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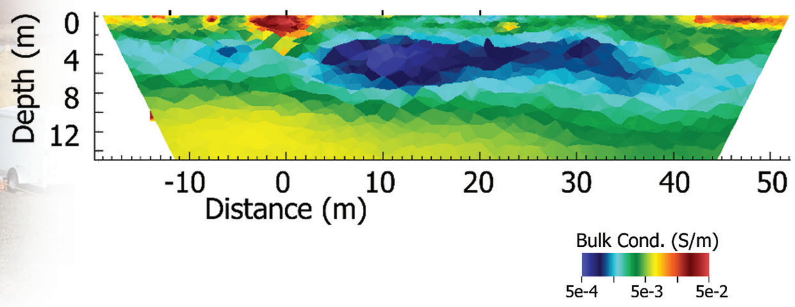


ENVIRONMENTAL RESTORATION

# Geophysical Methods for Characterization and Monitoring at Groundwater Remediation Sites

## Introduction

Geophysical methods have potential to improve characterization and monitoring at sites where groundwater remediation is planned or underway. Aquifer heterogeneity poses enormous challenges to groundwater remediation efforts, and new methods are needed to cost effectively (1) advance the development of conceptual site models (CSMs), (2) develop aquifer property and structural models for numerical flow and transport models, and (3) monitor the implementation and performance of remediation operations. Compared to conventional hydrologic measurements, such as invasive coring or direct sampling, geophysical surveys are non-invasive and more cost-effectively provide information over larger areas. This fact sheet focuses on the application of geophysical tools in support of environmental remediation. The following topics are discussed:

- Why use geophysics?
- What geophysical methods are available?
- Where/when do different geophysical methods work?

More information on the application of geophysical methods at remediation sites can be found at the end of this fact sheet.

## Why Use Geophysics?

The characterization of aquifer properties and monitoring of subsurface processes remains a major challenge to groundwater remediation efforts, particularly at complex sites, which include highly heterogeneous and fractured-rock environments. Traditional *in situ* measurement of geologic properties (e.g., permeability) and hydraulic and chemical conditions (e.g., contaminant concentrations, soil moisture) remains primarily invasive and point-scale, relying on borings and drillings and providing information local to boreholes and test holes. Traditional approaches can bear high financial and labor costs and lead to interpretations based on relatively few observations over large areas. At groundwater remediation sites, direct invasive sampling can be severely limited due to inaccessibility caused by existing infrastructure, the hazardous nature of the groundwater constituents, and (or) the likelihood of enhancing contaminant transport pathways.

Geophysical methods offer the potential to overcome some of the limitations of conventional *in situ* hydrologic sampling. Geophysical properties can potentially be related to rock or soil type, fracture porosity, permeability, water content, and the chemical properties of the pore fluids (e.g., total dissolved solids or total organic acids). Geophysical methods are to some extent scalable, allowing investigation depths and resolution (usually a trade off with depth of investigation) to be user-defined through appropriate selection and survey design. Most geophysical methods are non-invasive when applied from the ground surface or minimally invasive when applied from a smaller subset of boreholes than would be needed to characterize an equivalent volume using *in situ* sampling. Depending on borehole construction, borehole, single-hole, and cross-hole techniques can use existing boreholes installed for other purposes.

Geophysical methods also provide spatially continuous information, making them attractive for interpolating structures away from or between boreholes.

Geophysical methods are never a direct substitute for *in situ* sampling because they indirectly measure hydrogeological properties (e.g., permeability) or contaminant properties (e.g., concentration). Instead, the relationship between measured geophysical properties and hydrogeological properties of interest must be well understood to avoid potential misinterpretation of geophysical information.

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**August 2018**

For all forms of imaging, it is important to note that the produced images represent blurry, blunted proxies of physical properties; hence, geophysical results are best interpreted in combination with established *in situ* measurement methods, which provide calibration and/or ground truth. For these reasons, a background in geophysics and inverse problems is helpful for avoiding pitfalls when interpreting results.

### What Geophysical Methods Are Available?

Geophysical methods can be divided into surface-based methods, borehole logging methods, and single-hole and cross-hole methods (Rubin and Hubbard, 2005), each offering different scales of investigation and resolution (Figure 1). Together, these methods comprise the "Geophysical Toolbox." Borehole logging methods provide the best resolution but sample the smallest volume of an aquifer, whereas surface methods sample the largest volume of aquifer but provide the lowest resolution. Cross-hole and single-hole imaging methods are intermediate between surface and borehole logging methods in terms of sample volume and resolution (see http://www.environmentalrestoration.wiki), providing information in between or away from boreholes, respectively.

