Monitoring Groundwater Injection and Production with Passive Seismic Interferometry

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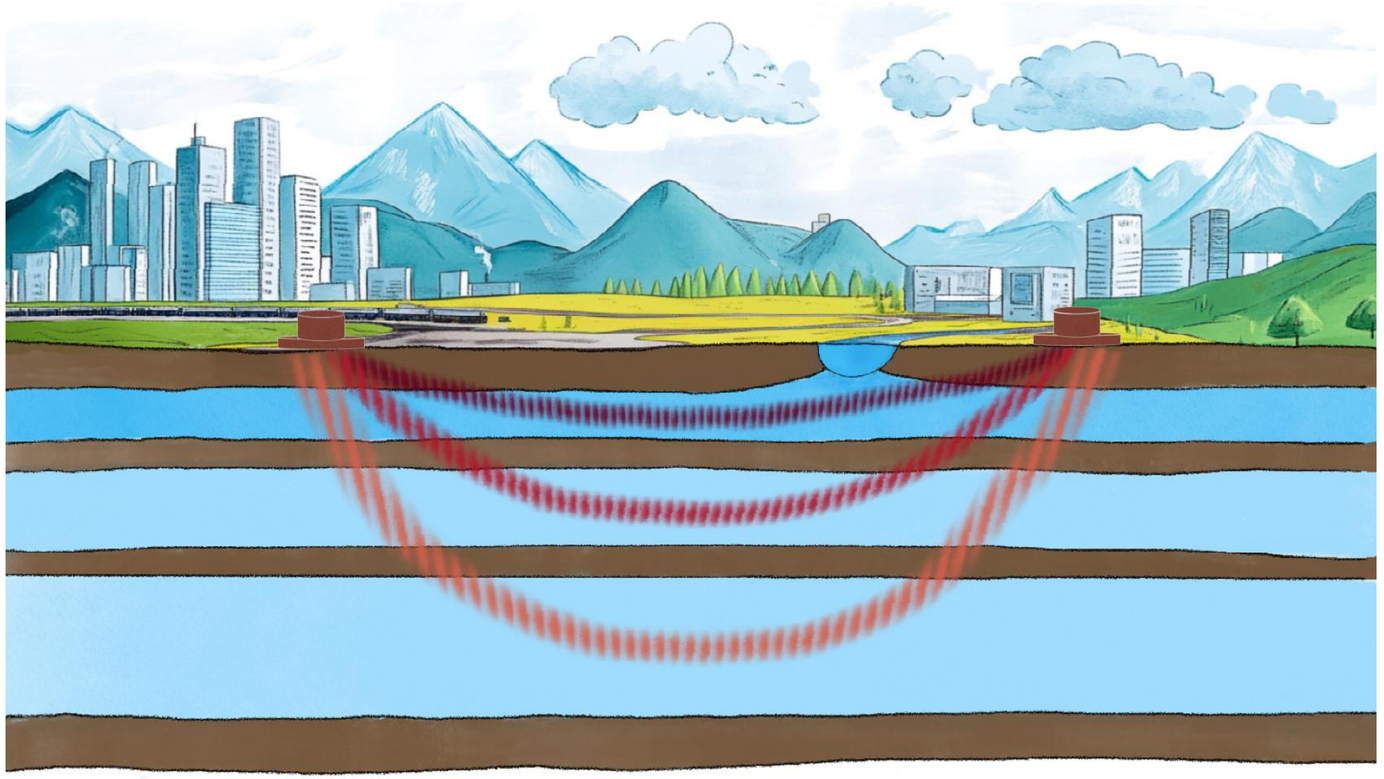
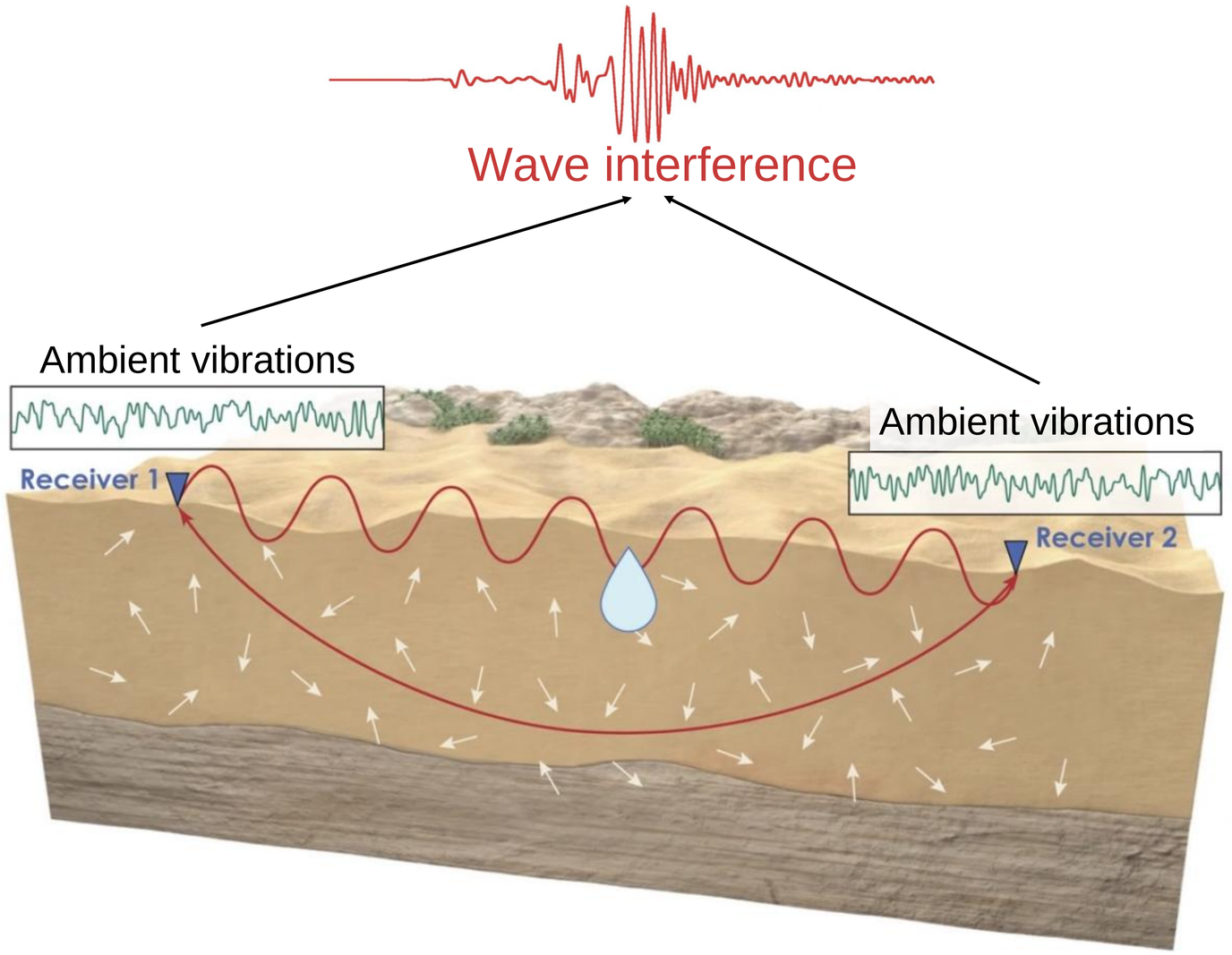
A State-of-the-art Seismic Monitoring Tool

- Using seismometers to **continuously** monitor subsurface pore pressure
  —> Proactive monitoring beyond seismicity

- Based on ambient seismic vibrations, no need for earthquakes or active sources
  —> Cost-effective, real-time monitoring at field scale



The Passive Seismic Interferometry Technique



- Ambient ground vibrations:
  — existing everywhere all the time
  — noisy and random

- Wave interference of ambient vibrations:
  informs about the seismic structure in the medium between two seismic receivers

- Allows to measure *seismic property changes* continuously in time
  (cost-effective, non-invasive)

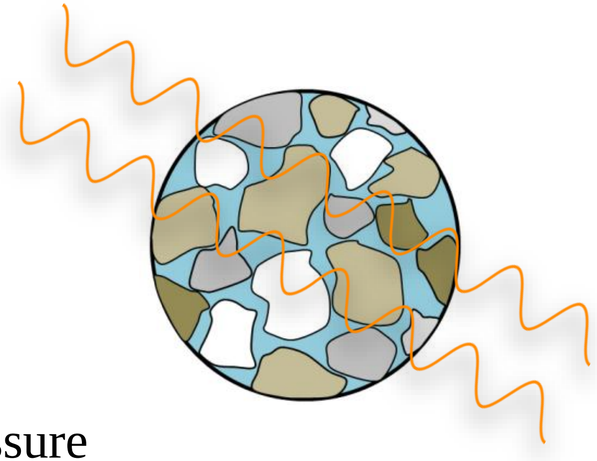
Campillo & Paul, 2003; Shapiro & Campillo, 2004; Yao et al., 2006; Prieto & Beroza, 2008 + many others

