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Geophysical Method Selection: Matching Study Goals, Method Capabilities and Limitations, and Site Condition

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Software and documentation reference:

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.



Polling Question #1

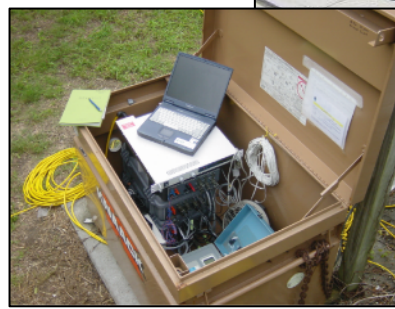
1. What do you think is the greatest impediment to more widespread and effective use of geophysics?

- a. cost vs. benefit
- b. lack of information/training to select the right geophysical methods/tools
- c. end users often don't know how to use geophysical results
- d. bad experiences - instances where geophysics hasn't 'worked'



Outline

- The Geophysical Toolbox
- Why geophysics?
- Information by method
- Scale vs. Resolution Tradeoff
- Method selection
 - Spreadsheet Tool
 - Using the tool
- Next steps after selecting methods
 - Feasibility Assessment
 - Will geophysics 'work'?
 - Realistic expectations
 - SEER
- Wrap up



Polling Question #2

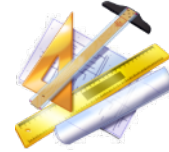
2. It's best to use geophysical methods together because

- a. Multiple types of information can reduce non-uniqueness
- b. Different methods have different strengths and weaknesses
- c. Not every method works at every site
- d. all of the above

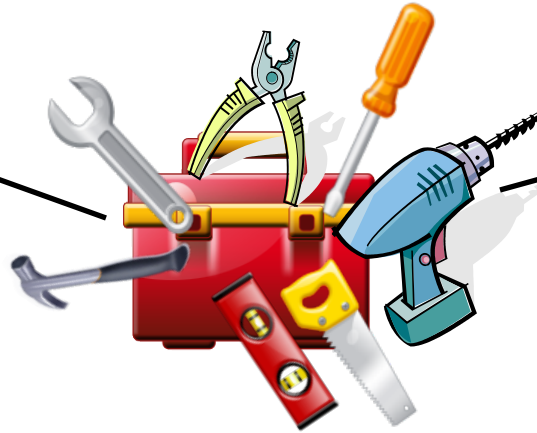
The Geophysical Toolbox



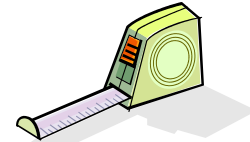
Borehole geophysics
(high resolution,
near-hole
information)



Crosshole
imaging
(information
between holes,
time-lapse
potential)



Surface geophysics
(large areas,
inexpensive)



Conventional
hydrologic
measurements
(calibration and
groundtruth)

NO SINGLE TOOL CAN WORK FOR
EVERY PROBLEM/SITE

SYNERGY BETWEEN METHODS –
JOINT INTERPRETATION

Abraham Maslow(1966), “I suppose it is tempting, if the only tool you have is a hammer, to treat everything as if it were a nail”



[after *Day-Lewis, F.D., Slater, L.D, Johnson, C.D., Terry, N., and Werkema, D., 2017, An overview of geophysical technologies appropriate for characterization and monitoring at fractured-rock sites, Journal of Environmental Management, <http://dx.doi.org/10.1016/j.jenvman.2017.04.033>*]

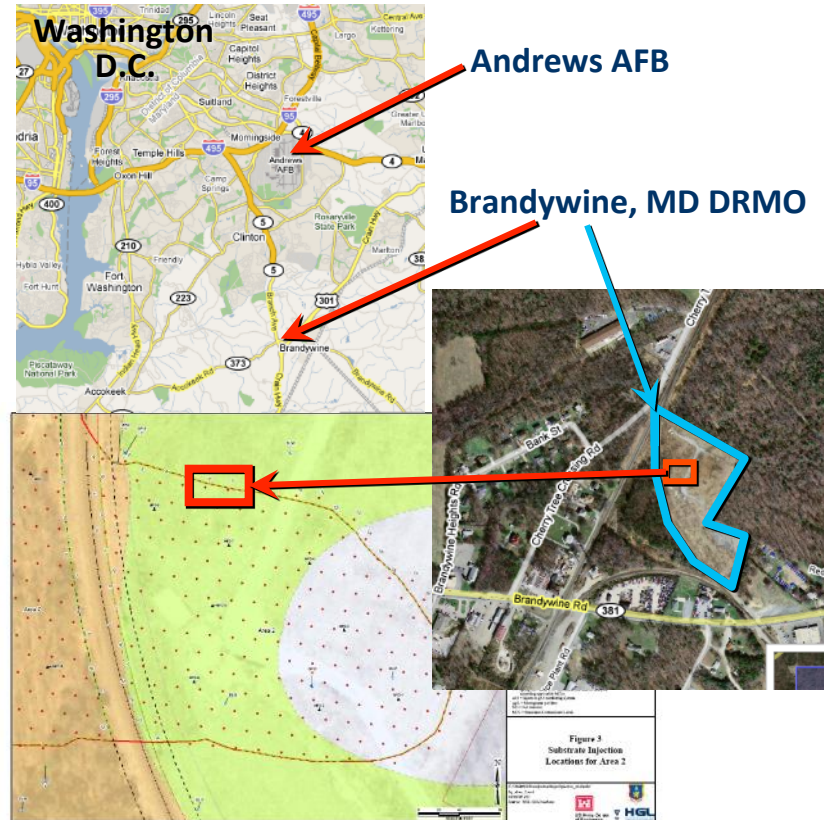
Method	Geophysical Property	Relevant Hydrologic Property/Parameter	Acquisition method(s)
Seismic refraction & reflection	Seismic velocities & reflectivity (bulk & shear moduli)	Depth to bedrock, water table, aquifer boundaries	Lab, borehole, crosshole, surface
DC Electrical Resistivity (ER)	Electrical resistivity	Water content, salinity, pore fluid, porosity, lithology	Lab, borehole, crosshole, surface
Induced polarization (IP)	Chargeability	Surface area of pores/grains, lithology	Lab, crosshole, surface
Spontaneous Potential (SP)	Spontaneous potential	Flow through porous medium, redox potential	Lab, borehole, crosshole, surface
Ground penetrating radar (GPR)	Dielectric constant, electrical conductivity	Water content, salinity, pore fluid, porosity, lithology	Lab, crosshole, surface
Electromagnetic (EM)	Electrical resistivity	Water content, salinity, pore fluid, porosity, lithology	Lab, borehole, crosshole, surface, airborne
Conventional borehole logging: caliper, gamma, sonic, etc.	Many	Many: fracture locations, clay content, lithology, etc.	Borehole
Advanced borehole logging: ATV/OTV, flowmeter, etc.	Many	Many: fracture locations, lithology, transmissivity, etc.	Borehole