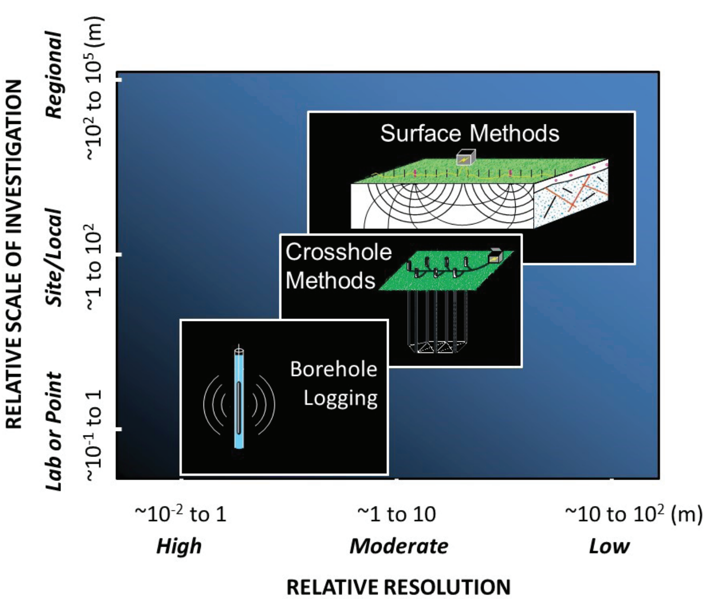


**Figure 1. Schematic diagram showing the tradeoff between scale of investigation and resolution for borehole, cross-hole, and surface geophysical methods. (*Courtesy of USGS*)**

### Surface-Based Methods

Surface-based methods have potential applications for mapping depth to bedrock, thickness of weathered zones, depth to water table, rock and soil type, major faults, and fracture zones (Day-Lewis et al., 2017). Surface-based methods involve collection of land surface measurements using electrodes, geophones, antennas, and other devices. These methods can be passive or active, the latter involving a stimulus to the earth (e.g., application of electrical current). Although surface-based methods do not offer the resolution possible with borehole, single-hole, or cross-hole methods, they are (1) less invasive, requiring no boreholes, and (2) capable of covering much larger areas at lower cost. Application of surface methods is limited in areas of substantial infrastructure, such as underground utilities and pipes. For most surface-based methods, processing and/or inversion of acquired data is necessary to derive properties of interest. Although commercial processing software is available for many methods, processing and interpretation are not as straightforward as for borehole logging methods. Table 1 provides an overview of the information provided by individual surface methods, although application of the Geophysical Toolbox combination of methods is invariably the best strategy.

## Borehole Logging Methods

Borehole logging geophysical methods are routinely used in site investigations and provide high-resolution information about rock and soil type, fluid properties, and borehole conditions along a vertical profile. A logging tool is lowered into a borehole and a sensor records vertical variations in a geophysical property for a localized volume of material beyond the borehole wall adjacent to the logging tool. Commonly, a suite of logs will be collected because logging costs increase only incrementally for each additional log and interpretation is better constrained when based on multiple data types. Tools are designed for use in boreholes with a range of diameters, with the slim-hole tools capable of working in 2-inch wells. Most geophysical logs provide a direct measure of a geophysical property. Commercial software for processing and visualization of borehole logs is mature, and comparison of multiple logs collected as a suite can provide valuable insight into geological structure. Table 2 provides an overview of the information provided by individual borehole methods.

