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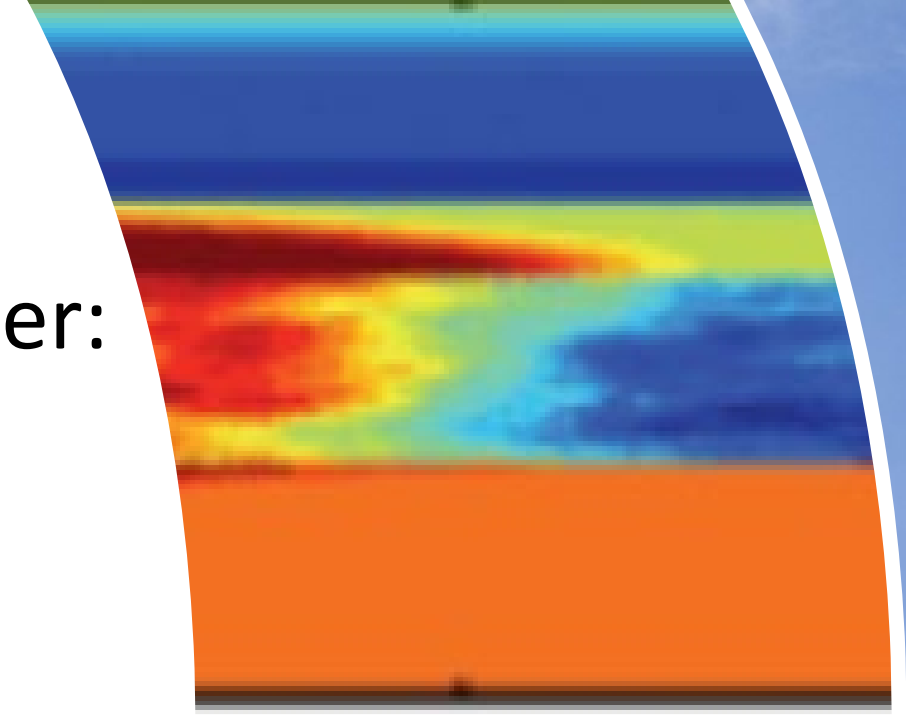
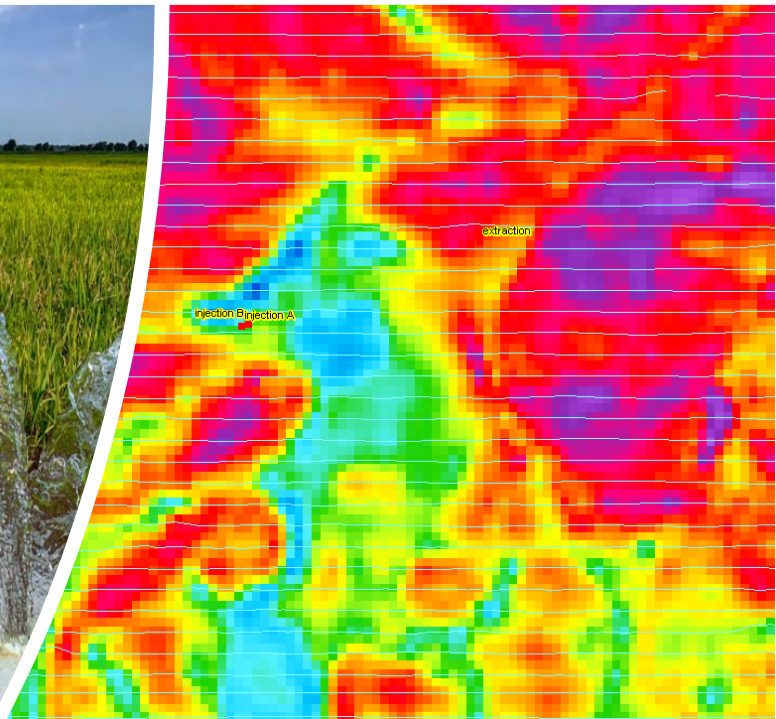
# Geophysics to Groundwater: Methods, Modeling, and Measurements to Inform Subsurface Properties






Burke Minsley

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Denver, CO

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

# Outline

- **What is the right geophysical method or survey design for a specific question(s)?** Using coupled hydrogeophysical modeling to develop effective measurement and monitoring strategies

- **What do the red-blue geophysical images mean?** Developing hydrogeologic interpretations—with uncertainty—from geophysical models

- **A case study:** Airborne geophysics to characterize aquifer structure in support of a managed aquifer recharge pilot study in Mississippi

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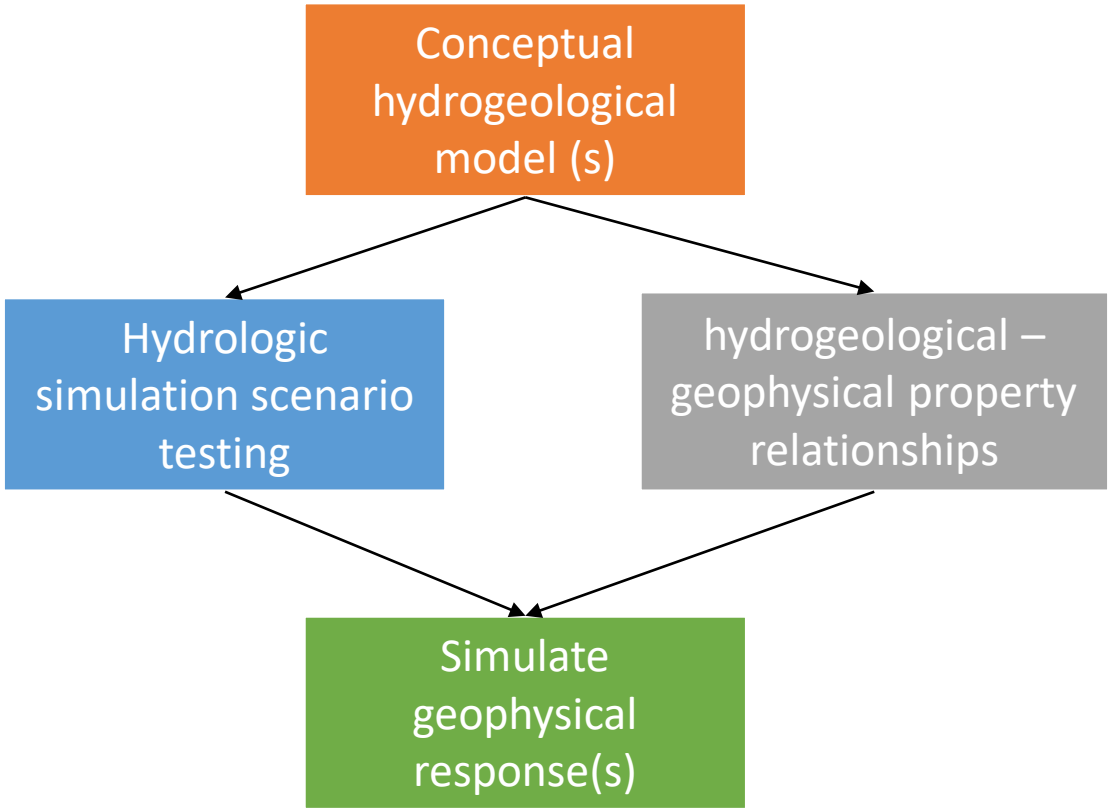
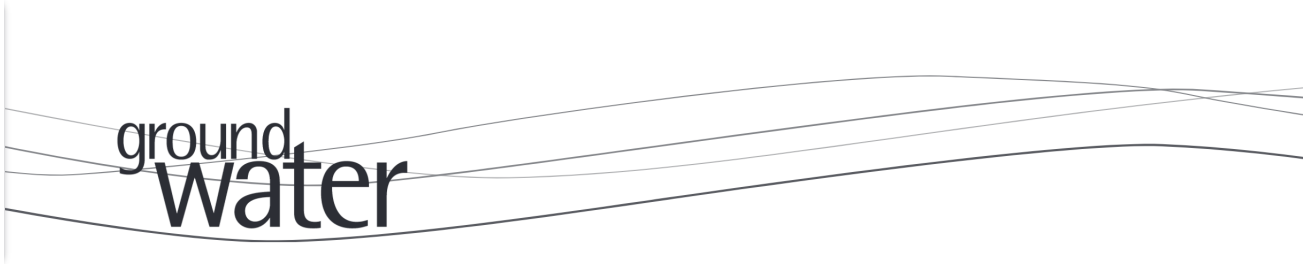
# What geophysical method(s) and survey design will best answer my questions?




