In the name of Allah

Linking Ground Deformation to Subsurface Anisotropy: Integrating InSAR, PDE Modeling, and Bayesian Inference

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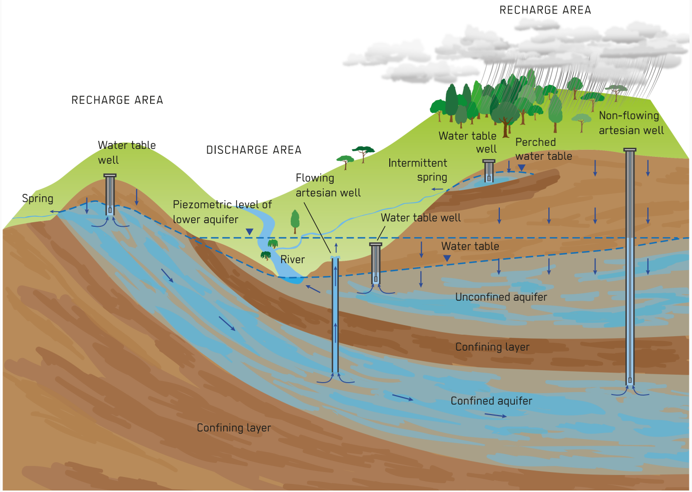
Chapter 1. Introduction

Big picture



From Coerver et al. (2021)

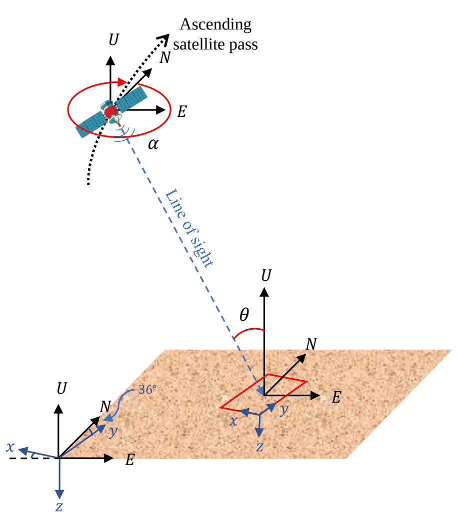
Big picture

San Joaquin Valley, California
Land surface subsidence $9\,\mathrm{m}$
from 1925 to 1977

From Galloway & Burbey (2011)

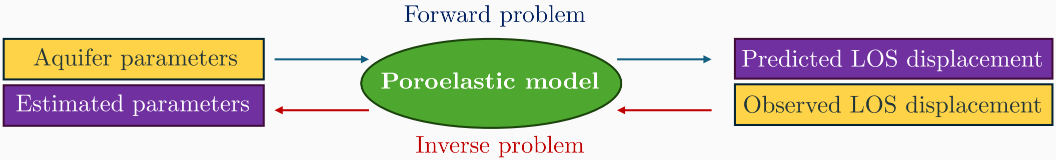
InSAR

- InSAR: a powerful technique for measuring surface displacement.
- Recent work (Alghamdi et al., 2024; Salehian Ghamsari et al., 2025) has proposed **InSAR** (Interferometric Synthetic Aperture Radar) data to improve aquifer property estimation.



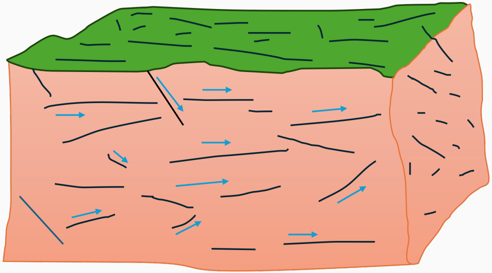
PDE model linking flow and deformation

- **Poroelastic PDE** couples:
  - Groundwater flow
  - Surface displacement
- Enables inversion: infer aquifer properties (storage coefficients and hydraulic conductivity) from **InSAR** observations (Bonì et al., 2020; Hu et al., 2018; Bonì et al., 2016; Chaussard et al., 2014).

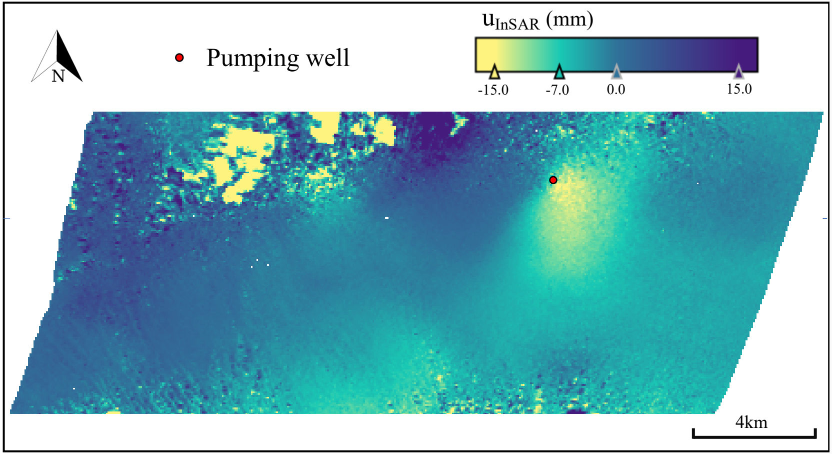


Anisotropic hydraulic conductivity (AHC) in fractured aquifer

- Many aquifers show **anisotropic** flow created by fractures and faults.
- Most Bayesian methods (Alghamdi, 2020) assume **isotropy**, oversimplifying reality.
- Use an **AHC tensor** in poroelasticity to capture anisotropy.