**Table 1. Surface-based geophysical methods**

| Method | Lateral Extent of Survey Region (meters) | Depth of Survey Region (meters) | Resolution (meters) | Recovered Properties of Interest | Potential Targets | Characterization (C) or Monitoring (M) |
|---|---|---|---|---|---|---|
| **Electrical Resistivity** | 1 to 100 | 1 to 100 | 0.5 to 10 | DC electrical conductivity | Fracture zones, Amendment monitoring | C, M |
| **Ground Penetrating Radar** | 1 to 1000 | 1 to 50 | 0.1 to 10 | Dielectric constant at frequencies of 1MHz to 1GHz | Lithology, geologic contacts, water table | C, M |
| **Electro-Magnetic Induction** | 1 to 10000 | 1 to 100 | 0.5 to 10 | Electrical conductivity | Plume delineation, lithology | C, M |
| **Very Low Frequency Electromagnetism** | 1 to 10000 | 5 to 75 | 1 to 10 | Electrical conductivity | Faults, fracture zones | C |
| **Magnetometry** | 1 to 10000 | 1 to 100 | 0.5 to 10 | Magnetization, magnetic susceptibility | Treatment monitoring (metals) | C, M |
| **Seismic Reflection/ Refraction** | 1 to 1000 | 1 to 500 | 1 to 10 | Elastic wave velocities, attenuation | Geologic contacts, water table, lithology | C |
| **Induced Polarization** | 1 to 1000 | 1 to 100 | 0.5 to 10 | Imaginary part of the complex electrical conductivity at frequencies from mHz to kHz | Permeability estimation, amendment monitoring | C, M |
| **Surface Nuclear Magnetic Resonance** | 10 to 100 | 1 to 100 | 1 to 10 | Relaxation time constant | Depth to groundwater, permeability, water content | C, M |
| **Self Potential** | 1 to 1000 | 1 to 100 | 0.5 to 10 | Electrodiffusion potential, redox potential, streaming potential | Groundwater flow directions | C, M |

**Table 2. Borehole geophysical logging methods**

| Geophysical Method | Hole Type[1] | Depth of Penetration (meters) | Vertical Resolution (meters) | Recovered Properties of Interest | Potential Targets | Characterization (C) or Monitoring (M) |
|---|---|---|---|---|---|---|
| **Caliper** | O,C,S,P | N/A | 0.05 | Diameter of borehole | Fracture locations, guidance for packer placement | C |
| **Electromagnetic Induction** | O,C,S | 0.5 | 0.5 | Electrical conductivity | Contaminant plume delineation, lithology, porefluid conductivity | C, M |
| **Magnetic Susceptibility** | O,C,S | 0.5 | 0.5 | Magnetic susceptibility | Iron minerals (magnetite), Treatment monitoring involving metals | C, M |
| **Sonic Logging** | O | 0.2 to 1 | 0.1 | Compressional wave velocity shear wave velocity tube wave velocity | Porosity, lithology, cement bond evaluation; fracture evaluation, lithology, mechanical properties, fracture permeability | C |
| **Single Point Resistance** | O | N/A | 0.05 | Resistance | Characterization of lithology | C |
| **Normal Resistivity** | O | 0.2 to 1.6 | 0.05 to 1.6 | Electrical resistivity | Porosity, permeability | C, M |
| **Nuclear Magnetic Resonance** | O,C,S | 0.3 | 0.25 to 1 | Relaxation time constant | Porosity, permeability | C, M |
| **Self Potential** | O | N/A | 0.5 | Electro-diffusion potential, redox potential, streaming potential Thermoelectric potential | Groundwater flow directions | C, M |
| **Fluid Conductivity/ Temperature** | O | None | 0.05 | Fluid electrical conductivity, temperature | Total dissolve solids, fracture locations, solute or amendment monitoring | C, M |
| **Television** | O | None | 0.05 | Video or digital image | Fracture locations, lithology, formation of precipitates, turbidity, flocculation due to amendments | C, M |
| **Acoustic Televiewer** | O | None | 0.0005 | Acoustic reflectivity and borehole diameter | Fracture locations and orientations, lithology, borehole diameter | C |
| **Optical Televiewer** | O | None | 0.0005 | Red, green, blue color and light intensity | Fracture locations and orientations, lithology | C |
| **Flowmeter** | O,S | 1 to 100 | N/A | Vertical flow | Transmissivity and far-field head of fractures or layers | C |
| **Gamma** | P | 0.3 | 0.05 | Gamma emissions | Lithology and potential fractures at contacts | C |

[1] Hole type: Codes indicate the typical well construction for application of these logs.
O – open hole; C – plastic-cased hole; S – slotted plastic casing; P – steel pipe or casing

## Single-hole and Cross-hole Imaging Methods

Single-hole imaging involves measurements made in a single borehole (e.g., reflection-mode radar) or between a borehole and land surface (e.g., vertical seismic profiles) of properties extending away from the borehole. Cross-hole methods involve measurements made between two boreholes (e.g., electrical resistivity tomography). Data from cross-hole methods are analyzed to produce two- or three-dimensional (2D or 3D) images of geophysical properties between boreholes. As for surface-based methods, mature processing software exists; however, processing is not as straightforward as for borehole logging methods. The maximum possible distance between boreholes depends on the strength of the source (transmitter, electrical current, etc.), geologic conditions, and the resolution required. For all cross-hole techniques, it is desirable for the imaged region to have a ratio of vertical-to-horizontal dimension greater than 1, and preferably greater than 1.5 to maintain adequate resolution in the inter-borehole region; thus, two boreholes with 30 meters available for antennas or electrodes would limit the interwell offset to 15 meters. Table 3 provides an overview of the information provided by single-hole and cross-hole imaging methods.