## Hydrogeophysical Methods for Analyzing Aquifer Storage and Recovery Systems

by Burke J. Minsley[1,2], Jonathan Ajo-Franklin[3], Amitabha Mukhopadhyay[4], and Frank Dale Morgan[2]

**Abstract**

Hydrogeophysical methods are presented that support the siting and monitoring of aquifer storage and recovery (ASR) systems. These methods are presented as numerical simulations in the context of a proposed ASR experiment in Kuwait, although the techniques are applicable to numerous ASR projects. Bulk geophysical properties are calculated directly from ASR flow and solute transport simulations using standard petrophysical relationships and are used to simulate the dynamic geophysical response to ASR. This strategy provides a quantitative framework for determining site-specific geophysical methods and data acquisition geometries that can provide the most useful information about the ASR implementation. An axisymmetric, coupled fluid flow and solute transport model simulates injection, storage, and withdrawal of fresh water (salinity ~500 ppm) into the Dammam aquifer, a tertiary carbonate formation with native salinity approximately 6000 ppm. Sensitivity

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*Minsley et al., Groundwater, 2011*

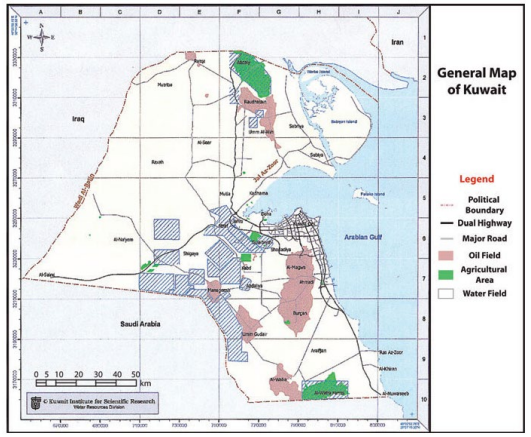
# What geophysical method(s) and survey design will best answer my questions?

Conceptual hydrogeological model (s)

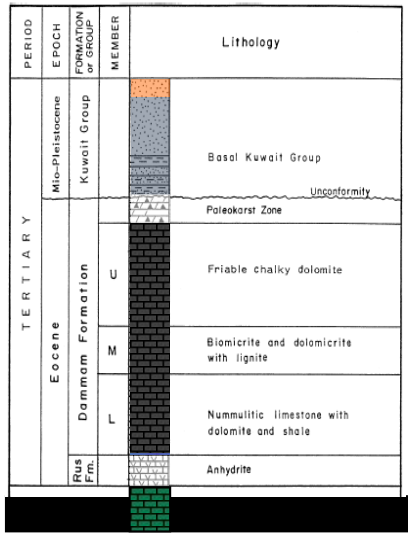
Hydrologic simulation scenario testing

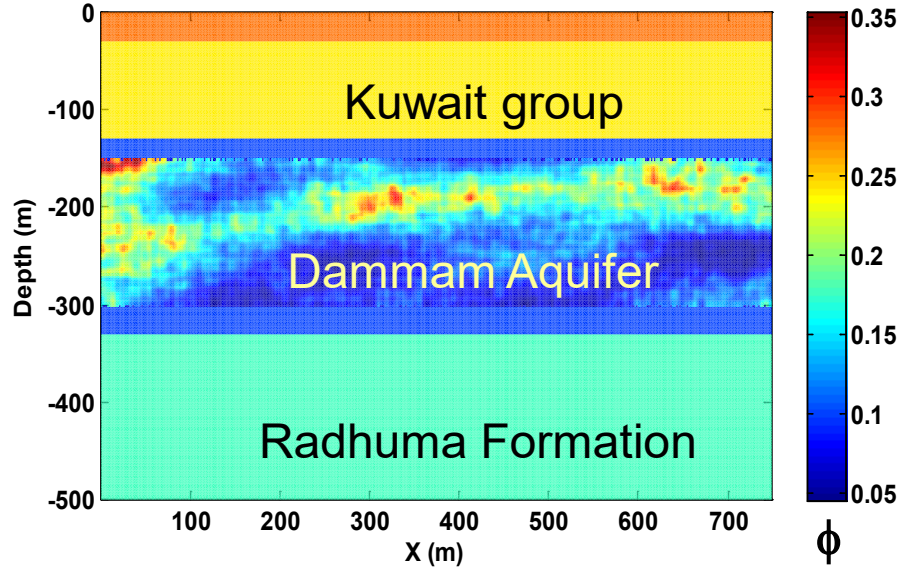
hydrogeological – geophysical property relationships

Simulate geophysical response(s)




*Al-Awadi et al., Hydrogeology J. (2005)*

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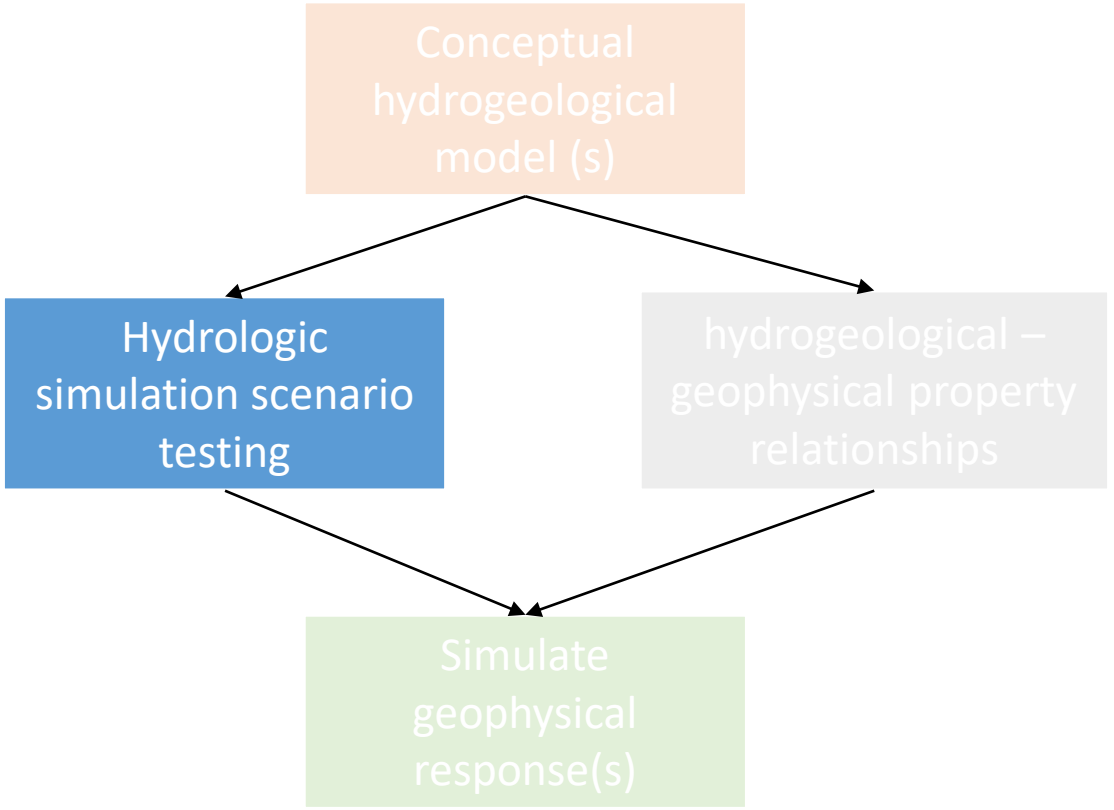
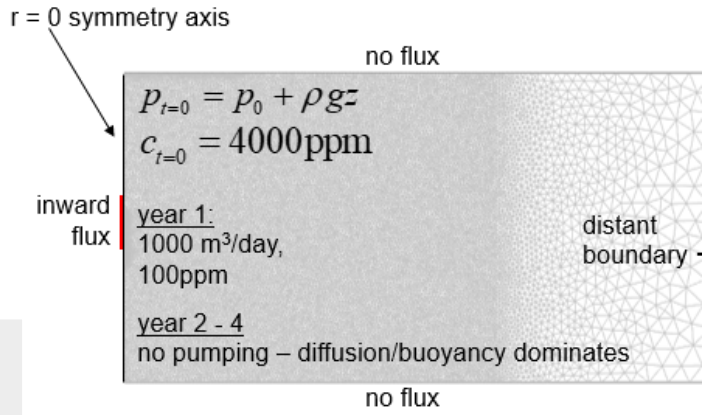


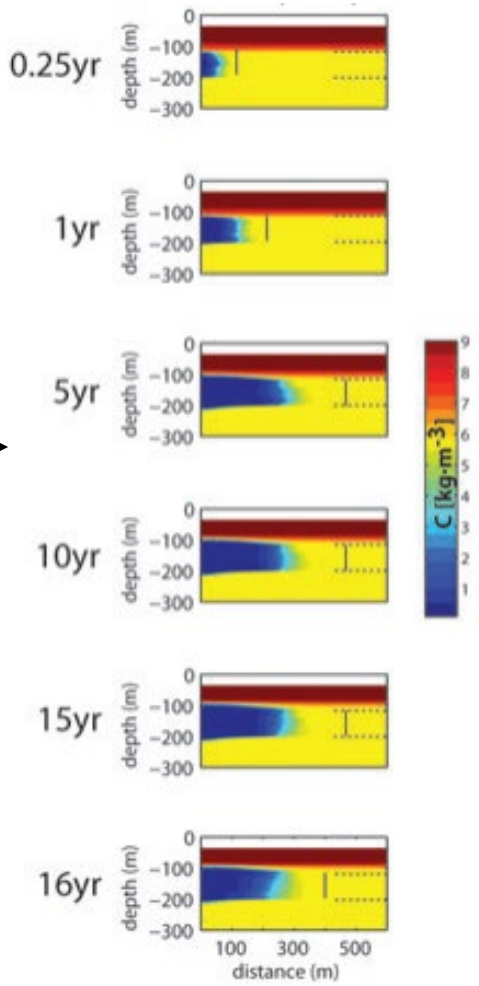




Fluid mass balance:

$$\rho S \frac{\partial p}{\partial t} + \phi \frac{\partial \rho}{\partial c}\frac{\partial c}{\partial t} + \nabla \cdot (\rho q) = \rho Q$$

