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Deep Vadose Zone Monitoring Strategy for the Hanford Central Plateau

September 2018

CE Strickland
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RD Mackley
TC Johnson

U.S. DEPARTMENT OF ENERGY

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Pacific Northwest National Laboratory
Richland, Washington 99352

Executive Summary

The vadose zone within the Hanford Central Plateau contains large quantities of mobile contaminants that have not yet reached the groundwater. Deep vadose zone (DVZ) contamination is located below the depth of direct contaminant exposure potential, but may be a current and/or potential future source of groundwater contamination. Monitoring to observe subsurface processes and driving forces related to contaminant transport or to directly observe contaminant movement in the DVZ provides remedy performance information prior to contaminants reaching the groundwater and thereby is an important element of a remedy implementation.

Contaminant migration in the vadose zone at the Hanford Site is a slow process (decades to hundreds of years). The use of groundwater monitoring alone may be unable to provide timely information to verify long-term remedy performance, but these data are needed to better parameterize predictive models that will provide a means for assessing/predicting long-term performance. Monitoring the long-term behavior of natural subsurface systems and the performance of remedial actions will be critical to implementing and validating cleanup strategies. DVZ monitoring components include methods and technologies for directly and indirectly measuring moisture conditions and contaminant flux to groundwater, providing early-warning monitoring of unexpected or unacceptable DVZ behaviors. To date, a comprehensive strategy for vadose zone monitoring has not been developed. This report addresses the need to identify appropriate technologies and monitoring configurations for a DVZ monitoring strategy applicable to the Hanford Central Plateau. As monitoring development recommendations in this report are implemented, components of this strategy may need to evolve over time.

Monitoring technologies have seen many recent advancements and have been successfully demonstrated for a wide range of groundwater and vadose zone applications, including soil desiccation, surface barriers, and amendment infiltration/injections. Building on recent advancements, a comprehensive review of existing and emerging long-term DVZ monitoring technologies is presented within the context of an overall monitoring strategy for the Hanford Central Plateau. In the near future, remedial actions will be selected for many waste sites on the Central Plateau. Selection and implementation of remediation technologies will require vadose-zone characterization/monitoring programs that are designed to support effective remedy design and implementation (e.g. refine the conceptual site model), verify the effectiveness of remedial actions, and provide an early indication of future contaminant flux from vadose-zone sources to groundwater.

An important consideration for monitoring is the intensity of monitoring needed. The evolution of monitoring intensity and the types of monitoring technologies used over time must be consistent with the stage of remediation and be suitable for transition to long-term monitoring. It is anticipated that the monitoring configuration will evolve over time, where more intense methods/frequency of monitoring will progress to less intensive methods/frequency of monitoring.

Due to the very long time scales involved, predictive numerical modeling will be needed to make remedy decisions and will require accurate site-specific information. Monitoring data must be integrated with modeling analyses to facilitate feedback between predictive model results, verification monitoring, and refinement of the conceptual site model. These interpretive aspects of the monitoring program are not directly included in this report. However, the overall monitoring strategy discussed in this report was developed with data interpretation and predictive model integration as an important design consideration.

Three fundamental categories of remediation scenarios are presented for use in describing monitoring methods and deployment configurations: monitored natural attenuation, application of a surface barriers, and in situ remediation. Several variants of these remediation scenarios and associated monitoring are

also discussed. Monitoring configurations and associated technologies were selected for each remediation scenario and are described based on their ability to meet monitoring objectives during each phase of remediation, while minimizing monitoring costs. In each scenario, a combination of remote, surface-deployed, and subsurface-deployed approaches are identified. In most cases, technologies that minimize the need for permanent surface or subsurface infrastructure are preferred to avoid equipment degradation issues that will inevitably occur over long timeframes.

In some cases, a technology selected for a monitoring configuration would require additional development and testing to demonstrate that it has sufficient maturity for the designated use (e.g., electromagnetic imaging needs additional development of data interpretation for subsurface imaging). Each of the identified technologies has strengths and weaknesses, such that no single technology is the best choice and a combination of technologies is recommended. Promising technologies that can provide potential advantages warrant further development. For all of the geophysical and remote sensing techniques, improved data interpretation and data management will also improve their use for meeting monitoring objectives.

The information in this report can be used as a resource for planning future vadose zone monitoring and developing site-specific designs relevant to Hanford Central Plateau remediation. The monitoring strategies are intended to provide cost-effective, viable approaches that meet vadose zone monitoring objectives.

Acknowledgments

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Acronyms and Abbreviations

ARAR	applicable or relevant and appropriate requirement
CCU_c	Cold Creek Unit caliche
CCU_g	Cold Creek Unit gravel
CCU_z	Cold Creek Unit silt
COC	contaminant of concern
CSEM	controlled source electromagnetic measurements
DVZ	deep vadose zone
EC	electrical conductivity
EM	electromagnetic
EMI	electromagnetic induction
EPA	U.S. Environmental Protection Agency
ERT	electrical resistivity tomography
GPR	ground-penetrating radar
GW	groundwater
InSAR	interferometric synthetic aperture radar
LiDAR	light detection and ranging
MNA	monitored natural attenuation
NQAP	Nuclear Quality Assurance Program
OU	operable unit
PCAP	passive capillary samplers
PRB	permeable reactive barrier
PVC	polyvinyl chloride
RCRA	Resource Conservation and Recovery Act
SOMERS	Scientific Opportunities for Monitoring Environmental Remediation Sites
TI	technical impractibility
VZ	vadose zone

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1.0 Introduction

Deep vadose zone (DVZ) contamination is located below the depth of direct contaminant exposure potential, but may be a current or potential future source of groundwater contamination. Movement of contamination from the DVZ to the groundwater creates the potential for exposure and risk to receptors through the groundwater pathway. For sites where DVZ contaminants need to be addressed through monitored natural attenuation (MNA) or other remediation approaches, performance of the DVZ remedy is determined by reduction of contaminant flux to the groundwater such that groundwater protection objectives are met. Monitoring to observe subsurface processes and driving forces related to contaminant transport or to directly observe contaminant movement in the DVZ provides remedy performance information prior to contaminants reaching the groundwater and thereby is an important element of a remedy implementation.

The vadose zone within the Hanford Central Plateau contains large quantities of mobile contaminants that have not yet reached the groundwater. The flux of contaminants through the vadose zone is a primary quantity influencing future groundwater contamination. Active remediation technologies under consideration will address contamination by reducing the flux of contaminants to groundwater. Even under natural recharge conditions, contaminant migration in the vadose zone at the Hanford Site is a slow process (decades to hundreds of years).

The use of groundwater monitoring alone may be unable to provide timely information to verify long-term remedy performance. Monitoring vadose zone moisture and contaminant conditions can serve as an "early" indicator of remedy performance. Effective monitoring methods include quantitative information about contaminants in the vadose zone over long periods of time. Monitoring the long-term behavior of natural subsurface systems and the performance of remedial actions is critical to implementing and validating cleanup strategies.

DVZ monitoring components include methods and technologies for directly and indirectly measuring moisture conditions (both moisture content and water potential) and contaminant flux to groundwater, identification and monitoring of improved biological indicators that may help determine potential impacts on the environment, and the development of monitoring methodologies for the early detection of unexpected or unacceptable DVZ behaviors such as adverse changes in contaminant movement. Development and implementation of monitoring systems and approaches will need to address specific data needed for the likely categories of remediation scenarios expected at Hanford to effectively manage remediation, evaluate remedy performance, and provide the basis for remedy closure.

Monitoring technologies have seen many advancements recently and have been successfully demonstrated for a wide range of groundwater and vadose zone applications at the Hanford Site including soil desiccation (Truex et al. 2013), surface barriers (Strickland et al. 2010; DOE 2016a), and amendment infiltration/injections (CHPRC 2016). Building on these recent advancements, a comprehensive review of existing and emerging long-term DVZ monitoring technologies is presented within the context of an overall monitoring strategy for the Hanford Central Plateau.

An important consideration for monitoring is the intensity of monitoring needed. The Scientific Opportunities for Monitoring Environmental Remediation Sites (SOMERS, Bunn et al. 2012) document describes how the evolution of monitoring intensity and monitoring technologies over time must be consistent with the stage of remediation and enable transition to long-term monitoring. Thus, monitoring configurations presented herein were developed to include monitoring intensity changes in conjunction with evolution of the phase of remediation for a vadose zone site.

Due to the very long time scales involved, predictive modeling will be needed to make remedy decisions, and will require accurate site-specific information. Monitoring data must be integrated with modeling analyses to facilitate feedback between predictive model results, verification monitoring, and refinement of the conceptual site model. The recent development of the E4D software (Johnson 2014) is a key advancement in data interpretation and linkage of monitoring data with predictive modeling. Although the data interpretation aspects of monitoring are not directly included in this report, the overall monitoring strategy discussed in this report was developed with data interpretation and predictive model integration as an important monitoring system design consideration.

This document provides a comprehensive review of the site-specific context and challenges for long-term DVZ monitoring and how existing and emerging monitoring technologies can be implemented into an overall DVZ monitoring strategy for the Hanford Central Plateau. In the near future, remedial actions will be selected for many waste sites on the Central Plateau. Selection and implementation of remediation will require vadose zone characterization/monitoring programs that are designed to support effective remedy design and implementation (e.g. refine the conceptual site model), verify the effectiveness of remedial actions, and provide an early indication of future contaminant flux from vadose-zone sources to groundwater.

2.0 Monitoring Context and Needs for the Central Plateau Deep Vadose Zone

2.1 Background

The Hanford Central Plateau, located in the middle of the Hanford Site (Figure 1), was where historical chemical processing of irradiated fuels for recovery of plutonium and other materials occurred. Multiple wastes were discharged to the subsurface, resulting in vadose zone and groundwater contamination.

The U.S. Department of Energy (DOE 2008) examined the available information on potential deep vadose zone contamination of technetium and uranium in partial fulfillment of Tri-Party Agreement Milestone M-015-50, *Submit a Treatability Test Work Plan for Deep Vadose Zone Technetium and Uranium to Ecology and EPA* (Ecology et al. 2018). The available information included disposal inventories, depth of contamination, and potential risk to groundwater (Eslinger et al. 2006). Although the information sources have large uncertainties, DOE (2008) identified specific waste sites with discharges to the vadose zone that would benefit from remedies that are protective of groundwater (Figure 2). A majority of waste sites with deep vadose zone contamination in the Central Plateau are assigned to the 200-DV-1, 200-EA-1, 200-WA-1, and 200-BC-1 Operable Units (OUs).

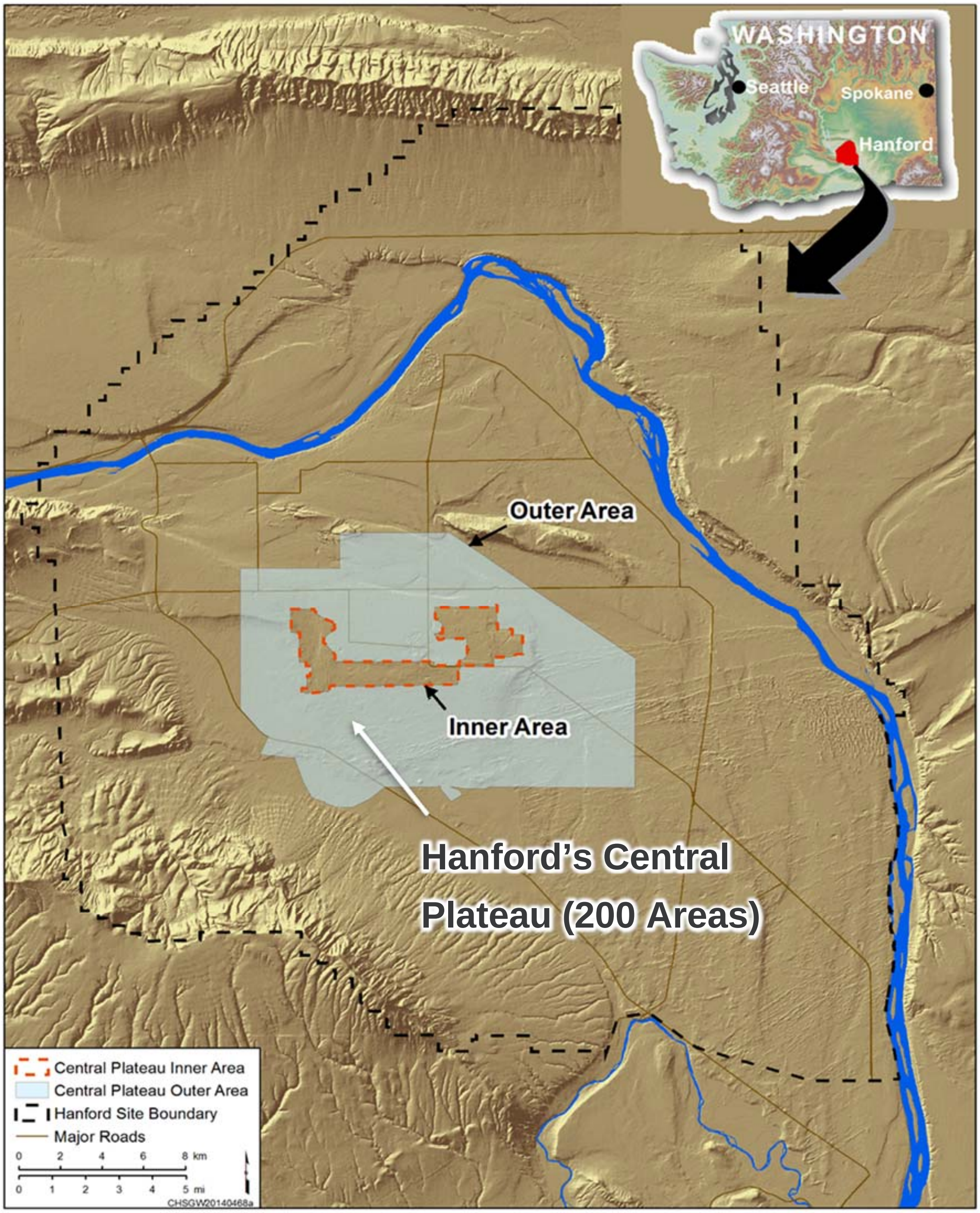

Figure 1. Hanford Site and Central Plateau location.

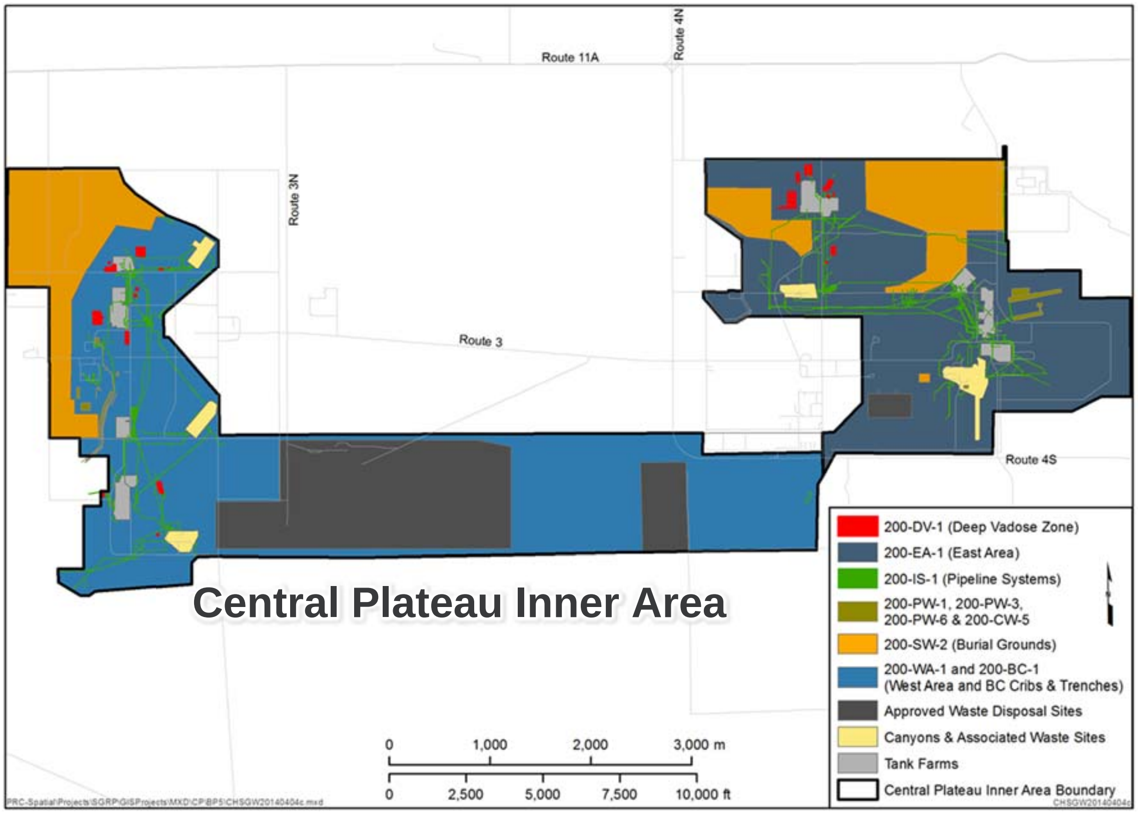

Figure 2. Map showing source zone operable units within the Hanford Central Plateau Inner Area.

The thickness and stratigraphy of the vadose zone varies across the Inner Area. The vadose zone thickness ranges from approximately 71 to 78 m (234 to 255 ft) in the north part of the 200 West area and from approximately 67 to 73 m (221 to 238 ft) in the south part of the 200 West area. In these areas, the vadose zone is composed of the Hanford formation, the Cold Creek Unit silt (CCU_z) and caliche (CCU_c), the Ringold Taylor Flats sediments, and Ringold sediments. The vadose zone in the north part of the 200 East area ranges from 70 to 82 m (230 to 270 ft) thick and is composed of the Hanford formation and the CCU_z and CCU gravel (CCU_g). Beneath the south part of the 200 East waste sites, the vadose zone ranges from 85 to 104 m (280 to 340 ft) thick and is composed of Hanford formation, the Cold Creek Unit gravel (CCU_g) in places, the Ringold Taylor Flats sediments locally in the vicinity of the BC-Cribs, and Ringold sediments. The water table lies within the Ringold sediments in the 200 West Area, within the Hanford formation and CCU_g unit in the north part of the 200 East Area and in the Cold Creek Unit gravel (CCU_g), Ringold Taylor Flats sediments, and Ringold sediments in the south part of the 200 East area.

At many sites where liquid waste was discharged, the vadose zone is contaminated across the full thickness to the water table. Thus, monitoring approaches will need to consider potential applications for any of the depths and the various DVZ hydrostratigraphic units. This is illustrated conceptually in Figure 3.

