On Recovering Changes of Water Head from Satellite Ground Deformation Data

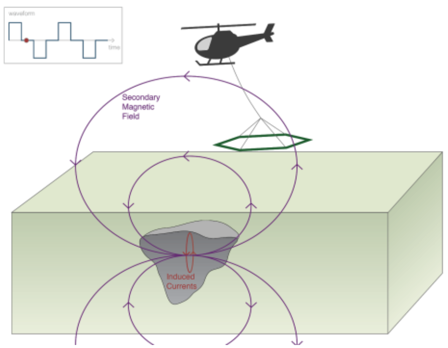
(Example: The Central Valley of California)

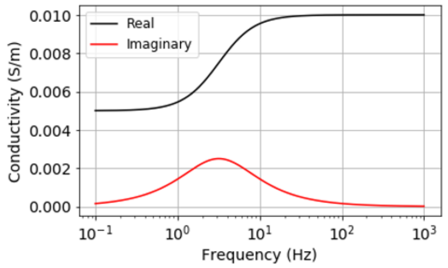
Seogi Kang

Environmental Geophysical Group, Stanford University

👋 hello (a bit about me)

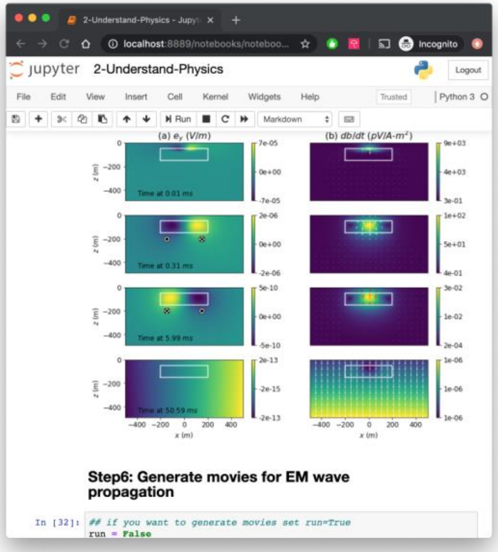
Computational EM geophysics





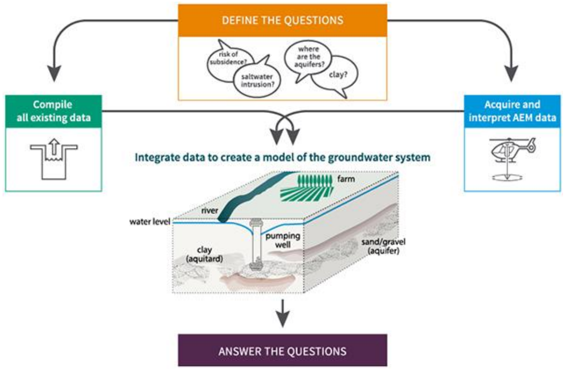
THE UNIVERSITY OF BRITISH COLUMBIA

Open-source software



simpeg

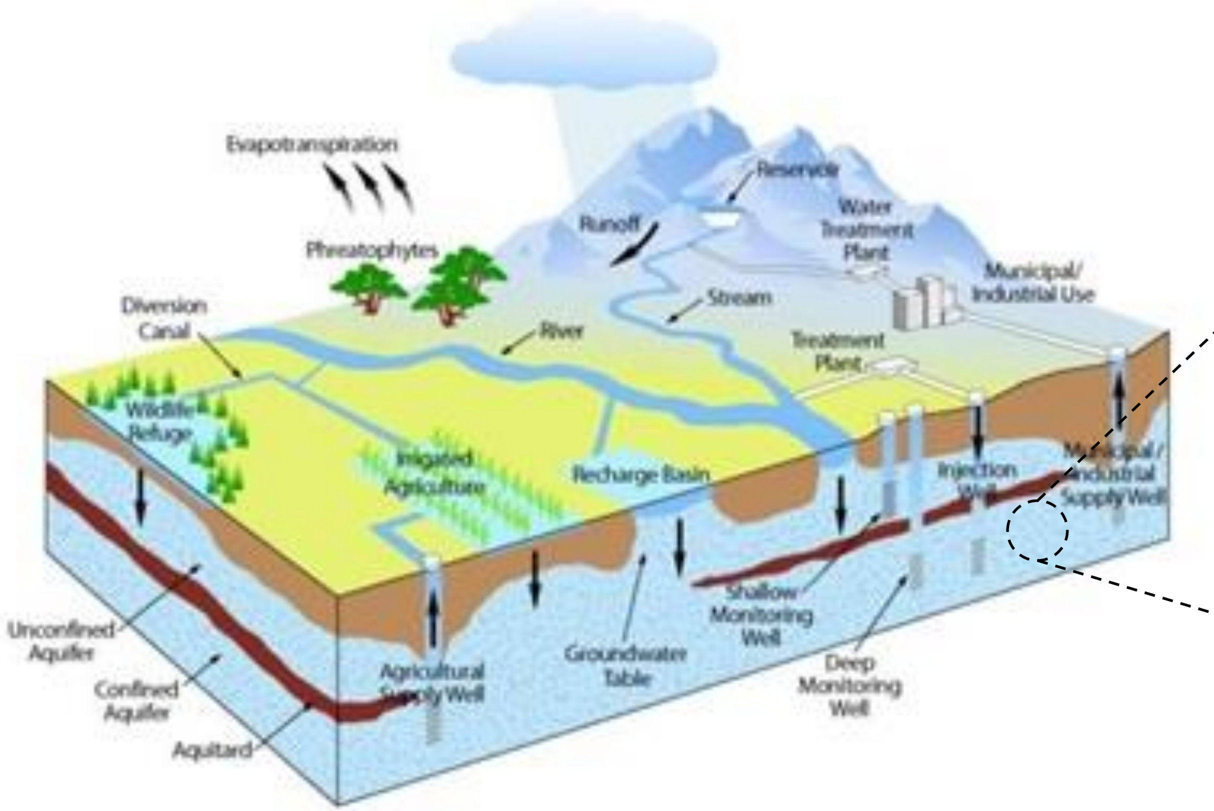
Groundwater science & management

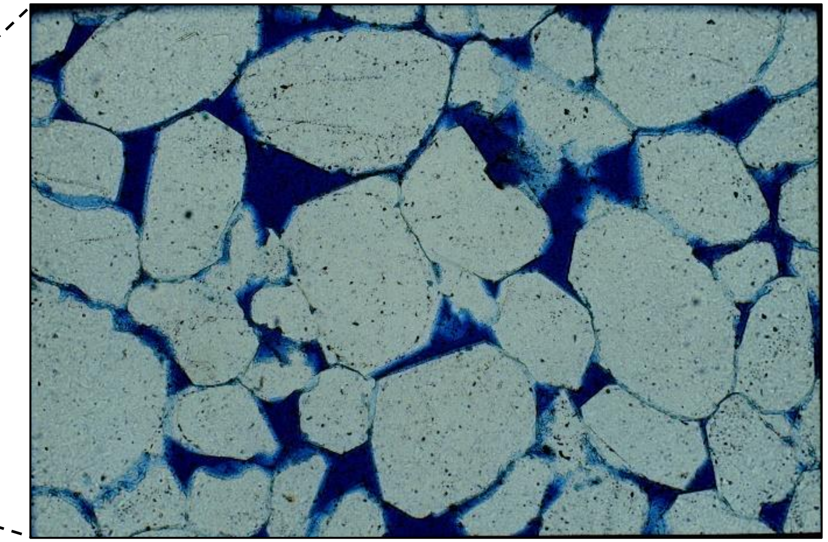


Stanford University

97% of all liquid freshwater

Groundwater

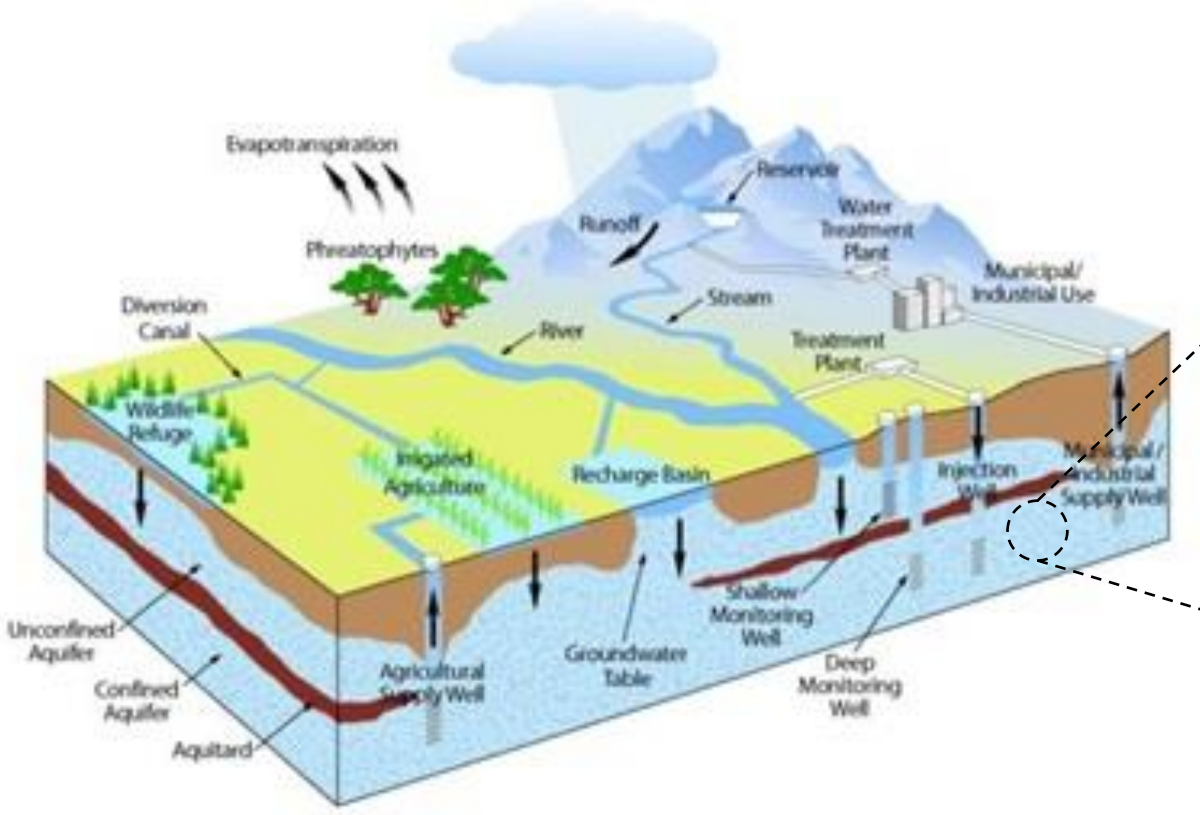