InSAR



InSAR-observed deformation of Nevada aquifer pumping test (Burbey et al., 2006; Alghamdi et al., 2021)

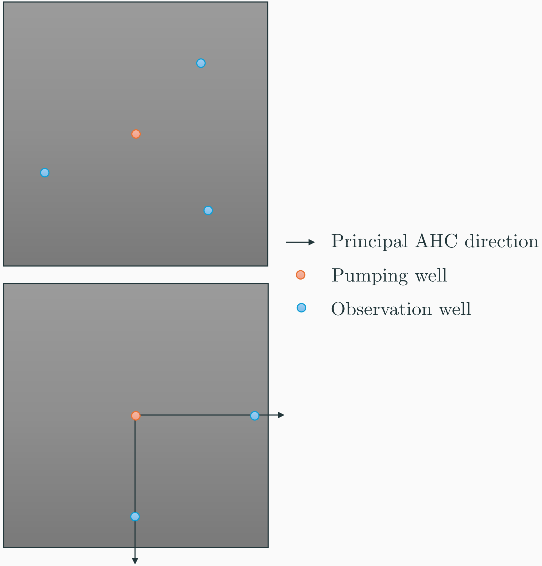
Research questions

1. Can a **poroelastic finite element model**, incorporating AHC, reliably simulate aquifer behavior and predict its signature in InSAR LOS surface displacements?
2. Does **InSAR** surface displacement contain valuable information about **anisotropic hydraulic conductivity (AHC)** in groundwater models?
3. Can structural geological data be incorporated into a **probabilistic model** to represent prior knowledge of AHC?
4. How can a complex model of an aquifer with PDE and probabilistic components be **automatically differentiated**?

Forward model

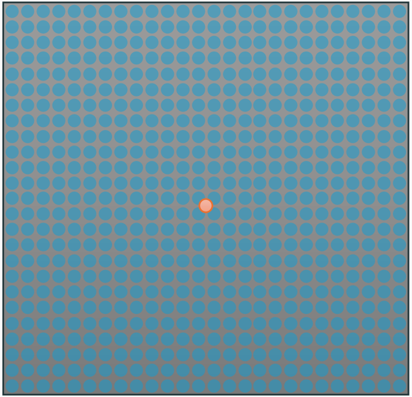
Prior work

- Papadopulos (1965) $\rightarrow$ the importance of AHC in aquifers
- Heilweil & Hsieh (2006)$\rightarrow$ AHC could be inferred from two observation wells assumed to be aligned with the principal directions of AHC



InSAR: full field data for Aquifer Models

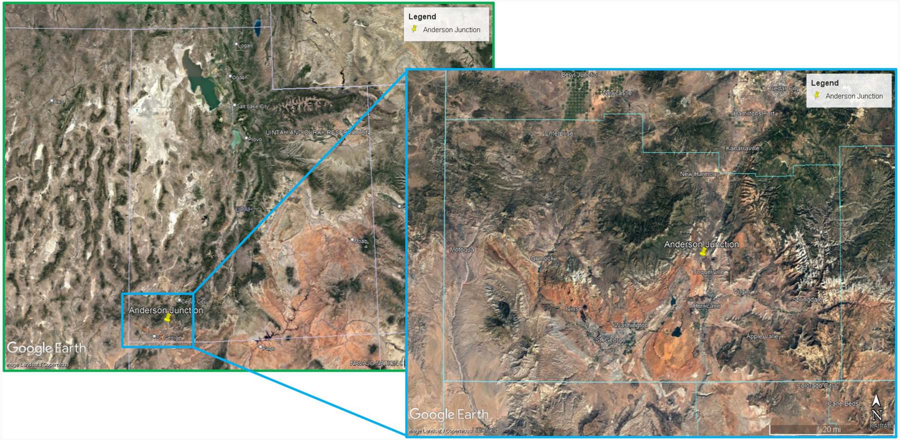
Does **InSAR** surface displacement contain valuable information about **anisotropic hydraulic conductivity (AHC)** in groundwater models?