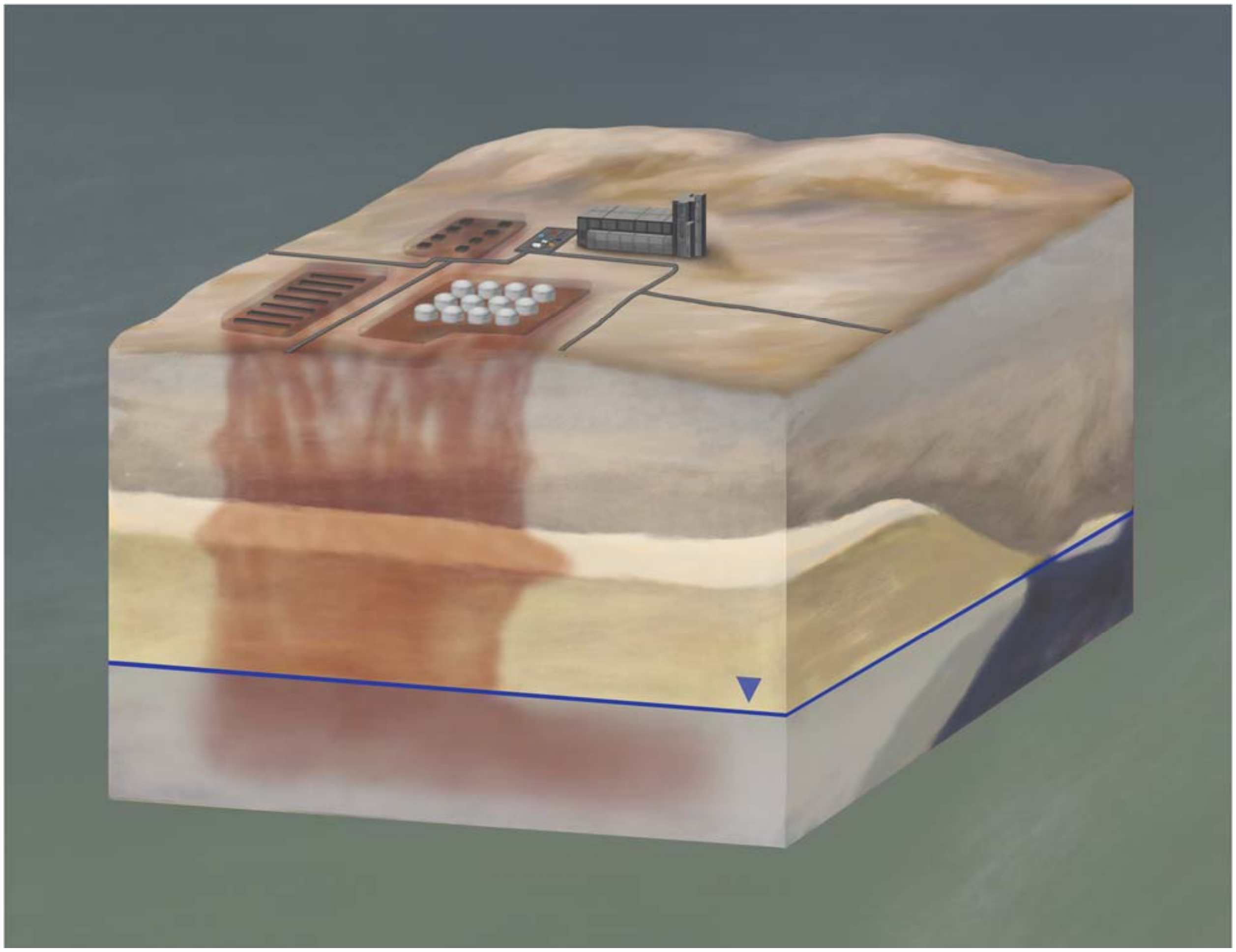

Figure 3. Conceptual view of the Hanford Central Plateau Deep Vadose Zone monitoring setting.

2.2 Coupled System Contaminant Dynamics

2.2.1 Vadose Zone and Groundwater Contaminant Transport

This section presents a brief description of vadose zone transport processes and largely follows Truex and Carroll (2013). Several different processes control transport in the vadose zone compared to groundwater systems. These differences in transport processes impact contaminant attenuation behavior and need to be evaluated during the remedy evaluation process. In particular for the unsaturated vadose zone, physical transport processes including advection, dispersion, and diffusion are critical to understanding contaminant transport in the vadose zone, primarily because (1) there is a nonlinear relationship between water content and hydraulic conductivity that complicates water and contaminant flux, and (2) subsurface interfaces can dramatically impact vertical moisture and contaminant movement. In addition, the nature of recharge at the water table and mixing of recharge water with groundwater are important relative to the resultant groundwater contaminant concentrations. There is significant information about relevant biogeochemical processes due to their dominant roles in contaminant attenuation in groundwater systems, but these processes must be evaluated in the context of the vadose zone properties, especially due to the presence of a gas phase.

2.2.1.1 Physical Transport Processes and Controlling Features

The physical processes controlling fluid flow in the vadose zone are quite different from those within the groundwater system. In addition, the transport attenuation processes are generally more significant in the vadose zone compared to the groundwater system. The nonlinear relationship between water content and hydraulic conductivity must be considered in evaluating flow and transport through the vadose zone. Ultimately, a primary driving force for long-term transport is often the net recharge at ground surface, a function of precipitation, infiltration, and transpiration processes. Subsurface interfaces that separate zones of different particle size distributions and properties (i.e., layering) are also important due to the impact on unsaturated flow processes. Preferred flow pathways can occur at interfaces and may be important in the overall rate of vertical contaminant movement (e.g., dipping layers, vertical features such as clastic dikes, or fractures). Smaller-scale interfaces may also be important relative to intra- or inter-particle contaminant diffusion and the relative mobility of water and contaminants within different micro-scale regimes of the subsurface. Specific features of vadose zone moisture transport are discussed in the following sections.

2.2.1.2 Moisture Retention

The groundwater system pore space is saturated with water, but within the vadose zone, some gas (i.e., air) is present, resulting in the existence of three phases: solid and two fluids (water and gas). Common conceptual models of unsaturated fluid flow idealize subsurface materials as a group of effective capillaries and ignores the adsorptive effects. Capillary forces act on pore water in the vadose zone and impact fluid flow and water content distributions (Cohen and Mercer 1990; Hillel 1998). The capillary pressure is also commonly referred to as suction or tension.

This relationship of capillary pressure, or matric potential, versus water content is termed the water or moisture retention curve (Figure 4). The capillary pressure generally increases nonlinearly with decreasing water content. Alternatively, capillarity generally increases with decreasing pore radius (or decreasing grain size). Thus, the largest pores drain first and water contents are generally higher for finer-grained materials. The last water to drain comes from the smallest pores. The dependence of the water content on the capillary pressure is a characteristic property of a soil (Figure 4). General properties of the characteristic relationship are dependent on soil texture, pore size distribution, and geometry. Two commonly used functions that describe the relationship between matric potential and saturation are given by Brooks and Corey (1964) and van Genuchten (1980). These water retention functions generally perform well under moderately moist conditions. Over the entire moisture range water flow occurs due to both capillary and adsorptive forces but under dry conditions is dominated by the latter. Extension of the Brooks and Corey and van Genuchten water retention functions to include adsorptive effects has been investigated by several researchers (Campbell and Shiozawa 1992; Rossi and Nimmo 1994; Fayer and Simmons 1995; Webb 2000; Lebeau and Konrad 2010; Zhang 2011).

Moisture retention relationships also vary depending on the direction and history (hysteresis) of change in water content. Hysteresis is known to occur in multiphase immiscible systems in intermediate saturation ranges, which complicates the prediction of constitutive relationships (Kechavarzi et al. 2005). Hysteresis is created by a combination of pore processes including saturation of variable pore sizes, saturation-dependent residual saturations, and non-wetting fluid entrapment (Lenhard 1992; Lenhard et al. 2004).

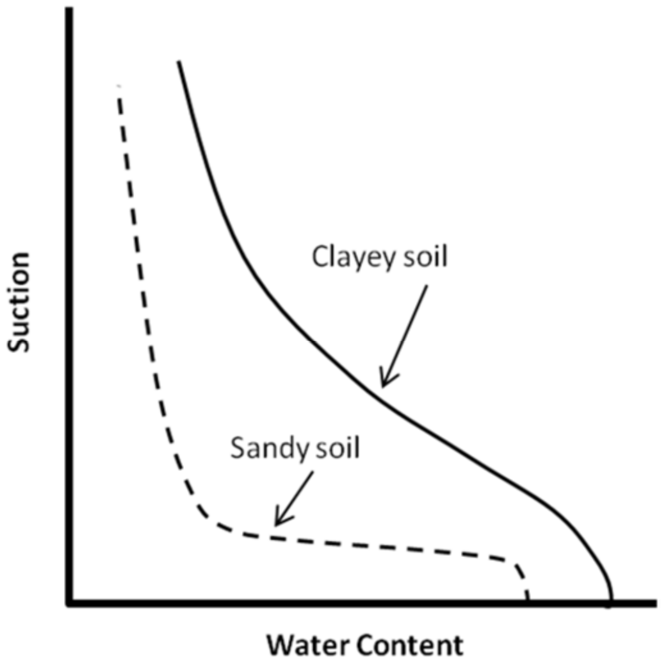

Figure 4. Moisture retention curve showing relation of water content and matric potential for sandy (dashed lined) and clayey soils (solid line).

2.2.1.3 Darcy's Law, Hydraulic Conductivity, and Relative Permeability

Groundwater systems are water saturated, and thus only liquid water is available for fluid flow. For groundwater systems, the Darcy flux is a function of the hydraulic conductivity and the hydraulic gradient (Darcy 1856). Water movement in the vadose zone can also be described with a version of Darcy's law that was modified by Buckingham (1907). The driving force for water flux is the hydraulic head gradient, which in the vadose zone can be separated into the matric potential head gradient and the gravity gradient. Gravity works to induce vertical migration of water, but the rate of movement is a function of gravity, capillary, and adsorptive forces.

The primary difference for Darcy's law in the vadose zone is that the hydraulic conductivity is not a constant for a given porous medium. The unsaturated hydraulic conductivity is highly variable as a function of the water content. The relative water permeability of a given soil can change over many orders of magnitude with changes in saturation and can be estimated from the saturated hydraulic conductivity and water retention function (Burdine 1953; Mualem 1976) even under dry conditions.

2.2.1.4 Unsaturated Water Flow and Recharge

Recharge is generally defined as the rate at which water enters an aquifer from any source. Recharge occurring across the Hanford Site Central Plateau is transmitted through the vadose zone to the underlying groundwater aquifer. All precipitation may not infiltrate (e.g., surface run-off), and all infiltrated water may not recharge the groundwater system (e.g., due mainly to evapotranspiration and vadose zone storage). The flux of water at depths below the influence of evapotranspiration can be used to predict future recharge. Recharge rates at the Hanford Site range from near zero to more than 100 mm/yr (Gee 1987; Fayer and Szecsody 2004; Rockhold et al. 2009) and primarily depend on surface soil and vegetation conditions.

Increased infiltration flux rates due to temporary releases are short-lived transient behaviors, and infiltration rates decay exponentially until they reach the long-term, natural recharge rate of infiltration. As water content decreases during this drainage process, the relative ratio of capillary to gravity force increase, which induces more lateral flow and increases retention and immobilization of water within vadose zone pores. This restriction to vertical flow with decreasing water content during drainage is also enhanced by the nonlinear decreases in hydraulic conductivity. Spatial variations in hydraulic conductivity typically enhance these restrictions to vertical flow and induce increased lateral flow, which further reduces water content during drainage.

Infiltrated water released into the vadose zone will migrate through the vadose zone vertically and mix into the groundwater. For sites where a water pulse was added, post-discharge conditions will tend to relax toward more natural recharge-driven conditions over time. With an appropriate understanding of sediment properties and an assessment of the recharge-driven flux conditions for the site, flux to groundwater can be bound to values between the recharge-driven flux and the flux that corresponds to current or expected maximum saturation conditions in the vadose zone. These values then relate to the characteristic shape of the flux curves. An example of another complicating factor that may need to be assessed is the movement of water out of a perched zone. Site data can potentially be used to determine the current position on the saturation/flux curve and thereby assess the expected changes in the future as the site relaxes back toward recharge-driven conditions.

2.2.1.5 Contaminant Attenuation Processes

Contaminant transport is impacted by solubility, sorption, and degradation/decay processes that are a function of the contaminant properties and the biogeochemistry in the vadose zone. These processes are essentially the same as those presented and described in detail in the U.S. Environmental Protection Agency (EPA) technical protocol for MNA of inorganic contaminants in groundwater (EPA 2007a,b, 2010; ITRC 2010) and described with respect to conceptual site models by Truex et al. (2011a). Potential considerations unique to the vadose zone include the following items:

- Presence of a gas phase that may be important for some biogeochemical processes related to its interaction and impact on pore water chemistry
- “Extreme” chemistry or physical processes due to waste fluid properties
- Long residence times of contaminated pore water that may be more likely to favor equilibrium chemistry conditions and enable slower kinetic reactions to proceed more fully than in a faster-flowing groundwater setting

These processes need to be evaluated and considered in combination with the factors controlling water flux to the groundwater to estimate the contaminant flux to groundwater.

Attenuation processes decrease contaminant concentrations or migration rates such that, over the long term, the combined impact is a cumulative contaminant reduction response that may be greater than the impact of any individual process.

2.3 Remedy Technology Status

The 200-ZP-1 groundwater OU is the only OU in the Central Plateau with a final record of decision. This record of decision includes pump-and-treat and MNA, but does not address any ongoing sources to groundwater. Pump-and-treat has also been initiated as interim measures for the groundwater in the 200-UP-1 and 200-BC-1 OUs, again without addressing ongoing sources to groundwater. Water extraction for the perched water zone in the B-Complex is occurring as a removal action for the 200-DV-1 vadose zone OU. The Prototype Hanford Barrier is in place over the 216-B-57 crib, functionally providing infiltration control at this site as well as enabling collection of data for surface barrier performance, design, and monitoring. Interim surface barriers have been deployed at selected tank farms, also providing localized infiltration control and enabling collection of data (Zhang et al. 2007, 2011).

In addition to the above remedies, removal actions, and operational actions related to vadose zone contamination, candidate deep vadose zone remediation technologies have been compiled and a limited number of treatability tests have been conducted. The DVZ Treatability Test Plan (DOE 2008) outlined an array of technologies for treatability testing. The effort included test activities for: in situ gas-phase technologies (desiccation and uranium reactive gas sequestration), grouting technologies, soil flushing, and surface barriers. In addition to technology-specific activities, efforts included vadose zone remediation technology reviews and workshop activities administered under the 200-DV-1 OU RI/FS and RFI/CMS work plan (DOE 2016b), culminating in a final review and assessment documented in *Technology Evaluation and Treatability Studies Assessment for the Hanford Central Plateau Deep Vadose Zone*[1] and, most recently, the technology review as part of this document.

2.4 Monitoring Scenarios

Based on the above information, categories of potential vadose zone remedies were assigned and used as scenarios for which remedy performance and long-term monitoring will be needed. Scenarios included MNA, surface barrier, and in situ remediation. Variants of these scenarios are also discussed. The only receptor for these scenarios is associated with the groundwater pathway (as is the case for non-volatile inorganic contaminants in the DVZ). Scenarios for excavation, and contaminant extraction were not included because the focus of the document is in situ or surface barrier remedies. In situ physical stabilization (e.g., verification of in situ grouting integrity) was not included because it is not widely applicable to the Hanford Central Plateau vadose zone (Truex et al. 2011b). However, the other scenarios and associated monitoring may be relevant to a site after excavation, contaminant extraction, or in situ physical stabilization are applied. Scenarios and associated monitoring configurations are described in Section 4.0.

[1] DOE. 2017. *Technology Evaluation and Treatability Studies Assessment for the Hanford Central Plateau Deep Vadose Zone*. DOE/RL-2017-58, Decisional Draft, U.S. Department of Energy, Richland Operations Office, Richland, WA.

3.0 Monitoring Technologies

3.1 Vadose Zone Properties

Predictive modeling is needed for remedy decisions and optimization and requires site-specific information on geochemical and physical properties. As discussed in the previous section, one of the most critical features influencing future impacts to groundwater is contaminant flux. Several properties influence flux to groundwater, including the spatial distribution of contaminant concentrations, permeability, porosity, moisture content, and matric potential. Information must also be acquired soon enough for timely decision-making in system response.

The ultimate goal of vadose zone remediation is to assure that contaminant mass flux can be maintained at levels where regulatory thresholds, such as groundwater maximum concentration limits, will not be exceeded. For some scenarios, including soil desiccation and surface barriers, contaminant flux is reduced by removing moisture from the subsurface, lowering the unsaturated hydraulic conductivity and water flux, which in turn reduces all fluxes. One measure of satisfactory remedy performance is demonstrating that unsaturated hydraulic conductivity can be maintained sufficiently low using knowledge of soil texture and measurements of moisture or matric potential.

Sediment/rock samples in the vadose zone provide detailed information on a wide range of properties (i.e., porosity, permeability, moisture content, and contaminant concentrations). This information is critical to the overall characterization and monitoring strategy but is limited to a discrete number of locations and discrete times. Continuous sampling methods that cover broad spatial areas can be used to improve flux estimates. Monitoring methods described here can be used independently and in combination to provide data that improves understanding of system behavior. These include point-scale sensors and geophysical methods that are sensitive to moisture content, matric potential, and electrical conductivity/salinity. These methods will be discussed along with their potential for characterization and monitoring in the DVZ.

3.2 Overview of Monitoring Configurations

Multiple configurations of monitoring systems are relevant to monitoring the vadose zone. Figure 5 and Table 1 provide an overview of the different categories of monitoring methods. Each method utilizes one or more type of monitoring technology and has specific information target(s) in the vadose zone, although multiple methods provide similar information. Table 2 contains a checklist summary of the information obtainable from the multitude of DVZ monitoring technologies presented here.

Sections 3.3 through 3.9 describe the primary monitoring technology categories and how they can be deployed as part of the configurations shown in Figure 5. Importantly, a monitoring system for a vadose zone waste site or waste site complex will incorporate and integrate multiple configurations as needed spatially and temporally to meet monitoring objectives. Discussion of integrated configurations for different types of remediation scenarios is provided in Section 4.0.

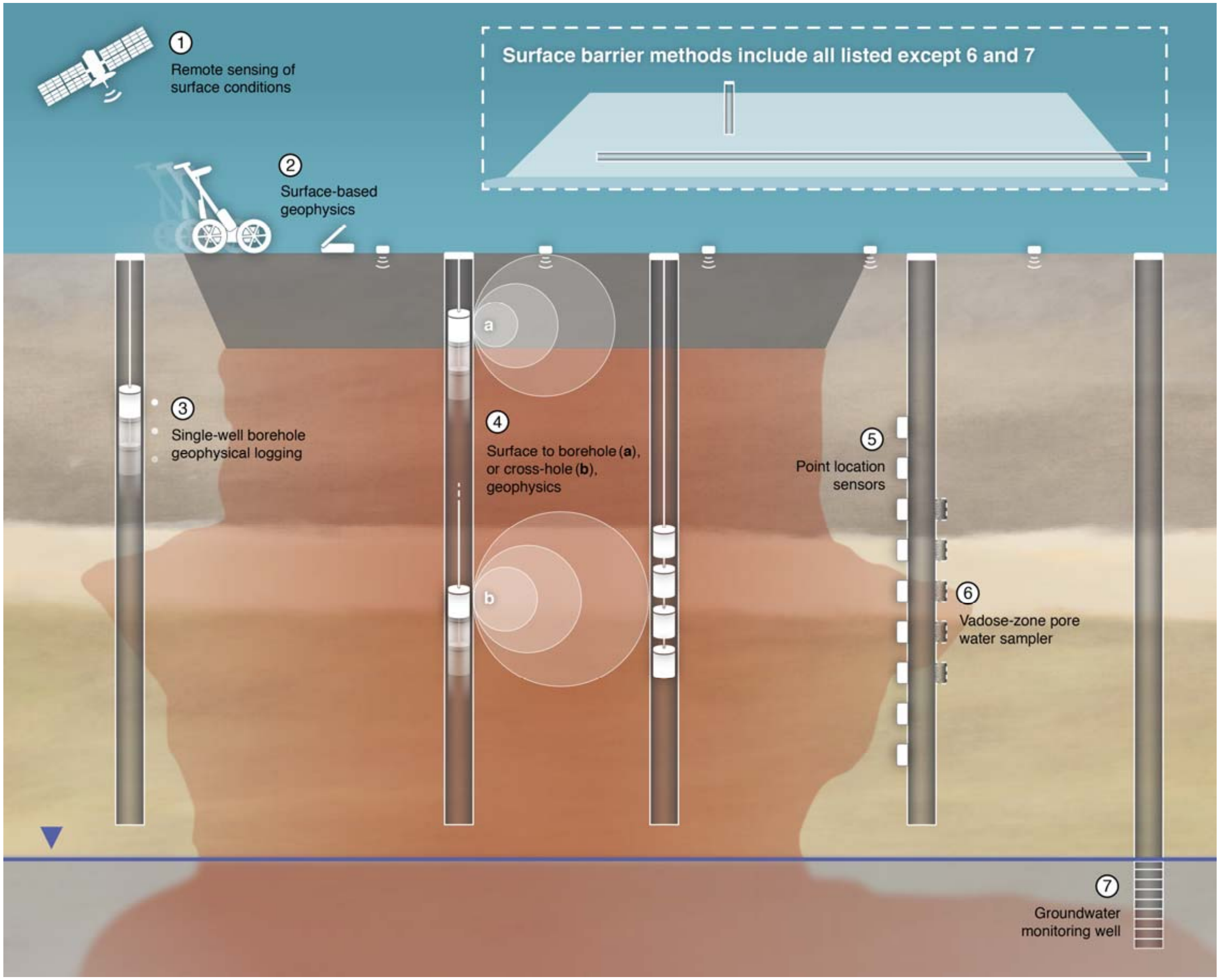

Figure 5. DVZ monitoring methods. Numbers shown inside white circles correspond to the numbered monitoring methods in Table 1.