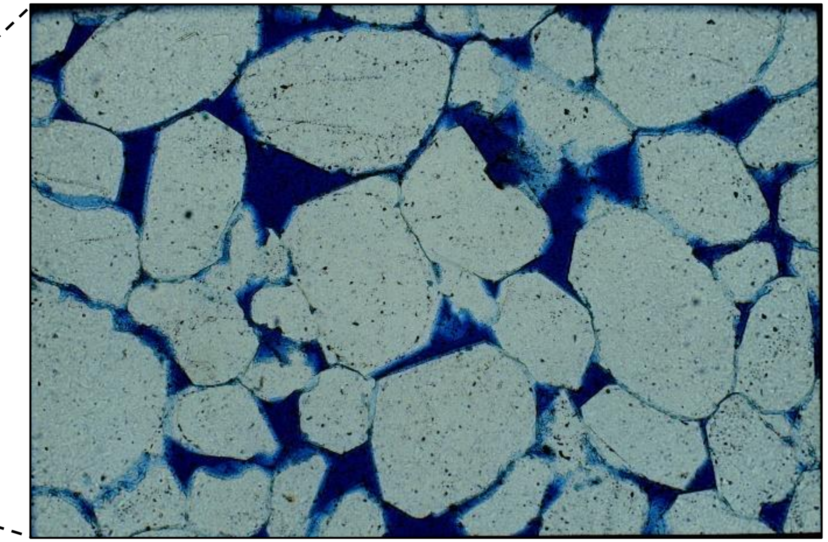


population growth
climate change

97% of all liquid freshwater

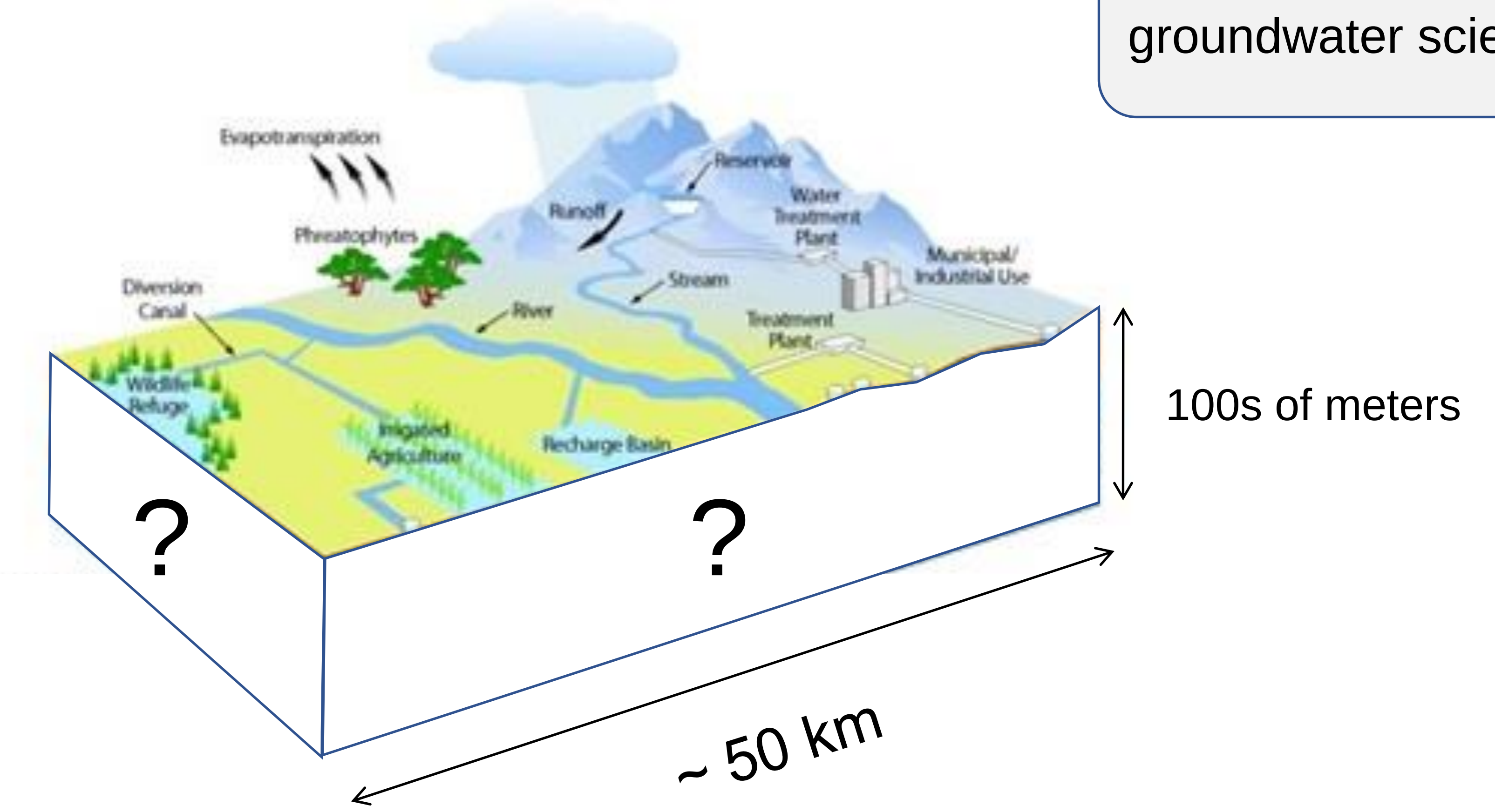
Groundwater





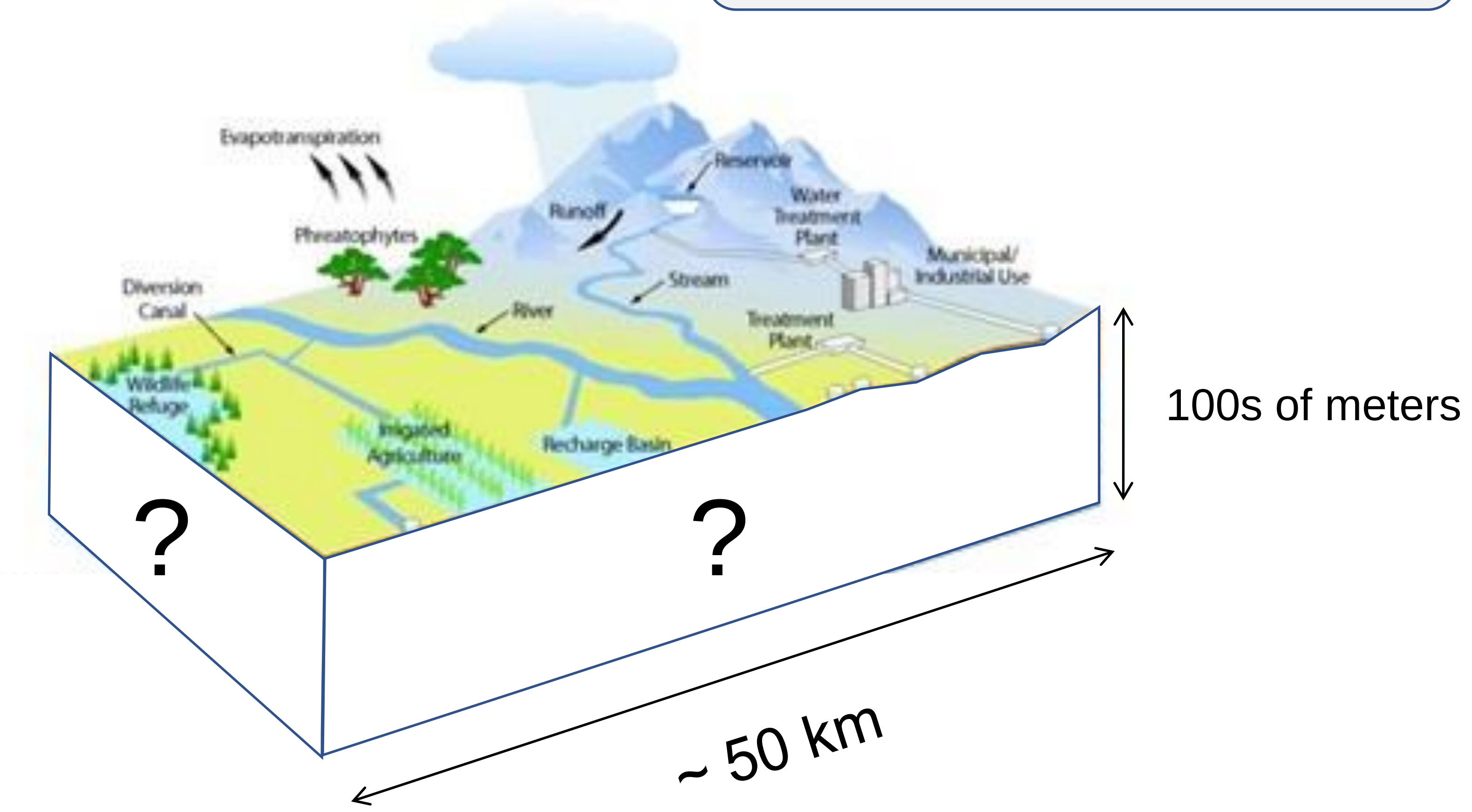
population growth
climate change

We need to see below the ground for groundwater science & management.



Earth Imaging

Recovering spatial and temporal distribution of head



Remote sensing techniques

Satellite

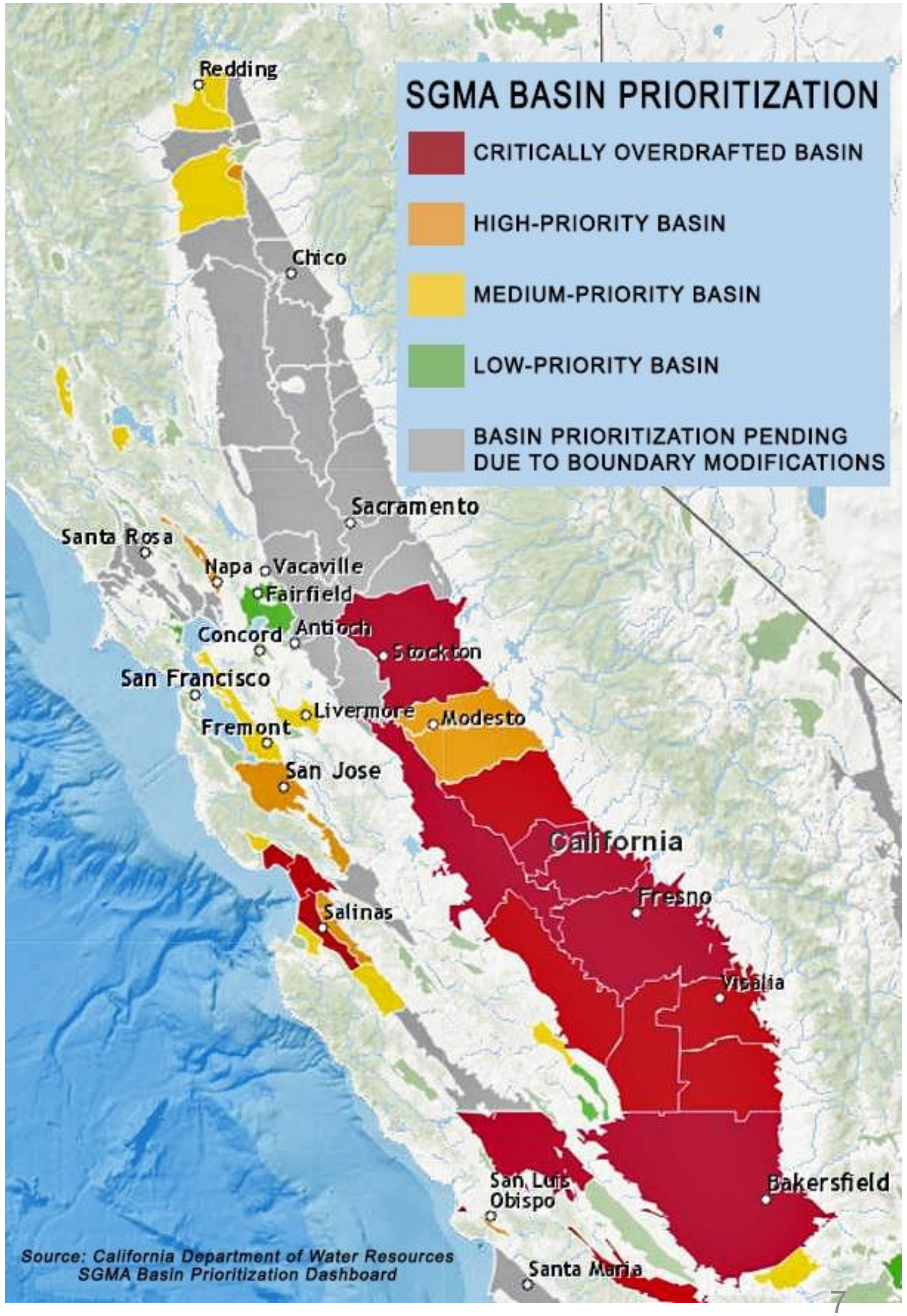
Airborne

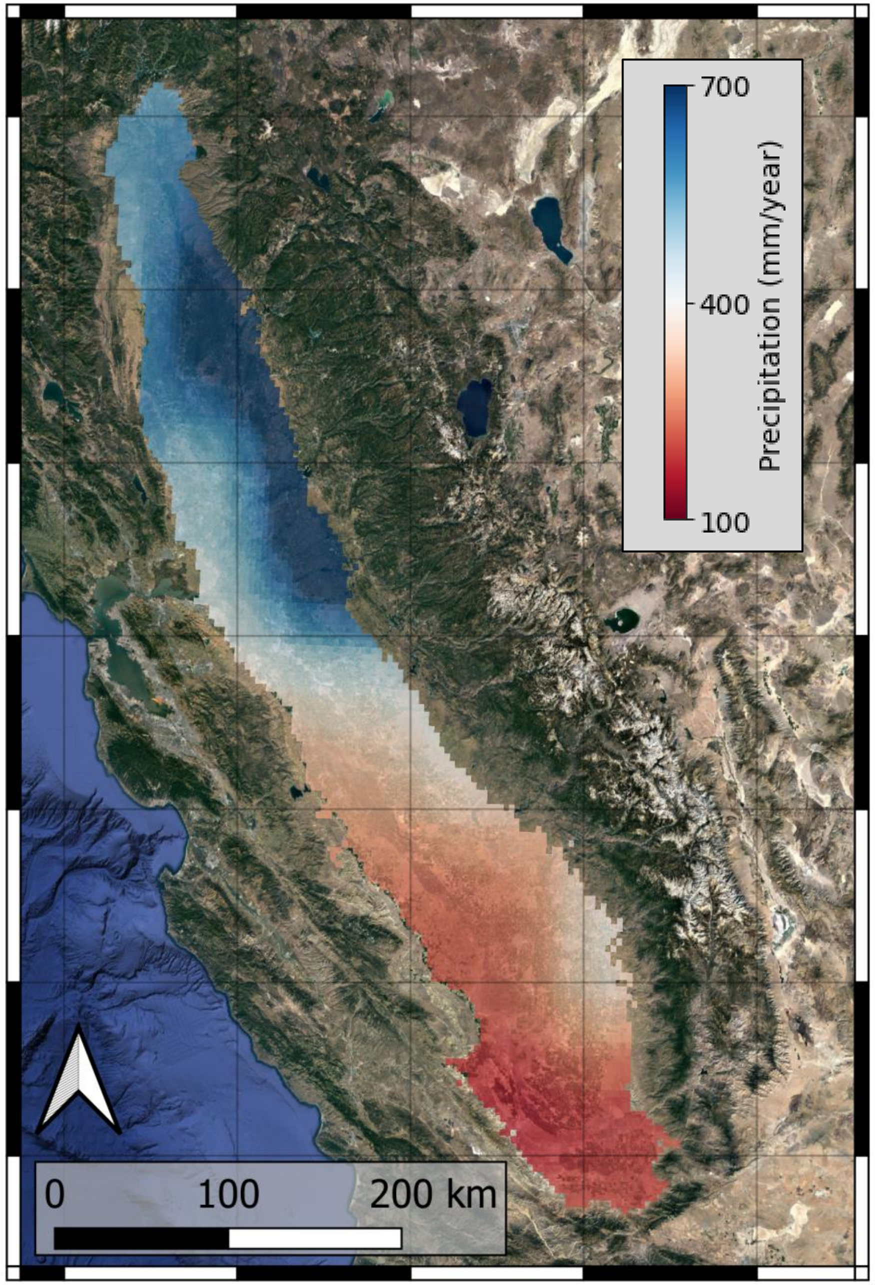
Central Valley of California

Some facts about the Central Valley:

- $17 billion crop value
- 25% of nation's food
- using less than 1% of nation's farmland

Sustainable Groundwater Management Act (SGMA, 2014)



