid interpretation of overall performance and potentially limit the need for conventional compliance monitoring.

Monitoring strategies that go beyond optimizing detection-well networks need to be developed. This includes combining new and developing technologies with comprehensive approaches in monitoring with increased focus on system-wide monitoring. As part of this development there will also be the need for strategies that allow the transition from the detection-well monitoring networks to more “natural system” approaches.

Mass Flux/Mass Discharge Measurement: A Systems-Based Approach.

“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). Mass flux is a way to describe contaminant mobility. 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 or groundwater/surface water). “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) [14].

Mass flux/mass discharge measurements provide a basis for the conceptual model development, establishment of remedial action objectives, process, performance monitoring optimization, and long-term monitoring compliance. Remediation is targeted at meeting remediation goals by mitigating unacceptable contaminant concentrations (e.g., above the maximum contaminant level) and/or altering contaminant fate and transport (e.g., slowing contaminant flux towards potential receptors). Remedies are evaluated, designed, and implemented based on a CSM. In addition to measuring contaminant concentrations at compliance locations, monitoring can be designed to track the controlling elements that govern the remedy process and remedy impact on contaminant fate and transport [14, 15, 16].

The approach for mass flux/mass discharge measurements can also provide multiple lines of evidence for a remedy through collection of data that demonstrates the processes identified for remedy success are occurring as intended. Lines of evidence may be supported through monitoring of site “master variables” (e.g., key geochemical parameters and hydraulic state variables such as hydraulic head or moisture content) or other parameters that are indicators of the key elements that govern the remedy process. The lines of evidence approach enable the potential to use alternative monitoring strategies that are not solely based on contaminant concentration monitoring.

Specifically, scientific and technical challenges as well as opportunities related to mass flux/mass discharge approaches include: accuracy and precision; means to assess uncertainties in mass flux measurements; spatially-integrated measurement methods; and systems-based monitoring strategies. Confidence and acceptance in mass flux/mass discharge measurement methods will likely grow among the environmental remediation community with more application of the approach.

TOOLS THAT SUPPORT SYSTEMS-BASED MONITORING APPROACHES AND REQUIRE SCIENTIFIC AND TECHNICAL ADVANCEMENT

DOE recognizes the importance of developing scientifically-defensible and cost-effective monitoring approaches that can be used over long timeframes and at large scales. Such systems-based approaches to monitoring may supplement or partially replace repeated point-based monitoring of contaminant concentrations. The framework of systems-based monitoring includes lines of evidence and flux-based monitoring programs. Through the process of developing the SOMERS document, the inter-disciplinary group of authors and contributors focused on tools that can be used to support systems-based monitoring approaches and afford opportunity for additional scientific and technical advancements.

Geophysical Assessment Tools, including Geophysics and Remote Sensing.

The overall objective of geophysical assessment tools is to provide spatial subsurface information. 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 down-hole 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, localized anomalies). Geophysical measurements are indirect, and therefore rarely produce specific tactile measurements.

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 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.

Challenges and opportunities for advancing the use of geophysical assessment tools in systems-based monitoring approaches include: advancements to improve geophysical characterization of watershed and sub-watershed-scale features; improved integration of multiple geophysical methods as lines of evidence; better integration of geophysical assessment data into predictive models; and use of geophysical tools in monitoring programs to detect changes over time. Successful and optimal incorporation of individual or complementary geophysical methods (especially when correlating borehole measurements over catchment or larger areas) depends on the practitioner’s familiarity with the capabilities, limitations, resolution, sensitivities, and uniqueness of these tools and of subsurface properties at the site.

Bioassessment Tools, ranging from Molecular to Species and Community Measurement Tools.

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. 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 endpoints for characterization and remediation. 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.

There are a wide variety of tools, technologies and approaches for measuring biological endpoints or biological indicators. Collectively these are termed “bioassessment tools”, and include Molecular Biological Tools (MBTs) and Environmental Molecular Diagnostics (EMDs). Bioassessment tools provide data that can be used in conjunction with geochemical information to better understand and describe contaminant fate and transport processes at a site [17]. They can be used to measure contaminant flux or stability dependent on different management metrics. Biological indicators for non-microbes can be measured using many of these same bioassessment tools in addition to other approaches and tools that examine non-molecular endpoints such as species assemblages, mortality, growth, and reproductive success.