Legend
Anderson Junction
Anderson Junction
Google Earth
N

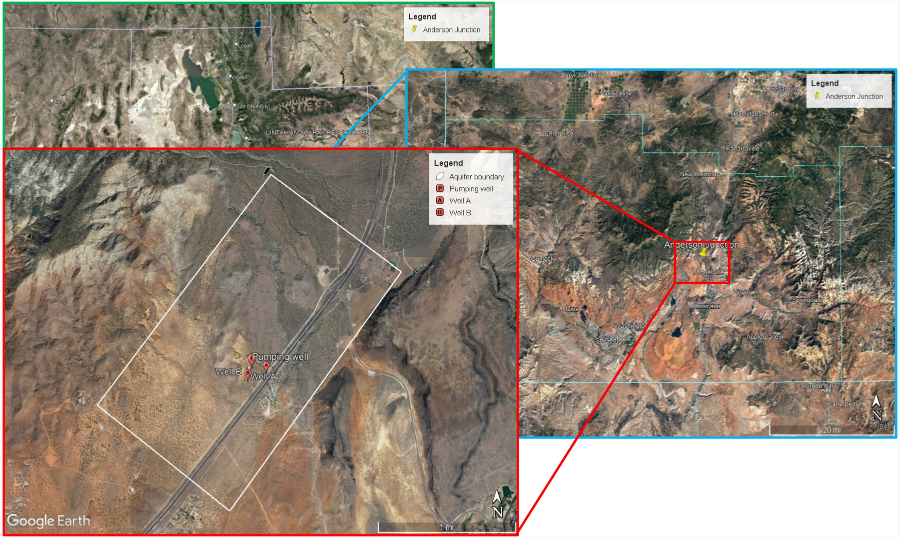
Utah, USA.

Case study



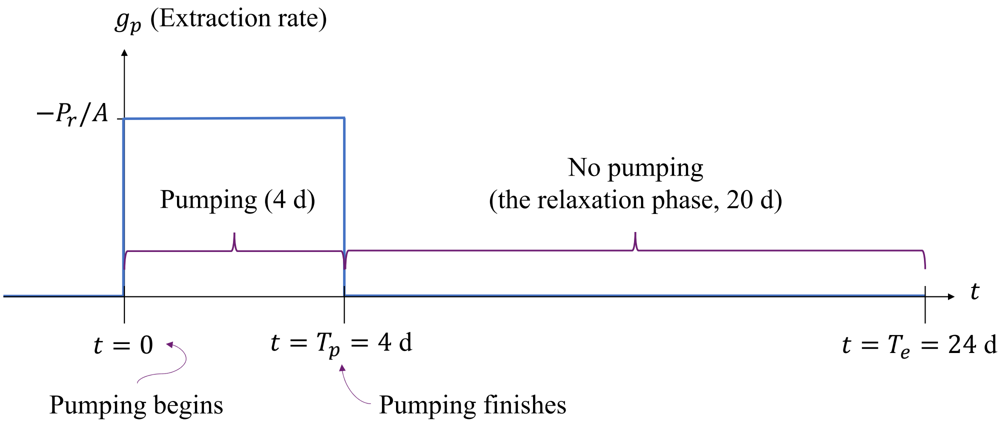
Washington, Utah, USA.

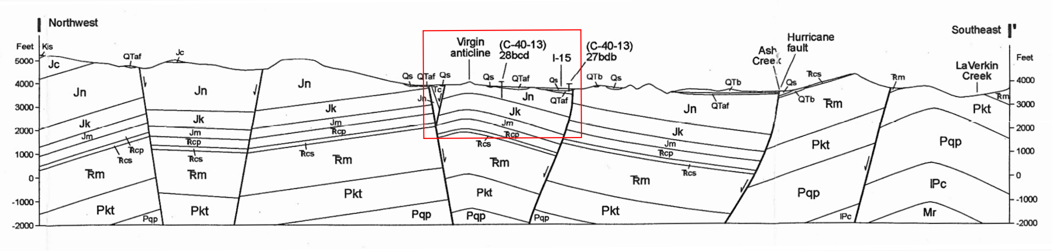
Case study



Anderson Junction aquifer, Utah.

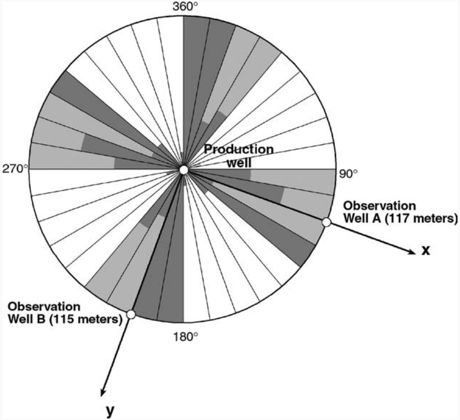
Aquifer test





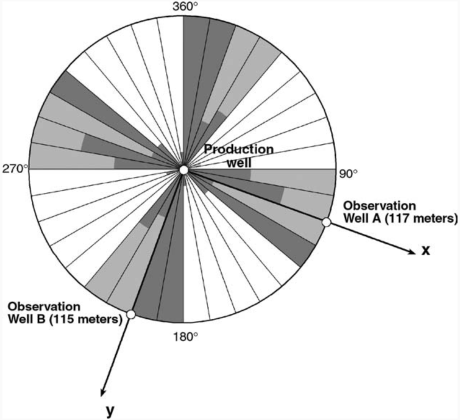
Cross section of the Anderson Junction area (Hurlow, 1998).