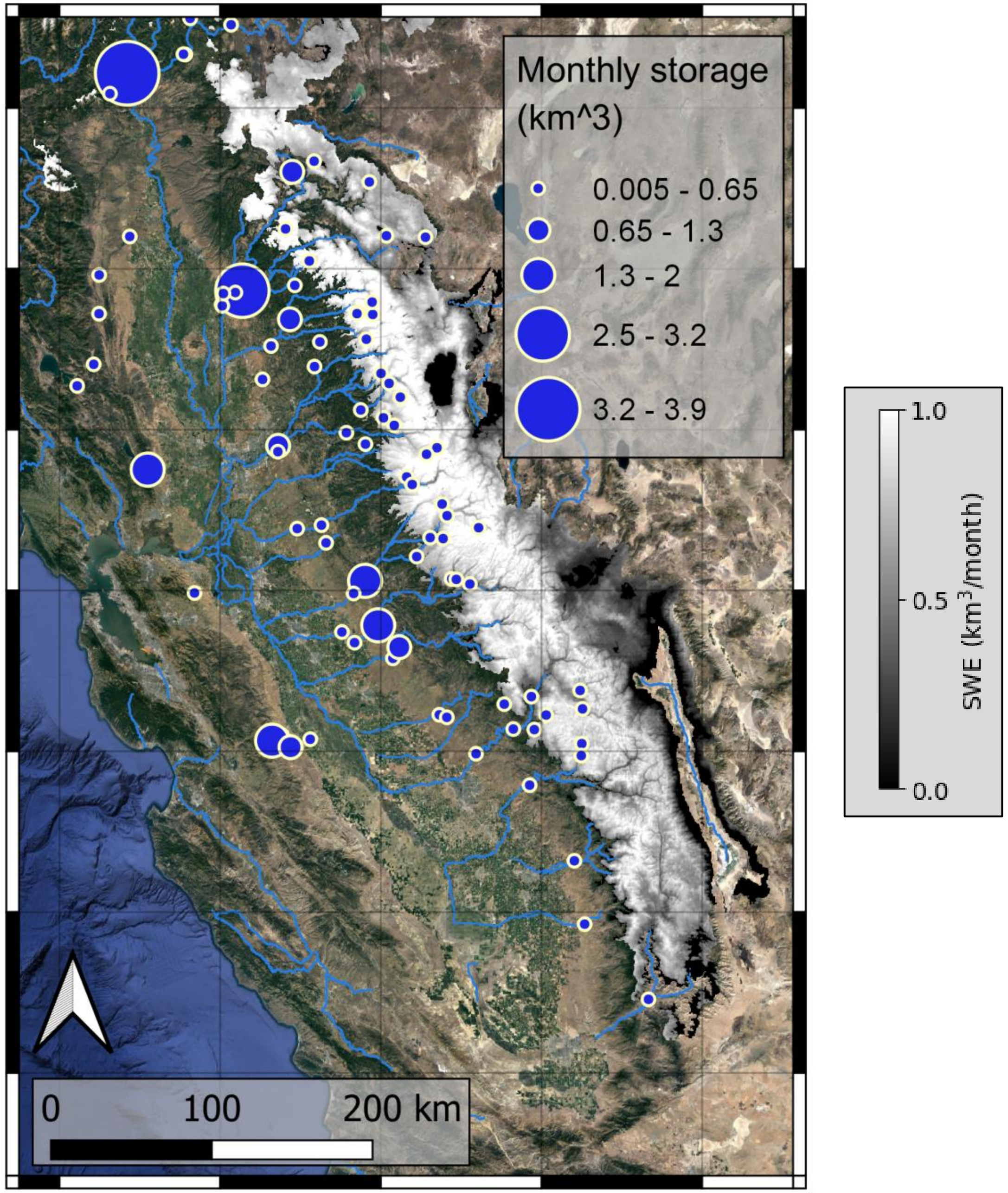


North – Sacramento Valley

More precipitation

South – San Joaquin Valley

Less precipitation



North – Sacramento Valley

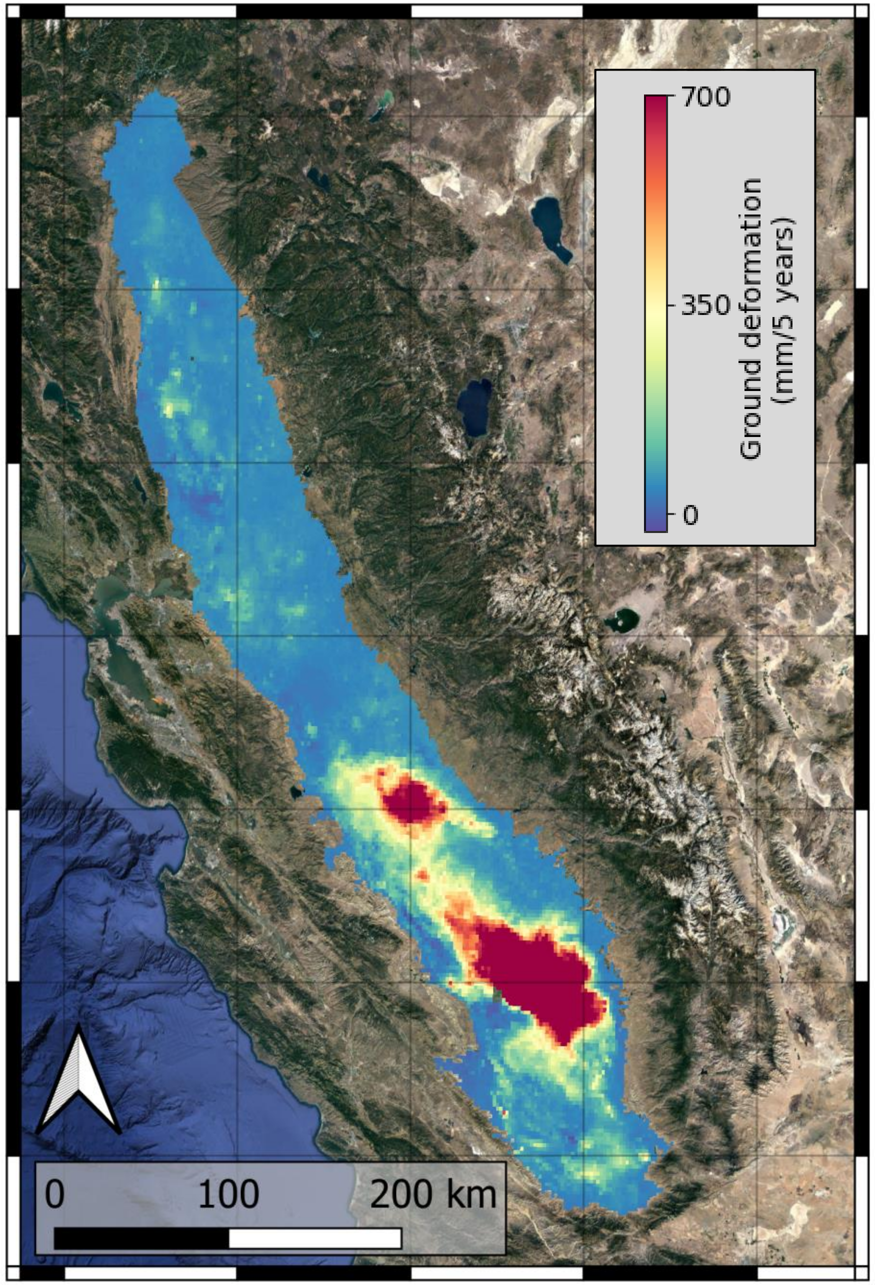
More surface water supply

South – San Joaquin Valley

Less surface water supply

More pumping of groundwater in the warmer, drier south.

Reservoir storage



North – Sacramento Valley

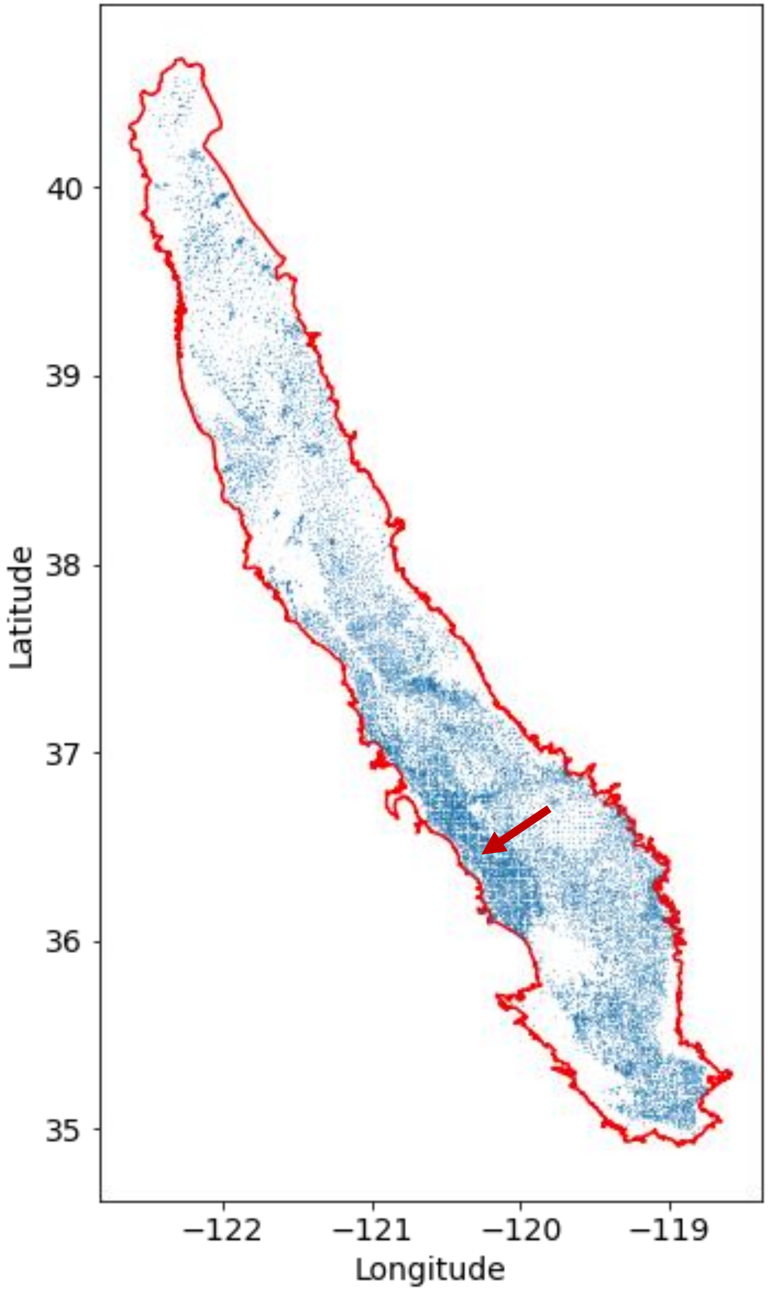
More surface water supply

South – San Joaquin Valley

Less surface water supply

More pumping of groundwater in the warmer, drier south.

Causes more subsidence



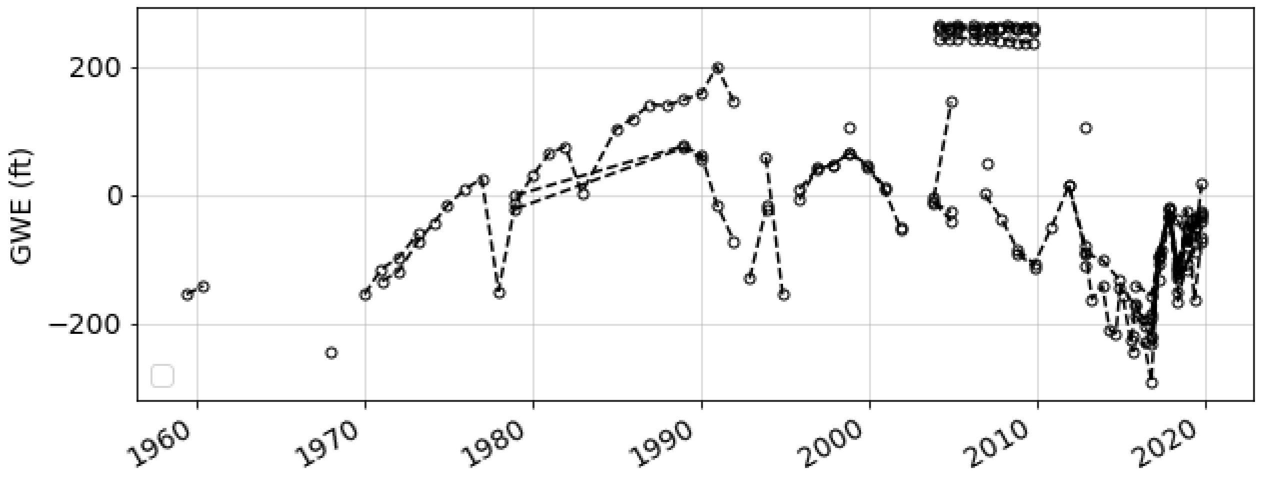
Head data in the Central Valley

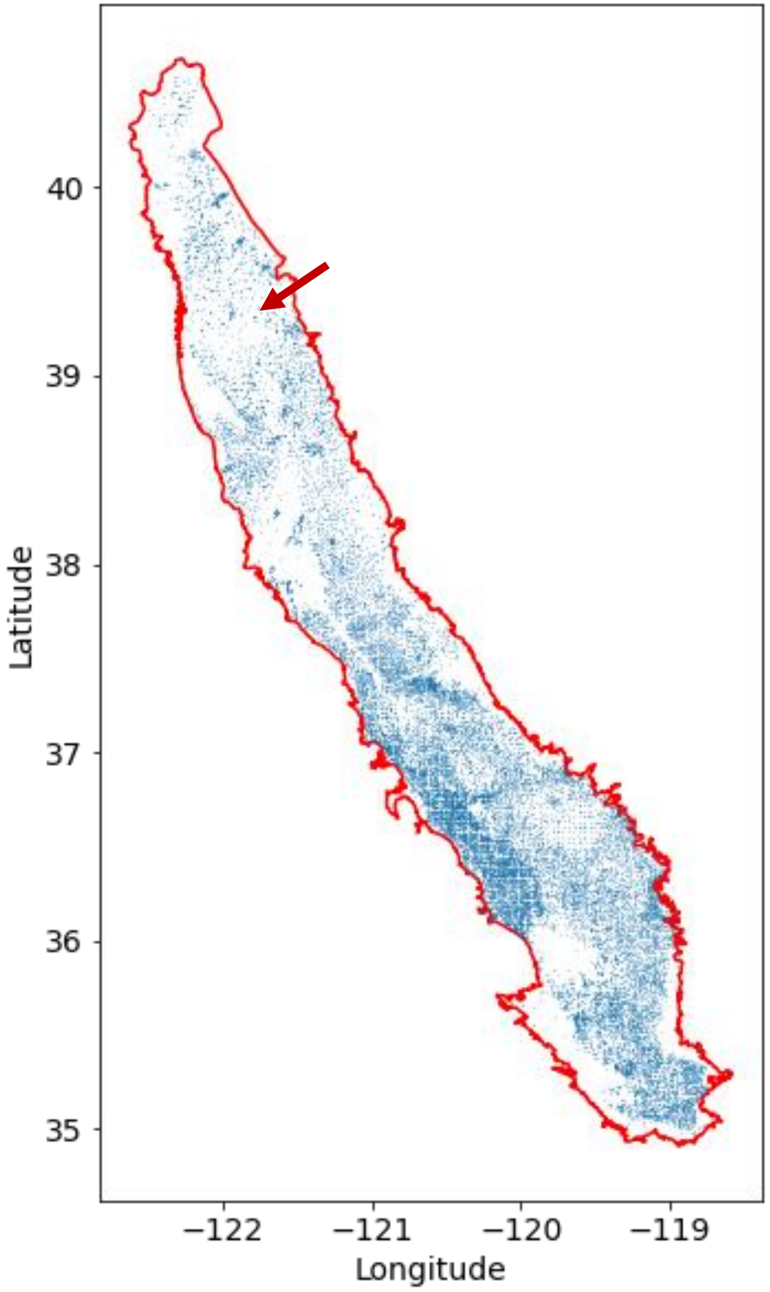
22624 well locations measuring head (domestic, irrigation, monitoring)