Example: Brandywine DRMO

Background

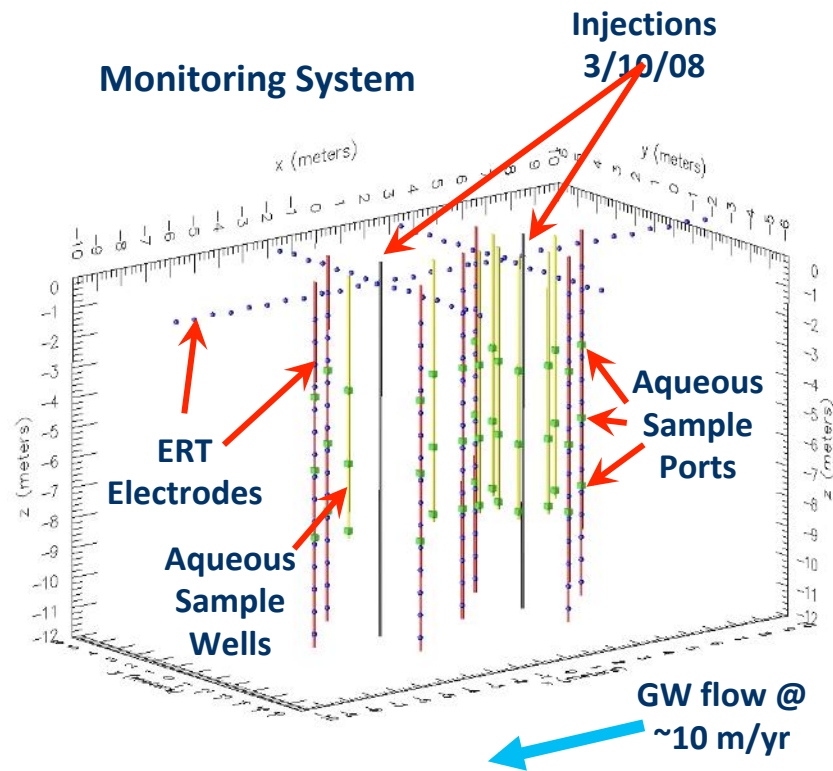
Brandywine, MD Defense Reutilization Marketing Office (DRMO) (Andrews AFB)

- TCE-contaminated groundwater
- Upper 12 m unconfined aquifer
- Spreading to residential neighborhood
- ROD – Enhanced bioremediation
- Amendment injections ~20 ft spacing (~1,000)
- ESTCP Dem/Val effort to monitor two injection points at boundary of treatment area



Example: Brandywine DRMO

- Highly instrumented subsurface monitoring system
- 8 3-port chemical sampling wells
- 7 ERT/chemical sampling wells
- 105 total borehole electrodes
- ER data autonomously collected once every two days for 2.5 years
- Strategically-timed comprehensive chemical sampling



Example: Brandywine DRMO

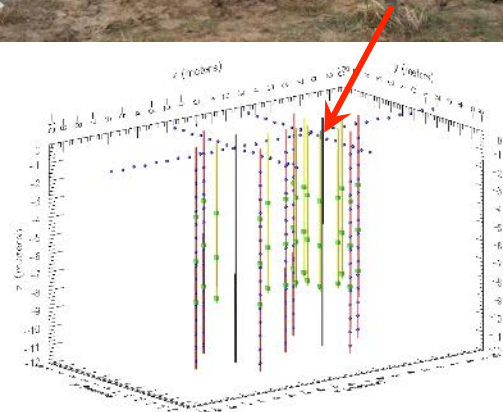
Injections occurred via direct push in March 2008

Recipe

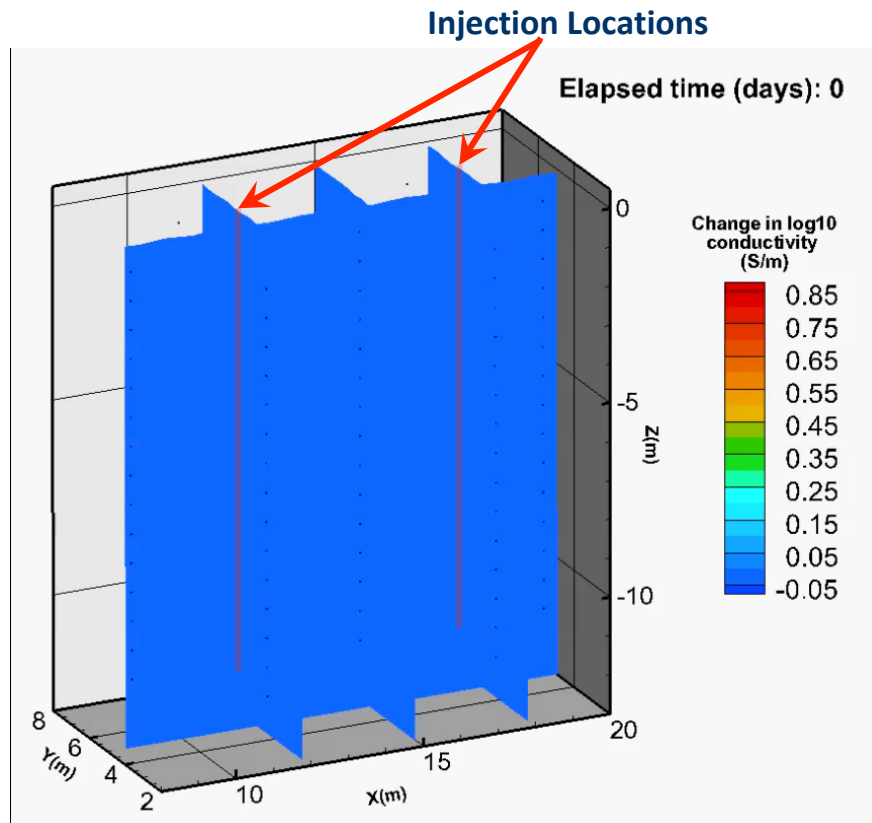
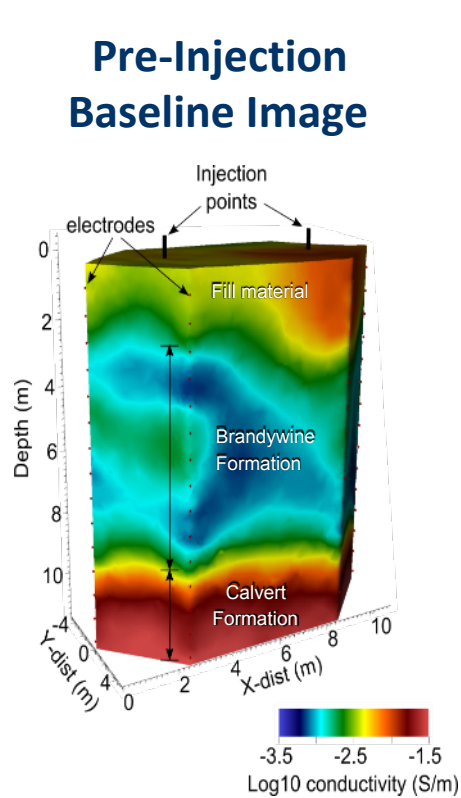
- 250 gallons of ABC (Anaerobic Biochem, mixture of lactates, fatty acids, and phosphate buffer)
- 3,200 gallons of water
- 466 lbs NaHCO_3
- Injectate conductivity 15 mS/cm, pH 8