## Where/When Do Different Geophysical Methods Work?

For geophysics to be effective in addressing a site remediation problem, two conditions must be met. First, there must be measurable contrast in a geophysical property between the target of interest and the background. Second, a method must be available that can detect this contrast at the location (distance from the sensors) of the target and with sufficient spatial resolution. Once these conditions are met, the site conditions must be carefully considered. Even if the former two conditions are satisfied, specific site conditions (e.g., geology, anthropogenic sources of noise that corrupt the sensors) can render a method ineffective.

The ability of a given method to detect a specific target with sufficient resolution under site-specific conditions can be evaluated using synthetic modeling, also called pre-modeling. In pre-modeling (Figure 2), computer software is used to predict the images that would result from a geophysical survey for a hypothetical target (e.g., underground storage tank, amendment distribution, non-aqueous phase liquid pool) under hypothetical field conditions (e.g., rock or soil type and structure). The images are then evaluated to determine whether the method would "see" the target sufficiently well. Pre-modeling of geophysical datasets can thus be used to evaluate whether specific geophysical measurements at a site are likely to be worthwhile, providing an objective basis for moving forward with a geophysical survey. Field deployment of geophysics should only occur after the pre-modeling predicts a positive outcome, along with general assessment of site suitability for performing a geophysical survey.

**Table 3. Single-hole and cross-hole geophysical imaging methods**

| Single-hole and Crosshole Geophysical Imaging Methods | Resolution of Measurement (meters) | Recovered Parameters of Interest | Potential Targets | Characterization (C) or Monitoring (M) |
|---|---|---|---|---|
| **Electrical Resistivity Tomography** | 0.1 to 10 | DC electrical conductivity | Fracture zones, lithology, amendment monitoring | C,M |
| **Ground Penetrating Radar (Transmission Tomography)** | 0.1 to 5 | Electromagnetic velocity at antenna frequency (between 60MHz and 250MHz) and attenuation | Lithology and geologic contacts, major discrete fractures, fracture zones, transport in fractures, amendment monitoring | C,M |
| **Ground Penetrating Radar (Reflection)** | 0.1 to 1 | Locations and orientations of reflectors | Geologic contacts, locations and orientations of discrete fractures | C,M |
| **Seismic Transmission Tomography** | 1 to 5 | Elastic wave velocities, attenuation | Fracture zones, lithology | C |

Two recently released software tools have been developed to help remediation project managers (RPMs) and contractors make informed decisions about geophysics. The Fractured Rock Geophysical Toolbox – Method Selection Tool (FRGT-MST) (https://water.usgs.gov/ogw/bgas/frgt/) helps identify which geophysical methods are likely to be appropriate for a specific fractured-rock site. The tool includes logic to identify methods useful for satisfying specified goals (e.g., electrical methods can support amendment monitoring) and then reject methods based on site conditions (e.g., ground penetrating radar is ineffective in clayey soils, and electromagnetic induction logging will not work in steel-cased boreholes) (Day-Lewis et al., 2016).

The Scenario Evaluator for Electrical Resistivity (SEER) (https://water.usgs.gov/ogw/bgas/seer/) allows user entry of a specific site for electrical resistivity pre-modeling for a variety of hypothetical targets including dense non-aqueous phase and light non-aqueous phase plumes, and underground storage tanks (Terry et al., 2017). SEER demonstrates the workflow that geophysical professionals can use to evaluate the potential of electrical resistivity for imaging various targets and for monitoring amendment releases. Information on these software tools can be found at the end of this fact sheet.