The scientific and technical challenges and opportunities for bioassessment tools include: advancement of targeted tools (e.g., metabolite or protein targets incorporated into sensors for deployment and flux measurements); advancement of discovery tools (e.g., application of metabolomic or proteomic tools for characterization of functional potential of biotic community analyses); and application of bioassessment tools in remediation programs to demonstrate confidence and acceptance of their value as lines of evidence for monitoring progress to meeting cleanup criteria.

Surrogates and Indicators, including Biological, Chemical and Physical-based Measurement Tools.

Surrogate and/or indicator parameters or analytes can be monitored in place of targeted parameters or analytes that are more difficult or expensive to measure as long as the distribution and transport characteristics of the surrogate are well-correlated to the distribution and transport of the target parameter [13]. An indicator parameter or analyte is measured to provide information about remedy performance, contaminant transport, or some other topic of interest. To apply a surrogate or indicator in a monitoring program, the measured value of the surrogate or indicator must be correlated (or functionally representative) to the property or process of interest for meeting the goals of the monitoring program. As such, a systems-based CSM and related lines of evidence need to be developed to identify and quantify this correlation. Additionally, the surrogate/indicator information should be considered in terms of how it relates to meeting monitoring objectives.

Application of surrogate/indicator approaches offers significant potential for improving the cost effectiveness of site characterization and monitoring and is integral to a systems-based approach for monitoring. The following challenges/opportunities should be considered in advancing surrogate/indicator monitoring approaches. Establish specific correlations between the data provided by candidate surrogate/indicator approaches and key subsurface processes and parameters for natural attenuation, promising remedies, and priority contaminants. Develop and test new tools that provide measurement alternatives for promising surrogate/indicator parameters and analytes. Examine the potential to increase the robustness remedy performance interpretation by integrating biological, chemical, and physical surrogate/indicator data.

When transferring the concept of surrogates and indicators to environmental restoration, the approach needs to consider that regulatory guidelines for cleanup standards are primarily based on contaminant concentrations. Key challenges and opportunities for developing and proposing alternative monitoring strategies that incorporate surrogates and indicators to replace or reduce the frequency of contaminant monitoring are expected to include: demonstration of a strong scientific basis for correlations between the surrogate/indicator parameters and the regulated parameters; and quantification of uncertainty associated with measurement of the surrogate/indicator parameter and its interpretation for meeting the specified monitoring objective.

Predictive Analysis Tools, ranging from Parametric Analyses to Detailed Analytical and Numerical Models.

Predictive analyses integrate scientific data and monitoring results from environmental systems into a common framework to inform or test the CSM, make predictions, and inform decision-making. 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: integrate data to construct a valid CSM; test alternative CSMs; calibrate the model and use inverse modeling to make predictions; and use model results to inform monitoring programs and vice versa (e.g., identifying data gaps, and evaluate design parameters to improve effectiveness of remediation and management systems).

The challenges and opportunities for advancing the use of predictive analysis tools in systems-based monitoring approaches include: development of a predictive modeling tool and approach that is robust and can be used to inform or refine the CSM and monitoring programs in various remedial phases, particularly at complex sites; use of predictive analyses to test and verify or refine CSMs; and simplified tools for building predictive models based on CSMs. DOE has been devoting considerable resources both in Office of Science and Environmental Management (EM) to develop subsurface fate and transport models. Among these programs, EM's Advanced Scientific Computing for Environmental Management (ASCEM) initiative is developing a modular and open-source high performance computing capability to focus on the critical needs to understand and quantify subsurface flow and contaminant transport in complex hydrogeologic systems, which can be applied to long-term monitoring programs and systems-based monitoring approaches. Continuing collaboration with other organizations can benefit the application of predictive analysis tools developed for other applications that are appropriate for use with remediation sites.

Information Management Tools, including Analytical and Geospatial Database Systems.

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. 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 ecology.

The characteristics of any robust environmental information management system are multi-faceted and address the needs of multiple participants in the remediation process [18]. Integrated datasets that can be used to evaluate monitoring objectives, including the effectiveness of remedial actions and long-term protectiveness of human and environmental health. Data must be archived and maintained in a way that preserves its integrity while still allowing for significant additions and efficient search and retrieval. Data and information from the system can be used to effectively support environmental management decisions (data and information type, quantity, quality, and timeliness). The process of using data and information to support environmental management decisions is transparent and traceable. To the extent that it does not pose a security risk, critical data and information should be accessible by project managers, contractors, and other site stakeholders. An example of the latter is DOE's Office of

Legacy Management (LM) Geospatial Environmental Mapping System (GEMS), which is available online at: http://gems.LM.doe.gov .

