Advancing Earth Imaging Techniques for Improved Understanding of Groundwater Systems

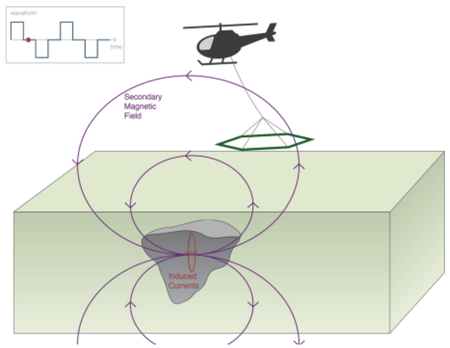
(Example: The Central Valley of California)

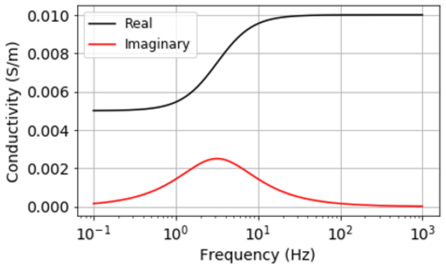
Seogi Kang

Stanford University

👋 hello (a bit about me)

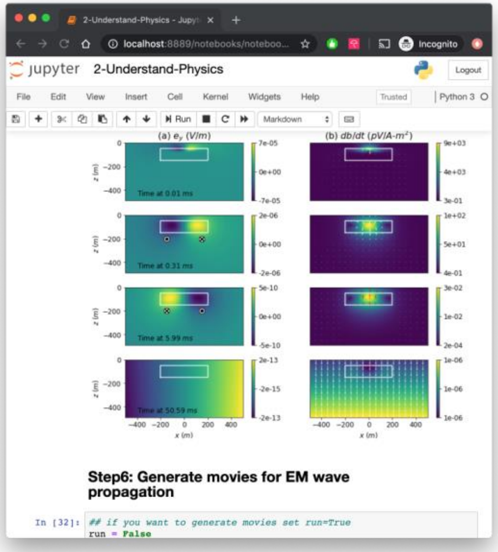
Computational EM geophysics





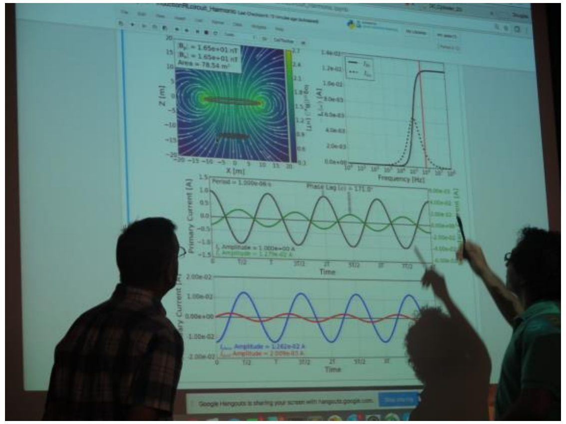
THE UNIVERSITY OF BRITISH COLUMBIA

Open-source software



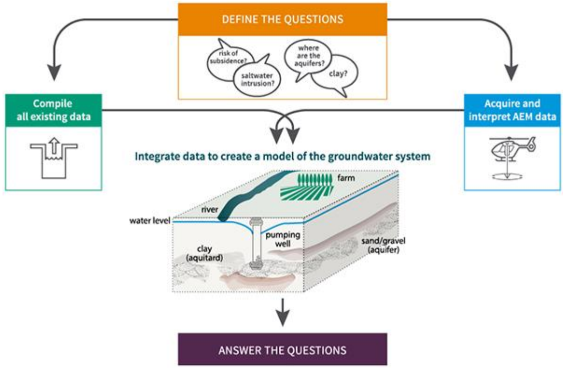
simpeg

Open research & education



GeoSci.xyz

Groundwater science & management



Stanford University

Water matters.

https://www.amnh.org/explore/ology/water/what-is-water

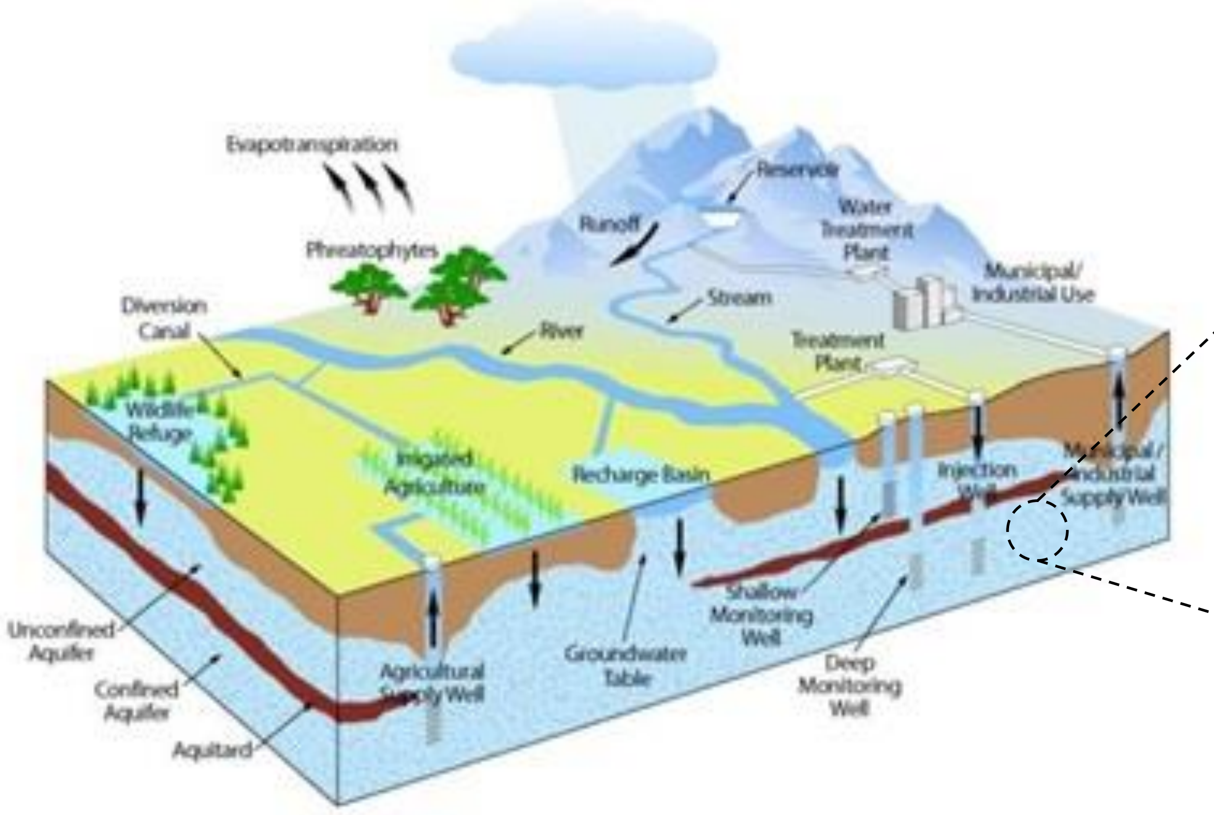

Wet year: 2017
Lake Oroville, CA, U.S.A

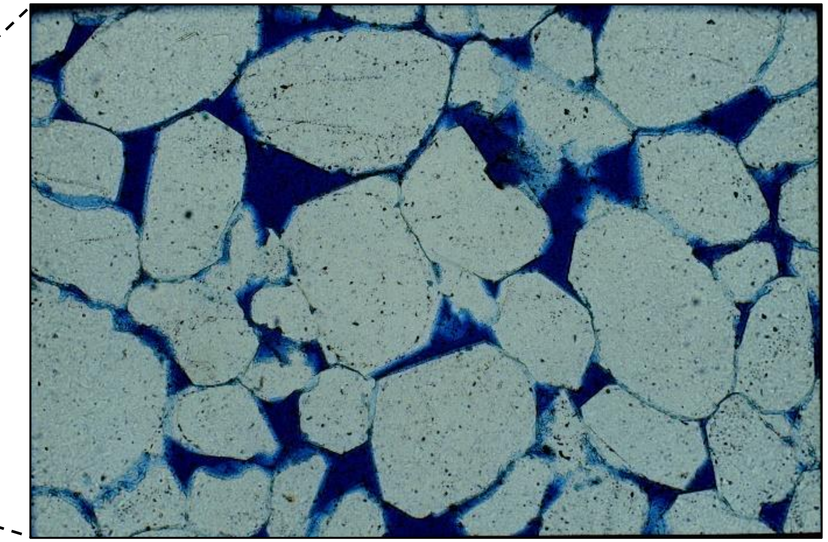

Wet year: 2017
Lake Oroville, CA, U.S.A.


Drought year: 2014

97% of all liquid freshwater

Groundwater

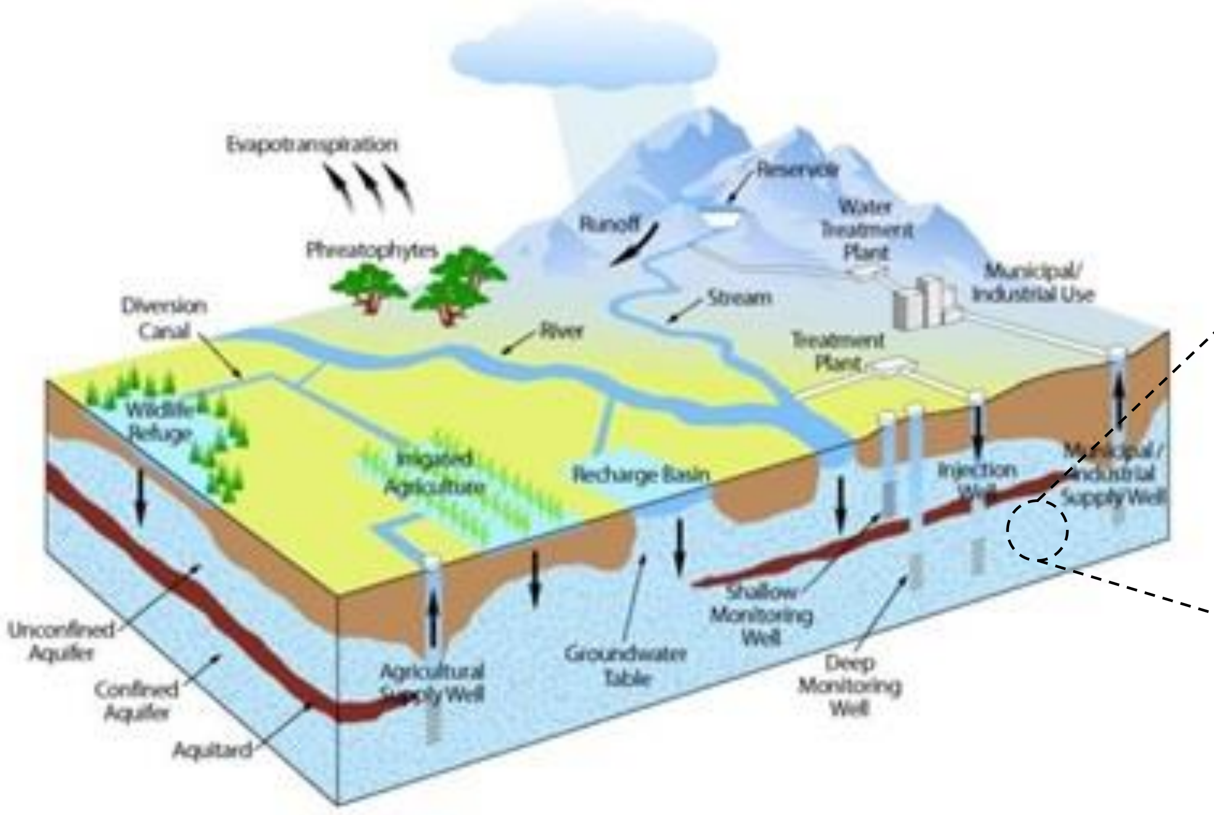


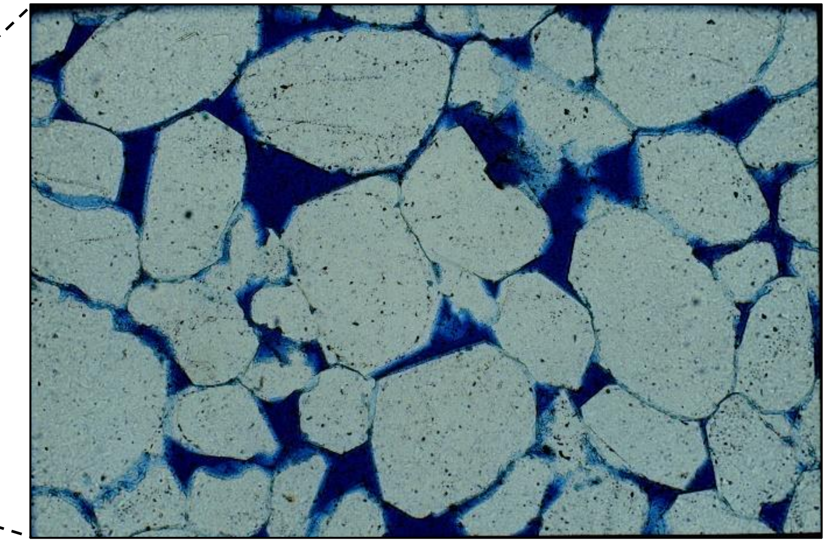


population growth
climate change

97% of all liquid freshwater

Groundwater





RESEARCH

GROUNDWATER

Global groundwater wells at risk of running dry

Scott Jasechko[1]* and Debra Perrone[2]

Science

NO WATER FOR IRRIGATION

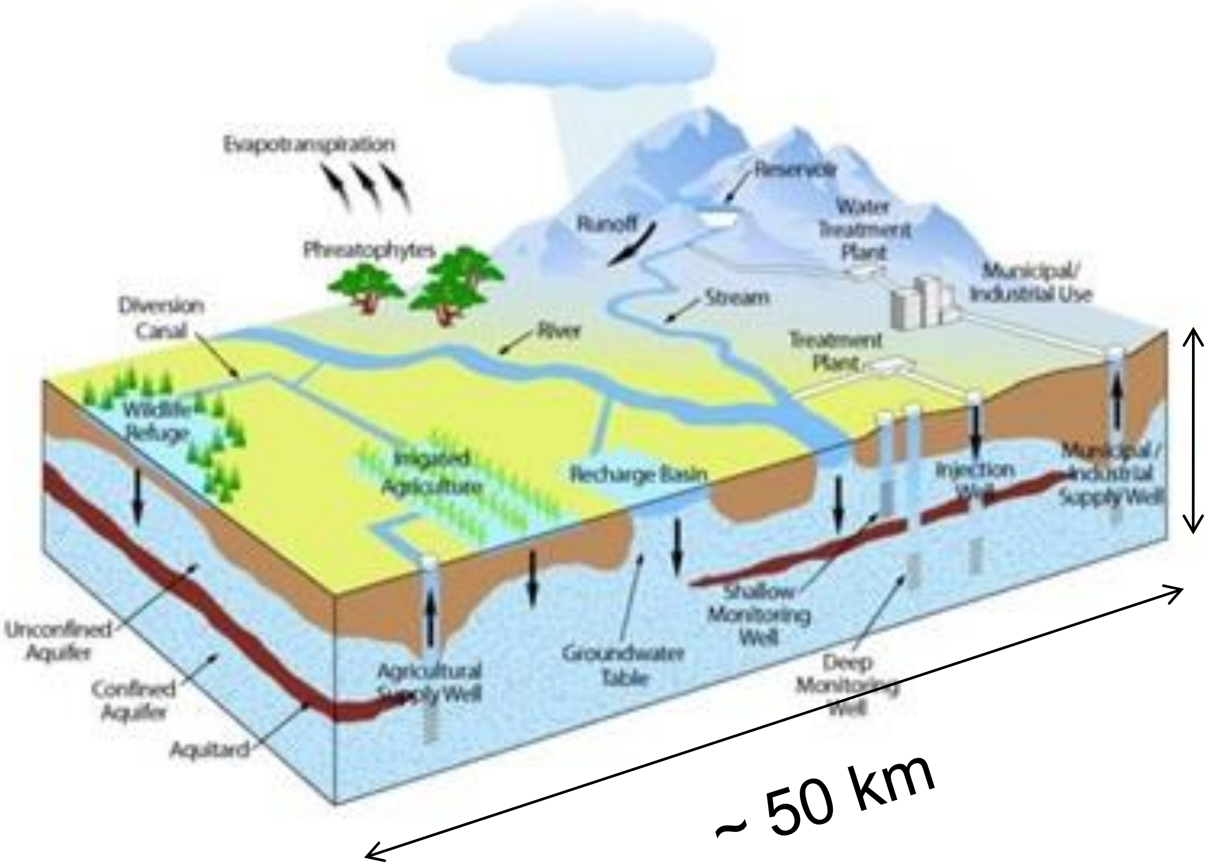
Almond Farmers Ripping Out Trees

Morris (from Bloomberg; 2021)

For improved understanding of groundwater systems

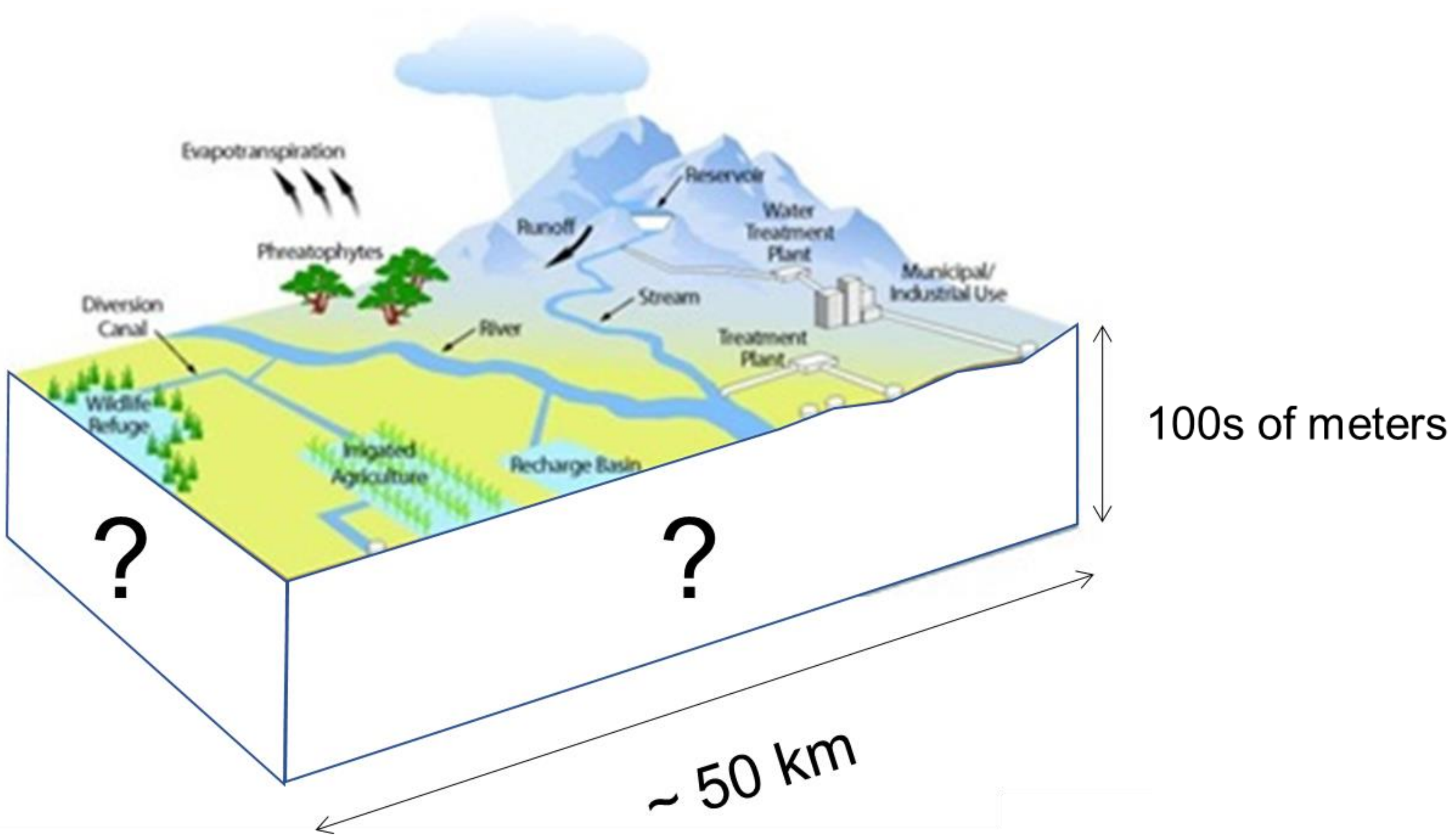
Need to “monitor” groundwater systems

Groundwater flow & volume



100s of meters

CANNOT pursue groundwater science & management without seeing "under" the ground



Traditional approach: Well-based

Drilling a well

Pros:

- Accurate point information
- Direct information
  - hydrogeology (e.g., lithology)
  - groundwater head

Cons:

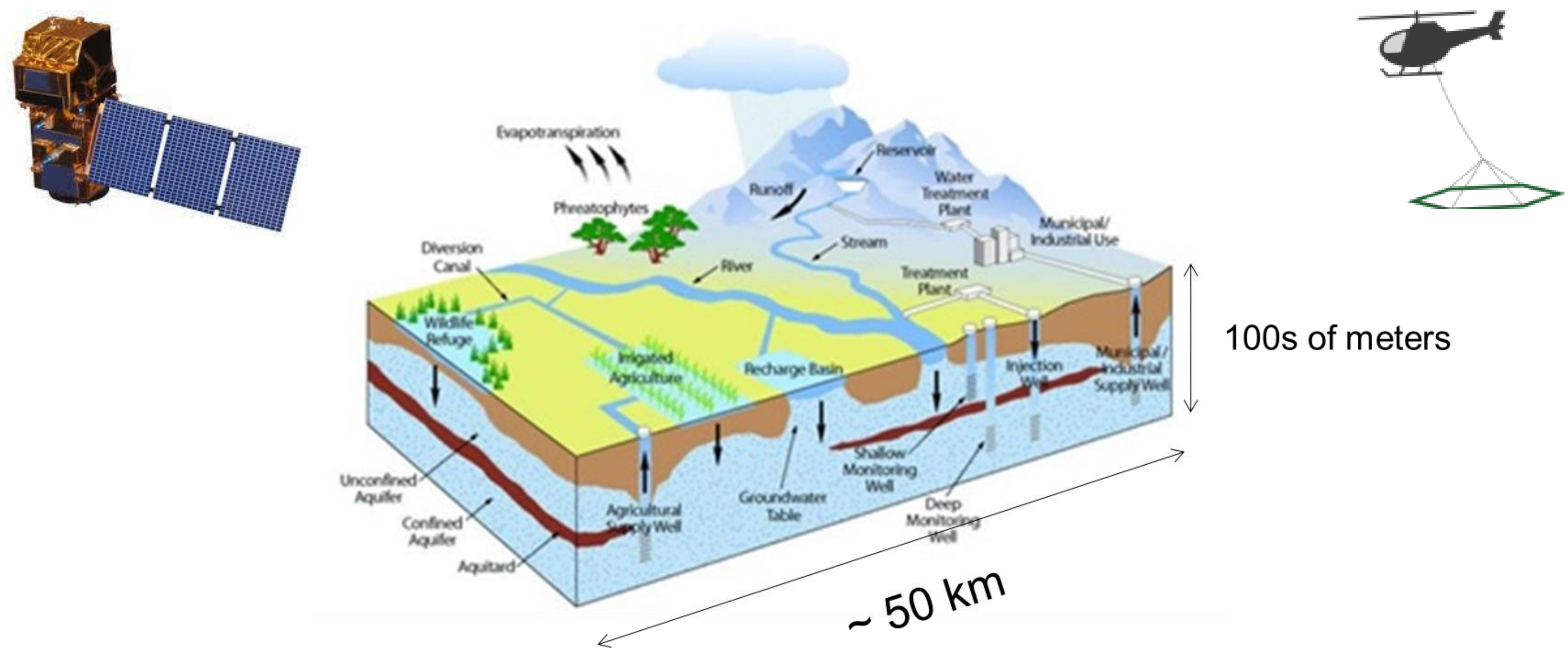
- Variable quality
- Low spatial density in lateral dimensions
- Decreasing coverage with increasing depth (due to increasing drilling cost)