Solute transport:

$$\phi \rho \frac{\partial c}{\partial t} + \rho q \cdot \nabla c = \nabla \cdot (\phi \rho D \cdot \nabla c)$$

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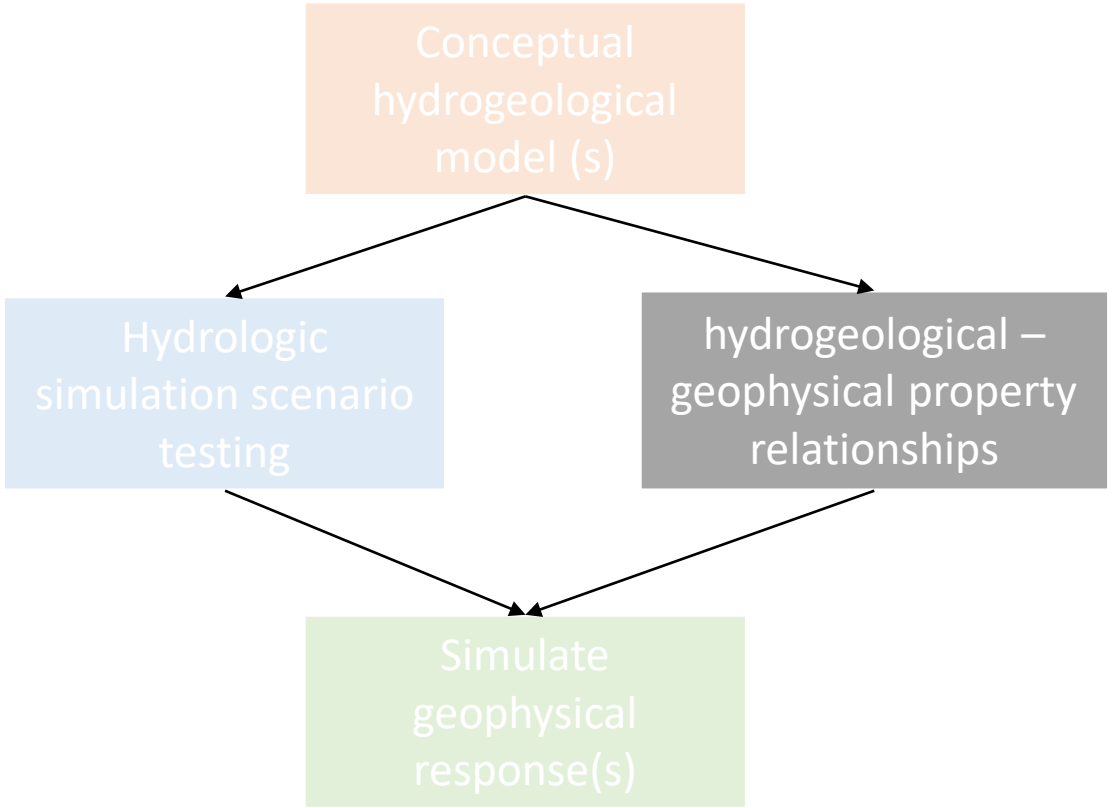
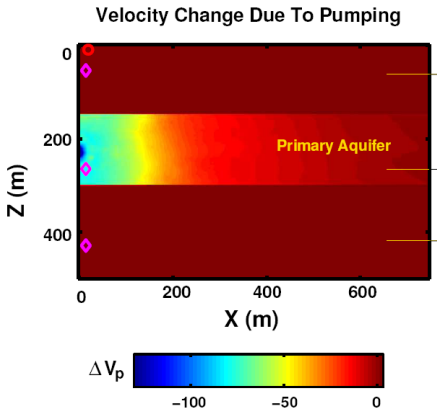
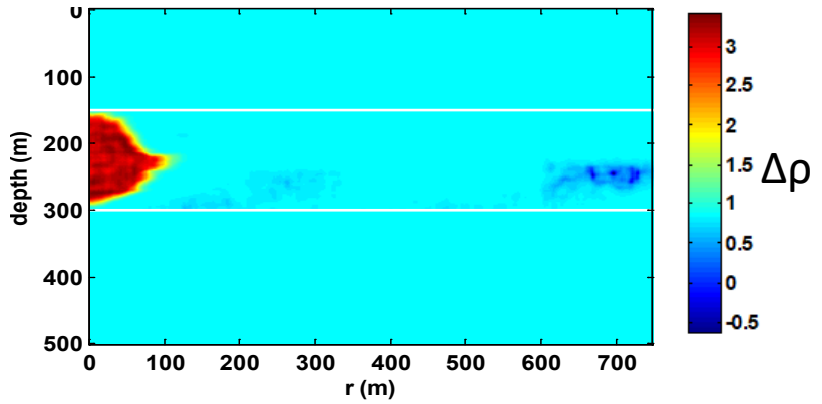



**Modeled pore pressure → seismic velocity: change after one year of injection**

**Modeled fluid salinity → electrical resistivity: : change after one year of injection**

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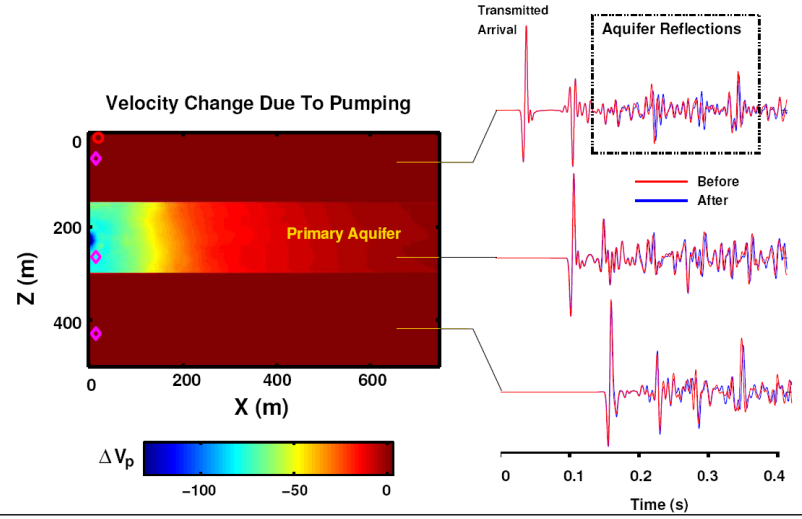
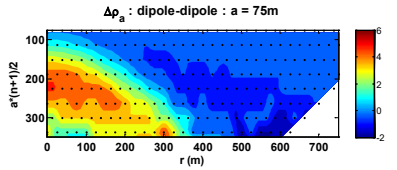
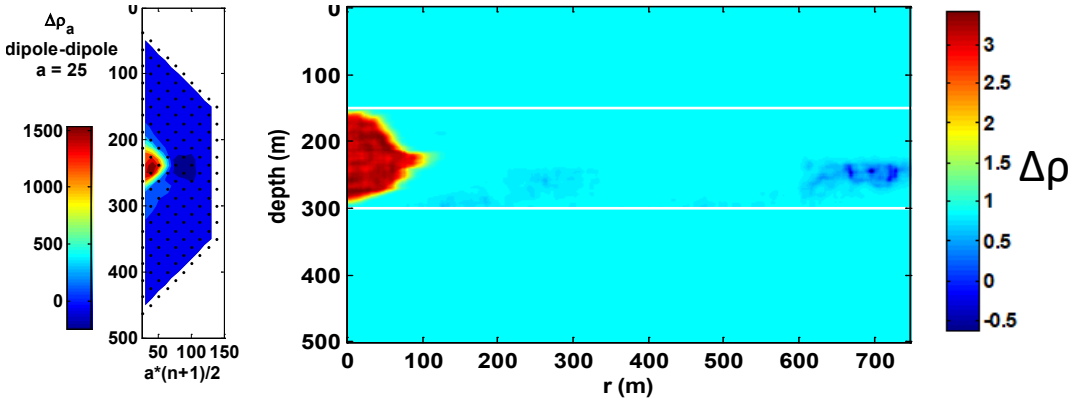