Broad challenges and opportunities for improving information management of environmental monitoring data remain [18]. These include: providing efficiencies in 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; and leveraging data management system to forge consensus among stakeholders during transition periods or other key decision-making timeframes.

SYSTEMS-BASED MONITORING SCENARIOS

In SOMERS, the demonstration of the application of systems-based monitoring approaches and identification of scientific opportunities and changes to implement the new framework for monitoring is through a series of scenarios for environmental remediation. Scenarios for monitoring environmental remediation are discussed for the vadose zone, groundwater, groundwater/surface water interface, and surface water.

Vadose Zone.

The deep vadose zone (i.e., depths below the limit of contact with surface receptors) may require remediation to prevent exposure via contaminant transport to the surface (e.g., vapor intrusion) or to protect groundwater. In this context, the vadose zone is a pathway for contaminant transport, upward or downward. The rate of contaminant movement through the vadose zone (the mass flux/discharge) is a primary parameter used to assess potential impacts at the ground surface or in groundwater. Vadose zone monitoring data provide information that can be used to: establish background conditions at variable depths; identify potential releases from disposal sites or other anthropogenic activities; or verify that active or passive (e.g., MNA) remedies are effectively mitigating transport of contaminants. Vadose zone monitoring may be needed when examining potential disposal sites for baseline conditions (i.e., before site activity commences), or understanding the effectiveness of remedies that leave contaminants in place (e.g., in situ vadose zone treatment, MNA or use of surface barriers). For these applications, vadose zone monitoring provides an opportunity to evaluate the remedy and verify performance before media of concern (e.g., groundwater) are negatively impacted.

A primary goal of monitoring for contaminants is to provide information to understand and quantify the contaminant distribution in the vadose zone and transport to groundwater. Monitoring data can be, and should be, used as part of an overall strategy for predicting future states. Predictive (numerical) analyses are also part of that strategy, as are the iterative nature of monitoring and modeling. The results of predictive analyses and the refinement of these analyses with monitoring data can be important to the interpretation of monitoring data, in terms of verifying appropriate remedy performance. For most sites, waste disposal has already occurred, but important information may be available to describe site conditions during the time of active disposal. If these data are available, they can be related to predictions of, or monitoring approaches for, describing the contaminant flux to the groundwater. Key components of vadose-zone monitoring based on the generic transport framework are: vapor phase (for volatile contaminants); water flux; contaminant flux and its relationship with water flux; remediation processes; and volumetric moisture and contaminant measurements.

The SOMERS document discusses further the challenges and opportunities for vadose monitoring and associated tools. These include: integrating monitoring with predictive analyses; opportunities for design approaches; and monitoring techniques for specific parameters.

Groundwater.

The groundwater zone is typically defined as the water-saturated volume in the subsurface that is located beneath the unsaturated or partially saturated vadose zone with the upper surface defined by the water table. At any particular location, there may be more than one groundwater zone of interest, which may be completely or partly isolated from each other by geological or other impermeable layers. Even within a single, hydraulically-connected groundwater zone, there is rarely a homogeneous distribution of groundwater flow. The identification of a contaminant in a groundwater sample from a well is often the first indication of contamination and leads to initiation of an environmental response. Environmental response can mean additional characterization, remediation, or monitoring either at the direction of regulatory agencies or as a voluntary response (usually in anticipation of regulatory direction).

Although remedial actions have traditionally been focused on the contaminant concentrations in the groundwater, several other parameters are crucial to an accurate and useful conceptual model of groundwater at a contaminated site. These include “master variables”, or the key variables that control the chemistry of the groundwater system. Often several indicators of changes in the groundwater are overlooked or minimized as an indicator, including the boundary conditions producing and controlling groundwater flow and biological/chemical distribution and transport. In addition, temporal changes in boundary conditions or remedial actions often result in changes to both the distribution of contaminants and groundwater flow. These other parameters are often leading indicators of change in the groundwater and can be used to increase responsiveness and reduce costs of monitoring.

The SOMERS document discusses further the challenges and opportunities for groundwater monitoring and associated tools, including integrating monitoring with predictive analyses for addressing heterogeneity and complexity as well as natural attenuation capacity; multiple lines of evidence including master variables into systems-based management of monitoring approaches; opportunities for design approaches; and monitoring boundary conditions.