Relative change in v
(with respect to v at a reference time and location)

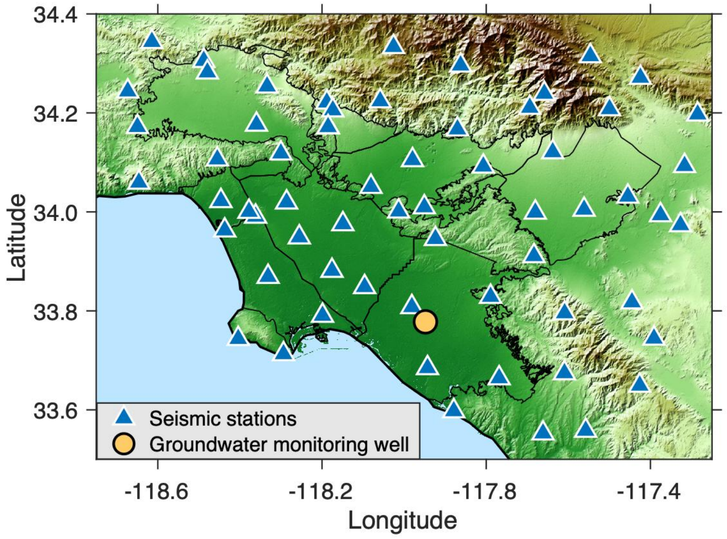
$$\frac{\Delta v}{v}$$

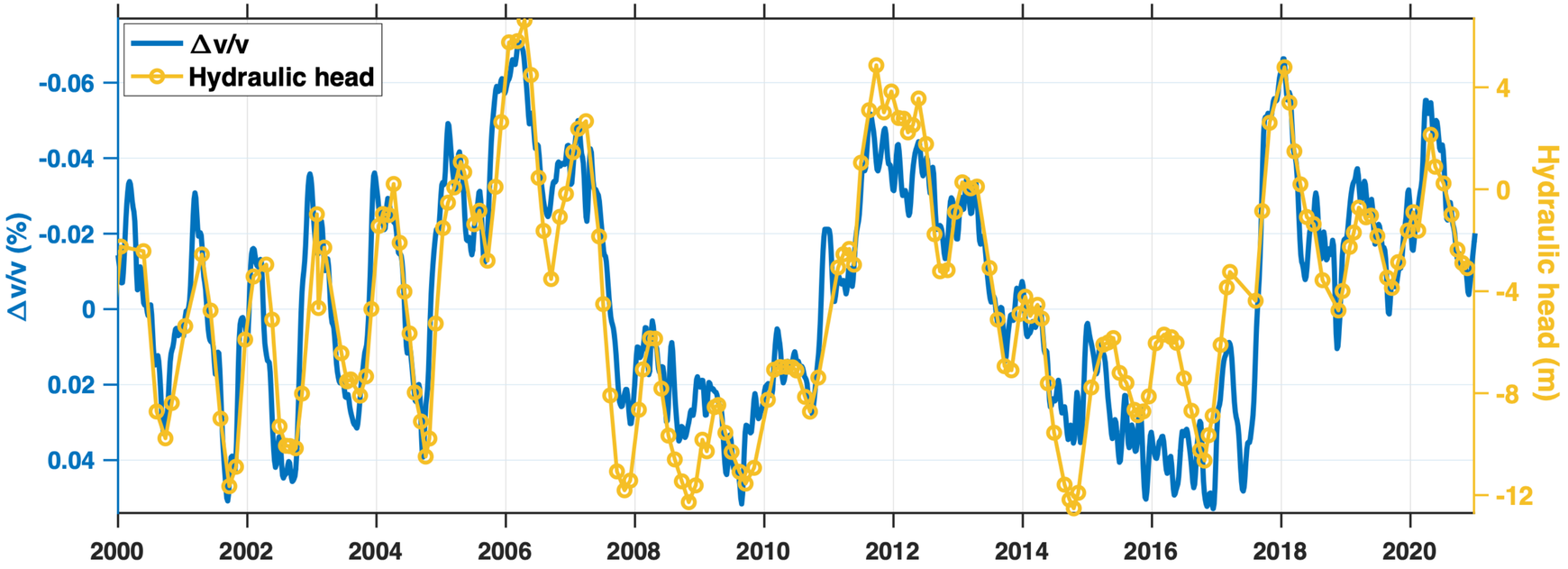
v: seismic velocity

a measure of pore pressure



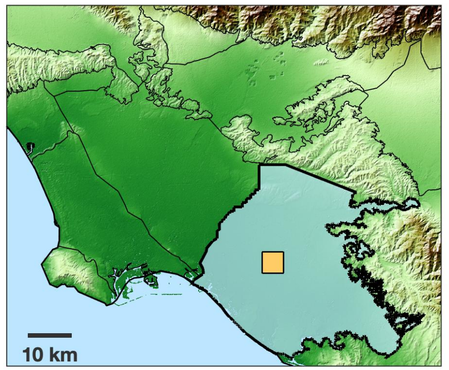
Greater Los Angeles, California

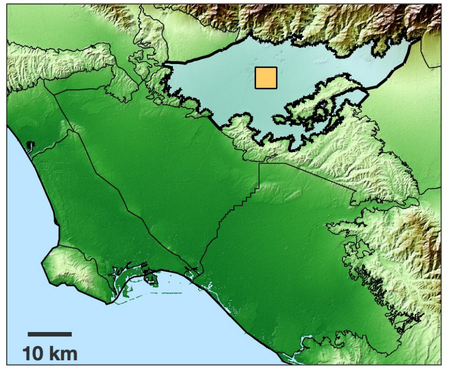


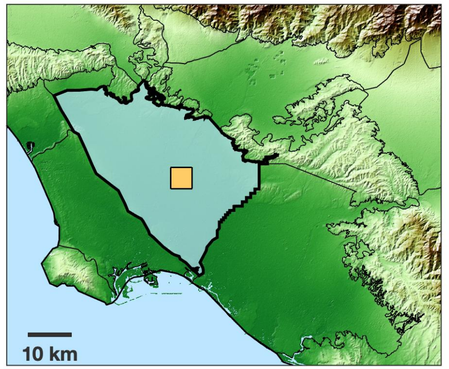


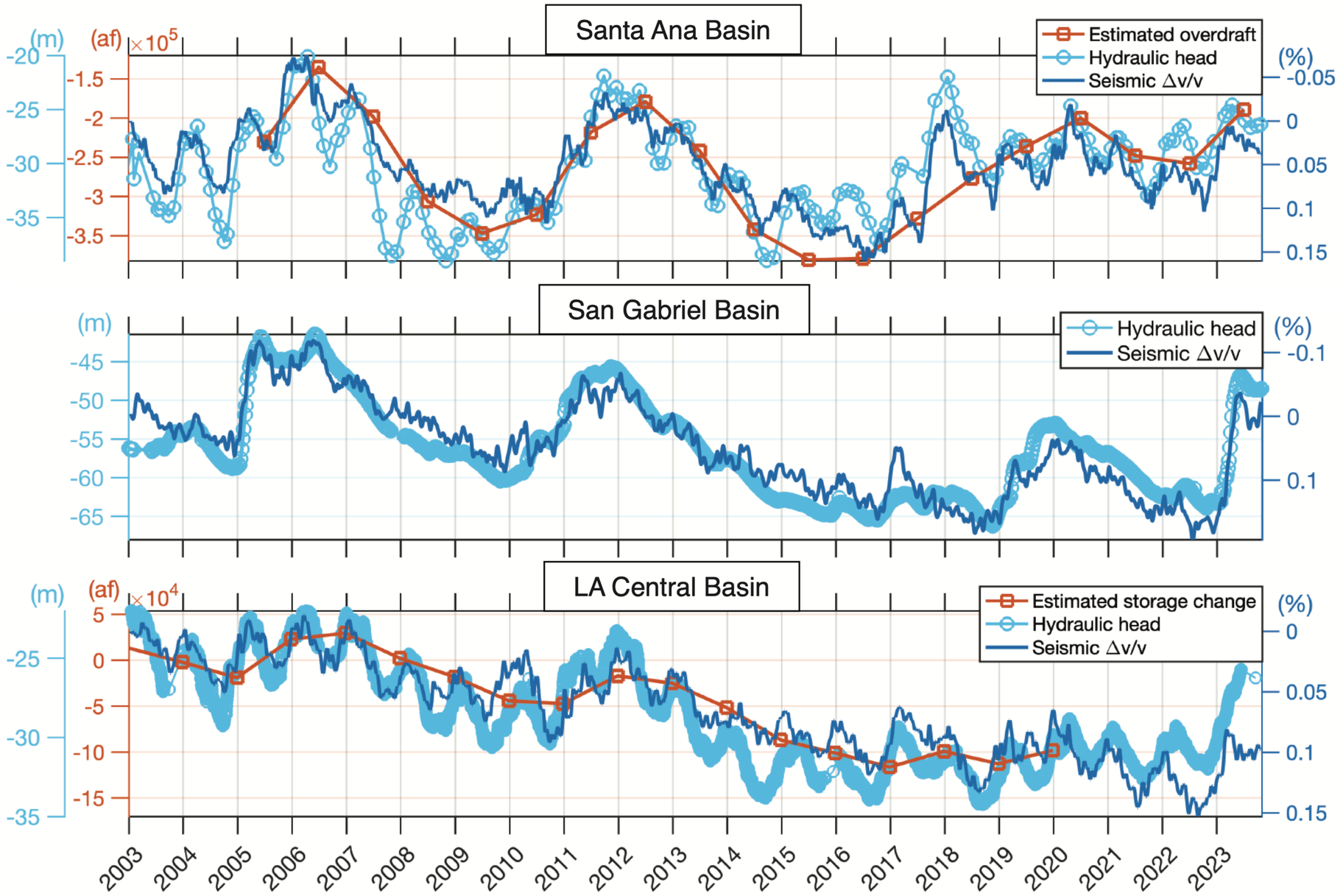
Mao et al. (2022), Nature Communications