Fracturing

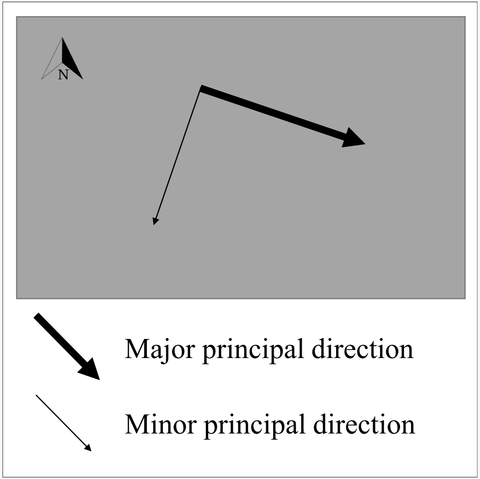


Rose diagram (Heilweil & Hsieh, 2006).

Fracturing



Rose diagram Heilweil & Hsieh (2006).



Three-field Biot equations with AHC

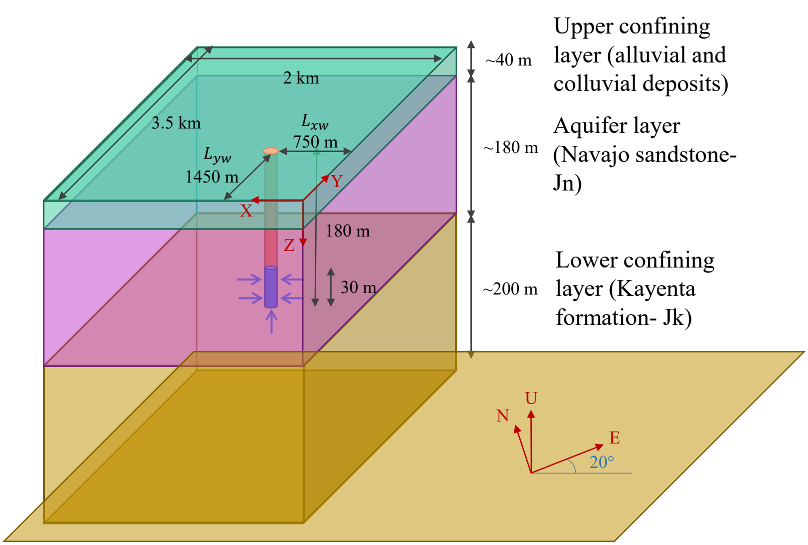
Find the fluid-pore pressure p, deformation u and fluid flux q such that:

$$
\begin{aligned}
(S_\epsilon p + \alpha \nabla \cdot u)_t + \nabla \cdot q &= f_p, \\
-\nabla \cdot \bar{\sigma}(u, p) &= f_u, \\
\boxed{q + k \nabla p = 0}
\end{aligned}
$$

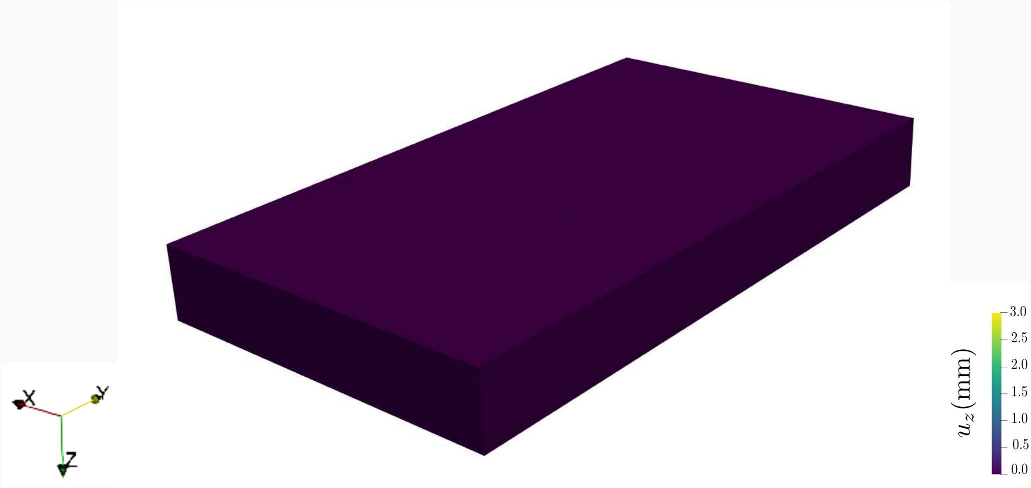
We take hydraulic conductivity (k) to be a diagonal matrix when the principal directions of anisotropy align with the model coordinate system

$$
k = \begin{bmatrix} k_{xx} & 0 & 0 \\ 0 & k_{yy} & 0 \\ 0 & 0 & k_{zz} \end{bmatrix}.
$$

