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Geophysical method selections, investigations, and translation for characterization and monitoring goals

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2023 Global Summit on Environmental Remediation
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U.S. DEPARTMENT OF ENERGY BATTELLE

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Outline

- The Geophysical Toolbox
- Scale vs. Resolution Tradeoff
- Characterization vs. Monitoring
- Method Selection
- Desktop Feasibility Assessment
- Recent Advances
    - ERT
    - Mobile EM surveying
- Summary

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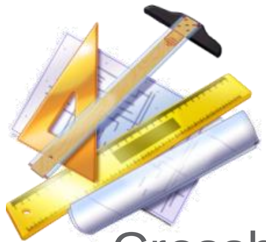
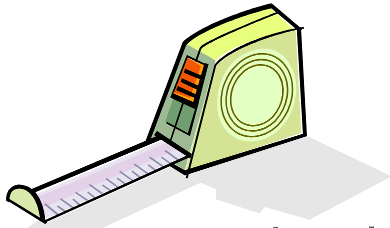
The Hydrogeophysical Toolbox

Borehole geophysics (high resolution, near-hole information)



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

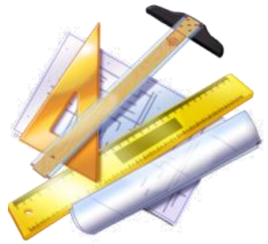
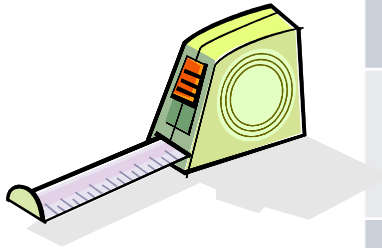
Surface geophysics (large areas, inexpensive)



Conventional hydrologic measurements (calibration and groundtruth)

NO SINGLE TOOL CAN WORK FOR EVERY PROBLEM/SITE

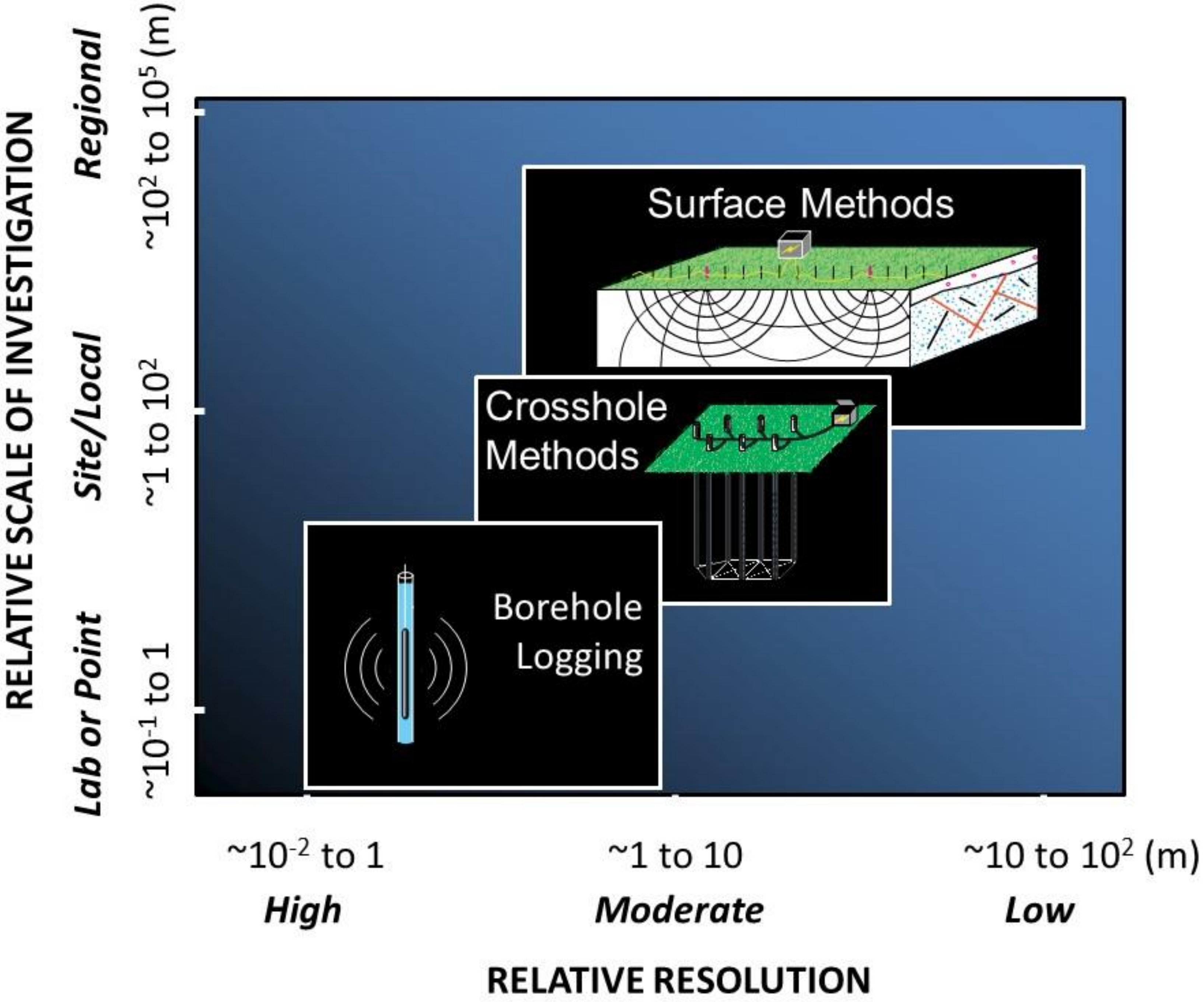
SYNERGY BETWEEN METHODS – JOINT INTERPRETATION

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

[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]