Subwatershed-scale comparisons of seismic $\Delta v/v$ & hydraulic head



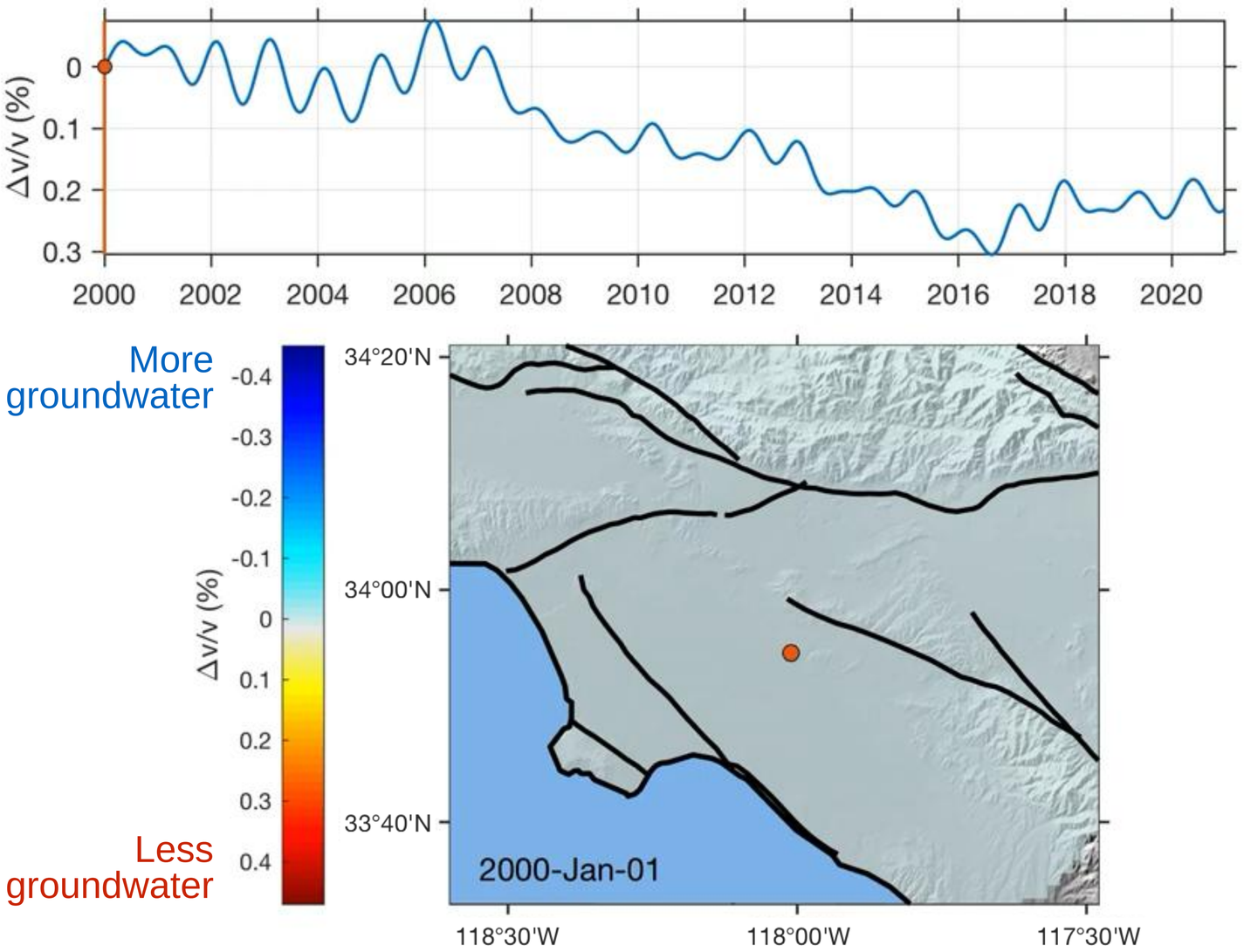






Mao et al. (2025), Science

Space-time measurements of seismic $\Delta v/v$ in Los Angeles

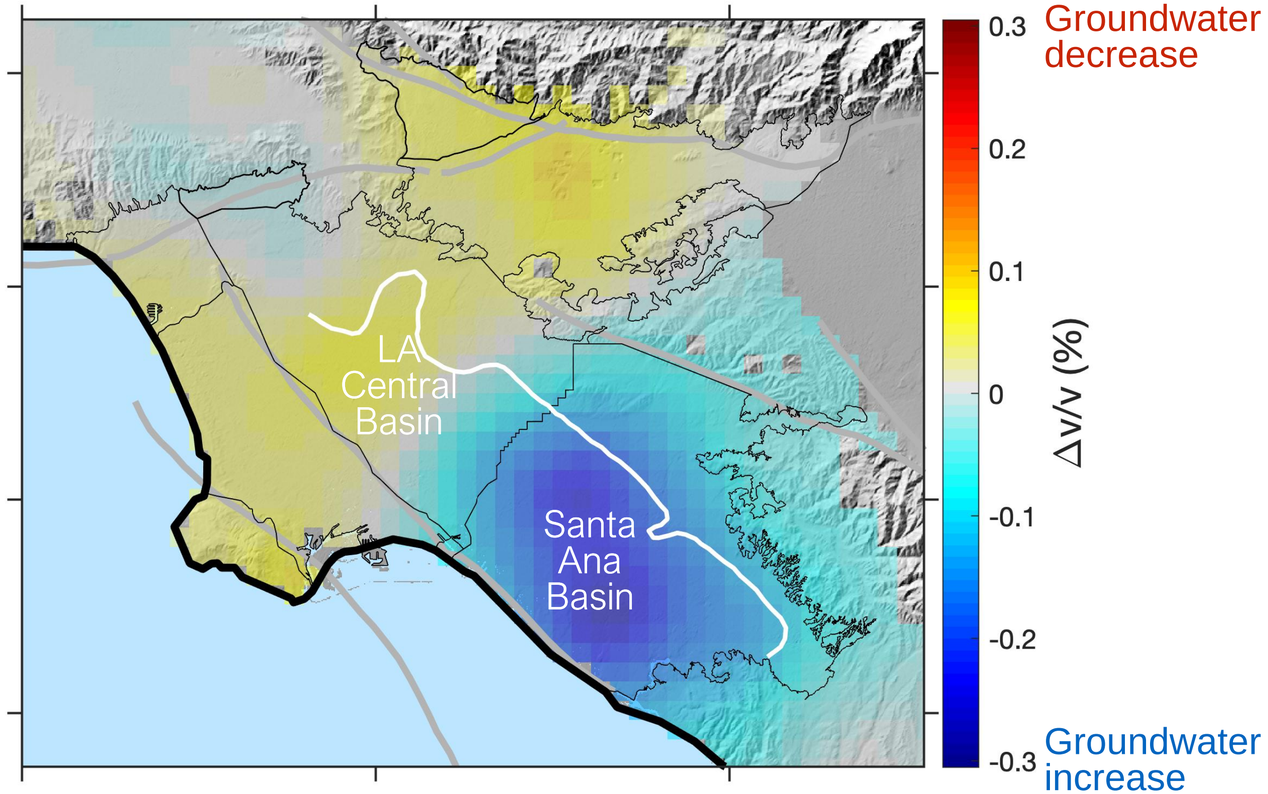


Mao et al. (2022), Nature Communications

Spatial imaging of $\Delta v/v$

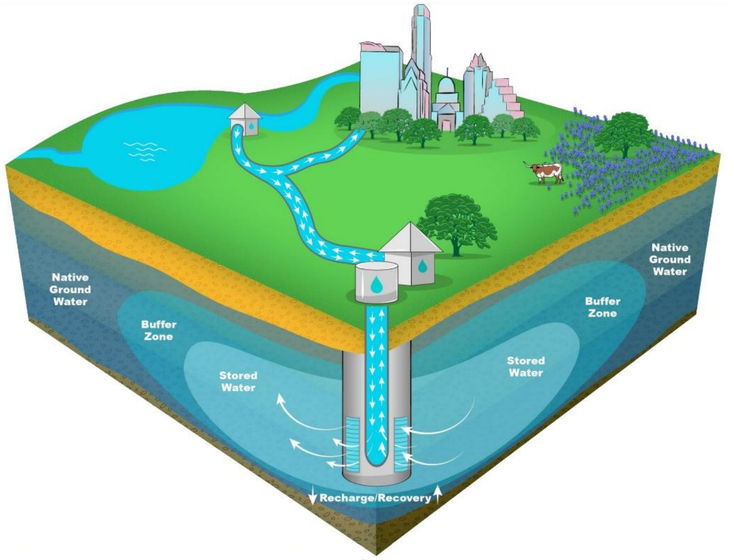
Net change in Summer, 2017

