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.

U.S. Department of the Interior
U.S. Geological Survey

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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'

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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

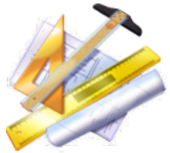
b. Different methods have different strengths and weaknesses

c. Not every method works at every site

d. all of the above

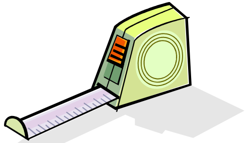
The Geophysical Toolbox

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

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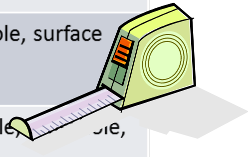
Abraham Maslow(1966), "I suppose it is tempting, if the only tool you have is a hammer, to treat everything as if it were a nail"

[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

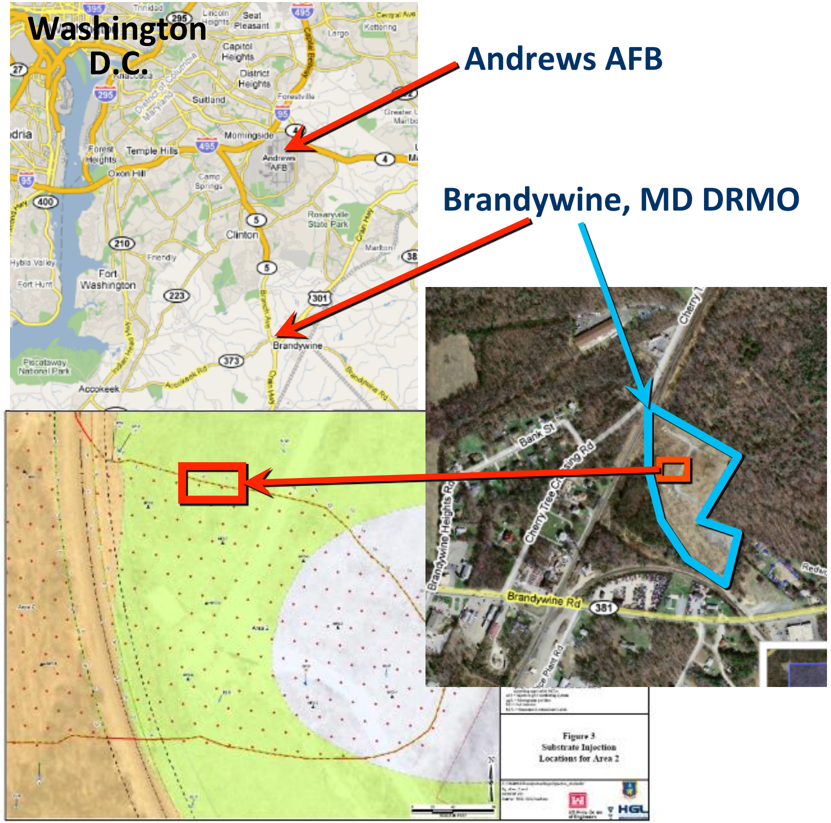



Example: Brandywine DRMO

Background

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

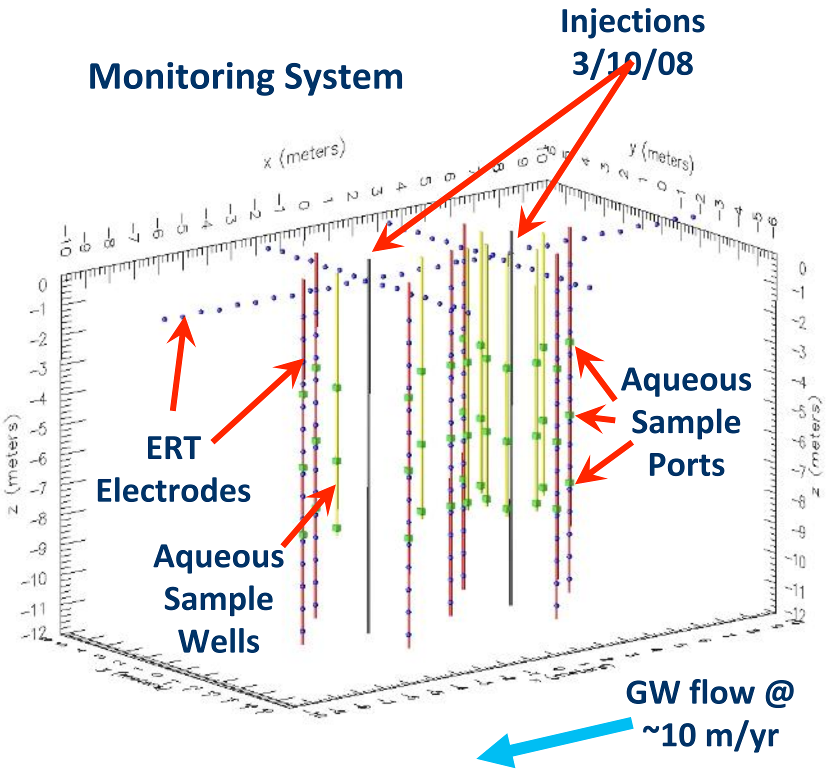
- TCE-contaminated groundwater
- Upper 12 m unconfined aquifer
- Spreading to residential neighborhood
- ROD – Enhanced bioremediation
- Amendment injections ~20 ft spacing (~1,000)
- ESTCP Dem/Val effort to monitor two injection points at boundary of treatment area