Usually, time sampling rate is 2 per year

Head levels are not measured for all time span

Plotting head from 17 wells





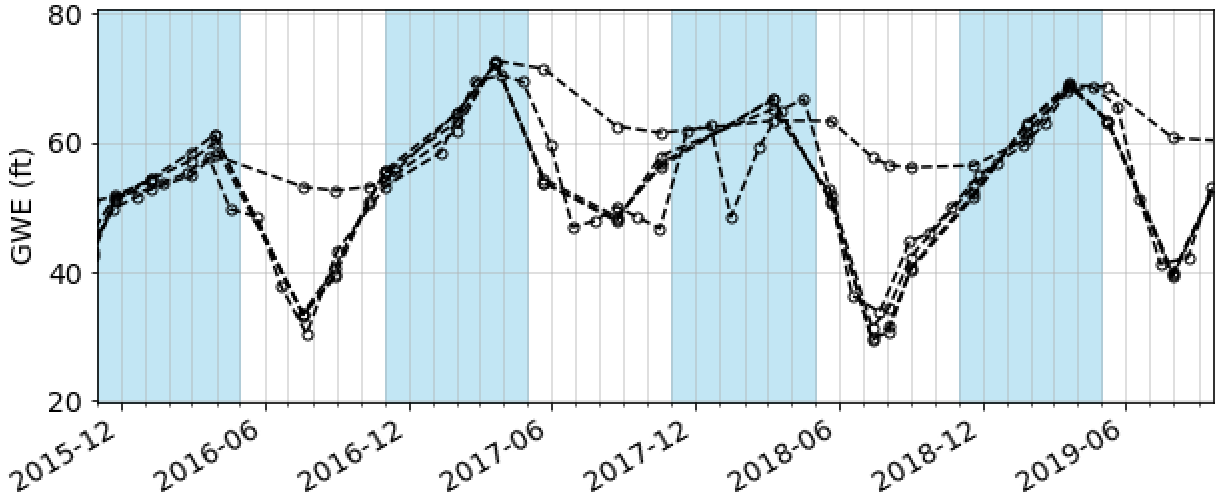
Head data in the Central Valley

22624 well locations measuring head (domestic, irrigation, monitoring)

Usually, time sampling rate is 2 per year

Head levels are not measured for all time span

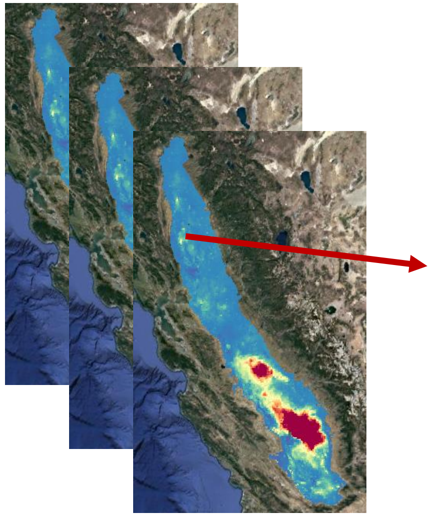
Plotting head from 6 wells

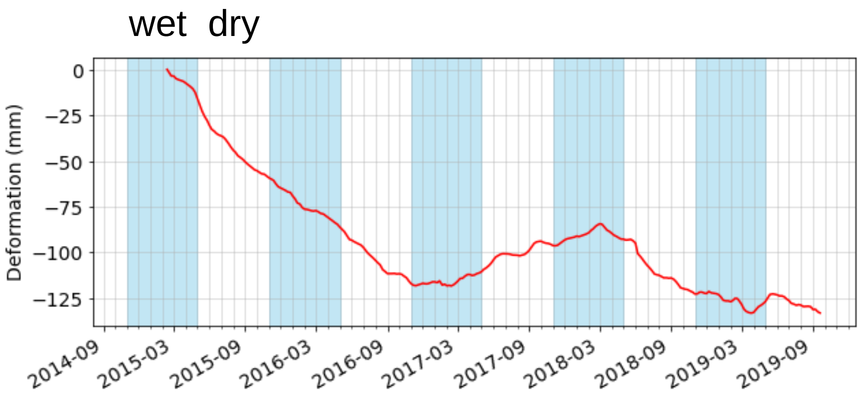


Research question

"Can we recover water head from the satellite ground deformation data?"

Deformation data





Water head

?

Outline

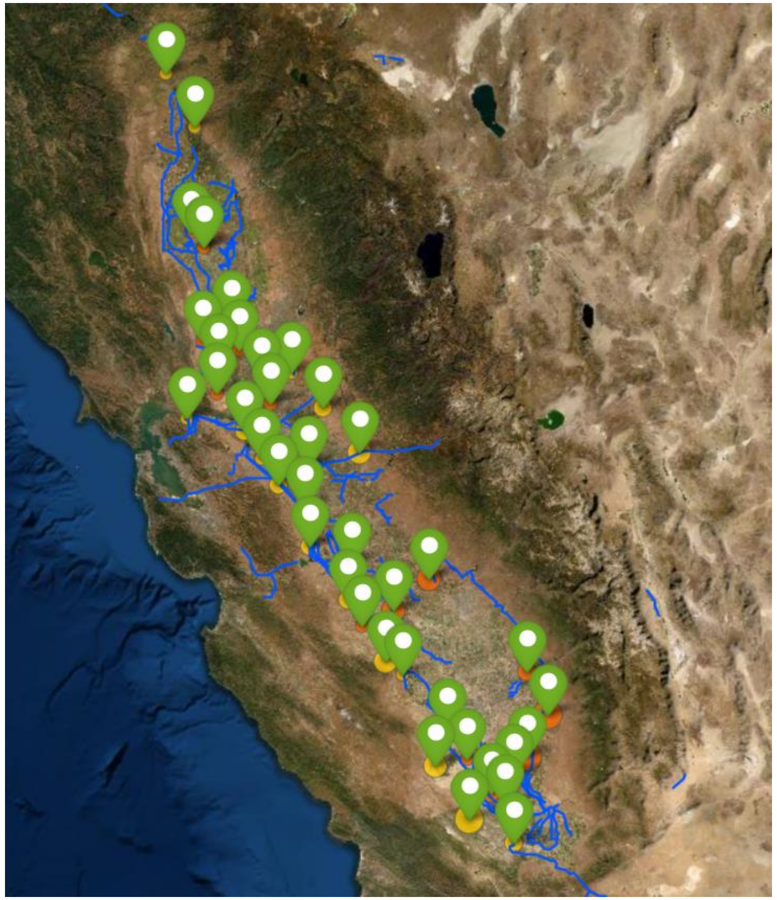
- Measurements of ground deformation
- Relationship between head and deformation
- Forward simulation
- Data analysis
- Inverse problem
- Summary & outlook

How do we measure ground deformation?

On the ground - GPS

GPS station

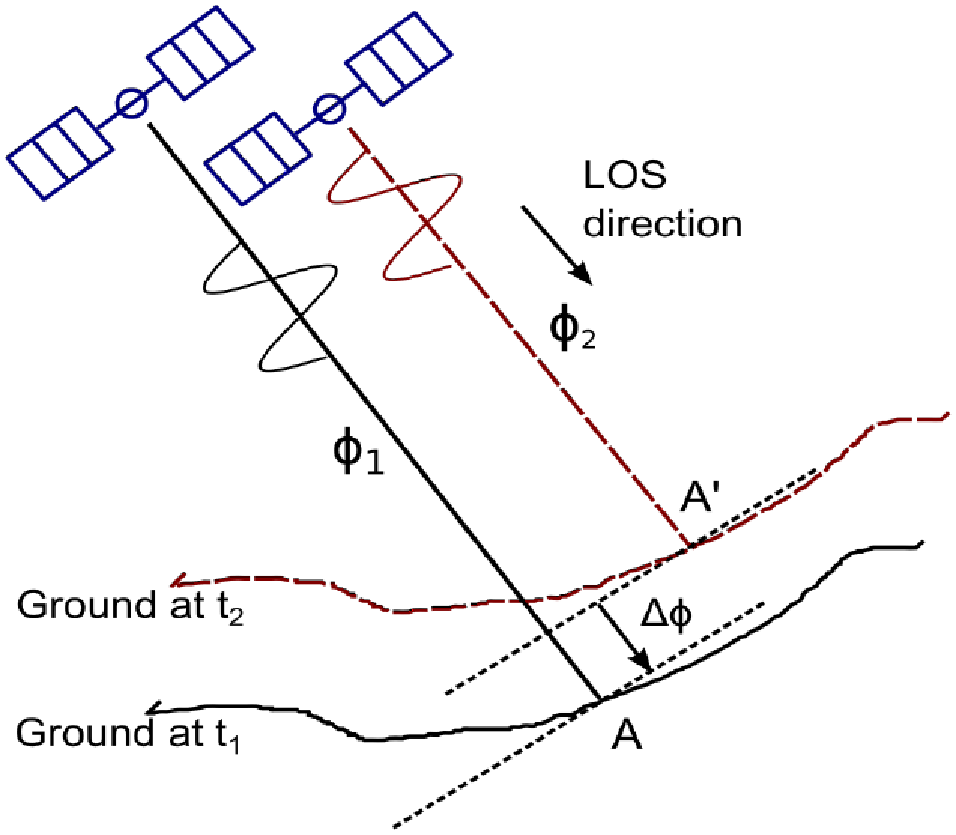
GPS stations in the Central Valley



https://ca.water.usgs.gov/land_subsidence/central-valley-subsidence-data.html

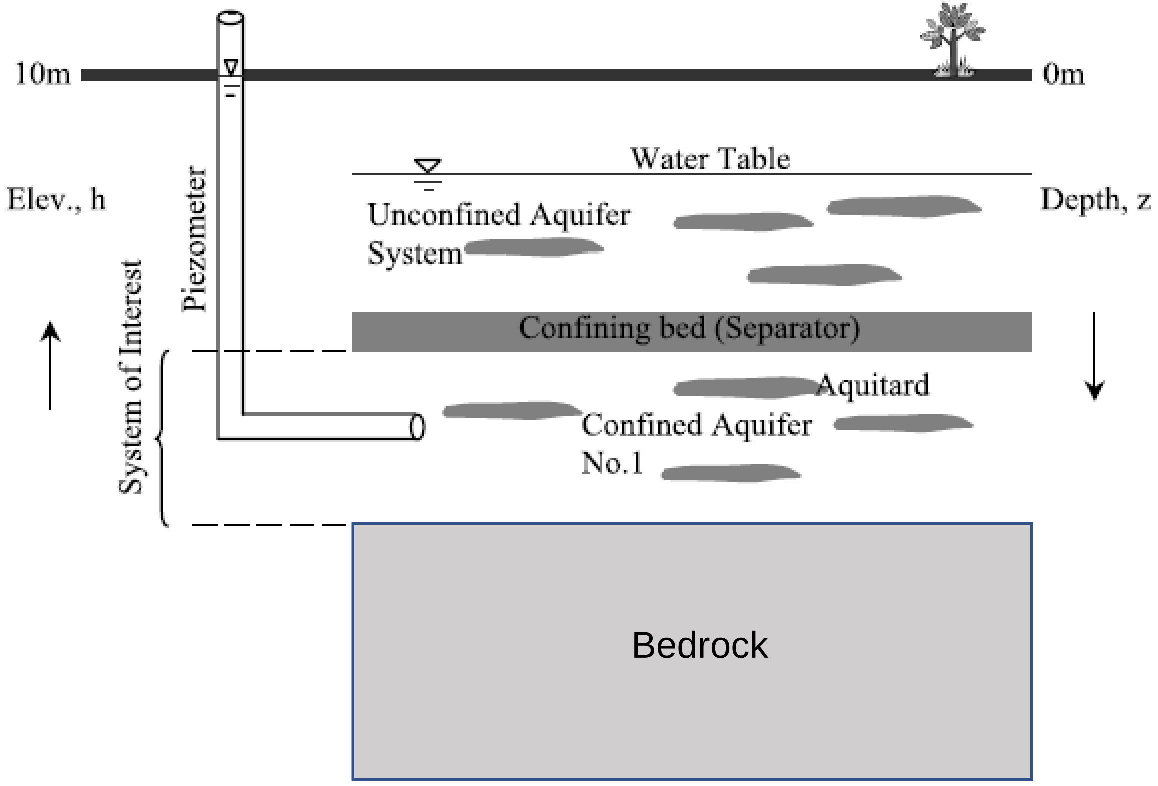
How do we measure ground deformation?

From satellite – Interferometric Synthetic Aperture Radar (InSAR)



Every 6 days
25 m horizontal sampling
About ~1-2 cm accuracy

Physics of the ground deformation



Liu and Helm (2007)

Pumping groundwater

Reduces the head

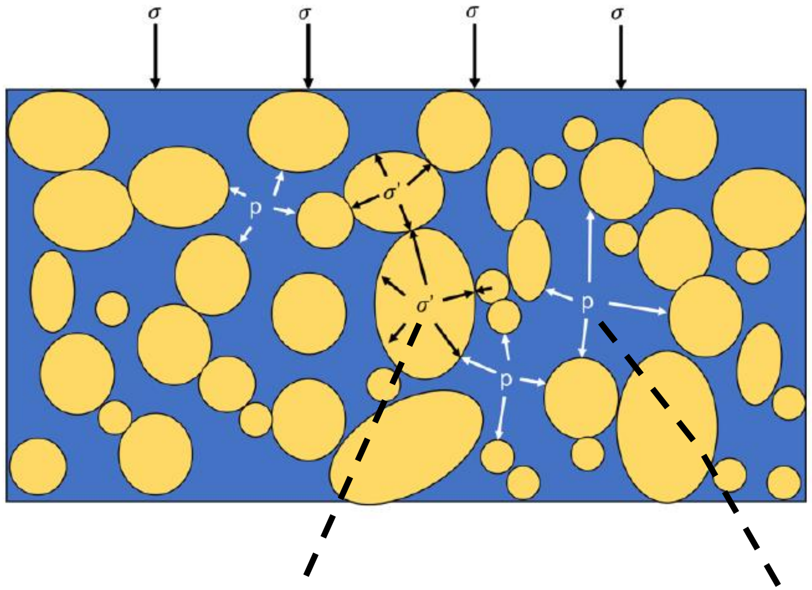
Drains water from clays to sands

Compacts the (interbedded) clays

Compressibility of clay >> compressibility of sand (due to different grain geometry)