(Managed Aquifer Recharge)



Surface recharge facilities

Groundwater injection wells



Mao et al. (2022). Nat. Commun.

Mao et al., to submit

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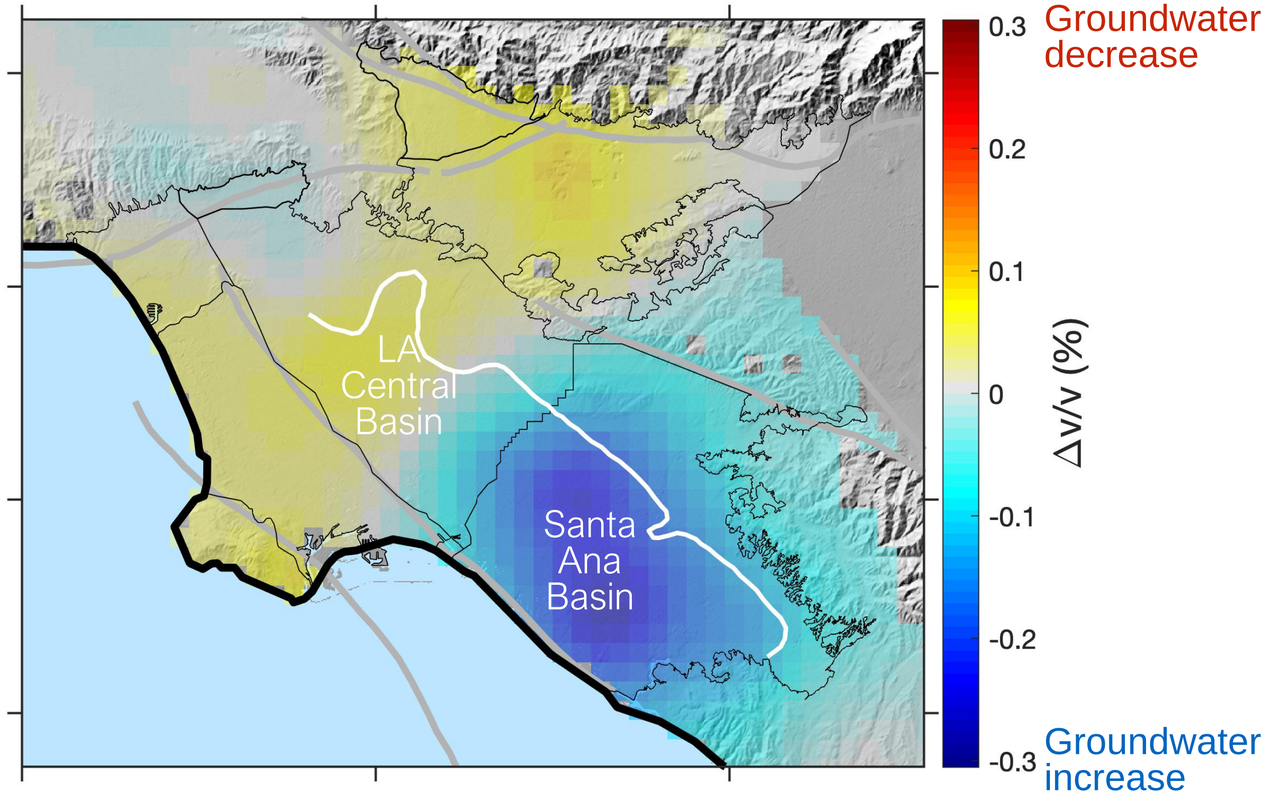
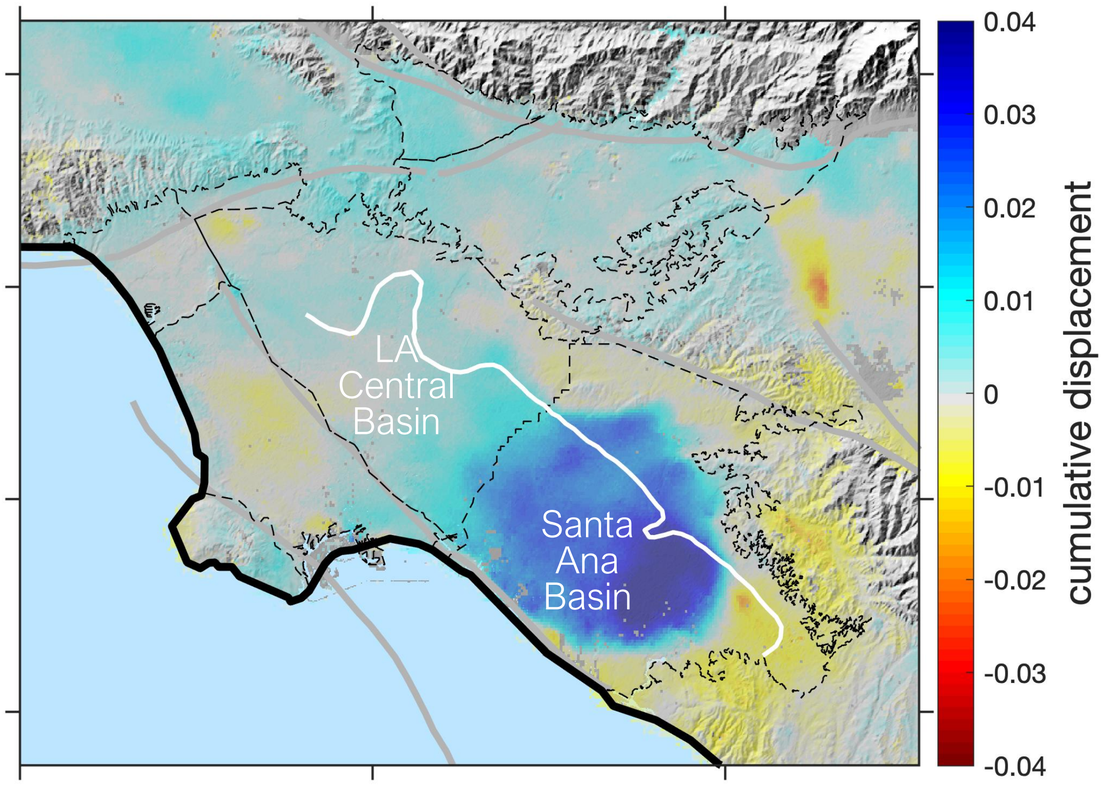


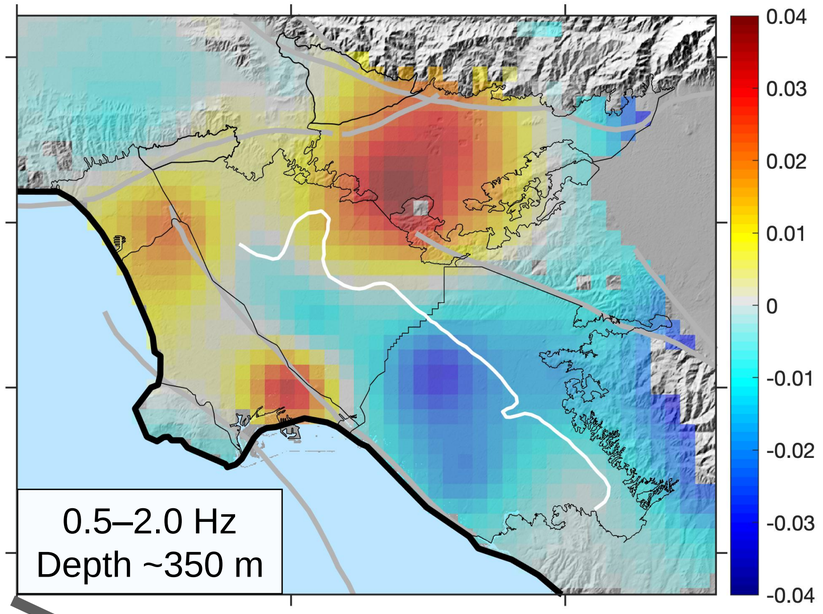
- A measure of:
  elastic moduli & bulk density *at depth*