Large data gap between wells and at deeper depths

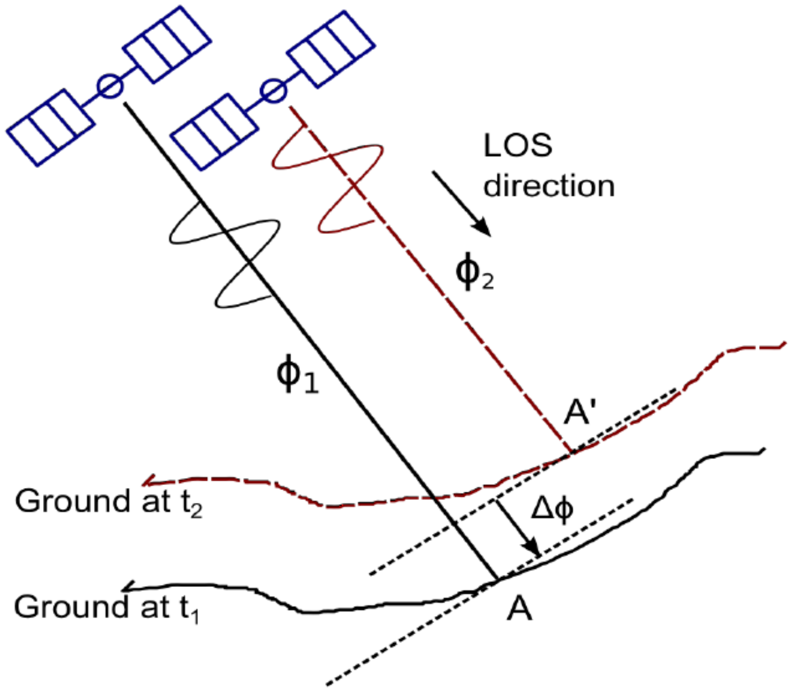
Alternate approach: Earth imaging techniques

Satellite Interferometric Synthetic Aperture Radar (InSAR)

Airborne Electromagnetic (AEM) Method

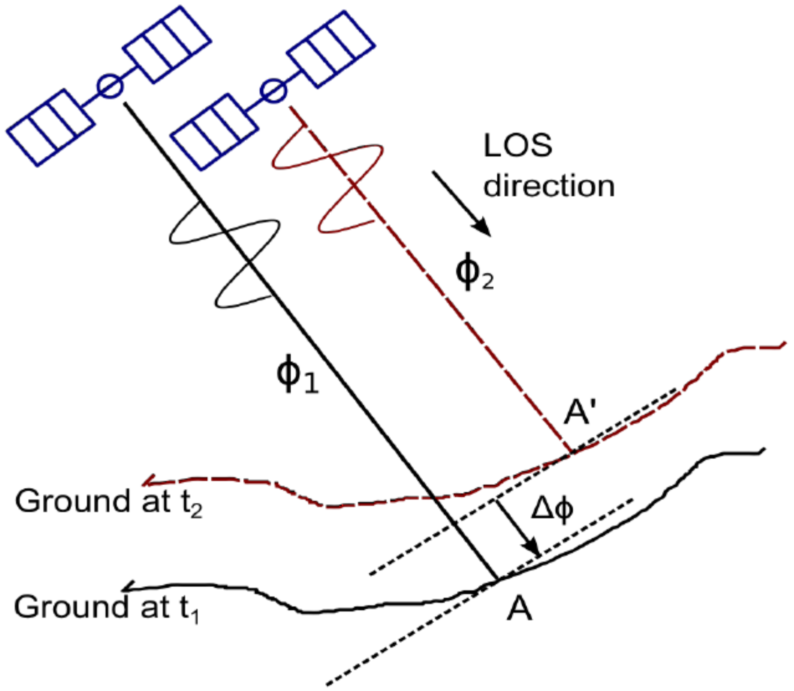


InSAR for monitoring groundwater head



Spatial and temporal changes in groundwater head are encoded in the ground deformation

InSAR for monitoring groundwater head



Spatial and temporal changes in groundwater head are encoded in the ground deformation

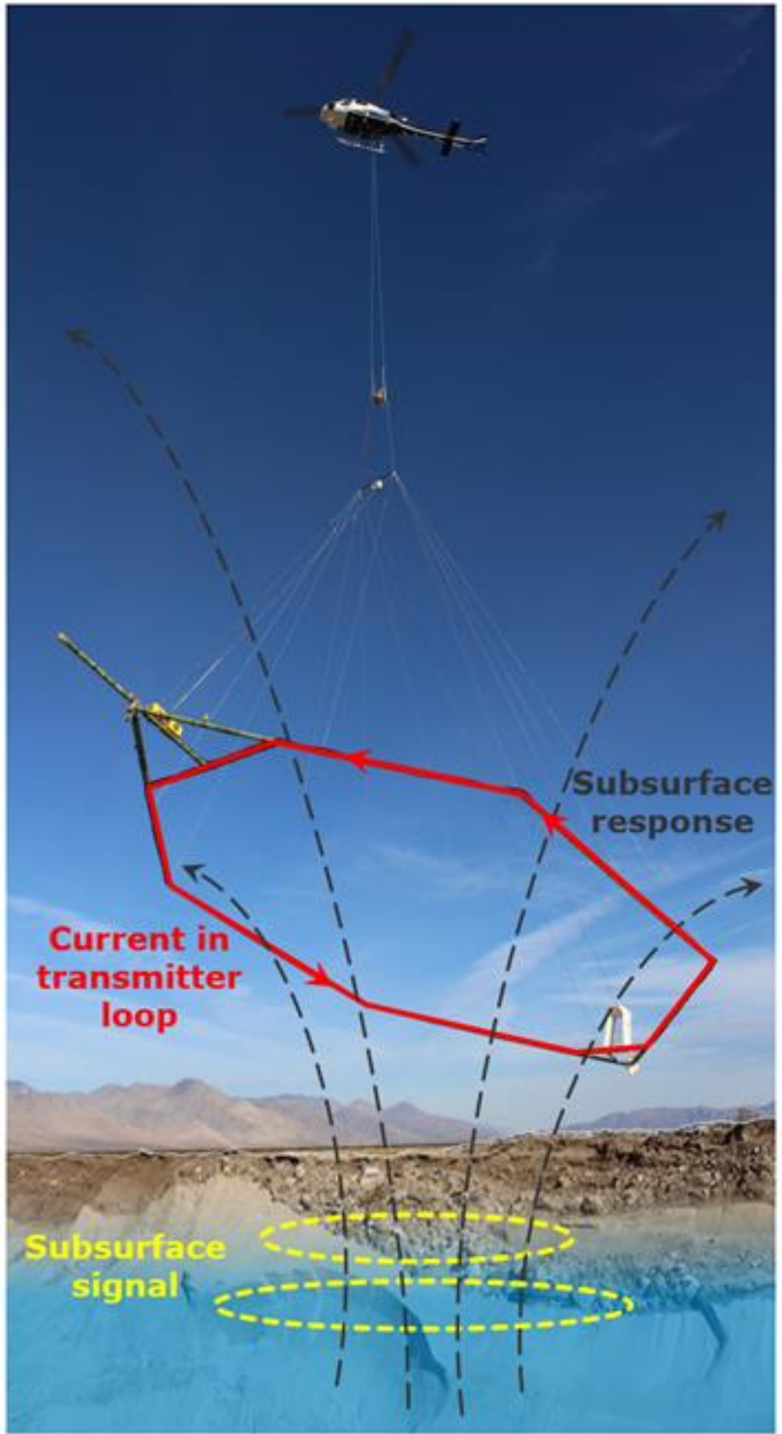
Pros

- Great spatial coverage: Earth surface
- High spatial density: 20-100 m
- Good temporal sampling rate: 6-12 days
- Sensitive to the head in the deeper aquifers (confined or semi-confined)

Cons

- Indirect information about the head
- Other factors affecting deformation

  Hydrologic loading
  (water, ice, snow)
  …



AEM method for imaging the subsurface

Pros:

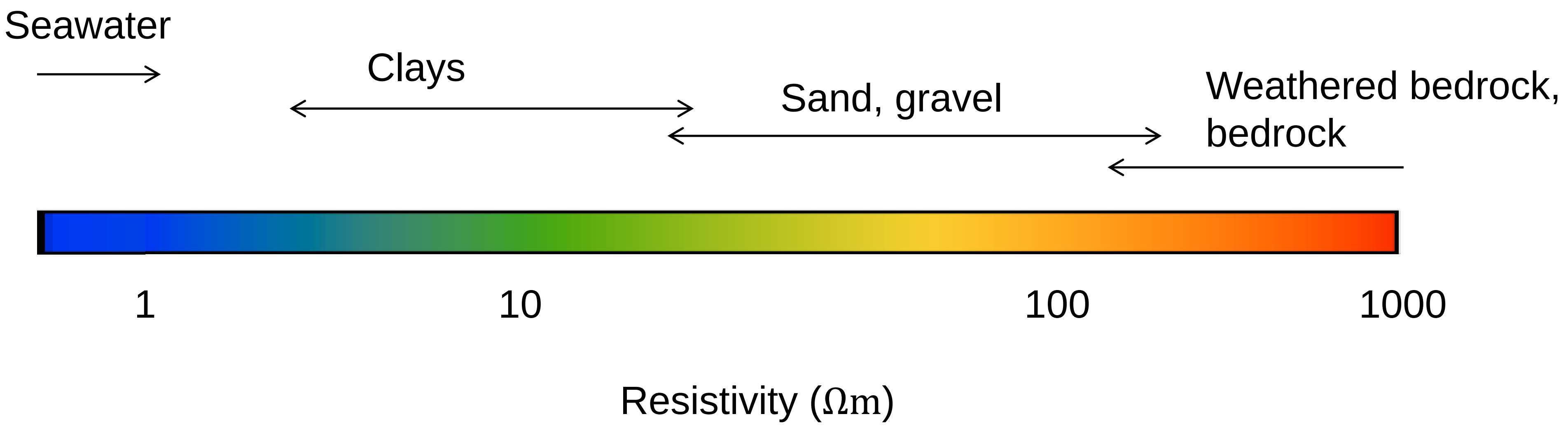
- Can rapidly map out large area
  (e.g., 100 km/hr)
- Sensitive to the large-scale feature

Cons:

- Provide indirect information
  (electrical resistivity)
- Limited resolution
  (degrading with depth)

CDWR (2021)

Electrical resistivity: ρ (Ωm)



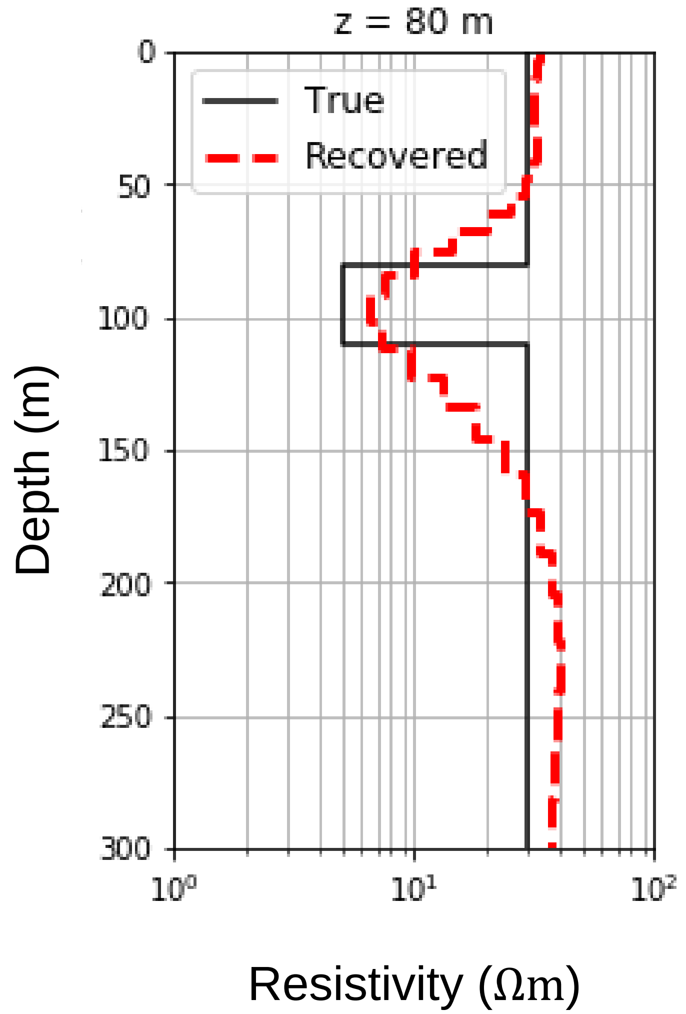
Varies over many orders of magnitude

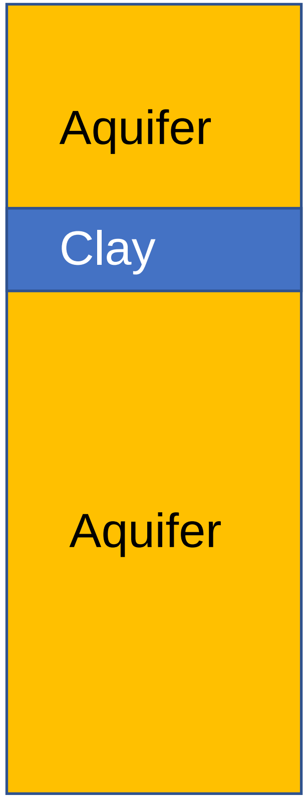
Depends on many factors:

- Sediment/Rock type – clay content is key factor
- Water content
- Connectivity of pores
- Salinity of the water

Limited resolution of the AEM data

Clay layer embedded in a homogenous aquifer



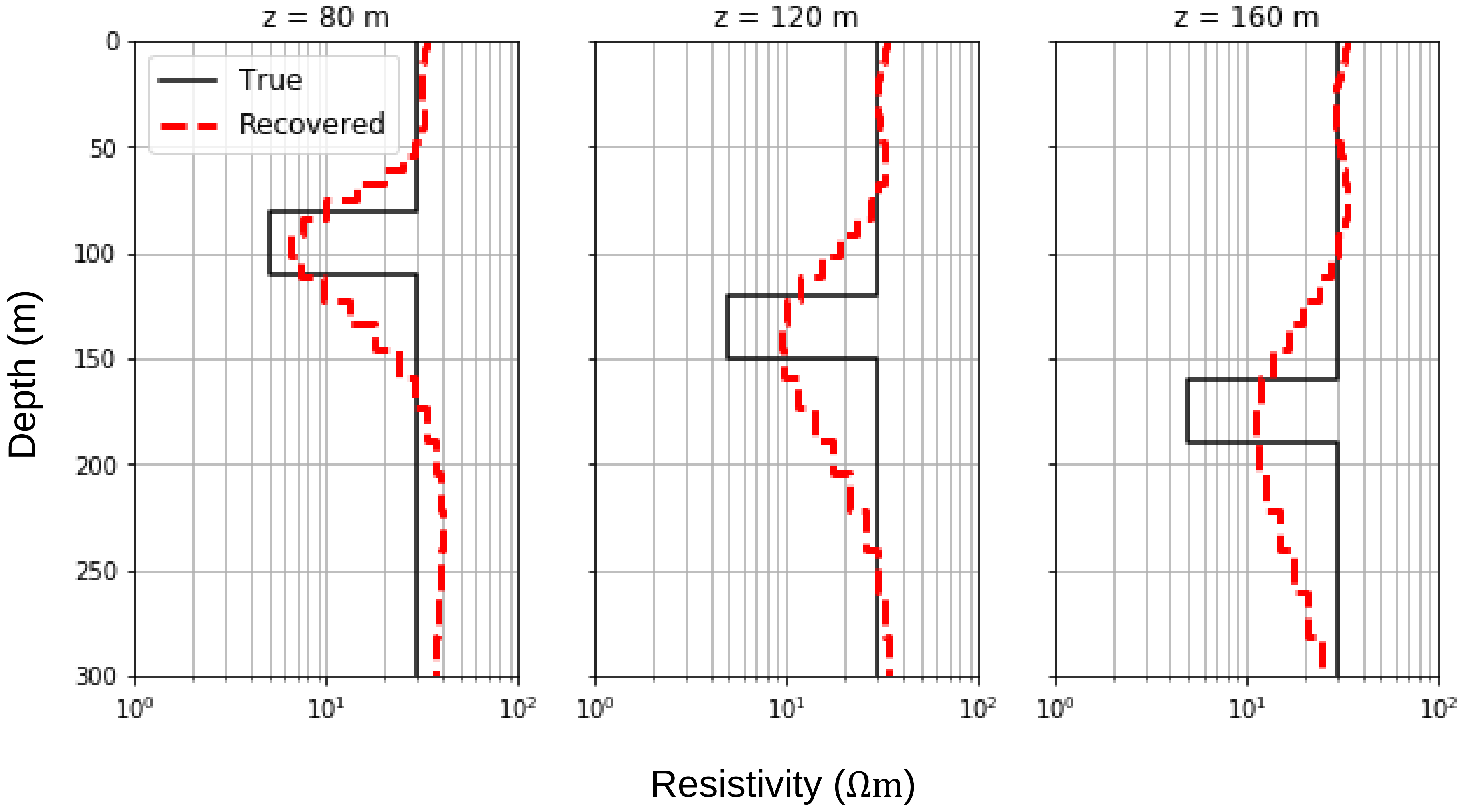


Smoothed layer boundaries due to

- Degrading resolution with depth
- Assumed “smooth” transition in resistivity (in the imaging process)

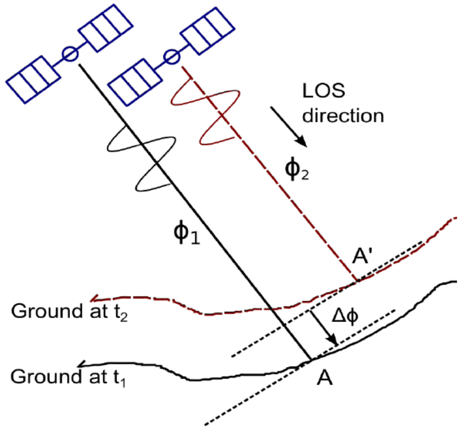
Limited resolution of the AEM data

Clay layer embedded in a homogenous aquifer (variable depth)



An overarching scientific question

How do we integrate modern remote sensing data and traditional well data to *image the subsurface* and *monitor groundwater systems*?



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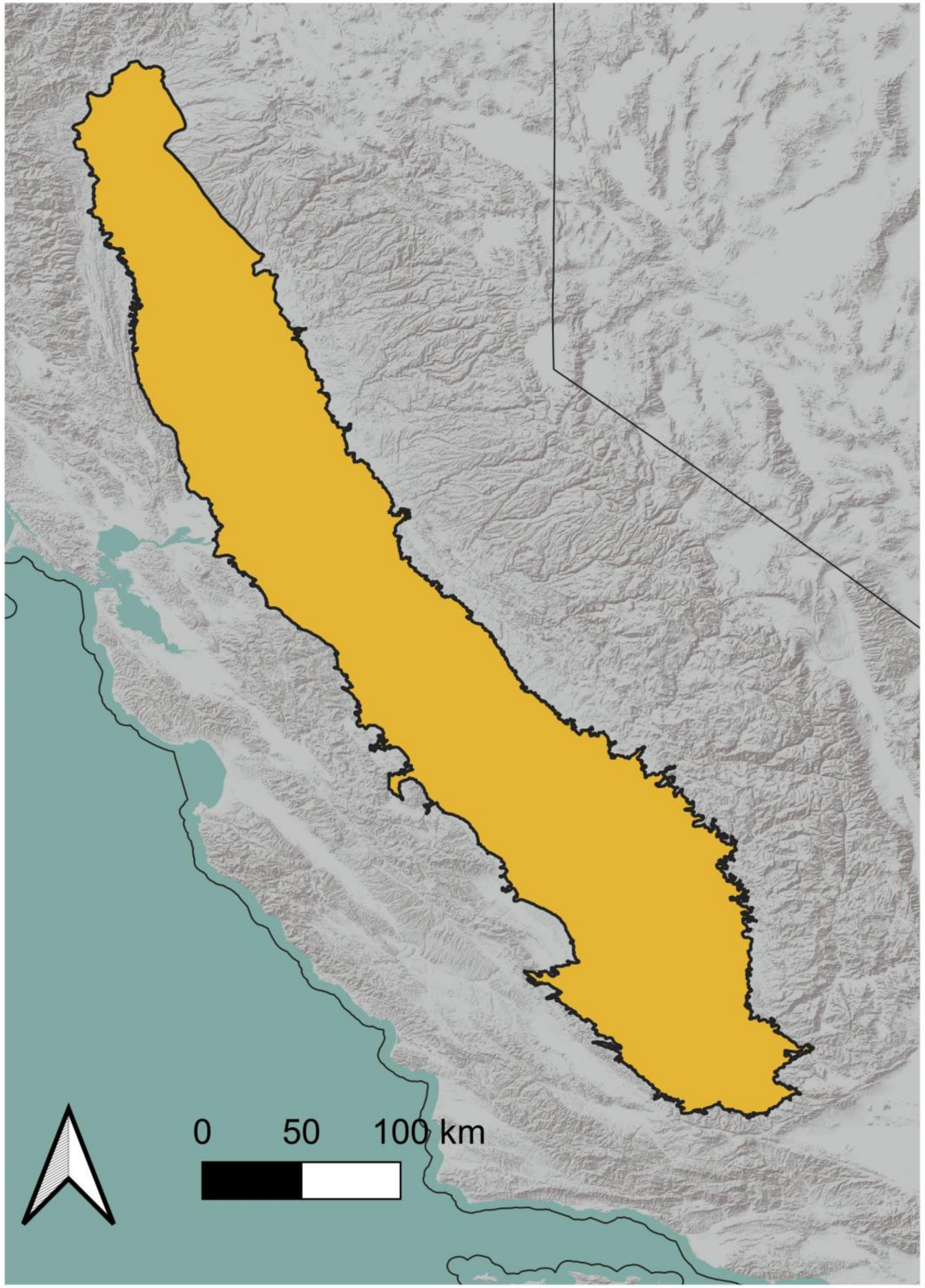
Central Valley of California

Very productive farmland

  Significant amount of surface & ground water

Severe droughts in California: 2012-2016

Sustainable Groundwater Management Act (SGMA, 2014)