Johnson et al., 2015, Groundwater

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

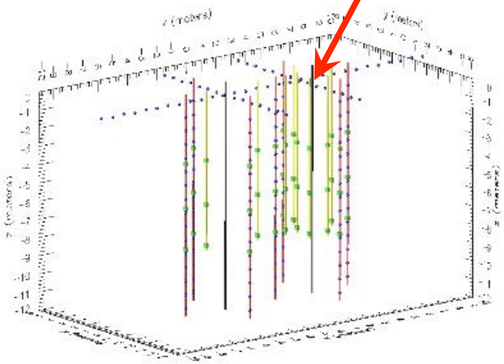


Example: Brandywine DRMO

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

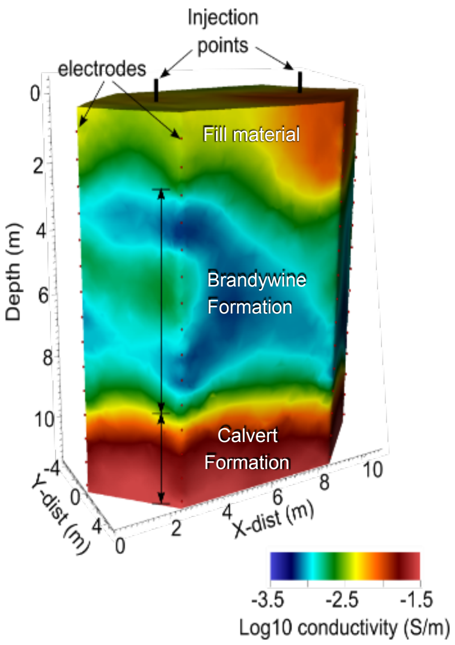


Procedure

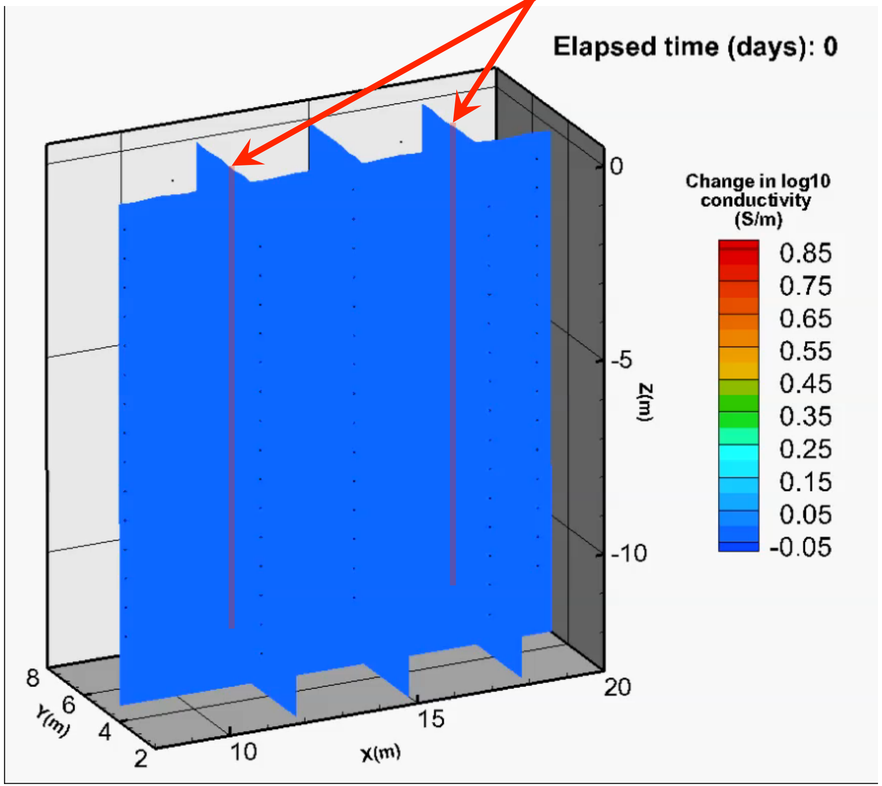
- Direct push injection pipe to 34 feet bgs
- Inject 36 gallons of amendment @ 1 foot intervals
- Total ~ 950 gallons/location

Example: Brandywine DRMO

Pre-Injection Baseline Image



Injection Locations



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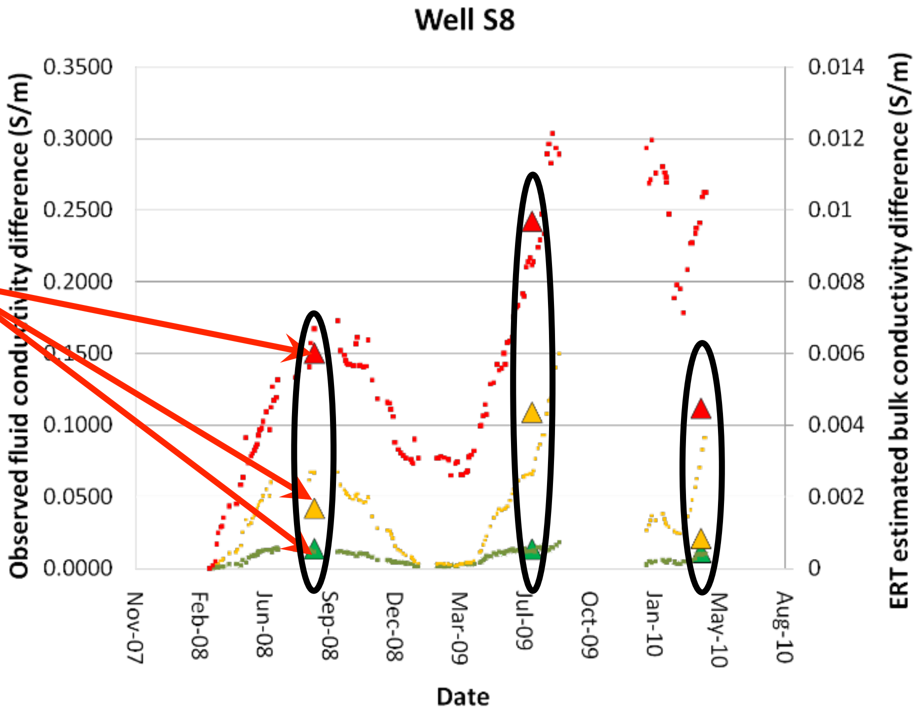
Case Studies

Example: Brandywine DRMO

Fluid specific conductance values collected at 3 depths and discrete sample times