Procedure

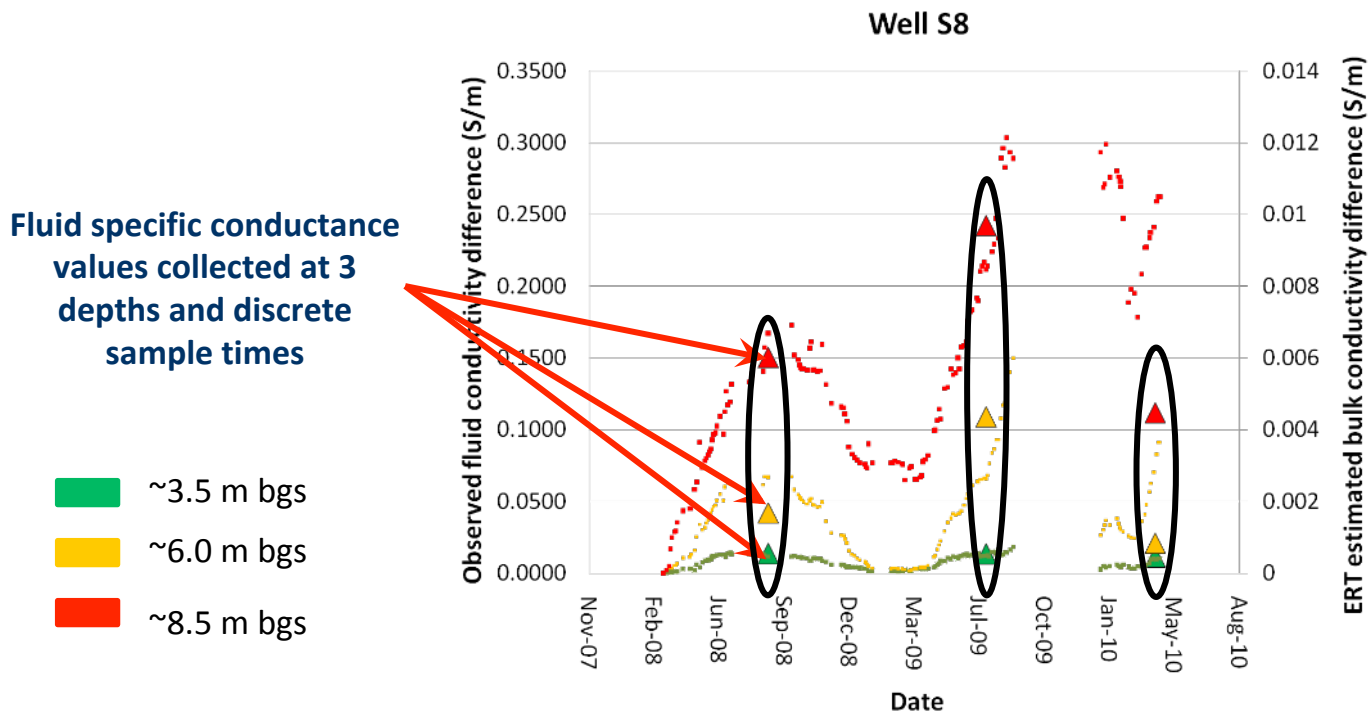
- Direct push injection pipe to 34 feet bgs
- Inject 36 gallons of amendment @ 1 foot intervals
- Total ~ 950 gallons/location



Example: Brandywine DRMO



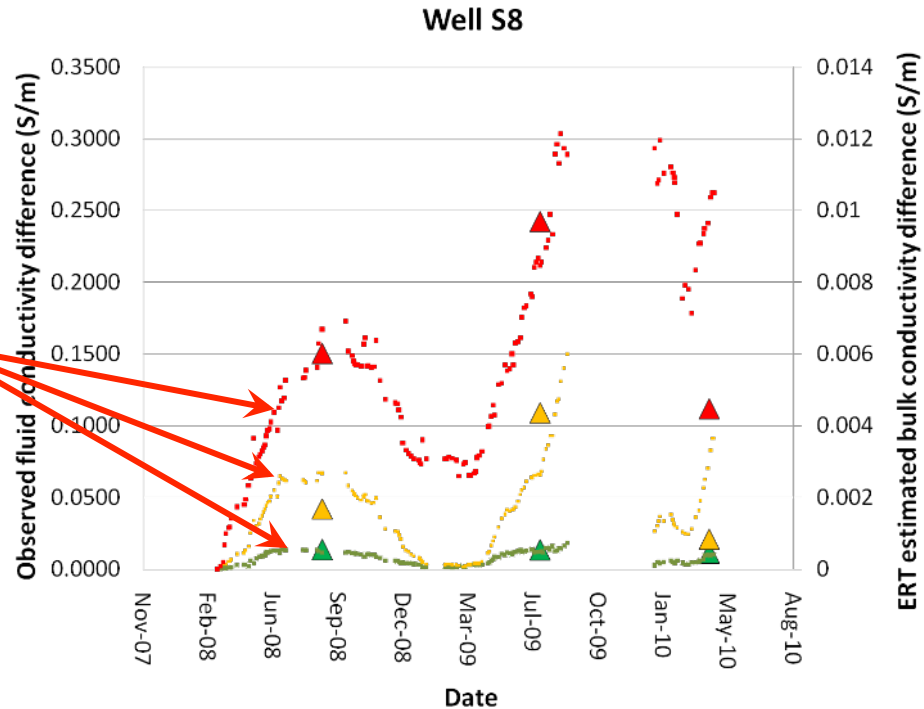
Example: Brandywine DRMO



Example: Brandywine DRMO

Bulk conductivity difference
time-series extracted from ERT
images at sample port
locations

- ~3.5 m bgs
- ~6.0 m bgs
- ~8.5 m bgs



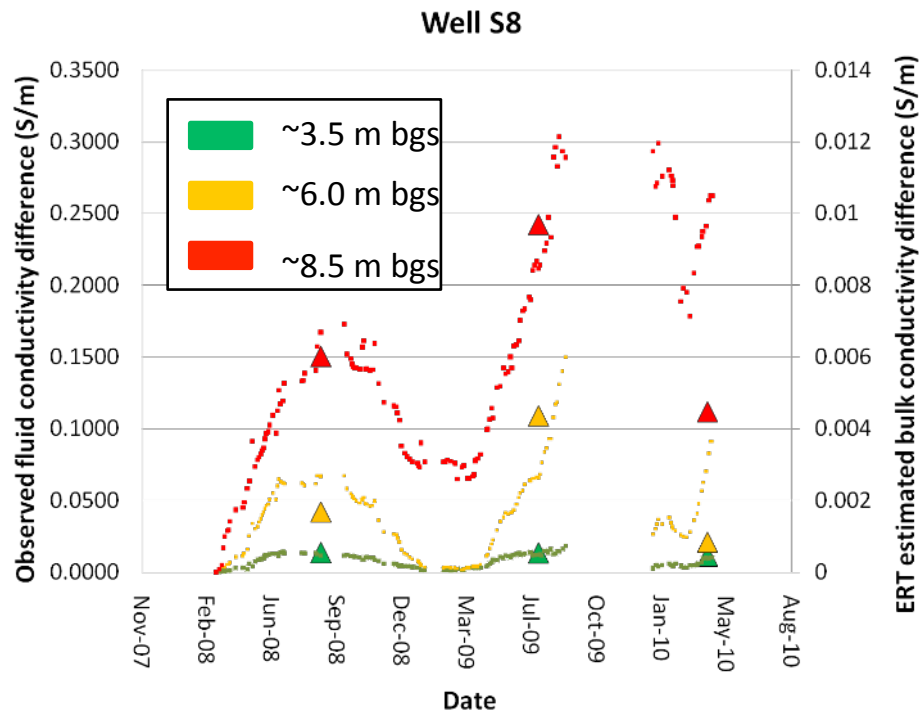
Example: Brandywine DRMO

Evidence

- Changes in bulk conductivity and fluid conductivity are highly correlated for first two sampling events ($R^2 = 0.87$ over all sample ports)
- Last event: increase in bulk conductivity, decrease in fluid conductivity...

Interpretation

- Change in solid phase properties between second and third sampling event
 - a) Increase in porosity?
 - b) Increase in surface area?
 - c) Metallic mineral precipitation?