Table 1. Vadose zone monitoring methods summary.

Monitoring Method	Types of Technologies	Summary of Information Provided
1. Remote sensing of surface conditions	InSAR, LiDAR, hyperspectral, meteorological	Spatial distribution of surface boundary conditions important to vadose zone moisture and contaminant transport (e.g., recharge, erosion, intrusion).
2. Surface-based geophysics for the subsurface	EMI, GPR, ERT, Seismic (EMI, GPR, and ERT can be coupled with a tracer)	Subsurface 3D distribution of moisture content/matric potential, subsurface infrastructure, indirect indicators of subsurface hydrogeologic properties; Autonomous (e.g., ERT) can be applied to provide continuous temporal data.
3. Single borehole geophysical logging	EMI, GPR, ERT, Seismic, Gravity, spectral gamma, neutron probe	Subsurface vertical profile of moisture content/matric potential, radionuclide concentration (e.g., spectral gamma), subsurface infrastructure, indirect measures of subsurface hydrogeologic properties; Autonomous (e.g., ERT) can be applied to provide continuous temporal data.
4. Cross-hole or surface-borehole geophysical logging	EMI, GPR, ERT, Seismic (EMI, GPR, and ERT can be coupled with a tracer)	Subsurface 2D (and 3D) cross sections of moisture content/matric potential, subsurface infrastructure, indirect measures of subsurface hydrogeologic properties; Autonomous techniques (e.g., ERT) can be applied to provide continuous temporal data.
5. Point-location sensors	In situ sensors or sensors deployed at a fixed measurement location.	Temperature, moisture content, matric potential, humidity, contaminant/chemical data at a specific location. Can be arranged as a vertical set of sensors in a borehole or at the surface.
6. Point-location pore water/soil gas samplers	Sampling ports to collect water or gas for aboveground analysis by a field instrument or in the laboratory	Water or gas chemical constituent analyses.
7. Groundwater monitoring well	Sample collection or in situ probes	Groundwater contaminant/constituent concentration/flux, and water level information to evaluate vadose zone impact to groundwater.

EMI is electromagnetic induction; ERT is electrical resistivity tomography; GPR is ground-penetrating radar.

Table 2. Information obtained from vadose zone monitoring technologies.

Types of Technology	Technology Summary	Type of Information							
		Land surface displacement	Vegetation	Recharge	Imaging	Contaminant Concentration	Moisture Content	Matric Potential	Temperature
Interferometric synthetic aperture radar (InSAR)	Satellite-based measurement of land surface features and displacement through time. Typical spatial resolution: meter horizontal, millimeter to centimeter vertical.	✓			2D				
Light detection and ranging (LiDAR)	Airborne or surface-based measurement of land surface features and displacement through time. Typical spatial resolution: decimeter horizontal, millimeter to centimeter vertical.	✓	✓		2D				
Hyperspectral imaging	Satellite-based mapping of vegetation (type and density), moisture, and soil surface properties that contribute to estimates of recharge and deep-drainage. Typical spatial resolution horizontal and vertical: meter.		✓	✓	2D		✓		
Ground penetrating radar (GPR)	Surface or borehole-based generation and measurement of high-frequency (MHz-GHz) electromagnetic fields. Provides 3D imaging and temporal changes in bulk electrical conductivity (EC) and permittivity. Typical spatial resolution horizontal and vertical: decimeter to meter. Maximum sensing depth of several meters.				3D	✓	✓	✓	✓
Electrical resistivity tomography (ERT)	Surface or borehole-based generation and measurement of low-frequency (DC-Hz) electric fields. Provides 3D imaging and temporal changes in bulk EC. Typical spatial resolution horizontal and vertical dependent on distance and electrode separation: meter or less cross-borehole, lower resolution from surface.				3D	✓	✓		✓
Controlled source electromagnetic measurements (CSEM)	Aerial, surface or borehole-based generation and measurement of low-frequency (Hz-kHz) electromagnetic fields. Provides 3D imaging and temporal changes in bulk EC. Unlike ERT, CSEM does not require electrical contact with the ground. Typical spatial resolution horizontal and vertical: meter.				3D	✓	✓		✓

Types of Technology	Technology Summary		Type of Information						
		Land surface displacement	Vegetation	Recharge	Imaging	Contaminant Concentration	Moisture Content	Matric Potential	Temperature
Seismic	Surface or borehole-based generation and measurement of low-frequency (Hz-kHz) displacement/velocity/acceleration fields. Provides 3D imaging and temporal changes in seismic velocity. Typical spatial resolution horizontal and vertical: meter.				3D		✓	✓	
Gravity	Aerial, surface or borehole-based measurement of subsurface material density variations. Typical spatial resolution horizontal and vertical: meter.				2D		✓		
Electromagnetic induction (EMI)	Single borehole-based low-frequency (Hz-KHz) electromagnetic (EM) signal. Provides estimates of vertical distribution and temporal changes in EC along a single borehole. Typical spatial resolution: decimeter vertical.					✓	✓		✓
Capacitance probes	Borehole-deployed measurement of the overall capacitance of the subsurface which provides an estimate of electrical permittivity. Typical spatial resolution: centimeter vertical.						✓		
Spectral gamma	Single borehole-based measurement of gamma (gross and spectral) radiation emitted by naturally-occurring and anthropogenic radionuclides. Typical spatial resolution: decimeter vertical.					✓			
Neutron probe	Single borehole-based method for determining distribution and temporal changes in soil moisture content using an active neutron source. Typical spatial resolution: decimeter vertical.						✓		
In-situ sensors	Buried sensors in the subsurface that provide a range of properties including soil moisture content, bulk EC, thermal conductivity, specific heat, temperature, and matric potential. Highly sensitive to backfill material and near-sensor region.					✓	✓	✓	✓
Pore-water or gas sampler	Repeat collection of soil pore water or gas that can be analyzed to provide a direct measurement of aqueous and soil gas constituents over time. Methods include tension/suction porous cup and passive capillary samplers.					✓			

3.3 Surface and Cross-Borehole Geophysical Imaging

Geophysical methods are able to interrogate relatively large volumes within the subsurface using either active or passive sources. Active source methods introduce a source of energy that interacts with subsurface materials and is detected at one or more nearby receiving locations. Examples of active source geophysical methods include ERT, GPR, and CSEM. Passive methods measure signals generated by naturally occurring energy sources and include methods such as gamma logging and gravity. Geophysical methods can be deployed in various configurations and can be grouped according to the source and receiver geometry. The four deployment configurations discussed in this report are single borehole, surface, surface-borehole, and cross-borehole. Each of these configurations has different sensitivities (e.g., larger/smaller measurement volume, signal to noise) and other attributes such as ease of deployment that contribute to the overall advantages/disadvantages for each type.

Geophysical methods depend on indirect measurements that are interpreted as model parameters (e.g., wave velocity or EC) defining material structures through which the source interacts. The measured data are represented as a function of the model parameters which, for small material perturbations, can be linearized to provide a relationship between changes in measured data and model parameters. The sensitivity in this relationship defines the mapping between them (Strickland et al. 2015). The sensitive region for an individual measurement can be thought of as the overlap between source and receiver regions. Figure 6 through Figure 9 illustrate some of the salient features of this relationship. In each case, the approximate source region is shown in red and the receiver/measurement region in blue.

Surface-based methods only require access to the site surface and are the least invasive, but often provide the lowest spatial resolution at depths more than a few meters. Borehole methods require the use of at least one borehole, but once installed, repeat measurements can be made without any additional disturbance. Each of the configurations differs in the location of the sources and receivers. Surface methods position both the source and receiver at the surface, surface-borehole place either the source or receiver, but not both, at the surface with the other down borehole. Single borehole methods place both the source and receiver within the same borehole. Cross-borehole methods involve lowering an energy source into a borehole and measuring the resulting field with a receiving antenna that is lowered down another borehole. In all cases, acquiring measurements using a number of different source/receiver positions allows for 2D and 3D imaging of subsurface properties within the sensing volume of the surveys. Most single borehole measurements are logging tools that employ one fixed source receiver offset and are moved along the borehole, providing a 1D profile of the relevant properties immediately adjacent to the borehole.

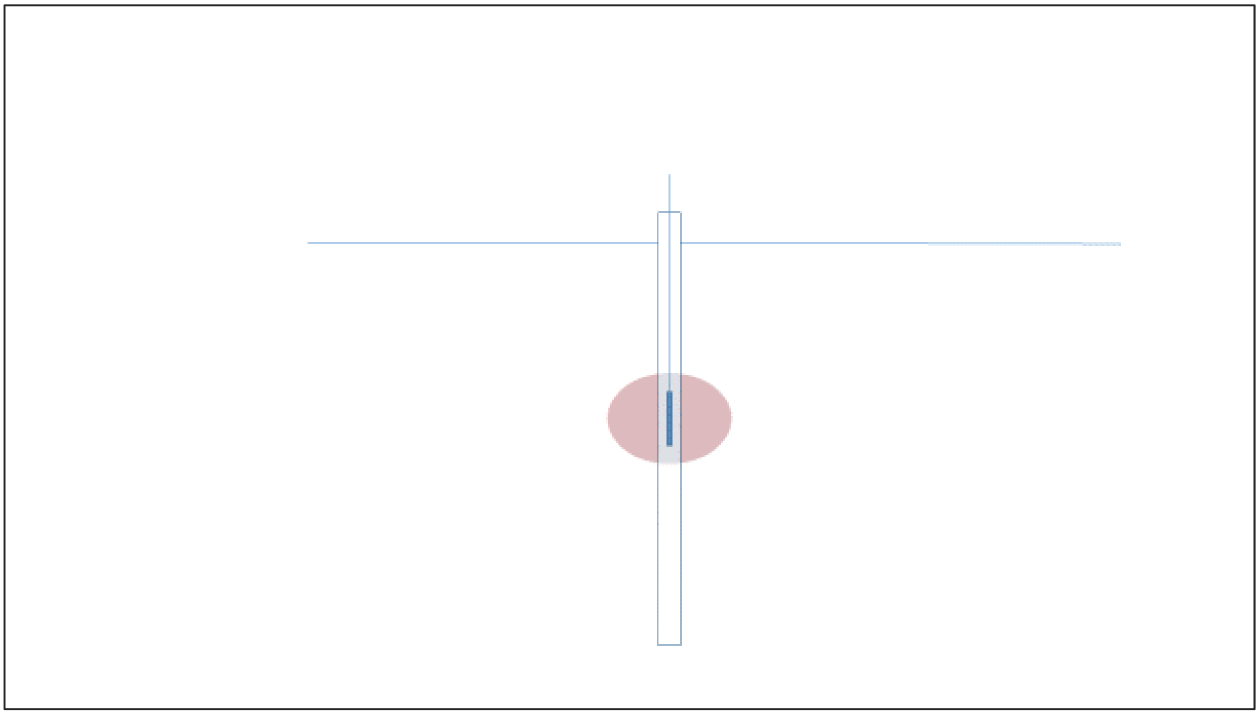

Figure 6. Single borehole configuration.

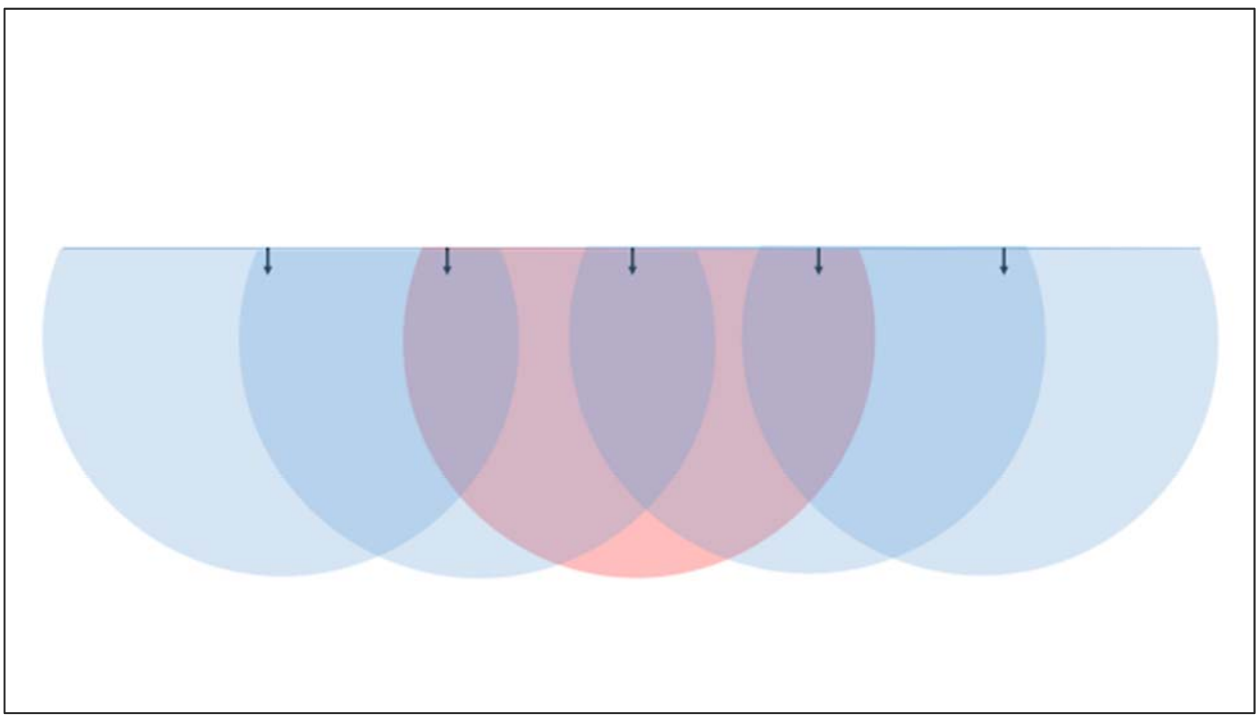

Figure 7. Surface configuration.

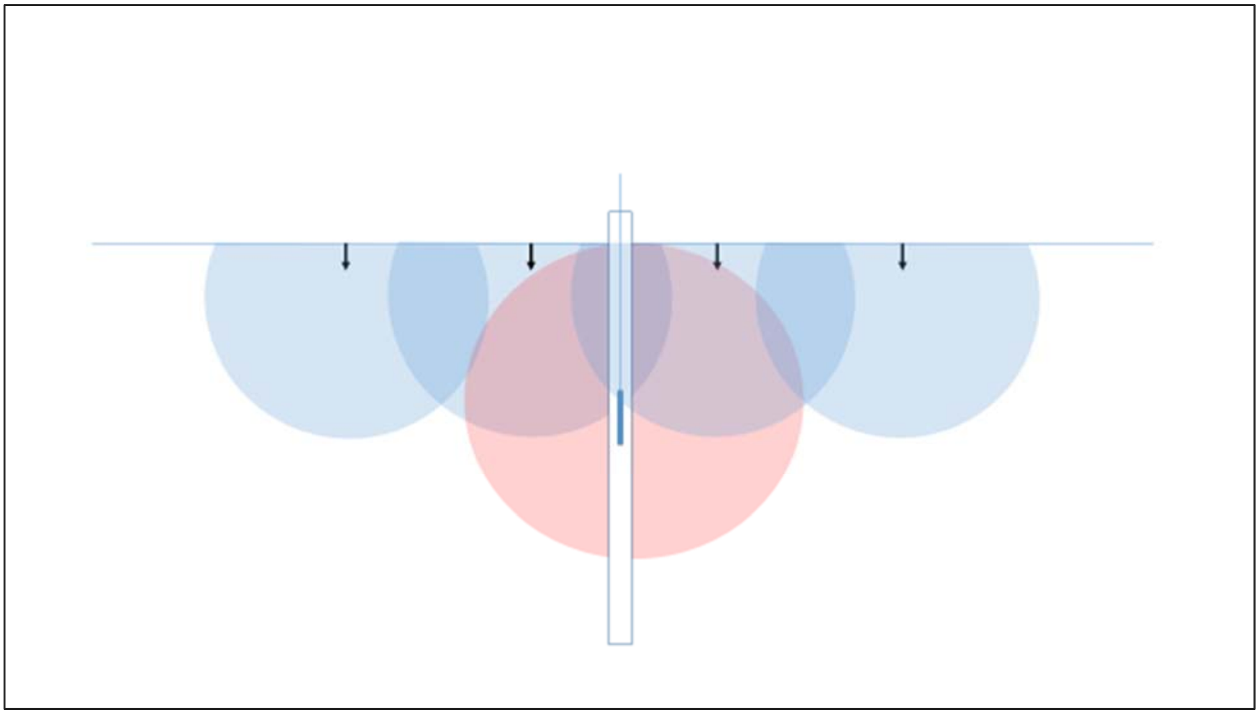

Figure 8. Surface-borehole configuration.

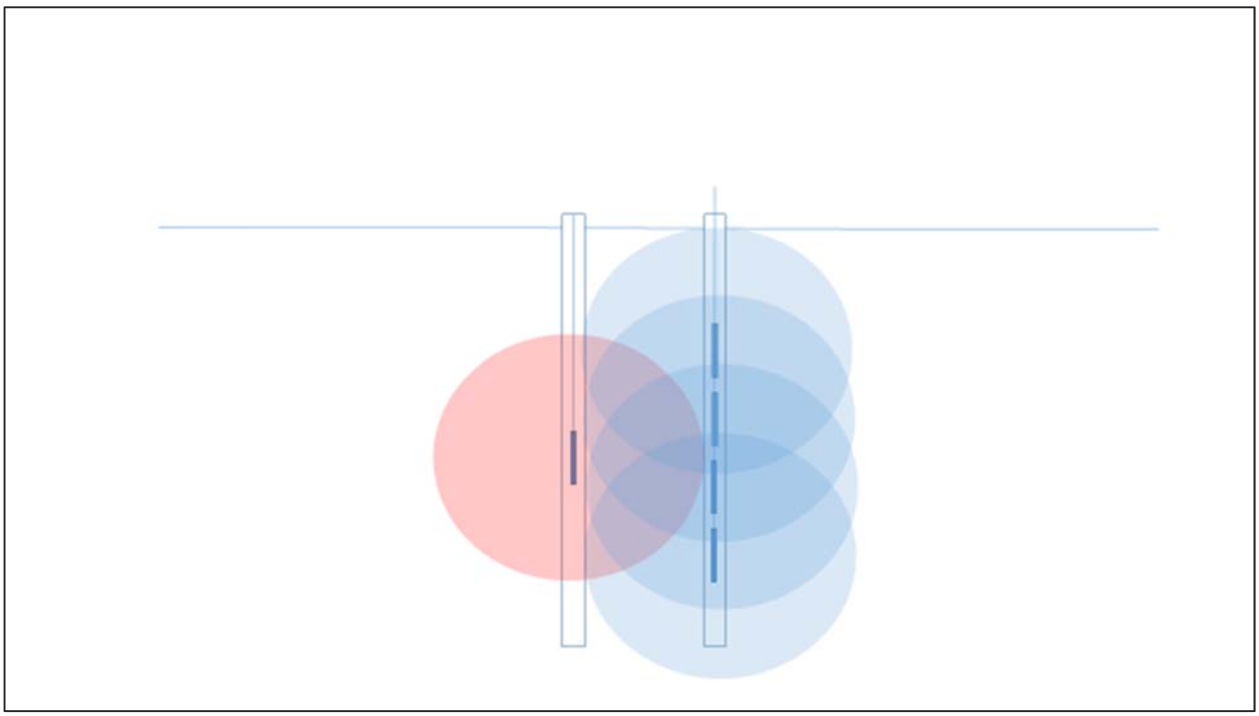

Figure 9. Cross-borehole configuration.