Simplified conceptual model of the Anderson Junction aquifer system

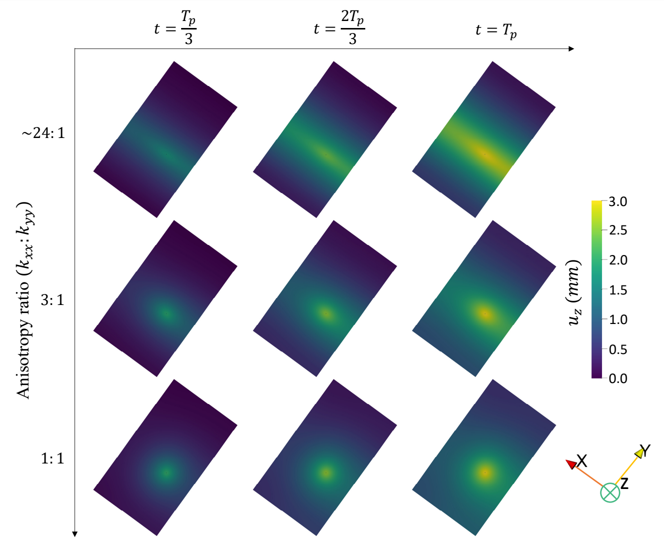


3D deformation



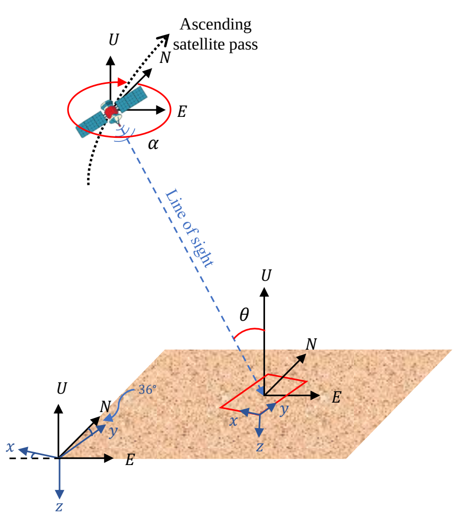
Magnified 3D deformation in the pumping phase and relaxation phase

Anisotropy ratio



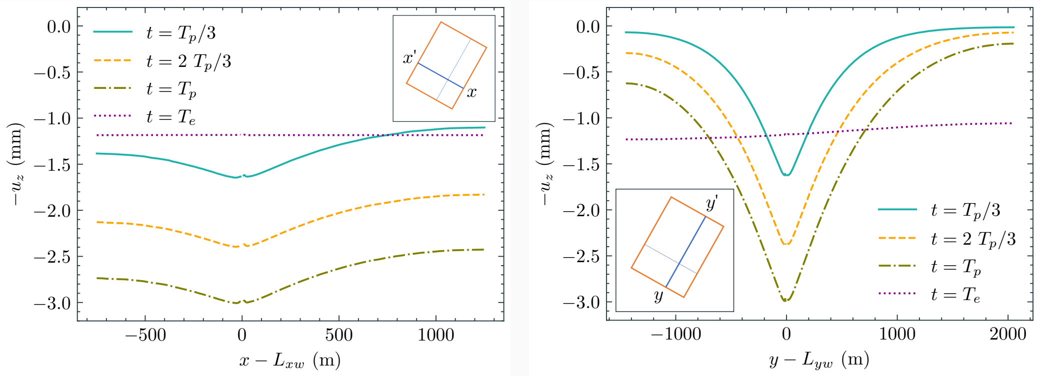
InSAR precision

- Sentinel-1 InSAR time series precision → less than 8 mm (Duan et al., 2020) or even 5 mm (Manunta et al., 2019).
- At least 8 mm of LOS surface displacement in a region around the well that shows the elliptical displacement to be able to demonstrate the AHC of the aquifer.



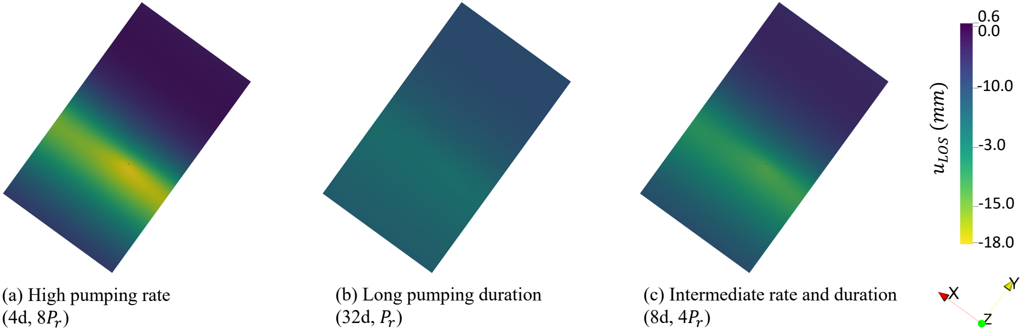
Anderson Junction surface displacement

Did the Anderson Junction aquifer test produce surface displacement that could be measured with InSAR?