Example: Brandywine DRMO

Other Evidence Supporting Biomineralization

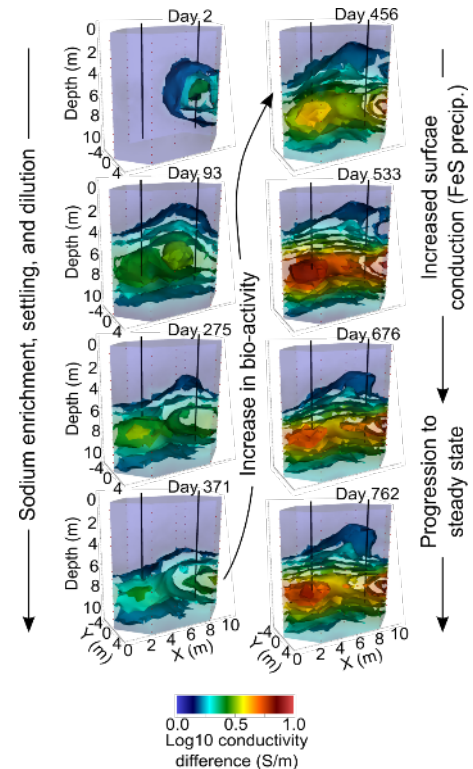
- Contractors note enhanced microbial activity in 5th quarter
- Sulfide precipitation part of reaction sequence
- Black particulate in several April 2010 samples
- Consistent with aqueous chemistry

Primary Implications and Impacts

- Amendment behavior autonomously monitored in 4D
- Solid phase alterations identified through comparison with fluid conductivity samples (simple and inexpensive)
- Demonstrated capability to image biomineralization...important diagnostic indicator for performance evaluation
- What about 'production' application at larger scales?

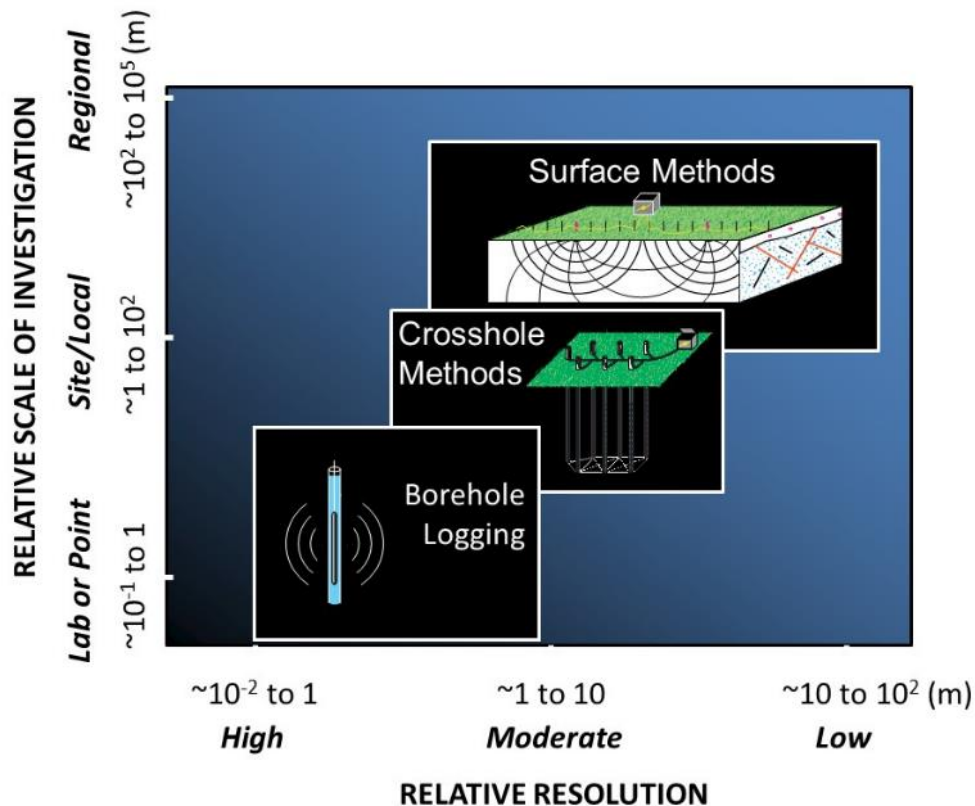
Geophysical outcomes:

- Filling gaps in space and time



Johnson et al., 2015. *Groundwater*.

Scale vs. Resolution Tradeoff



Method Selection

Excel-based tool used to identify methods that:

- Address project goals (e.g., develop CSM vs. develop numerical model)
- Are likely to work at the given site (e.g., based on lithology, infrastructure)

Goal: Provide RPMs and regulators with a tool to help evaluate geophysical proposals and strategies for specific sites.

Caveat: Only a first step and guide!

The screenshot shows an Excel spreadsheet titled "FRGT METHOD SELECTION TOOL". The spreadsheet content includes:

- Header:** "FRGT METHOD SELECTION TOOL" in a blue banner.
- Logos:** USGS (science for a changing world), Rutgers University, and ESTCP (Environmental Security Technology Certification Program).
- Authors:** by F.D. Day-Lewis, C.D. Johnson, L.D. Slater, J.D. Robinson, D. Ntariagiannis, and C. L. Boyden.
- Contact Info:** <http://water.usgs.gov/ogw/baas>
- Last updated:** 02/26/2015
- Program Design:** This program was designed to run in Excel- Microsoft Office 2010.
- SUMMARY:** The Fractured Rock Geophysical Toolbox comprises a suite of geophysical methods for aquifer characterization and monitoring. This spreadsheet-based tool is designed to assist project managers and scientists in selecting tools that (1) satisfy study goals, and (2) are feasible for application at a given site, based on site characteristics as entered by the user.
- INSTALLATION:** Just use this spreadsheet. You may need to reset macro security to include the location of this file as a "trusted site." Go to "Excel Options" under the "Office Button." The spreadsheet is designed for use in Excel 2010 or later.
- INPUT:** The user must enter a site description and study goals using on the FRGT MATRIX worksheet using the numeric up-downs and menus provided.
- OUTPUT:** The spreadsheet will indicate the degree to which methods will be useful for satisfying project goals and which methods are likely feasible given the characteristics of the site.
- DISCLAIMER:** In our experience no one tool or single method achieves all goals when working in fractured-rock aquifers. We encourage a multi-disciplined approach that uses methods that measure different subsurface properties, thereby improving the detection, characterization, and interpretation of the aquifer. This FRGT utility is intended to help select methods and to assess their appropriateness and the potential for success given the goals of your investigation. Results at any one site may vary depending on the actual tools and acquisition settings used. We recommend that when making tool selections you read the manuals or consult the vendors for the range