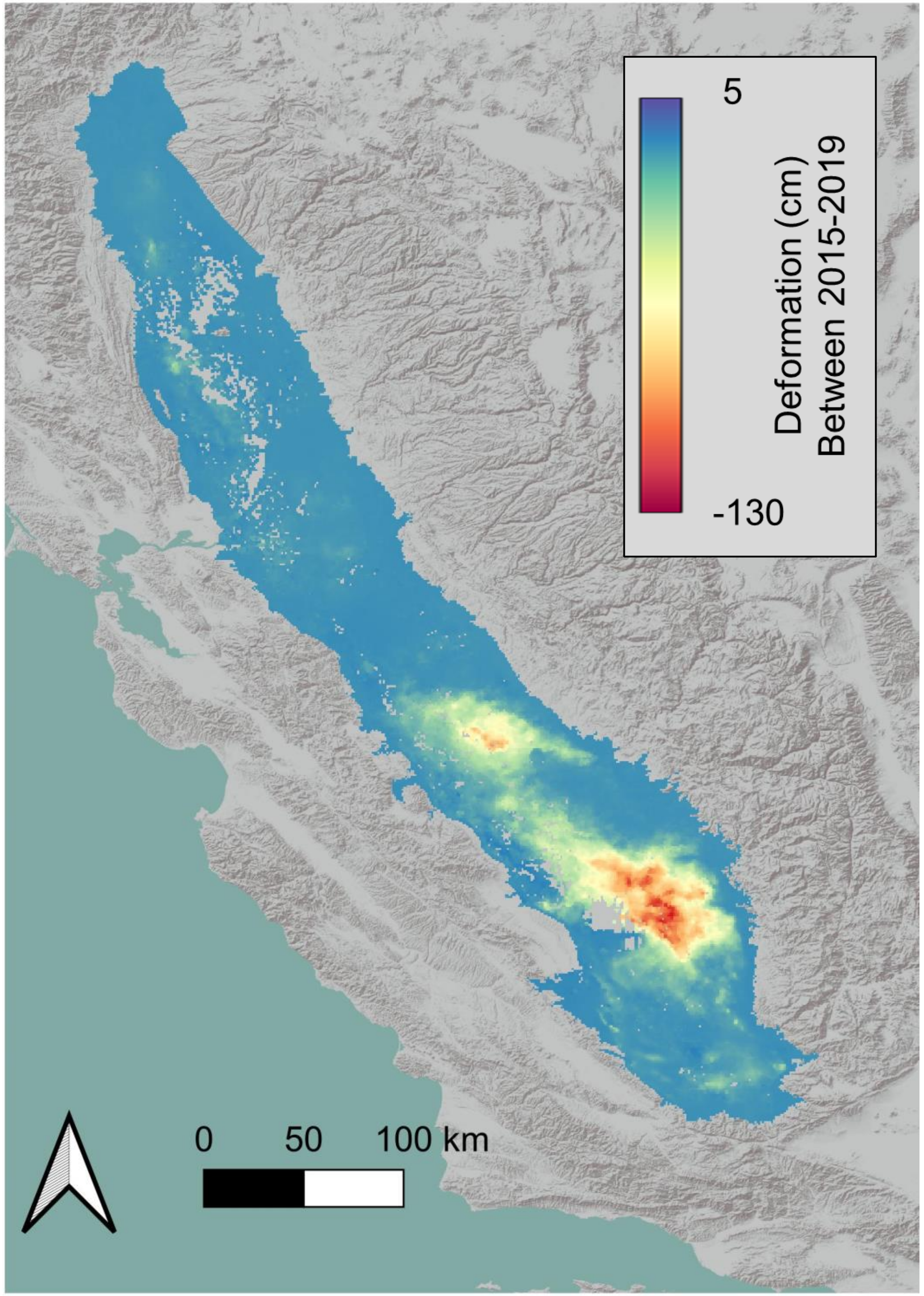
Central Valley of California

North – Sacramento Valley

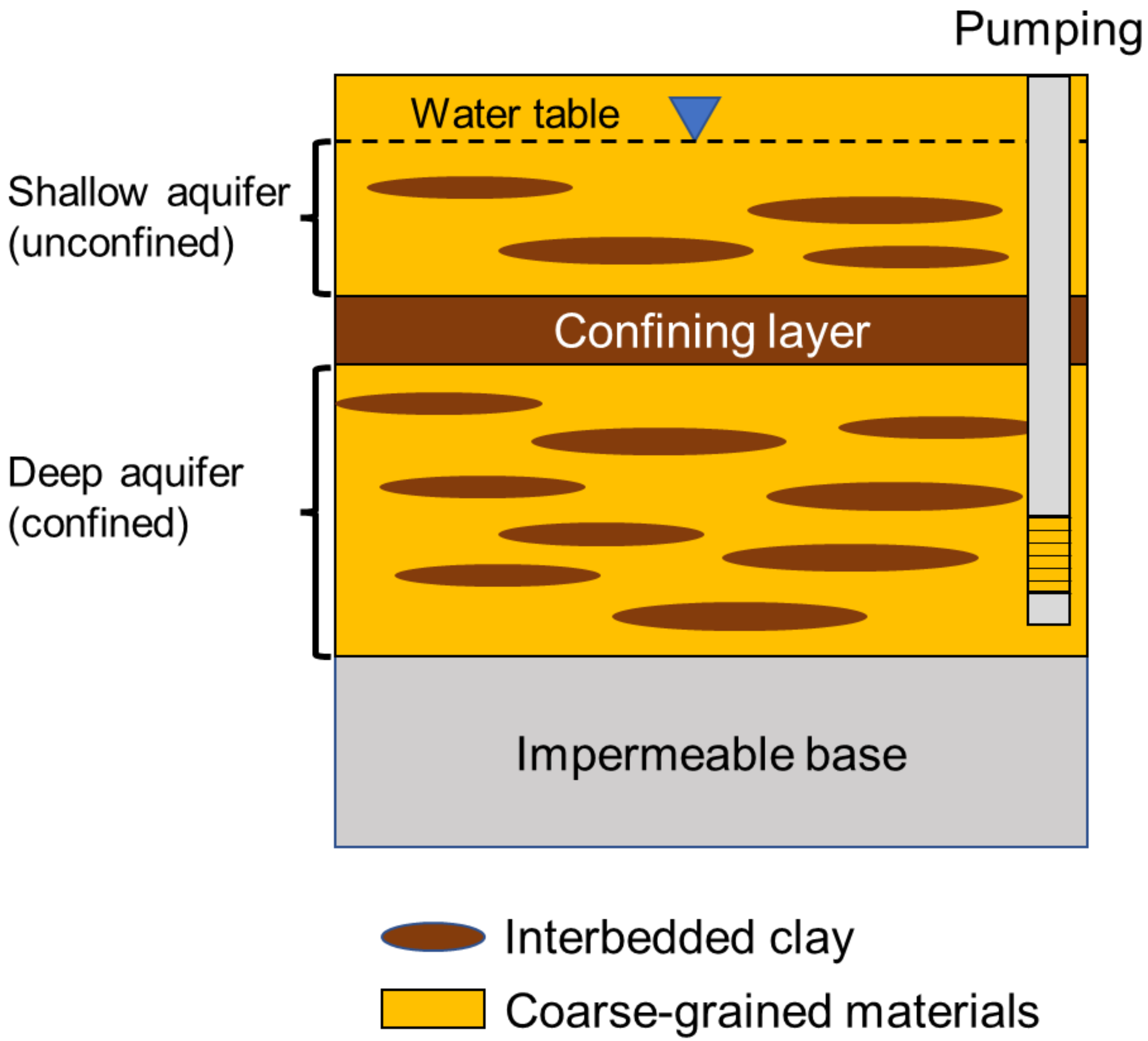
South – San Joaquin Valley

More pumping of groundwater
in the warmer, drier south.

Causes more <u>subsidence</u>



Aquifer system of the Central Valley

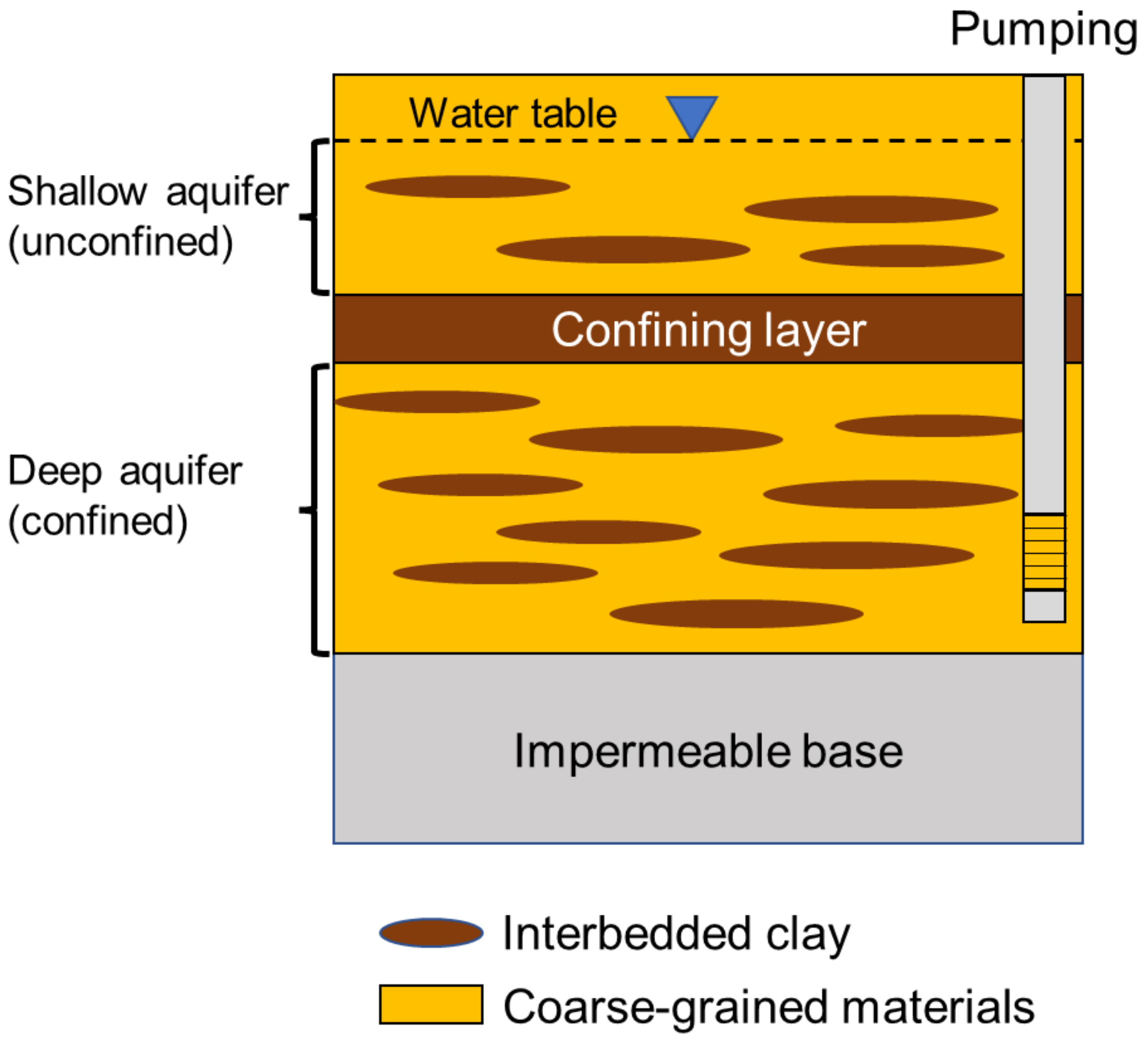


Composed of sediments

Numerous interbedded clays

Regional confining unit – Corcoran Clay

Conceptual model of the surface deformation



Pumping groundwater

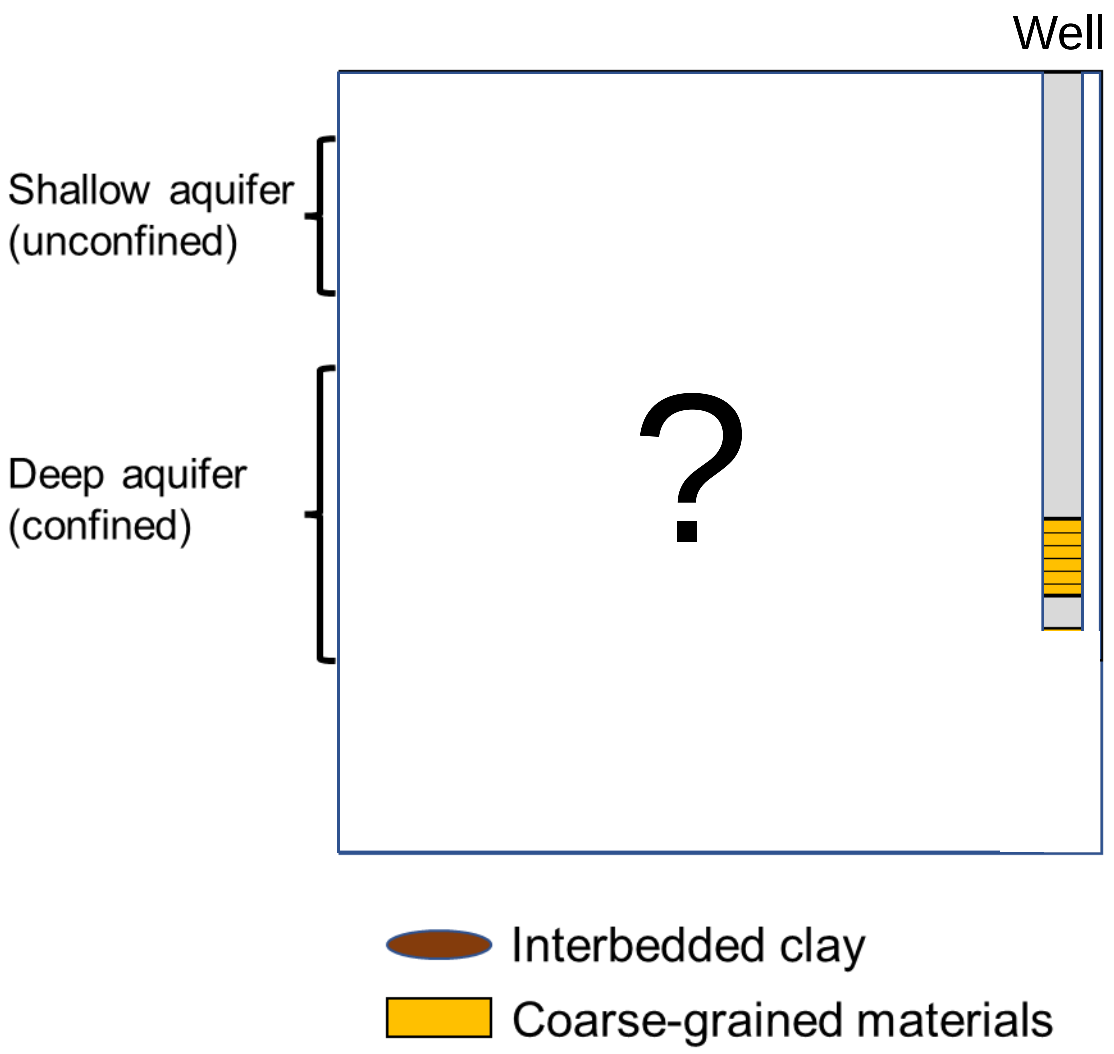
- Reduces the head
- Drains water from clays to coarse (diffusive process; takes time)
- Compacts the interbedded clays (head changes of the clays)

clay compressibility >> coarse compressibility

Driving force: Head change (in the deep confined aquifer)

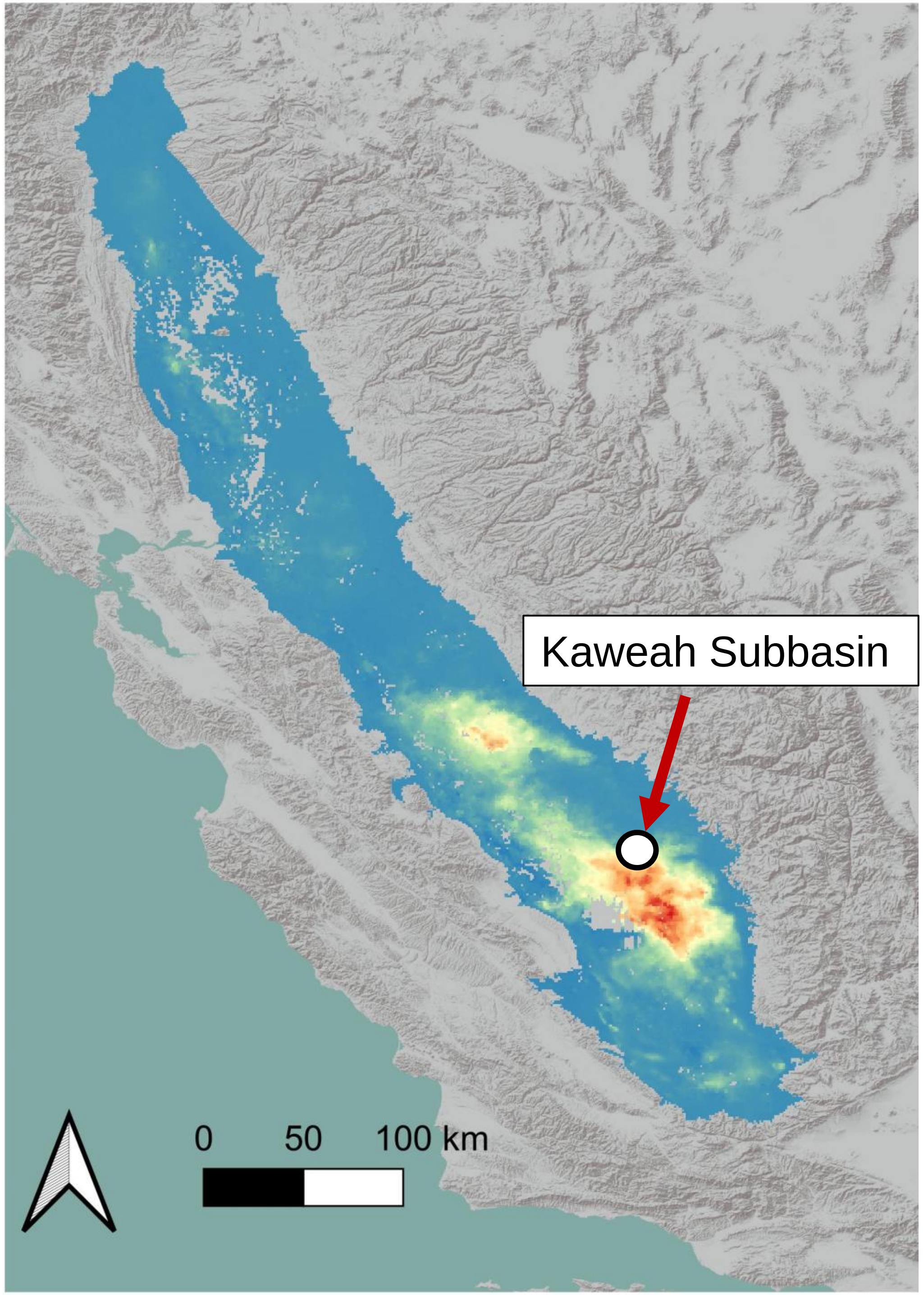
Modulation: Interbedded clays

But …



Subsurface hydrogeology is unknown

Measured head measurements are sparse in space and time

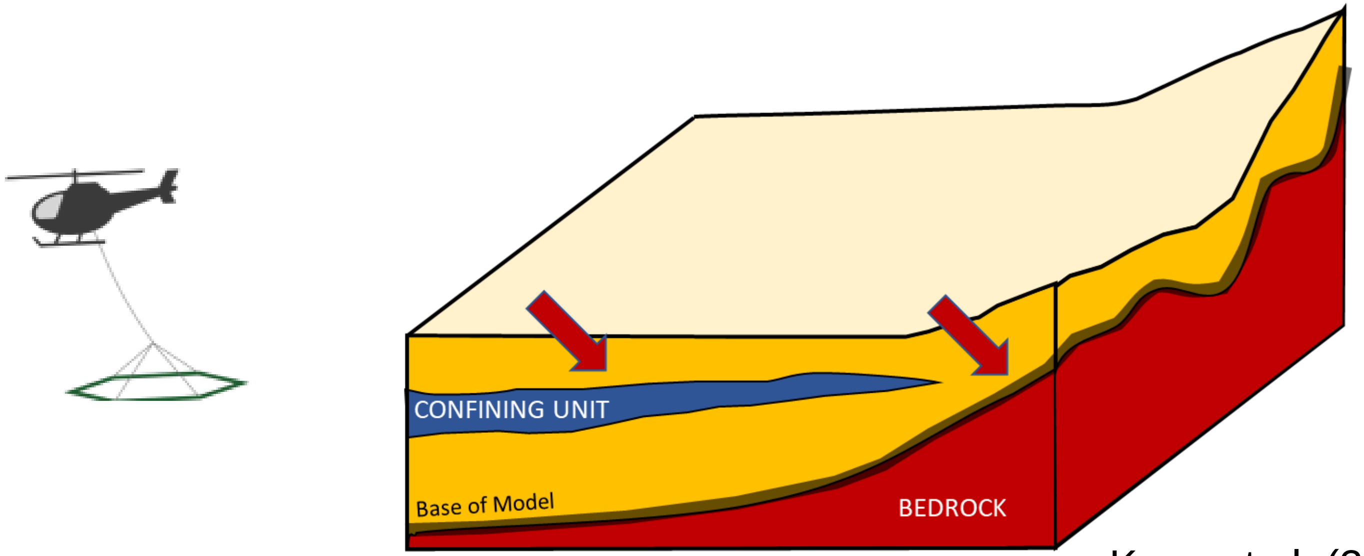


AEM for imaging the large-scale structure

InSAR for monitoring groundwater head

Case study in Kaweah Subbasin in California, U.S.A.

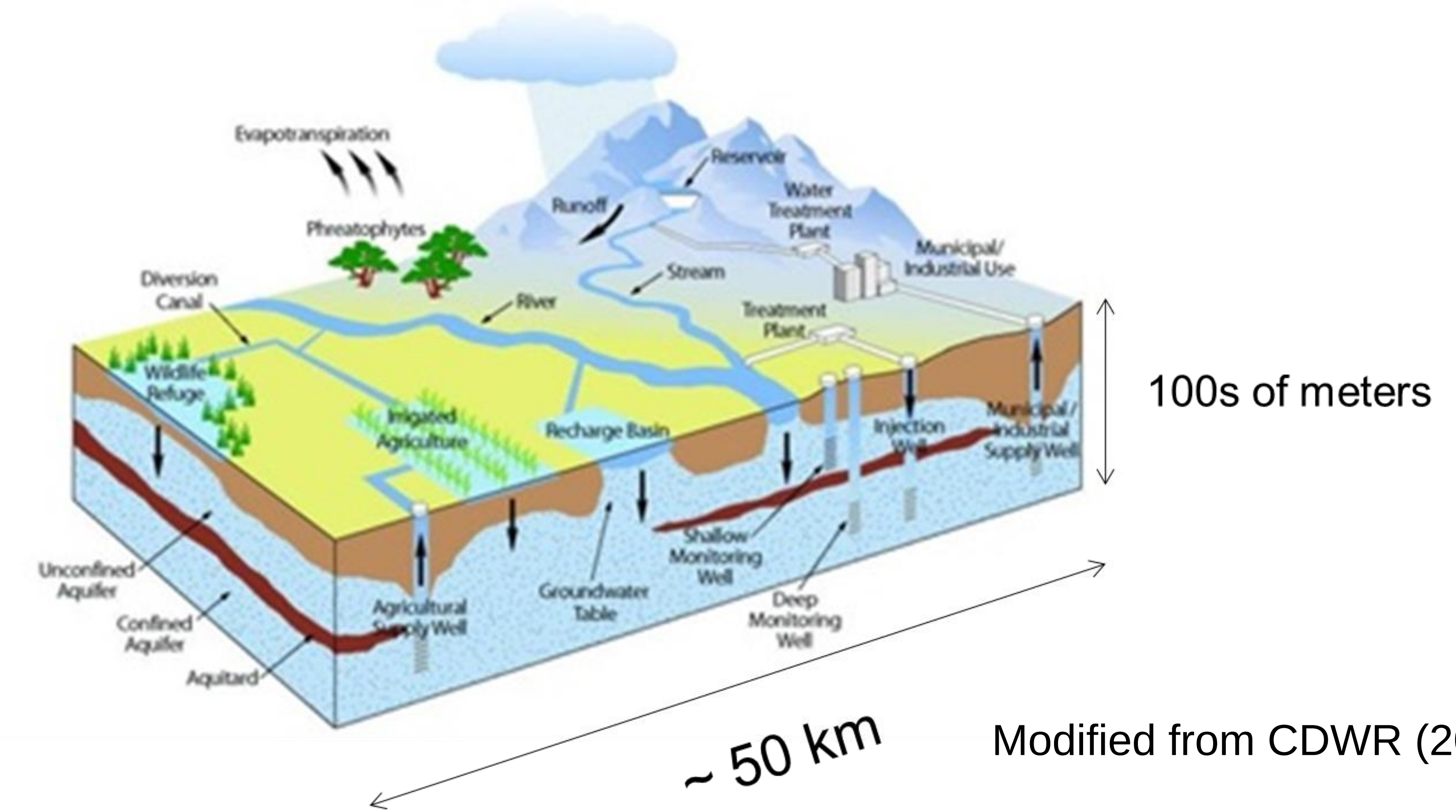
"Improved Imaging of the Large-Scale Structure of a Groundwater System with AEM data"



Kang et al. (2022)
Water Resources and Research

Groundwater model

A foundation for sustainable groundwater management.