3.3.1 Electrical and Electromagnetic Methods

Geoelectrical and EM methods such as ERT, GPR, and CSEM have been widely used for subsurface imaging in both near-surface and deeper environments (Wilt et al. 1995; Peterson 2001; Binley et al. 2002; Zhdanov 2002).

EM phenomena are governed by Maxwell's equations, which can be combined to produce vector wave equations (Griffiths 1999) for the electric and magnetic fields. Maxwell's vector wave equations are used to simulate the EM fields for both GPR and CSEM. A central aspect of any wave is the propagation constant, which can be decomposed into two key attributes: the phase and attenuation constants. The phase velocity can be determined from the phase constant and along with the attenuation influence the signal that is ultimately measured. For EM waves, the phase velocity and attenuation constant are functions of both the EC and permittivity of the material through which the wave propagates.

At very low frequencies, the electric field can be approximated as the negative gradient of a scalar electric potential or voltage. Maxwell's equations can be simplified to produce the continuity equation describing the electric potential field that results from direct current electrical sources introduced into an electrically conductive material. The continuity equation forms the basis for simulating the applied currents and the potentials that arise for ERT. GPR, CSEM, and ERT are described in more detail below.

3.3.1.1 Ground Penetrating Radar

GPR methods image the subsurface distribution of EC and permittivity and in turn can be used to characterize and monitor both moisture and contamination within the DVZ. GPR systems consist of either a continuous wave or impulse generator that is used to transmit a high frequency (MHz-GHz) EM signal into the ground that is detected by a receiving antenna. GPR can be implemented both at the surface and within boreholes. GPR methods have been used to provide information on geologic structure, EC, and moisture content (Huisman et al. 2001; Binley et. al 2002; Day-Lewis et al. 2002; Truex et al. 2013).

As discussed earlier, the EM velocity depends on the EC and permittivity of subsurface media as well as the frequency of the propagating wave. The material properties are seldom known, so two assumptions are (1) the magnetic permeability is equal to that of free-space, and (2) the EC is much less than the product of the frequency and electrical permittivity, often termed low-loss conditions. Under these conditions, the EM velocity only depends on the electrical permittivity.

The electrical permittivity of geological media is strongly dependent on moisture content because of the large difference between water and typical mineral components. The apparent permittivity, ε_a, can be determined from the observed velocity of an EM pulse propagating through the sediment/rock. The term apparent is used here to mean the permittivity value that is inferred from measurement of the velocity of an electromagnetic wave at a given frequency. Under low-loss conditions, it has been shown that the volumetric moisture content is a linear function of the square root of the apparent electrical permittivity and largely independent of soil texture (Topp et al. 1980; Ledieu et al. 1986; Topp and Ferré 2002).

GPR surveys can be performed using both surface-based and cross-borehole configurations. Surface GPR has been effectively used to map shallow geologic structure and soil moisture variations (Hubbard et al. 1997; Strickland et al. 2010). Surface-based GPR is able to interrogate just a few meters and may only have utility in monitoring surface barriers. Since barriers will likely be emplaced at many waste sites on the Hanford Site, GPR may be a cost-effective approach for monitoring shallow moisture content. Surface GPR has already been shown to be an efficient method for non-intrusively monitoring moisture conditions within a surface barrier on the Hanford Site (Strickland et al. 2010). Cross-borehole GPR (Figure 10) has also been successfully used for imaging moisture content and changes that occur in response to soil desiccation applied at the Hanford Site (Truex et al. 2013). Due to the presence of high contaminant concentrations, most notably nitrate, low-loss conditions do not apply to many areas of the Hanford Site. In general, EM velocity depends on both the permittivity and EC of the material. Acquiring multiple types of geophysical measurements (i.e., ERT, CSEM/EMI, and GPR) over a wide range of frequencies, it is possible to independently determine both permittivity and EC leading to improved moisture content estimates.

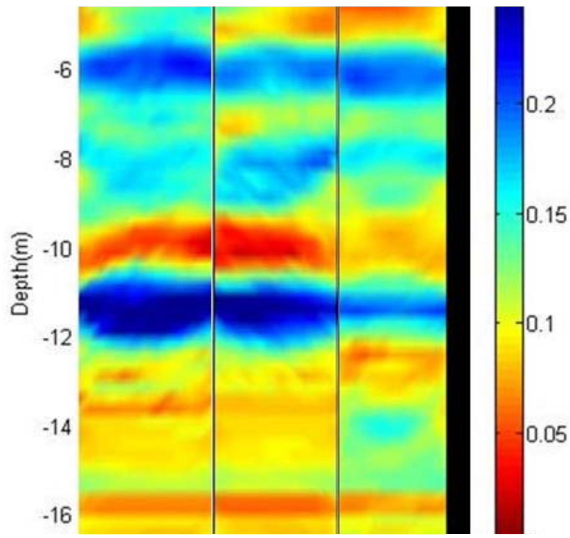

Figure 10. Image of EM velocity for the Hanford soil-desiccation DVZ treatability test using cross-borehole GPR.

3.3.1.2 Electrical Resistivity Imaging

Electrical resistivity imaging (ERI), also known as electrical resistivity tomography (ERT), is a geophysical method that can be used to image the spatial distribution of bulk EC within the subsurface. Over the last few decades technological advancements instrumentation and data processing have resulted in numerous ERT monitoring applications (Ramirez et al 1993; Slater et al. 2000) including at the Hanford Site.

The bulk (composite mixture of both sediment/rock and fluid) EC, inverse of resistivity, is a useful metric for characterizing the subsurface. EC is sensitive to several important variables influencing contaminant flow and transport, including pore water solute concentration, moisture content, and soil texture (Slater and Lesmes 2002).

The bulk EC of the subsurface has been widely observed to follow the empirical Archie's law (Archie 1942) in low clay content, non-conductive sediments. The EC of both aqueous solutions and bulk soil/rock also depends on temperature. The temperature dependence of bulk conductivity in the vadose zone depends on water content, but is always monotonic so that a change in temperature will correspond proportionally with changes in bulk conductivity (Friedman 2005; Ruijin et al. 2011).

On the Hanford Site, ERT has been used to image the distribution of contamination and monitor changes in moisture content and delivery of electrically conductive amendments (Johnson et al. 2010; Truex et al 2013). Figure 11 illustrates one example where ERT was used to monitor moisture content changes that occurred during the soil desiccation treatability test.

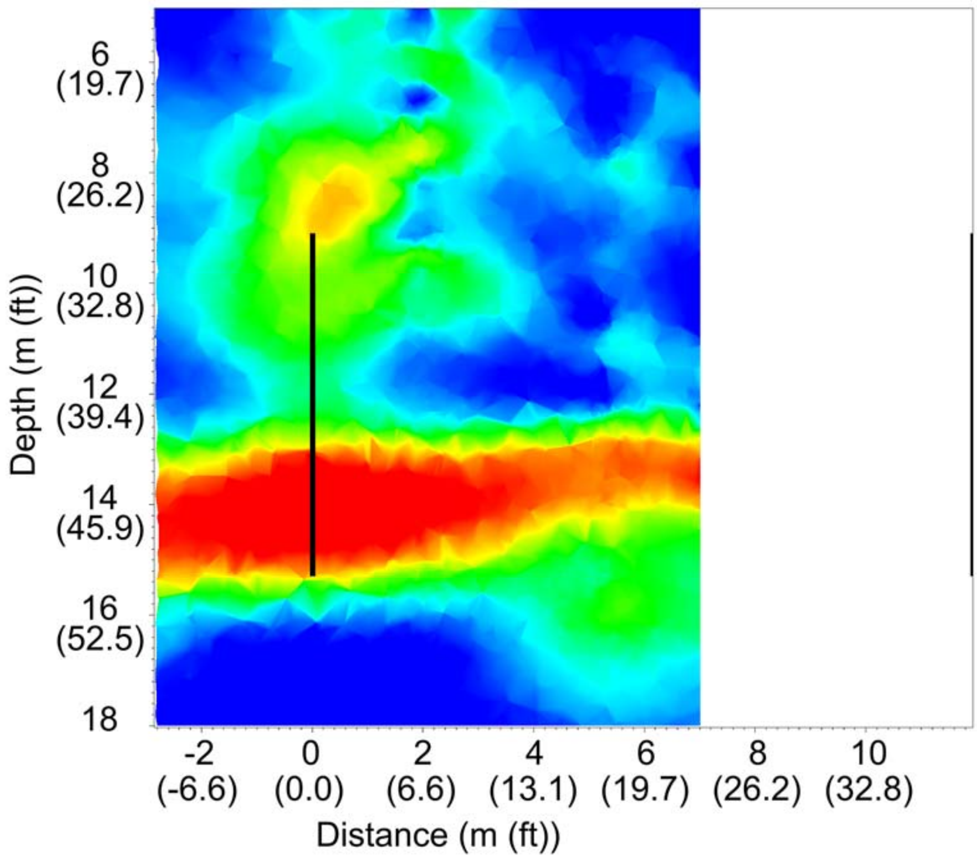

Figure 11. Image of bulk EC for the Hanford soil-desiccation DVZ treatability test using cross-borehole ERT.

3.3.1.3 Controlled Source Electromagnetics

CSEM is a widely used geophysical method for both near-surface and deep applications ranging from petroleum exploration to environmental characterization (Constable and Srnka 2007; Wilt et al. 1995). The method can be acquired using land, marine, or aerial configurations to estimate of the bulk EC of the subsurface. The method can be used to image the distribution of contamination and monitor changes in moisture content and electrically conductive contamination (e.g., high nitrate concentrations) or amendments. Similar to high frequency (MHz) EM methods like GPR, lower frequency (Hz-KHz) CSEM measurements transmit EM into the ground that is sensed using a receiving device. While GPR employs antennae that predominantly generate and detect electric fields, low frequency methods utilize sources that produce relatively large magnetic fields in conjunction with sensors that are able to measure the resulting magnetic fields induced in subsurface media.

Assuming the magnetic permeability is equal to that of free space, at the low frequencies used in CSEM EM attenuation and phase velocity do not depend on electrical permittivity and are functions of only frequency and EC.

Like ERT, CSEM is capable of imaging the distribution of EC and, if repeatedly acquired, changes in EC over time. CSEM can also be deployed at the surface, within a single borehole, or cross-borehole. Unlike

ERT, CSEM does not require electrical contact with the ground and can be deployed within non-electrically conductive boreholes.

3.3.2 Seismic

Seismic-based geophysical methods can provide estimates of moisture content and matric potential (including spatial distribution and temporal changes) in the DVZ. Seismic wave propagation is governed by elastodynamic theory. Stress, displacement, deformation, strain, and motion are central to the behavior of elastic/seismic waves. Elastic waves are stress/displacement waves. Unlike EM waves that propagate through isotropic media at a single velocity, elastic waves in solid media exhibit two velocities for different types of body waves (compressional and shear waves).

The mechanical properties that determine seismic velocities of geologic materials depend on the stress state that is applied. In general, as the overburden or confining stress (due to the weight of the overlying material) increases so does the compressional and shear velocity. Since unsaturated systems consist of three phases, solid matrix, and two fluids (typically water and air), effective stress must be considered across all three phases (Terzaghi 1925). Effective stress is defined as the difference between confining stress and fluid pressure.

It has been generally understood that the effective stress and therefore the seismic velocity of sediments, depends on moisture content and matric potential (Brutsaert and Luthin 1964; Bishop and Blight 1963). Recent research has identified matric potential as a relatively large influence on the observed seismic velocity (Santamarina et al. 2001; Lu and Sabatier 2009; Whalley et al. 2012). Whalley et al. (2012) developed a model of seismic velocity as a function of effective stress for a range of sediment types and obtained excellent fits to their observations. A reformulation of this model along with measurements of seismic velocity and overburden stress can be used to estimate matric potential (Figure 12). Following a similar approach, seismic velocity tomography in unsaturated sediments may be used to image the spatial distribution of matric potential. Under very dry conditions, like those that occur beneath surface barriers and in zones of desiccation, matric potential is a better performance indicator than moisture content (Zhang et al. 2011).

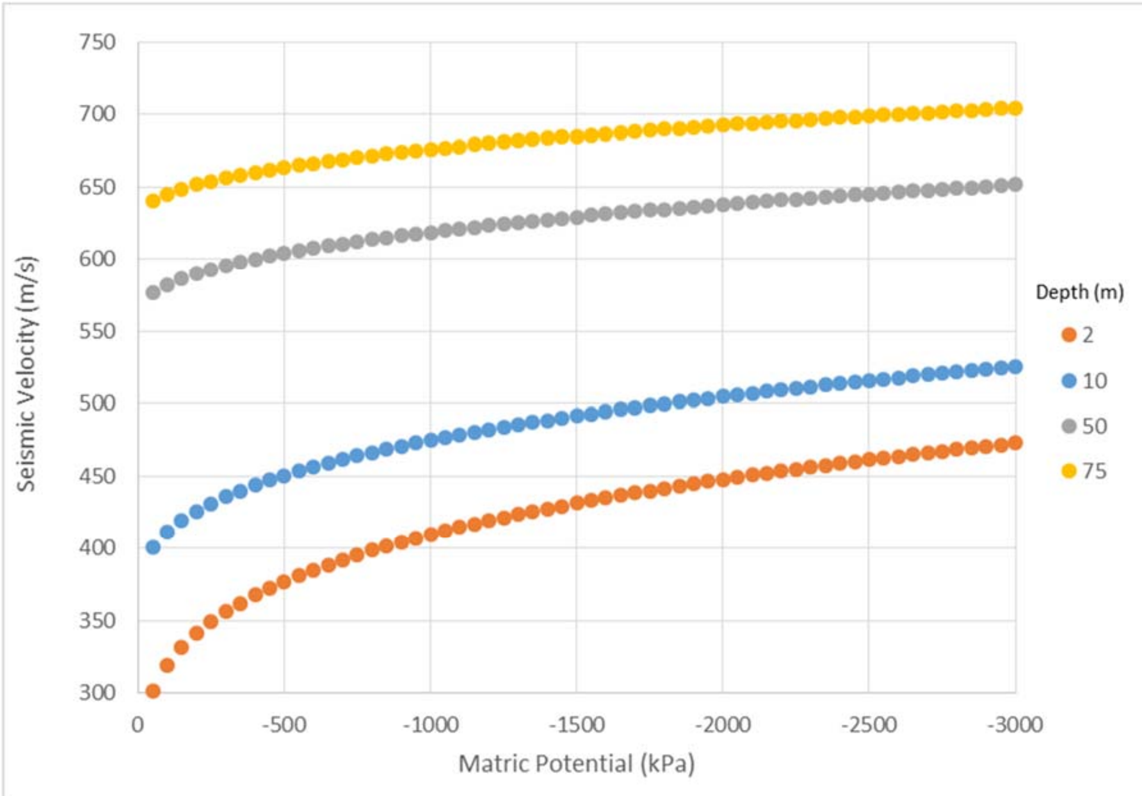

Figure 12. Functional relationship illustrating the dependence of seismic velocity on overburden depth/stress and matric potential at depths of 2, 10, 50, and 75 m.

3.4 Single Borehole Logs

3.4.1 Neutron Moisture

Neutron scattering probes can be used to determine soil volumetric moisture content, and have become a standard method for determining in situ moisture content over the past several decades (Hignett and Evett 2002). A neutron probe consists of an energetic neutron source (e.g., Am-241/Be) and a thermal neutron detector (typically He^3) that can be lowered into a cased borehole to acquire measurements. When placed in a borehole, the energetic (MeV) neutron source develops a dense cloud of thermal neutrons that can be measured by the detector placed near the source. The concentration of thermalized neutrons is largely affected by hydrogen atoms from the water present, but also by both soil density and elemental composition. Elements that absorb neutrons are often found at low concentrations in sediments and the neutron probe response is mainly affected by changes in moisture content (Truex et al. 2013). The response of the probe can be converted to volumetric moisture content using site-specific relationships that depend on the sediment type and borehole configuration (e.g. materials and completion geometry).

Neutron moisture logs have been widely used at the Hanford Site, mainly for determining moisture variations for newly constructed boreholes. Repeat logs have also been acquired and successfully used to monitor moisture content changes that occur either naturally or in response to active remediation. Data can provide 0.1 to 0.3 meter vertical resolution and are locally sensitive to a region surrounding the borehole that is approximately 0.1 to 0.5 meters in radius from the measurement location (Hignett and Evett 2002).

3.4.2 Gamma-ray logs

A gamma ray log measures the amount of gamma radiation that is emitted by the sediments and rocks surrounding a borehole. The amount of gamma radiation that is detected depends on the quantities of both naturally occurring and anthropogenic radionuclides that are present in the geological material surrounding the borehole. Major gamma emitters naturally found in typical geologic materials include K^{40}, Th^{232}, and U^{238}. For a given sediment or rock type, the concentrations of the major emitters is approximately known and can be used to estimate the density of the material and their ratios can be used to help identify changes in lithology. Spectral gamma logs can identify the relative amounts of individual emitters and a gross gamma log reflects the composite of all gamma emissions that fall within the detection energy band.

Like neutron moisture, gamma logs have been acquired during construction of many boreholes on the Hanford Site; however, the utility of the method for monitoring is limited and not commonly performed.

3.4.3 Borehole Electromagnetic Methods

Similar to surface and cross-borehole configurations described earlier, subsurface EM properties such as moisture content and EC of a volume immediately surrounding a single borehole can also be measured. Two of the most common methods are capacitance and EMI probes.

Capacitance probes consist of electrodes/antennae that are driven by a high frequency (MHz) sinusoidal EM source and measure the resulting signal. The media surrounding the electrodes contributes to the overall capacitance of the system and can be measured by the device. Capacitance probe measurements have been shown to be proportional to the apparent electrical permittivity. One limitation of existing commercially available instruments is that the measurement is only sensitive to a small distance (0.01-0.1 meter) from the electrodes, resulting in relatively large interferences from the near borehole environment. The electrode geometry (e.g., electrode size and separation distance) influences the measurement, including the size and shape of the sensitive volume, and is one attribute that can be adjusted depending on the desired response characteristics (Paltineanu and Starr 1997). High EC can also impact the measured apparent permittivity and will depend on the frequency of the source. The use of multiple frequencies can be used to correct for EC effects.

Low frequency (kHz) EM measurement can also be performed in a single borehole. EM coils are typically employed whereby one is used as an EM transmitter and the other detects the magnetic field at an adjacent depth. At low frequencies, the phase shift in the EM signal depends only on the frequency and EC of the surrounding media. Borehole EMI logs can provide high vertical resolution (0.2-0.75 meter) of the material bulk EC.