Scale vs. Resolution



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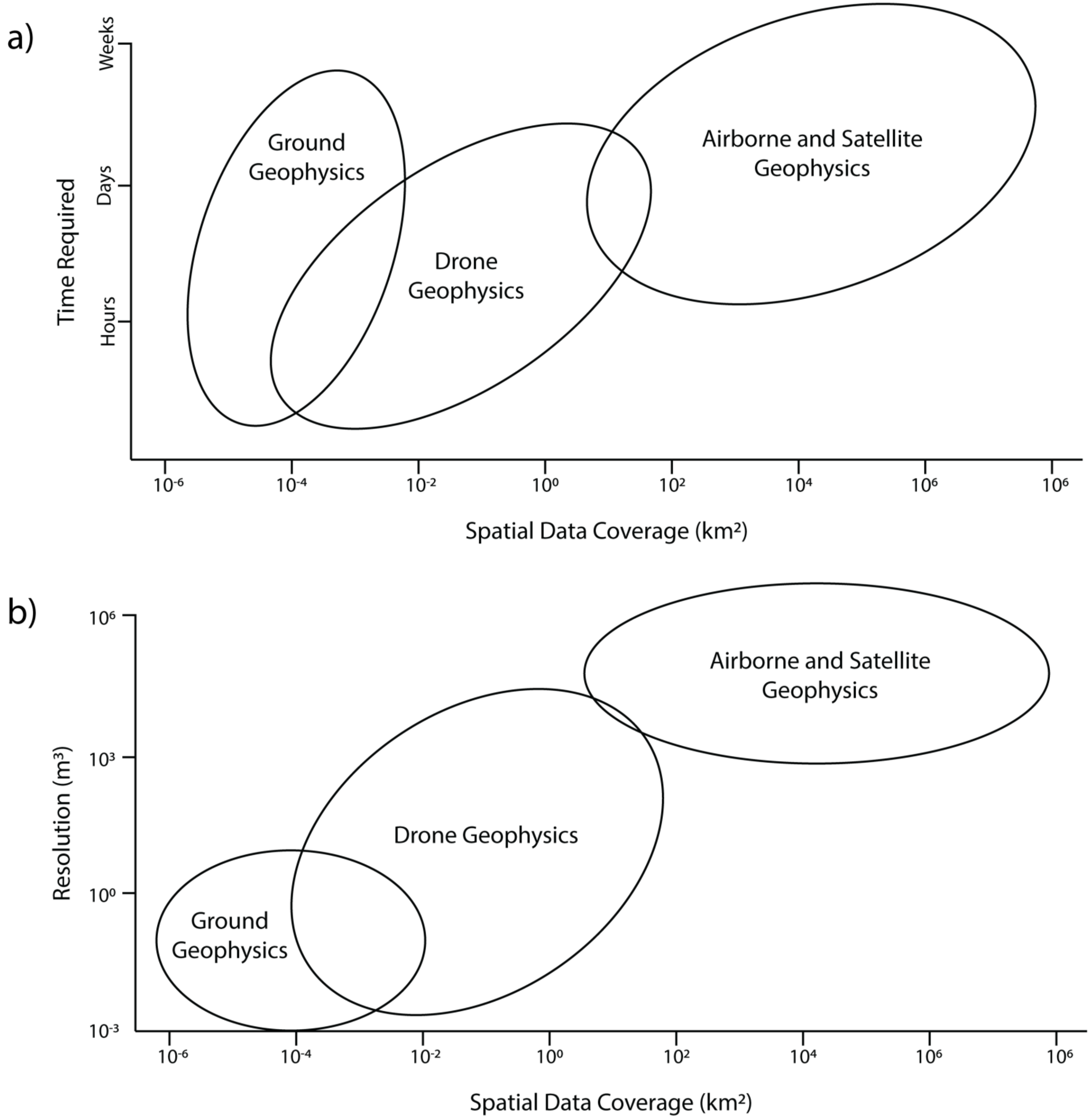
Another way to look at this tradeoff

- Time vs. coverage
- Resolution vs. coverage
- Drones (especially UAV) have potential to transform and overturn these tradeoffs



[Mangel et al., 2022]

The Goal of Characterization

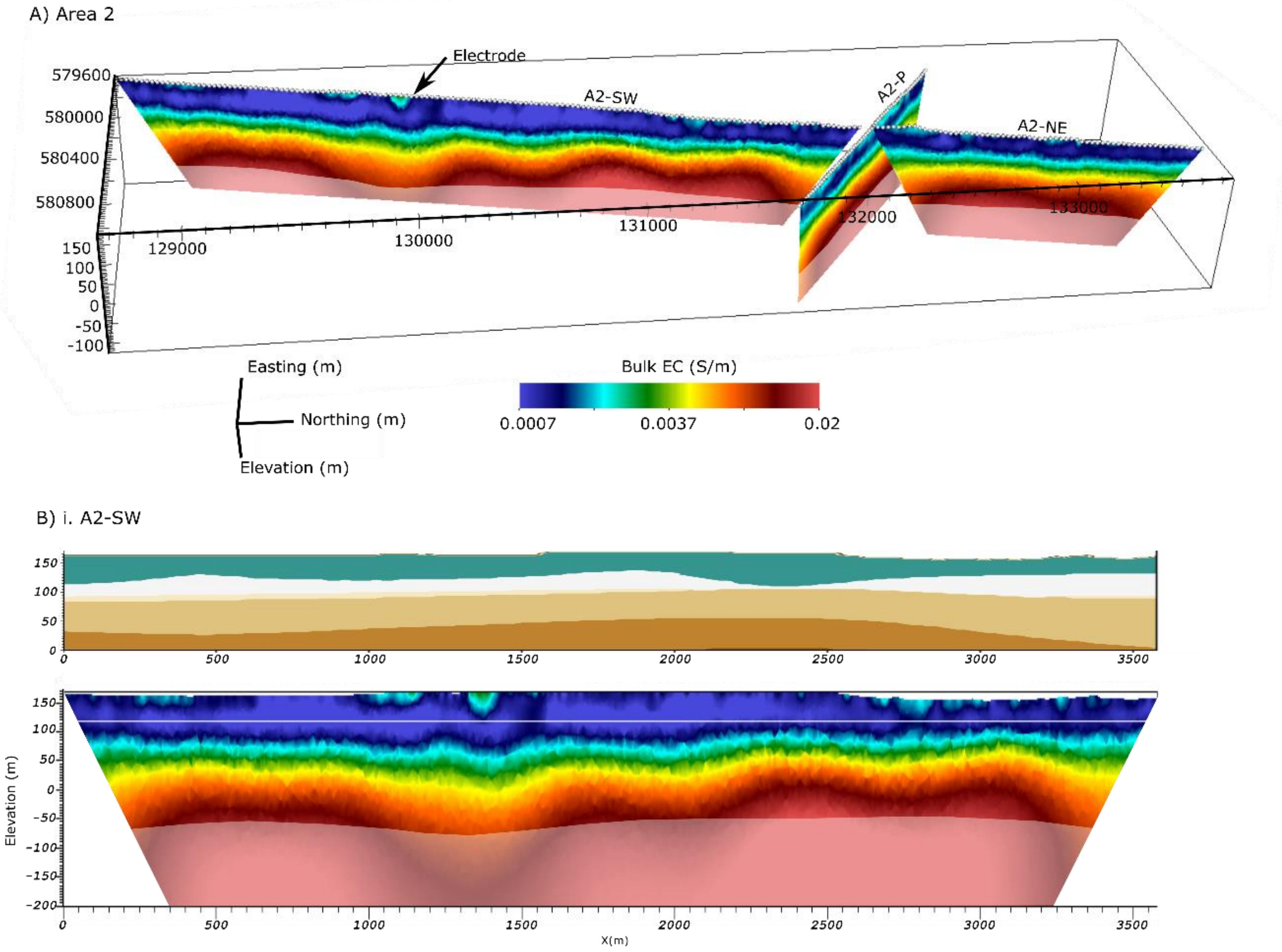
Conceptual Model / Hydrogeologic Framework:

- Aquifer architecture/plumbing network; i.e., the spatial distribution of high-permeability features, geologic contacts/boundaries, fracture zones, etc.
- Understanding (statistical?) of aquifer heterogeneity not deterministically identified

Simulation Model / Attaching #'s to the Framework:

- A quantitative description of aquifer properties in 3D: Hydraulic conductivity, porosity, etc. for input to MODFLOW, STOMP, PFLOTRAN, etc.