Physics of the ground deformation

σ_T: total stress



σ': effective stress

p: pore pressure

Ground deformation

$$\sigma_T = \sigma' + p$$

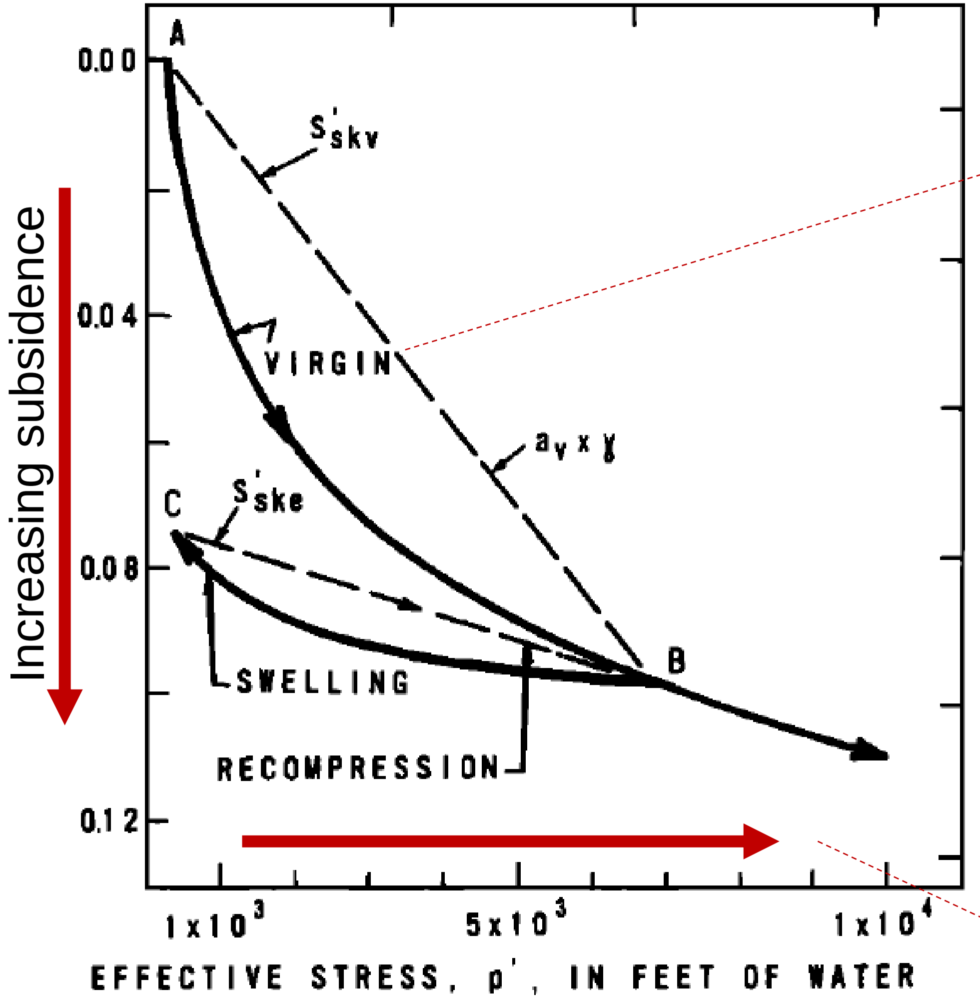
$$d\sigma' = -dp = -\rho g dh$$

(assuming constant σ_T in time)

Deformation: $$db = b_0(\alpha\rho g)dh = b_0 S_{\text{sk}} dh$$

b_0: initial clay thickness
α: compressibility
ρ: density
g: gravitational acceleration
S_{sk}: Skeletal specific storage

Hysteresis



Helm (1975)

Ground deformation

$$db = b_0 S_{\mathrm{sk}} dh$$

With a linear assumption

$$db = \begin{cases} \text{Elastic: } & b_0 S_{\mathrm{ske}} dh \ (h > h_{\mathrm{min}}) \\ \text{Inelastic: (permanent loss) } & b_0 S_{\mathrm{skv}} dh \ (h \le h_{\mathrm{min}}) \end{cases}$$

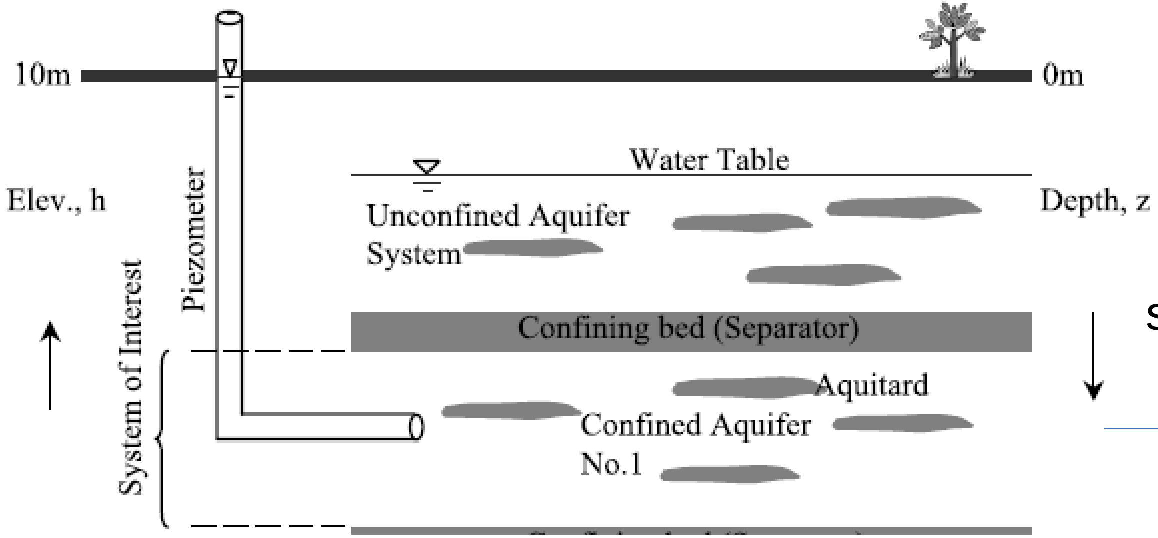
h_{min}: pre-consolidation head

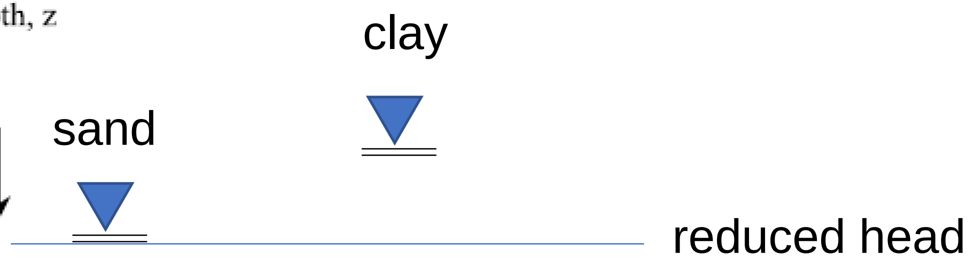
$$S_{\mathrm{skv}} \gg S_{\mathrm{ske}}$$

Reducing head

Delay of head

Dupuit-Forchheimer assumption: $dh_{\mathrm{aquifer}}/dz = 0$





$$\frac{K_v}{S_{sk}}\frac{\partial^2 h}{\partial z^2} = -\frac{\partial h}{\partial t}$$

Reduction of head due to pumping

Delay of head → drainage of water from clay to sand

Compaction of clays

$$db = \begin{cases} \text{Elastic:} & b_0 S_{\mathrm{ske}} dh \ (h > h_{\mathrm{min}}) \\ \text{Permanent (loss):} & b_0 S_{\mathrm{skv}} dh \ (h \le h_{\mathrm{min}}) \end{cases}$$

Forward simulation

Governing equations

$$\frac{K_v}{S_{sk}}\frac{\partial^2 h}{\partial z^2} = -\frac{\partial h}{\partial t}$$

Initial condition:
$h(z; t = 0) = h^0_{\mathrm{aquifer}}$

Boundary condition:
$h(z = z_1 = z_2; t) = h_{\mathrm{aquifer}}(t)$

$$S_{\mathrm{sk}} = \begin{cases} \text{Elastic: } S_{\mathrm{ske}}\ (h > h_{\min}) \\ \text{Permanent (loss): } S_{\mathrm{skv}}\ (h \le h_{\min}) \end{cases}$$

Forward simulation

Governing equations

$$\frac{K_v}{S_{sk}} \frac{\partial^2 h}{\partial z^2} = -\frac{\partial h}{\partial t}$$

Initial condition:
$h(z; t = 0) = h_{\mathrm{aquifer}}^{0}$

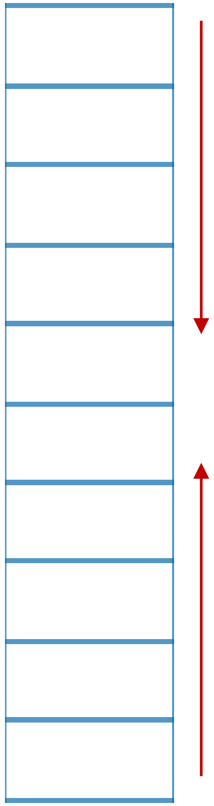
Boundary condition:
$h(z = z_1 = z_2; t) = h_{\mathrm{aquifer}}(t)$

$$S_{\mathrm{sk}} = \begin{cases} \text{Elastic: } S_{\mathrm{ske}}\ (h > h_{\mathrm{min}}) \\ \text{Permanent (loss): } S_{\mathrm{skv}}\ (h \leq h_{\mathrm{min}}) \end{cases}$$

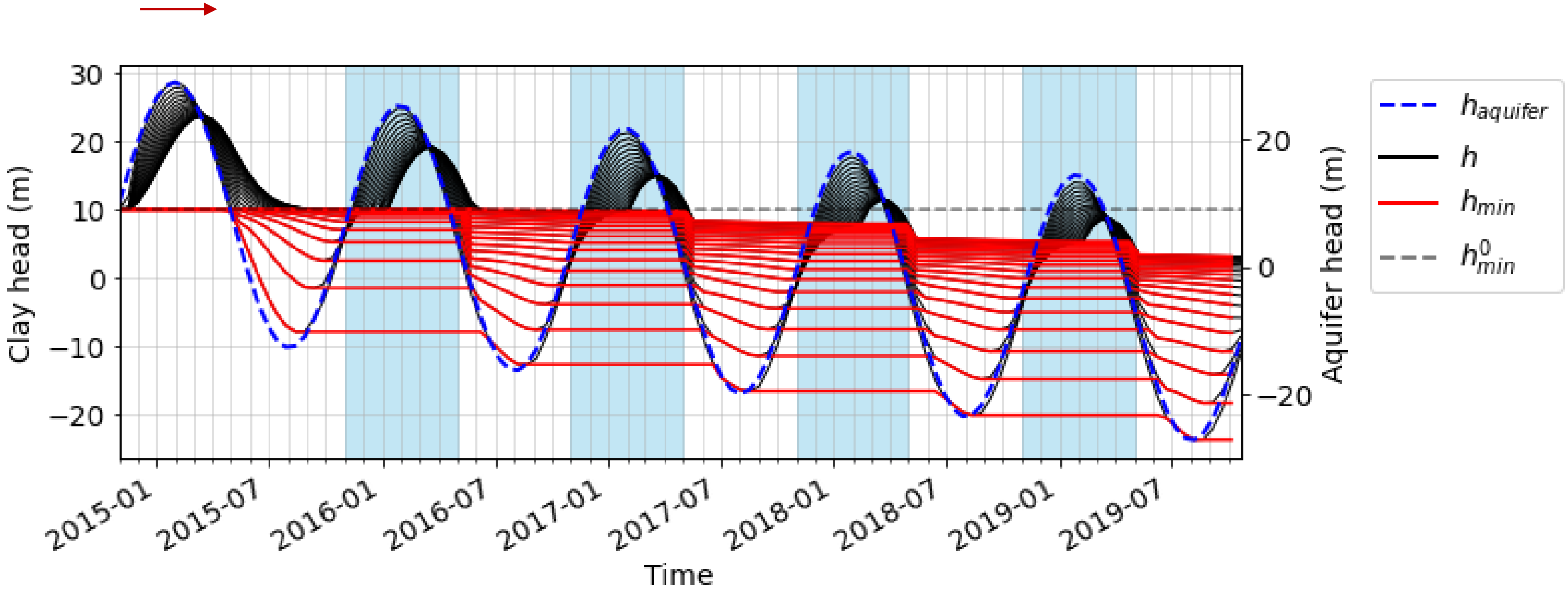
Solve for h with given h_{min}, K_{v}, S_{ske}, S_{skv}, h_{aquifer}

Display of heads as a function of time

Vertical cells



Delayed heads



$h_{\mathrm{min}} - h^0_{\mathrm{min}}$ → permanent subsidence

Evaluation of ground deformation (vertical)

$$dB_{i\ \text{clay}}^{k} = \begin{cases} \text{Elastic:} & b_0 S_{\text{ske}}^{k}(h_i^k - h_{i\ min}^{k})\ (h_i^k > h_{\text{min}_i}^{k}) \\ \text{Permanent (loss):} & b_0 S_{\text{skv}}^{k}(h_{i\ min}^{k} - h_{min}^{0})\ (h_i^k \le h_{\text{min}_i}^{k}) \end{cases}$$

i: i-th cell
k: k-th time

b_0: thickness of the clay bed

Deformation from a clay interbed: $dB_{\text{clay}}(t) = \sum dB_{i_{\text{clay}}}(t)$

$$db = \begin{cases} \text{Elastic:} & b_0 S_{\text{ske}} dh\ (h > h_{\text{min}}) \\ \text{Permanent (loss):} & b_0 S_{\text{skv}} dh\ (h \le h_{\text{min}}) \end{cases}$$

→ dB: is a cumulative sum of db

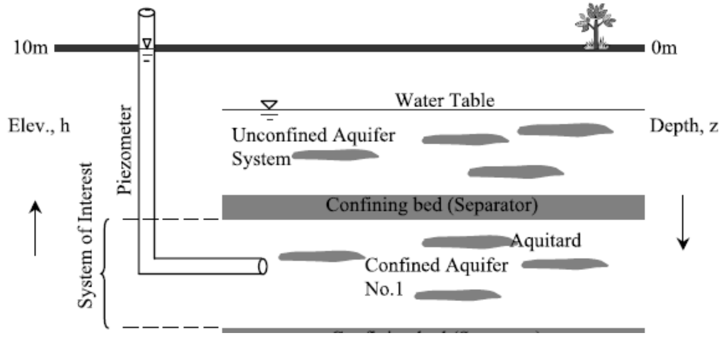
Handling many clay beds (Helm, 1975)

Deformation from a clay interbed: $$dB_{\text{clay}}(t) = \sum ddB_{i\,\text{clay}}(t)$$

Equivalent layer thickness

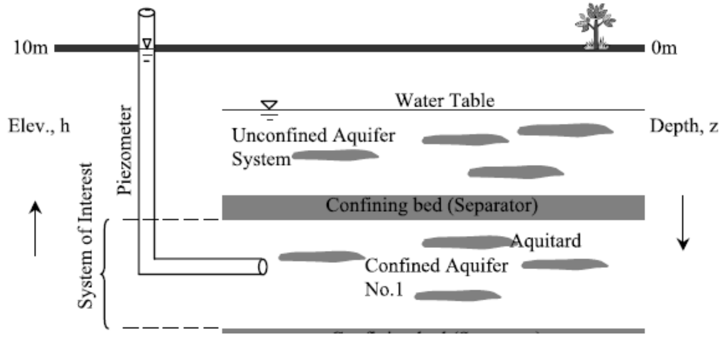
$$b_{\text{equiv}} = \frac{1}{N}\sqrt{\sum b_j^2}$$

$$n_{\text{equiv}} = \sum b_j / b_{\text{equiv}}$$



Deformation from many clay interbeds: $$dB_{\text{clay}}^{\text{equiv}}(t) = n_{\text{equiv}} \sum dB_i^{\text{equiv}}(t)$$