3.4.4 Gravity

Gravity measurements can provide estimates of variations in the density of geologic media. Gravity measurements can be used to estimate not only density at the time the initial measurements are acquired but also changes in density over time using time-lapse surveys. Within the DVZ, density changes are likely dominated by water content and the method can used to monitor changes in volumetric soil moisture content. The gravitational acceleration on the Earth depends on several factors that include position (latitude and longitude), elevation, tidal effects, and density variations (Telford et al. 1990). Variations in the density of subsurface materials result in small local changes in acceleration.

Time-lapse gravity has been used since 1961 (Allis and Hunt 1986), but substantial improvements in gravimeter technology, and the advent of highly precise GPSs, have led to rapid growth in microgravity applications in recent years. This technology has been successfully applied to a range of applications including geothermal energy, volcano monitoring, reservoir characterization (Biegert et al. 2008) and groundwater monitoring (Chapman et al. 2008; Leirião et al. 2009; Bonneville et al. 2015).

The sensitivity of gravity measurements acquired at the surface decreases rapidly with depth. Surface based surveys can be very useful for mapping subsurface densities to provide characterization data such as estimates of depth to bedrock. Subtle density perturbations due to moisture content changes in the DVZ may be difficult to identify using surface measurements. Borehole gravity measurements, however, can also be performed and are commercially available and capable of detecting density (as well as volumetric moisture content) variations of 1% to 2% (MacQueen and Mann 2007). This level of accuracy is comparable to that of a neutron moisture log but has a radius of influence that is many meters. The large radius of influence can provide information on subsurface properties located substantial distances from the borehole, minimizing the effects of near borehole interferences.

3.5 Pore Water Sampling

Analogous to water sampling from saturated groundwater aquifers, pore water collection from the vadose zone can provide direct measurement of the aqueous constituents that are present. Pore water can be extracted from soil samples in the laboratory or in situ using various approaches. Commonly used methods include tension/suction porous cup and passive capillary samplers.

Suction samplers utilize a porous cup or tube geometry that is placed so that its outer surface is in contact with soil. A partial vacuum is applied to the interior that causes pore water to be drawn into the device under the condition that the vacuum does not exceed the air entry pressure of the porous material (otherwise soil gas/air will be drawn in). A number of complications have been identified (McGuire et al. 1992) such as clogging, pressure/duration dependent results, and adsorption of analytes or contamination by the sampler porous material. Common sampler materials are ceramic, stainless steels, fritted glass, and Teflon, and each possesses both advantages and disadvantages. The effects of adsorption to the sampler on measured contaminant concentrations is generally less of a problem for Teflon and fritted glass, followed by stainless steel, with ceramic having the largest effect.

Passive capillary samplers (PCAPs) are constructed by placing a wicking material (typically a rope made of many individual fibers) in contact with soil that introduces a hanging water column to create tension on the soil proportional to the length of the wick (Brown et al. 1986; Knutson and Selker 1994; Frisbee et al. 2010). Unlike suction samplers that require applying a vacuum to the device, PCAPs passively collect soil pore water. PCAPs have been shown to work well over a wide range of soil conditions, but are ineffective at high matric potentials due to limitations on the amount of tension that can be applied. Fiberglass is commonly used for the wick material, but this material can impact the chemistry of the sample by the same adsorptive effects as discussed above for the suction samplers (Goyne et al. 2000; Perdrial et al. 2014). In general, constituents of the glass (e.g. Na, Si, B) can greatly impact the collected sample results but a wide range of other analytes are unaffected.

Vadose zone pore samplers are typically used in shallow settings less than 10 m deep; however, a number of commercially available suction cup samplers are available that can be installed at depths as high as 70 m. The installation of currently available deep samplers requires that they be installed in a borehole that has been constructed using annular fill materials (e.g., sand or diatomaceous earth) with properties that are different than the surrounding soils. Also, pore water samples are delivered to the surface via tubing that will limit the number of samplers that can be installed in an individual borehole. Like any buried device, maintenance of the subsurface components will be very limited.

Long-term collection of pore-water samples at multiple locations/depths within the DVZ can provide data on the migration of a wide range of mobile contaminants in situ.

3.6 Gas Sampling

The properties of subsurface gases can be important to contaminant transport in the DVZ for both passive and active remediation. In particular, remedies that inject gases will require information on the spatial and temporal distribution of gas concentrations to determine the size, shape, and overall effectiveness of the treatment. Injected gases can be used for pneumatic testing and as tracers to assess field scale site-specific gas permeability. The effectiveness of gas sampling has been demonstrated both elsewhere and on the Hanford Site (Truex et al. 2012).

The typical construction of a gas sampling device for the DVZ is similar to a pore water suction cup sampler and consists of a cup or tube that is attached to a tube extending to the surface. Unlike a pore water sampler that uses a water-permeable high air entry porous cup, a gas sampler requires a gas-permeable material.

3.7 In Situ Sensors

A variety of in situ sensors have been developed over the past several decades for measuring a range of properties including soil moisture content, bulk EC, thermal conductivity, specific heat, temperature, and matric potential. Sensors have been successfully deployed for a range of applications in the earth sciences as well as monitoring environmental remediation at the Hanford Site (Truex et al. 2012).

In situ sensors typically are buried in direct contact with the ground and have response times on the order of seconds to measure rapidly changing subsurface conditions. When installed in shallow settings near the surface, sensors can be backfilled with native materials. For DVZ applications, emplacement within boreholes is required and nearly always requires the use of non-native backfill. Most in situ moisture content sensors have very small sensitive volumes and the introduction of non-native materials directly surrounding the sensor can have a substantial impact for some types of measurements. Bulk EC, thermal conductivity, and specific heat are also quite sensitive to the region directly surrounding the sensors. Pressure, matric potential, and temperature are measurements less severely impacted by near field material variations.

For many applications, a combination of in situ sensors and other monitoring methods can provide a robust monitoring system. For instance, moisture content logging with a neutron probe that is less likely to be influenced by the near borehole environment could be used in concert with buried matric potential and temperature sensors to monitor active desiccation and/or surface barrier performance.

Another major factor impacting the use of in situ sensors is the time to failure. For DVZ monitoring, sensors will require emplacement many meters below the surface and would prevent maintenance on any buried components. Eventually, in situ sensors will fail and their service life needs to be considered in the monitoring strategy.

3.8 Land Surface Measurements

Deformation and erosion of the land surface are expected to impact the Hanford Site both now and far into the future. Several buried structures such as tunnels, cribs, trenches, and tanks exist onsite and create conditions where subsidence is likely. Over the timescales relevant to DVZ, erosion of surface structures like surface barriers can drastically affect the performance of the remedy. In addition, remedies that include fluid injection and extraction can cause substantial ground deformation. Deformation caused by injection/extraction of subsurface fluids has been a recognized phenomenon since the early to mid-1900s (Jacob 1940; Biot 1941). Recent scientific studies have examined land surface deformation that is associated with the injection of water for aquifer storage/recovery projects, as well as the injection of CO_2 associated with enhanced oil recovery and carbon sequestration projects (Morris et al. 2011; Vasco et al. 2010).

Damage to surface/subsurface structures can also occur due to earthquakes and should be considered as part of the long-term hazards. Several faults exist in the area that are capable producing significant ground motion ($M_w > 6$), although the rates of occurrence are on the order of a thousand years (Riedel et al. 1994; Zachariasen et al. 2006). The DVZ is expected to affect contaminant fate and transport over similar time scales and impacts due to potential seismic hazards should be monitored.

Surface deformation and erosion can be measured at discreet points using permanent GPS stations, tiltmeters, and annual differential GPS surveys. Surface displacements of the ground at a larger scale can also be measured accurately using InSAR and LiDAR (Morris et al. 2011; Vasco et al. 2010).

InSAR provides displacement measurements along the line-of-sight between an orbital synthetic aperture radar and the ground. Recovery of 3D displacements requires the use of three or more separate InSAR data sets that are acquired using non-coplanar geometries or supplemental information from ground-based GPS surveys. A wide range of surface characteristics and deformation types may be imaged by using different radar configurations. InSAR deformation measurements are corrupted by variations in the Earth's atmosphere and the surface scattering properties. Noise sources may be mitigated to varying degrees by radar parameter choices tailored to characteristics of the site as well as the timing and frequency of the data acquisitions and by making use of artificial reflectors. InSAR is able to spatially resolve features on the order of a few meters with average velocity and deformation measurements on the order of millimeter/year and millimeter respectively.

LiDAR is similar to InSAR except that is uses light pulses rather than radio waves to determine distances to the target. LiDAR can be acquired from the surface or using an aerial platform. Airborne LiDAR can efficiently cover large area and produce elevation maps that are accurate to a few centimeters. Repeat LiDAR survey can also be performed to determine surface deformation and erosion (Schmid and Hildebrand 2004) that are accurate to a few millimeters if used in conjunction with surface reference points.

Multispectral and hyperspectral remote sensing can also be used to provide information on surface vegetation that is important to contaminant fate and transport on the Hanford Site. Many natural materials located at the surface of the Earth absorb ultraviolet, optical, and infrared radiation and measurement of those spectra can be used as a diagnostic tool. Remote sensing based hyperspectral imaging methods record a broad spectrum of electromagnetic energy reflected from the surface across a broad spatial domain. Hyperspectral imaging data can be used to map vegetation type, density, moisture, as well as soil surface properties. Satellite based hyperspectral remote sensing data provide valuable inputs for monitoring surface conditions that strongly contribute to estimates of deep-drainage/recharge.

3.9 Recharge Monitoring

Recharge occurring across the Hanford Site Central Plateau is transmitted through the vadose zone to the underlying groundwater aquifer. The water table beneath the Central Plateau is approximately 80 m below ground surface and direct measurement of recharge is impractical. Recharge and hydraulic properties are two factors having the greatest effect on contaminant fate and transport on the Hanford Site (Dai et al. 2017) and under very low flux conditions recharge rate shows the highest sensitivity (Bacon and McGrail 2002).

The flux of water at depths below the influence of evapotranspiration, deep drainage rate, can be used to predict future recharge. In arid environments, deep drainage rates can be measured using several methods including lysimeters and tracers. Lysimeters are water collection structures used to directly measure the volume of water that percolates through the soil above. In some cases, a drainage base performance criteria may be specified and lysimeters can be used to assess the effectiveness of the remedy. One drawback of using a lysimeter for long-term monitoring is the need to continually measure drainage which, given the expected lifetime of the remedy, may significantly increase monitoring costs.

Tracers can also be used to quantify deep-drainage/recharge at an individual waste site. Several common tracers types exist and differ mainly in the source and/or analyte involved, e.g., naturally occurring (Cl^-), historical isotopic perturbations (^3H, ^{36}Cl), and tracers that are intentionally released. Both naturally occurring and historical tracers have been used at a number of sites, including Hanford. At radiologically contaminated sites like Hanford, waste site-specific source concentrations may impact the use of historical tracers, and lead to significant differences in recharge estimates determined using lysimeters (Fayer and Szecsody 2004). Applied tracers also have potential for recharge monitoring in the Hanford DVZ. Large vadose zone nitrate sources currently exist and create highly elevated EC in those sediments. Electrical geophysical methods can be used to track the evolution of the nitrate source to estimate flux. Tracers with high EC and/or additional conservative solutes can also be applied at the surface and monitored with either geophysical or vadose pore water samplers in a similar fashion.

As discussed above, recharge rates at the Hanford Site range from near zero to more than 100 mm/yr (Gee 1987; Fayer and Szecsody 2004; Rockhold et al. 2009) depending on surface soil and vegetation conditions. Surface conditions have changed dramatically prior to, during, and after production operations onsite and the potential exists for changing conditions in the future. Previous studies have contributed to an understanding of recharge on the Hanford Site and have recommended that long-term deep drainage and meteorological monitoring continue.

3.10 Joint Data Interpretation

The goal of each geophysical imaging method, in conjunction with the identified vadose zone sampling methods, is to determine the unknown subsurface properties that produce the best match to the observed data, within measurement error. Given a model of the spatial distribution of the relevant properties (e.g., conductivity, permittivity, velocity) as well as a set of source and receiver locations, the governing equations can be used to generate synthetic data that can be compared to the corresponding measured data. The results of this optimization, or inversion, process is nearly always non-unique such that many different models are able to fit the data.

As discussed earlier, each monitoring method exhibits different sensitivities to the underlying subsurface properties of interest. For instance, neutron moisture probe measurements mainly depend on moisture and EMI measures EC, which is a function of several factors including moisture content, fluid conductivity, soil texture, and temperature. By combining multiple measurement types, additional information can be obtained. One example is the combination of neutron and EMI borehole logs (Figure 13) that can be interpreted together to provide an estimate of major solute concentration (Figure 14). Introduction of information obtained from sediment samples and/or pore water analysis could also be used to further constrain the problem and lead to refined estimates. Finally, if such measurements are repeated over time, estimates of water or contaminant flux are also possible.

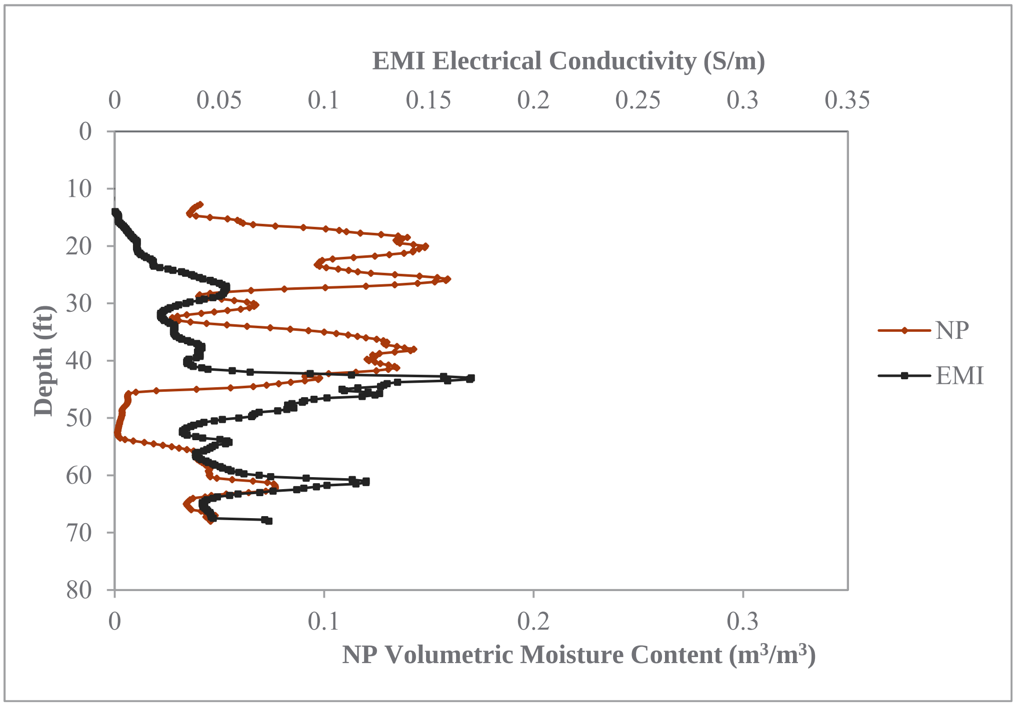

Figure 13. EMI and neutron probe single borehole logs from the soil desiccation DVZ treatability test.

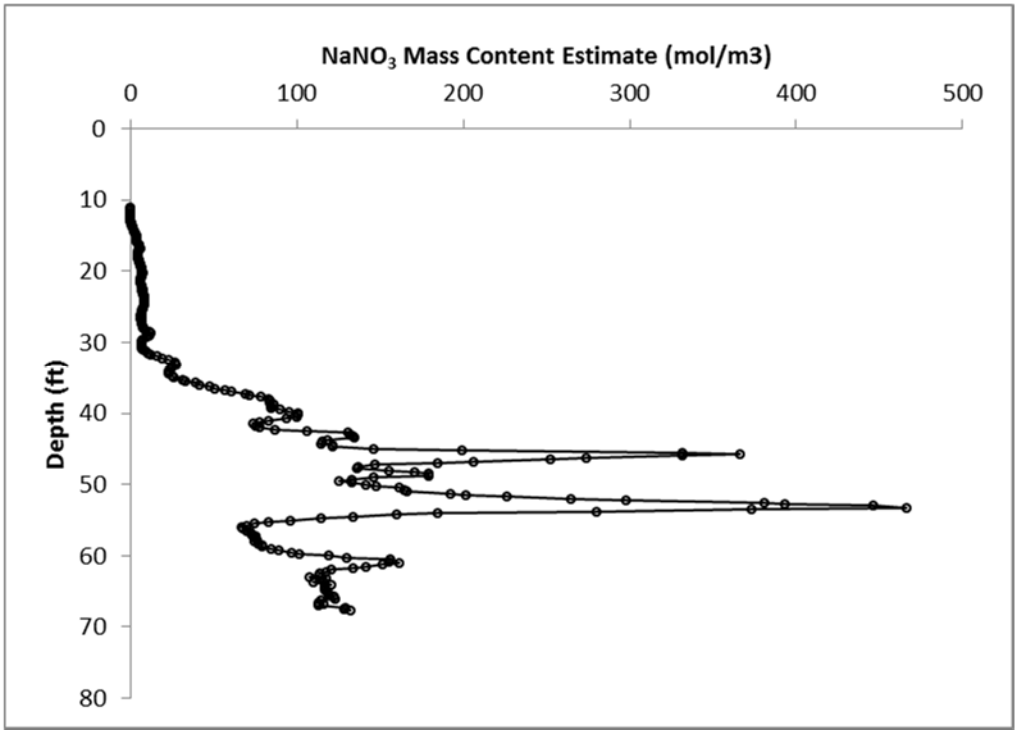

Figure 14. Combined interpretation of EMI and neutron logs to estimate vadose zone nitrate solute concentrations.

The preceding example illustrates the potential for joint processing of different types of borehole logs, but further integration with surface and cross-borehole data can also be included.

3.11 Integrated Monitoring

An optimal monitoring strategy should consider the entire system of process and properties that affect the observed outcome. This integrated systems-based monitoring approach can lead to increased effectiveness, reduced costs, and improvements in our understanding of system behavior.

One aspect of environmental remediation monitoring is that several stages exist throughout the lifetime of the project each with different regulatory objectives. The *Resource Conservation and Recovery Act* (RCRA) and *Comprehensive Environmental Response, Compensation, and Liability Act* process identifies a number of monitoring stages: characterization, remedial action process and performance, and long-term (Gilmore et al. 2006). The characterization stage aims to collect information on the nature and extent of contaminants, and controlling processes, which can be used to develop an initial conceptual site model and define the scope of remedy options. The next stage is remedy monitoring from remedial feasibility/treatability through implementation of the selected remedial action. Once sufficient information has been gained on the understanding of the system and remedy performance, long-term monitoring can begin. Each of the stages can identify distinct needs; however, a great deal of overlap naturally exists. Progressing through the various stages provides additional information that improves confidence in our understanding of system behavior. A well designed monitoring strategy should provide the data required to meet that objective and do so in a cost-effective manner. The time scales involved with each stage are also important since the monitoring duration and frequency will directly impact the monitoring costs. At the Hanford Site, some rough bounds on the timeframes are that characterization, remedial action, and long-term monitoring would be on the order of years, decades, and centuries respectively. Another consideration is regarding the maintenance of the monitoring methods. Sensors can provide critical information in the short term during characterization and feasibility/treatability testing but will eventually fail, making them more appropriate for short-term monitoring. By contrast, long-term monitoring systems that allow for extended and variable periods between measurements reduce costs due to lower maintenance.