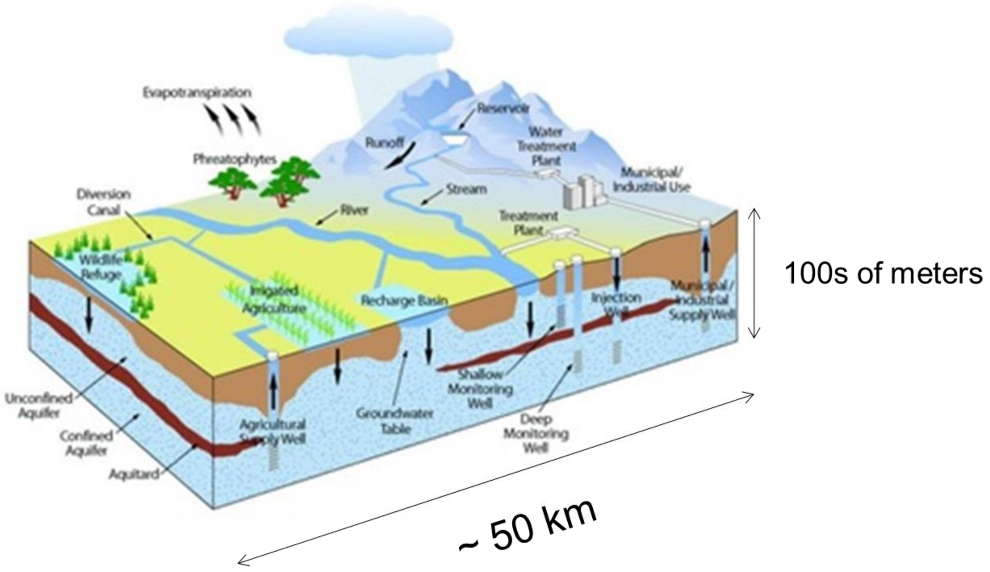


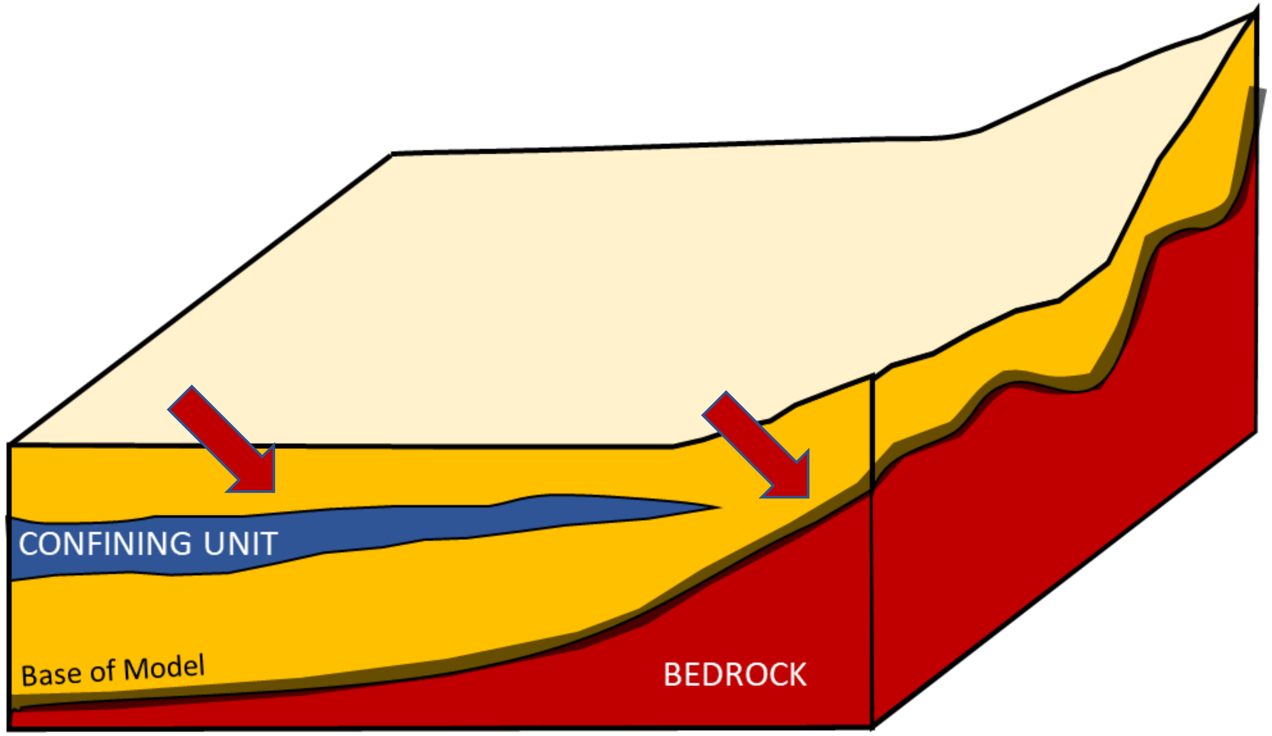
Modified from CDWR (2019)

Groundwater model

Large-scale structure of groundwater systems is required input.

Examples of key features: confining layer, top of bedrock



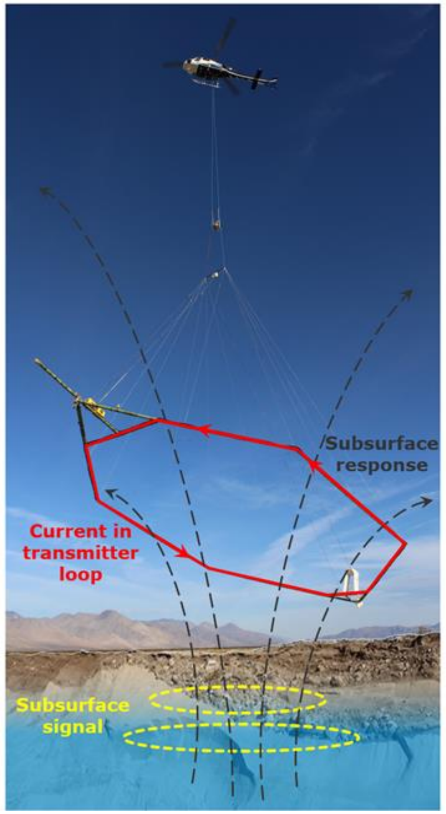


Development of a new approach to map out the large-scale structure:

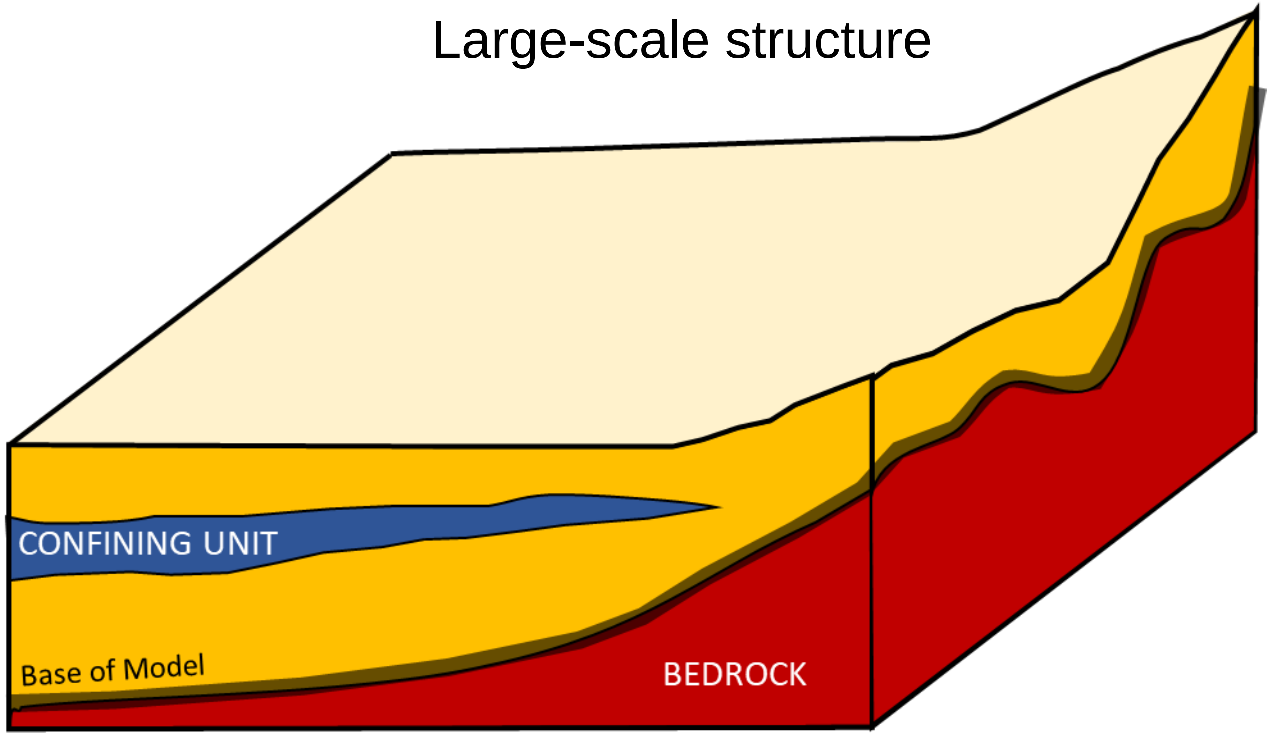
Data source: AEM data + a few high-quality wells

Key improvement: incorporating "prior knowledge" into inversion step

AEM method

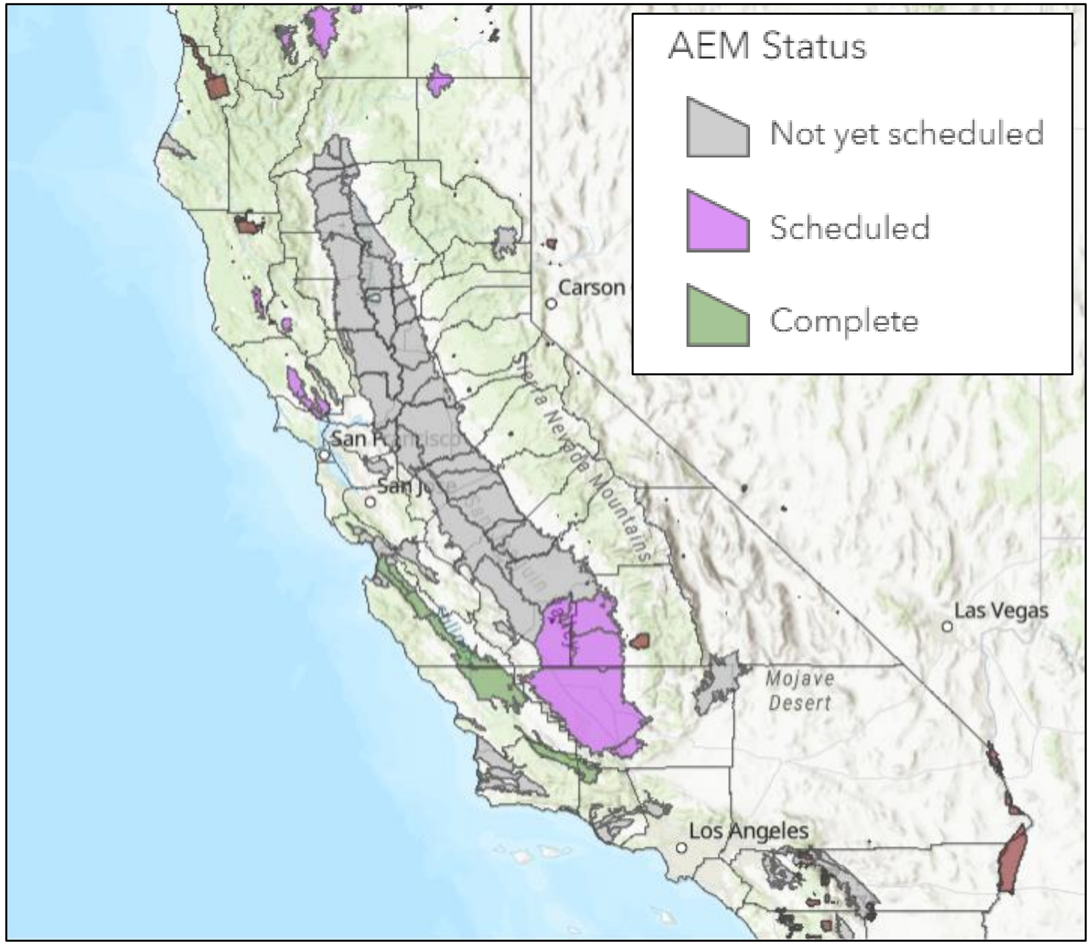


Large-scale structure



Large-scale AEM project (led by DWR)

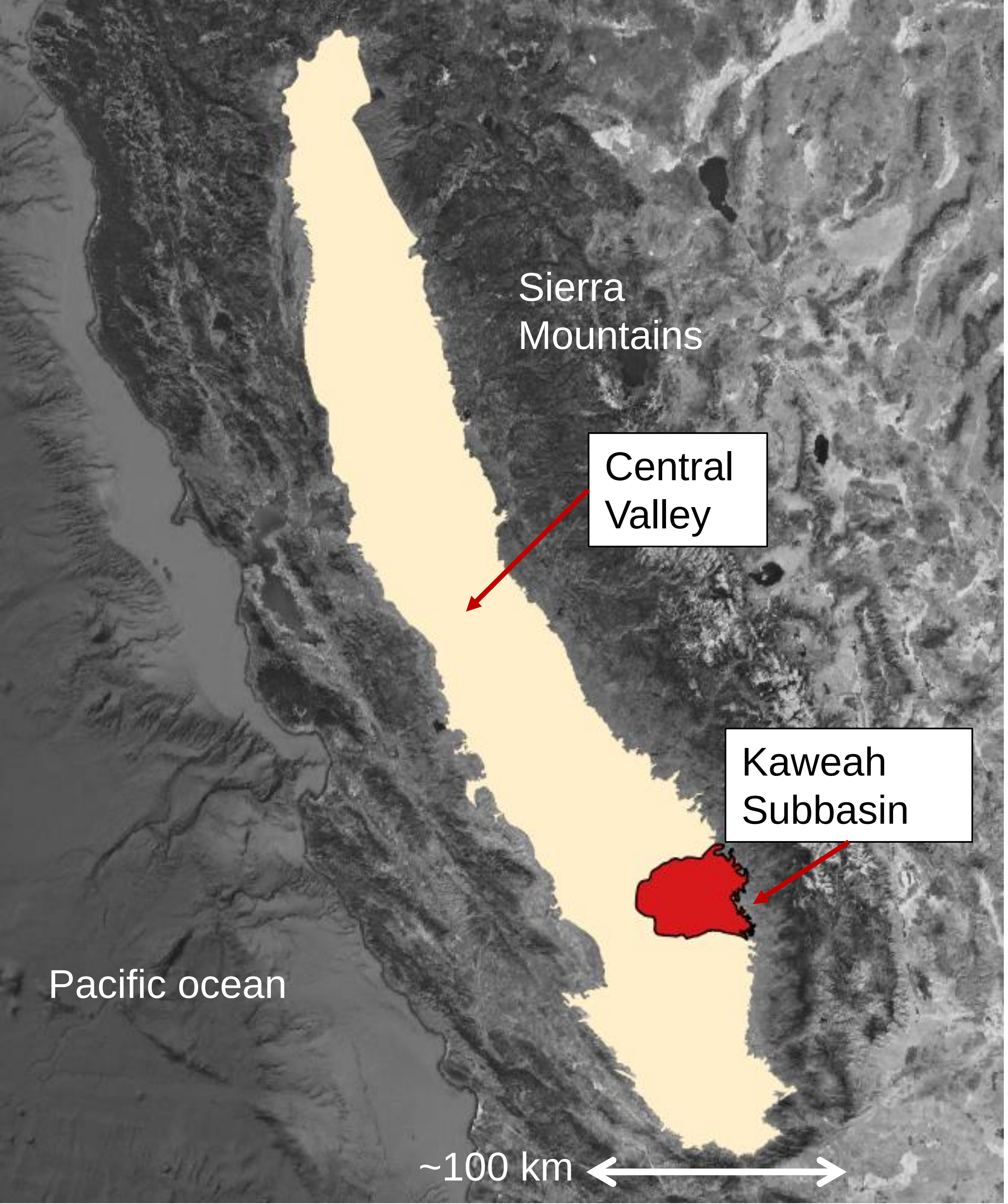
Location map



CDWR (2021)

Will cover California's high- and medium-priority groundwater basins

A great opportunity to transfer the developed technology into other regions so that they can support the process of constructing high-quality hydrogeologic model.



Study area: Kaweah Subbasin

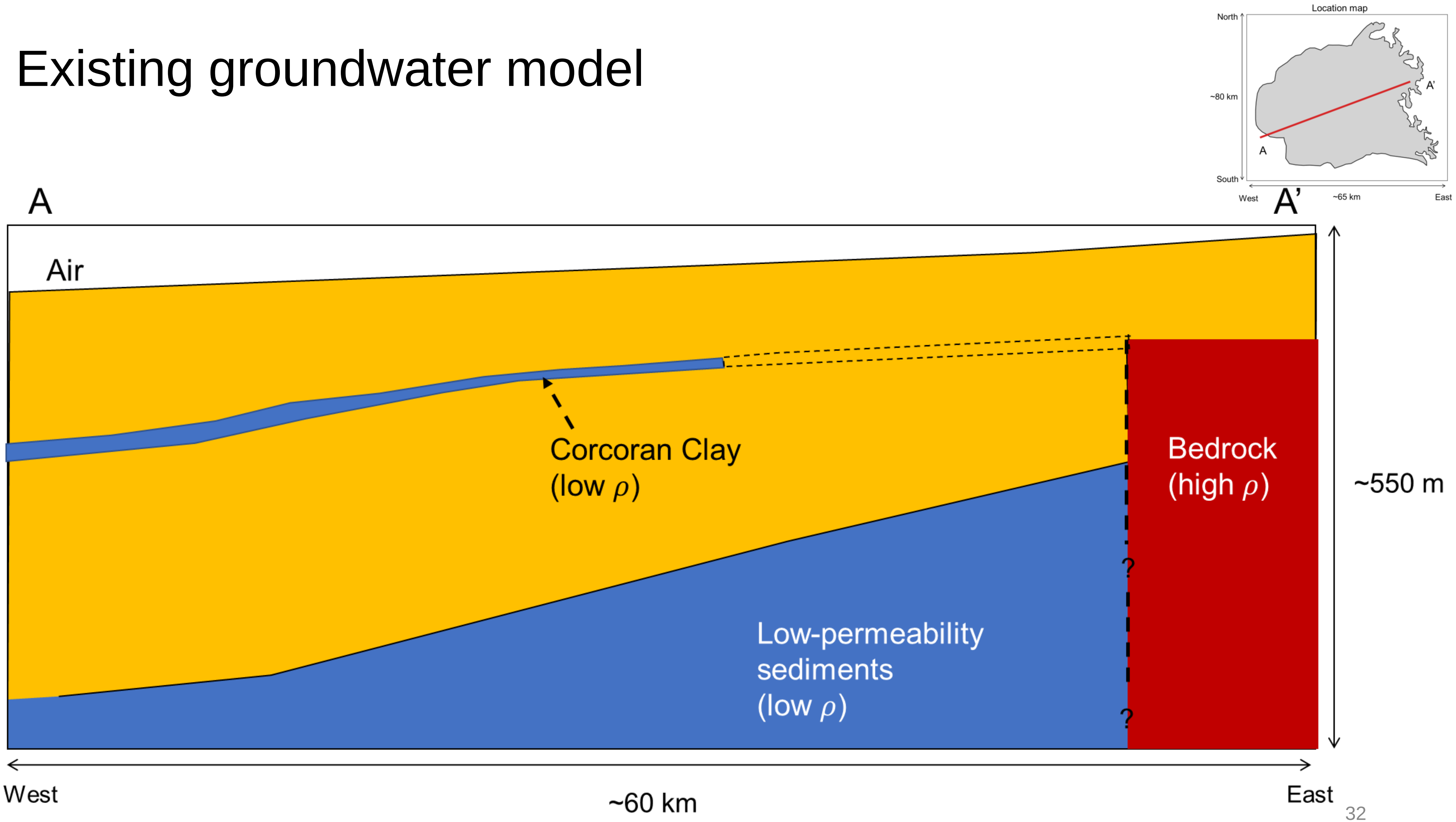
Located in San Joaquin Valley

High groundwater demand
- Less surface water & precipitation
- Warmer drier weather

Significant subsidence due to pumping (~20 cm/year)

One of the critically over-drafted basins

Existing groundwater model



Targets that we aim to resolve & prior knowledge

Top of the bedrock:

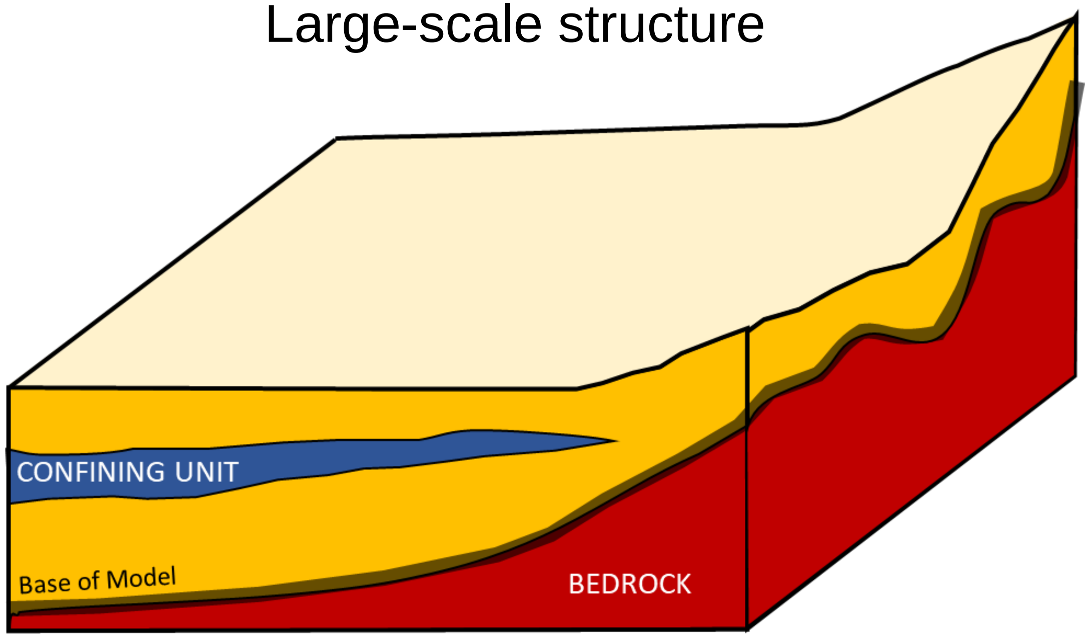
- large resistivity contrast between the bedrock and overlying sediments.

Confining layer – the Corcoran Clay:

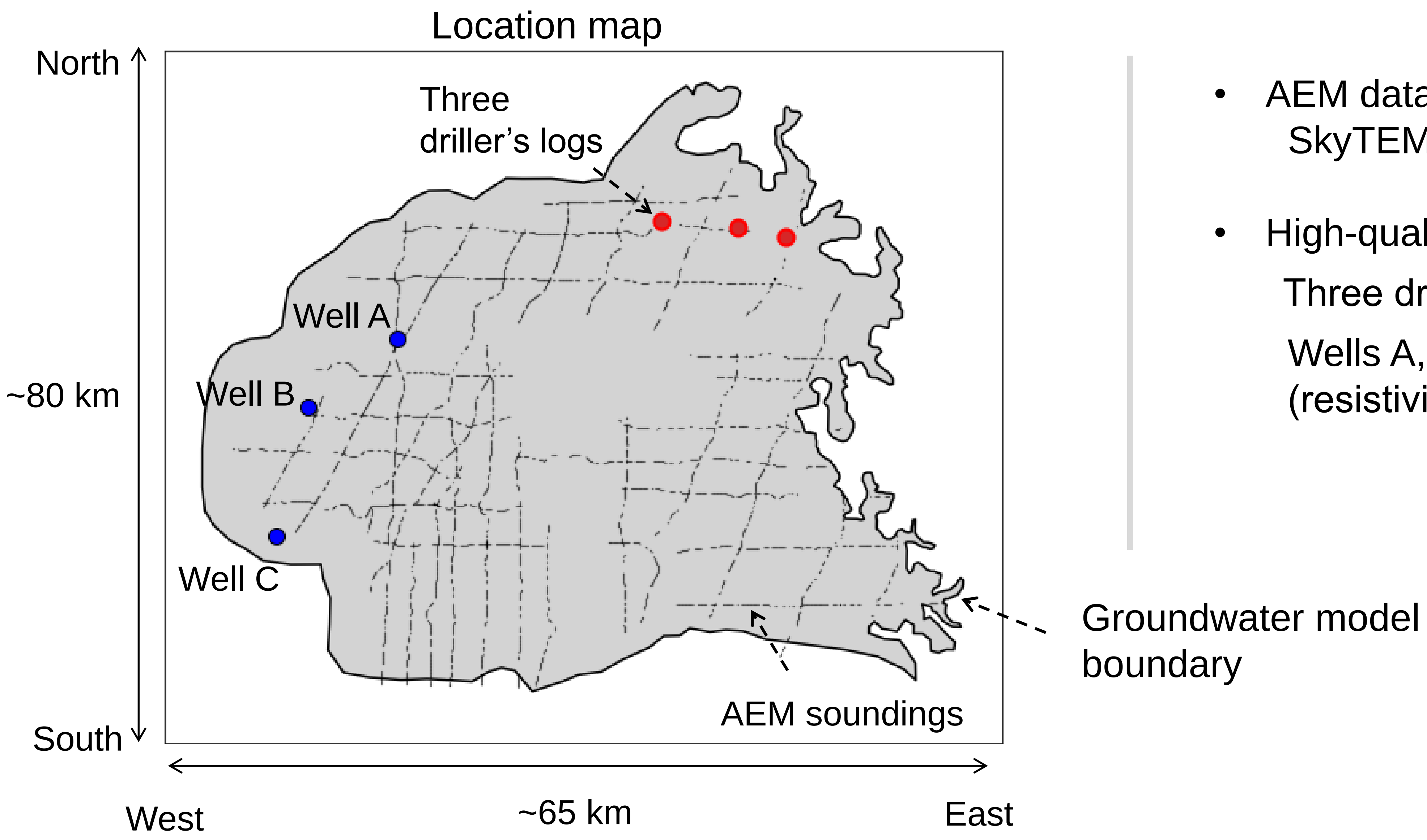
- a large resistivity contrast between the Clay and surrounding aquifers.