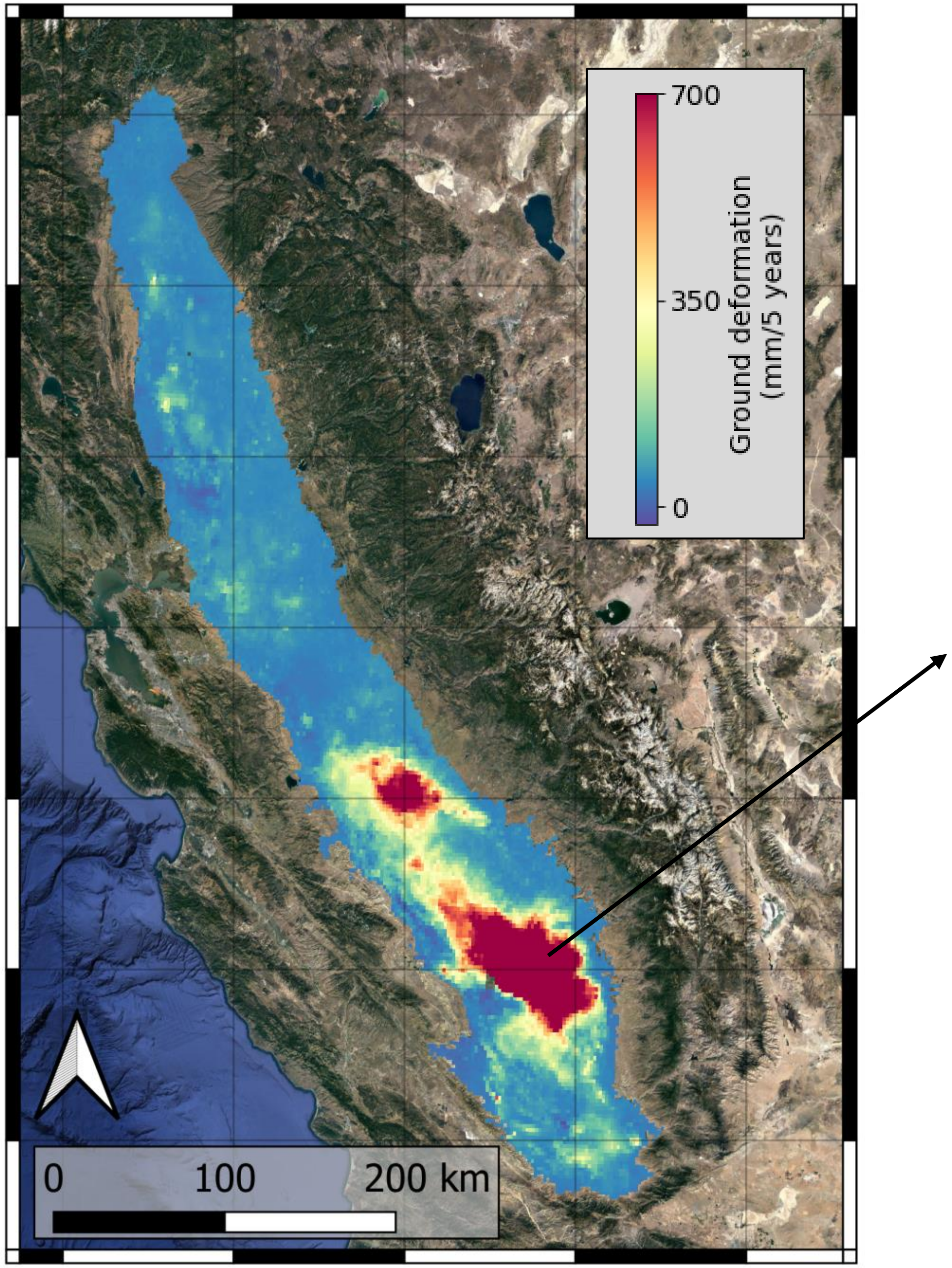
Deformation due to the aquifer



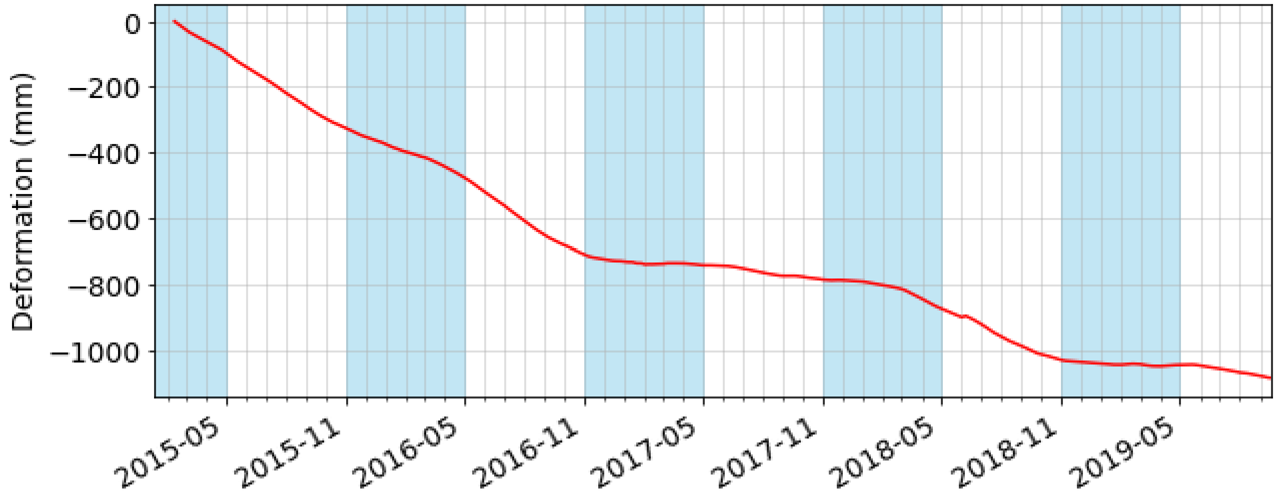
Deformation from many clay interbeds: $$dB_{\text{clay}}^{\text{equiv}}(t) = n_{\text{equiv}} \sum dB_i^{\text{equiv}}(t)$$

Deformation due to aquifer: $$dB_{\text{aquifer}}(t) = b_{\text{aquifer}} S_{\text{sk}}^{\text{aquifer}} \left(h_{\text{aquifer}}(t) - h_{\text{aquifer}}^{0}\right)$$

Deformation: $$dB(t) = dB_{\text{clay}}^{\text{equiv}}(t) + dB_{\text{aquifer}}(t)$$

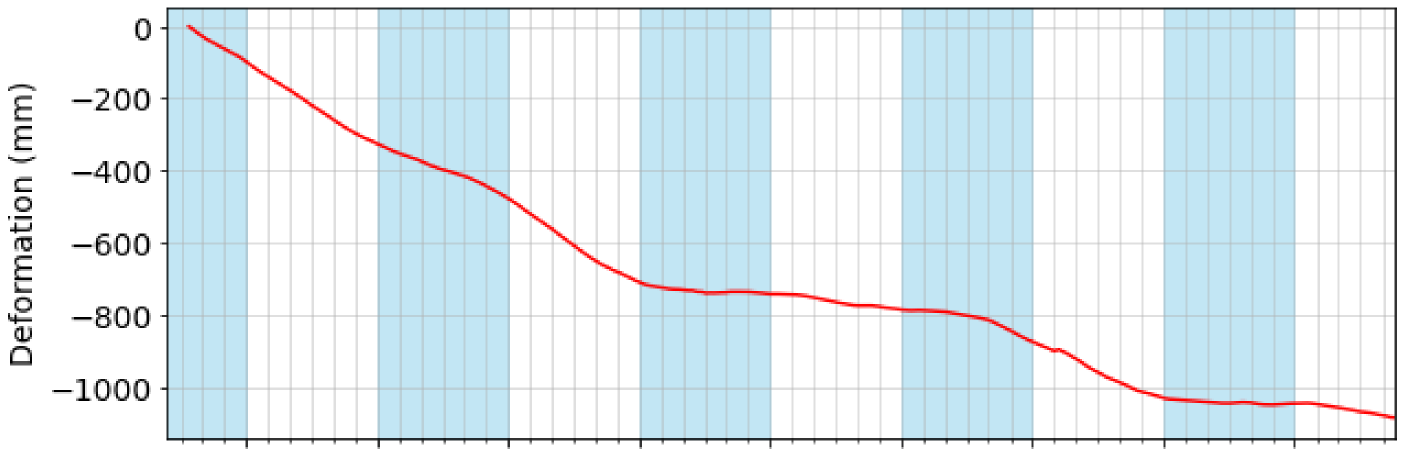


Is 1000 mm (for 5 years) subsidence reasonable?

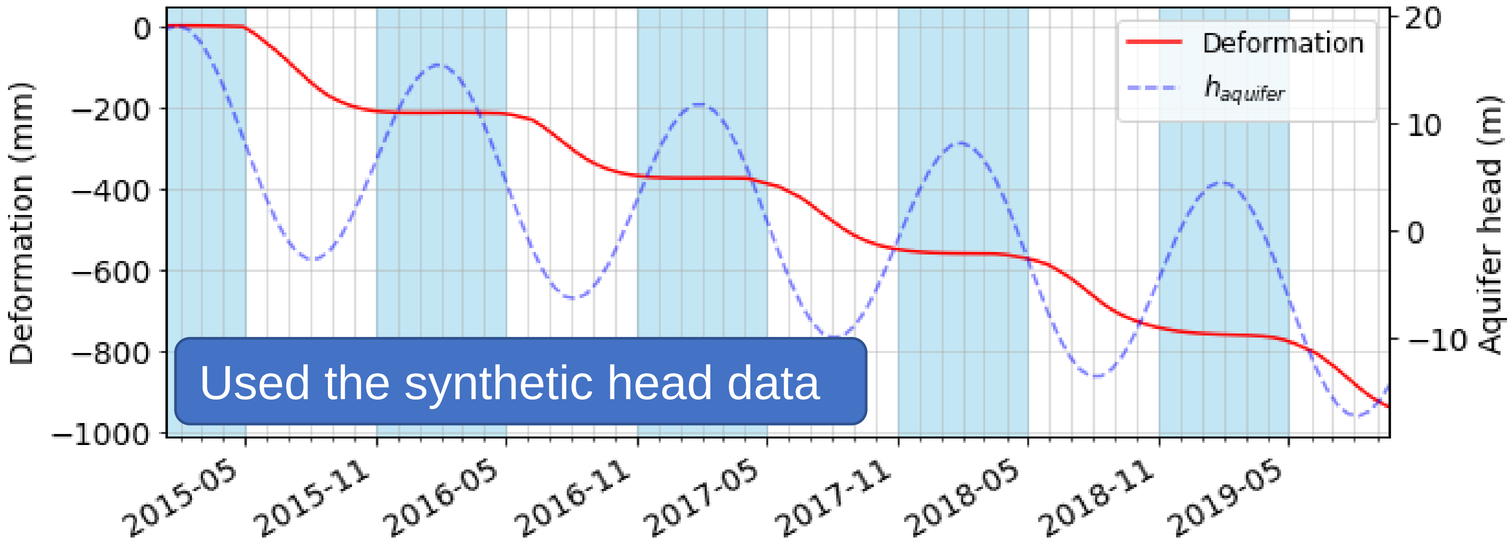


Measured vs. Simulated (with parameters from the previous studies)

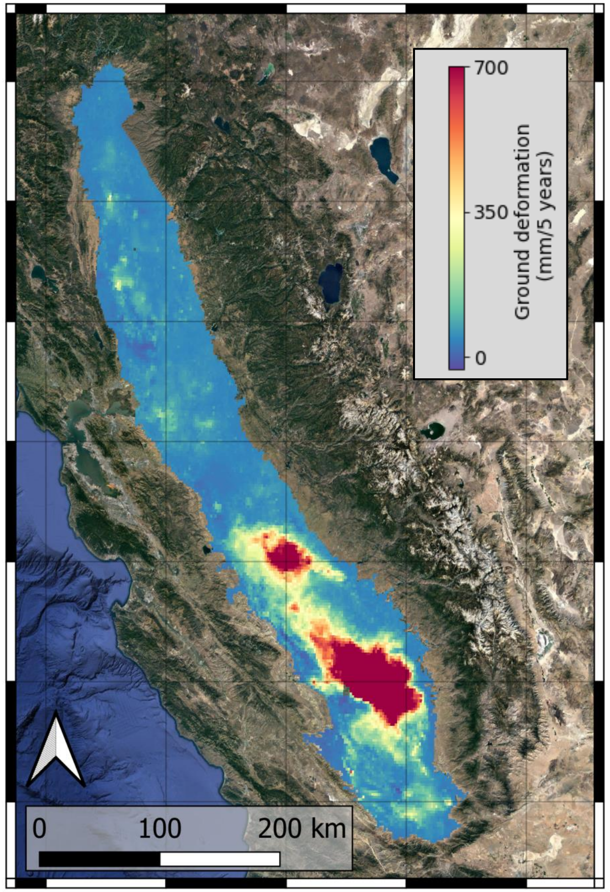
Measured



Simulated



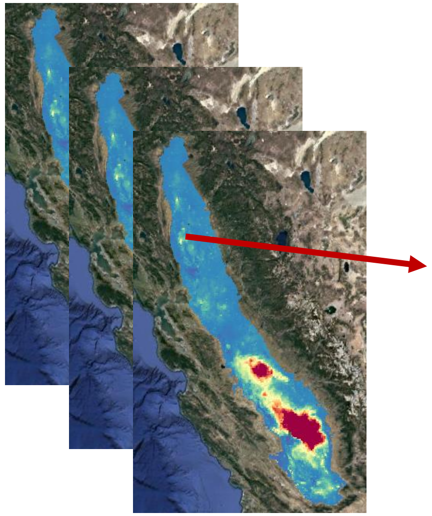
Data analysis: “understanding measured responses”