**Predicted change in seismic waveforms**




**Predicted change in surface or borehole resistivity data**

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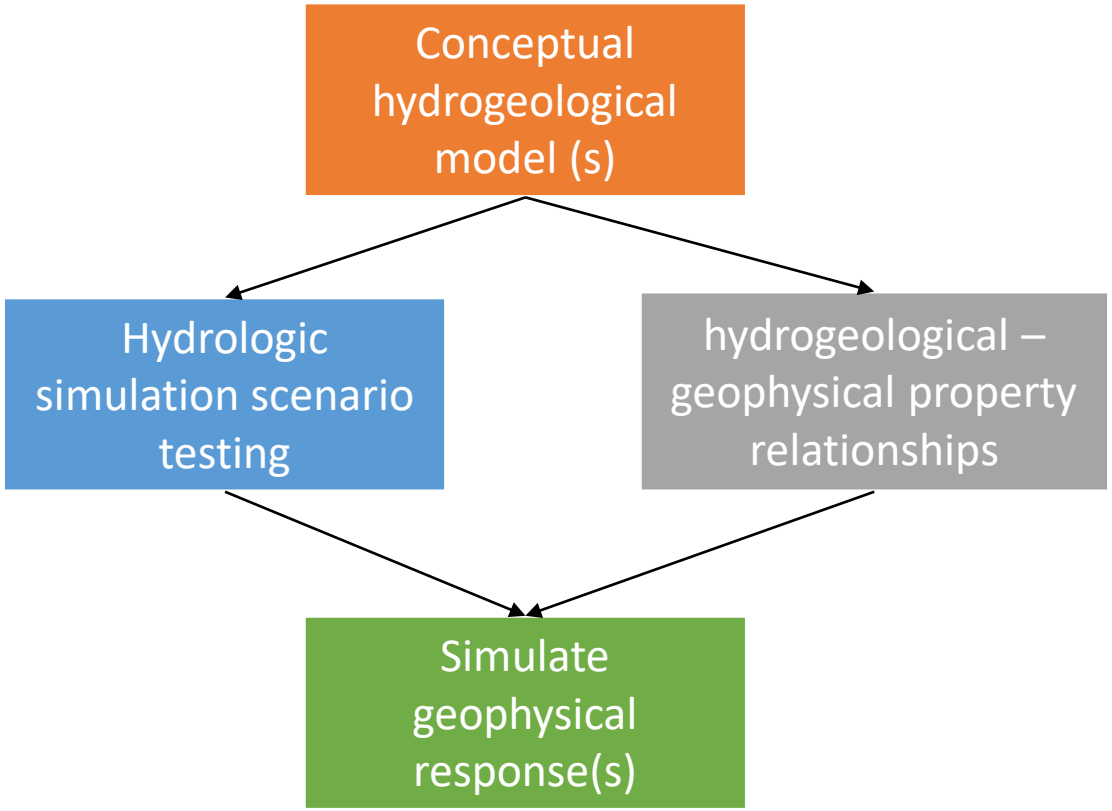


| | |
|---|---|
| **Seismic** | **• monitor pressure changes during injection / recovery (diffusive)**<br>**• baseline structural mapping**<br>**• information is primarly near injection location** |
| **Resistivity** | **• monitor extent of freshwater plume (advective)**<br>**• baseline structural mapping**<br>**• depth of freshwater plume is a challenge for surface resistivity** |

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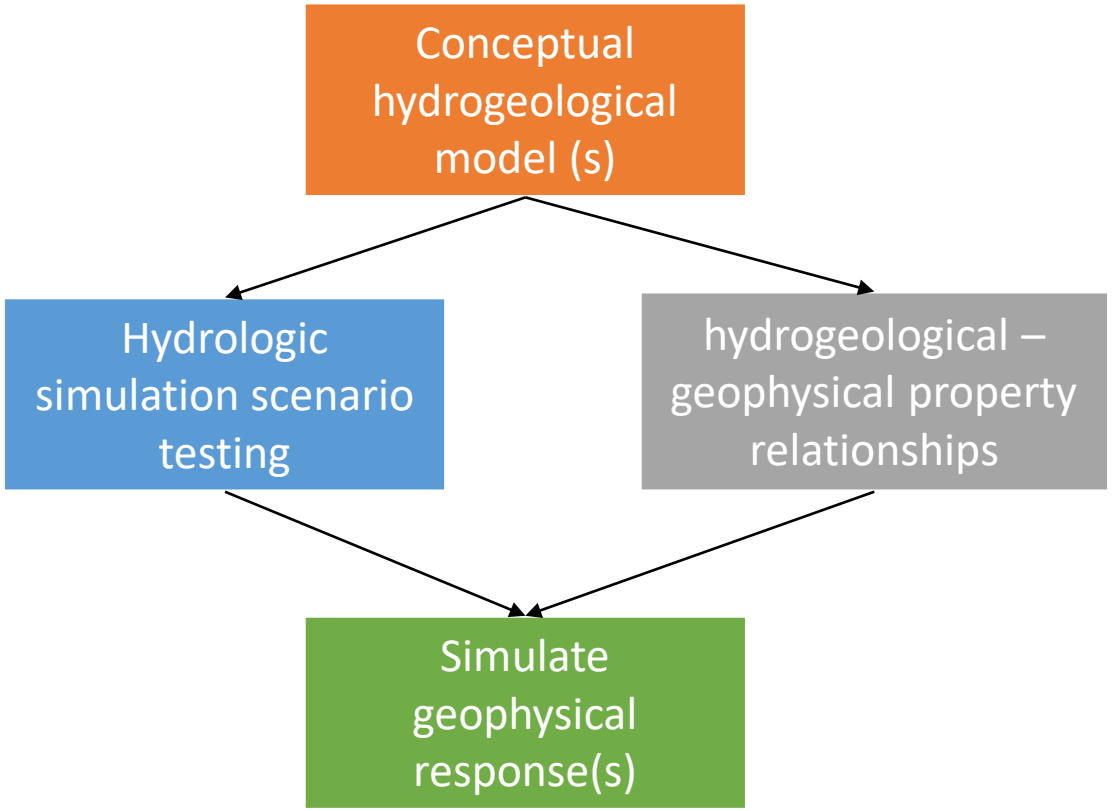
# What do the red-blue geophysical images mean?

## Developing hydrogeologic interpretations, with uncertainty, from geophysical models




**Easy: given known properties, what is the geophysical response?**

**Hard: given geophysical data, what are the unknown hydrogeologic properties?**

**Uncertainty and non-uniqueness from geophysical data -> geophysical model -> hydrogeologic properties**

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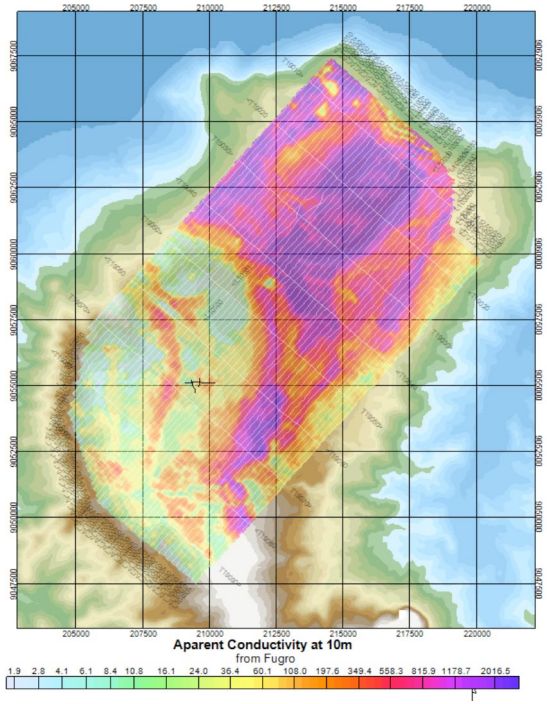
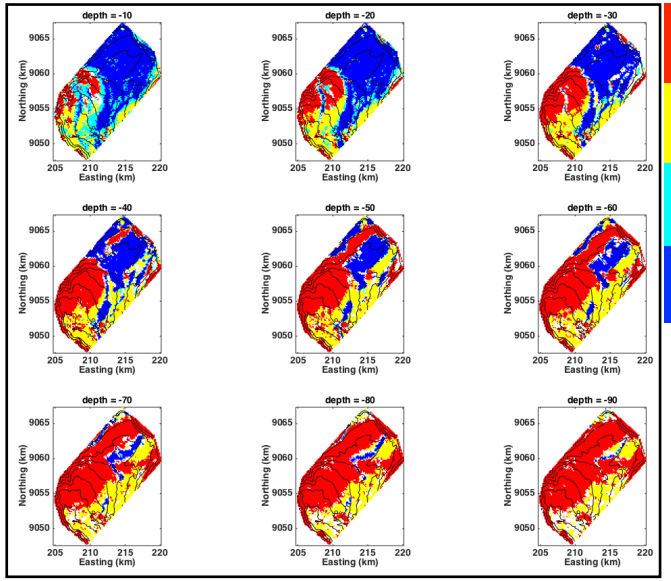
# What do the red-blue geophysical images mean?