- thickness of the clay << thickness of the aquifers

Large-scale structure



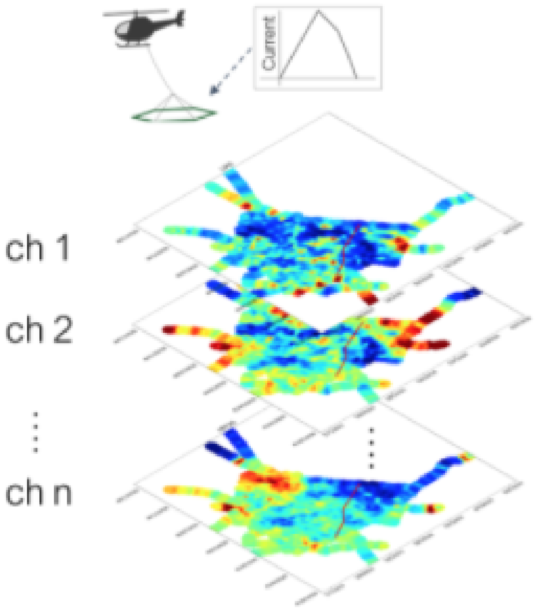
Available data



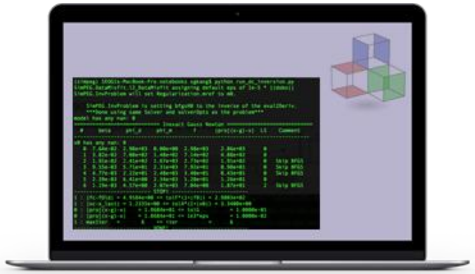
- AEM data (2018)
  SkyTEM system
- High-quality well data:
  Three driller's logs (bedrock)
  Wells A, B, C (Corcoran Clay)
  (resistivity and driller's logs)

AEM inversion methodology

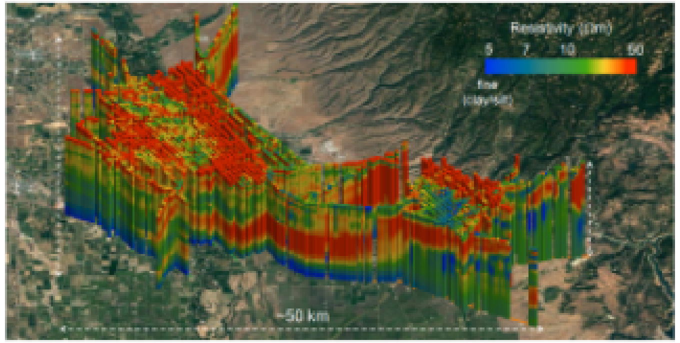
Data



Inversion



Resistivity



https://www.simpeg.xyz

Developed under an open-source geophysics software, SimPEG

Start with conventional inversion approach

(assume smooth transition of resistivity in vertical and lateral directions)

Inversion methodology

minimize $\phi = \phi_d + \beta\phi_m$

subject to $m_L < m < m_H$

- ϕ_d: data misfit
- ϕ_m: regularization
- β: trade-off parameter
- m_L, m_H: lower and upper bounds

smallness — smoothness

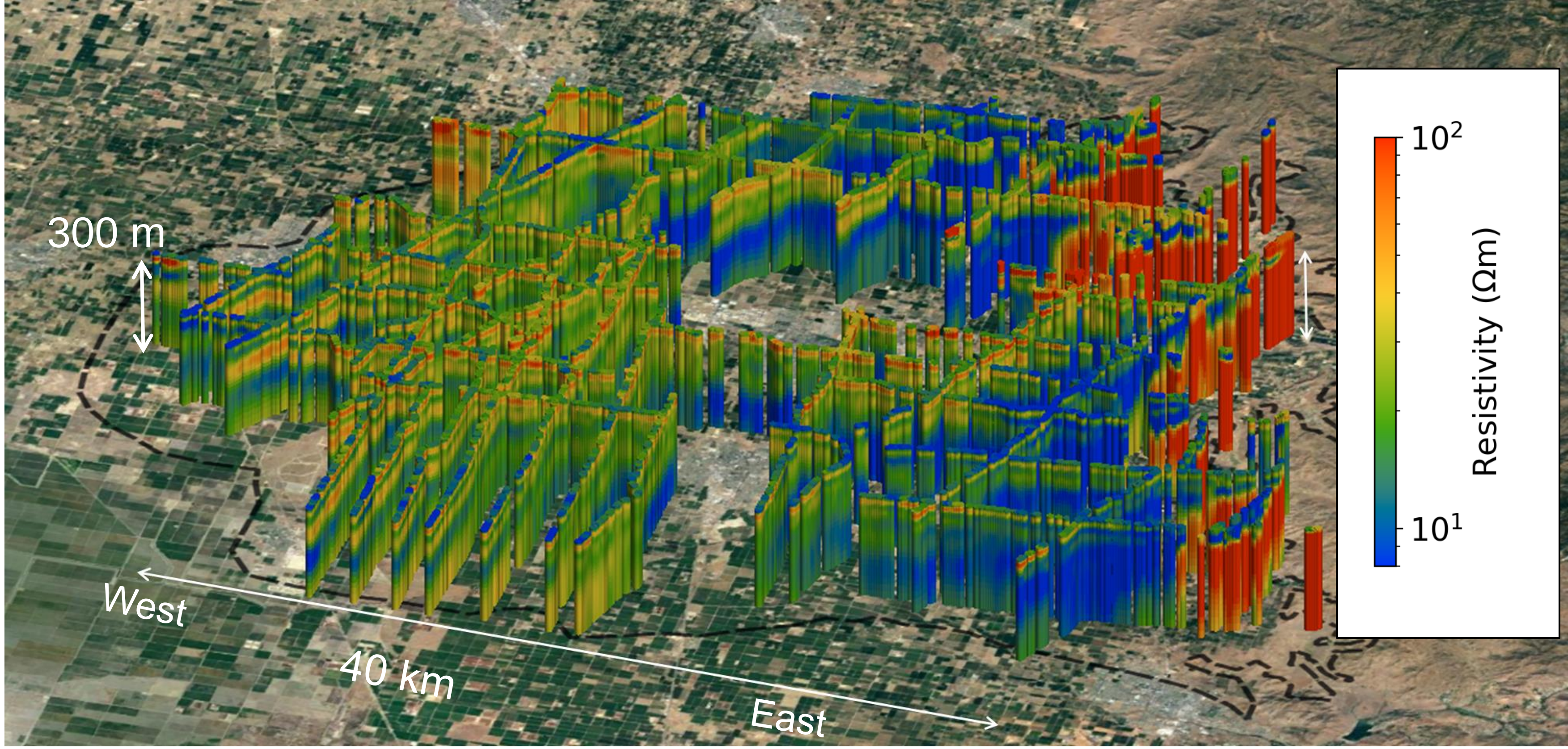
$$\phi_m = \alpha_s \int_v (m - m_{ref})^2 dv + \alpha_r \int_v \left(\frac{dm}{dr}\right)^2 dr + \alpha_z \int_v \left(\frac{dm}{dz}\right)^2 dz$$

horizontal direction — vertical direction

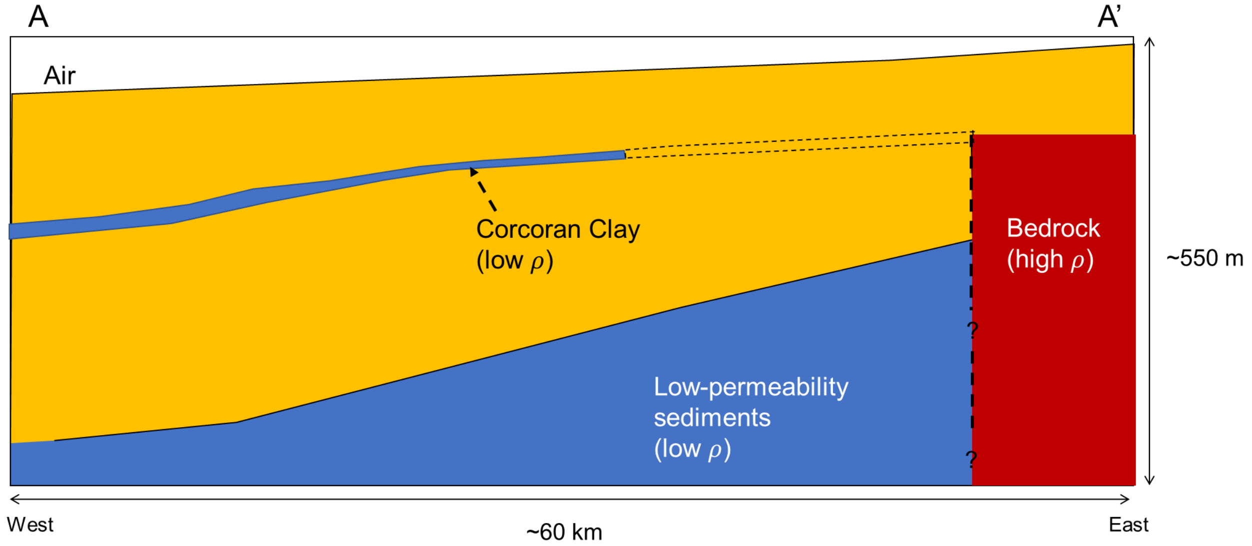
Flexibility

- m_0 — Initial guess
- m_{ref} — Prior knowledge
- $\alpha_s, \alpha_r, \alpha_z$ — Relative importance of the norms

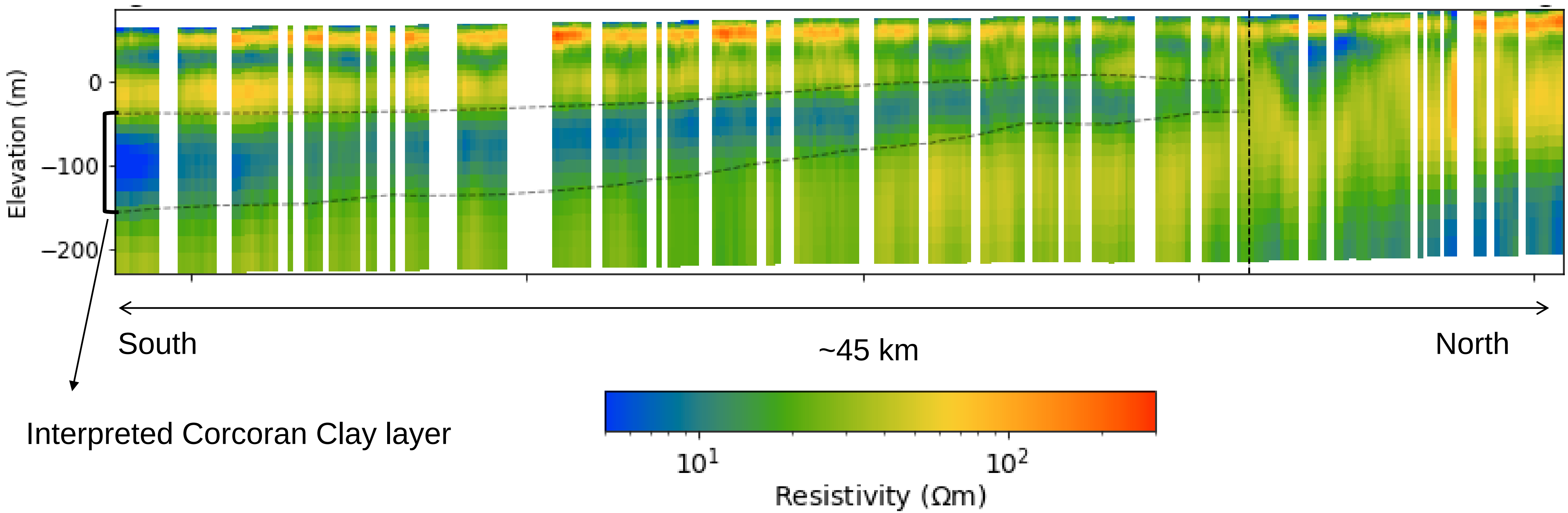
3D resistivity model



Groundwater model



Corcoran Clay

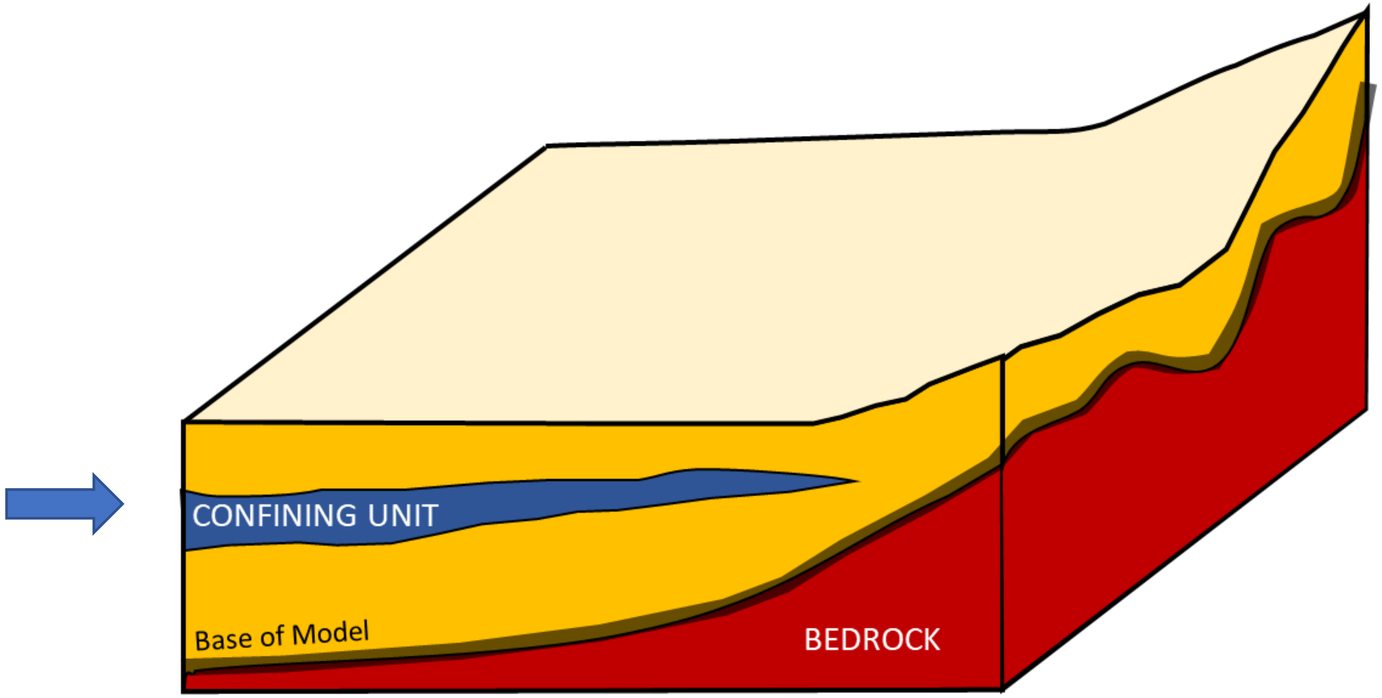


Smoothed layer boundaries, and thick Corcoran Clay (~100 m thickness)

Use targeted inversion approach

(utilize the prior knowledge of the targets)

Corcoran Clay layer



Modify norms

minimize $\phi = \phi_d + \beta\phi_m$

subject to $m_L < m < m_H$

ϕ_d: data misfit
ϕ_m: regularization
β: trade-off parameter
m_L, m_H: lower and upper bounds

smallness p_s — p_r smoothness — p_z

$$\phi_m = \alpha_s \int_v (m - m_{ref})^2 dv + \alpha_r \int_v \left(\frac{dm}{dr}\right)^2 dr + \alpha_z \int_v \left(\frac{dm}{dz}\right)^2 dz$$

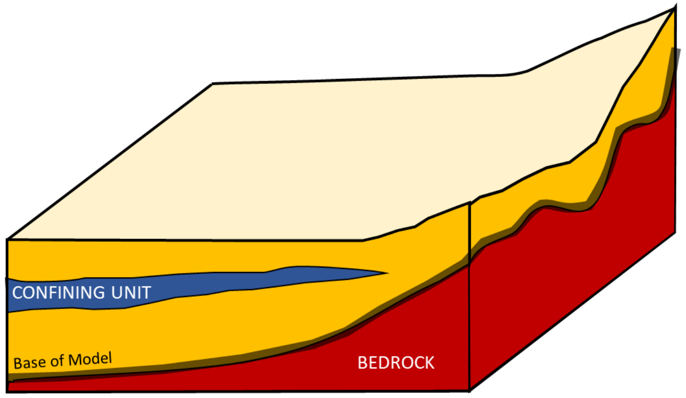
horizontal direction — vertical direction

Flexibility

m_0	Initial guess
m_{ref}	Prior knowledge
$\alpha_s, \alpha_r, \alpha_z$	Relative importance of the norms
p_s, p_r, p_z	p-norm for each term in ϕ_m

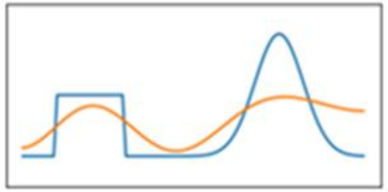
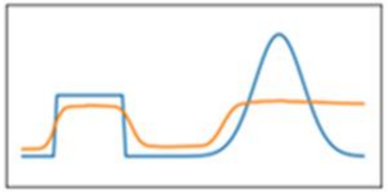
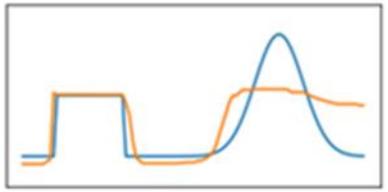
Fournier and Oldenburg (2019)

Character of Lp-norms

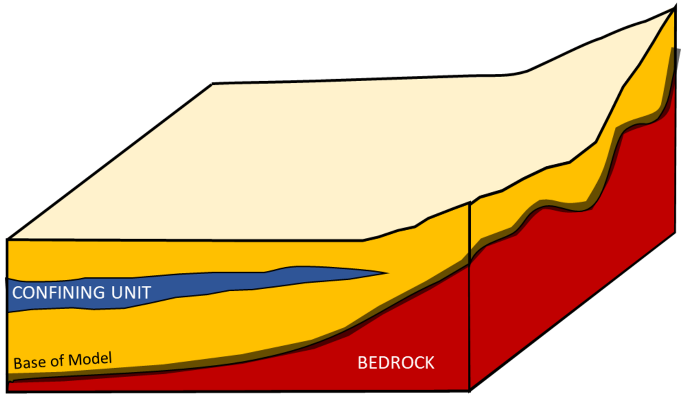


<u>Confining layer – the Corcoran Clay:</u>

- a large resistivity contrast between the Corcoran Clay and surrounding aquifers.
- thickness of the clay << thickness of the aquifers

	p=2	p=1	p=0
only ϕ_z			
	z	z	z

Character of Lp-norms



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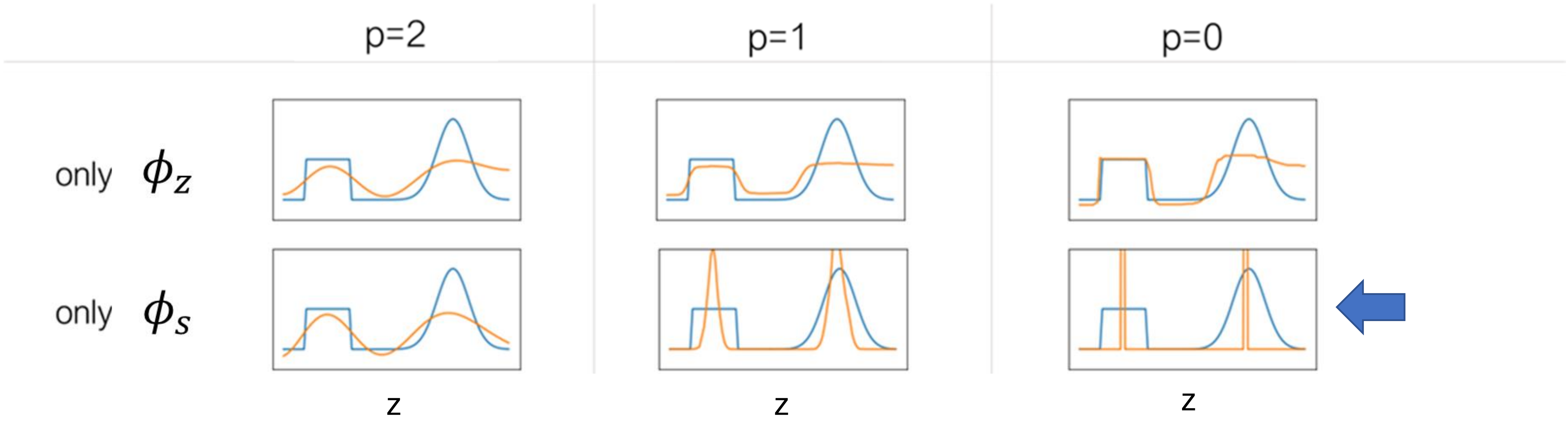
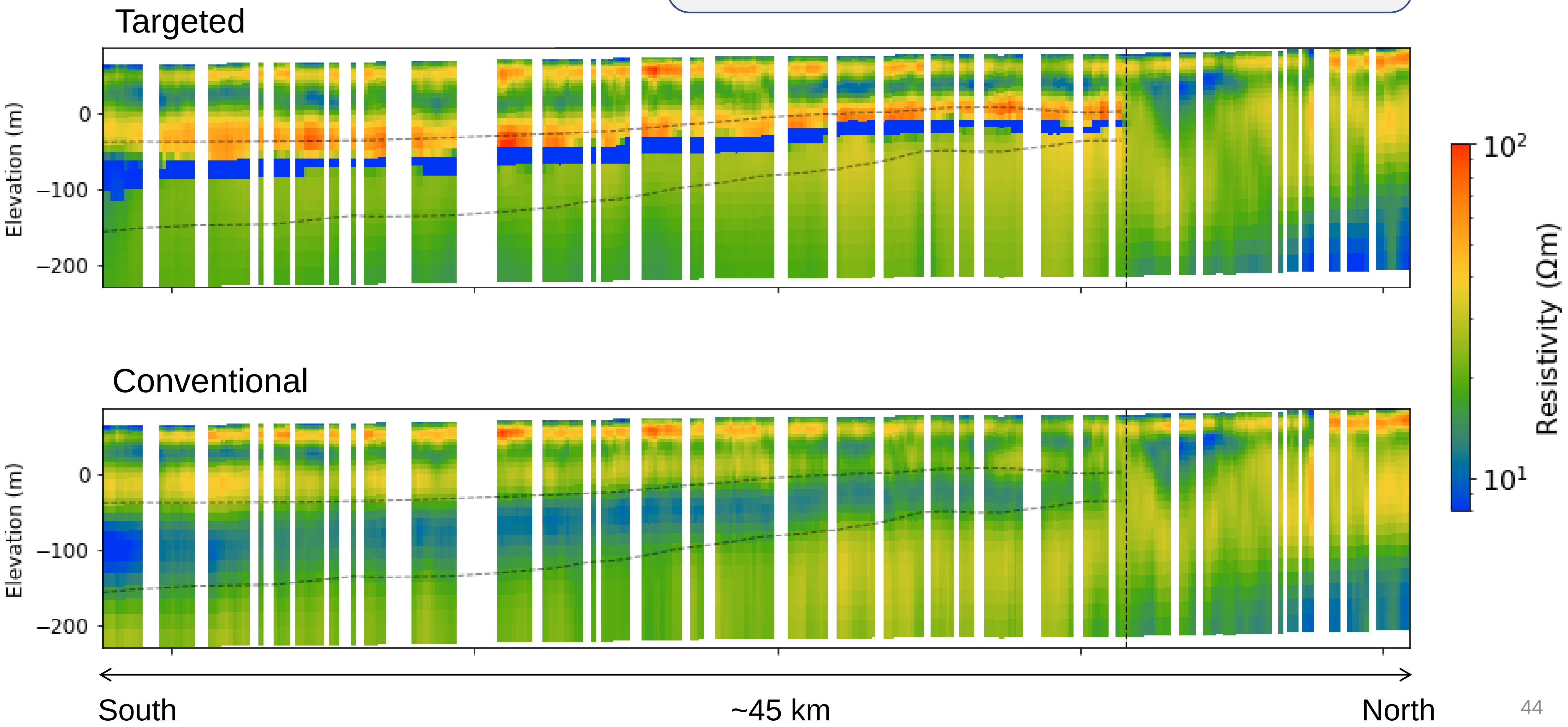
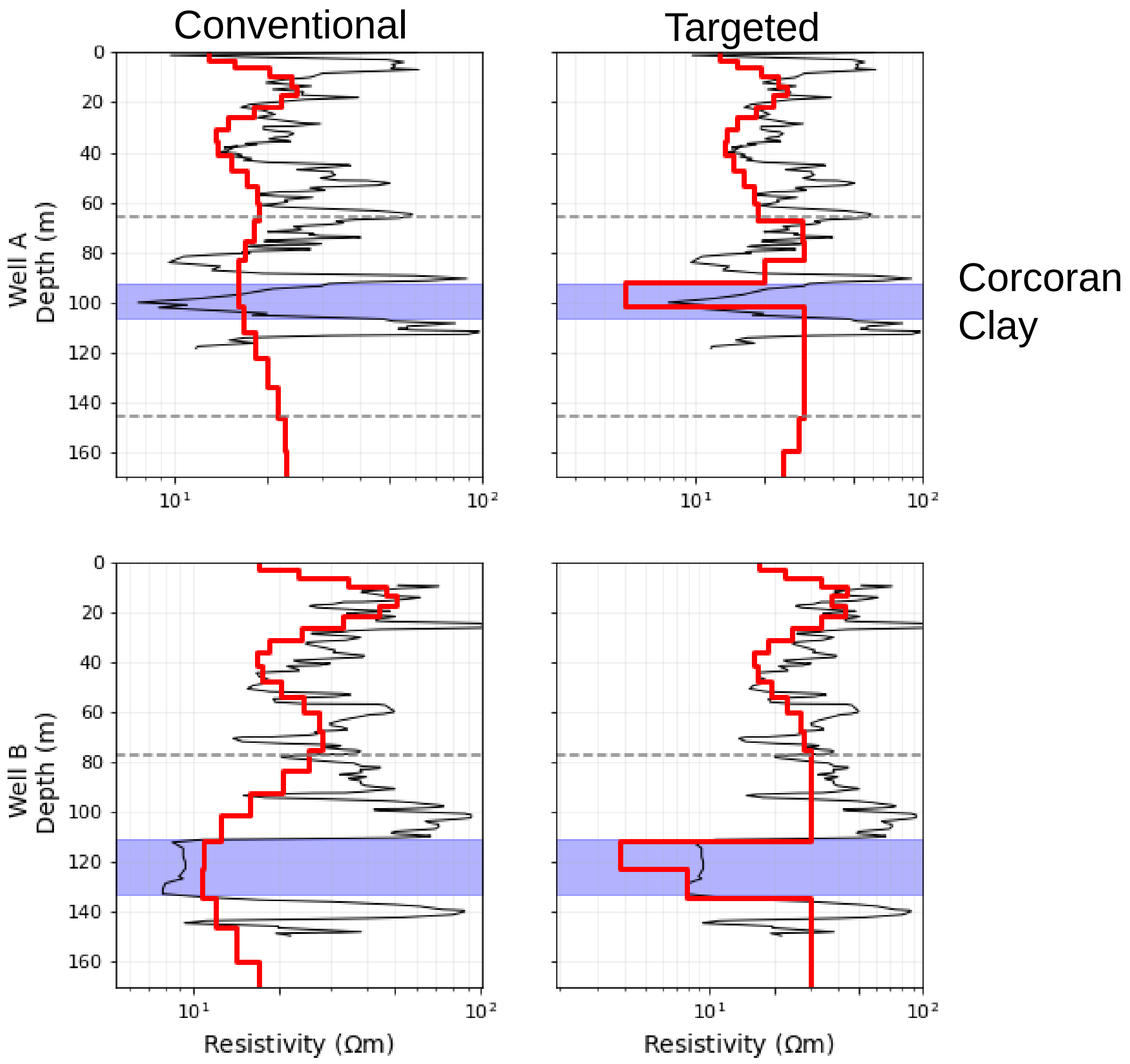