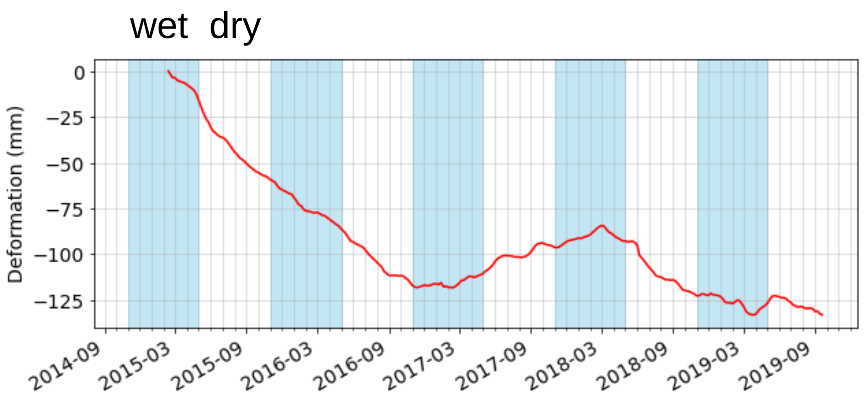


~5 M set of time series (every 6 day for 5 years)
25 m horizontal sampling

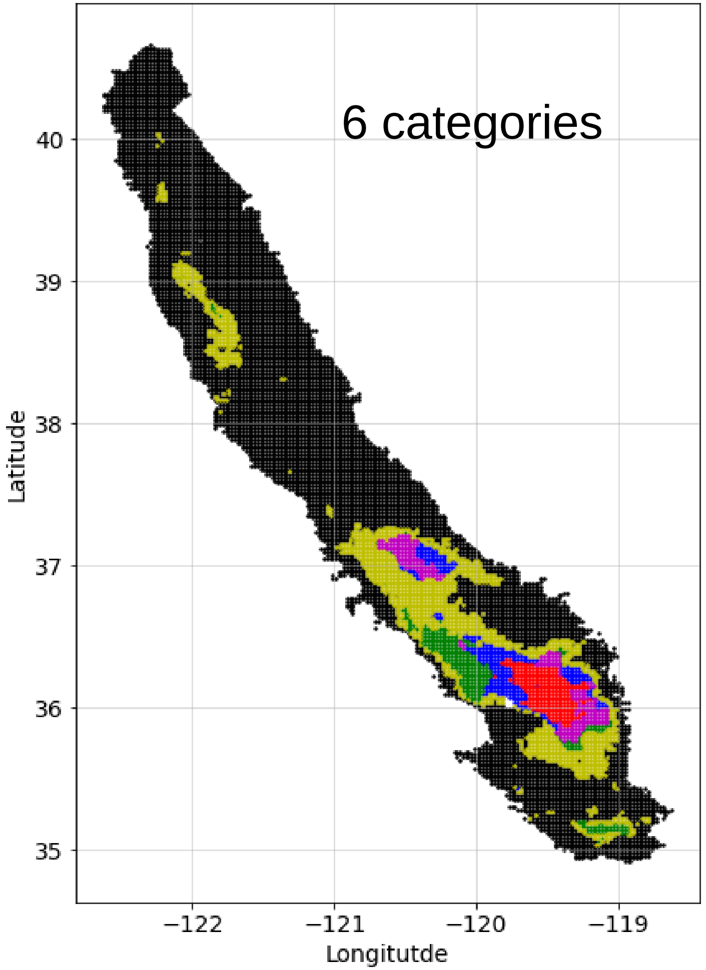
A simple unsupervised learning: K-means clustering