Hanford GFM and ERT cross sections



[Robinson et al., Env. Proc., 2022]

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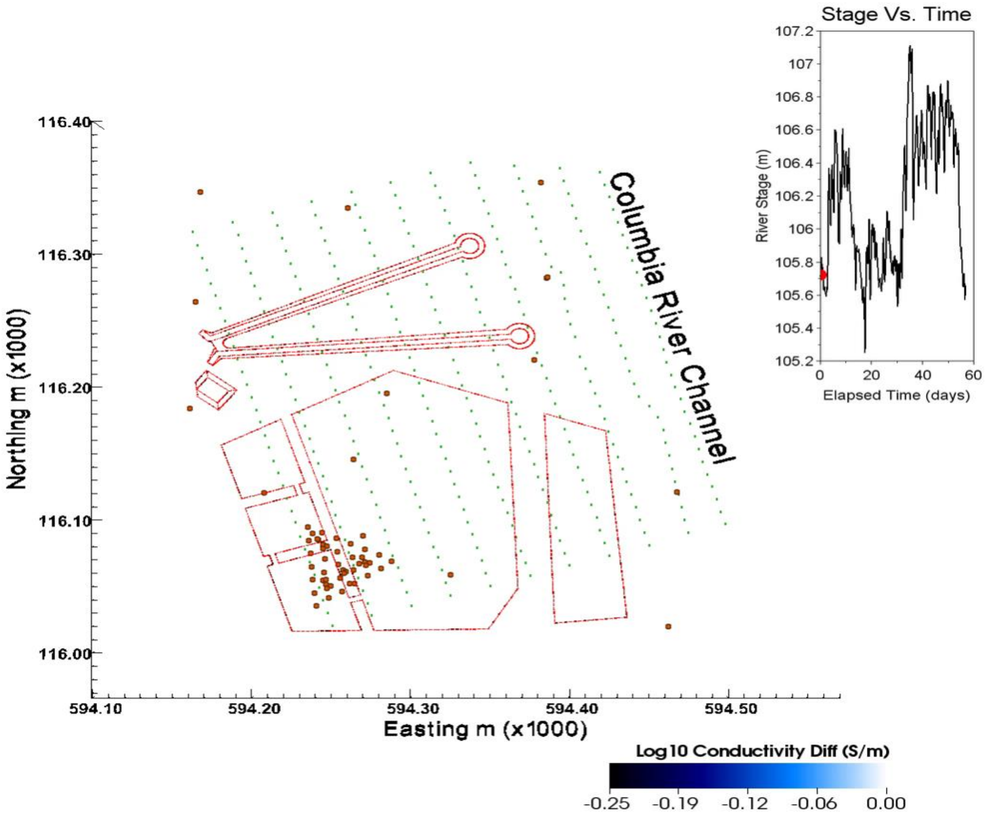
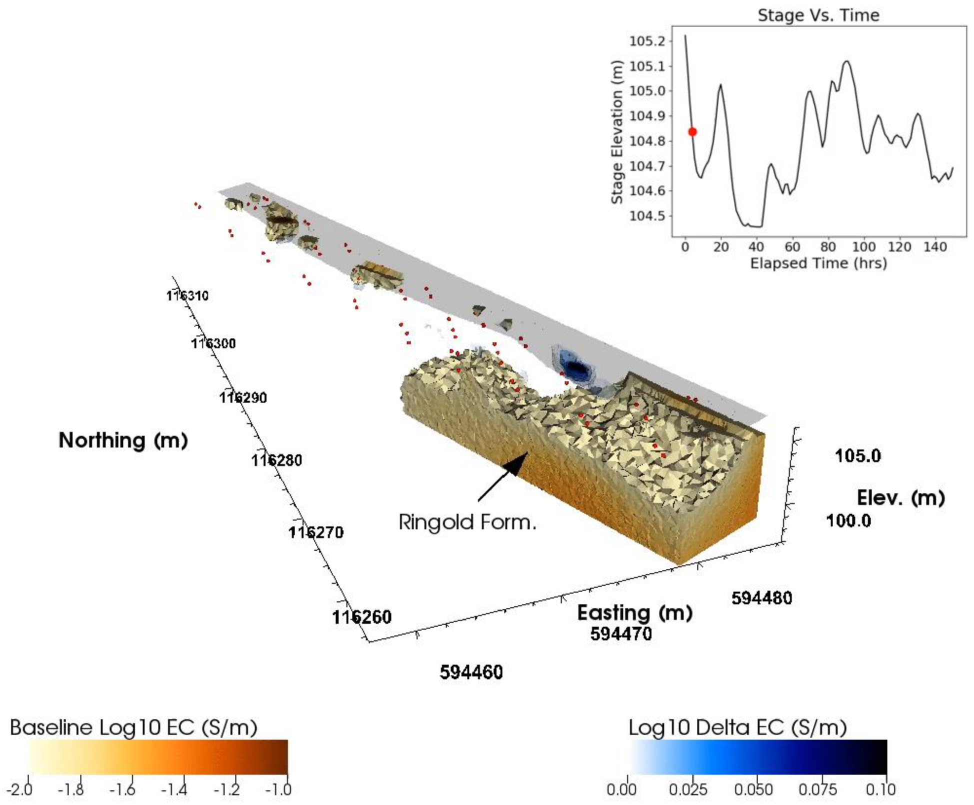
The Goal of Monitoring

<u>Understanding changes in:</u>

- Tracer migration
- Amendment effects
- Contaminant migration (needs contrast)
- Precipitation reactions (porosity reduction)
- Biostimulation
- Moisture dynamics
- Pore clogging
- Examples: Hanford

Examples of stage-driven aquifer/river interaction (Credit: Tim Johnson, PNNL)