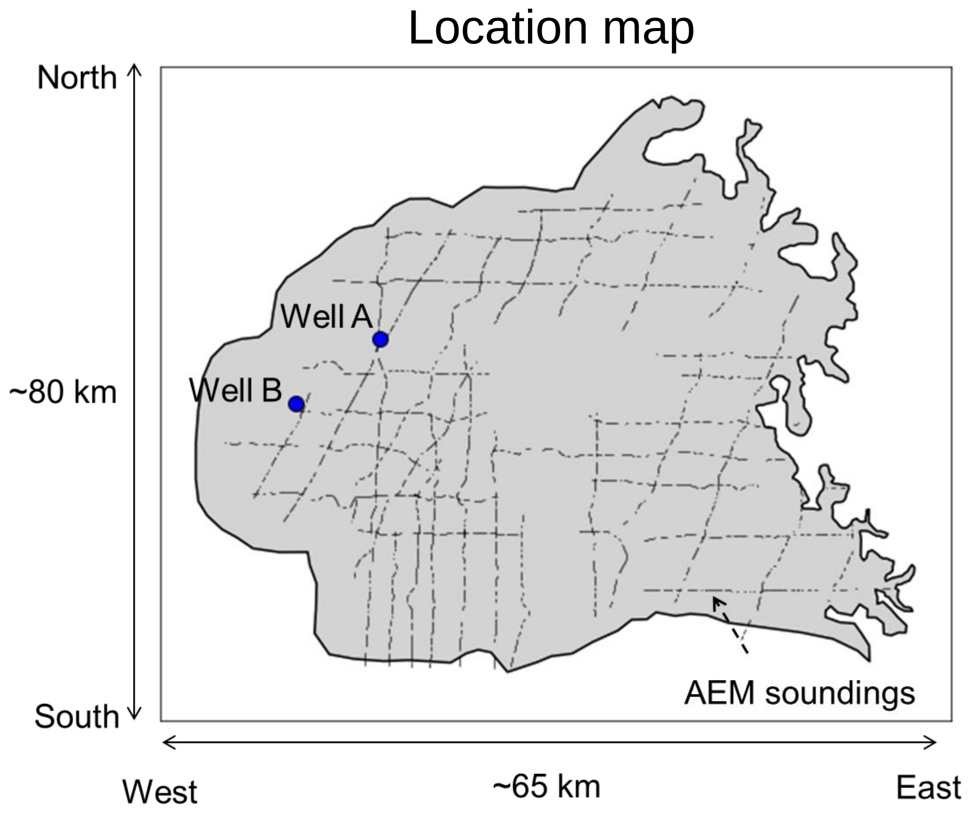
Corcoran Clay

Abrupt transition of resistivity at the Clay boundaries
Significant reduction of the Clay thickness
Increased depth to the Clay

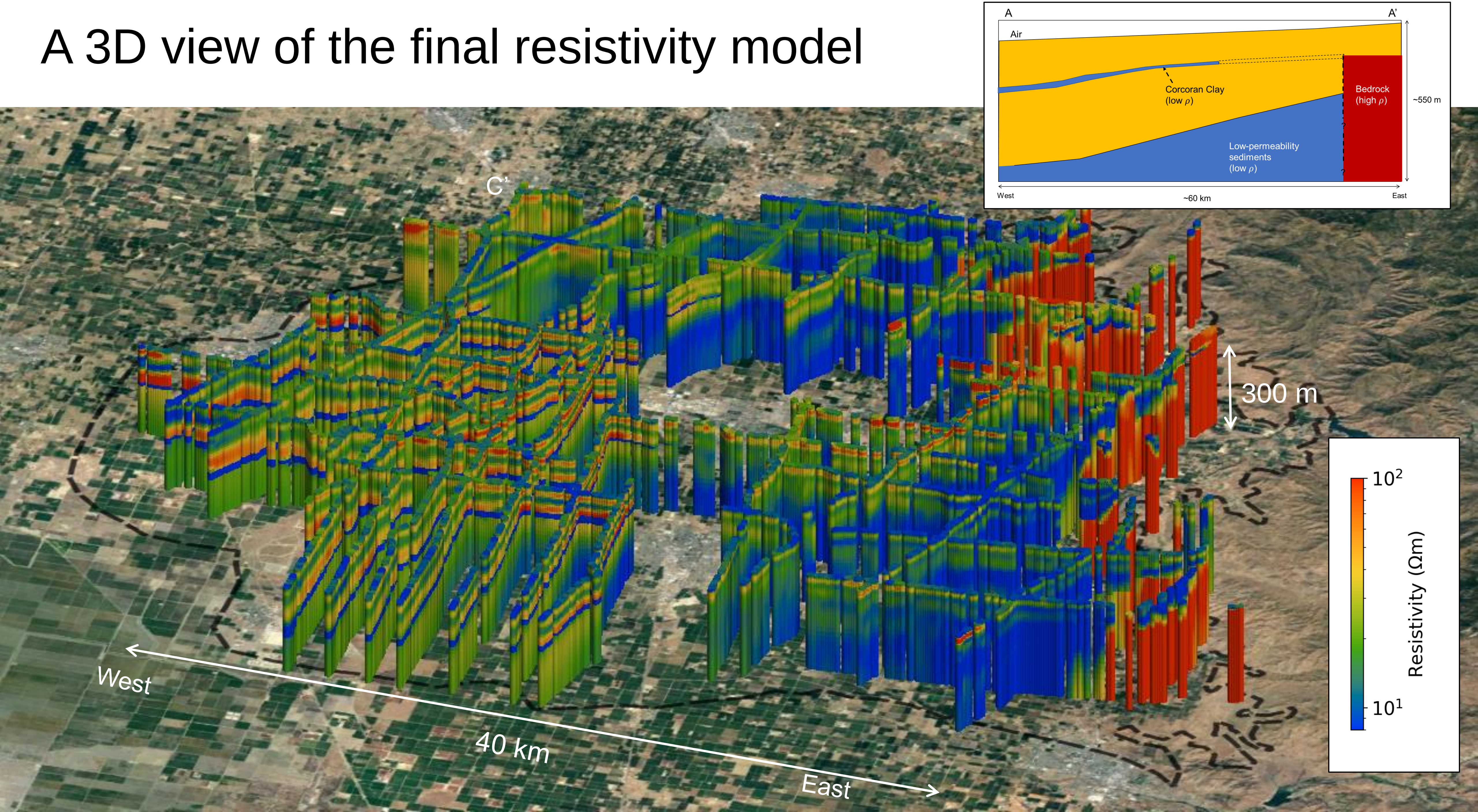


Comparison with the well data (Wells A & B)





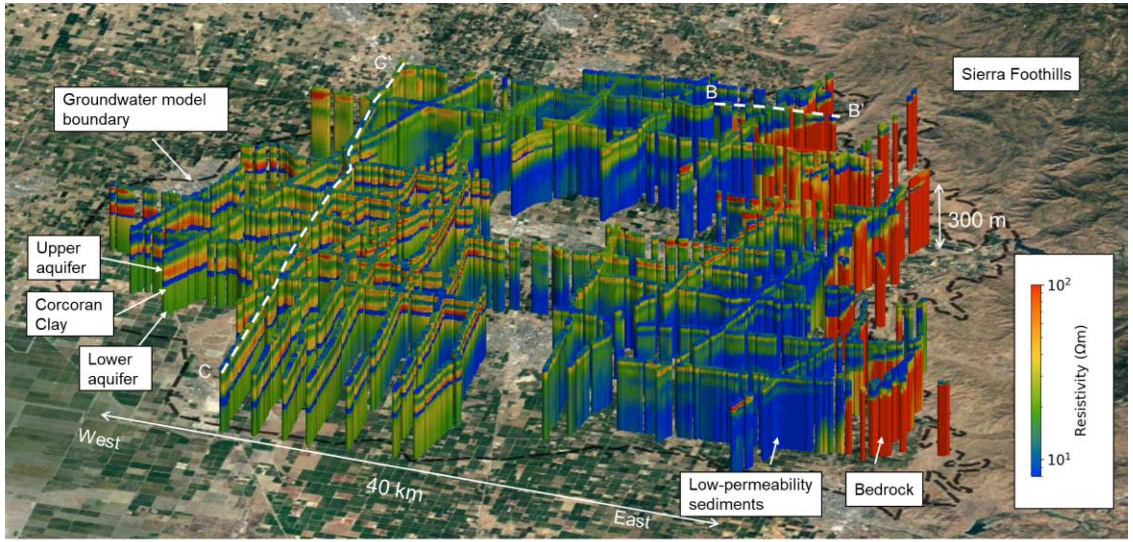
A 3D view of the final resistivity model



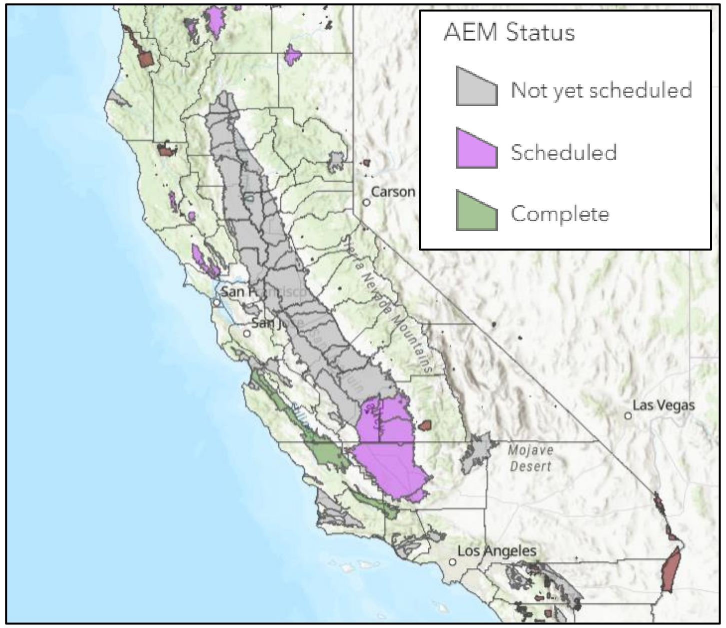
Summary

The developed approach is transferrable to other regions, and can be used to develop a high-quality groundwater model from AEM data

Targeted inversion approach

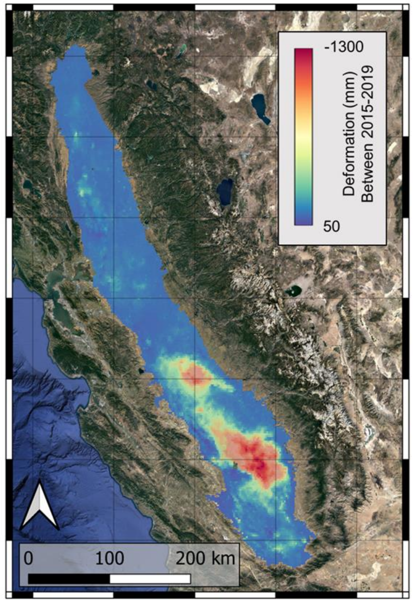


Large-scale AEM project in California



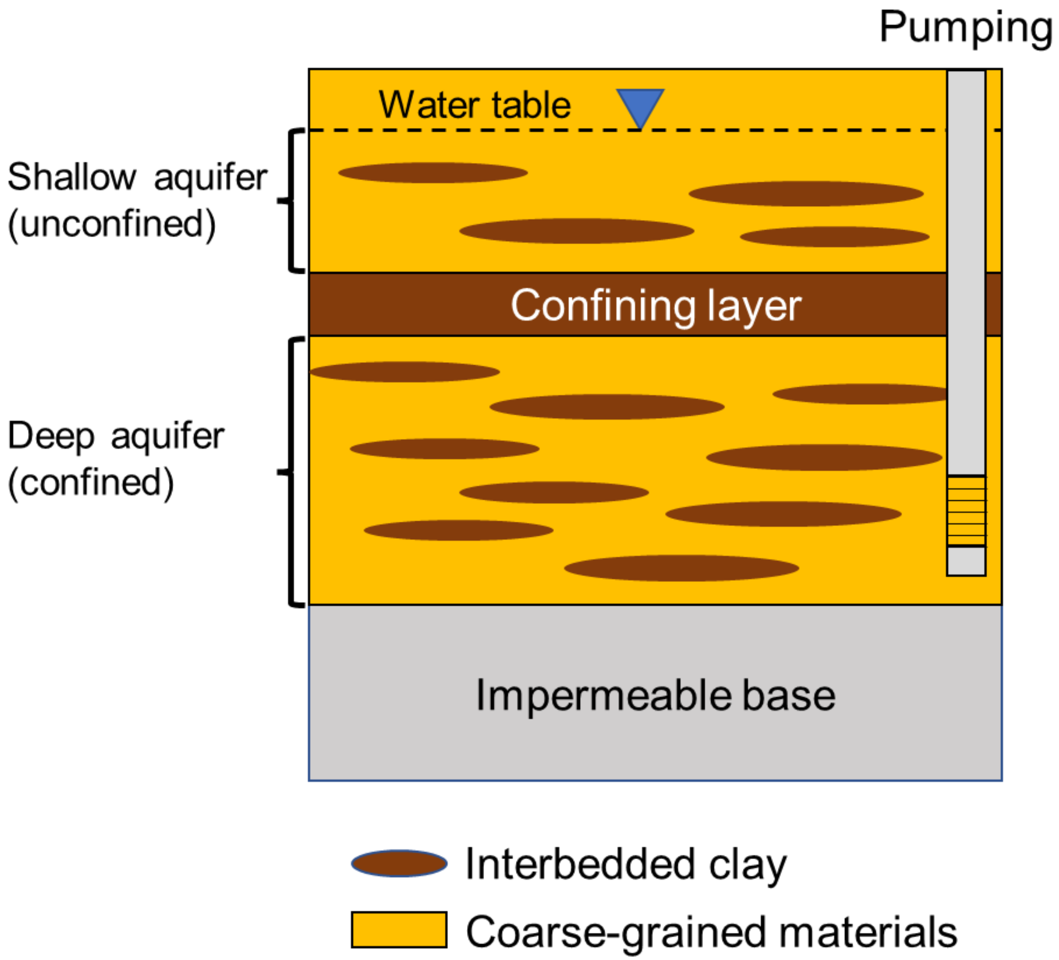
Case study in the Central Valley of California, U.S.A.

"Recovering groundwater head from InSAR surface deformation data"



Kang et al. (2022)
In preparation

Conceptual model of the surface deformation



Pumping groundwater

Reduces the head

Drains water from clays to coarse (diffusive process; takes time)

Compacts the interbedded clays (head changes of the clays)

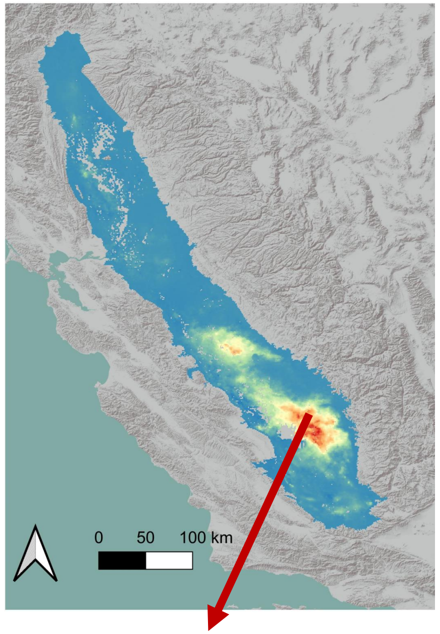
clay compressibility >> coarse compressibility

Driving force: Head change (in the confined aquifer)