~3.5 m bgs

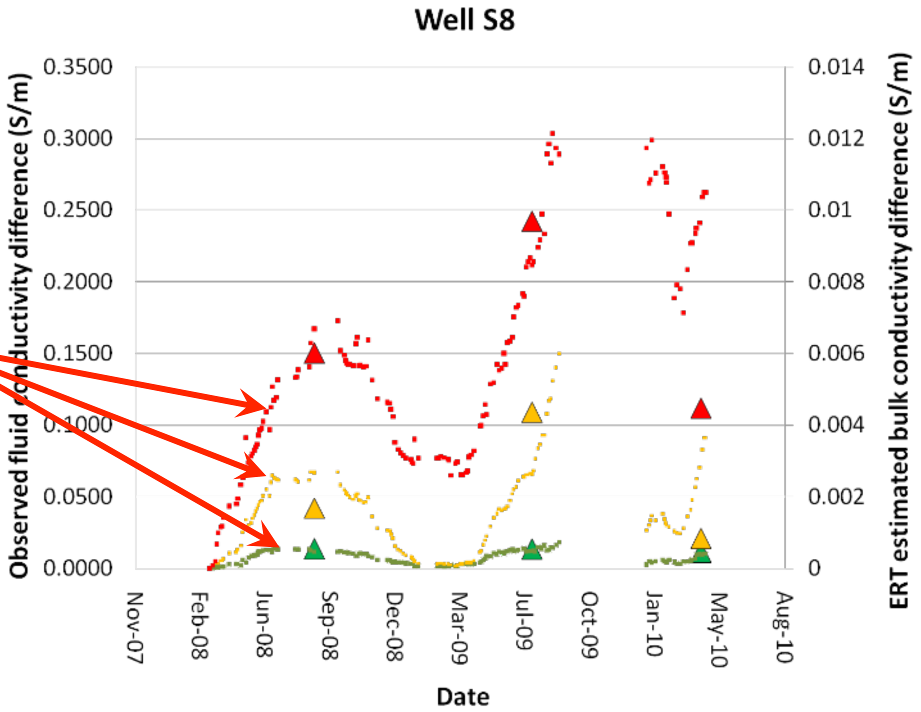
~6.0 m bgs

~8.5 m bgs

Case Studies

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

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Case Studies

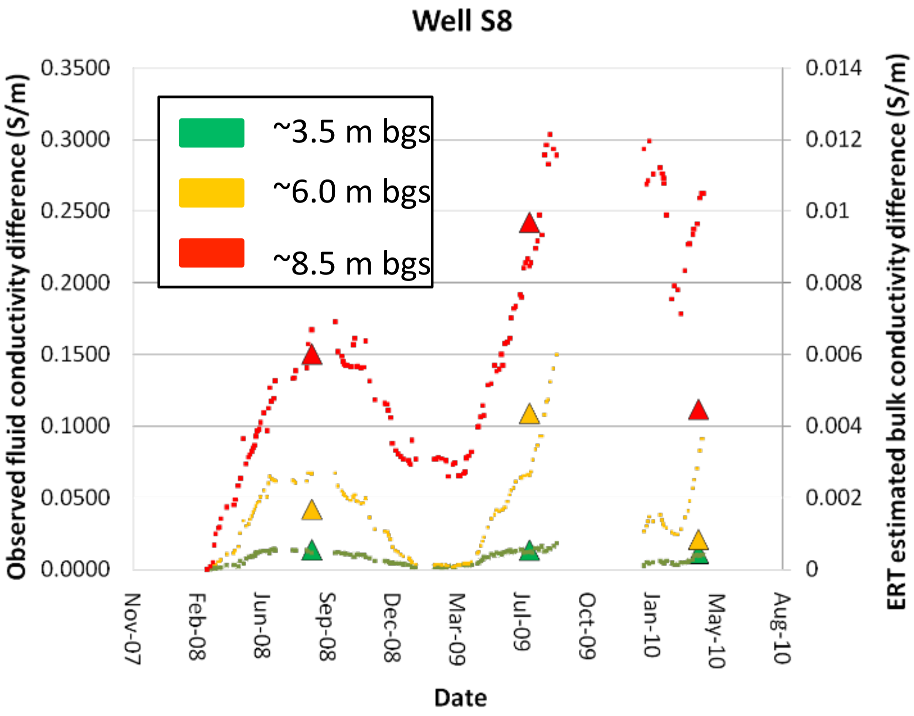
Example: Brandywine DRMO

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?



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Case Studies

Example: Brandywine DRMO

Other Evidence Supporting Biomineralization

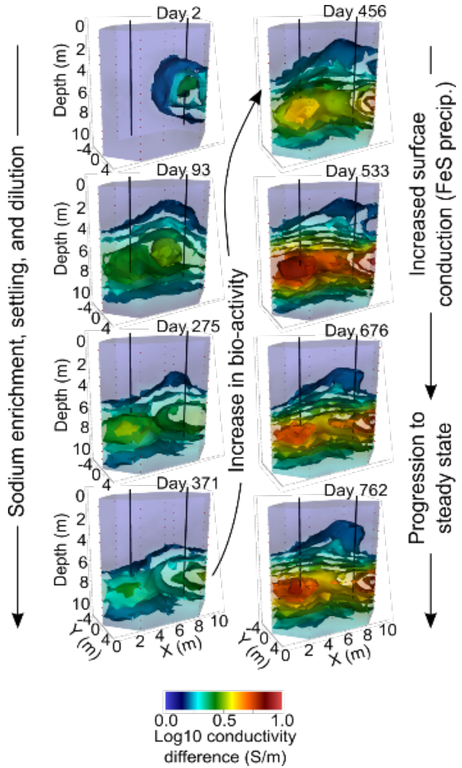
- Contractors note enhanced microbial activity in 5th quarter
- Sulfide precipitation part of reaction sequence
- Black particulate in several April 2010 samples
- Consistent with aqueous chemistry

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*.