Nearly all monitoring methods useful for vadose zone monitoring also have application to groundwater monitoring. Integration of vadose zone and groundwater monitoring should be considered in the overall strategy to reduce duplication and interferences with separate systems. An example would be integration of vadose zone pore water and groundwater sampling. A great deal of overlap exists such that field crews and sample handling/management can be shared for both endeavors. Another example is the use of geophysical logs and imaging surveys. Surveys that are performed in the vadose zone can be simply extended into the groundwater to simultaneously log and image both zones. Another example is the use of injection and extraction wells as opportunistic monitoring wells. Many of the borehole-based geophysical monitoring methods can be deployed within injection and extraction wells and their placement and construction should be integrated early on into the overall remedy design.

4.0 Remediation Scenarios and Associated Monitoring Strategies

In this section, the monitoring technology information in Section 3 is incorporated into conceptual monitoring strategies for the monitoring scenarios described in Section 2. The conceptual strategies show how monitoring systems for the vadose zone could be configured to provide an effective approach for future deployment in the Hanford Central Plateau. Envisioning these strategies is intended to help guide, and provide relevance for, efforts to develop and test monitoring technologies. In addition, these monitoring strategies may be useful during Central Plateau remediation strategy and remedial investigation/feasibility study efforts by providing a resource for planning of future monitoring systems to meet vadose zone remediation needs.

For each monitoring scenario, conceptual monitoring strategies are developed that describe the type of monitoring applied, the data generated and how it is used, integration of multiple monitoring approaches, and expected temporal or spatial evolution of the monitoring approaches. Detailed configuration of monitoring systems is not provided because the scenarios are not site-specific.

Three fundamental categories of remediation scenarios are presented for use in describing monitoring configurations. These scenarios are MNA, application of a surface barrier, and in situ remediation. In some cases, where more significant remediation is required, in situ remediation may be applied and a surface barrier also emplaced on the site. In those cases, a combined monitoring approach starting with the in situ remediation configuration and transitioning to the surface barrier configuration is relevant. An important consideration for monitoring the scenarios is the intensity of monitoring needed.

The scenarios below present a basic configuration that is representative of a baseline, low-intensity configuration. The scenarios then identify additions to this configuration that may be appropriate to some sites where the situation warrants more detailed information about contaminant migration or remedy performance. It is also anticipated that the monitoring configuration will evolve over time where more intense methods/frequency of monitoring will progress to less intensive methods/frequency of monitoring. These changes are described for each of the scenarios. Variants of scenarios are also discussed.

4.1 Monitored Natural Attenuation Scenario

MNA is typically applied for groundwater plumes as described in EPA MNA protocols (EPA 2007a,b, 2010, 2015), but is also relevant to contamination in the vadose zone (EPA 1999). The vadose zone component is important in the context of the source control and source quantification aspects of a groundwater MNA remedy. For an MNA remedy, attenuation would be expected to maintain the contaminant flux from the vadose zone to the groundwater low enough that groundwater objectives are met (e.g., a groundwater contaminant concentration at a specified location and time). Thus, the MNA remedy does not depend on meeting a threshold concentration in the vadose zone unless the threshold is related to meeting the groundwater objectives.

4.1.1 Data Quality Objectives

MNA implementation would require providing evidence that attenuation in the vadose zone is and will continue to meet the groundwater objectives. While groundwater monitoring ultimately is used to demonstrate compliance and MNA success, vadose zone monitoring is applied to demonstrate attenuation conditions and contaminant flux are acceptable and support verification that groundwater objectives will not be exceeded in the future. Table 3 lists anticipated categories of data quality objectives for an MNA remedy.

Table 3. Data quality objective categories for MNA.

Data Quality Objective[(a)]	Supporting Data/Applicability
"Demonstrate that natural attenuation is occurring according to expectations"	• Moisture and contaminant data that can be used to evaluate whether contaminant flux is in the acceptable range • Data confirming the activity of biogeochemical attenuation processes is in the acceptable range • Data confirming that pore water chemistry is in the range acceptable for biogeochemical attenuation processes • Groundwater data showing that contaminant flux from the vadose zone is meeting expected range groundwater contaminant concentration
"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"	• Data for water and contaminant fluxes showing that these are in the range acceptable for attenuation goals • Data confirming the activity of biogeochemical attenuation processes is in the acceptable range • Data confirming that pore water chemistry is in the range acceptable for biogeochemical attenuation processes
"Identify any potentially toxic and/or mobile transformation products"	Not applicable for Hanford primary contaminants
"Verify that the plume(s) is not expanding (either down gradient, laterally or vertically)"	Not applicable for the vadose zone – this is a groundwater plume objective
"Verify no unacceptable impact to downgradient receptor"	Not applicable for the vadose zone – this is a groundwater plume objective
"Detect new releases of contaminants to the environment that could impact the effectiveness of the natural attenuation remedy"	Administrative or monitoring data to evaluate potential new contaminant releases
"Demonstrate the efficacy of institutional controls that were put in place to protect potential receptors"	Administrative action
"Verify attainment of remediation objectives"	Not applicable for the vadose zone – this is a groundwater plume objective

(a) Direct quotes from the "Performance Monitoring and Evaluation" subsection within the "Implementation" section of EPA (1999).

4.1.2 Configuration

The intensity of MNA monitoring should be adjusted based on the expected contaminant flux to groundwater. More intense monitoring, for a period needed to reduced uncertainty in remedy performance predictions, is appropriate for those sites where MNA performance is uncertain. For instance, these sites may have a predicted contaminant flux is close to thresholds that would exceed groundwater concentration objectives. Another example would be sites where MNA in the vadose zone is needed to meet groundwater objectives. Sites with deep contamination and/or high inventories of mobile contaminants may be candidates for more intense monitoring, but this determination would ultimately be made based on the baseline risk assessment and any subsequent feasibility study and remedial design/remedial action work plan assessments. For sites where it is more certain that contaminant flux from the vadose zone will not produce groundwater concentrations of concern, less intense monitoring can be applied. Sites with low discharge inventories of mobile contaminants where contaminants are currently located shallow in the vadose zone may be candidates for less intense monitoring, again with the ultimate determination based on more detailed site-specific assessments. For some sites, no vadose zone monitoring may be warranted. Table 4 shows components of an MNA monitoring strategy for sites where monitoring is warranted. A graded approach to these elements would be applied based on the site conditions.

Figure 15 shows a conceptual depiction of the monitoring components for an MNA scenario. In the figure, baseline monitoring elements include borehole logging, surface and surface-borehole geophysics, surface mapping, and a linkage to the groundwater plume monitoring element (e.g., groundwater monitoring wells). At sites where the baseline risk has determined remediation is needed, the monitoring configuration anticipates that a characterization borehole would be present at the site. It is recommended when a characterization borehole is installed that, at a minimum, it should be completed to provide access for logging tools. Essentially, this requires installation of blank 2-inch polyvinyl chloride (PVC) casing. The ability to log for moisture conditions (e.g., EMI, gravity, or neutron probes) and contaminant of concern (COC) concentrations (or a COC indicator like bulk conductivity using EMI or ERT) is important to support MNA monitoring, especially in the relatively short term (<30 yr) to establish moisture and contaminant flux conditions through periodic logging surveys. The borehole logging would also be used in conjunction with surface geophysical surveys (EMI or ERT) to provide more volumetric measures of moisture and COC (or COC indicator) distribution and movement. Surface mapping for meteorology (temperature and precipitation) and vegetation type, density, and distribution are necessary inputs to recharge estimates. Surface mapping of topography may also be needed to evaluate any erosional or settling changes that may be important to estimation of recharge. Long-term monitoring would evolve toward use of surface mapping and infrequent geophysical surveys with confirmation of groundwater plumes integrated into the long-term groundwater monitoring program.

Additional monitoring elements may be needed in the short term (<30 yr) for some sites to provide verification of attenuation processes and performance. These monitoring elements may include pore water or gas samplers to verify COC concentrations and/or indicators of attenuation processes through laboratory analysis of samples. Spectral gamma logging may also be applicable for some contaminants to evaluate migration. If there are specific subsurface zones of concern with respect to attenuation or contaminant migration, cross-hole geophysics can be used to investigate moisture or COC (or COC indicator) distribution and movement (EMI, ERT, or GPR). A direct measure of recharge may also be needed at some sites and could be provided by monitoring migration of an added tracer solution with surface or surface-borehole ERT or EMI.

Table 4. MNA monitoring strategy components where intense monitoring is needed for an unsaturated site.

Component	Purpose	Interpretation	Discussion
Pore water/soil gas sampler	Provide pore water samples to verify COC concentrations and/or indicators of attenuation processes.	Samples are analyzed for constituent concentrations that can be mapped to attenuation process verification or used as input to evaluating contaminant flux based on changes in COC vertical profile.	Verification of attenuation and contamination concentration by pore water sampling may be important for some applications if attenuation relies on specific conditions, has high uncertainty, or contaminants cannot be tracked well by non-sampling methods. This is an early/mid phase component to verify performance, with the frequency of use declining over time and likely ceasing.
Volumetric or vertical profile of COC or indicator distribution and/or flux	Quantify COC or indicator distribution for use in evaluating COC or moisture flux and identifying any changes (drainage, recharge change).	COC or indicator distribution is compared to those from transport simulations to verify conditions are within the range deemed acceptable for MNA performance. Data are also used directly to examine changes in COC or indicator distribution as a measure/indication of COC flux.	This is an early/mid phase component to verify flux conditions. For COC or indicators, use of probes or other geophysics may be a higher resolution, less intensive means to provide flux data than collection of pore-water samples. Over time the less intense monitoring would be applied to infrequently supplement early-phase trend data
Volumetric or vertical profile of moisture content/matric potential	Quantify moisture content and/or matric potential for use in evaluating moisture flux and identifying any changes (drainage, recharge change).	Moisture conditions are compared to those used in transport simulations to verify conditions are within the range deemed acceptable for MNA performance. Data are also used directly to examine changes in distribution of moisture conditions as a measure/indication of moisture flux.	This is an early/mid phase component to verify flux conditions. Over time less intense monitoring for recharge conditions may be sufficient (e.g., vegetation mapping and meteorology) with infrequent verification by subsurface measurements.
Remote sensing of surface and near-surface conditions	Quantify surface conditions for use in verifying recharge conditions.	Vegetation is mapped to assess recharge and evaluated to ensure values are within range deemed acceptable for contaminant flux. Erosion and deformation are mapped and related to impacts for recharge.	This is a long-term approach once early-phase data establishes trends in moisture and contaminant flux.
Meteorology	Quantify precipitation for use in verifying recharge conditions.	Precipitation is correlated to recharge rates and evaluated to ensure values are within range deemed acceptable for MNA performance.	This is a long-term approach once early-phase data establishes trends in moisture and contaminant flux.
Groundwater well monitoring	Quantify COC or indicator concentrations in relation to objectives. Quantify water level over time to define groundwater (GW)/vadose zone (VZ) interface location.	COC concentrations enable direct interpretation for groundwater objectives. Indicator concentrations are interpreted to estimate flux of an indicator from the VZ to the GW. Water level is evaluated with respect to VZ thickness compared to predicted conditions.	This is a fundamental part of a coupled VZ/GW remedy to meet groundwater objectives. However, COC data is a lagging indicator of VZ contaminant conditions, so insufficient at some sites. Water level data is likely available from larger scale aquifer monitoring.

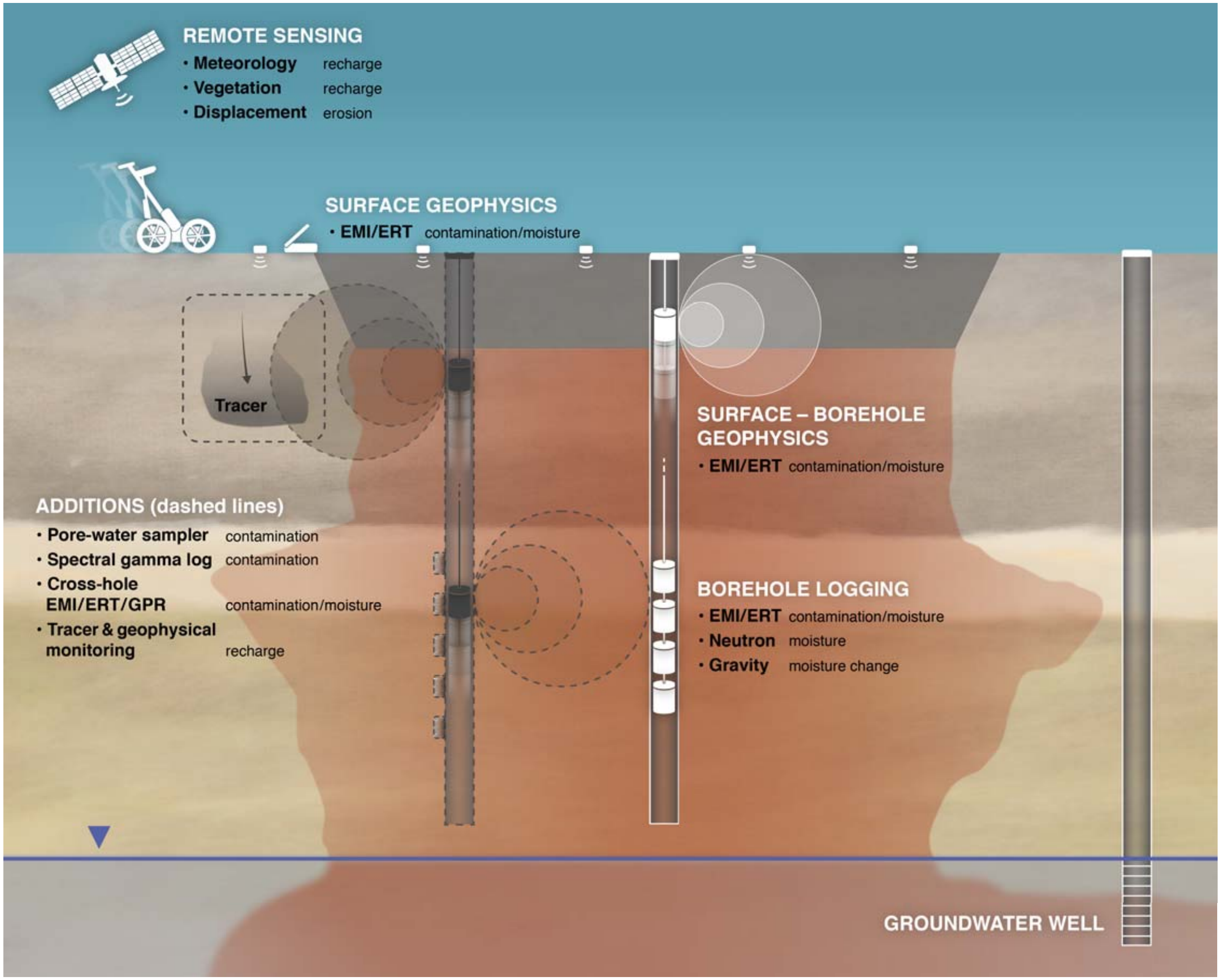

Figure 15. Conceptual depiction of the monitoring components for a MNA remedy configuration.

4.1.3 ARAR (e.g., TI) Waiver/Administrative Management Variant

An ARAR (applicable or relevant and appropriate requirements) waiver or administrative management is not the same as applying MNA as a remedy. However, these approaches would have monitoring needs similar to those of MNA. For an ARAR waiver or administrative management required conditions, either internal to the administered zone or at the border of the administrated zone, would be defined. As for MNA, the conditions for the vadose zone would be associated with meeting conditions for the groundwater pathway and would be expected to maintain the contaminant flux from the vadose zone to the groundwater low enough that groundwater objectives are met. For the vadose zone, implementation would involve either a defined threshold condition in the vadose zone or evidence that conditions in the vadose zone are within a range anticipated to continue to meet the groundwater objectives. Compared to MNA, demonstration of these conditions may be different than the approach used to demonstrate vadose zone attenuation (i.e., the specifications of the MNA directive may not be applied). Functionally, demonstration of threshold concentrations or contaminant flux conditions in the vadose zone may be a minimal vadose zone monitoring requirement for use in conjunction with groundwater monitoring that would ultimately be used to demonstrate compliance. Table 5 lists anticipated categories of data quality objectives for an ARAR [technical impractibility (TI)] waiver/administrative management remedy.

Table 5. Anticipated Data Quality Objective Categories for an ARAR (TI) waiver/administrative management remedy.

Data Quality Objective	Supporting Data/Applicability
Demonstrate that contaminant flux from the vadose zone is below a threshold value that enables groundwater to meet expectations of the ARAR waiver	• Moisture and contaminant data that can be used to evaluate whether contaminant flux is in the acceptable range • Data confirming the activity of biogeochemical attenuation processes is in the acceptable range • Groundwater data showing that contaminant flux from the vadose zone is meeting expected range groundwater contaminant concentration
Verify meeting the ARAR-waiver requirements for the groundwater (e.g., protectiveness and other identified objectives)	Not applicable for the vadose zone – groundwater focused objective
Detect new releases of contaminants to the environment that could impact the ability for the groundwater to meet expectations of the ARAR waiver	Administrative or monitoring data to evaluate potential new contaminant releases.
Demonstrate the efficacy of institutional controls associated with the ARAR waiver	Administrative action

Compared to MNA, monitoring for an ARAR (TI) waiver/administrative management remedy may be different than the approach used to demonstrate vadose zone attenuation (i.e., the specifications of the MNA directive may not be applied). Functionally, demonstration of threshold concentrations or contaminant flux conditions in the vadose zone may be a minimal vadose zone monitoring requirement for use in conjunction with groundwater monitoring that would ultimately be used to demonstrate compliance. For sites where it is more certain that contaminant flux from the vadose zone will not produce groundwater concentrations of concern, less intense monitoring can be applied. Sites with low discharge inventories of mobile contaminants in the shallow vadose zone may also be candidates for less intense monitoring, with the ultimate determination based on more detailed site-specific assessments. For some sites, no vadose zone monitoring may be warranted.

Potential components of an ARAR (TI) waiver/administrative management monitoring strategy are essentially the same as for the MNA scenario. However, a graded approach to these elements would be applied based on the site conditions and monitoring is anticipated to be relatively low intensity compared to MNA monitoring with a primary focus on compliance.

4.2 Surface Barrier Scenario

A remedy using a surface barrier is selected and designed to alter vadose zone moisture flux conditions to limit the contaminant flux from the vadose zone to the groundwater at levels that assure groundwater objectives are met. The remedy does not depend on meeting a threshold concentration in the vadose zone unless this threshold is related to meeting the groundwater objectives.

4.2.1 Data Quality Objectives

Remedy implementation requires providing evidence that application of the surface barrier has and will continue to alter moisture conditions and associated contaminant migration in the vadose zone to meet the groundwater objectives. While groundwater monitoring ultimately is used to demonstrate compliance and remedy success, vadose zone monitoring is applied to demonstrate moisture and contaminant conditions are acceptable based on the designed vadose zone conditions and support verification that groundwater objectives will not be exceeded in the future. Table 6 lists anticipated categories of data quality objectives for a surface barrier remedy.

Table 6. Anticipated data quality objective categories for a surface barrier/desiccation remedy.

Data Quality Objective	Supporting Data/Applicability
Demonstrate that contaminant flux from the vadose zone is below a threshold value that enables groundwater to meet remediation objectives	• Moisture and contaminant data that can be used to evaluate whether contaminant flux is in the acceptable range • Data confirming the activity of biogeochemical attenuation processes is in the acceptable range • Groundwater data showing that contaminant flux from the vadose zone is meeting expected range groundwater contaminant concentration
Verify that the physical and biogeochemical conditions of surface barrier remedy components are within designed tolerances	• Moisture, contaminant, physical, or other data that can be used to evaluate surface barrier integrity and performance of designed components • Moisture data that can be used to evaluate subsurface status in relation to predicted performance • Data for site conditions to evaluate conditions in comparison to the design conditions (e.g., annual precipitation)
Detect new releases of contaminants to the environment that could impact the ability for the remedy to meet groundwater objectives	Administrative or monitoring data to evaluate potential new contaminant releases.
Demonstrate the efficacy of institutional controls associated with the remedy	Administrative action

4.2.2 Configuration

Table 7 shows components of a surface barrier remedy monitoring strategy. Except for the monitoring directly in the constructed barrier, the monitoring elements are essentially the same as for the MNA scenario. However, monitoring for a surface barrier remedy would be phased to initially verify expected performance of the surface barrier based on progress toward achieving targets for reduction in moisture content and associated moisture/contaminant flux. This type of monitoring may be more intense that what is applied for an MNA scenario. Over time, monitoring emphasis would shift to verifying maintenance of target moisture conditions, demonstrating maintenance of acceptable surface barrier design conditions, and confirming that contaminant migration is controlled. Longer-term, monitoring may revert to indirect indicators of performance such as indicators of surface conditions and subsurface moisture conditions.