Groundwater/Surface Water Interface.

For the SOMERS document, the groundwater/surface water was considered as the region beneath the bottom of a surface water body where conditions change from a groundwater dominated system to a surface water dominated system within the substrate. The interface includes the entire region where spatial and temporal interchanges of water occur. This region can include hyporheic zones, where groundwater enters and mixes with the surface water 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 demonstrated that salmonoid species seek out hyporheic regions in rivers for construction of their redds, ensuring their eggs and alvin develop in nutrient- and oxygen-rich substrate [19].

The value of monitoring the groundwater/surface water interface is associated with the remediation objectives and regulatory requirements for an environmental remediation site. Both the hydraulic gradients of the groundwater and surface water have to be evaluated and integrated with an understanding of the temporal and spatial variability of the region. Geochemical conditions may change the contaminant as it passes through gradients 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 completeness of the CSM, and the relationship of the region to the remedial action.

The challenges and opportunities for the groundwater/surface water interface are discussed in detail in the SOMERS document. These include: identification and understanding of key features in the evaluation of either the groundwater or surface water boundary's CSM; integration of interface into overall systems-based monitoring efforts; and incorporation of heterogeneity and scale into systems-based approach to support decision making.

Surface Water.

There are major challenges to effectively monitor surface water over the long-term at remediation sites. Complex surface water systems may have in-stream sources of contamination and multiple additional sources or stressors to surface water. Multiple and varied regulatory drivers/criteria which impact surface water monitoring needs. Non-DOE facility discharges in watersheds and community stakeholder involvement in surface water issues, coupled with a complex DOE-facility regulatory environment, can make communication and decision-making a challenge. Quantifying surface water contaminant flux is important to address Clean Water Act regulations (e.g., total maximum daily loads(TMDLs)) and for evaluating changes in response to remedial actions, but is difficult to measure in some aquatic systems (without building weirs or dams). Unique metrics for surface water include measures for assessing human and ecological health, biological criteria, and non-point source problems (erosion, siltation, habitat effects). Defining clear causes of surface water impacts, and quantifying and prioritizing sources and potential remedial or abatements actions, can be difficult.

The surface water monitoring framework of the future may include a number of valuable elements. Key characteristics of a good surface water framework include being watershed based, spatially and temporally explicit, consistent and repeatable, quantitative, and multidisciplinary. The monitoring framework must balance consistency with the need to incorporate new tools and strategies that might provide more useful information at less cost. Increasingly surface water monitoring programs are flux based, consistent with the focus of some regulatory requirements like TMDLs, which focus on loading. Given the multiple and complex stressors affecting surface water systems, a useful feature of surface water monitoring frameworks is the ability to separate out DOE-related anthropogenic sources from natural variation.

There are a number of opportunities for better surface water monitoring regimes. Establish clear goals of monitoring and develop better conceptual models up front that can define the monitoring and scientific needs. Standardization of spatial and temporal strategies of monitoring plans can provide more useful and cost effective data. For surface water, a watershed-based strategy that uses integration points and multiple key metrics is advocated. A good surface water monitoring program must maintain consistency in methods while also incorporating new knowledge or research and making commensurate prudent changes to environmental management, remediation strategies, and monitoring regimes as necessary. An adaptive management type approach optimized to address DOE monitoring goals is recommended. Special investigations and causal studies should consider the newest technologies and methods (e.g., new flux measurement techniques). Integrated approaches, decision-support tools, and communication strategies across programs that conduct monitoring (within watershed, within a DOE site, and across the DOE complex), and improved communications with regulators and stakeholders, can help ensure surface water monitoring addresses key shared goals and data is leveraged and costs minimized.

END STATES FOR ENVIRONMENTAL REMEDIATION SITES

The overall purpose of environmental remediation is protection of human health and the environment. Several remedial objectives are developed based on site-specific understanding to meet this overall goal. Once remedial objectives have been met, remediation is then complete and the site has reached its end state. Typically, the most desirable end state is unrestricted use. However, some sites require continued use restrictions (e.g., land use controls, water use restrictions, or other institutional controls) after remediation is complete, due to the presence of residual contamination left in place that could pose a risk to human health or environment.

At most highly complex sites, remedial action objectives may be difficult to achieve. Technical limitations at complex sites and factors considered during comprehensive analysis of the site (e.g., life-cycle costs, sustainability impacts, resource consumption) have been cited by site managers and regulators as challenges that require alternative approaches to select remedies that are protective of human health and welfare and of the environment [16].