Developing hydrogeologic interpretations, with uncertainty, from geophysical models

Resistivity

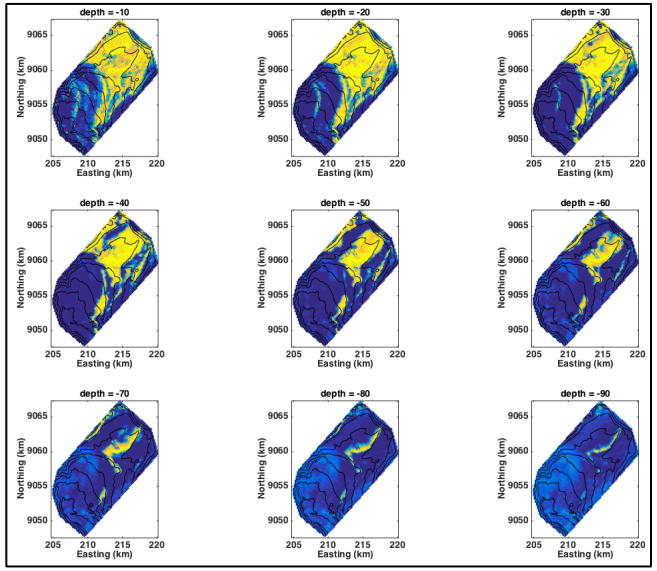



Fine (clay)

'Most probable' lithology

Coarse (limestone)




Probability (limestone)

*Minsley & Ley-Cooper, 2015*

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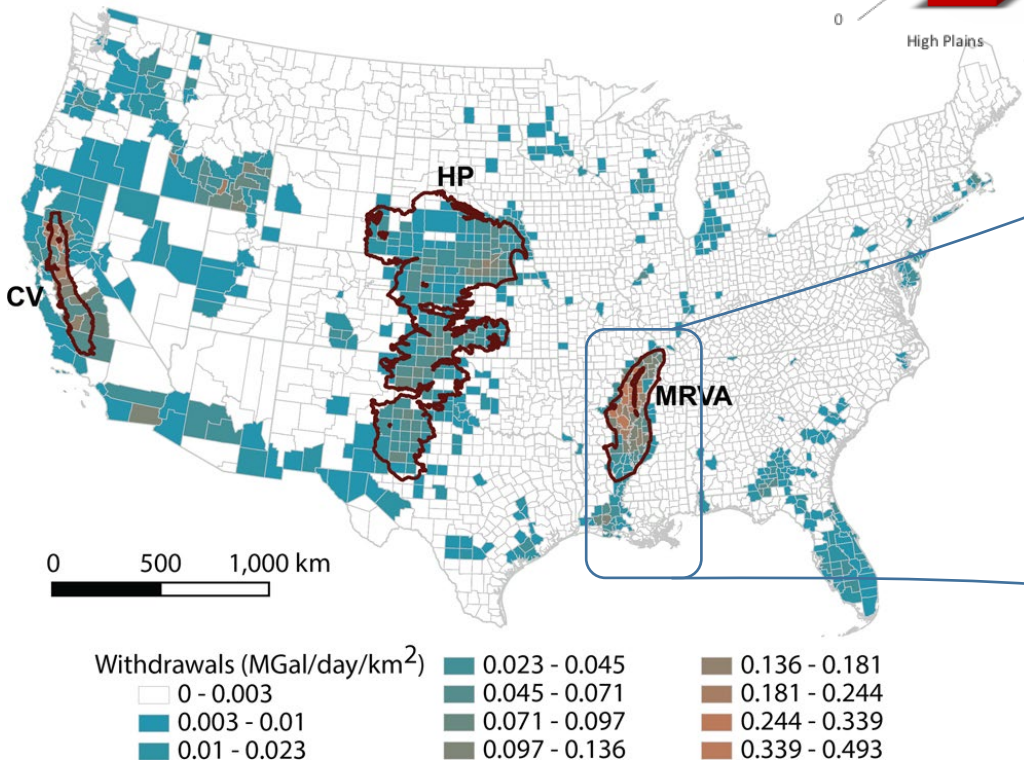
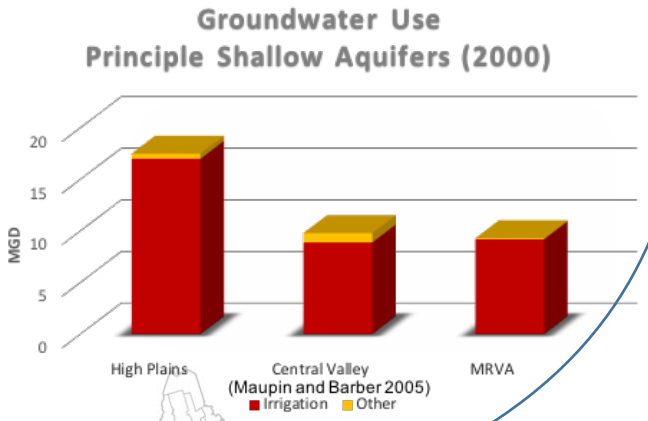
# Mississippi Alluvial Plain (MAP): An economic engine

## Withdrawals by county

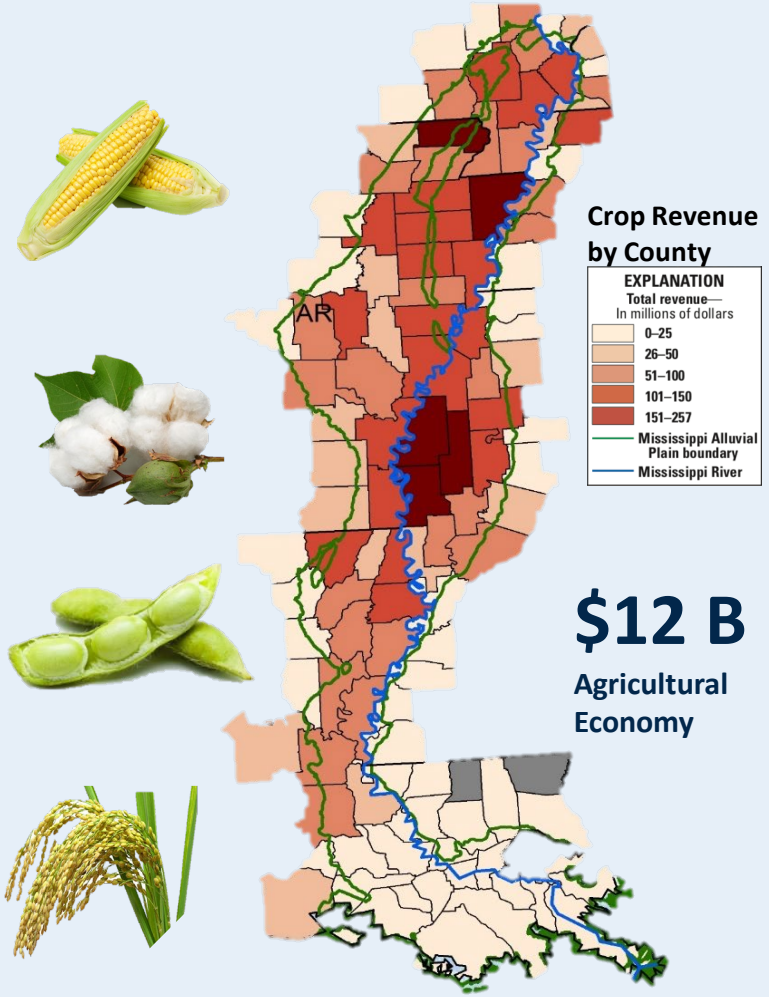
(from Lovelace et al., 2020 based on 2015 data)




## Economic Importance

(Alhassan et al. 2019)




**$12 B**

**Agricultural Economy**

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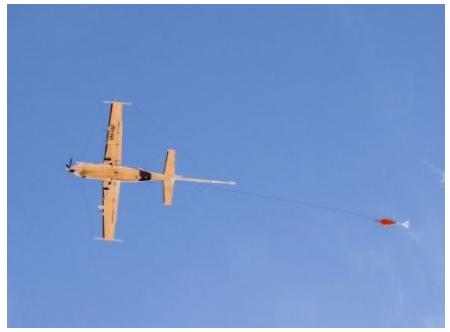
# MAP AEM surveys 2018 - 2022