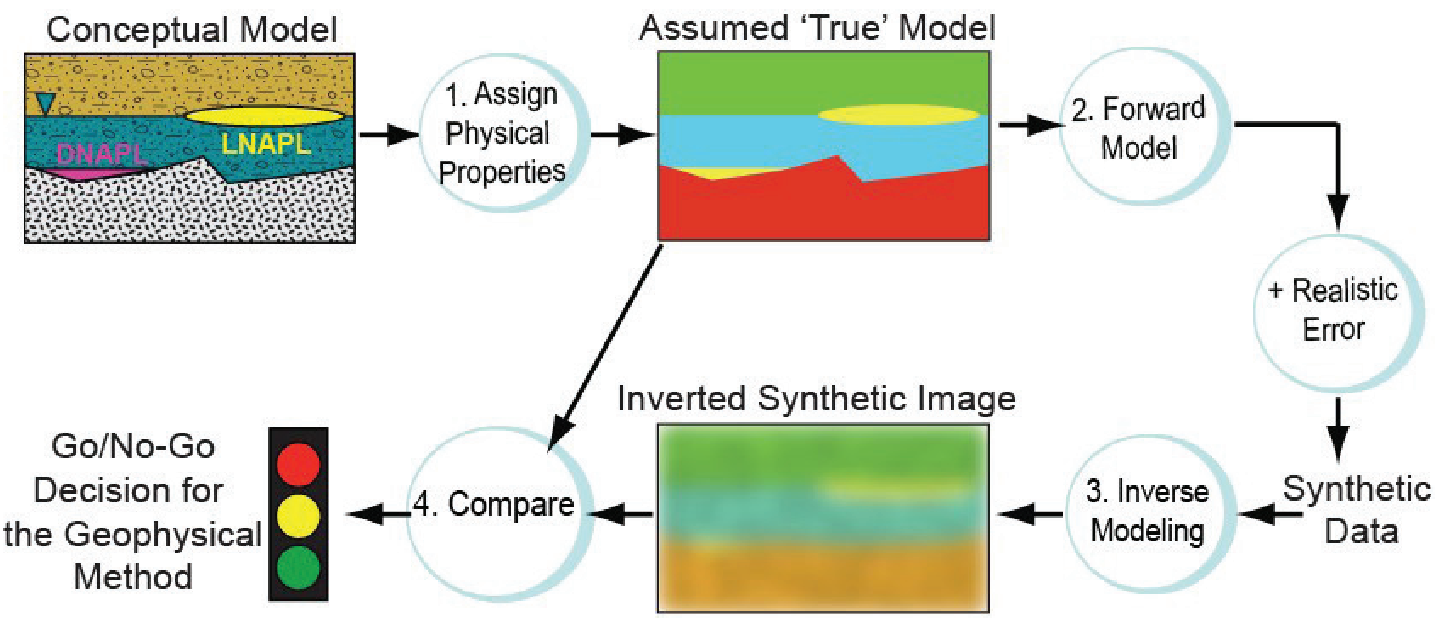


**Figure 2. The four-step synthetic pre-modeling workflow: (1) assign best-guess physical properties for the hypothetical subsurface model; (2) forward model, i.e., calculate the data that would result from the assumed "true" model entered by the user in the first step and corrupt the data with random errors for realism, generating synthetic data; (3) analyze the synthetic data by inverse modeling to produce an image; and (4) compare the inverted synthetic image with the assumed true model. If the synthetic image does not sufficiently resolve the target sought, i.e., a light non-aqueous phase liquid plume in this schematic, the method will likely fail and should be rejected. (*Courtesy of USGS.)***

## Case Study: Tracking Amendment Delivery within a Shallow Unconfined Aquifer

Electrical imaging was used in a study at Joint Base Lewis McChord, in Washington State, to evaluate the effectiveness of a shear thinning fluid (STF) to improve the distribution of an amendment for remediation of trichloroethene in groundwater (Truex et al., 2015). Aquifer heterogeneity results in non-uniform distribution of amendments, with low-permeability zones left unpenetrated and untreated, thus impeding the effectiveness of engineered remediation. In a field demonstration of a STF-enhanced amendment injection (Environmental Security Technology Certification Program (ESTCP) project ER-0913), electrical imaging was used to compare (1) a baseline injection of a sodium bromide tracer and (2) injection of an amendment (ethyl lactate) and STF (a xanthum gum polymer), labeled with an ionic tracer (potassium chloride) (Figure 3). Electrical geophysical images were consistent with sampling results, showing that the STF led to moderate improvement in amendment distribution, with faster breakthrough in low-permeability zones and more uniform coverage. Compared with direct sampling, which provides information only at sparsely distributed sampling points, the geophysical results revealed the amendment distribution—and untreated zones—between boreholes.