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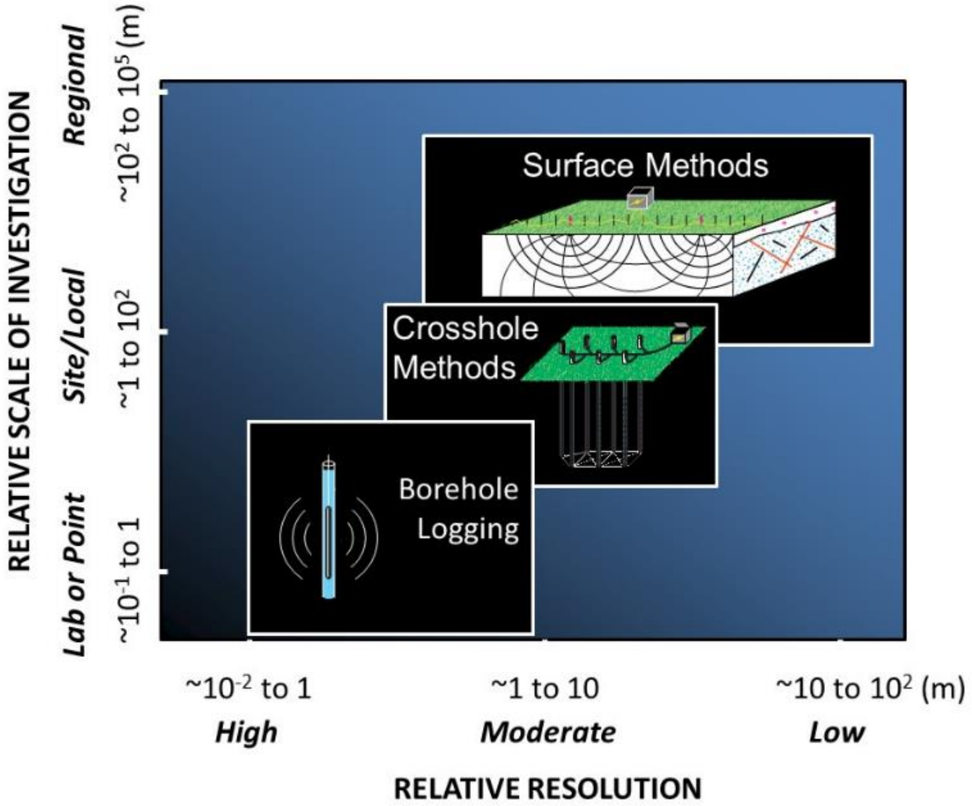
Case Studies

Scale vs. Resolution Tradeoff



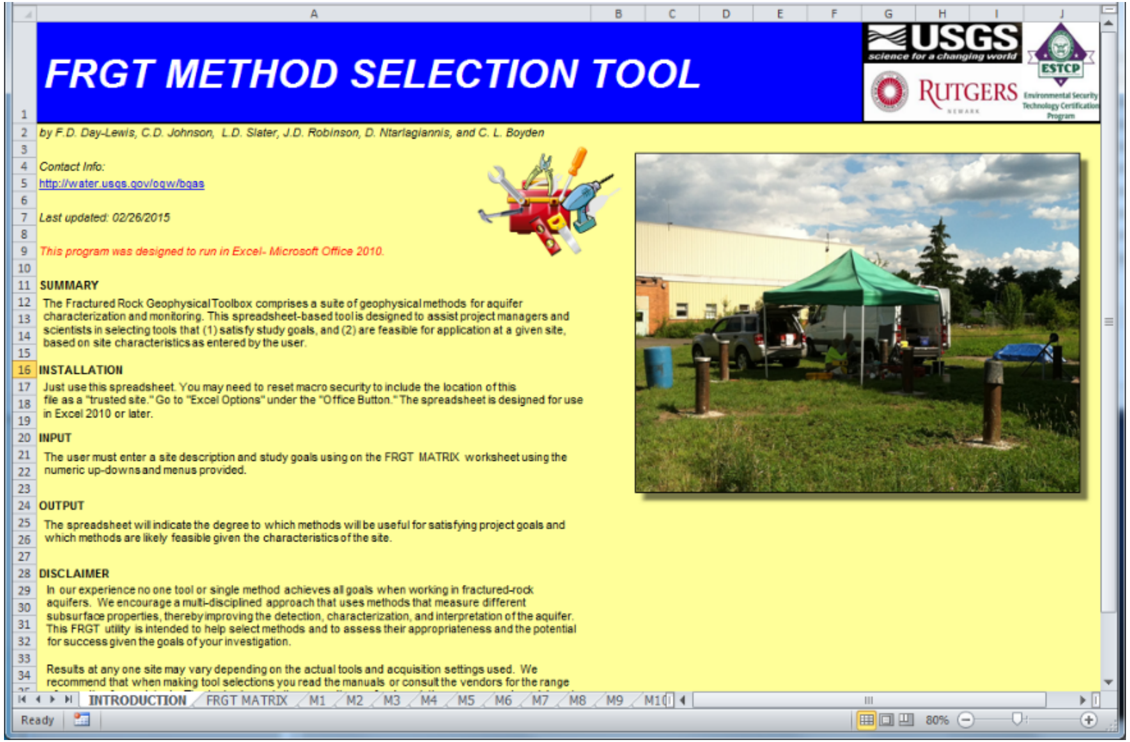
Method Selection

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!