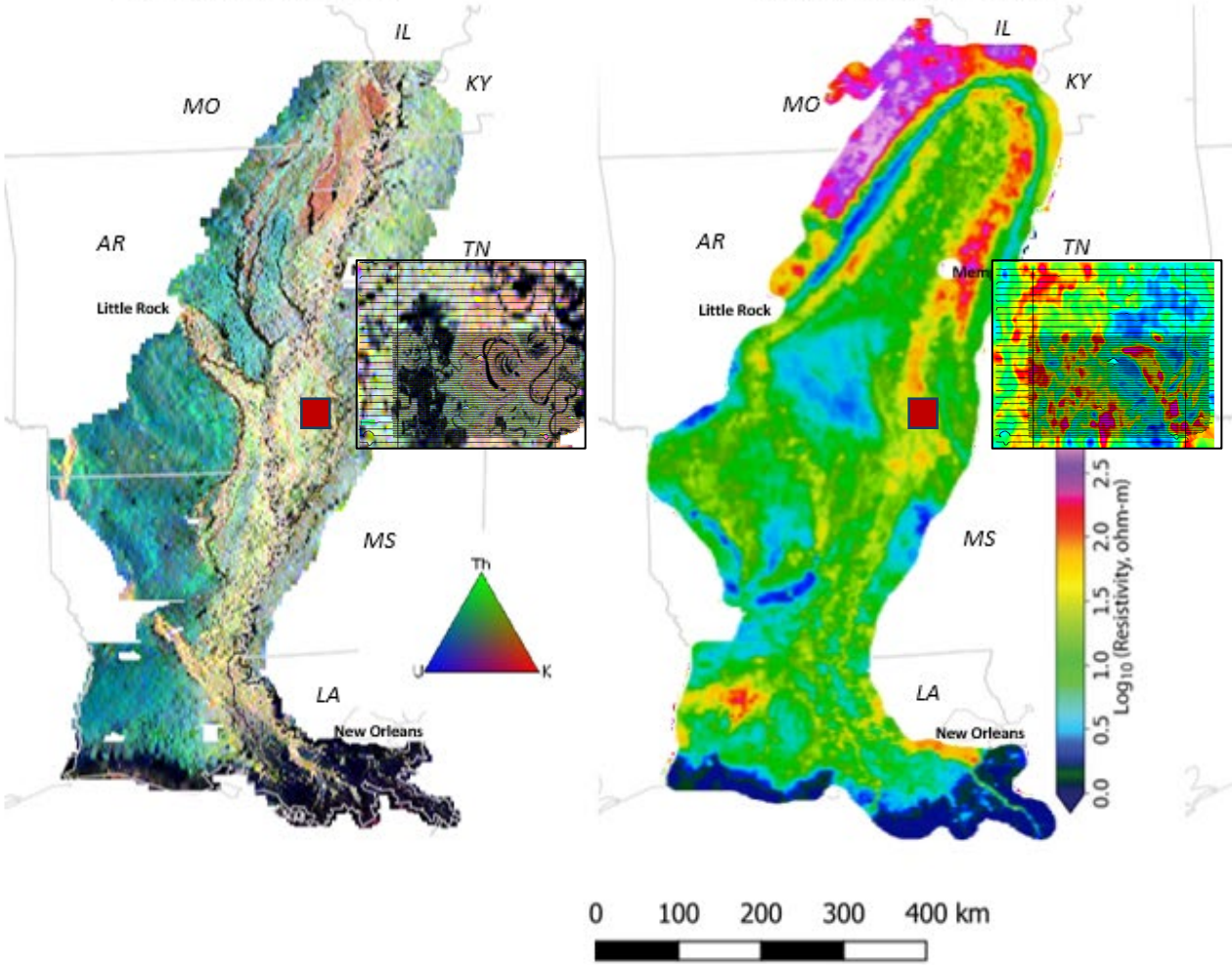
*Total completed 82,000+ line-km over more than 250,000 km$^2$ covering parts of 7 states*



Radiometric:
Upper 20-30 cm
Soils & recharge

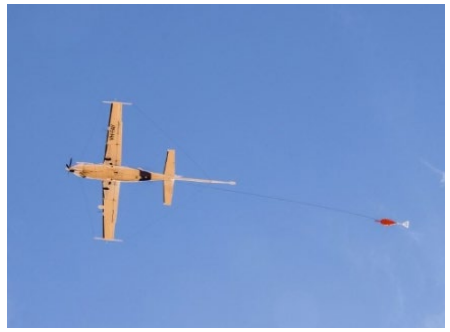
Resistivity:
1-300 m
Lithology & salinity

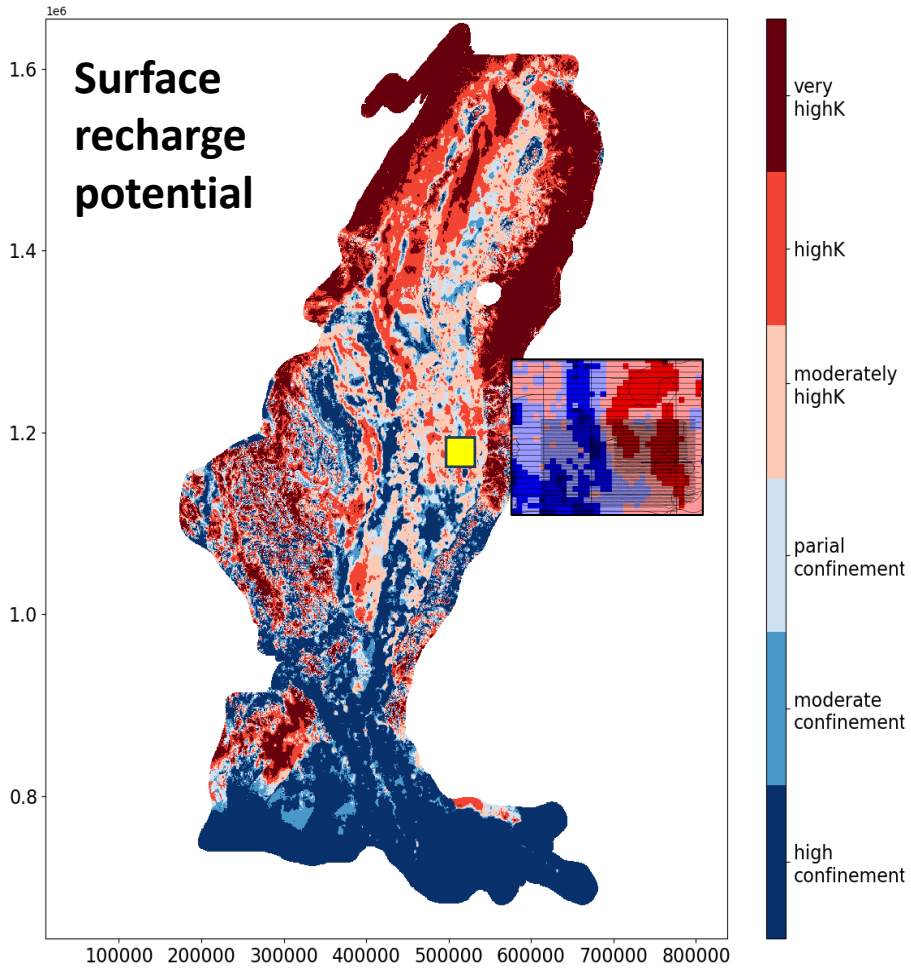
Magnetic:
100 m - kms
Basement structure