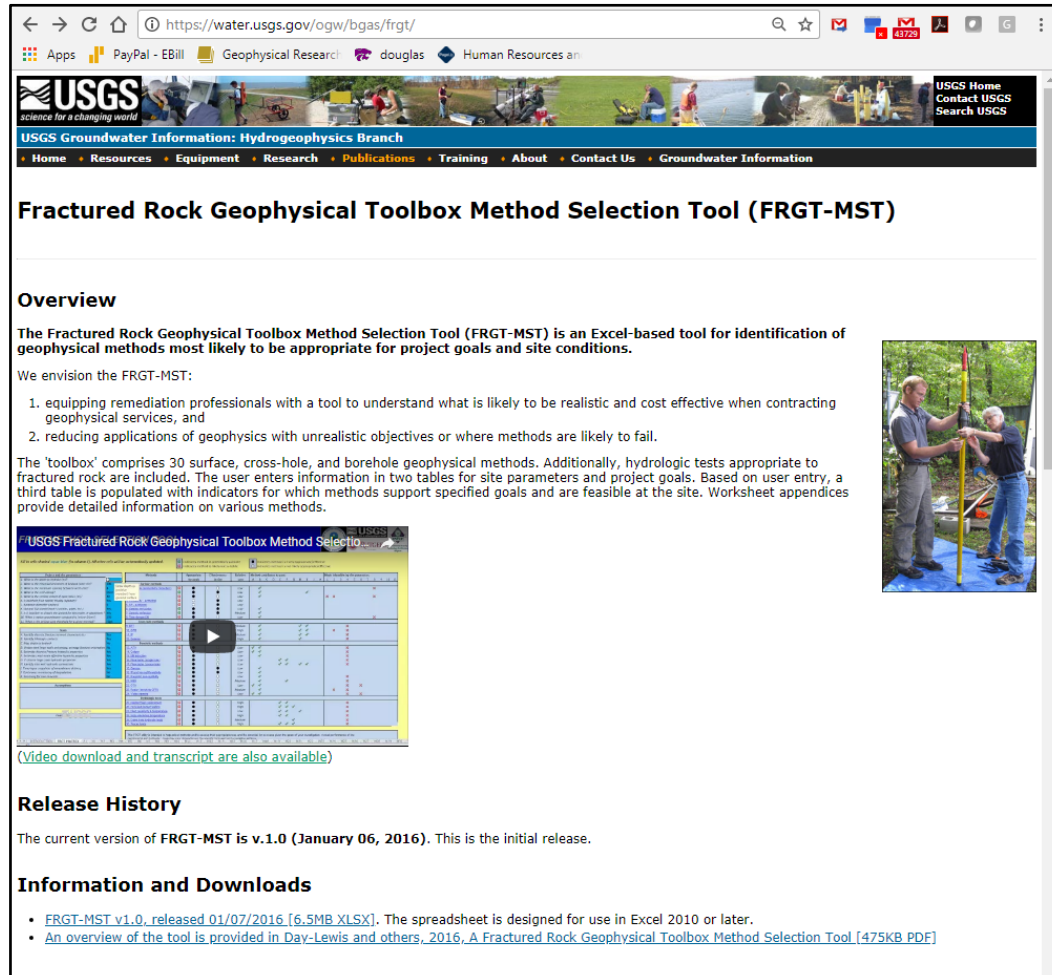
The spreadsheet interface also shows a navigation bar with tabs for "INTRODUCTION", "FRGT MATRIX", and "M1" through "M10". A photograph of a field site with a green tent and equipment is visible on the right side of the spreadsheet.

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.

Funding from ESTCP (ESTCP ER-200118 and ESTCP ER 201567-T2 and from EPA.

Status:

- Served from:
<http://water.usgs.gov/ogw/frgt>
- Training video online at USGS



The screenshot shows a web browser displaying the USGS website for the Fractured Rock Geophysical Toolbox Method Selection Tool (FRGT-MST). The browser address bar shows the URL <https://water.usgs.gov/ogw/bgass/frgt/>. The website header includes the USGS logo and navigation links: Home, Resources, Equipment, Research, Publications, Training, About, Contact Us, and Groundwater Information. The main heading is "Fractured Rock Geophysical Toolbox Method Selection Tool (FRGT-MST)".

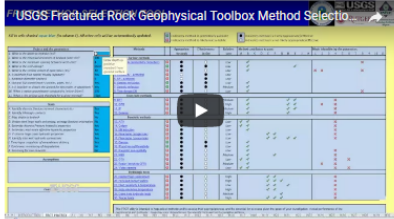
Overview

The Fractured Rock Geophysical Toolbox Method Selection Tool (FRGT-MST) is an Excel-based tool for identification of geophysical methods most likely to be appropriate for project goals and site conditions.


We envision the FRGT-MST:

1. equipping remediation professionals with a tool to understand what is likely to be realistic and cost effective when contracting geophysical services, and
2. reducing applications of geophysics with unrealistic objectives or where methods are likely to fail.

The 'toolbox' comprises 30 surface, cross-hole, and borehole geophysical methods. Additionally, hydrologic tests appropriate to fractured rock are included. The user enters information in two tables for site parameters and project goals. Based on user entry, a third table is populated with indicators for which methods support specified goals and are feasible at the site. Worksheet appendices provide detailed information on various methods.



[\(Video download and transcript are also available\)](#)



Release History


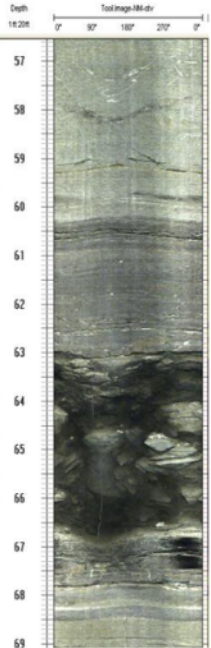
The current version of FRGT-MST is v.1.0 (January 06, 2016). This is the initial release.

Information and Downloads

- [FRGT-MST v1.0, released 01/07/2016 \[6.5MB XLSX\]](#). The spreadsheet is designed for use in Excel 2010 or later.
- [An overview of the tool is provided in Day-Lewis and others, 2016, A Fractured Rock Geophysical Toolbox Method Selection Tool \[475KB PDF\]](#)

FRGT Method Selection Tool

FRGT METHOD SELECTION TOOL	
Fill in cells shaded aqua-blue (in column C). All other cells will be automatically updated.	
● indicates method is appropriate for goals ● indicates method is not appropriate for goals	
Project and site parameters	
1. What is the depth to bedrock (m)?	15
2. What is the electrical resistivity of bedrock (ohm-m)?	100
3. What is the minimum spacing between wells (m)?	4
4. What is the well casing?	Open
5. What is the vertical extent of open holes (m)?	40
6. Is borehole fluid turbid/muddy (opaque)?	Yes
7. Borehole diameter (inches)	6
8. Cultural EM interference? (utilities, pipes, etc.)	Yes
9. Is it possible to disturb the ground for electrodes or geophones?	Yes
10. What is native groundwater conductivity (micro-S/cm)?	150
11. What is the project cost threshold for a given method?	High
Goals	
A. Identify discrete fracture network characteristics	Yes
B. Identify lithologic contacts	Yes
C. Map depth to bedrock	No
D. Understand large-scale anisotropy, average fracture orientations	No
E. Estimate discrete fracture hydraulic properties	Yes
F. Estimate small-scale effective hydraulic properties	Yes
G. Estimate large-scale hydraulic properties	Yes
H. Identify interwell hydraulic connections	Yes
I. Time-lapse snapshots of amendment delivery	Yes
J. Continuous monitoring of degradation	No
K. Screening for iron minerals	No
Assumptions	
Comments	
This FRGT utility is intended to help select methods and to assess geophysical and hydraulic tools may vary depending on the specific	

A	B	C
1	Borehole Method M-22	Return to FRGT Matrix
2	M22. Optical Televiewer (OTV)	
3	Measured: Optical Image	
4	Provides:	
5	<ul style="list-style-type: none"> Oriented optical image Can be used in air- and water-filled boreholes Identify fracture and structural orientation Determine borehole deviation Lithology and structural features of rock Visual contamination 	
6	Details:	
7	<ul style="list-style-type: none"> Log at speeds of up to 4 m/min Log borehole diameters from 3-8in (66-210mm) Hard to see fractures in dark or foliated rocks and can not be used in muddy wells Can see staining associated with water chemistry 	
8	Cost Level: Low	
9	Reference: Williams, J.H., and Johnson, C.D., 2000, Borehole-wall imaging with acoustic and optical televiwers for fractured-bedrock aquifer investigations: Proceedings of the 7th Minerals and Geotechnical Logging Symposium, Golden, Colo., October 24-26, 2000, p. 43-53.	
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Training Video