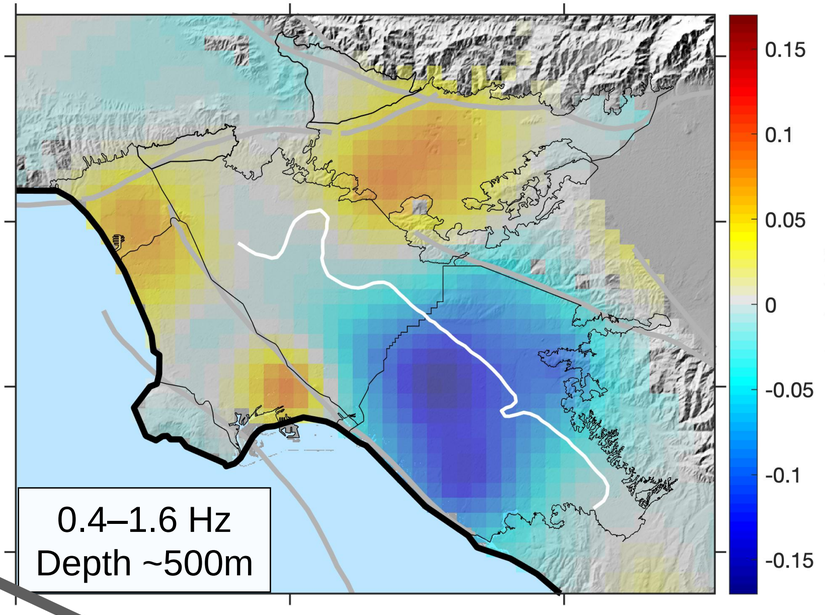
Deformation (from InSAR)

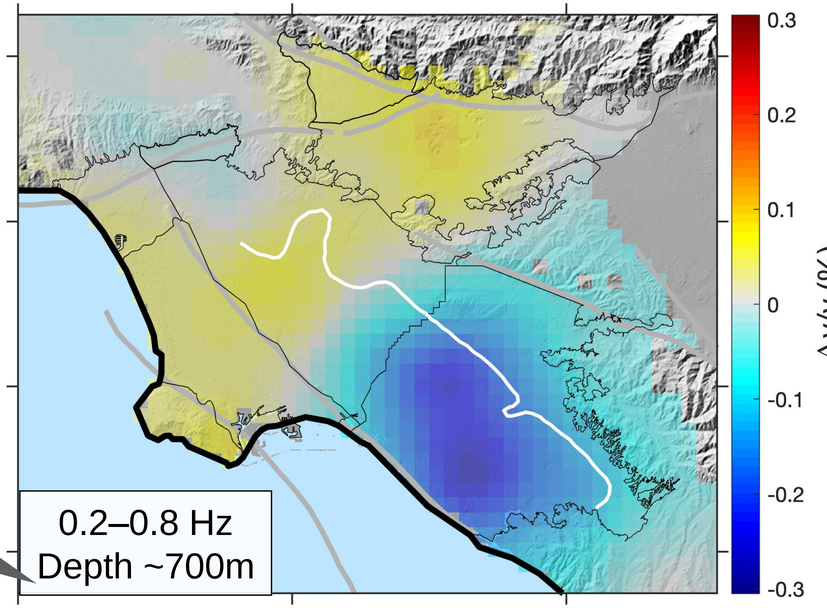


- A measure of:
  vertical displacement *at surface*

Mao et al. (2022). Nat. Commun.
Mao et al., to submit







shallower

deeper

Net change in Summer, 2017

(Managed Aquifer Recharge)

Mao et al., to submit

Spatio-temporal seismic $\Delta v/v$

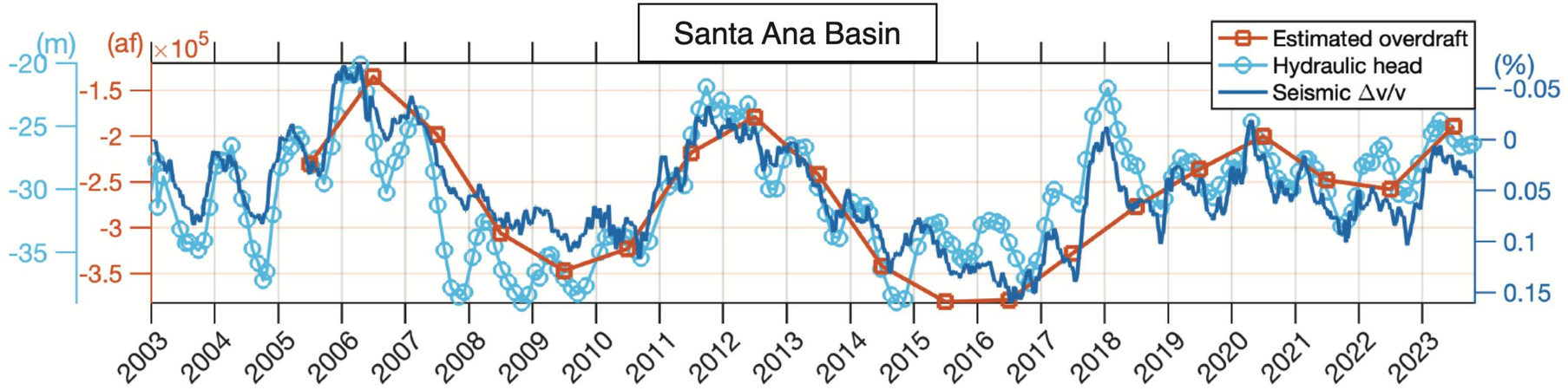
— Time series verified by hydraulic head, spatial images verified by InSAR

— Allows to characterize hydraulic head across a wide range of depths

— A cost-effective, non-invasive observation to aid in groundwater management

- significantly enhances the spatiotemporal resolution of well data
- independent from & complementary to existing hydrologic monitoring/modeling

Large number of existing seismometers in Permian ⟷ (Expensive) groundwater monitoring wells



Eagle Ford Basin, TX

Observations

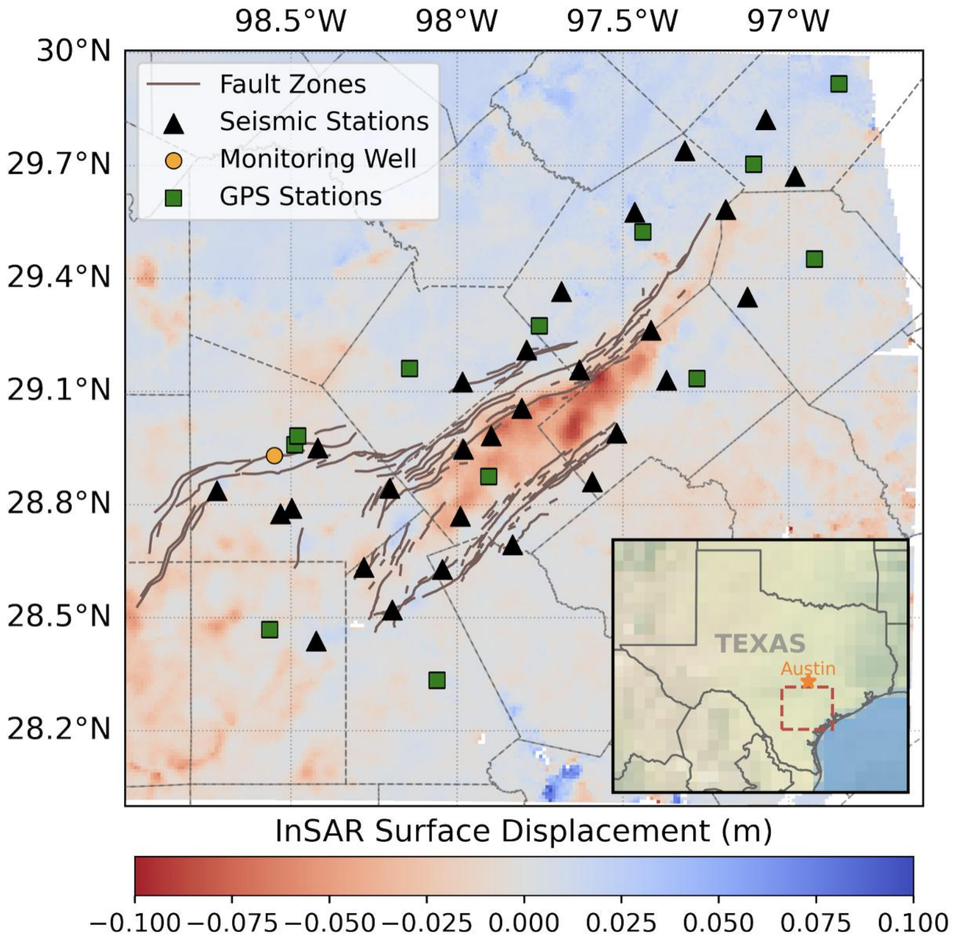
- Induced seismicity
- Surface subsidence (up to ~33.6 mm/yr in basin center)