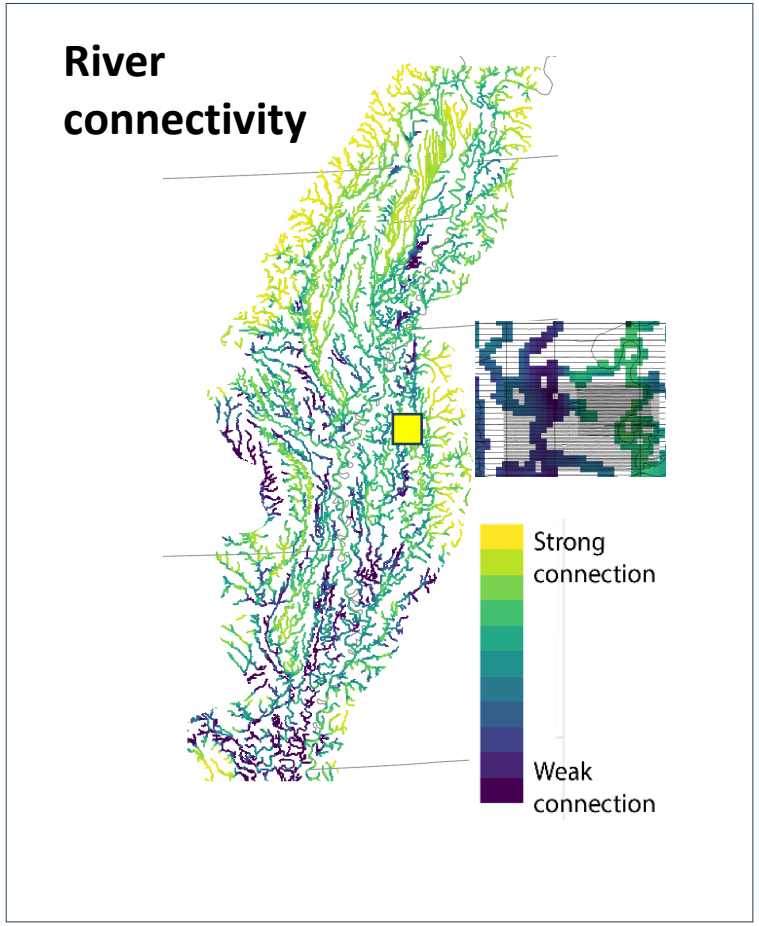



Minsley et al., Communications Earth & Environment, 2021

# Examples of translating geophysical results to hydrogeologic properties of interest

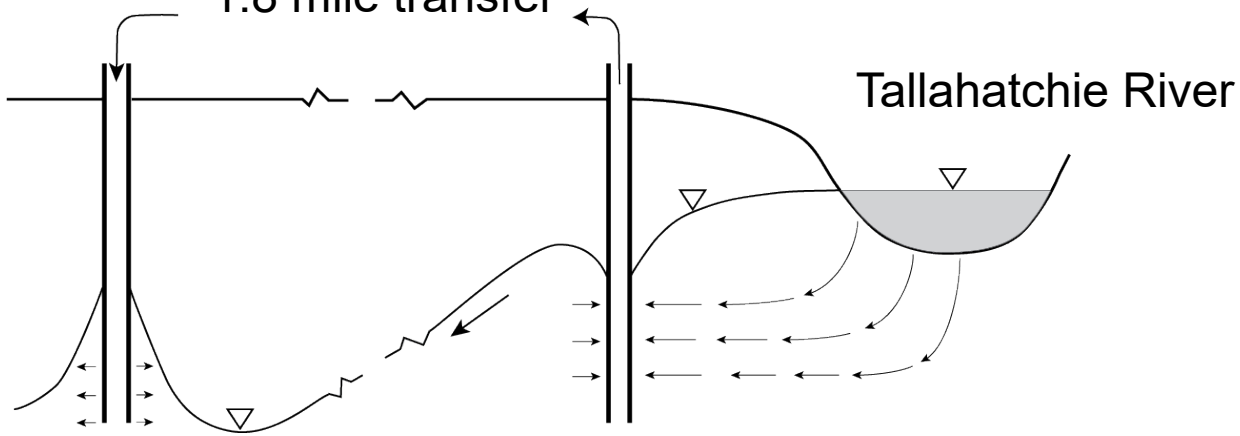


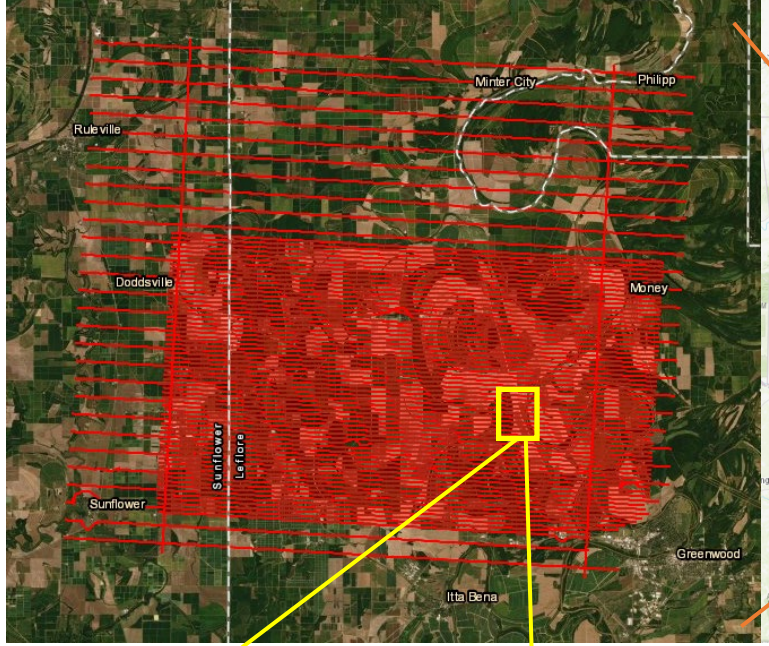


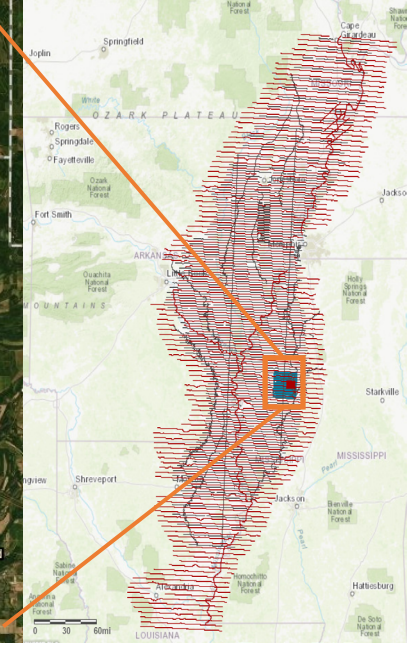



# Bank filtration, transfer, and injection: Mapping aquifer structure to inform aquifer recharge pilot project installation


1 extraction, 2 injection wells
1.8 mile transfer

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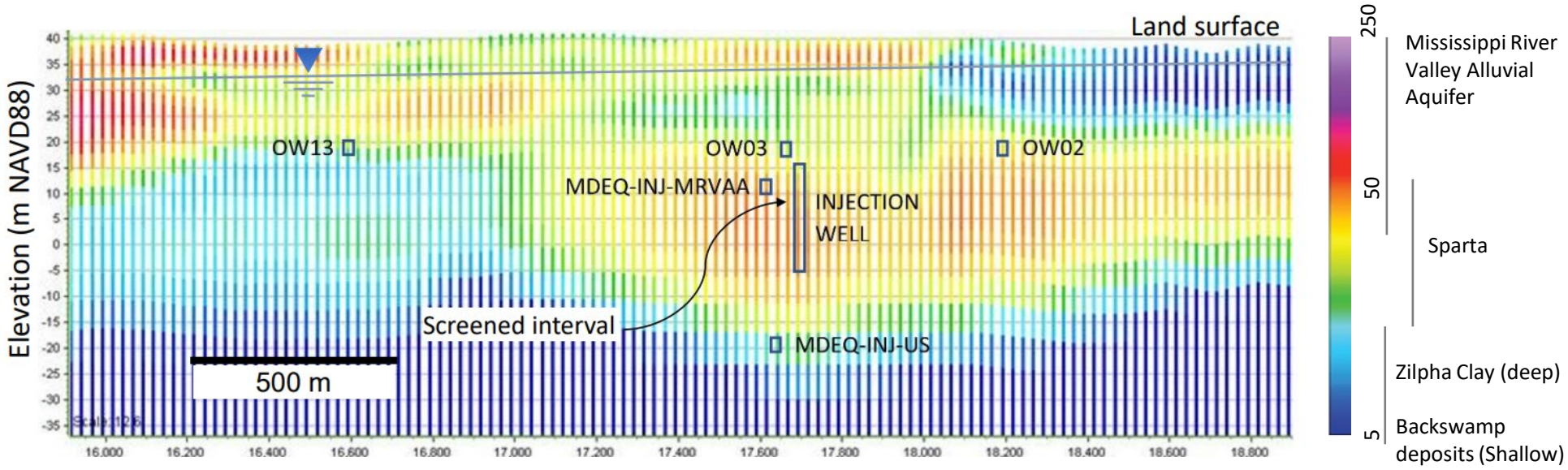
# AEM survey shows complex geological heterogeneity

- Higher resistivity (warmer colors) represent coarser sediments
- Heterogeneity is a key control on groundwater flow and quality
- Variations in lithology likely contribute to soil piping at injection & extraction wells