Most highly complex sites have implemented active remediation technologies at some point in time, either at full-scale or pilot-scale levels. Case studies [16] provide examples of the types of site conditions that may lead to an evaluation of alternative endpoints, as well as tools and analyses used in site-specific evaluations to demonstrate the appropriateness of alternative endpoints and gain stakeholder support for their use. Examples of alternative endpoints include technical impracticability (TI) waivers, other Applicable or Relevant and Appropriate Requirements (ARAR) waivers, Alternate Concentration Limits (ACLs), and a variety of groundwater management/containment zone designations used by state cleanup programs.

Alternative endpoints have been used at a variety of complex sites in different cleanup programs to address surface water, groundwater, soils and sediment contamination to focus remedial efforts on achieving near-term objectives and meeting realistic long-term cleanup objectives. A review of case studies using alternative endpoints identified the use of excavation, free product recovery, thermal treatment, in-situ chemical oxidation, bioremediation, and air sparging/soil vapor extraction in conjunction with alternate endpoints including TI waivers. Alternative endpoints have also been used in combination with passive remediation such as MNA and monitored natural recovery, and with long-term management and/or containment approaches. Thus, alternative endpoints are not a way to avoid remediation.

From the perspective of DOE environmental remediation programs, alternative endpoints may provide several benefits. Alternative endpoints may establish common expectations for remedy performance, minimizing the risk of re-opening a remedy at a later date. Agreement on alternative endpoints provides a way to formally recognize and mitigate the potential reality that groundwater cleanup goals will not be achieved within a reasonable timeframe. Also, the agreement can distinguish between technology performance objectives over the short-term and the overall long-term goal. Costs savings and efficient use of resources can be achieved through alternative endpoints by directing remediation efforts towards achieving near-term objectives and/or realistic long-term cleanup requirements. And the process provides a pathway towards establishing a site remedy and transitioning to long-term management.

End state selection is incorporated typically in the remedial objectives determined before the Remedial Investigation/Feasibility Study stage and prior to collecting process monitoring data. End states, such as unrestricted use or site closure with land use controls, often drive the selection of appropriate remedial objectives. The remedial objectives that are selected in turn drive the type of monitoring (process, performance, and long-term monitoring) that is conducted to measure progress towards remedial objectives. Monitoring data can also provide feedback on several other aspects of remedial progress, including the estimated timeframe for remediation. Long-term monitoring strategies at these sites tend to be less focused on progress towards meeting remedial objectives and more focused on protection of human health and the environment despite the presence of residual contamination.

FOLLOW ON OPPORTUNITIES FOR SOMERS

Monitoring at DOE sites is an inter-departmental initiative as well as an inter-disciplinary area. In the past, DOE LM has conducted monitoring program optimization efforts focused on long-term monitoring [20] as has DOE EM focused on improving long-term monitoring [18]. DOE's Office of Technology Innovation and Development supports monitoring through their mission of transforming science and innovation into practical solutions for environmental cleanup. The DOE Office of Groundwater and Soil Remediation is responsible for developing these technologies for transfer to the site contractors for field implementation. Finally, improving monitoring efforts is also of broad interest beyond DOE. The Interstate Technology and Regulatory Council (ITRC), state regulators, Department of Defense, Environmental Protection Agency, other federal agencies, academia, and industry have also conducted parallel efforts to improve monitoring.

REFERENCES

1. NRC. 2003. Environmental cleanup at Navy facilities: Adaptive site management. National Research Council, National Academies Press, Washington, D.C.
2. Reed, S., and J. James. 2010. Environmental Restoration Overview, Mountain Creek Industrial Center. July 16.
3. Bartram, J., and R. Balance (eds.). 1996. Water Quality Monitoring - A Practical Guide to the Design and Implementation of Freshwater Quality Studies and Monitoring Programmes. United Nations Environment Programme and the World Health Organization.
4. EPA. 2011. Environmental Cleanup Best Management Practices: Effective Use of the Project Life Cycle Conceptual Site Model. EMA 542-F-11-011. Environmental Protection Agency, Office of Solid Waste and Emergency Response, Washington, D.C.
5. EPA. 2004. Handbook of groundwater protection and cleanup policies for RCRA Corrective Action. EPA530-R-04-030. Environmental Protection Agency, Office of Solid Waste and Emergency Response, Washington, D.C.
6. ESTCP. 2009. Reductions in DNAPL Longevity through Biological Flux Enhancement. Final Report. ESTCP Project ER-0438. Environmental Security Technology Certification Program, Arlington, VA.
7. EPA. 1994. Alternative Methods for Fluid Delivery and Recovery. EPA/625/R-94/003, U.S. Environmental Protection Agency, Office of Research and Development, Washington, D.C.
8. EPA. 1998. Technical Protocol for Evaluating Natural Attenuation of Chlorinated Solvents in Ground Water. EPA/600/R-98/128, U.S. Environmental Protection Agency, Office of Research and Development, Washington, D.C.
9. EPA. 2007. Monitored Natural Attenuation of Inorganic Contaminants in Groundwater, Vol. 1: Technical Basis for Assessment. EPA/600/R-07/139. Environmental Protection Agency,