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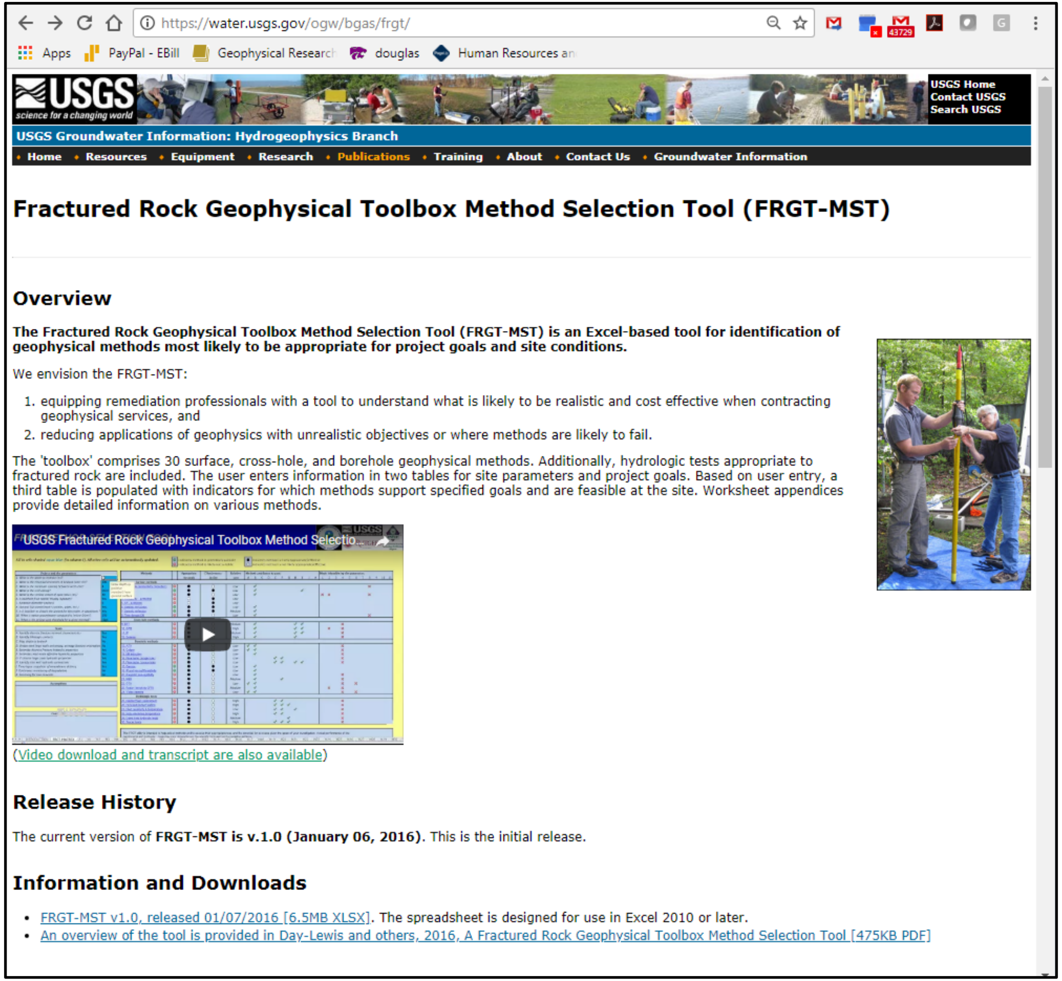
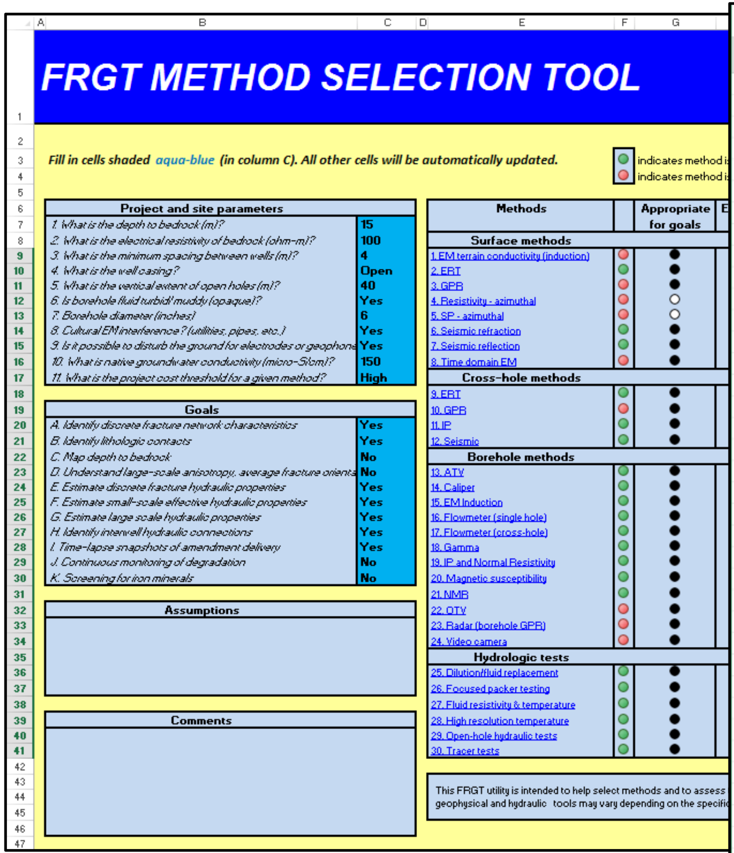
Funding from ESTCP (ESTCP ER-200118 and ESTCP ER 201567-T2 and from EPA.