Line of sight displacement of different scenarios

What modifications to the Anderson Junction aquifer test (4d, P_r) are necessary to enable displacement detection using InSAR?



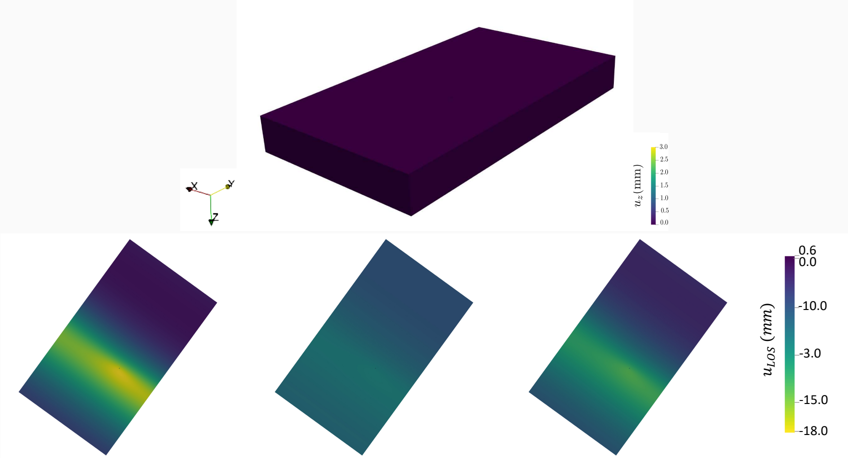
(a) High pumping rate (4d, $8P_r$) Max LOS def. = 18.0 mm

(b) Long pumping duration (32d, P_r) Max LOS def. = 8.6 mm

(c) Intermediate rate and duration (8d, $4P_r$) Max LOS def. = 13.3 mm

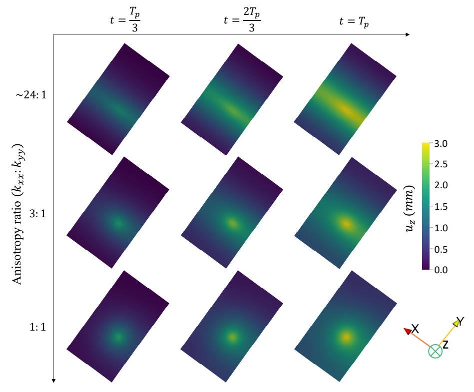
Conclusion

1. Can a **poroelastic finite element model**, incorporating AHC, reliably simulate aquifer behavior and predict its signature in InSAR LOS surface displacements?



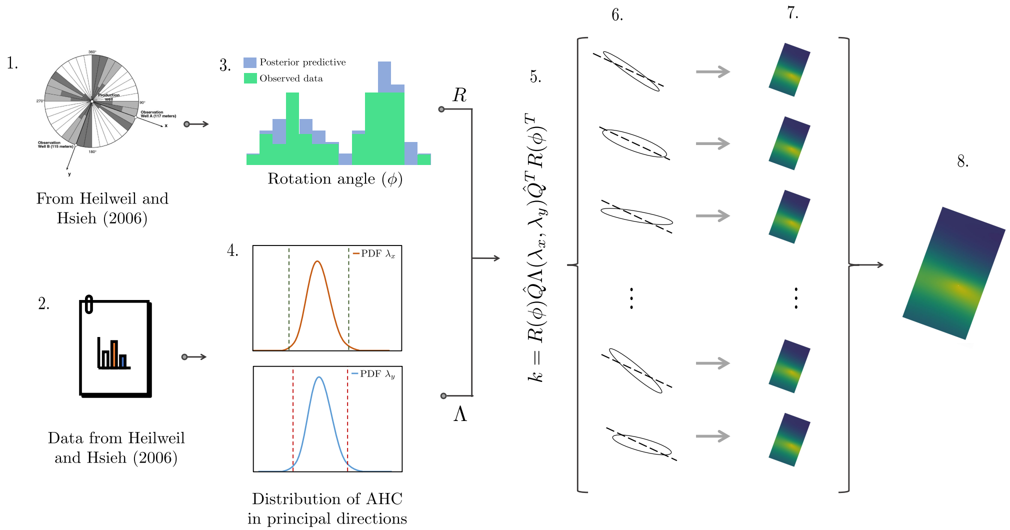
Conclusion

2. Does **InSAR** surface displacement contain valuable information about **anisotropic hydraulic conductivity (AHC)** in groundwater models?