National Risk Management Research Laboratory, Groundwater and Ecosystems Restoration Division, Ada, OK.

10. EPA. 2007. Monitored Natural Attenuation of Inorganic Contaminants in Groundwater, Vol. 2: Assessment for Non-Radionuclides Including Arsenic, Cadmium, Chromium, Copper, Lead, Nickel, Nitrate, Perchlorate, and Selenium. EPA/600/R-07/140. Environmental Protection Agency, National Risk Management Research Laboratory, Groundwater and Ecosystems Restoration Division, Ada, OK.

11. EPA. 2010. Monitored Natural Attenuation of Inorganic Contaminants in Ground Water Vol. 3: Assessment for Radionuclides Including Tritium, Radon, Strontium, Technetium, Uranium, Iodine, Radium, Thorium, Cesium, and Plutonium-Americium. EPA/600/R-10/093. Environmental Protection Agency, National Risk Management Research Laboratory, Groundwater and Ecosystems Restoration Division, Ada, OK.

12. Looney, B.B., T.O. Early, T. Gilmore, F.H. Chapelle., N.H. Cutshall, J. Ross, M. Ankeny, M. Heitkamp, D. Major, C.J. Newell, W.J. Waugh, G. Wein, K.M. Vangelas, K.M. Adams, and C.H. Sink. 2006. Advancing the Science of Natural and Enhanced Attenuation for Chlorinated Solvents. Final Technical Document for the Monitored Natural Attenuation and Enhanced Attenuation for Chlorinated Solvents Project. WSRC-STI-2006-00377. Savannah River National Laboratory, Aiken, SC.

13. Gilmore, T., B.B. Looney, N. Cutshall, D. Major, T. Wiedmeier, F.H. Chapelle, M. Truex, T. Early, M. Heitkamp, J. Waugh, D. Peterson, G. Wein, C. Bagwell, M. Ankeny, K.M. Vangelas, K.M. Adams, and C.H. Sink. 2006. Characterization and Monitoring of Natural Attenuation of Chlorinated Solvents in Ground Water: A Systems Approach. WSRC-STI-2006-00084, Rev. 1. Savannah River National Laboratory, Aiken, SC.

14. ITRC. 2010. Technology overview: Measurement and use of mass flux at chlorinated solvent sites. Interstate Technology & Regulatory Council, Integrated DNAPL Source Strategy Team. In press.

15. EPA. 2009. Record of Decision for the Commencement Bay – South Tacoma Channel Superfund Site, OU 1. Well 12A, Tacoma, Washington. October.

16. ESTCP. 2011. Assessing Alternative Endpoints for Groundwater Remediation at Contaminated Sites. Final Report. ESTCP Project ER-200832. Environmental Security Technology Certification Program, Arlington, VA.

17. SERDP. 2005. Final report. SERDP and ESTCP Expert Panel Workshop on Research and Development Needs for the Environmental Remediation Application of Molecular Biological Tools. October.

18. SRNL. 2009. DOE-EM Long-Term Monitoring Technical Forum. February 11-12, 2009. SRNL-RP-2009-99845. Savannah River National Laboratory, Aiken, SC.

19. Geist, D.R., and Dauble, D.D. 1998. Redd Site Selection and Spawning Habitat Use by Fall Chinook Salmon: The Importance of Geomorphic Features in Large Rivers. *Environmental Management* 22(5): 655–669.

20. Dayvault, J., S. Morrison, and J. Waugh. Overview of U.S. Department of Energy Office of Legacy Management Applied Science and Technology Program. WM2011 Conference, February 27-March 3, 2011, Phoenix, AZ.