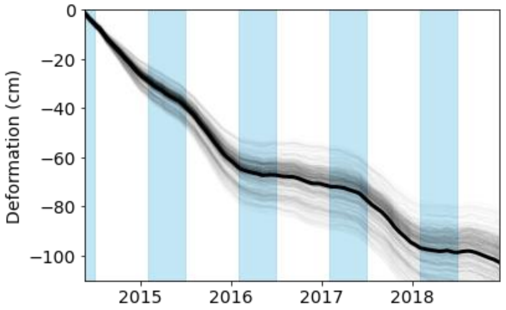
Modulation: Interbedded clays

Recovery of groundwater head

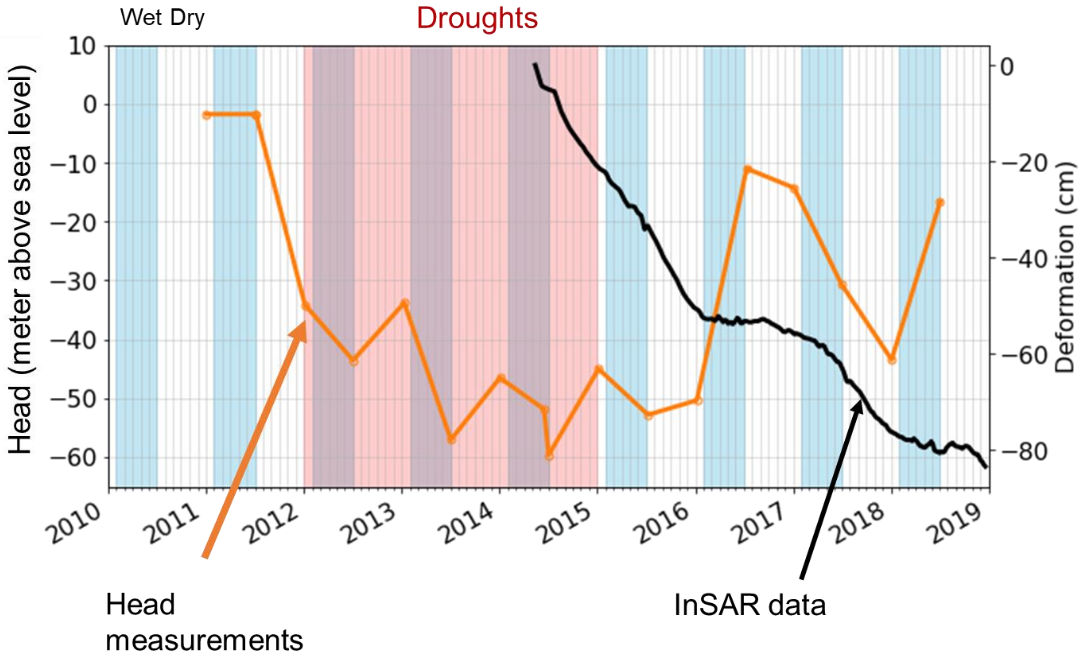
InSAR surface deformation data



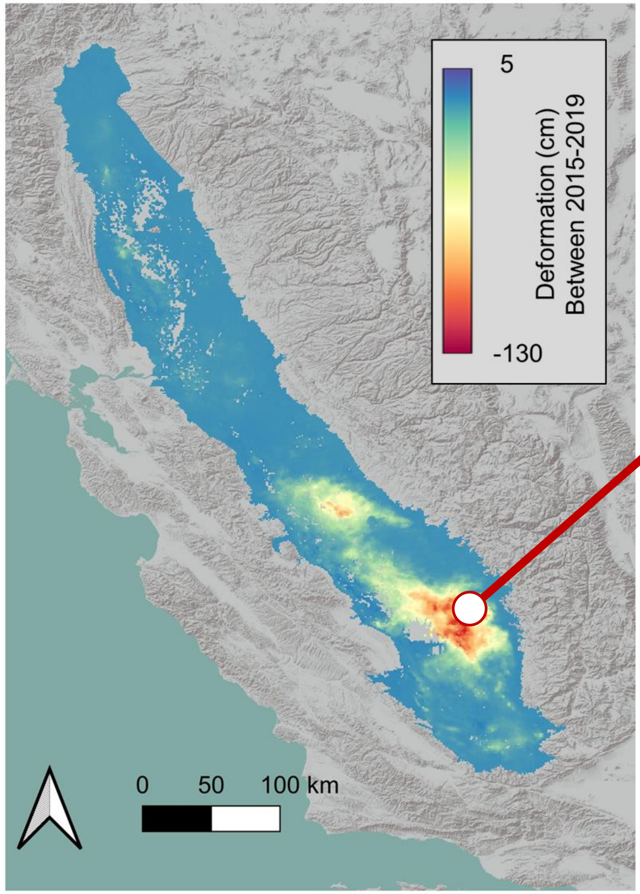
InSAR time-series

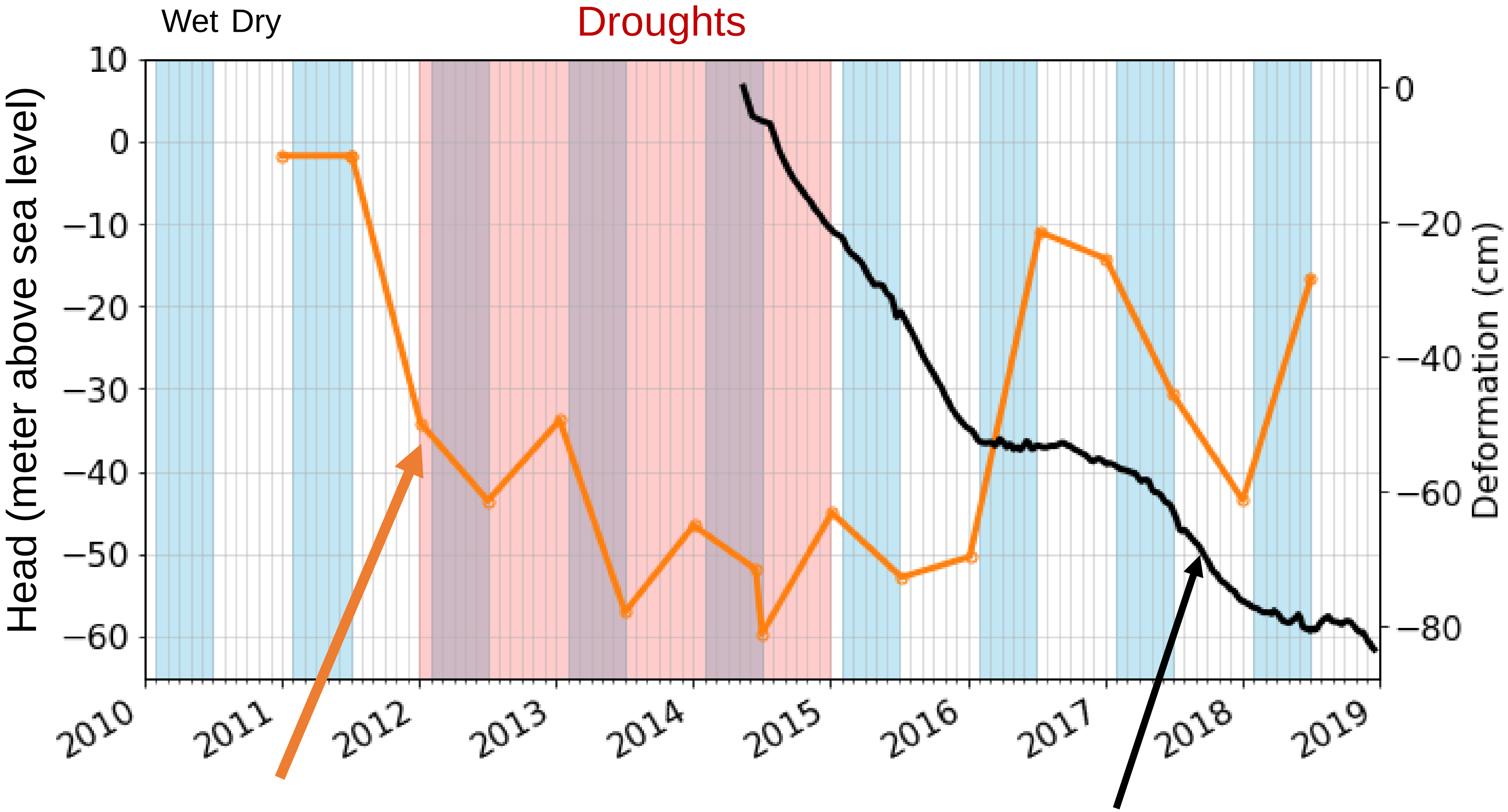


Groundwater head



Example of co-located InSAR data and head data

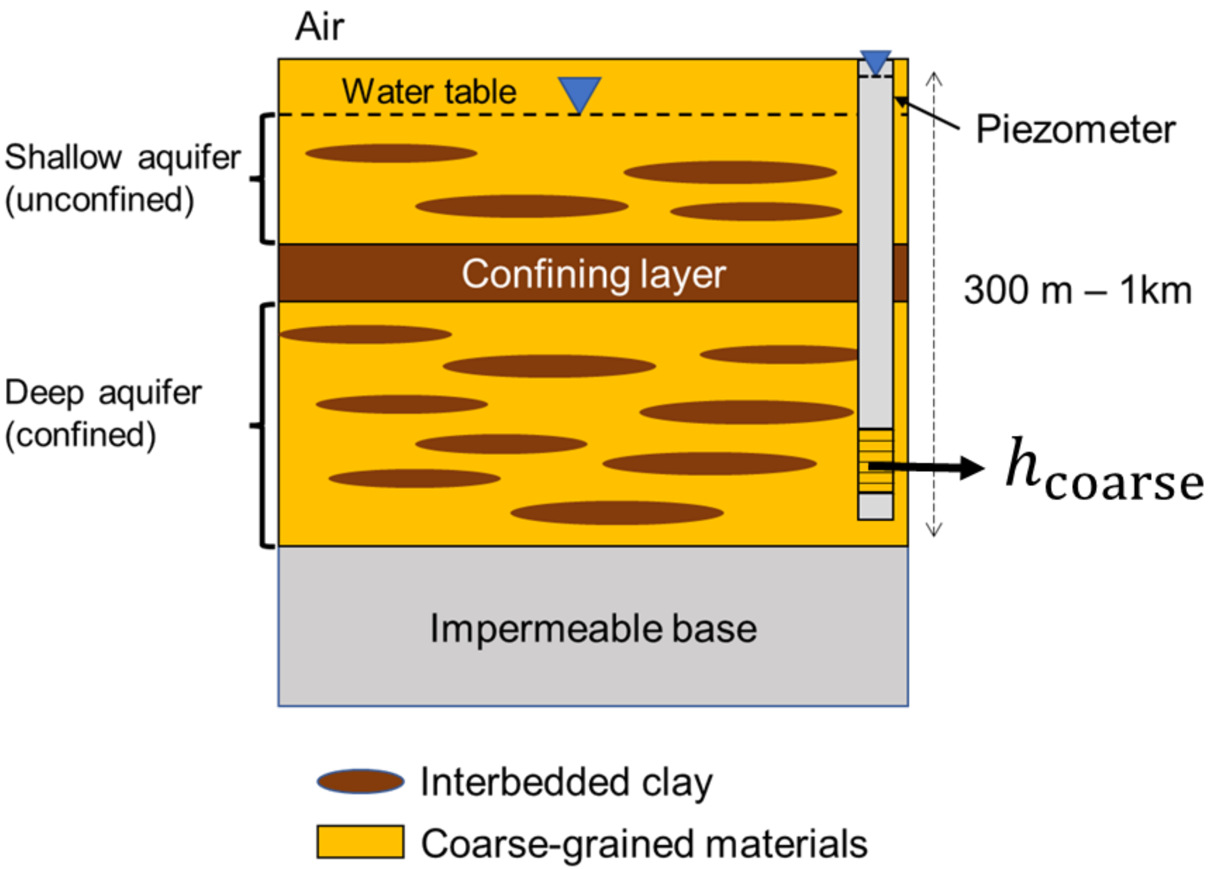




Head measurements

InSAR data

Recovery of groundwater head



Forward: $F\left[h_{\text{coarse}}; p_{\text{clays}}\right] = \text{InSAR data}$

Inverse (assume unknown is h_{coarse}):

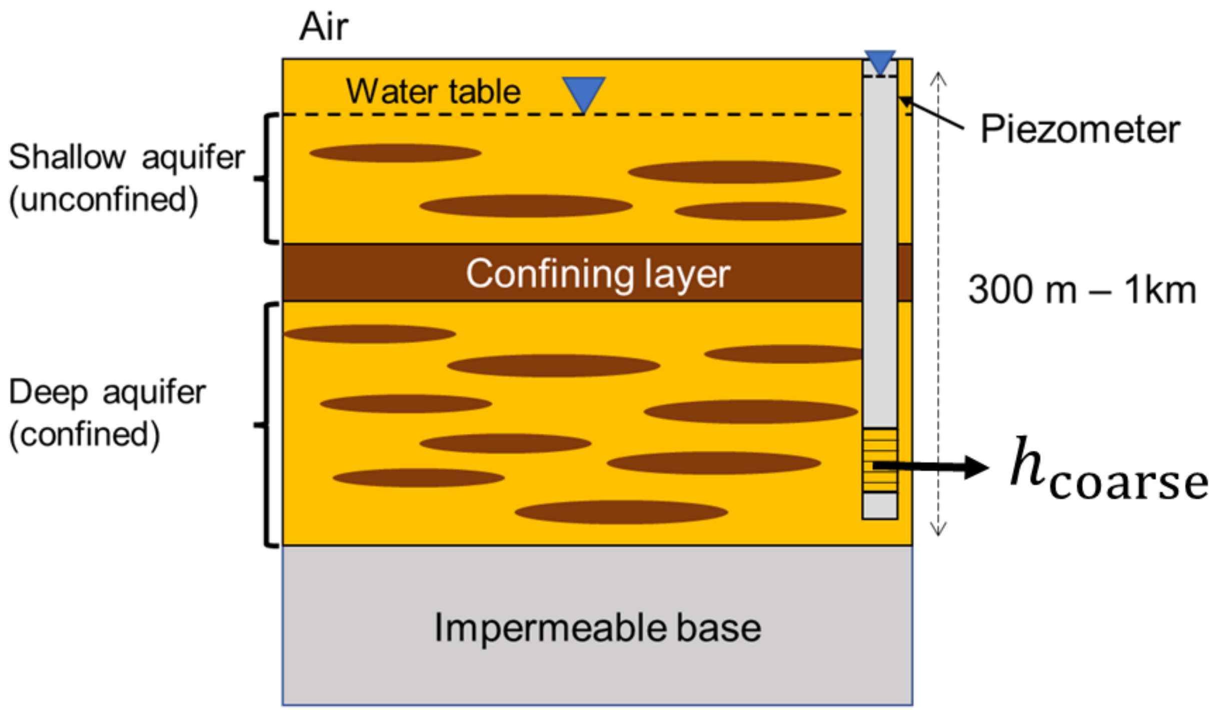
minimize: $\phi(m) = \phi_d + \beta\phi_m$

ϕ_d: data misfit
ϕ_m: regularization

Requires:

a) Forward simulation
b) Sensitivity calculation

Recovery of groundwater head



Forward: $F[h_{\text{coarse}}; p_{\text{clays}}] = \text{InSAR data}$

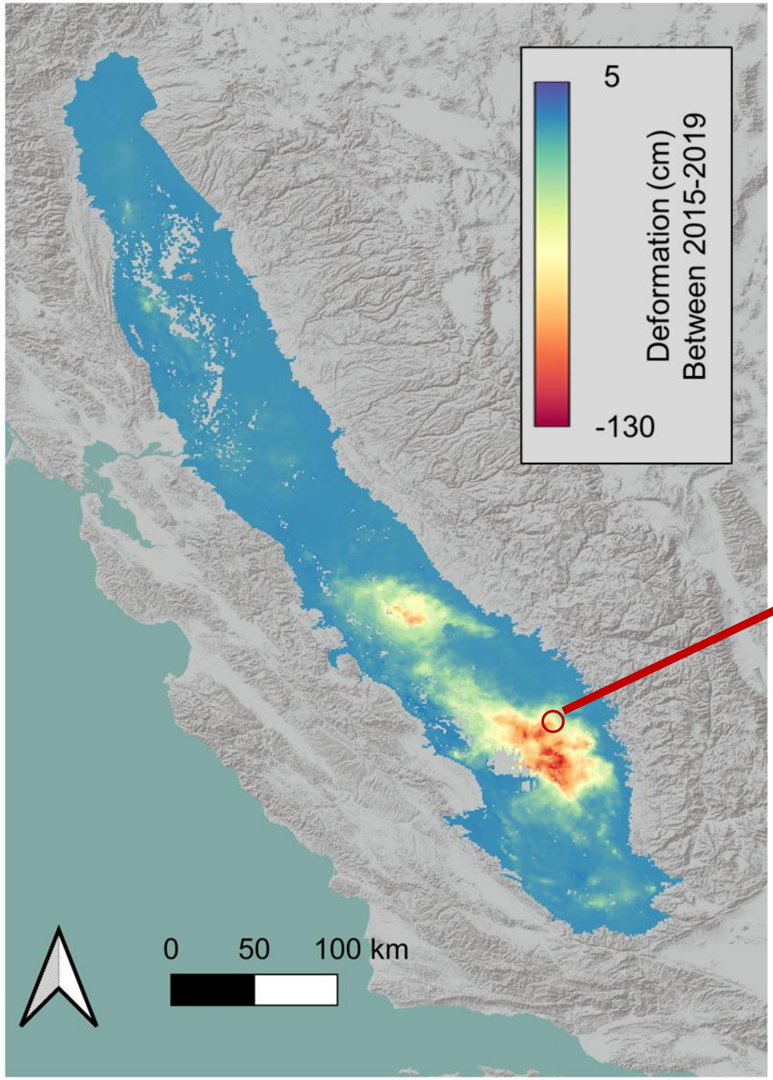
Inverse (assume unknown is h_{coarse}):

minimize: $\phi(m) = \phi_d + \beta\phi_m$

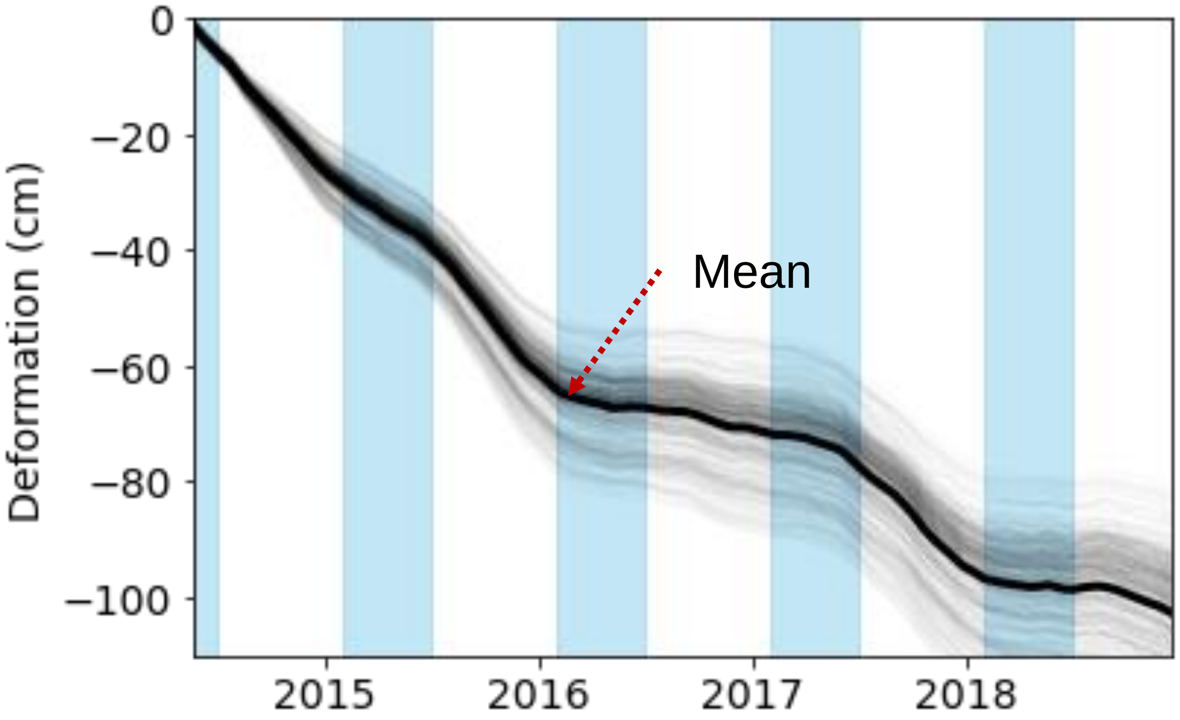
ϕ_d: data misfit
ϕ_m: regularization

Need to know properties of the clays, p_{clays}
(e.g., hydraulic conductivity, thickness, volume fraction)

Inversion example for proof-of-concept

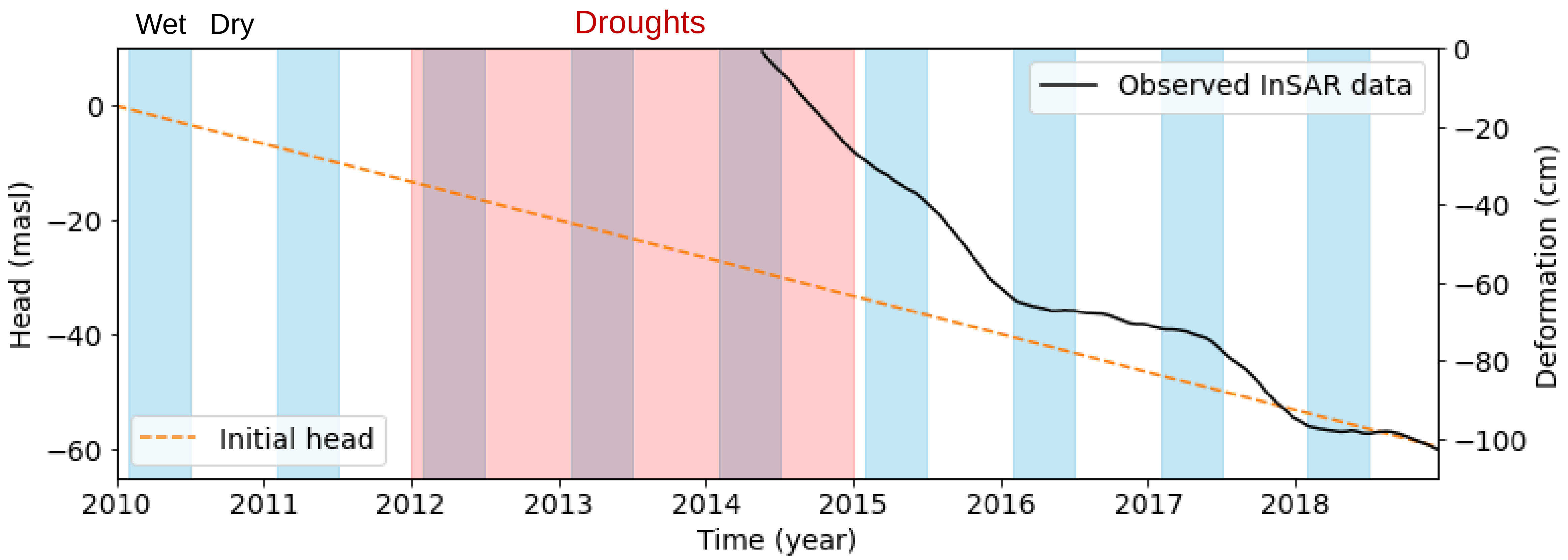


InSAR time series
within 3 km radius from the location

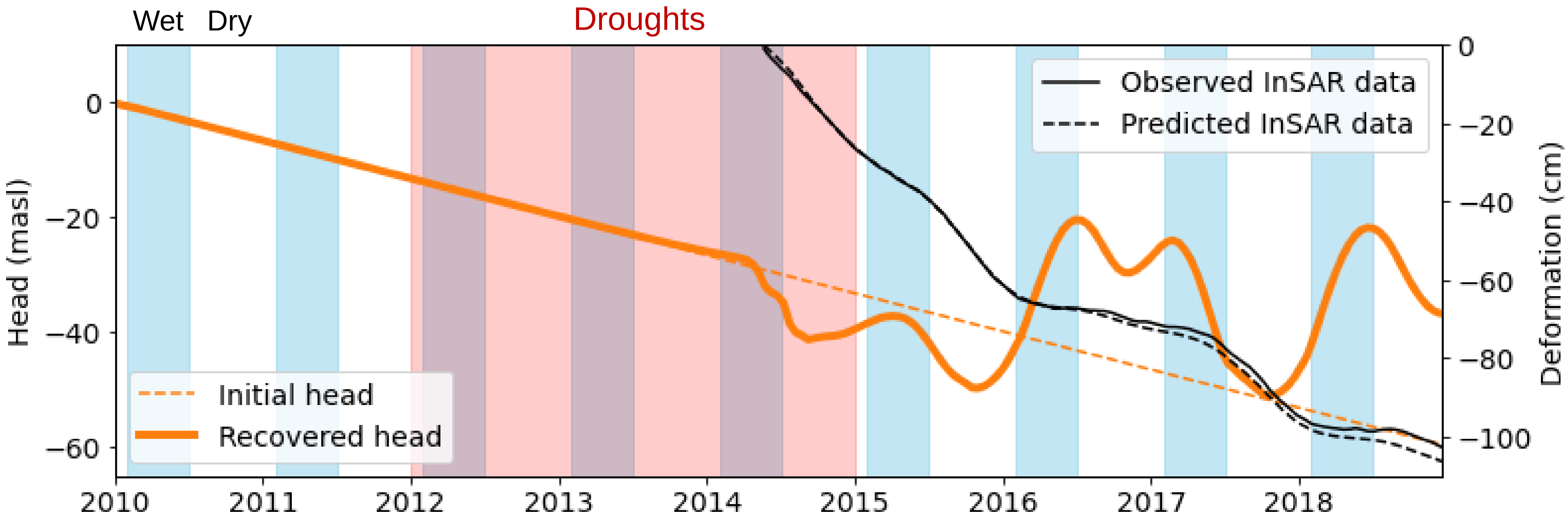


Used clay properties of the region from Smith and Knight (2019) for the inversion