Stochastic extention

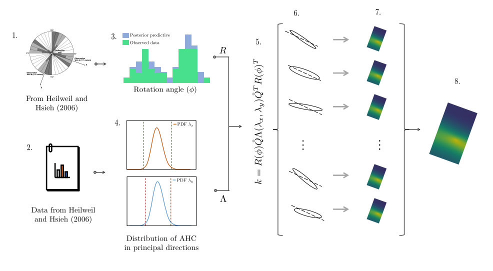
Methodology



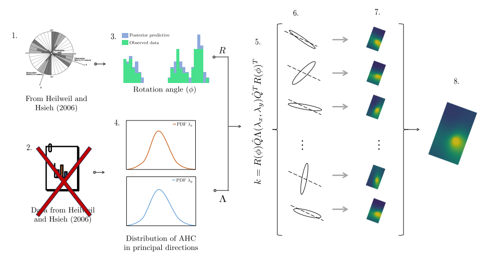
Conclusion

3. Can structural geological data be incorporated into a **probabilistic model** to represent prior knowledge of AHC?

- First scenario



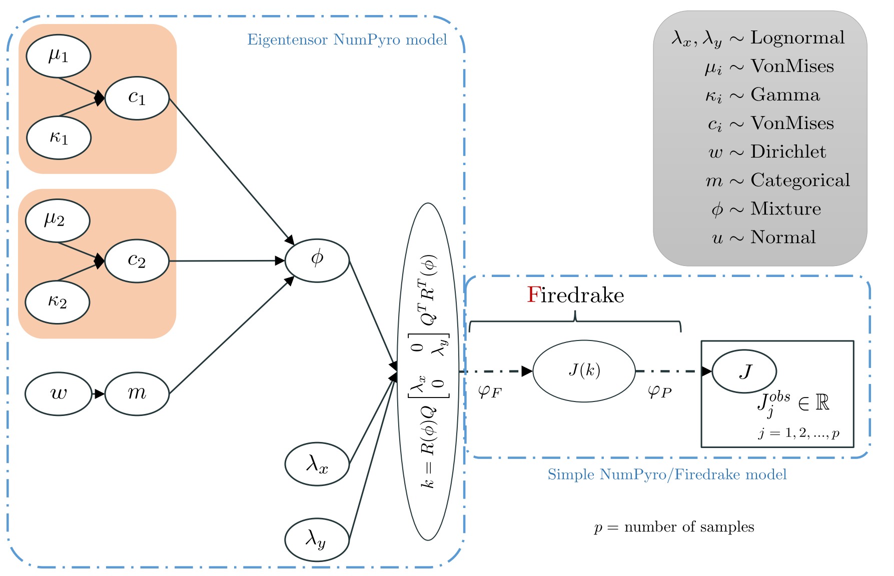
- Second scenario



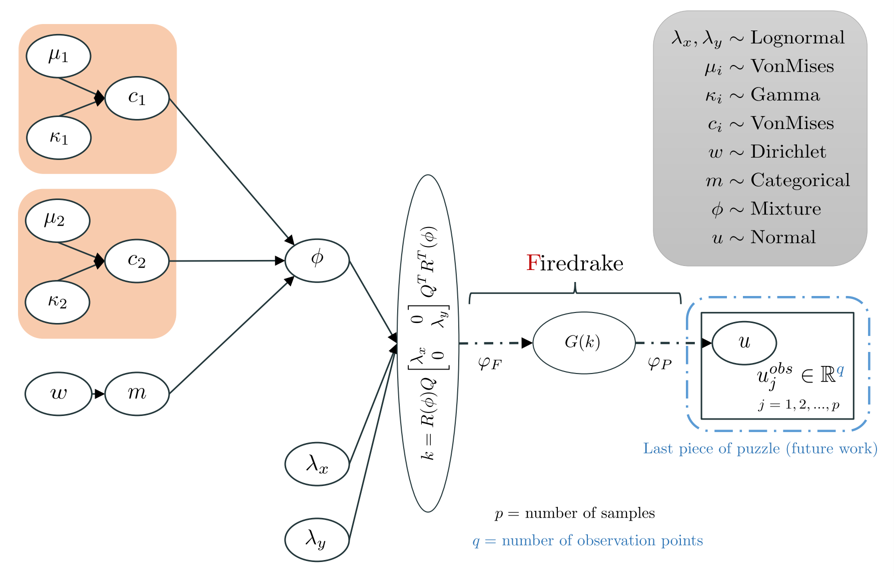
S. Salehian Ghamsari, T. van Dam, J. S. Hale. "A random model of anisotropic hydraulic conductivity tailored to the InSAR-based analysis of aquifers". (2025).