- <https://water.usgs.gov/ogw/bgas/frgt/>

**You've selected a method
(e.g., resistivity)**

***Where do you (or your
contractor) go from here?***

Polling Question #3

- 3. *What a geophysical methods is capable of seeing is a function of:***
- a. the geophysical technique, i.e., underlying physics of the measurements
 - b. the survey setup, e.g., electrode placement, distance between boreholes, etc.
 - c. noise/errors
 - d. the site-specific geology
 - e. all of the above

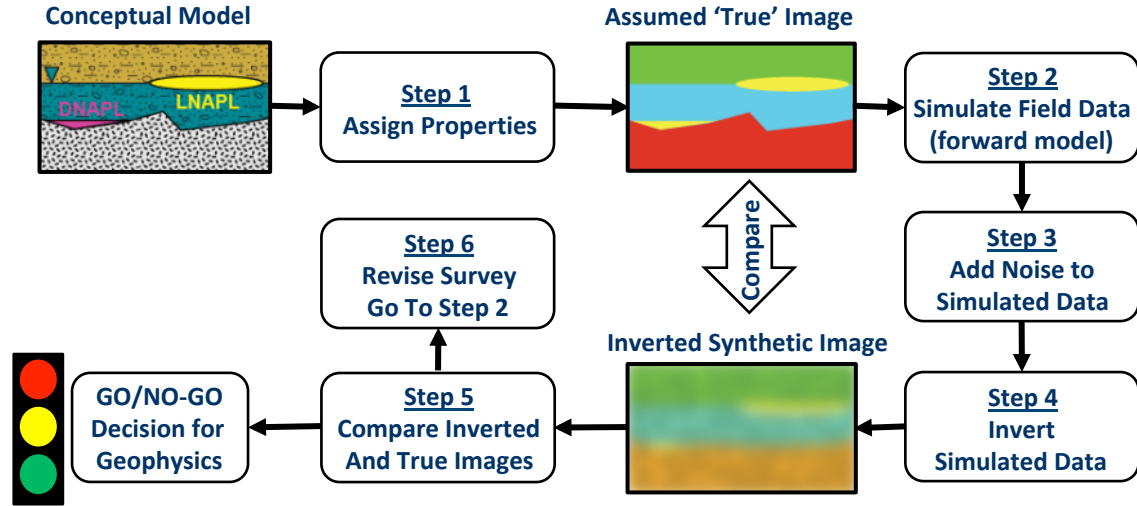
Desktop Feasibility Assessment

Risks:

- Will the method work under site-specific conditions with resolution needed to 'see' targets?
- How can we understand what's real vs. what's artifact?
- Which regions of the images are reliable vs. poorly resolved?

Strategies to mitigate risk:

- Pre-modeling **feasibility assessment** before going to the field
- 'Synthetic' modeling & image appraisal to aid interpretation



[after Day-Lewis, F.D., Slater, L.D, Johnson, C.D., Terry, N., and Werkema, D., 2017, An overview of geophysical technologies appropriate for characterization and monitoring at fractured-rock sites, *Journal of Environmental Management*, <http://dx.doi.org/10.1016/j.jenvman.2017.04.033>]

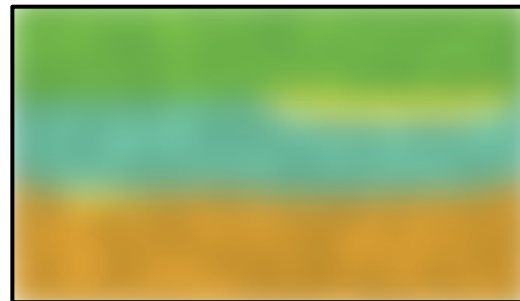


Realistic expectations

'Pre-modeling':

- Predict what you will 'see' based on one or more conceptual models, survey designs, and noise levels
- Pre-modeling can be performed using many COTS and public-domain geophysical software:
 - Rigorous numerical models
 - Simpler approximate tools (Resolution matrix)
- Forms the basis for
 - Survey design
 - go/no-go decision
 - Interpretation
- COMMONLY NOT EXPENSIVE OR BURDENSOME

Conceptual Model



Can we reliably 'see' or detect:

- LNAPL?
- DNAPL?
- Geology

If not, can we change our survey to do so?

Excel-based Pre-Modeling

Spreadsheet Functionality:

- ❑ Simple, user-friendly, requires no proprietary software
- ❑ Predict survey outcomes for **LIMITED** hypothetical target and measurement scenarios
- ❑ 3 template targets included in the spreadsheet can be modified by the user:
 - ❑ DNAPL plume
 - ❑ LNAPL plume
 - ❑ Blocks
 - ❑ Underground storage tank (UST)
- ❑ USGS web site :

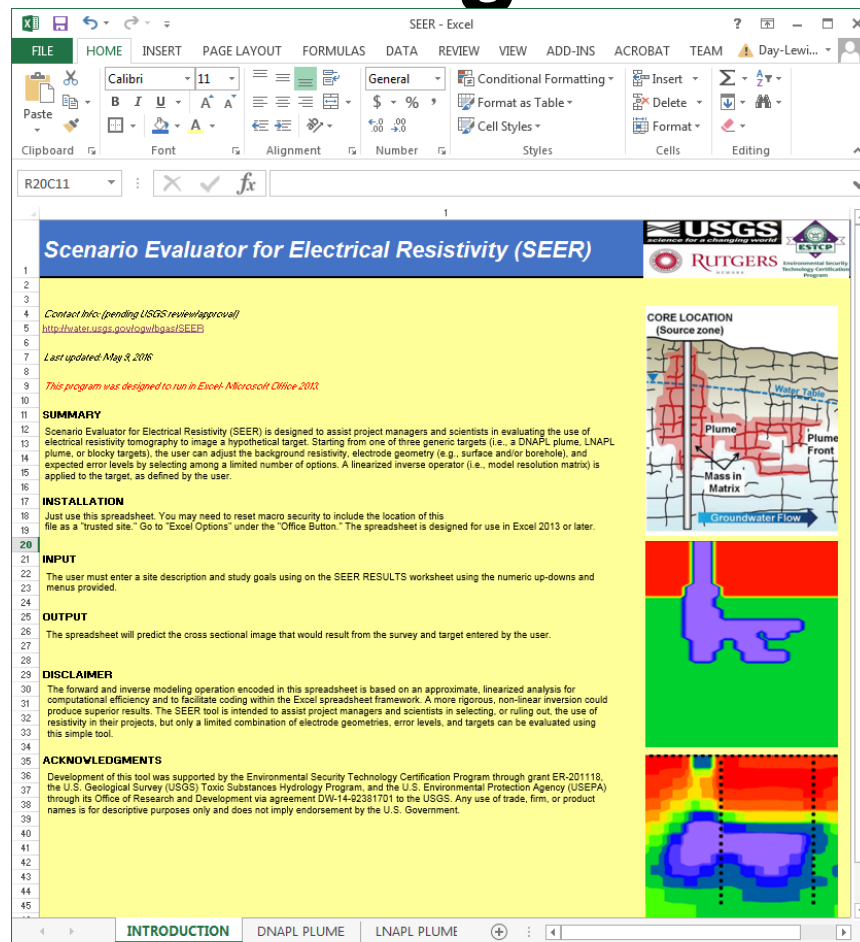
<https://water.usgs.gov/ogw/bgas/seer/>

Groundwater

Methods Note/

Scenario Evaluator for Electrical Resistivity Survey Pre-modeling Tool

by Neil Terry¹, Frederick D. Day-Lewis², Judith L. Robinson¹, Lee D. Slater³, Keith Halfon⁴, Andrew Binley⁵, John W. Lane Jr.⁶, and Dale Workman⁶



Training Video

- <https://water.usgs.gov/ogw/bgas/seer/>

SEER –How it works

Non-linear numerical methods are used in the inversion modeling, which takes expertise and time to process