Subsurface fluid budget

- Natural recharge from precipitation
- Groundwater pumping
- Oil&Gas production
- Waste water disposal

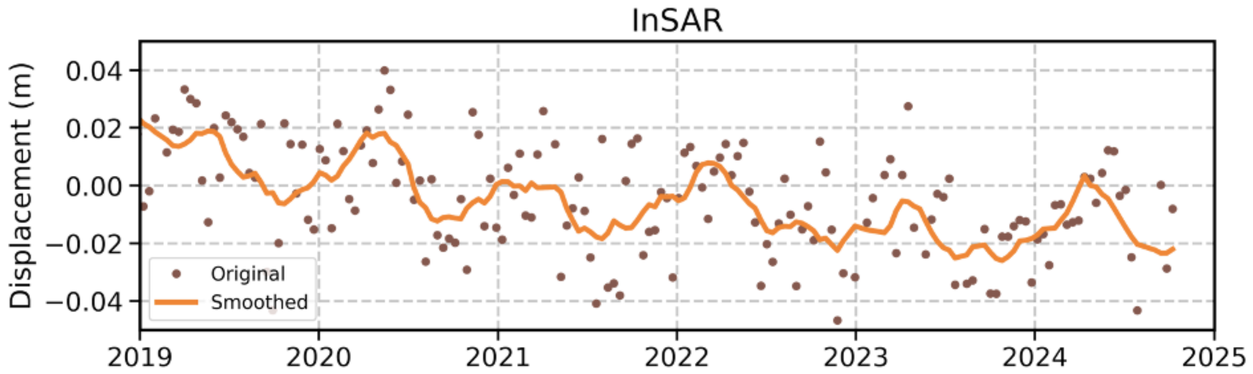
Depth

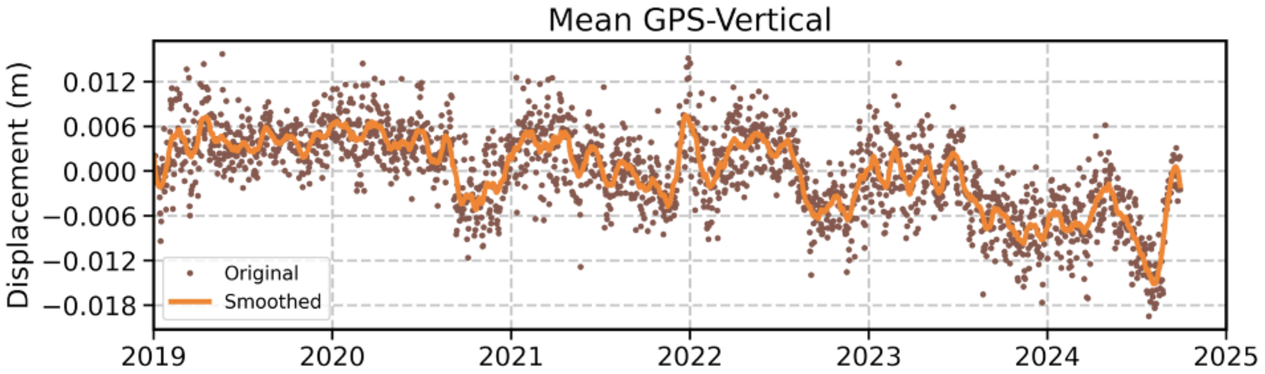
Land subsidence from 2019 to 2022

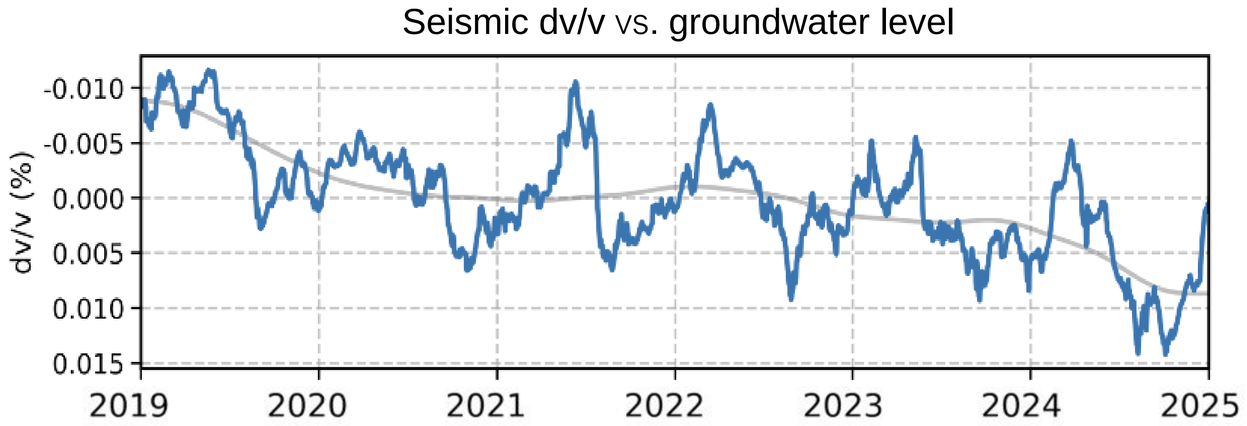


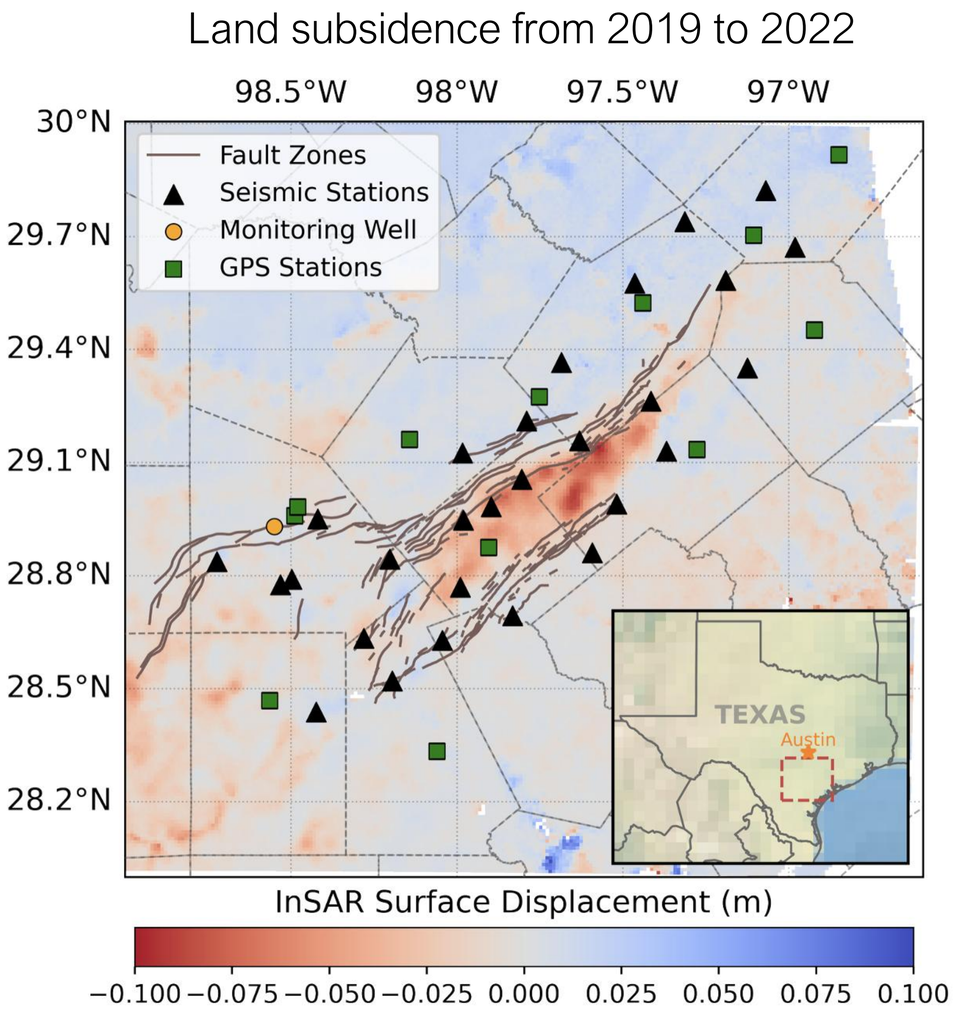
InSAR map derived by JPL (OPERA)
Seismic stations maintained by TexNet
Grigoratos et al., 2025; Zebker and Chen, 2024; McKeighan et al., 2022; Li et al., 2021