Inverse model

Probabilistic inverse problem (what we have accomplished)



Probabilistic inverse problem (overall NumPyro model and future work)



Deterministic inverse problem: Adjoint-based optimization

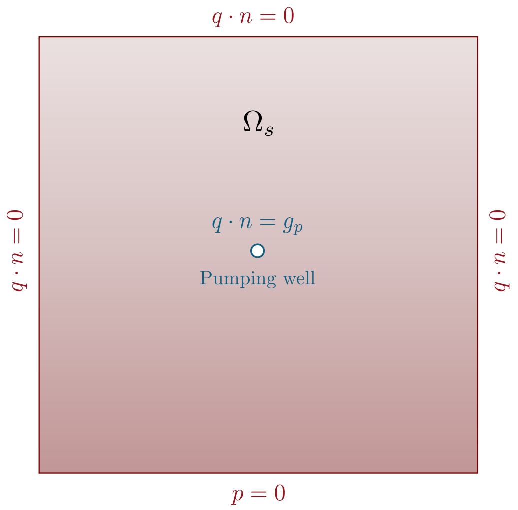
Forward model: 2D aquifer flow model

Find the fluid pore pressure $p_s : \Omega_s \times (0, T] \to \mathbb{R}$ such that

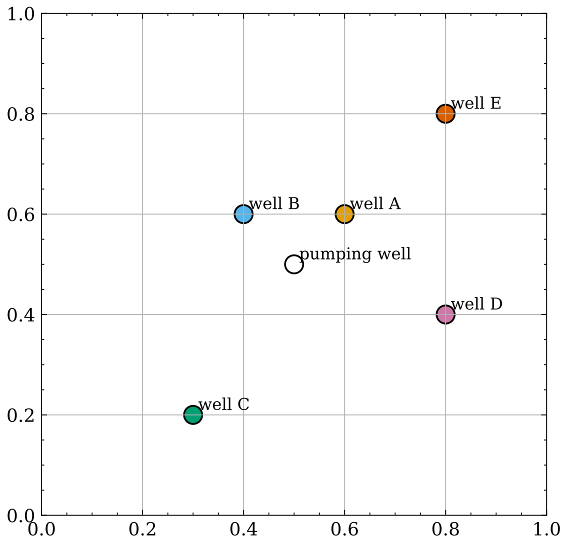
$$S\frac{\partial p_s}{\partial t} - \nabla \cdot (k \nabla p_s) = f_p \text{ on } \Omega_s \times (0, T]$$

The AHC is modeled as a second-rank SPD tensor in the x-y plane.

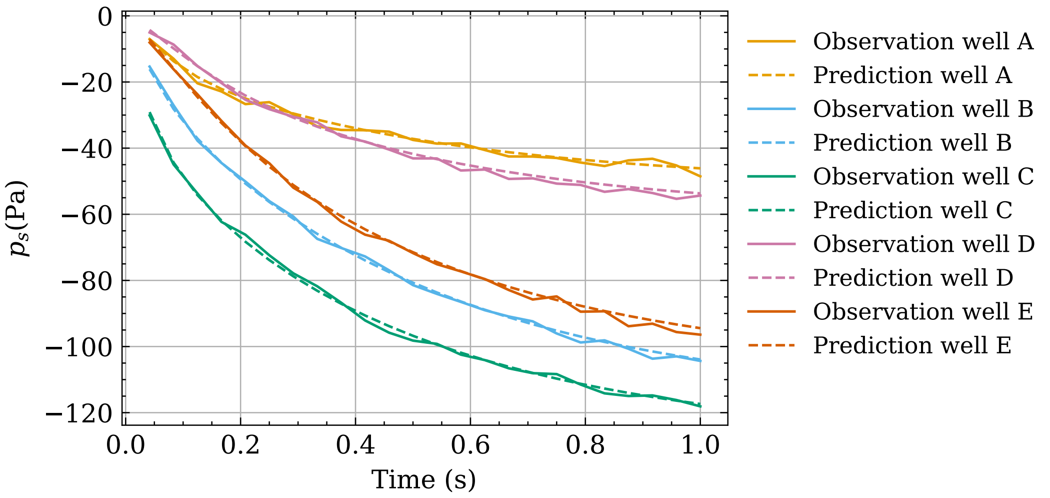
$$k = \begin{bmatrix} k_{xx} & k_{xy} \\ k_{xy} & k_{yy} \end{bmatrix}.$$



Location of synthetic observation wells



Inverse problem results



Take home messages

Aim:

- understanding aquifer system and estimating aquifer properties
- using InSAR technique instead of digging wells to make the process easier and cheaper

Contribution:

✓ we built a poroelastic finite element model to simulate an aquifer system with anisotropic hydraulic conductivity (AHC)

✓ we developed a flexible stochastic model of the AHC tensor

✓ we solved the deterministic inverse problem to estimate AHC

✈ we will solve the probabilistic inverse problem using an automatic Bayesian framework to estimate AHC

Acknowledgement

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☞ If you are interested in my research it would be great to chat with you further at this email address: sona.salehianghamsari@uni.lu

Any Question?

Thank you

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