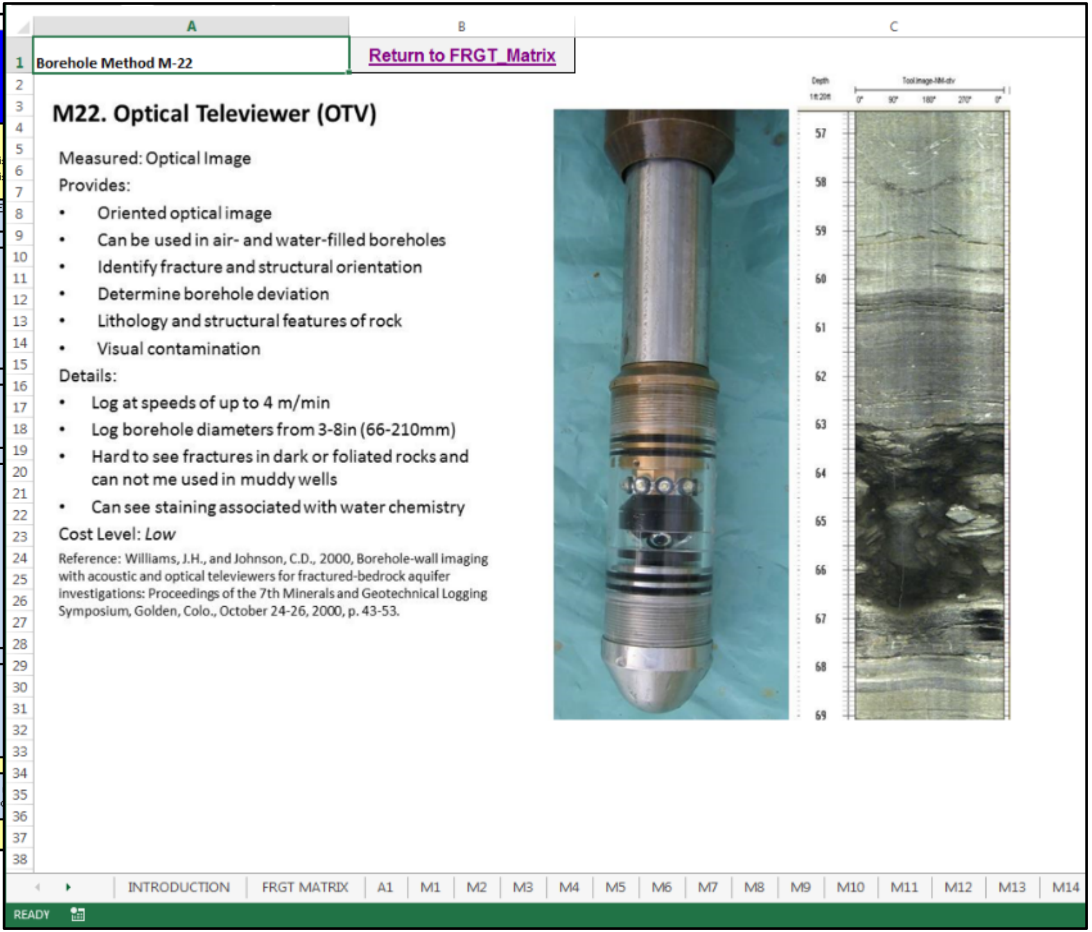
Status:

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



FRGT Method Selection Tool





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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?

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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

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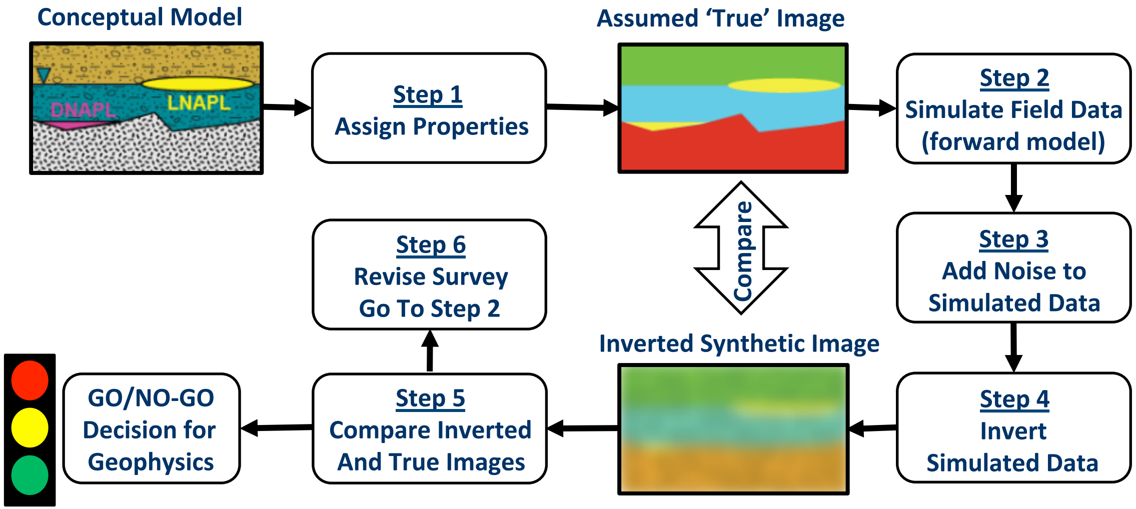
Desktop Feasibility Assessment

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



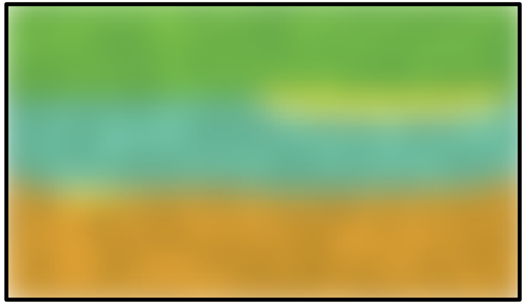
[after *Day-Lewis, F.D., Slater, L.D, Johnson, C.D., Terry, N., and Werkema, D., 2017, An overview of geophysical technologies appropriate for characterization and monitoring at fractured-rock sites, Journal of Environmental Management, http://dx.doi.org/10.1016/j.jenvman.2017.04.033*]

Realistic expectations

<u>‘Pre-modeling’:</u>

- 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?