Figure 16 shows a conceptual depiction of the monitoring components. In the figure, baseline monitoring elements include borehole logging, surface and surface-borehole geophysics, surface mapping, and a linkage to the groundwater plume monitoring element (e.g., groundwater monitoring well). At sites where the baseline risk has determined remediation is needed, the monitoring configuration anticipates that a characterization borehole would be present at the site. It is recommended when a characterization borehole is installed that, at a minimum, it should be converted to a logging borehole. Essentially, this requires installation of a blank 2-inch PVC riser. The ability to log for moisture conditions (e.g., EMI, gravity, or neutron probes) and COC concentrations (or a COC indicator like bulk conductivity using EMI or ERT) is important to support barrier monitoring, especially in the relatively short term (<30 yr) to establish moisture and contaminant flux conditions through periodic logging surveys. The borehole logging would also be used in conjunction with surface geophysical surveys (EMI, ERT, or seismic) to provide more volumetric measures of moisture and COC (or COC indicator) distribution and movement in the subsurface. Surface and surface-borehole logging (EMI, ERT, neutron, and seismic) provide information on moisture/matric potential distribution in the barrier as part of evaluating performance in limiting infiltration/recharge. Select locations for vertical moisture logging (neutron probe) would provide higher resolution confirmatory moisture data. Surface mapping for meteorology (temperature and precipitation) and vegetation type, density, and distribution are necessary inputs to recharge estimates in relation to inputs to the surface barrier and for assessing barrier performance elements like evapotranspiration. Surface mapping of topography would also be needed to evaluate any erosional or settling changes that are important to barrier performance assessment. Long-term monitoring would evolve toward use of surface mapping and infrequent geophysical surveys for the barrier (and potentially the subsurface) with confirmation of groundwater plumes integrated into the long-term groundwater monitoring program.

Additional monitoring elements may be needed in the short term (<30 yr) for some sites to provide verification of barrier performance in mitigating contaminant flux toward the groundwater. These monitoring elements may include pore-water or gas samplers to verify COC concentrations and/or indicators of attenuation processes through laboratory analysis of samples. Spectral gamma logging may also be applicable for some contaminants to evaluate migration. If there are specific subsurface zones of concern with respect to attenuation or contaminant migration, cross-hole geophysics for moisture or COC (or COC indicator) distribution and movement (EMI, ERT, or GPR). A direct measure of recharge may also be needed at some sites and could be provided by monitoring migration of an added tracer solution with surface or surface-borehole ERT or EMI.

Table 7. Surface barrier monitoring strategy components.

Component	Purpose	Interpretation	Discussion
Surface barrier volumetric, surface, and borehole data	Provide moisture, matric potential, and surface condition data to verify meeting barrier design performance.	Data provide spatial and vertical moisture information to compare to design infiltration control. Surface information is evaluated to assess evapotranspiration and deformation/erosion that are important for barrier performance.	Geophysical and remote sensing data can be used to evaluate components of barrier performance such as surface conditions, physical configuration, and moisture profiles necessary to confirm that the barrier is within design tolerances.
Pore-water/soil gas sampler	Provide pore water samples to verify COC concentrations and/or indicators of attenuation processes.	Samples are analyzed for constituent concentrations that can be used as input to evaluating contaminant flux based on changes in COC vertical profile.	Samples to evaluate COC movement in the early/mid-term may be needed for zones where drainage is of concern before the barrier can fully control contaminant flux. Samples may also be needed if attenuation is a component of the remedy as described for the MNA scenario.
Volumetric or vertical profile of COC or indicator distribution and/or flux	Quantify COC or indicator distribution for use in evaluating COC or moisture flux and identifying any changes (drainage, recharge change).	COC or indicator distribution is compared to those from transport simulations to verify conditions are within the range deemed acceptable for barrier performance. Data are also used directly to examine changes in COC or indicator distribution as a measure/indication of COC flux.	Data to evaluate COC movement in the early/mid-term may be needed for zones where drainage is of concern before the barrier can fully control contaminant flux. For COC or indicators, use of probes or other geophysics may be a higher resolution, less intensive means to provide flux data than collection of pore-water samples. Over time the less intense monitoring would be applied to infrequently supplement early-phase trend data
Volumetric or vertical profile of moisture content/matric potential	Quantify moisture content and/or matric potential for use in evaluating moisture flux and identifying any changes (drainage, recharge change).	Moisture conditions are compared to those used in transport simulations to verify conditions are within the range deemed acceptable for barrier performance. Data are also used directly to examine changes in distribution of moisture conditions as a measure/indication of moisture flux.	Moisture conditions are a primary indicator of performance with early/mid phase data needed to verify that moisture conditions progress toward and meet design targets. This early/mid phase component is important to verify design moisture/contaminant flux conditions. Over time less intense monitoring for recharge conditions may be sufficient (e.g., vegetation mapping, meteorology, surface barrier components) with infrequent verification by subsurface measurements.
Remote sensing of surface and near-surface conditions	Quantify surface conditions for use in verifying recharge conditions.	Vegetation is mapped to assess recharge and evaluated to ensure values are within range deemed acceptable for barrier performance. Erosion and deformation are mapped and related to impacts for recharge.	This is a long-term approach once early-phase data establishes trends in moisture and contaminant flux.
Meteorology	Quantify precipitation for use in verifying recharge conditions.	Precipitation is correlated to recharge rates and evaluated to ensure values are within range considered in the design for the surface barrier and for at the margins of the barrier.	This is a long-term approach once early-phase data establishes trends in moisture and contaminant flux.
Groundwater well monitoring	Quantify COC or indicator concentrations in relation to objectives. Quantify water level over time to define GW/VZ interface location.	COC concentrations enable direct interpretation for groundwater objectives. Indicator concentrations are interpreted to estimate flux of an indicator from the VZ to the GW. Water level is evaluated with respect to VZ thickness compared to predicted conditions.	This is a fundamental part of a coupled VZ/GW remedy to meet groundwater objectives. However, COC data is a lagging indicator of VZ contaminant conditions, so insufficient at some sites. Water level data is likely available from larger scale aquifer monitoring.

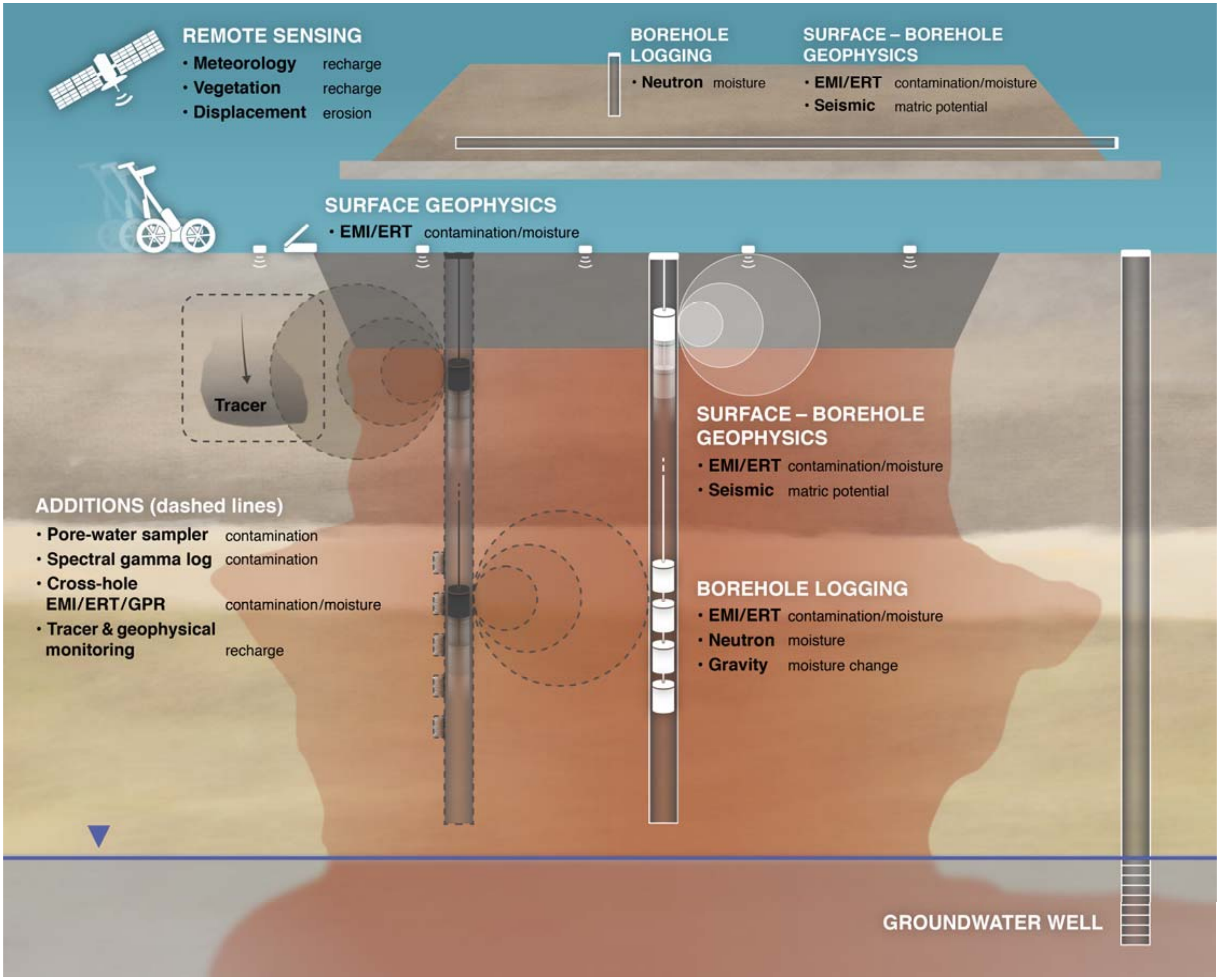

Figure 16. Conceptual depiction of the monitoring components for a surface barrier remedy configuration.

4.2.3 Surface Barrier/Desiccation Variant

A remedy using a combination of desiccation and a surface barrier is selected and designed to alter vadose zone moisture flux conditions to limit the contaminant flux from the vadose zone to the groundwater at levels that assure groundwater objectives are met. The remedy does not depend on meeting a threshold concentration in the vadose zone unless this threshold is related to meeting the groundwater objectives. Remedy implementation requires evidence that application of the surface barrier/desiccation has and will continue to alter moisture conditions and associated contaminant migration in the vadose zone to meet the groundwater objectives. While groundwater monitoring ultimately is used to demonstrate compliance and MNA success, vadose zone monitoring is applied to demonstrate moisture and contaminant conditions are acceptable based on the designed vadose zone conditions and support verification that groundwater objectives will not be exceeded in the future. Components of remedy implementation monitoring of the surface barrier need to verify maintenance of acceptable surface design conditions and progress toward limits on subsurface unsaturated hydraulic conductivity (estimated from moisture content and/or matric potential measurements) or contaminant migration targets. Components of remedy implementation monitoring for desiccation need to quantify moisture conditions in the desiccation zone to determine when re-application of desiccation is necessary and progress toward subsurface moisture content, matric potential, or contaminant migration targets. Long-term monitoring may revert to indirect indicators of performance. Table 8 lists anticipated categories of data quality objectives for a surface barrier/desiccation remedy.

Table 8. Anticipated Data Quality Objective Categories for a surface barrier/desiccation remedy

Data Quality Objective	Supporting Data/Applicability
Demonstrate that contaminant flux from the vadose zone is below a threshold value that enables groundwater to meet remediation objectives	• Moisture and contaminant data that can be used to evaluate whether contaminant flux is in the acceptable range • Data confirming the activity of biogeochemical attenuation processes is in the acceptable range • Groundwater data showing that contaminant flux from the vadose zone is meeting expected range groundwater contaminant concentration
Verify that the physical and biogeochemical conditions of surface barrier and desiccation remedy components are within designed tolerances	• Moisture, contaminant, physical, or other data that can be used to evaluate surface barrier integrity and performance of designed components • Moisture data that can be used to evaluate desiccation zone status in relation to predicted performance • Data for site conditions to evaluate conditions in comparison to the design conditions (e.g., annual precipitation)
Detect new releases of contaminants to the environment that could impact the ability for the remedy to meet groundwater objectives	Administrative or monitoring data to evaluate potential new contaminant releases.
Demonstrate the efficacy of institutional controls associated with the remedy	Administrative action

Monitoring for a surface barrier/desiccation remedy would be phased to initially verify expected performance of desiccation and the surface barrier based on progress toward achieving targets for reduction in moisture content and associated moisture/contaminant flux. This initial monitoring also needs to quantify moisture conditions in the desiccation zone to determine when re-application of desiccation is necessary. Over time, monitoring emphasis would shift to verifying maintenance of target moisture conditions, demonstrating maintenance of acceptable surface barrier design conditions, and confirming that contaminant migration is controlled. Longer-term, monitoring may revert to indirect indicators of performance such as indicators of surface conditions and subsurface moisture conditions.

Components of a surface barrier/desiccation remedy monitoring strategy are essentially the same as for the surface barrier scenario. As with a surface barrier only remedy, monitoring for a surface/desiccation barrier remedy would be phased to initially verify expected performance of the desiccation zone and the surface barrier based on progress toward achieving targets for reduction in moisture content and associated moisture/contaminant flux. However, because desiccation is implemented in situ, more intense subsurface monitoring of the desiccation zone using borehole logging and cross-hole geophysics for moisture conditions is applied during the desiccation period of the remedy. Over time, monitoring emphasis would shift to verifying maintenance of target moisture conditions, demonstrating maintenance of acceptable surface barrier design conditions, and confirming that contaminant migration is controlled. Longer-term, monitoring may revert to indirect indicators of performance such as indicators of surface conditions and subsurface moisture conditions.

4.3 In Situ Remediation Scenario

In situ remedies fall into several categories based on their mode of action. In situ remediation may be applied to sequester or degrade contaminants. Monitoring for each of these applications has similarities in configuration for monitoring of key remediation parameters in a target zone and monitoring of overall vadose zone conditions that relate to remediation performance.

A remedy based on in situ remediation is selected and designed to alter the mobility of vadose zone contaminants by forming low-solubility materials, creating materials that interact with contaminants and limit contaminant concentrations in the mobile aqueous phase, or degrading contaminants to non-hazardous products. Implementation is accomplished through liquid, gaseous, or particulate amendments that induce the remediation conditions. The remedy thereby aims to decrease contaminant mass or decreased contaminant mobility in the targeted treatment zone to maintain the contaminant flux from the vadose zone to the groundwater low enough that groundwater objectives are met. The remedy does not depend on meeting a threshold concentration in the vadose zone unless this threshold is related to meeting the groundwater objectives.

4.3.1 Data Quality Objectives

Remedy implementation requires providing evidence that amendments are adequately distributed to the targeted treatment zone and that any required alteration to the physical and/or biogeochemical conditions needed for contaminant sequestration or degradation has occurred. After implementation, monitoring would be associated with contaminant mobility/migration or related controlling factors (e.g., moisture or other indicators of sequestration/mobility) and demonstrating that conditions and associated contaminant migration in the vadose zone will continue to meet the groundwater objectives. Long-term monitoring may revert to indirect indicators of performance.

While groundwater monitoring ultimately is used to demonstrate compliance and MNA success, vadose zone monitoring would be applied to demonstrate moisture and contaminant conditions are acceptable based on the designed vadose zone conditions and support verification that groundwater objectives will not be exceeded in the future. Table 9 lists anticipated categories of data quality objectives for an in situ sequestration remedy.

Table 9. Anticipated Data Quality Objective Categories for an in situ sequestration remedy.

Data Quality Objective	Supporting Data/Applicability
Demonstrate that contaminant flux from the vadose zone is below a threshold value that enables groundwater to meet remediation objectives	• Moisture and contaminant data that can be used to evaluate whether contaminant flux is in the acceptable range • Data confirming the activity of biogeochemical sequestration, degradation, and/or attenuation processes are in the acceptable range • Data confirming that pore water chemistry is in the range acceptable for biogeochemical sequestration, degradation, and/or attenuation processes • Groundwater data showing that contaminant flux from the vadose zone is meeting expected range groundwater contaminant concentration
Verify that the physical and biogeochemical conditions of the in situ remedy components are within designed tolerances	• Remedy operational data that can be used to demonstrate implementation within the designed range • Moisture, contaminant, amendment, or other data that can be used to evaluate in situ remediation zone status in relation to predicted performance • Data confirming that pore water chemistry is in the range acceptable for biogeochemical sequestration, degradation, and/or attenuation processes • Data for site conditions to evaluate conditions in comparison to the design conditions (e.g., annual precipitation)
Detect new releases of contaminants to the environment that could impact the ability for the remedy to meet groundwater objectives	Administrative or monitoring data to evaluate potential new contaminant releases.
Demonstrate the efficacy of institutional controls associated with the remedy	Administrative action

4.3.2 Configuration

Monitoring for an in situ remedy would be phased to initially verify treatment zone conditions in comparison to design conditions. This initial monitoring would also need to quantify amendment conditions to verify appropriate distribution or the need for additional injection. Over time, monitoring emphasis would shift to verifying maintenance of target subsurface conditions and confirming that contaminant migration is controlled. Longer-term, monitoring may revert to indirect indicators of performance such as indicators of moisture and contaminant flux.

Table 10 shows components of an in situ sequestration remedy monitoring strategy. The monitoring would be focused on remedy implementation in the targeted zone and then verification of remedy performance with respect to mitigating contaminant flux to groundwater.

Figure 17 shows a conceptual depiction of the monitoring components. In the figure, baseline monitoring elements include borehole logging, surface and surface-borehole geophysics, surface mapping, and a linkage to the groundwater plume monitoring element (e.g., groundwater monitoring well). At sites where the baseline risk has determined remediation is needed and an in situ remedy is selected, the monitoring configuration anticipates that characterization boreholes and remediation boreholes are present at the site. It is recommended when a characterization borehole is installed that, at a minimum, it should be converted to a logging borehole for monitoring. Essentially, this requires installation of a blank 2-inch PVC riser. Remediation boreholes would include monitoring installations in addition to injection wells. The ability to log for moisture conditions (e.g., EMI, gravity, or neutron probes) and COC concentrations (or a COC indicator like bulk conductivity using EMI or ERT) is important to support remedy monitoring during implementation and continuing in the relatively short term (<30 yr) to establish moisture and contaminant flux conditions through periodic logging surveys. The borehole logging would also be used during remediation and post remediation in conjunction with surface geophysical surveys (EMI, ERT, or seismic) to provide more volumetric measures of moisture and COC (or COC indicator) distribution and movement in the subsurface. Cross-borehole logging (EMI, ERT, GPR, and seismic) is also likely needed to support remedy implementation, with continuation to provide post-remediation moisture and COC information in the treatment zone. Pore water or gas samplers during remedy implementation to verify remediation processes through laboratory analysis of samples would also be continued in the short term to verify remedy performance. Instrumented boreholes may also include sensors for monitoring during remedy implementation. Spectral gamma logging may also be applicable for some contaminants to evaluate COCs during and after remediation. A direct measure of recharge may also be needed at some sites and could be provided by monitoring migration of an added tracer solution with surface or surface-borehole ERT or EMI. Surface mapping for meteorology (temperature and precipitation) and vegetation type, density, and distribution are necessary inputs to recharge estimates. Surface mapping of topography may also be needed to evaluate any erosional or settling changes that may be important to estimation of recharge. Long-term monitoring would evolve toward use a configuration and approach similar to that described for MNA with fewer logging boreholes and eventual change to use of surface mapping and infrequent geophysical surveys with confirmation of groundwater plumes integrated into the long-term groundwater monitoring program.