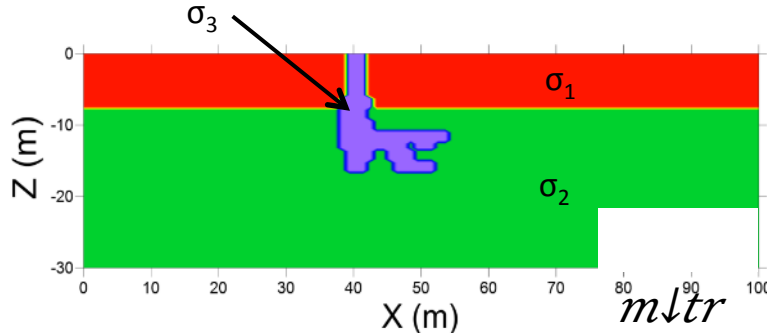
$$(J^T \downarrow k W^T \downarrow d W \downarrow d J \downarrow k + \alpha W^T \downarrow m W \downarrow m) \Delta m \downarrow k =$$



Numerical approach to solve for model, m

Using pre-calculated R , we can approximate the inverted model, m , with

$$m = R(m \downarrow k - m \downarrow ref)$$

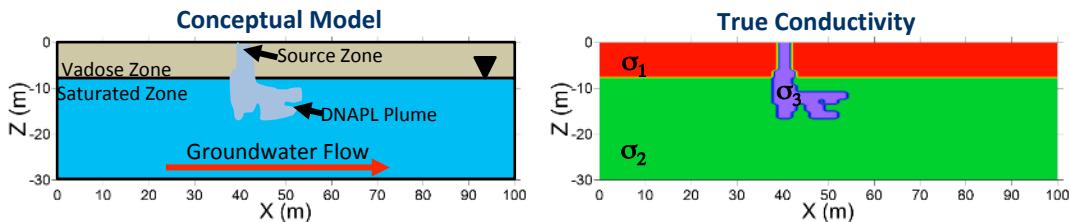


R : pre-calculated based on:

- Spacing and location of electrodes
- Number of electrodes
- Noise level
- Assumed model complexity

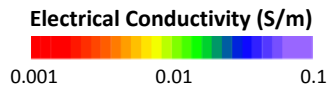
Example Feasibility Assessment: Imaging a DNAPL Plume

Step 1 Assign Electrical Conductivity



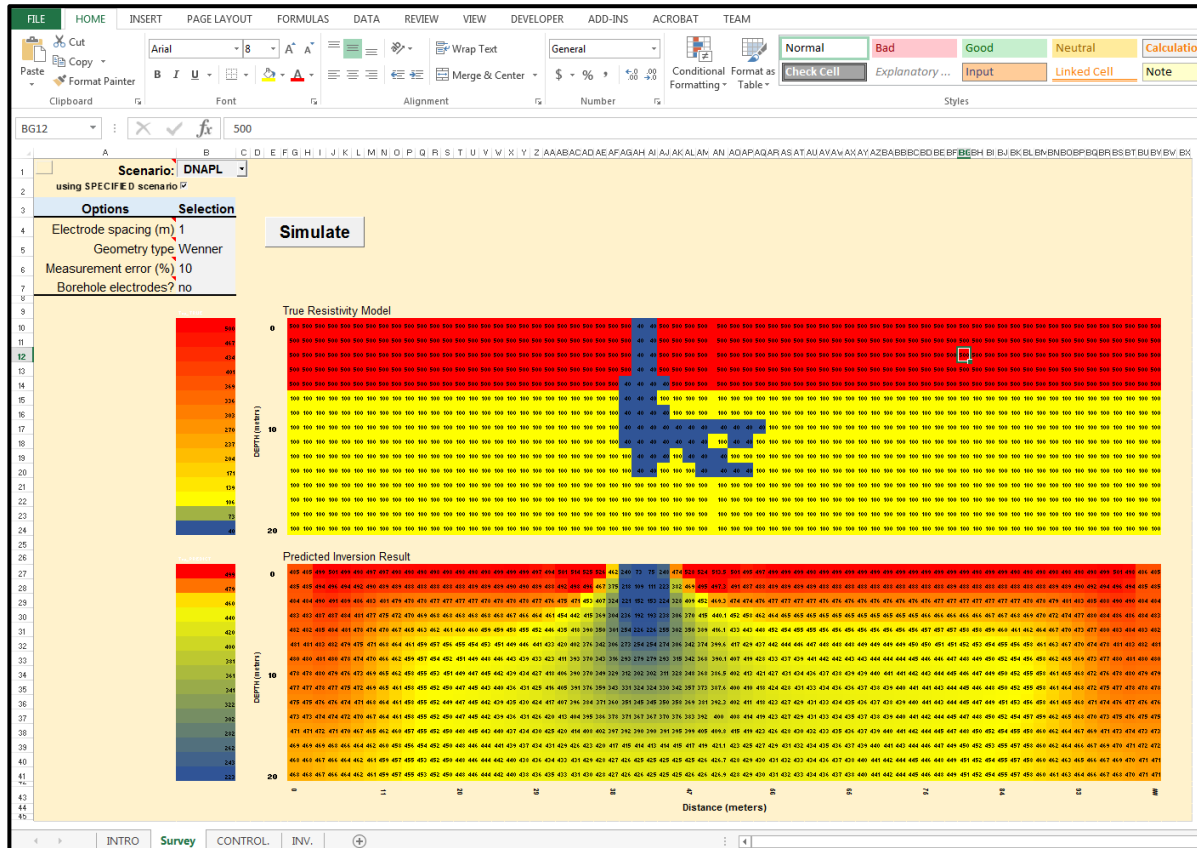
True conductivity estimated from

- Estimated saturation
- Estimated porosity
- Estimated native and DNAPL fluid conductivity

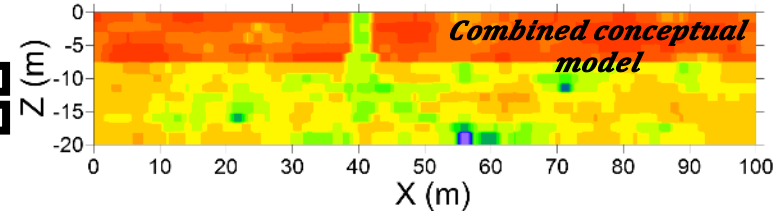
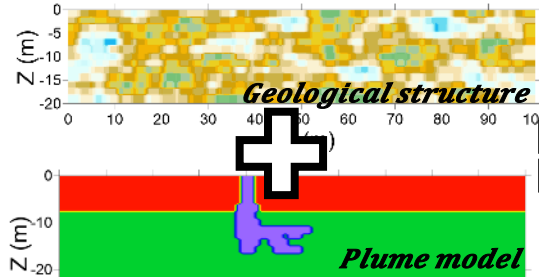


after Terry, N., Day-Lewis, F.D., Robinson, J., Slater, L.D., Halford, K., Binley, A., Lane, J.W., Werkema, D., 2017, *The Scenario Evaluator for Electrical Resistivity (SEER) Survey Design Tool, Groundwater*

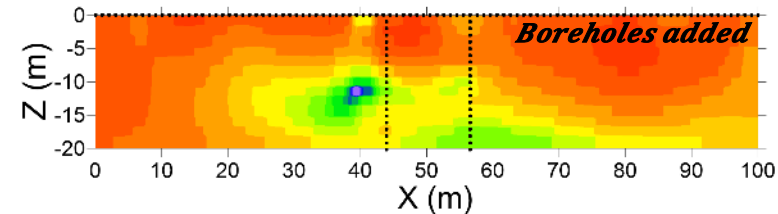
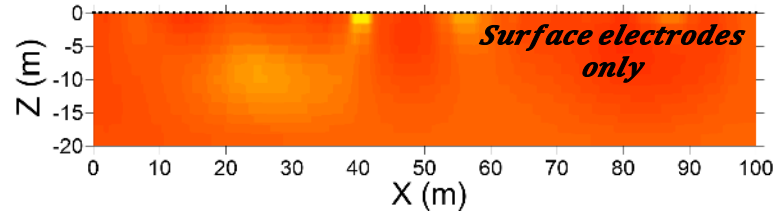
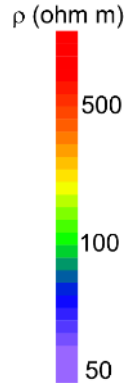
Example Feasibility Assessment: Imaging a DNAPL Plume (cont.)