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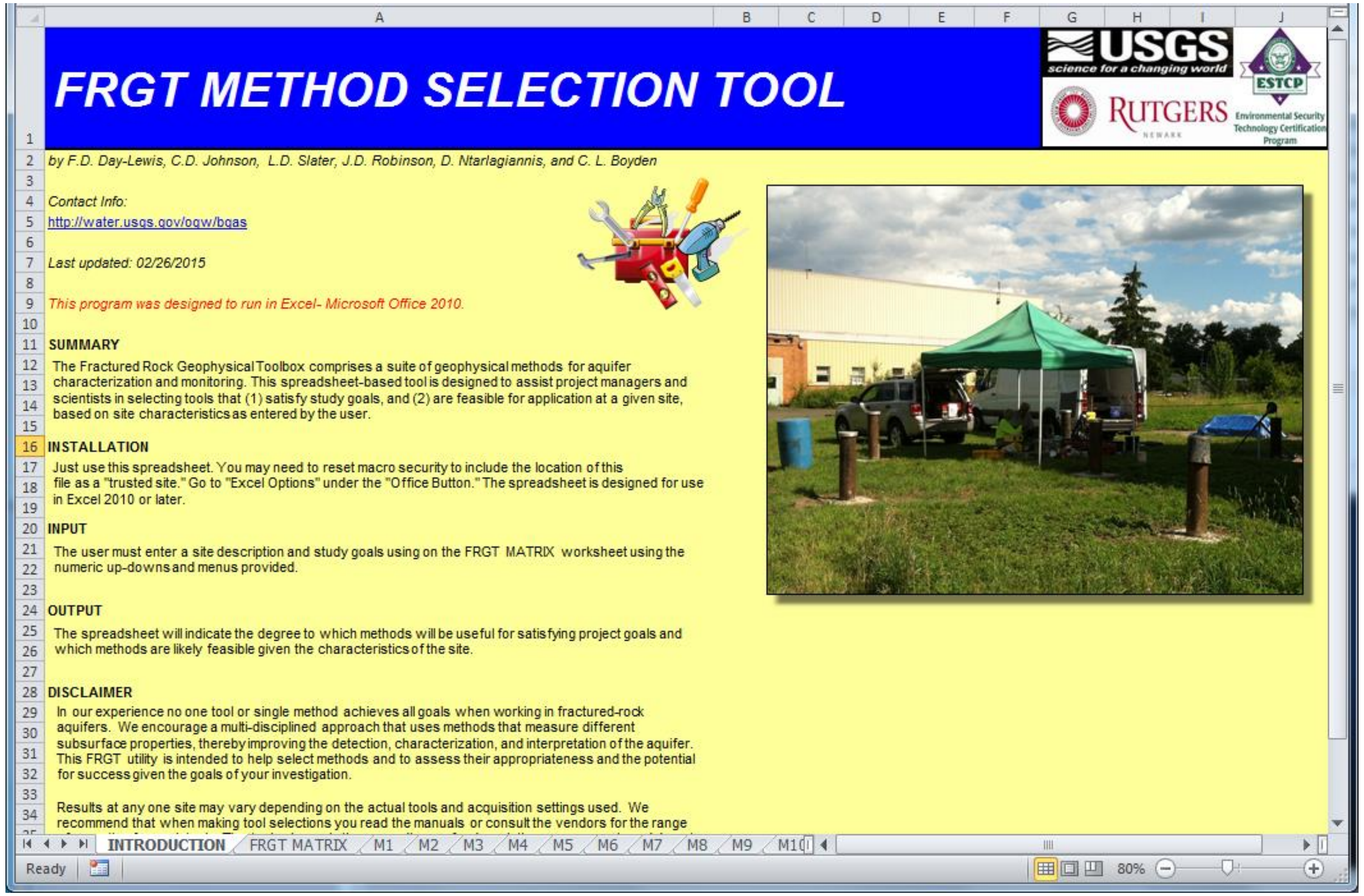
Method Selection Tools

Spreadsheet-based tools 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, <u>well construction</u>)
- Helps PMs & regulators evaluate geophysical strategies
- Caveat: Only a guide



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.

Fractured-Rock Geophysical Toolbox Method Selection Tool (FRGT-MST)

FRGT METHOD S

Fill in cells shaded aqua-blue (in column C). All oth

Project and site parameters

1. What is the depth to bedrock (m)?
2. What is the electrical resistivity of bedrock (ohm-m)?
3. What is the minimum spacing between wells (m)?
4. What is the well casing?
5. What is the vertical extent of open holes (m)?
6. Is borehole fluid turbid/muddy (opaque)?
7. Borehole diameter (inches)
8. Cultural EM interference? (utilities, pipes, etc.)
9. Is it possible to disturb the ground for electrodes or geop
10. What is native groundwater conductivity (micro-S/cm)?
11. What is the project cost threshold for a given method?

Goals

A. Identify discrete fracture network characteristics
B. Identify lithologic contacts
C. Map depth to bedrock
D. Understand large-scale anisotropy, average fracture ori
E. Estimate discrete fracture hydraulic properties
F. Estimate small-scale effective hydraulic properties
G. Estimate large scale hydraulic properties
H. Identify interwell hydraulic connections
I. Time-lapse snapshots of amendment delivery
J. Continuous monitoring of degradation
K. Screening for iron minerals

Assumptions

Comments

M8. Time Domain EM (TDEM)

Measured: Electromagnetic: resistivity

Provides information about:

- Lithology and bedrock surface
- Saturation

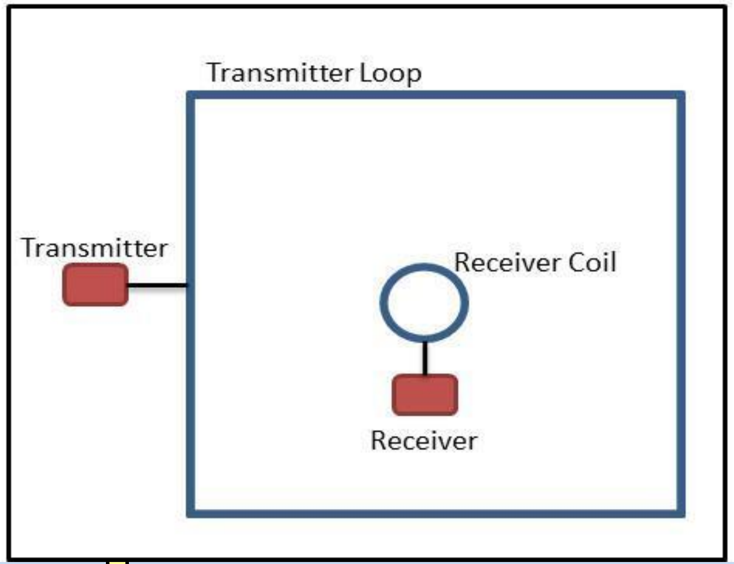
Details:

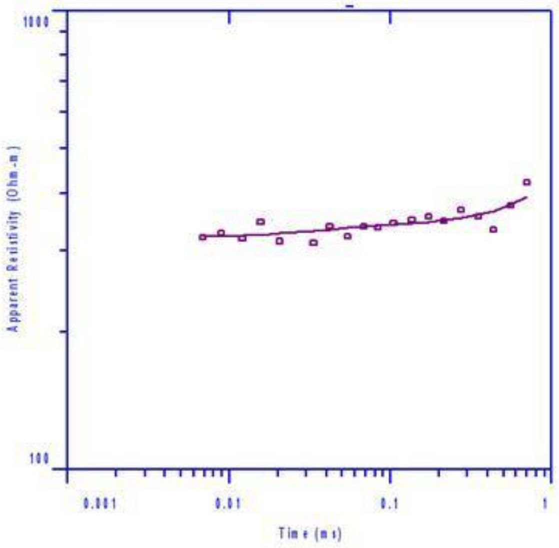
- Depth of investigation is generally 1.5 to 4 times the array size depending on site conditions and frequencies used
- Requires access and space for a square-array survey.
- No direct electrical contact with the ground needed
- Necessary that inherent electrical conductivity contrast is significant

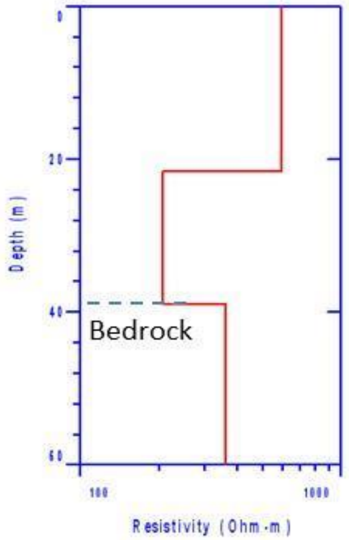
Cost Level: *Low*

Reference:

Frischknecht, Frank C., Labson, Victor F., Spies, Brian R., and Anderson, Walter L., 1991, Profiling methods using small sources, *in* Nabighian, Misac N., and Corbett, John D., eds., Electromagnetic Methods in Applied Geophysics - Applications Part A: Tulsa, Okalahoma, Society of Exploration Geophysicists, p. 105-270







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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. Actual performance of the geophysical and hydraulic tools may vary depending on the specific tool used and acquisition settings.