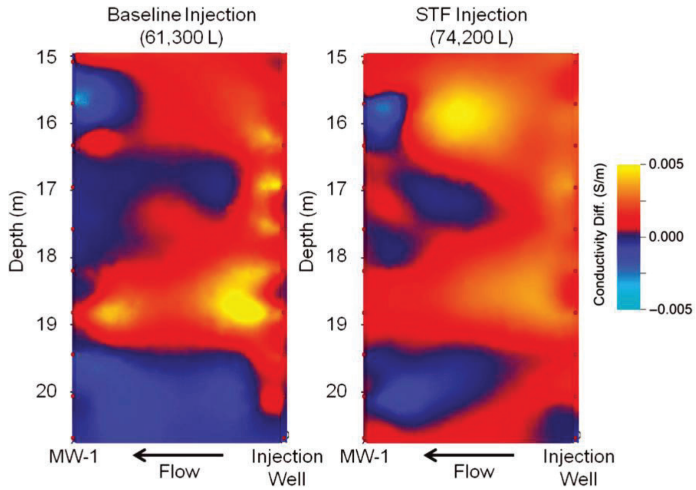


**Figure 3. Change in electrical conductivity (inverse of resistivity) from background conditions for a baseline injection of an ionic tracer (left) and injection of an amendment with a shear-thinning fluid (STF), a xanthum gum polymer. The addition of the STF resulted in more uniform distribution and greater penetration into low-permeability zones. *(Courtesy of ESTCP ER-200913 Final Report).***

## Additional Resources

Day-Lewis, F.D., Johnson, C.D., Slater, L.D., Robinson, J.L., Williams, J.H., Boyden, C.L., Werkema, D., Lane, J.W., 2016. A Fractured Rock Geophysical Toolbox Method Selection Tool, Groundwater. doi:10.1111/gwat.12397.

Day-Lewis, F.D., Slater, L.D., Robinson, J., Johnson, C.D., Terry, N., Werkema, D., 2017. An overview of geophysical technologies appropriate for characterization and monitoring at fractured-rock sites, Journal of Environmental Management, doi: 10.1016/j.jenvman.2017.04.033.

EnviroWiki introduction to geophysical methods: http://www.environmentalrestoration.wiki/index.php?title=Geophysical_Methods_-_Introduction.

Fractured Rock Geophysics Toolbox – Methods Selection Tool (FRGT-MST): http://water.usgs.gov/ogw/bgas/frgt/

Newell, C.J., Adamson, D.T., Truex, M.J., Zhong, L., 2014. Enhanced Amendment Delivery to Low-Permeability Zones for Chlorinated Solvent Source Area Bioremediation, Final Report, ESTCP Project ER-200913; Environmental Security Technology Certification Program. Available from: https://www.serdp-estcp.org/Program-Areas/Environmental-Restoration/Contaminated-Groundwater/Persistent-Contamination/ER-200913/(language)/eng-US. Accessed July 26, 2018.

Rubin, Y. and S. S. Hubbard (Editors), 2005. *Hydrogeophysics*. Springer, New York; 523p.

Scenario Evaluator for Electrical Resistivity (SEER): http://water.usgs.gov/ogw/bgas/seer/.

Terry, N., Day-Lewis, F.D., Robinson, J.L., Slater, L.D., Halford, K., Binley, A., Lane, J.W. and Werkema, D., 2017. Scenario Evaluator for Electrical Resistivity Survey Pre-modeling Tool, Groundwater. doi:10.1111/gwat.12522.

Truex, M.J., Vermeul, V.R., Adamson, D.T., Oostrom, M., Zhong, L., Mackley, R.D., Fritz, B.G., Horner, J.A., Johnson, T.C., Thomle, J.N., Newcomer, D.R., Johnson, C.D., Rysz, M., Wietsma, T.W. and Newell, C.J. 2015. Field Test of Enhanced Remedial Amendment Delivery Using a Shear-Thinning Fluid. Groundwater Monitoring and Remediation, 35: 34-45. doi:10.1111/gwmr.12101.

*The information contained in this factsheet is based on the 2017 RITS presentation "A Biogeophysics Strategy for Minimally Invasive Post Remediation Performance Assessment" presented by Dr. Tim Johnson (PNNL), Dr. Fred Day-Lewis (USGS), and Dr. Lee Slater (Rutgers University–Newark).*