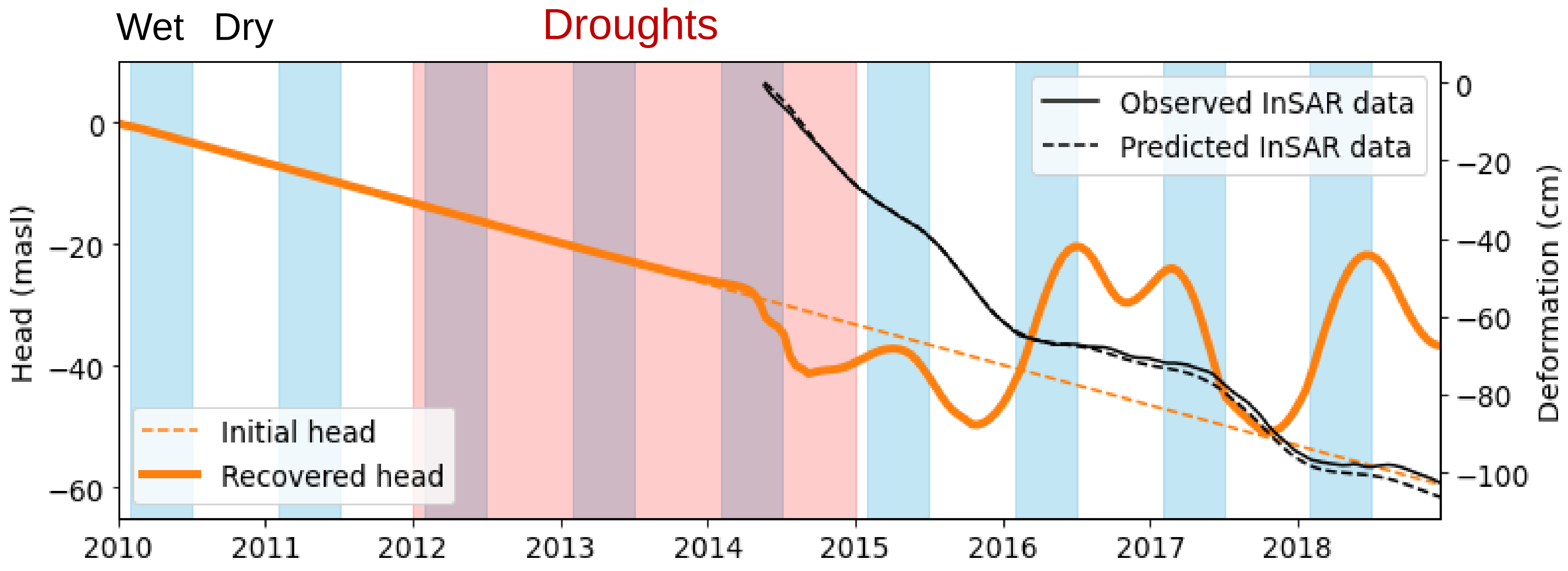
Observed InSAR data & Initial guess



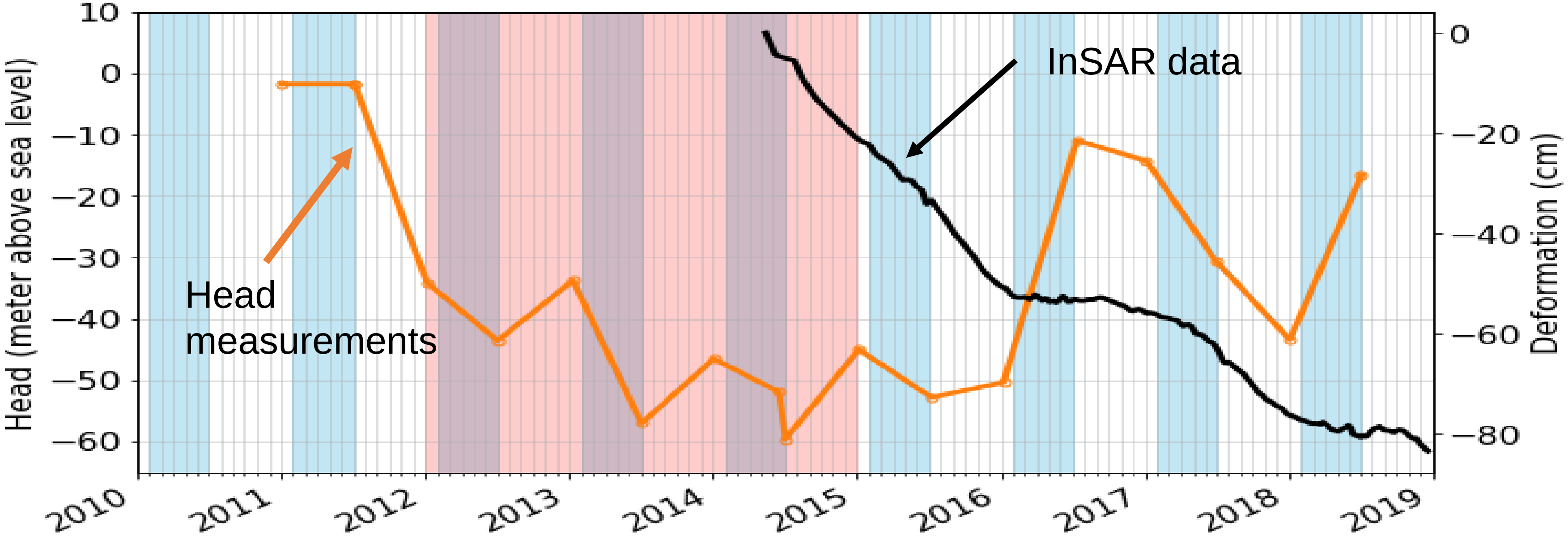
Recovered head



Inversion example



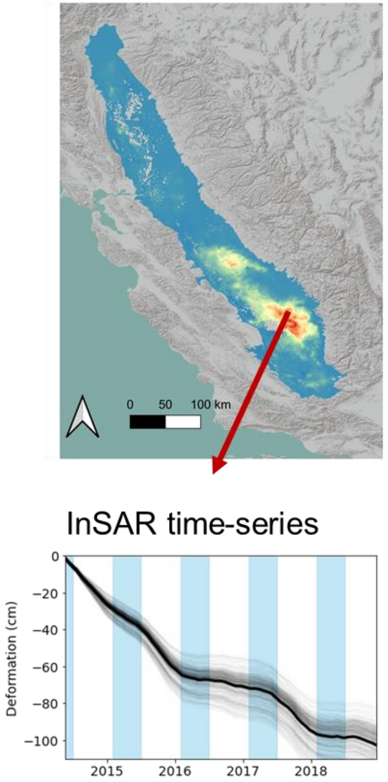
Co-located data



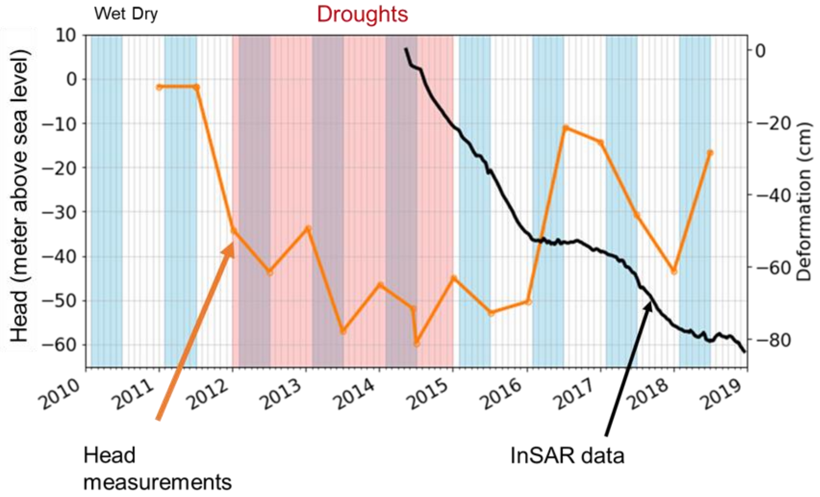
Summary

Showed the potential to utilize the InSAR data as a tool to monitor head changes in the semi-confined/confined aquifers in the Central Valley of California

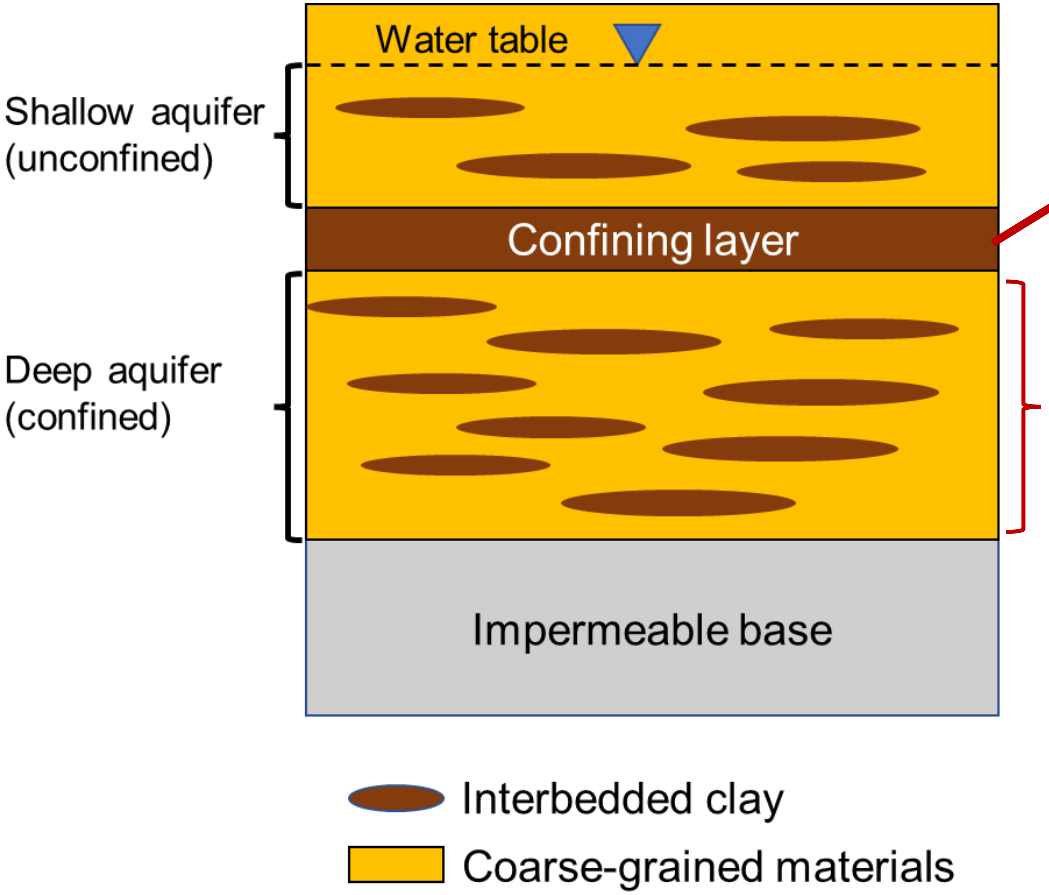
InSAR surface deformation data



Groundwater head



Data gap for extending this idea to a water basin?



a) The Corcoran Clay: depth, thickness

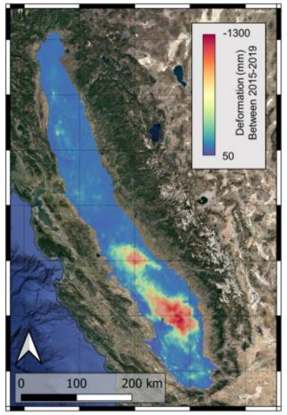
b) Thickness of the confined aquifer
c) Clay-fraction within the aquifer
…

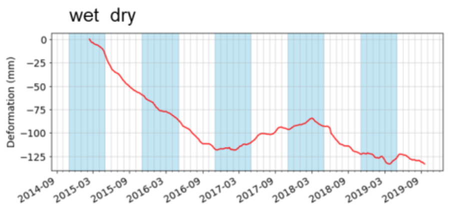
Integrate AEM data & Well data to obtain these

Outlook: Monitoring groundwater head

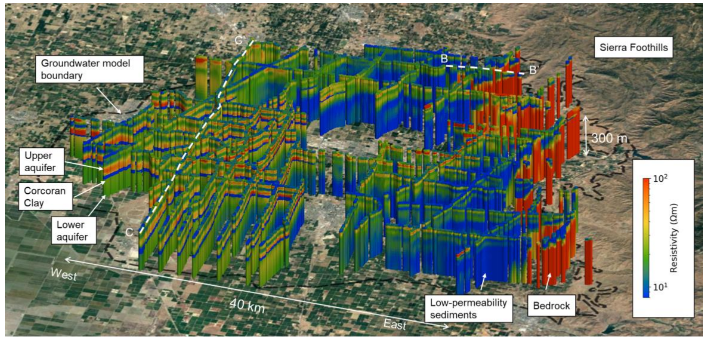
Remote Sensing Data

InSAR data: head information modulated by clays





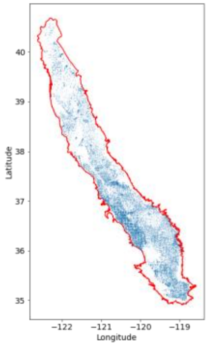
AEM data: distribution of the clays



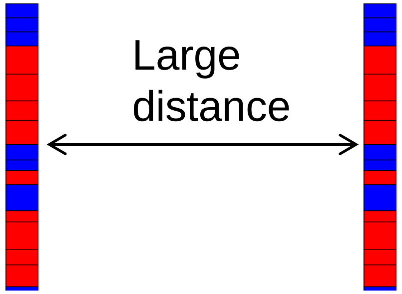
+

Well Data

Head data with sparse samplings



Lithologic data with sparse samplings



"Seek for the hydraulic head, $h(x, y;\ t)$ and parameters related to the clays, $\mathrm{p_{clays}}(x, y)$ that can fit the InSAR, AEM, well data favoring available prior information"

$$\text{minimize}\ \ \phi(m) = \phi_d(m) + \beta\phi_m(m)$$

ϕ_d: data misfit
ϕ_m: regularization
β: trade-off parameter

$$m = (h, \mathrm{p_{clays}})$$

$$\phi_{\mathrm{InSAR}} + \phi_{\mathrm{AEM}} + \phi_{\mathrm{well}}$$

Available prior information
(e.g., existing groundwater model)

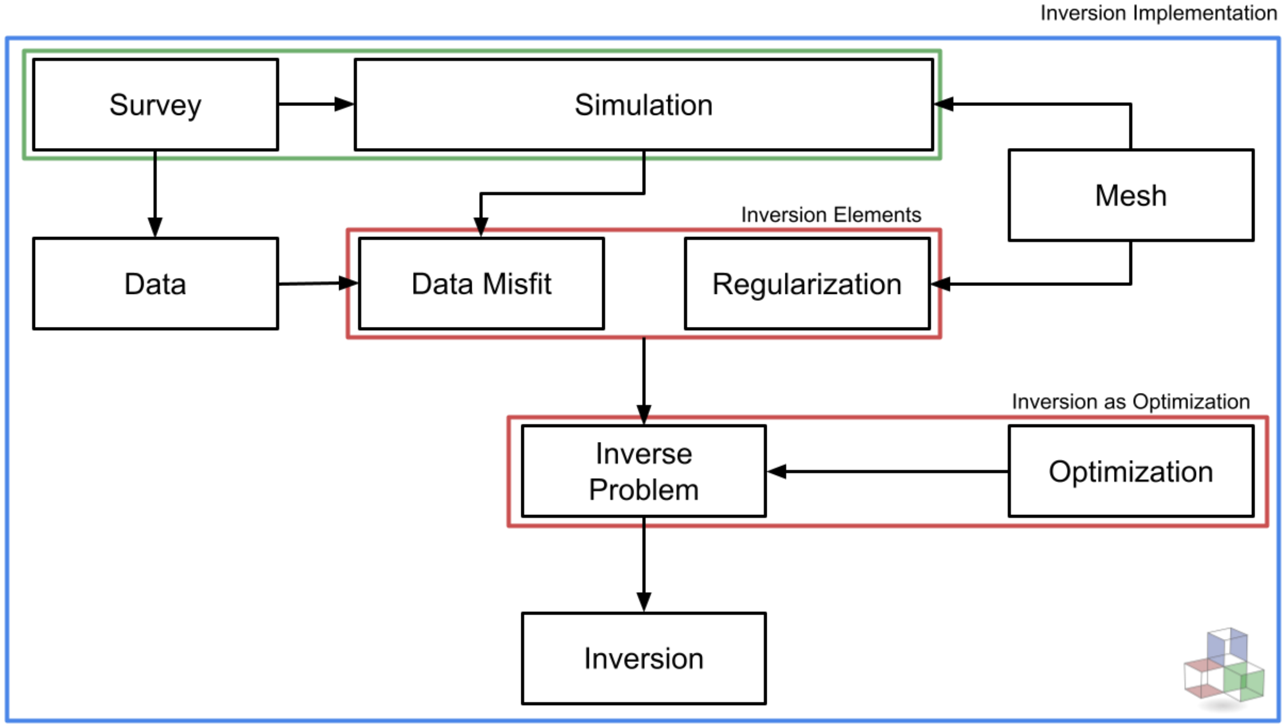
Need to couple the hydrologic process with the physics of the remote sensing data

open-source toolbox and framework for geophysical inversion

Modular, multi-physics

- Gravity
- Magnetics
- Direct current resistivity
- Induced polarization
- Electromagnetics
- Fluid flow (Richard's equation)

Cockett et al. (2015)



Research codes developed for my research are publicly available through the SimPEG: https://www.simpeg.xyz


Lindsey

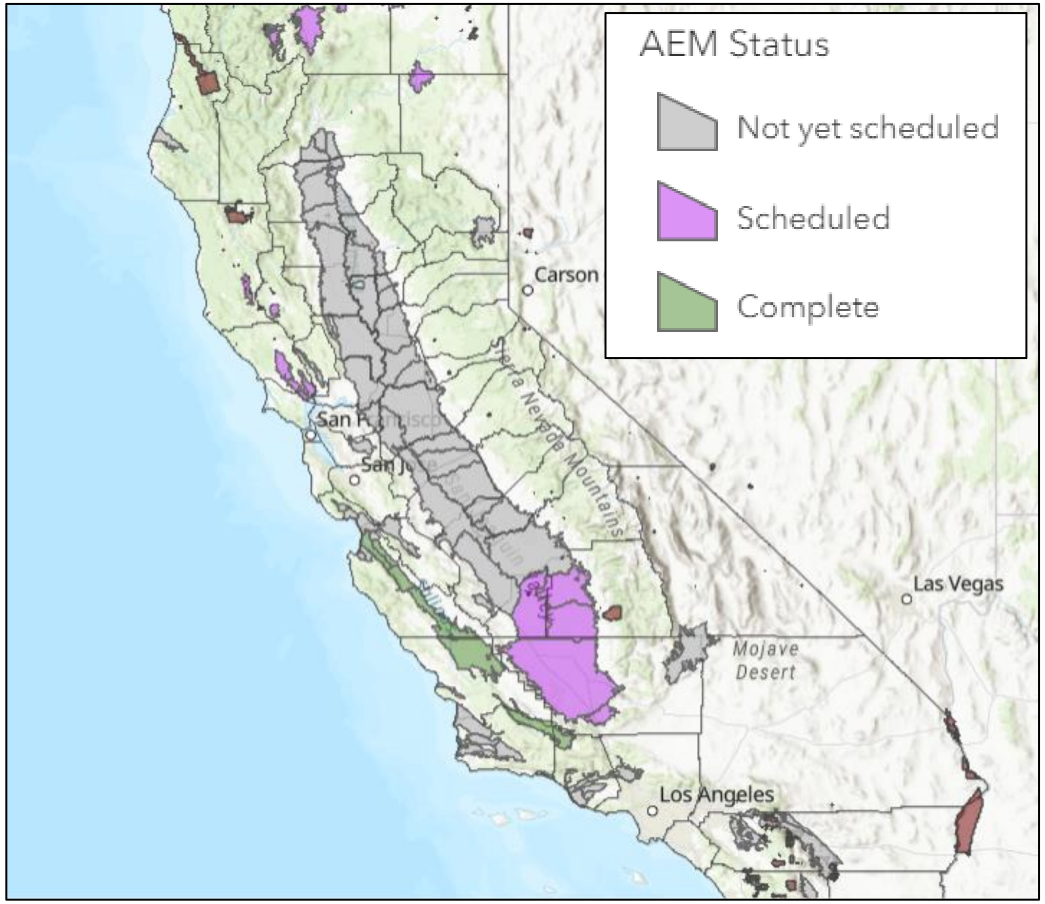

Seogi


Rowan


Doug

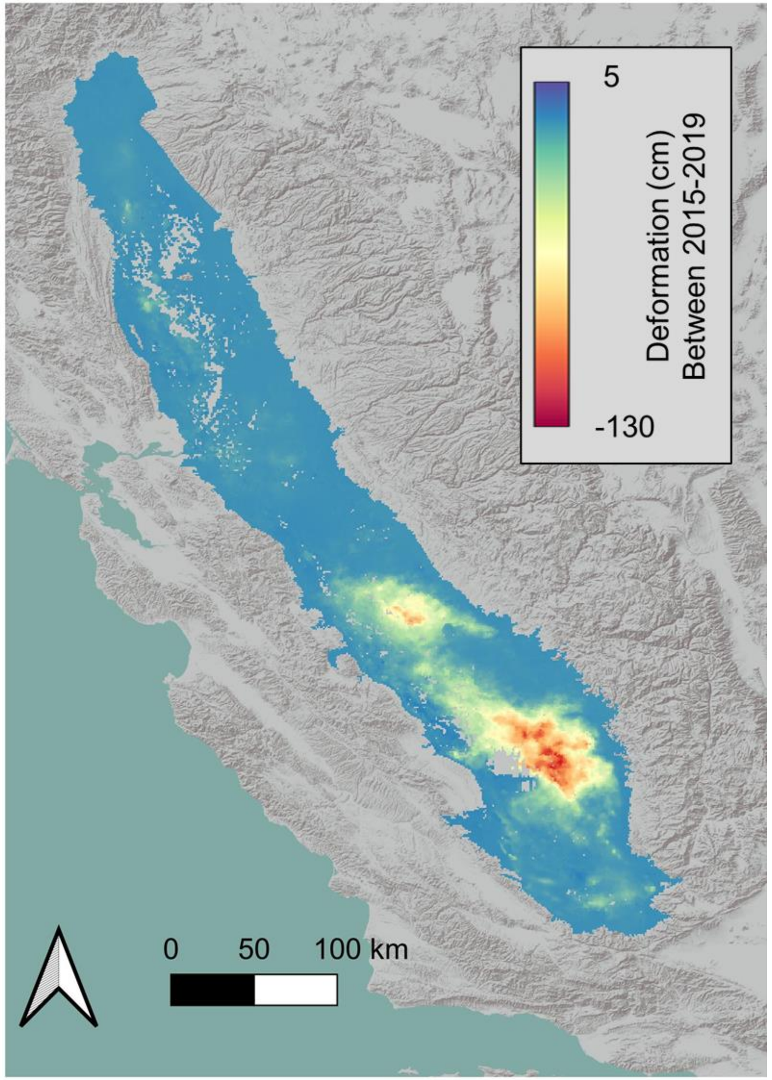
Larger volume of higher quality remote sensing data

Large-scale AEM project in CA



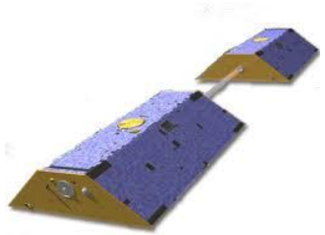
CDWR (2021)

Processed InSAR data (funded by CDWR)



Concluding remarks

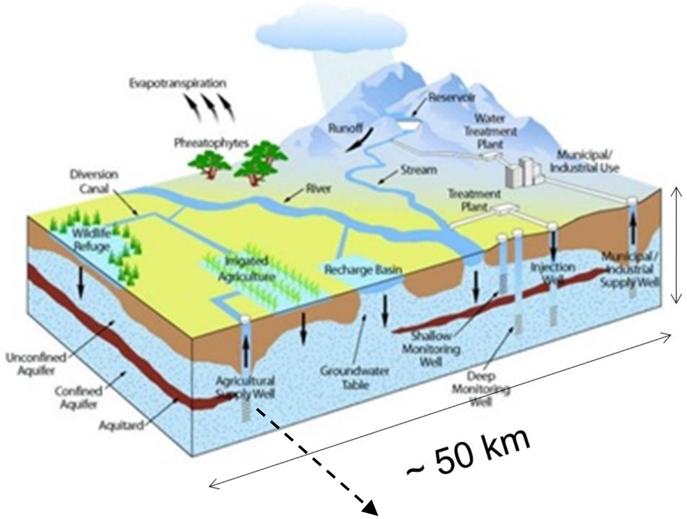
Sentinel (InSAR)



GRACE

…

Airborne EM



Ground-based EM ….

Traditional well data

Data Integration

Monitoring Spatial & Temporal

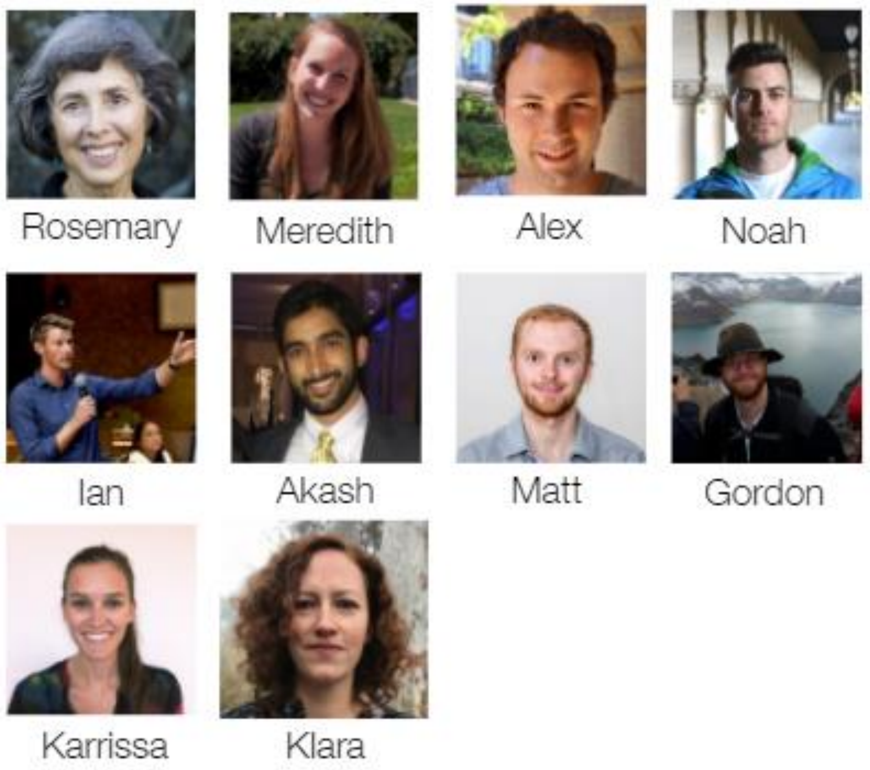
Changes in groundwater <u>head</u>
Changes in groundwater <u>volume</u>
…

My goal is to maximize the value of the Earth Imaging techniques for improved understanding of groundwater systems

Thank you!

simpeg

Stanford University



Acknowledgements

AEM data: acquired with the SkyTEM system; acquisition oversight, planning, and processing by Aqua Geo Frameworks, LLC.

InSAR data: processed by TREALTIMERA and provided by the California Department of Water Resources (CDWR).

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Thanks to the local GSAs

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Michael Hagman

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