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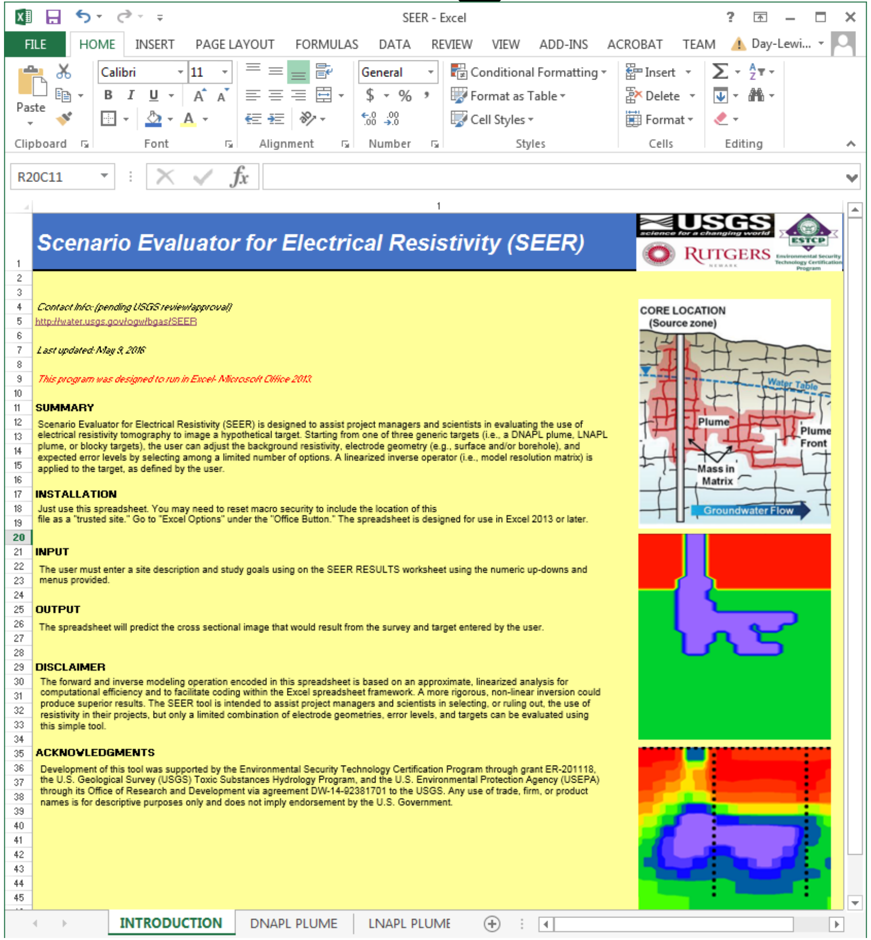
Excel-based Pre-Modeling

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 Terry[1], Frederick D. Day-Lewis[1], Judith L. Robinson[1], Lee D. Slater[1], Keith Halford[4], Andrew Binley[5], John W. Lane Jr[1], and Dale Werkema[6]

Training Video

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

SEER –How it works

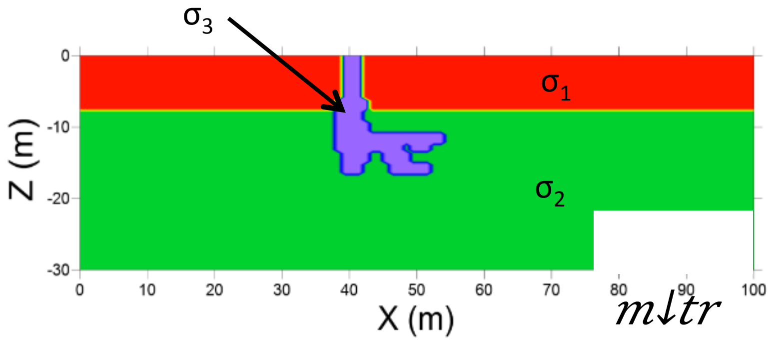
Non-linear numerical methods are used in the inversion modeling, which takes expertise and time to process

$$\left(J_k^T W_d^T W_d J_k + \alpha W_m^T W_m\right)\Delta m_k = J_k^T W_d^T W_d\left[d - f(m_k)\right] - \alpha W_m^T W_m\left(\boldsymbol{m_k} - m_{ref}\right)$$

Numerical approach to solve for model, m

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

$$m = R m_{true}$$



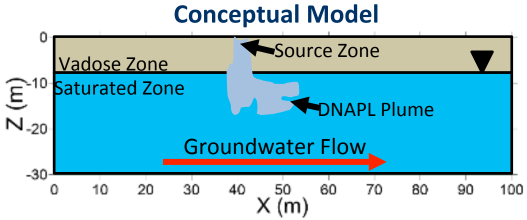
m_{true}

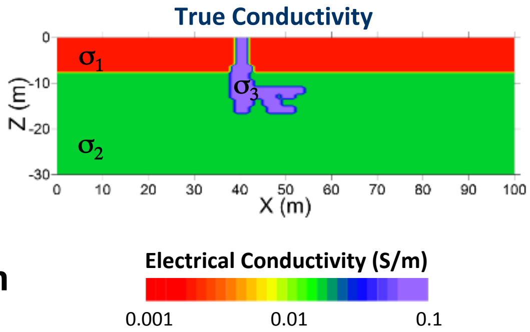
R: pre-calculated based on:

- 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*

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

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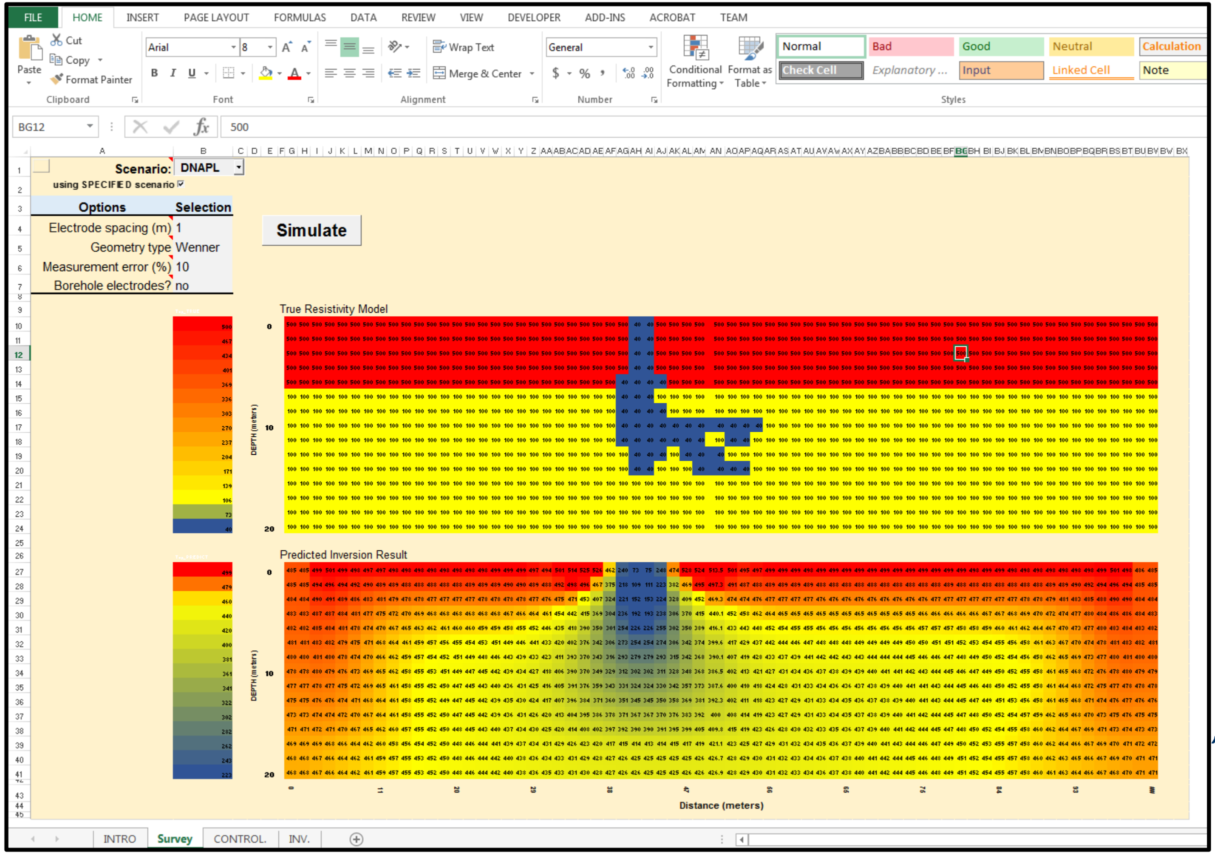
Example Feasibility Assessment: Imaging a DNAPL Plume (cont.)



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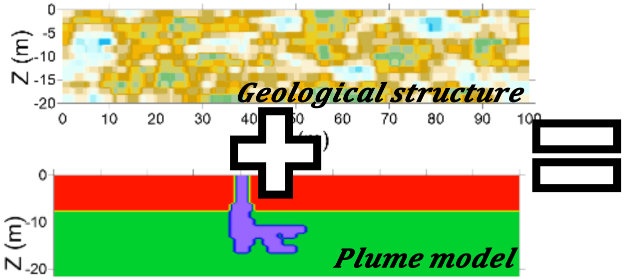
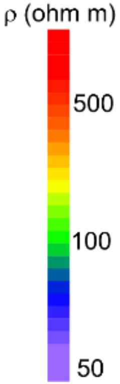
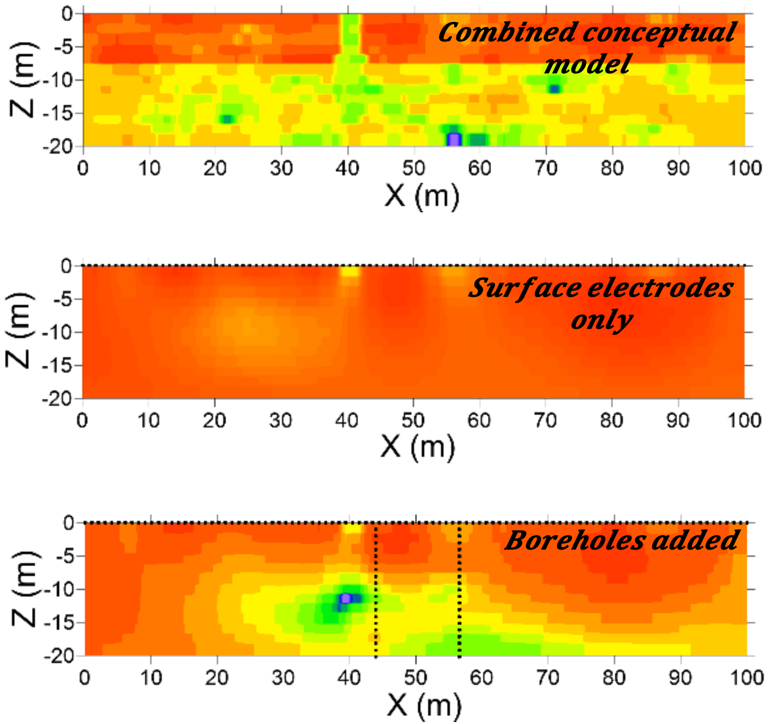
What if the Aquifer is Heterogeneous





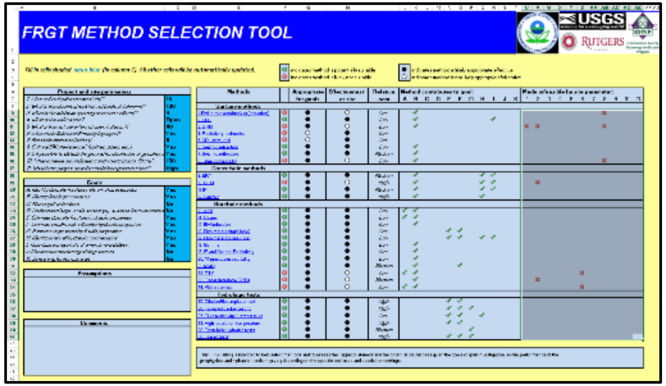


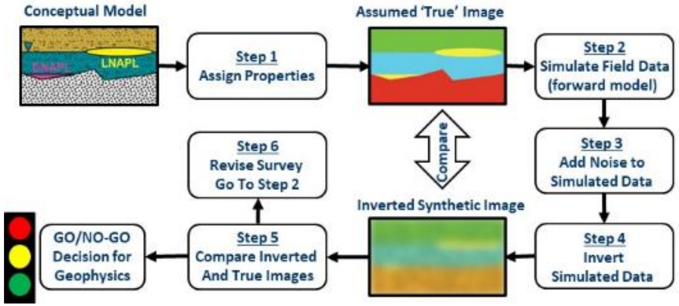
SEER

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





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