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Geophysical Remediation Monitoring Method Selection Tool (GRM-MST)

Groundwater

Technology Spotlight/ Technology Editor / Chris Lowry

A Geophysical Remediation Monitoring Method Selection Tool (GRM-MST)

JoshuaThompson[1,2], AdamMangel[1], and Frederick D.Day-Lewis[3]

Geophysical methods have potential to enable cost-effective performance monitoring for groundwater remediation, as demonstrated in numerous scientific investigations. However, geophysical performance monitoring has not fully transitioned to practice, and remediation professionals remain largely unaware of both the capabilities and limitations of geophysical methods in this context. Additional guidance is needed to help the groundwater community identify geophysical monitoring strategies that both (1) contribute to study goals and (2) are likely to be effective under site-specific conditions. The spreadsheet-based Geophysical Remediation Monitoring Method Selection Tool (GRM-MST) is intended to help practitioners identify relevant methods to monitor remediation operations and reduce the misapplication of geophysical methods. The GRM-MST is a Microsoft Excel-based decision support tool designed similarly to the Fractured Rock Geophysical Toolbox Method Selection Tool (Day-Lewis et al. 2016) and the Groundwater/Surface-Water Method Selection Tool (Hammett et al. 2022). Users of those tools will find the GRM-MST intuitive.

Relatively few environmental remediation professionals have backgrounds in geophysics, and relatively few geophysicists have backgrounds in remediation, yet some knowledge of both fields is required for appropriate method selection. The target audience for the GRM-MST comprises environmental professionals with some exposure to geophysics, but not necessarily formal coursework or training. The effectiveness of a monitoring method at a given site strongly depends on sensitivity to physical changes associated with a particular remedy. For example, electrical imaging methods are sensitive to and thus able to image the emplacement of amendments that manifest contrasts in bulk electrical conductivity because the amendments' fluid specific conductance differs substantially from that of native groundwater. Other methods (e.g., seismic) might not offer sensitivity to an aqueous phase amendment, but might be sensitive to other remedies (e.g., desiccation). Not every method will work for a particular problem, nor will every method work at a given site. Site conditions (e.g., geology, existing infrastructure, well constructions, and target depth) may limit the effectiveness or preclude altogether the use of some methods. For example, subsurface utilities or powerlines pose challenges to electromagnetic surveys.

To apply the GRM-MST, the user first identifies which of nine site remedies (Table 1) is to be monitored; these remedies do not comprise an exhaustive list but represent proven candidates for geophysical monitoring based on past research. Performance monitoring goals can include monitoring the spatial distribution of emplaced or injected amendments, assessing flow through permeable reactive barriers, checking for flow through caps or impermeable barriers, tracking biogeochemical signatures associated with contaminant degradation processes, or monitoring the progress of soil desiccation. Successful monitoring of these and other remedies is found in the groundwater and geophysical literature (e.g., Lane et al. 2006; Johnson et al. 2015, 2022). Such demonstrations and additional publications are summarized and cited in worksheet appendices for the nine methods considered (Table 2).

The second step in using the GRM-MST is to enter information about the site conditions. Salient site conditions include information about the presence of subsurface infrastructure, whether it is possible to disturb the ground, and whether GPS signal is impacted by tree canopy. Based

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Table 1
Remediation Technologies Considered in the GRM-MST

Permeable reactive barriers	Barriers/caps
Biostimulation	Thermal remediation
Groundwater pump and treat	Wetland/natural filtration
Soil or vadose zone desiccation	Monitored natural attenuation
Injections for sequestration and soil flushing	

Table 2
Geophysical Methods Considered in the GRM-MST

Direct-current electrical resistivity (surface/crosshole)	Time-domain induced polarization
Frequency-domain electromagnetic induction	Spectral induced polarization
Time-domain electromagnetic induction	Ground penetrating radar
Seismic methods	Magnetics
Thermal methods	

on the user input, the tool assesses the viability of seven prospective methods from the geophysical remediation monitoring toolbox (Table 2). For the specified remedy, the GRM-MST points the user to the appropriate tool(s) that is (are) not contraindicated by the circumstances of the site. The formulas and conditional formatting rules that constitute the GRM-MST logic are visible to the user within the unprotected spreadsheet. The example in the download is based on a desiccation experiment at the Hanford Site in eastern Washington state (Figure 1).

The monitoring of remediation operations using geophysical methods is an active area of research in hydrogeophysics and near-surface geophysics. Therefore, the GRM-MST is a forward-looking tool and considers several techniques that remain more in the domain of research than practice (i.e., crosshole radar and spectral induced polarization). The GRM-MST is a support tool, and it is highly recommended that geophysical experts be involved in the decision-making process. Ideally, premodeling "desktop feasibility" experiments would be used to further assess a geophysical method for a problem before going to the field. We stress that geophysical information is not a substitute for direct information from conventional sampling, coring, or other field testing. Geophysical information is only indirectly related to properties and parameters of interest and thus requires calibration and ground truth for interpretation. Despite these limitations, geophysical methods serve to fill gaps in space and time between more direct measurements or sampling, and thus can support more cost-effective performance monitoring.

Acknowledgments

The GRM-MST may be downloaded from the data repository associated with this article. The authors are grateful to Dorothy Linneman and Joaquin Cambeiro for constructive colleague reviews. This material was prepared as an account of work sponsored by an agency of the U.S. Government. Neither the U.S. Government nor the

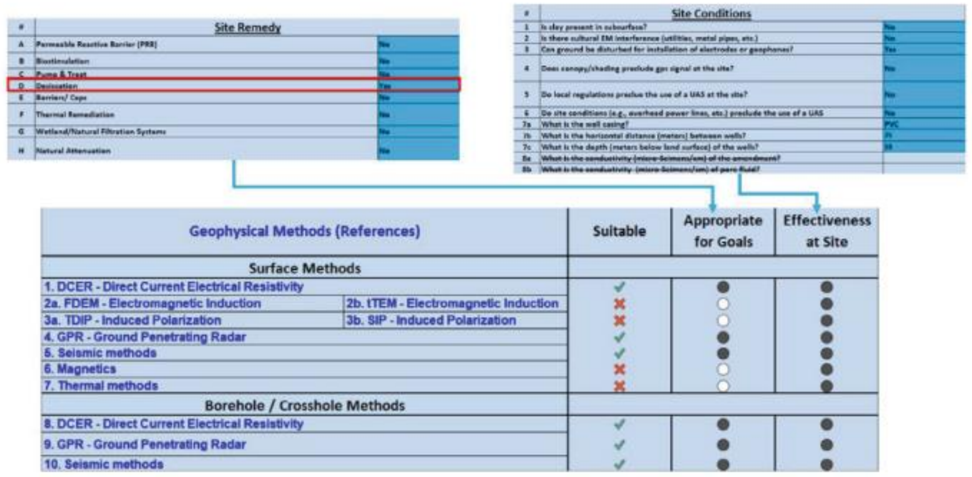

Figure 1. Screen capture of the GRM-MST with the default example, based on geophysical monitoring of a soil desiccation experiment at the Hanford Site in eastern Washington state.