Temporal changes inferred from geodetic vs. seismic









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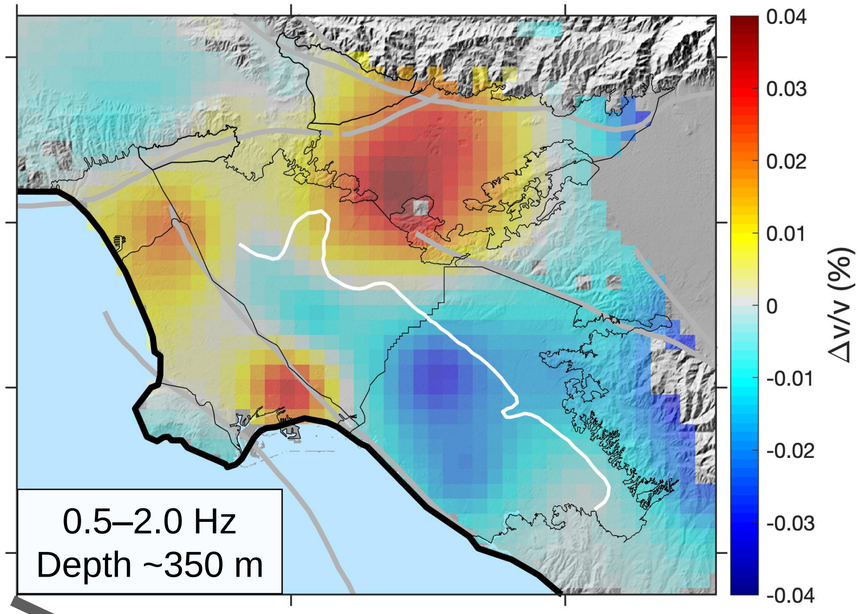
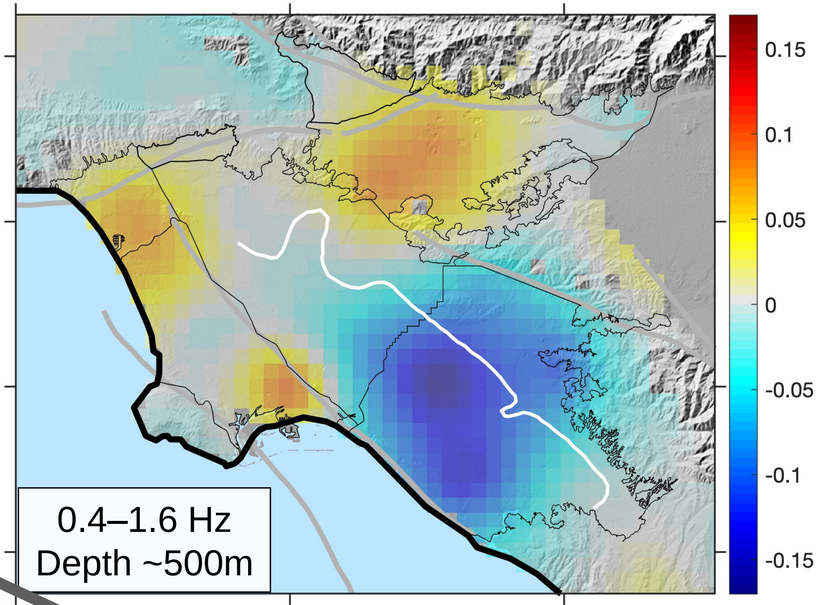
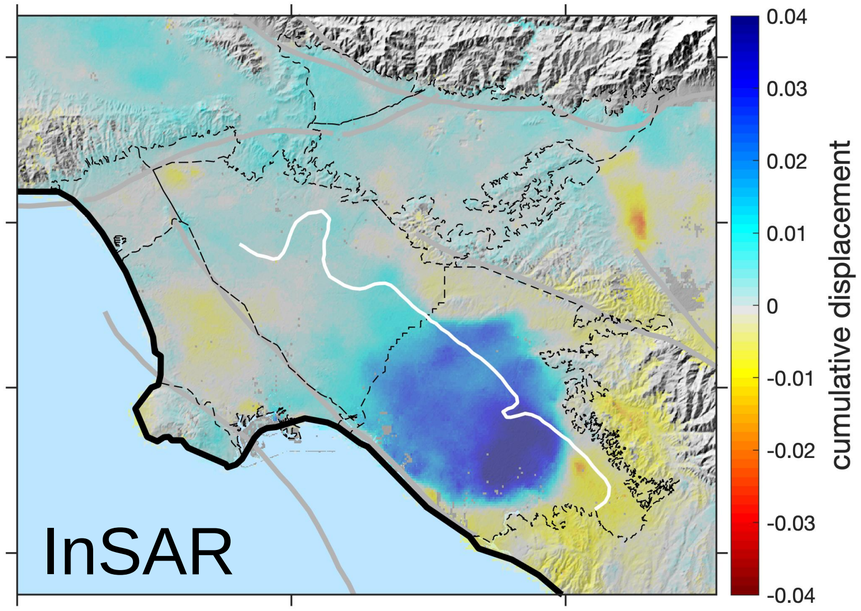
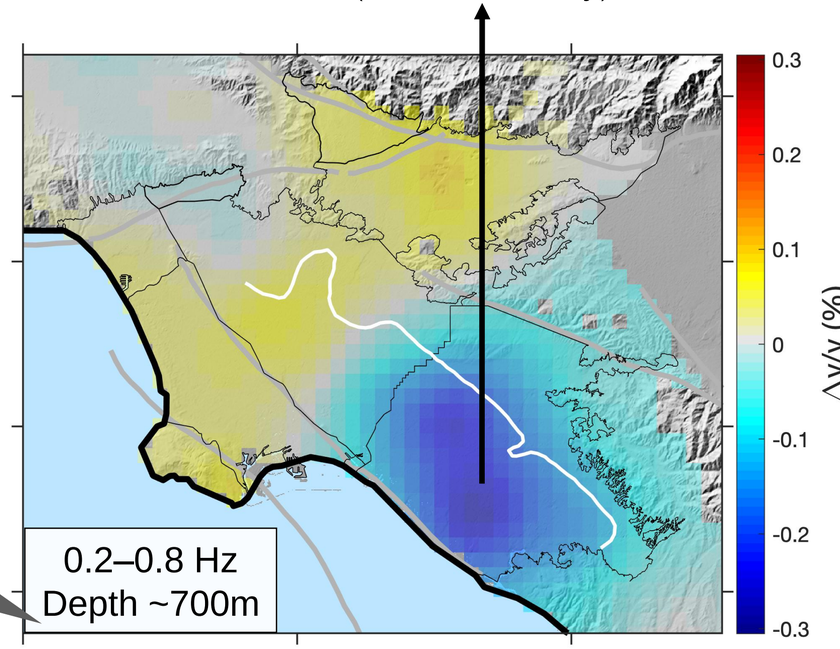






frequency decreases & depth increases

Deepest injection wells
(Fountain Valley)