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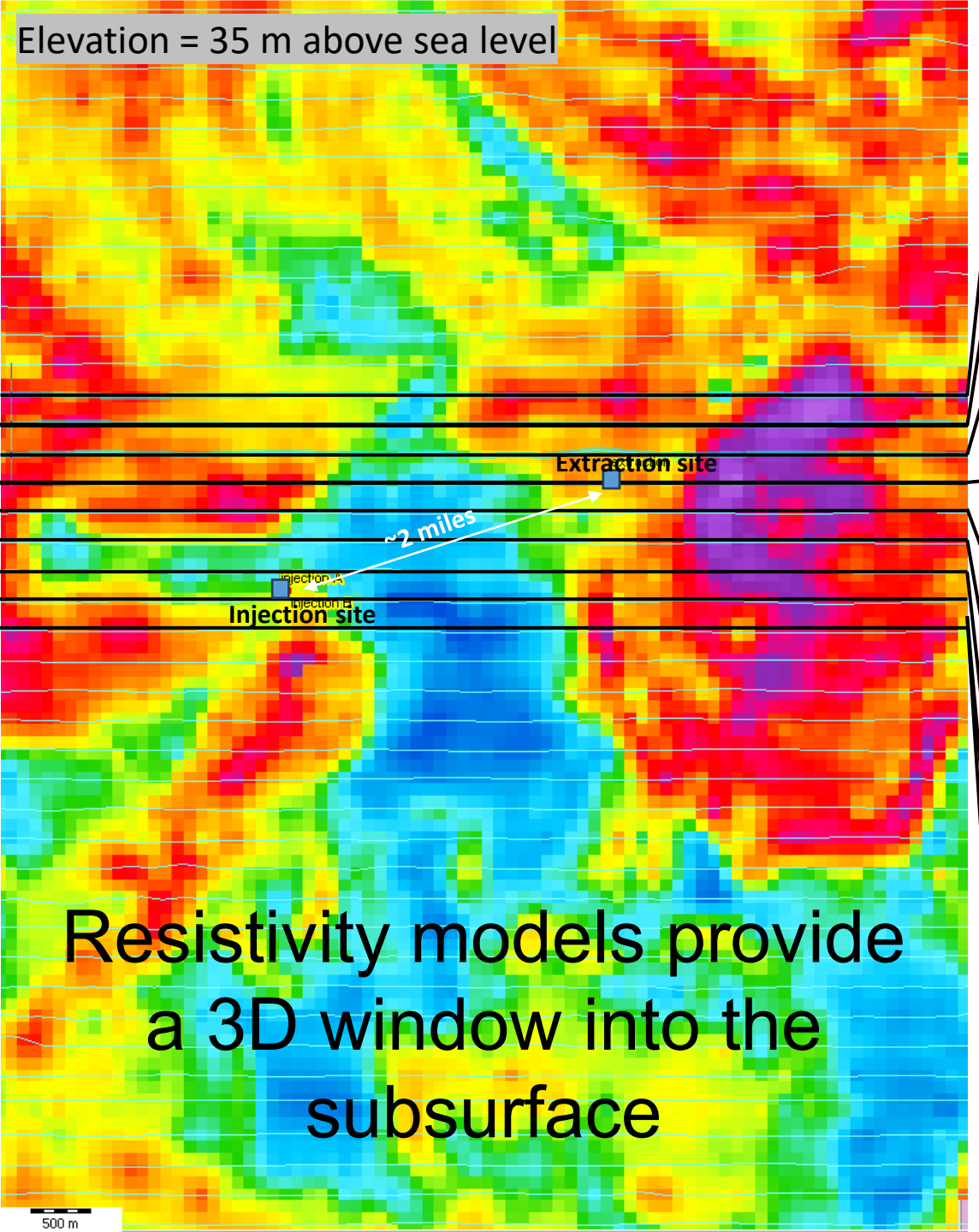
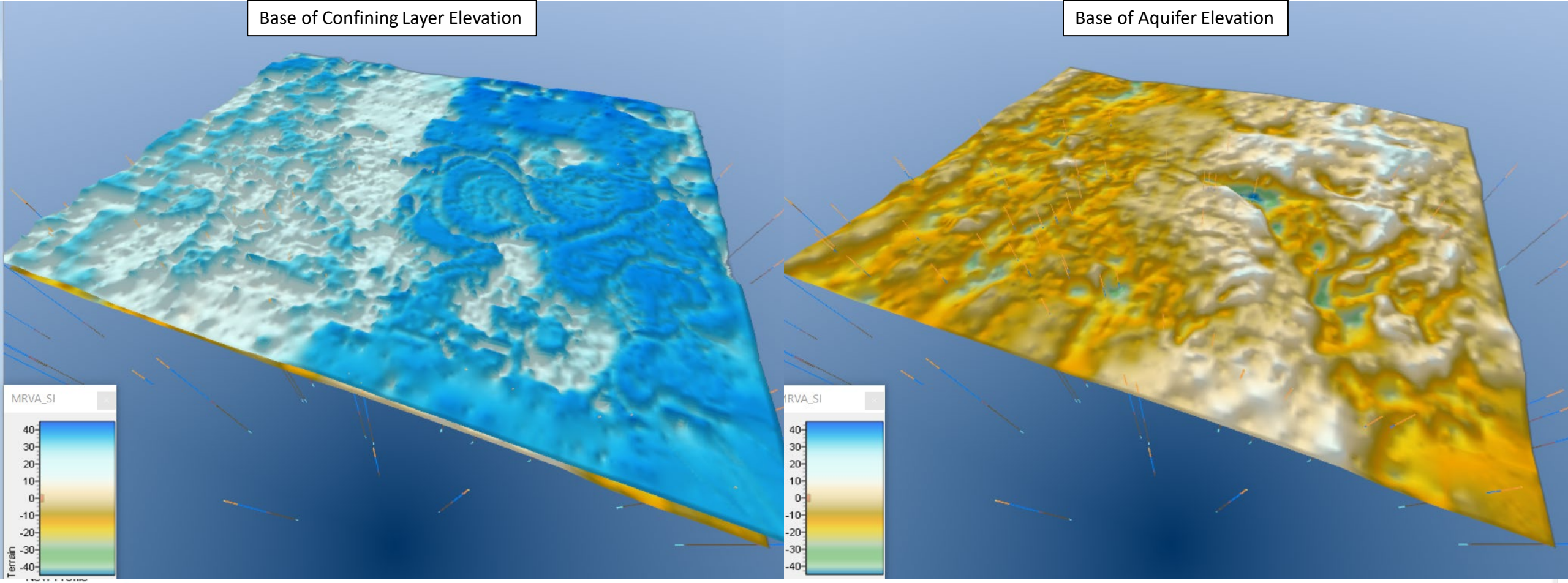
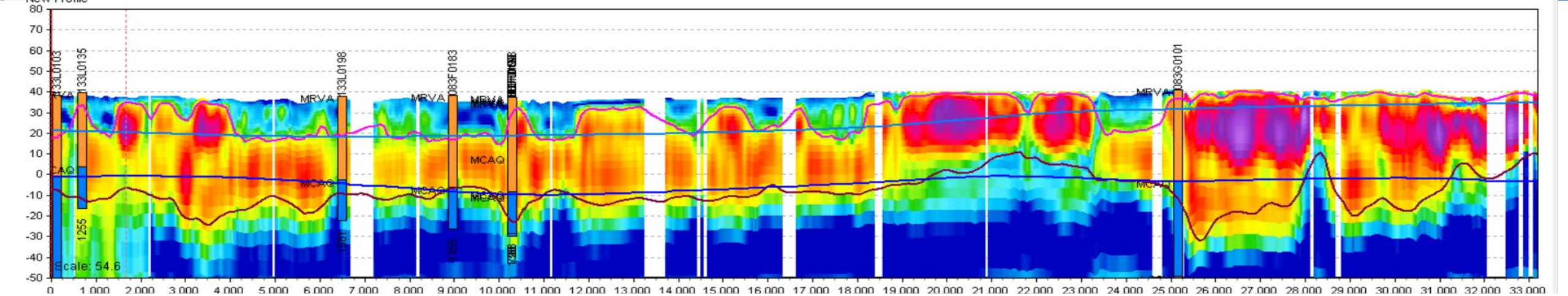
Slide credit: A.M. O'Reilly, USDA ARS


Elevation = 35 m above sea level
Extraction site
~2 miles
Injection A
Injection B
Injection site
Resistivity models provide a 3D window into the subsurface
500 m

Base of Confining Layer Elevation

Base of Aquifer Elevation

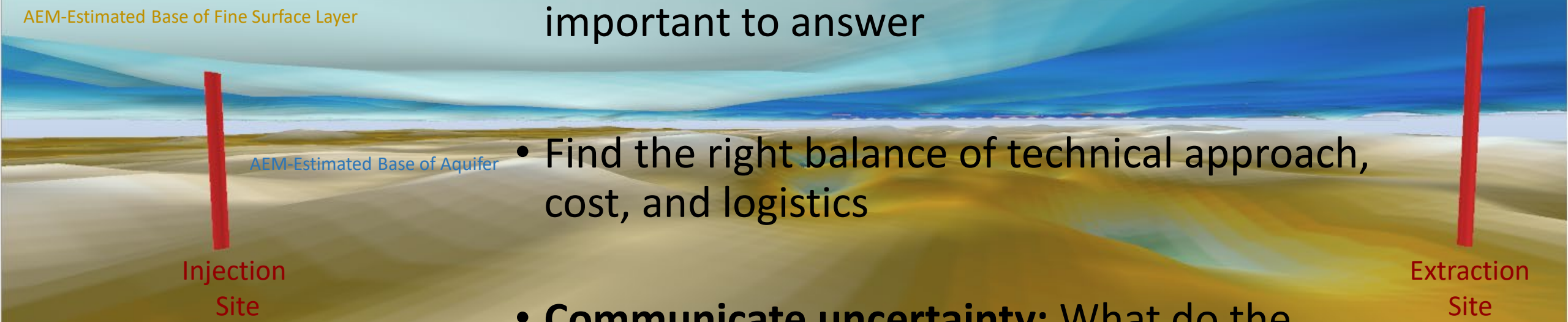


VIEW FROM WITHIN THE AQUIFER

# Summary

- **Identify the question:** Before deciding on geophysical methods, think about the hydrogeologic question(s) that are most important to answer




- Find the right balance of technical approach, cost, and logistics
- **Communicate uncertainty:** What do the geophysical results tell us (or not) about the subsurface?

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# References


- Minsley, B.J., Ajo-Franklin, J., Mukhopadhyay, A. and Morgan, F.D. (2011), Hydrogeophysical Methods for Analyzing Aquifer Storage and Recovery Systems. Groundwater, 49: 250-269. https://doi.org/10.1111/j.1745-6584.2010.00676.x.
- Minsley, B.J. & A. Yusen Ley-Cooper (2015) Quantifying model structural uncertainty and facies prediction for locating groundwater supplies in Timor-Leste using AEM data, ASEG Extended Abstracts, 2015:1, 1-4, DOI: 10.1071/ASEG2015ab126
- Minsley, B.J., Rigby, J.R., James, S.R. *et al.* Airborne geophysical surveys of the lower Mississippi Valley demonstrate system-scale mapping of subsurface architecture. *Commun Earth Environ* **2**, 131 (2021). https://doi.org/10.1038/s43247-021-00200-z
- Burton, B.L., Minsley, B.J., Bloss, B.R., Kress, W.H., Rigby, J.R., and Smith, B.D., 2020, High-resolution airborne geophysical survey of the Shellmound, Mississippi area: U.S. Geological Survey Scientific Investigations Map 3449, 2 sheets, https://doi.org/10.3133/sim3449.


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