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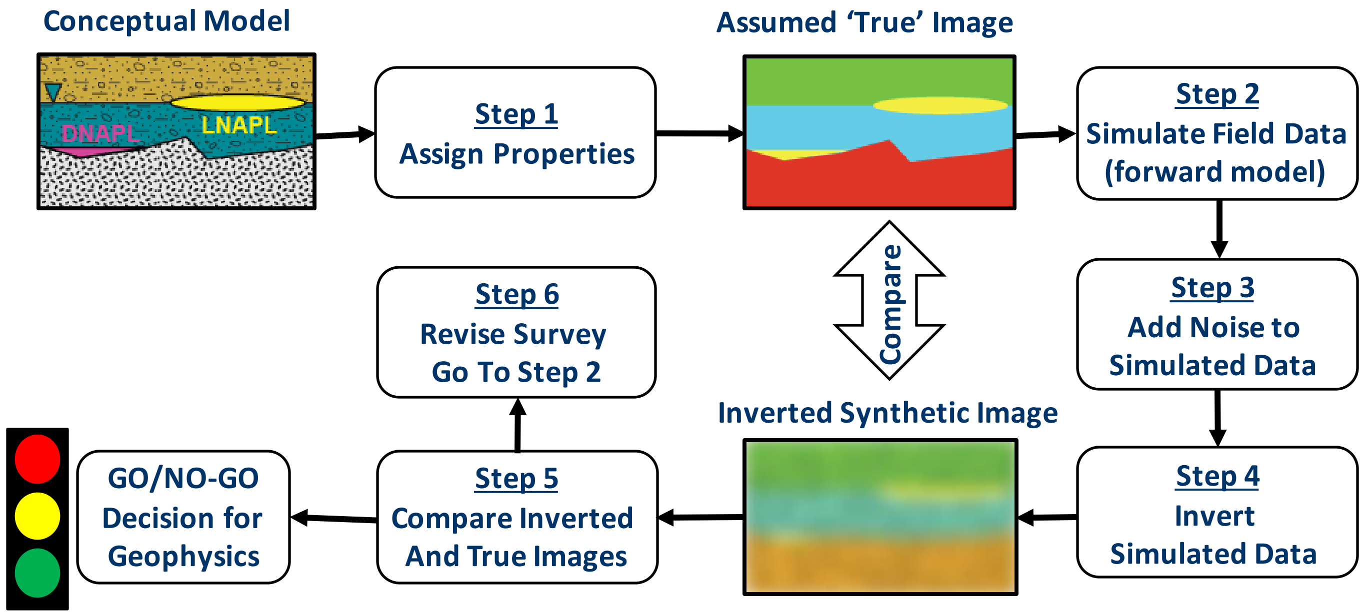
Desktop Feasibility Assessment

Pre modeling:

- 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' or 'in silico' experiments & 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*]

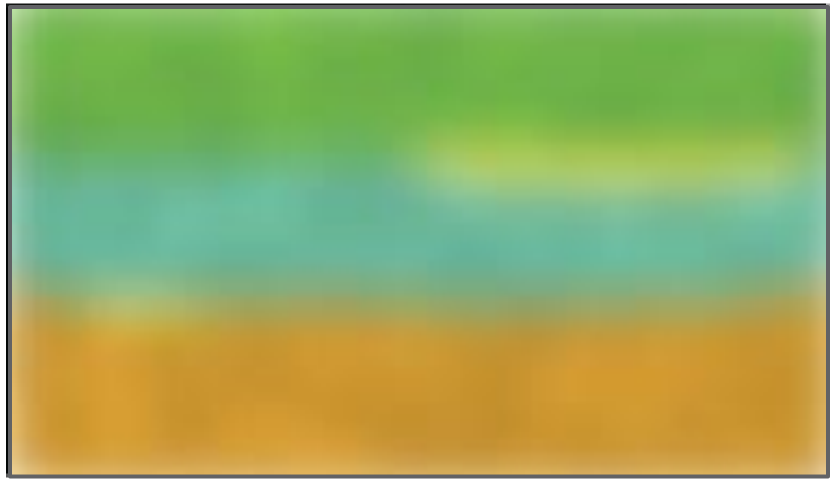
Realistic Expectations

‘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 E4D and many COTS and public-domain geophysical software:
    - Rigorous numerical models
    - Simpler approximate tools (Resolution matrix, e.g., SEER)
- Forms the basis for
    - Survey design
    - Go/No-Go decision
    - Interpretation

→**COMMONLY NOT EXPENSIVE OR BURDENSOME**

Conceptual Model



Can we reliably ‘see’ or detect:

- Contaminant?
- Geology

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

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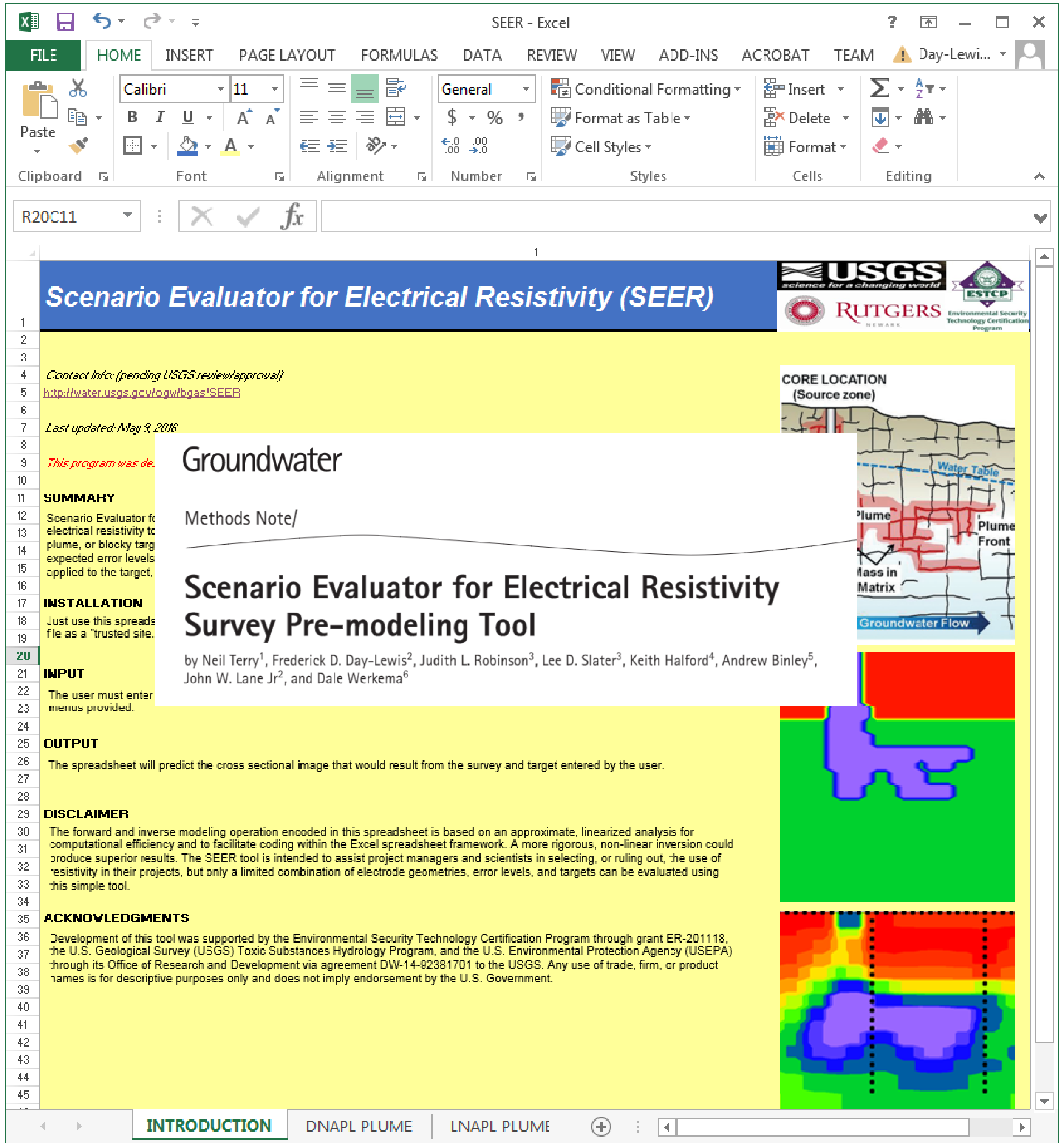
Excel-based pre modeling

Spreadsheet Functionality:

- Simple, user-friendly
- Predict survey outcomes for **LIMITED** hypothetical target and measurement scenarios
- 3 template targets included in the spreadsheet can be modified:
  - Underground storage tank (UST)
  - DNAPL plume
  - LNAPL plume



→ **PNNL has more sophisticated tools for this (e.g., E4D, PFLOTRAN)**

[Terry et al., GW, 2017]

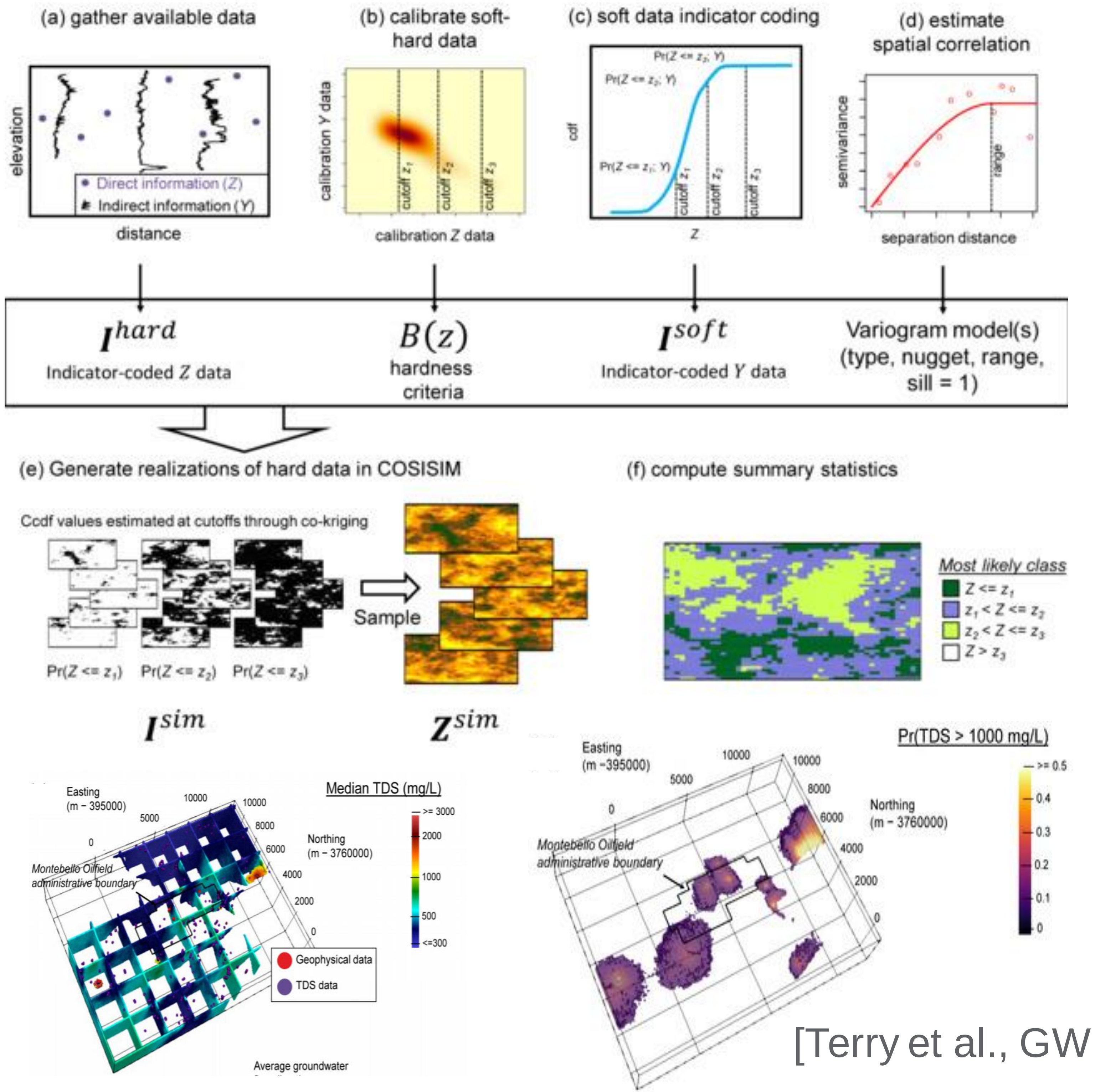
Translation

Tools:

- Petrophysics
- Geostatistics
- Coupled inversion
- Qualitative

Issues:

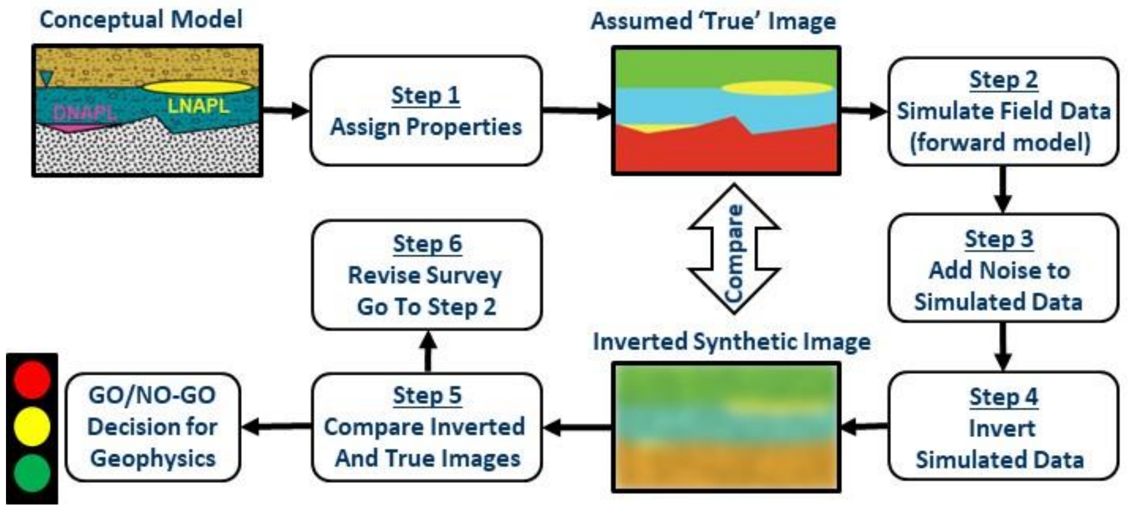
- Resolution/smoothing
- Non-uniqueness and uncertainty in petrophysical relations

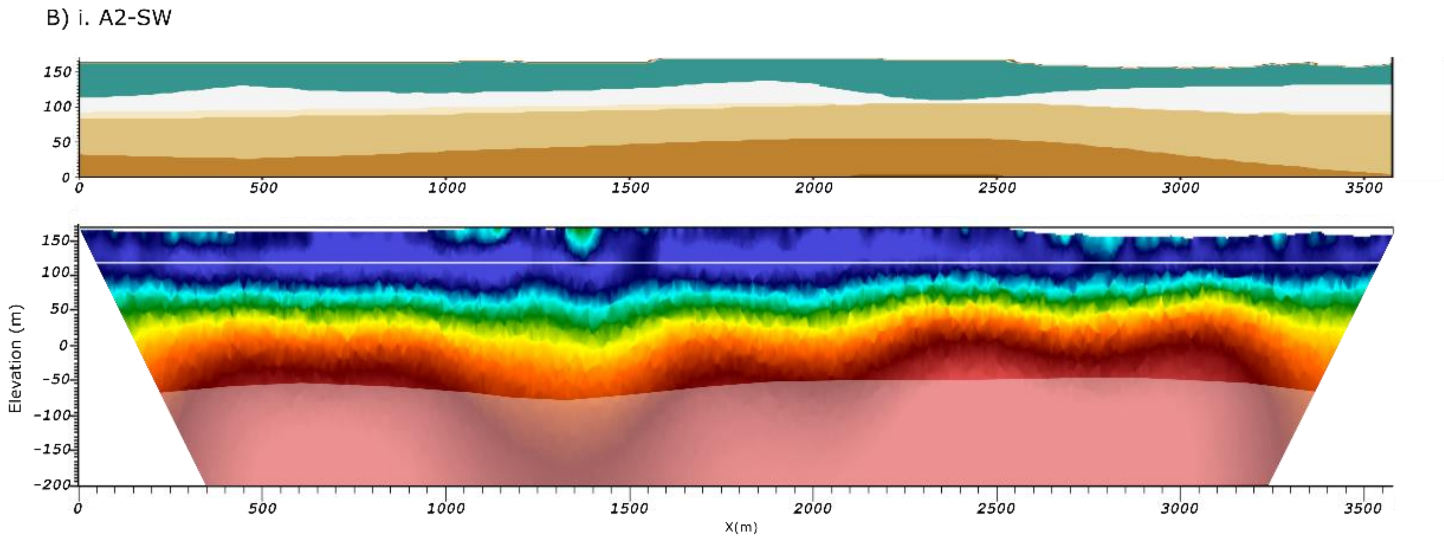


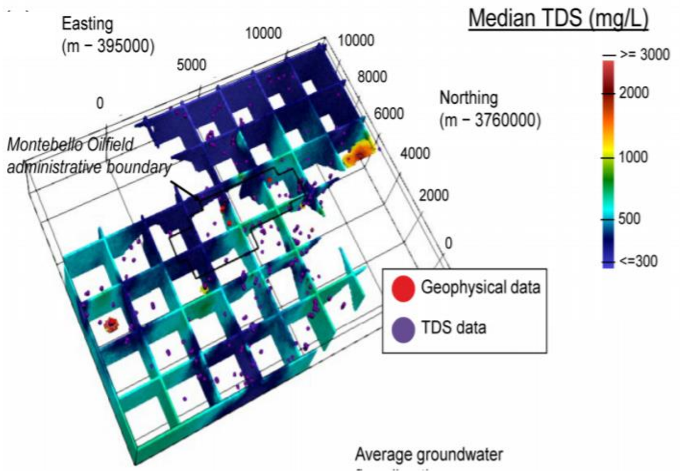
[Terry et al., GW, 2022]

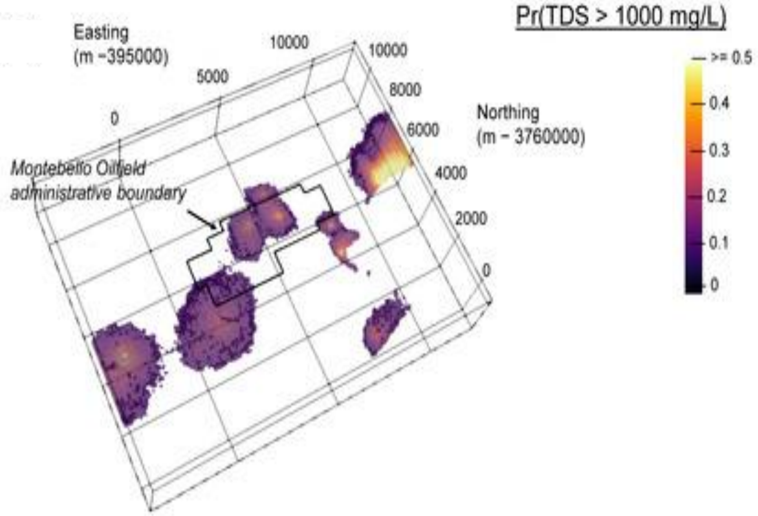
Summary

- Geophysical Toolbox
- Tradeoffs
- Characterization vs. Monitoring
- Guidance for method selection
  - Matching goals and site-based conditions
- Importance of pre-modeling
  - Go/no-go basis
  - Survey design
  - Aids interpretation
- Approaches to translation









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Thank you

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