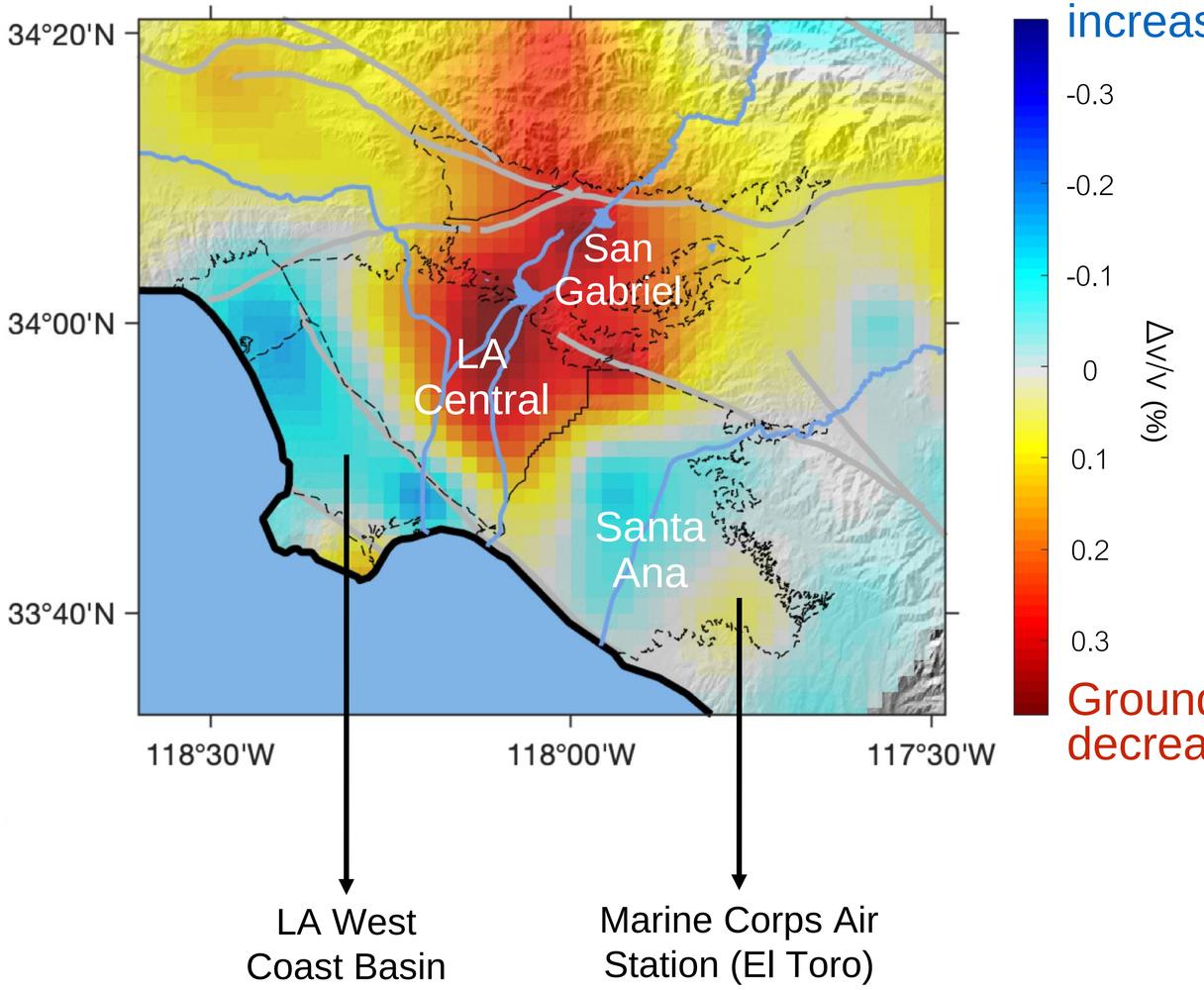
Net change in Summer, 2017

(Managed Aquifer Recharge)

Mao et al., to submit

Imaging the long-term trend of $\Delta v/v$

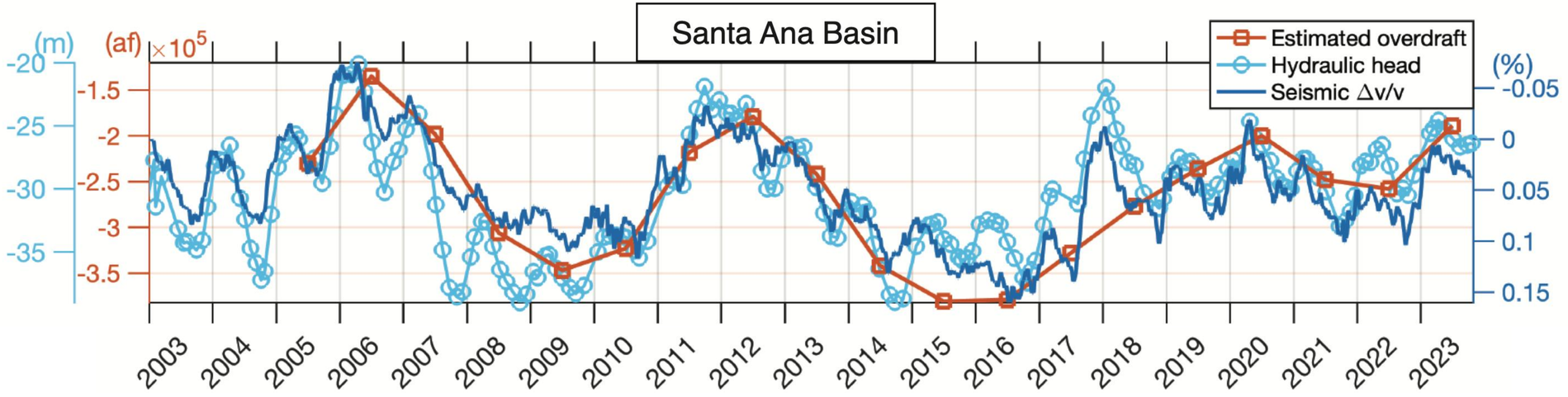
Net change from 2000 to 2020

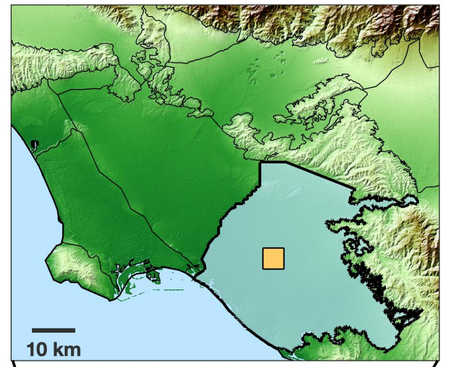


- Distinct net change in adjacent basins: due to different pumping policies in different water districts
- $\Delta v/v$: verifies and quantifies the impact of anthropogenic activities in shaping the shallow hydrologic systems
- A new way for assessing groundwater budget, complementary to hydrologic simulations

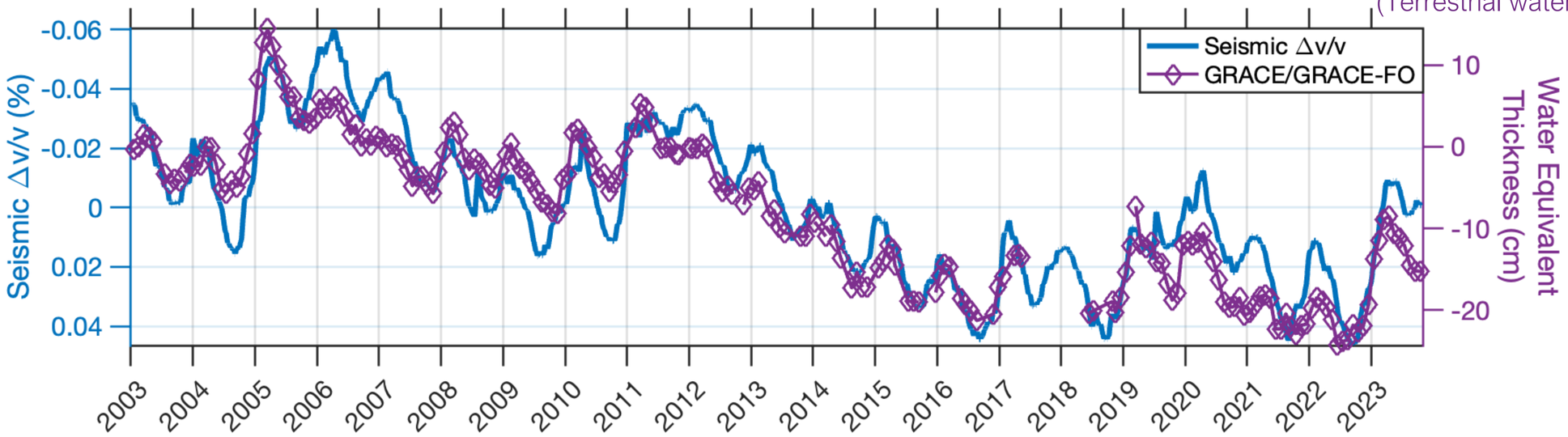
Mao et al. (2022), Nat. Commun.

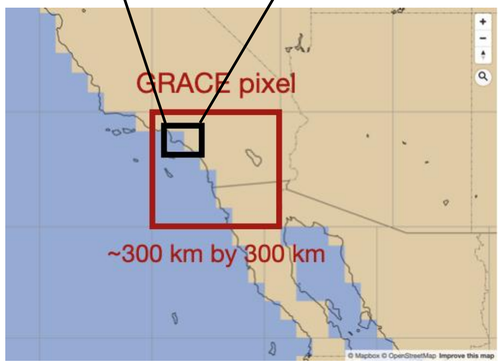
$\Delta v/v$ from sub-watershed scale to regional scale





Satellite gravimetry
(Terrestrial water storage)





Mao et al. (2025), Science