What if the Aquifer is Heterogeneous



<https://water.usgs.gov/ogw/bgas/seer/>

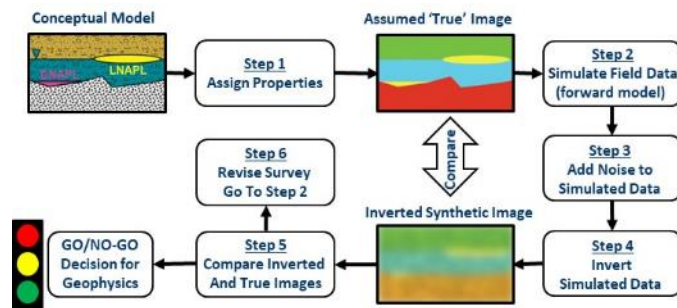


Summary

- Method selection: Identifying methods to achieve study objectives under site-specific constraints
 - Multiple methods commonly the way to go
 - FRGT-MST useful for this
- Pre modeling: Before going to the field, conduct a desktop feasibility assessment
 - Can the target(s) be resolved given site conditions, method limitations, reasonable survey geometry, etc.?
 - SEER useful for resistivity

FRGT METHOD SELECTION TOOL

Objective	Method	Resolution	Accuracy	Depth	Method constraints	Field of view
1. Determine the location and extent of the target(s)	1.1. DC resistivity	●	●	●	●	●
	1.2. Induced polarization	●	●	●	●	●
	1.3. Magnetotellurics	●	●	●	●	●
	1.4. Seismicity	●	●	●	●	●
2. Determine the lithology and geology of the target(s)	2.1. DC resistivity	●	●	●	●	●
	2.2. Induced polarization	●	●	●	●	●
	2.3. Magnetotellurics	●	●	●	●	●
	2.4. Seismicity	●	●	●	●	●
3. Determine the depth of the target(s)	3.1. DC resistivity	●	●	●	●	●
	3.2. Induced polarization	●	●	●	●	●
	3.3. Magnetotellurics	●	●	●	●	●
	3.4. Seismicity	●	●	●	●	●



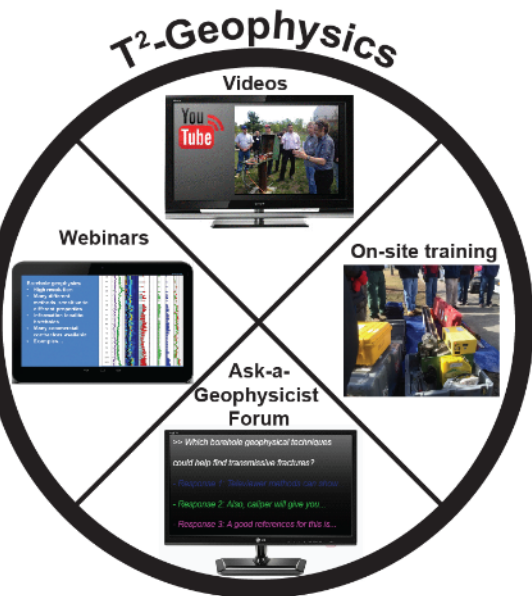
Polling Question #4

4. Which would you be most interested in?

- a. Groundwater/Surface-Water Method Selection Tool
- b. more tools like SEER, for other geophysical methods
- c. a geophysical best-practices document with case studies and sample data
- d. more online training videos

Resources

- <https://water.usgs.gov/ogw/bgag/frgt/>
- <https://water.usgs.gov/ogw/bgag/seer/>
- <https://www.enviro.wiki>
- <http://askageophysicist.net/>



USGS Fractured Rock Geology

USGS Scenario Evaluator

Scenario Evaluator for Electrical Resistivity (SEER) Survey Process

USGS Fractured Rock Geology Toolbox Method Selection Tool

USGS Fractured Rock Geology Toolbox Method Selection Tool

Journal of Environmental Management

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Research article

An overview of geophysical technologies appropriate for characterization and monitoring at fractured-rock sites

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ARTICLE INFO

ABSTRACT

Geophysical methods are used increasingly for characterization and monitoring at remediation sites in fractured-rock aquifers. The complex heterogeneity of fractured rock poses numerous challenges to groundwater remediation professionals, and new methods are needed to cost-effectively detect fracture and fracture-zone locations, orientations, and properties, and to develop conceptual site models for flow and transport. Despite the potential of geophysical methods for "seeing" rockbodies, they have been impeded by the adoption of geophysical methods by remediation professionals. This geophysical results are commonly only indirectly related to the properties of interest (e.g., permeability). In remediation professionals, and qualitative interpretations is required to convert geophysical results to hydrogeologic information. Additional direct-measurement projects are needed in the site remediation literature to fully realize geophysical methods from research to practice. Second, geophysical methods are commonly viewed as inherently risky by remediation professionals, although it is widely understood that a given method may or may not work at a particular site; the reasons are not always clear to end users of geophysical products. Synthetic modeling tools are used to research to assess the potential of a particular method to successfully image a target, but these tools are not widely used in industry. Here, we seek to advance the application of geophysical methods to solve problems facing remediation professionals, with respect to fractured rock aquifers. To this end, we: (1) provide an overview of geophysical methods applied to characterization and monitoring of fractured rock aquifers; (2) review case studies showcasing effective geophysical methods; and (3) discuss best practices for method selection and rejection based on synthetic modeling and decision support tools.

Published by Elsevier Ltd.

1. Introduction

The characterization of fractured rock aquifers and monitoring of hydrogeologic conditions within them remains a major challenge facing hydrologists and groundwater remediation professionals. The large variations in hydrologic properties over short distances in fractured rock result in preferential pathways for fluid flow and, to an even greater degree, for chemical transport - reduction relative to non-aggregates (non-aquifers). Fracture-related, channelized transport (Sang and Zhang, 1990) poses enormous challenges to the characterization and groundwater remediation.

Traditional in-situ "point scale" sampling of fractured rock properties (e.g. permeability) and conditions (e.g. contaminant concentrations) remains primarily based on invasive drilling approaches, the recovery of samples (e.g. cores, fluids) and the installation of field sampling apparatus for monitoring. Such approaches have particular high material and labor costs in arid and hard-rock systems, usually leading to interpretations based on relatively few observations over large areas. Point-scale measurements are also of limited utility, as it is widely recognized that hydrogeologic processes and properties are scale-dependent (e.g. Schmalzer et al., 1995), particularly in fractured rock. An environmental remediation site of limited size may not be accurately limited, for example, due to heterogeneity caused by existing infrastructure, the hazardous nature of the groundwater conditions, and/or the potential for drilling to enhance contaminant transport pathways.

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<http://dx.doi.org/10.1016/j.jenvman.2010.03.010>

0924-6460/\$ - see front matter © 2010 Elsevier Ltd.