Each in situ remedy may have a specific type of monitoring needed based on its mode of action. This section does not address these specific requirements, although it is expected that monitoring would be part of one of the categories discussed above.

Table 10. In situ remediation monitoring strategy components.

Component	Purpose	Interpretation	Discussion
Pore-water/soil gas sampler	Provide pore water samples to verify COC concentrations and/or indicators of treatment processes.	Samples are analyzed for constituent concentrations that can be used as input to evaluating contaminant flux based on changes in COC vertical profile.	Samples to evaluate amendment distribution, pore-water chemistry and COC movement in the early/mid-term may be needed for the targeted treatment zone. Samples may also be needed if attenuation is a component of the remedy as described for the MNA scenario.
Volumetric or vertical profile of COC or indicator distribution and/or flux	Quantify COC or indicator distribution for use in evaluating COC or moisture flux and identifying any changes (drainage, recharge change).	COC or indicator distribution is compared to the remedy design to verify conditions are within the range deemed acceptable treatment performance. Data are also used directly to examine changes in COC or indicator distribution as a measure/indication of COC flux.	Data to evaluate amendment distribution and COC movement in the early/mid-term may be needed for the treatment zone. For COC or indicators, use of probes or other geophysics may be a higher resolution, less intensive means to provide flux data than collection of pore-water samples. However, because this treatment directly acts on the contaminant, the monitoring would need to directly measure changes caused by the treatment (e.g., sequestration). Over time the less intense monitoring would be applied to infrequently supplement early-phase trend data
Volumetric or vertical profile of moisture content/matric potential	Quantify moisture content and/or matric potential for use in evaluating moisture flux and identifying any changes (drainage, recharge change).	Moisture conditions are compared to those used in transport simulations to verify conditions are within the range deemed acceptable for treatment performance. Data are also used directly to examine changes in distribution of moisture conditions as a measure/indication of moisture flux.	Moisture conditions are needed to interpret performance with early/mid phase data needed to establish that conditions are within design targets. Over time less intense monitoring for recharge conditions may be sufficient (e.g., vegetation mapping, meteorology) with infrequent verification by subsurface measurements.
Remote sensing of surface and near-surface conditions	Quantify surface conditions for use in verifying recharge conditions.	Vegetation is mapped to assess recharge and evaluated to ensure values are within range deemed acceptable for remedy performance. Erosion and deformation are mapped and related to impacts for recharge.	This is a long-term approach once early-phase data establishes trends in moisture and contaminant flux.
Meteorology	Quantify precipitation for use in verifying recharge conditions.	Precipitation is correlated to recharge rates and evaluated to ensure values are within range considered in the design.	This is a long-term approach once early-phase data establishes trends in moisture and contaminant flux.
Groundwater well monitoring	Quantify COC or indicator concentrations in relation to objectives. Quantify water level over time to define GW/VZ interface location.	COC concentrations enable direct interpretation for groundwater objectives. Indicator concentrations are interpreted to estimate flux of an indicator from the VZ to the GW. Water level is evaluated with respect to VZ thickness compared to predicted conditions.	This is a fundamental part of a coupled VZ/GW remedy to meet groundwater objectives. However, COC data is a lagging indicator of VZ contaminant conditions, so insufficient at some sites. Water level data is likely available from larger scale aquifer monitoring.

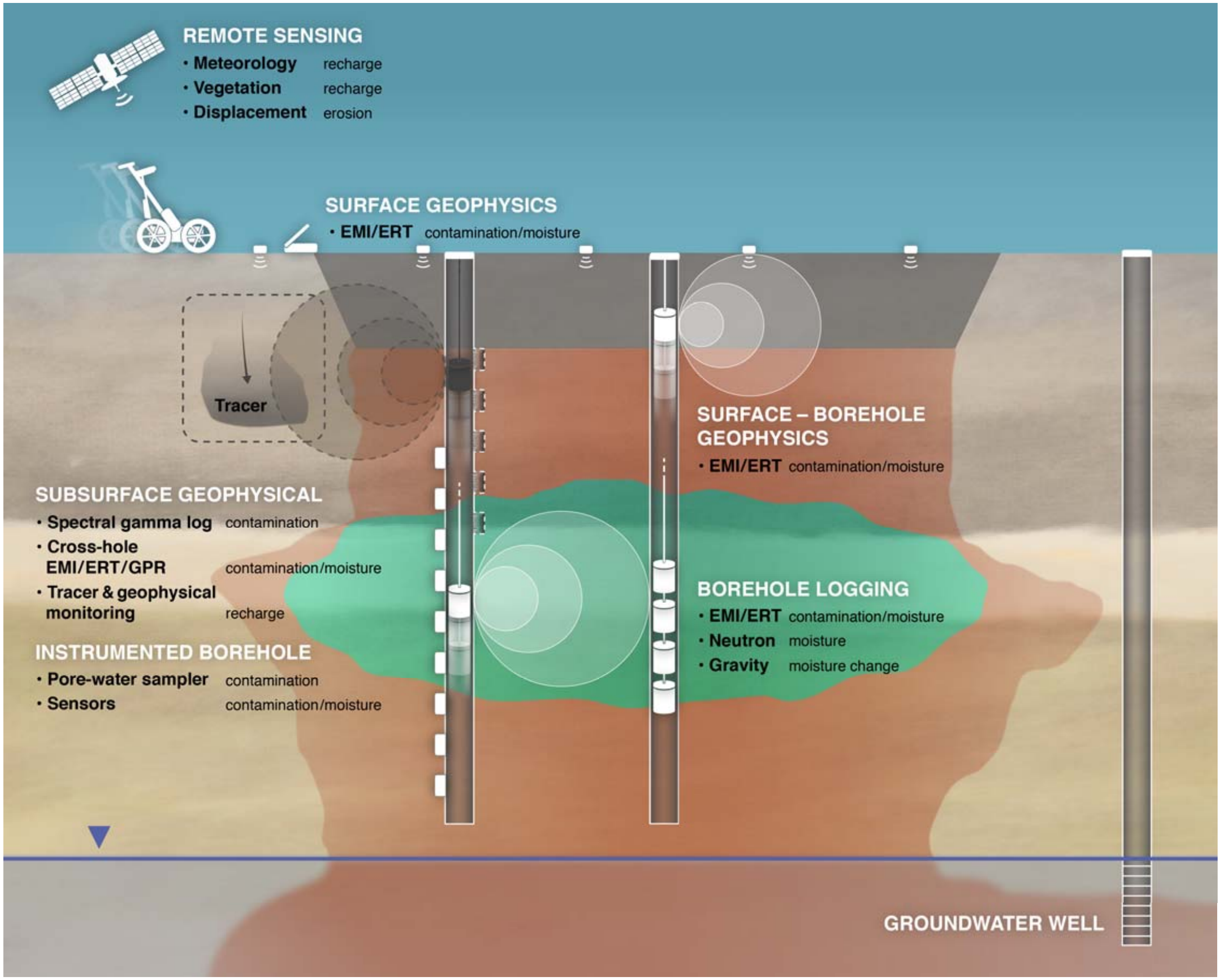

Figure 17. Conceptual depiction of the monitoring components for an in situ remedy configuration.

4.3.3 Water-Table Reactive Barrier Variant

A remedy based on an in situ permeable reactive barrier (PRB) may be possible at the water table interface to treat contaminants as they move from the vadose zone to the groundwater. This type of remedy is monitored like a groundwater PRB except that the influent contaminant flux to the PRB is from the vadose zone. Thus, some vadose zone monitoring to quantify the influent contaminant flux may be needed in relation to evaluating PRB performance. In this respect the vadose zone monitoring would be similar to vadose zone monitoring for MNA. Long-term monitoring may revert to indirect indicators of performance. Table 11 lists anticipated categories of data quality objectives for the vadose zone aspects of a PRB remedy.

Table 11. Anticipated data quality objective categories for the vadose zone aspects of a PRB remedy

Data Quality Objective	Supporting Data/Applicability
Demonstrate that contaminant flux from the vadose zone is below a threshold value that enables groundwater to meet remediation objectives	• Moisture and contaminant data that can be used to evaluate whether contaminant flux is in the acceptable range • Data confirming the activity of biogeochemical attenuation processes is in the acceptable range • Groundwater data showing that contaminant flux from the vadose zone is meeting expected range groundwater contaminant concentration
Verify that the physical and biogeochemical conditions of the permeable reactive barrier are within designed tolerances	Not applicable for the vadose zone – groundwater focused objective
Detect new releases of contaminants to the environment that could impact the ability for the remedy to meet groundwater objectives	Administrative or monitoring data to evaluate potential new contaminant releases.
Demonstrate the efficacy of institutional controls associated with the remedy	Administrative action

Components of monitoring for the vadose zone aspects of a PRB remedy are essentially the same as for the MNA scenario. Monitoring for the vadose zone aspects of a PRB remedy would be phased to initially verify contaminant flux in comparison to design conditions. Longer-term, monitoring may revert to indirect indicators of performance such as indicators of moisture and contaminant flux.

4.3.4 Surface Barrier/In Situ Remediation Variant:

A remedy based on a combination of a surface barrier and in situ remediation is selected and designed when a reduction in recharge is needed in addition to altering the mobility of vadose zone contaminants by forming low-solubility materials, creating materials that interact with contaminants and limit contaminant concentrations in the mobile aqueous phase, or degrading contaminants to non-hazardous products. Implementation is accomplished through liquid, gaseous, or particulate amendments that induce the remediation conditions in a targeted zone. The in situ component of the remedy would thereby aim to reduce contaminant mass or create contaminant mobility conditions in the targeted treatment zone that maintain the contaminant flux from the vadose zone to the groundwater low enough that groundwater objectives are met. A surface barrier is then used to provide additional remediation based on reducing water infiltration at the surface. The remedy does not depend on meeting a threshold concentration in the vadose zone unless this threshold is related to meeting the groundwater objectives.

Remedy implementation requires providing evidence that application of the surface barrier/in situ remediation has and will continue to alter moisture and contaminant conditions and associated contaminant migration in the vadose zone to meet the groundwater objectives. For the in situ remediation portion of the remedy, remedy implementation would require providing evidence that amendments were adequately distributed to the targeted treatment zone and altered biogeochemical conditions to create the desired contaminant sequestration or degradation. After in situ implementation, monitoring would be associated with contaminant mobility/migration or related controlling factors (e.g., moisture or other indicators of sequestration/mobility) and demonstrating that conditions and associated contaminant migration in the vadose zone will continue to meet the groundwater objectives. Long-term monitoring may revert to indirect indicators of performance.

While groundwater monitoring ultimately is used to demonstrate compliance and remedy success, vadose zone monitoring is applied to demonstrate moisture and contaminant conditions are acceptable based on the designed vadose zone conditions and support verification that groundwater objectives will not be exceeded in the future. Table 12 lists anticipated categories of data quality objectives for a surface barrier/in situ remediation remedy.

Table 12. Anticipated data quality objective categories for a surface barrier/in situ remediation remedy.

Data Quality Objective	Supporting Data/Applicability
Demonstrate that contaminant flux from the vadose zone is below a threshold value that enables groundwater to meet remediation objectives	• Moisture and contaminant data that can be used to evaluate whether contaminant flux is in the acceptable range • Data confirming the activity of biogeochemical remediation and attenuation processes are in the acceptable range • Groundwater data showing that contaminant flux from the vadose zone is meeting expected range groundwater contaminant concentration
Verify that the physical and biogeochemical conditions of surface barrier and in situ remedy components are within designed tolerances	• Moisture, contaminant, physical, or other data that can be used to evaluate surface barrier integrity and performance of designed components • Moisture, contaminant, amendment, or other data that can be used to evaluate in situ remediation zone status in relation to predicted performance • Data for site conditions to evaluate conditions in comparison to the design conditions (e.g., annual precipitation)
Detect new releases of contaminants to the environment that could impact the ability for the remedy to meet groundwater objectives	Administrative or monitoring data to evaluate potential new contaminant releases.
Demonstrate the efficacy of institutional controls associated with the remedy	Administrative action

Monitoring for a surface barrier/in situ remediation would be phased to initially verify expected performance of treatment and the surface barrier based on progress toward achieving targets for reduction in moisture content and associated moisture/contaminant flux. This initial monitoring also needs to verify treatment zone conditions in comparison to design conditions and quantify amendment conditions to verify appropriate distribution or the need for additional injection. Over time, monitoring emphasis would shift to verifying maintenance of target moisture/treatment conditions and confirming that contaminant migration is controlled. Longer-term, monitoring may revert to indirect indicators of performance such as indicators of surface conditions and subsurface moisture/contaminant flux conditions.

Components of a surface barrier/in situ remediation monitoring strategy are a combination of the components from the surface barrier scenario and the in situ remediation scenario. The monitoring would be focused on remedy implementation in the targeted zone and then verification of remedy and surface barrier performance with respect to mitigating contaminant flux to groundwater.

5.0 Monitoring Implementation Recommendations

This report presents information about vadose zone monitoring technologies and how they can be configured for monitoring remediation scenarios that are relevant to the Hanford Central Plateau vadose zone. The concept of monitoring in conjunction with different remediation phases was described in the SOMERS document (Bunn et al. 2012). This concept was applied in this report as a key consideration for developing the example monitoring configurations. The evolution of monitoring intensity and monitoring technologies over time needs to be consistent with the stage of remediation and transition to long-term monitoring. To this end, monitoring configurations and associated technologies were selected and described based on how well they would work in meeting the monitoring objectives for each phase of remediation and in minimizing monitoring cost while providing sufficient information. In each scenario, a combination of remote, surface-deployed, and subsurface-deployed approaches are included as monitoring elements. Subsurface-deployed components are identified typically for more intensive monitoring needs during in situ remediation and for use in establishing short-term remedy performance trends for all of the scenarios, when needed. A range of remote and surface-deployed approaches are available and would be favored for less intensive monitoring needs and as these needs evolve toward less intensive long-term monitoring. In most cases, technologies that do not require permanent surface or subsurface infrastructure are preferred to avoid infrastructure degradation issues. Thus, geophysical surveys are identified as important to vadose zone monitoring approaches.

As shown in this report, monitoring configurations include integration/interpretation of multiple types of data to meet monitoring objectives. Interpretation includes consideration of data collected over a given time period. However, it is also important to use early-time data to establish trends that are then included in the interpretation of later time data, enabling an evolution of data collection toward less intense methods and frequencies. Data interpretation has three fundamental aspects. First, data from an individual technique may need to be processed to relate the data to the parameter of interest for the monitoring type. Second, joint interpretation may be applied to either enhance quantification of a single parameter or as a means to quantify more comprehensive information such as an estimate of contaminant migration. Third, monitoring data can be integrated with modeling analyses to facilitate feedback between predictive model results, verification monitoring, and modification of the conceptual site model and related system simulation that is the basis for then applying refined predictive modeling. These data interpretation aspects of monitoring are not included in this report. However, the monitoring configurations shown for the remediation scenarios discussed above were developed with these aspects in mind.

In some cases, a technology selected for a monitoring configuration would require development and testing to demonstrate that it has sufficient maturity for the designated use. When these technologies have some advantages over more mature, but less robust approaches, development work may be warranted. For instance, ERT has been established as a useful technology for vadose zone monitoring. ERT is relatively robust in that only electrode infrastructure must be installed in the field. However, over very long timeframes (e.g., >10-20 yr), this infrastructure may need replacement. If installed within and engineered structure (i.e., surface barrier) or within a borehole, replacement could be difficult. EMI provides very similar information and is deployed as a survey where only minimal site infrastructure is needed (e.g., an access borehole) for subsurface (or surface-barrier) monitoring. However, application and interpretation of EMI data is less mature than for ERT. Because of its good potential for use in long-term monitoring, development of EMI applications and data interpretation is warranted.

Other candidates for additional development include seismic and gravity measurements because they can provide an independent volumetric measure of moisture changes (gravity) and matric potential (seismic) that enhance the interpretation of EMI or ERT. Monitoring is enhanced by application of gravity or seismic surveys because EMI and ERT are sensitive to both moisture content and fluid conductivity. Thus, an independent measure of moisture helps with the EMI/ERT interpretation of fluid conductivity and the related contaminant distribution.

For all of the geophysical and remote sensing techniques, improved data interpretation and data management would meet monitoring objectives. Each of these technologies is data intensive and requires interpretation to relate data to parameters or properties of interest. Advancements would also include development and demonstration of the most effective deployment approaches to provide useful data for the Hanford Central Plateau setting.

For intensive monitoring needs, collection of samples from the subsurface pore water or gas phase may be necessary. While gas-phase sampling is well developed, pore-water sampling for the vadose zone is difficult and advancements to improve the quantity and quality of samples retrieved would be of benefit. In particular, deployment of sampling as a vertical series of multiple sample points within a borehole is important to better represent conditions across the vadose zone and over time, rather than at a small number of points.

In most situations, the recharge rate is a key parameter related to remedy performance. Typically, indirect data are used to estimate recharge at a site. Use of a lysimeter to experimentally determine recharge at each site is prohibitively expensive for a monitoring program. Thus, ideas such as injection of a tracer and subsequent monitoring of its movement by geophysical methods should be developed and demonstrated as a direct, cost-effective means to determine recharge at a site.

The information in this report can be used as a resource for planning future vadose zone monitoring and developing site-specific designs for those sites that require monitoring. While vadose zone monitoring has not been widely applied for inorganic and radionuclide contaminants, there are a number of technologies that have capabilities relevant to remediation and long-term monitoring applications in the vadose zone. Thus, there are viable monitoring configurations that can be applied when needed for the Hanford Central Plateau. However, as described above, some additional development and demonstration efforts are warranted to verify monitoring technology performance and to enable more cost-effective configurations, especially for longer-term monitoring needs.

Remediation scenarios evaluated in this report are relevant to the Hanford Central Plateau. However, these configurations, especially for MNA and surface barriers, are also relevant for DOE Legacy Management applications. Current and ongoing monitoring advances through DOE Legacy Management efforts also offer important leveraging opportunities, especially in regard to remote sensing and geophysical technology applications.

6.0 Quality Assurance

The results presented in this report originate from work governed by the Pacific Northwest National Laboratory Nuclear Quality Assurance Program (NQAP). The NQAP implements the requirements of DOE Order 414.1D, *Quality Assurance*, and 10 CFR 830 Subpart A, *Quality Assurance Requirements*. The NQAP uses ASME NQA-1-2012, *Quality Assurance Requirements for Nuclear Facility Applications*, as its consensus standard and NQA-1-2012 Subpart 4.2.1 as the basis for its graded approach to quality.

Two quality grading levels are defined by the NQAP:

Basic Research - The required degree of formality and level of work control is limited. However, sufficient documentation is retained to allow the research to be performed again without recourse to the original researcher(s). The documentation is also reviewed by a technically competent individual other than the originator.

Not Basic Research - The level of work control is greater than basic research. Approved plans and procedures govern the research, software is qualified, calculations are documented and reviewed, externally sourced data is evaluated, and measuring instrumentation is calibrated. Sufficient documentation is retained to allow the research to be performed again without recourse to the original researcher(s). The documentation is also reviewed by a technically competent individual other than the originator.

The work supporting the results presented in this report was performed in accordance with the *Basic Research* grading level controls.

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