Cluster each time series of deformation



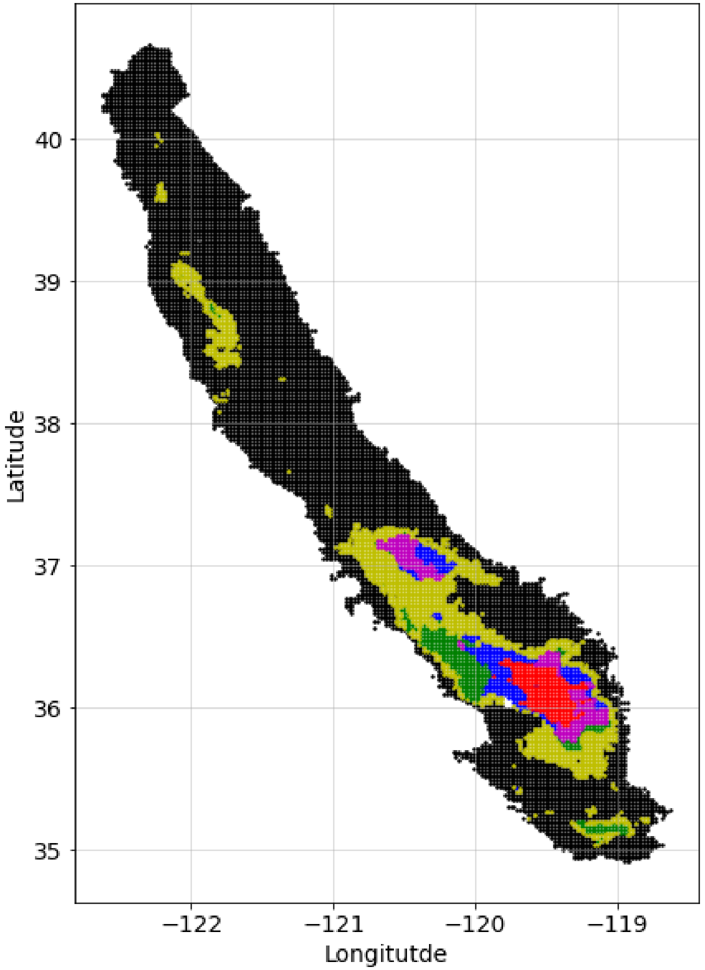


Classified time series on a map

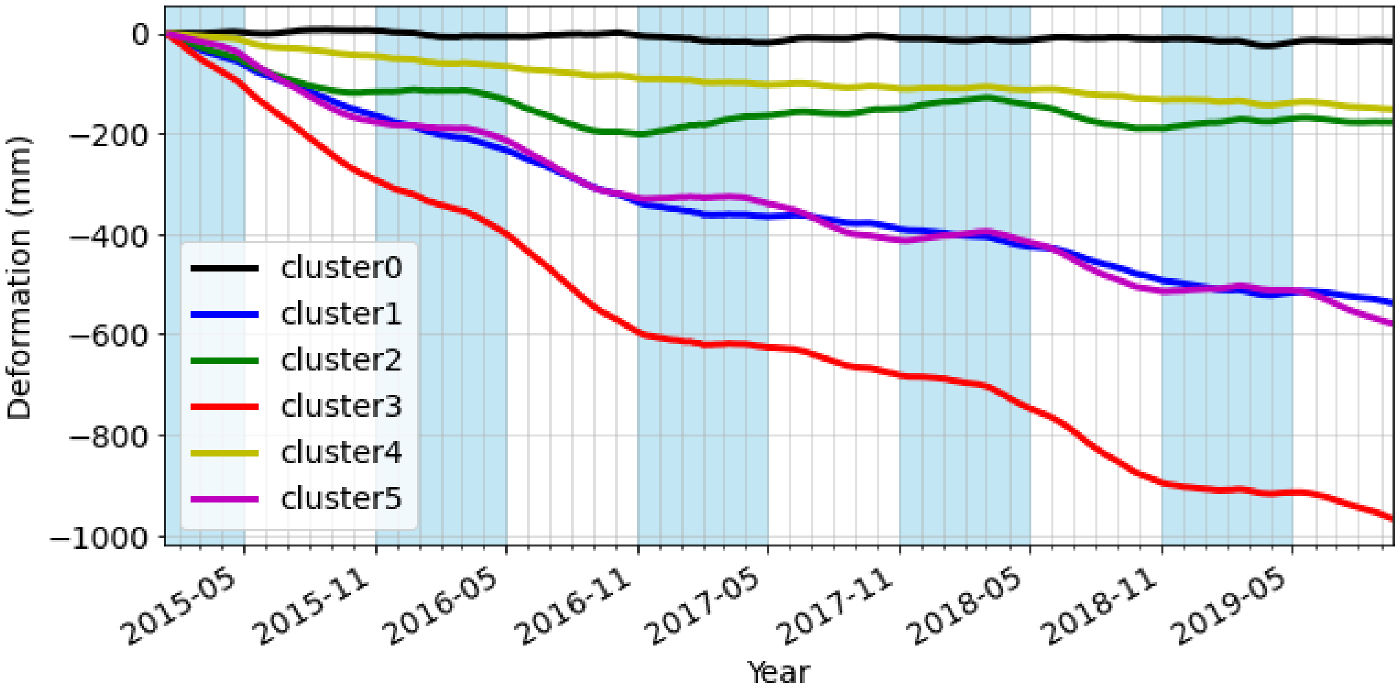


A simple unsupervised learning: K-means clustering

Classified time series on a map

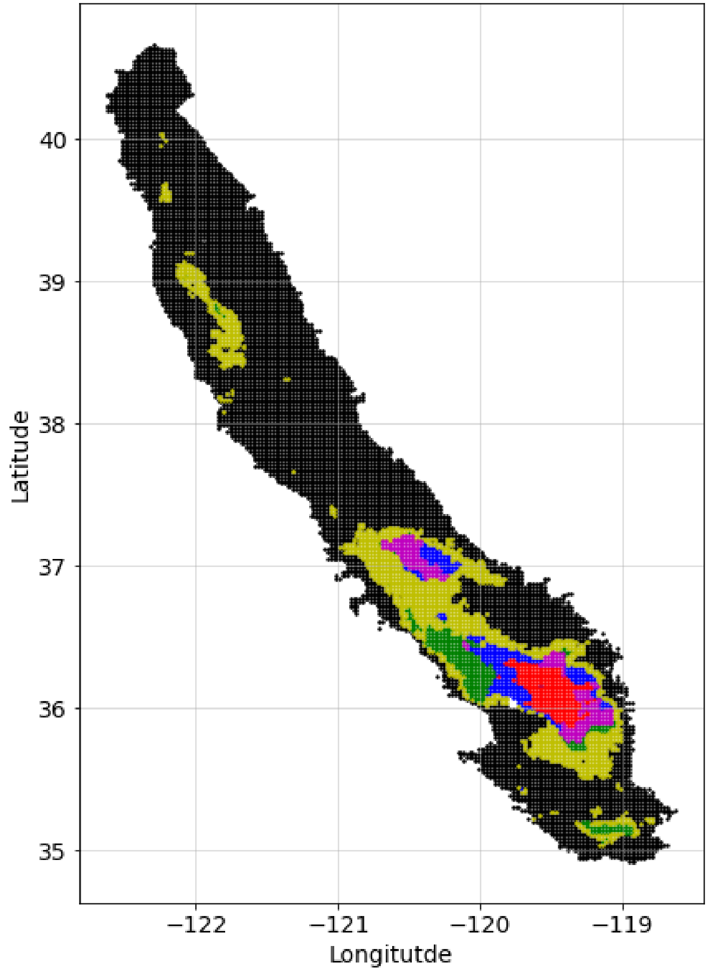


Mean time series for each cluster

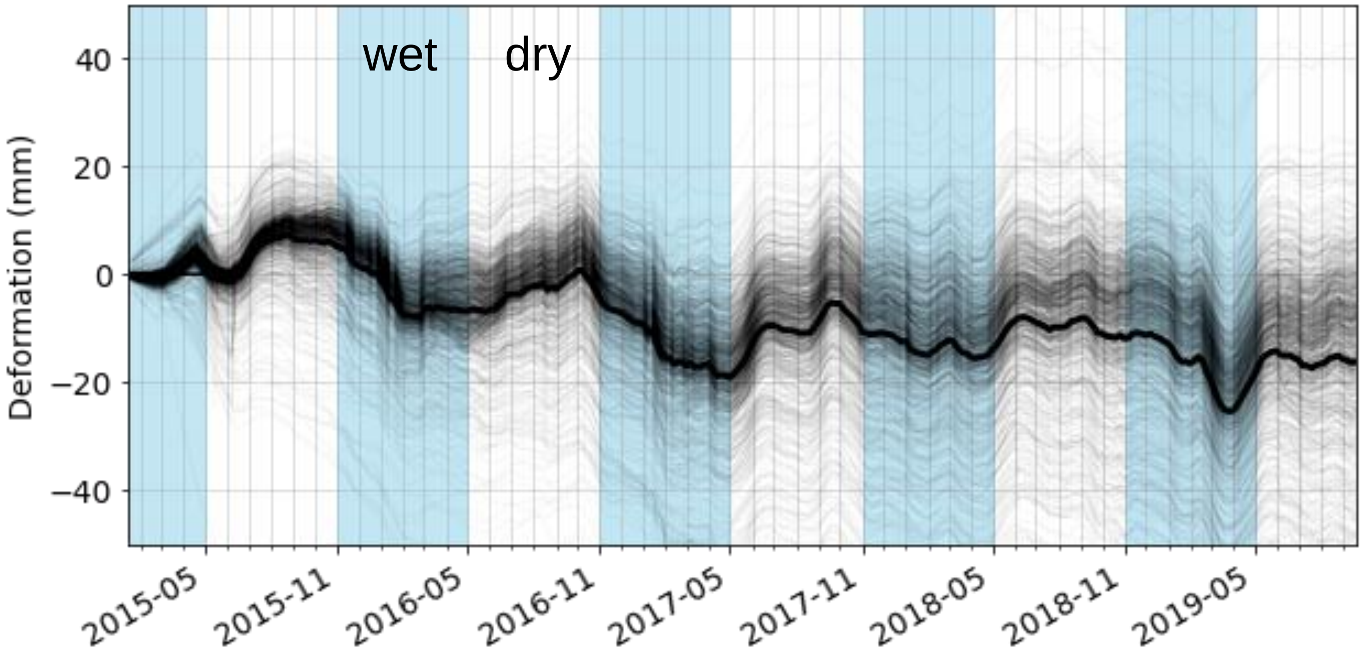


Cluster 1

Classified time series on a map



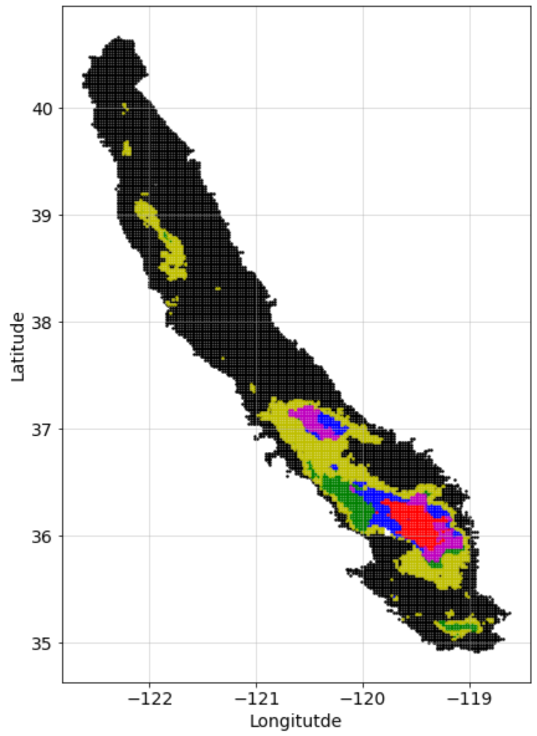
Mean time series for cluster 1

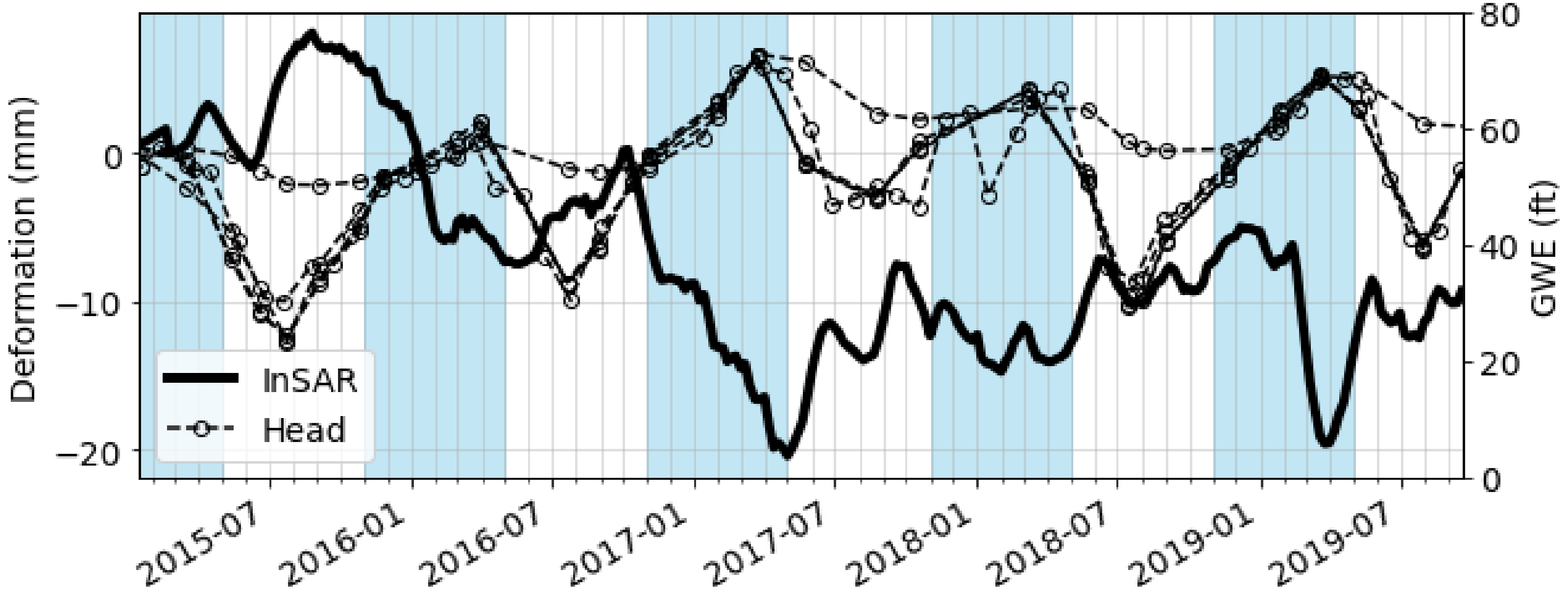


Anything odd to you?

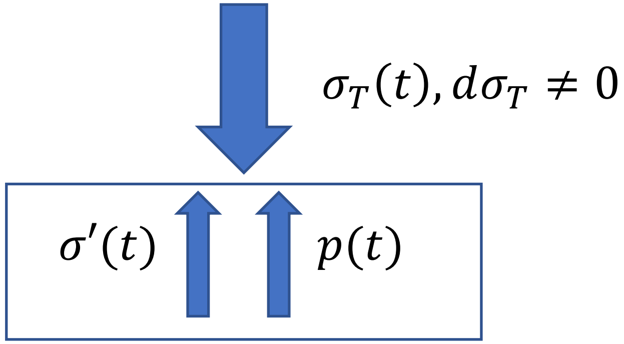
Cluster 1: co-located pair of deformation and head data

Location map





Other factors affecting the deformation signals



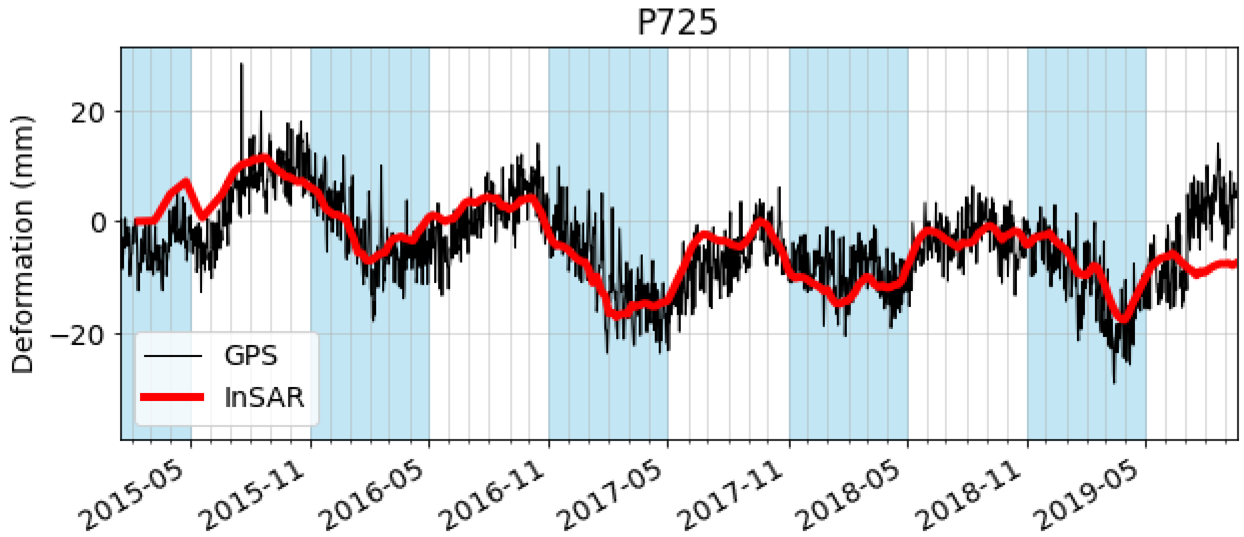
Loading/unloading of snowpack or soil moisture?

Loading to an unconfined aquifer?

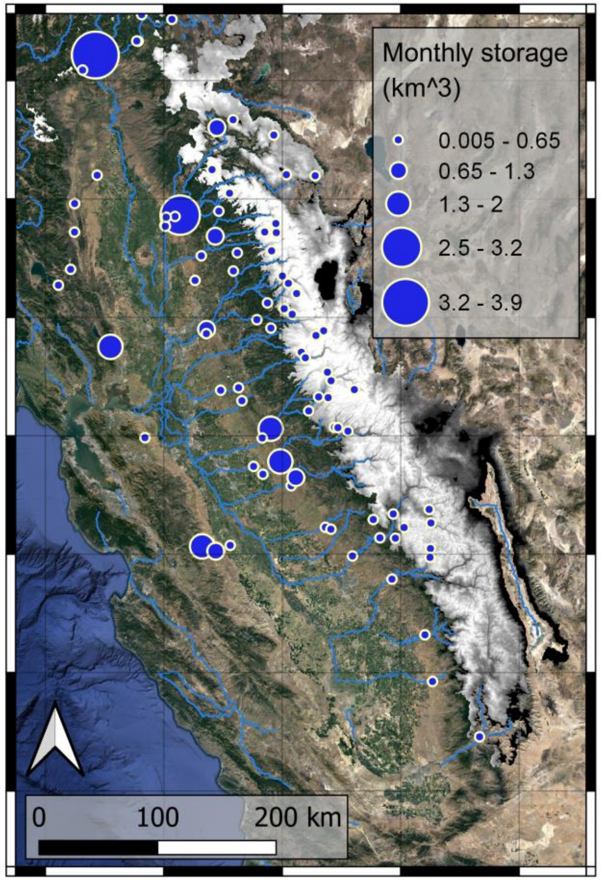
Atmospheric changes?

….

Comparison with a GPS station

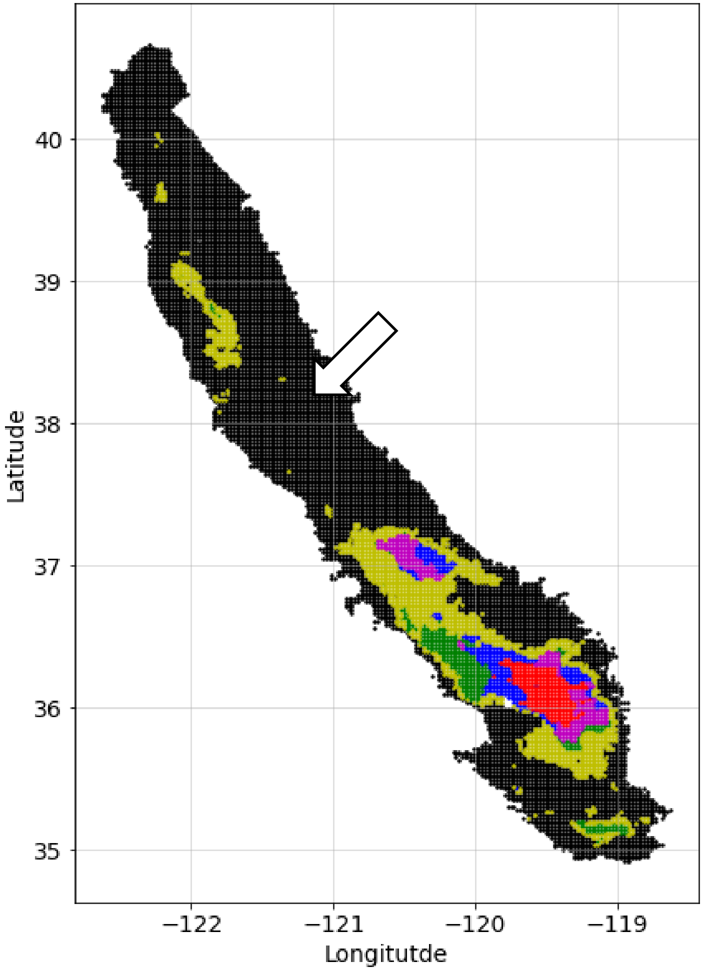


About couple of centimeter oscillations

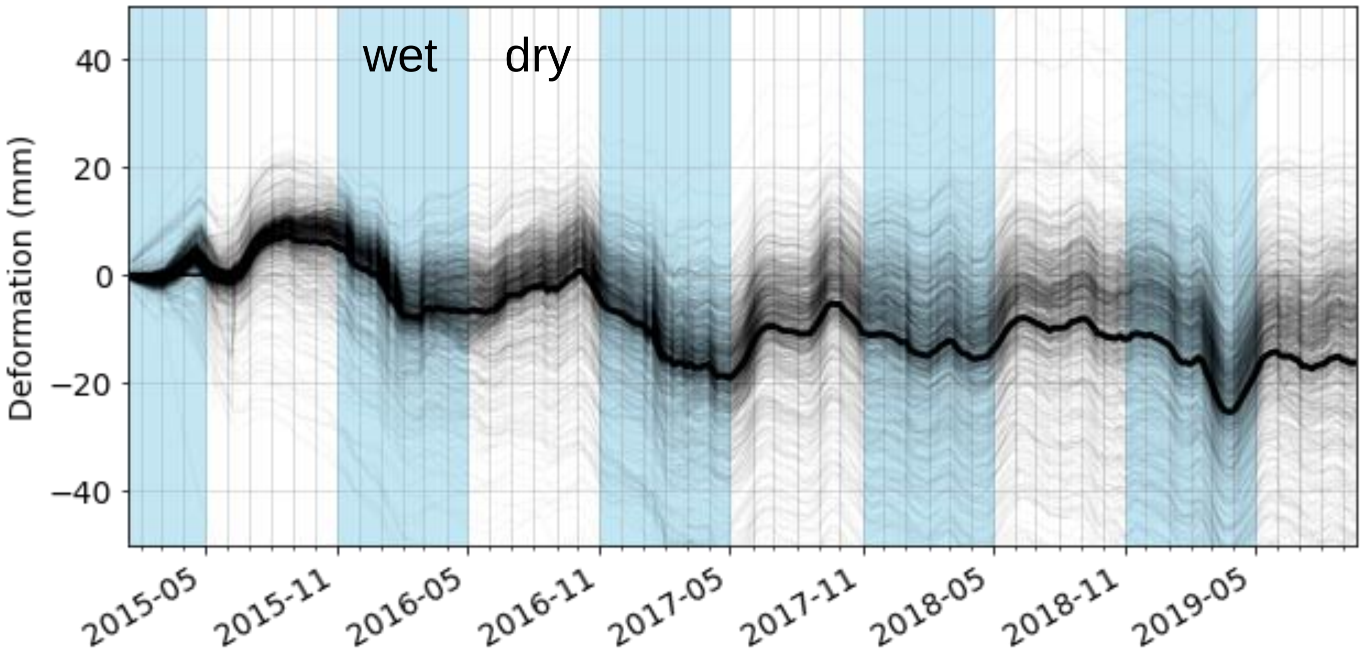


Relative low chance to recover head from these locations …

Classified time series on a map



All time series for cluster 1

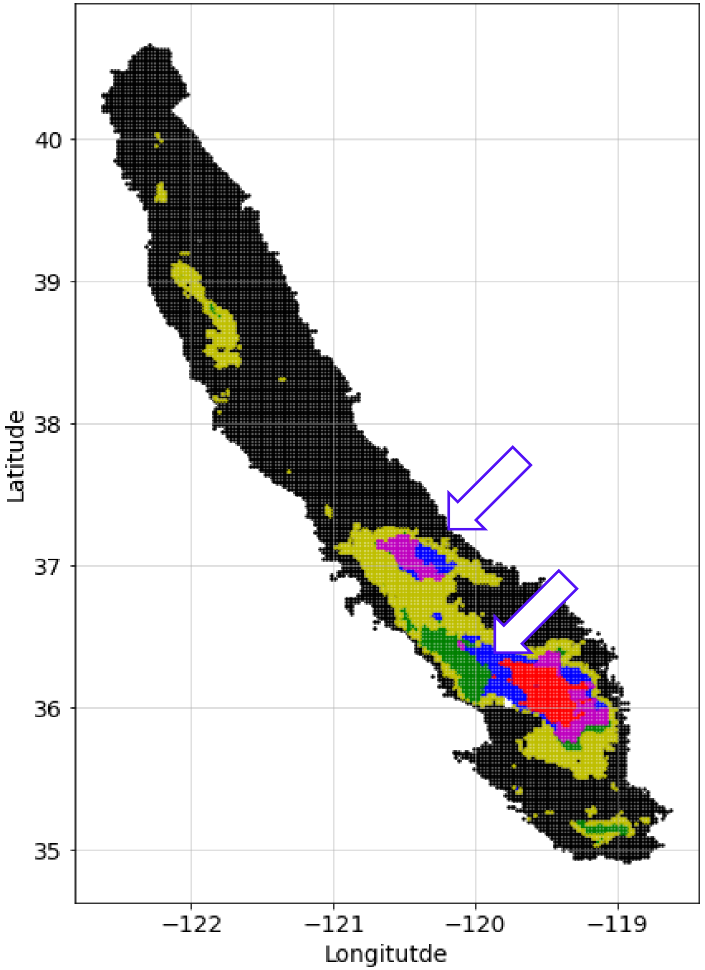


Dominated by the loading/unloading.

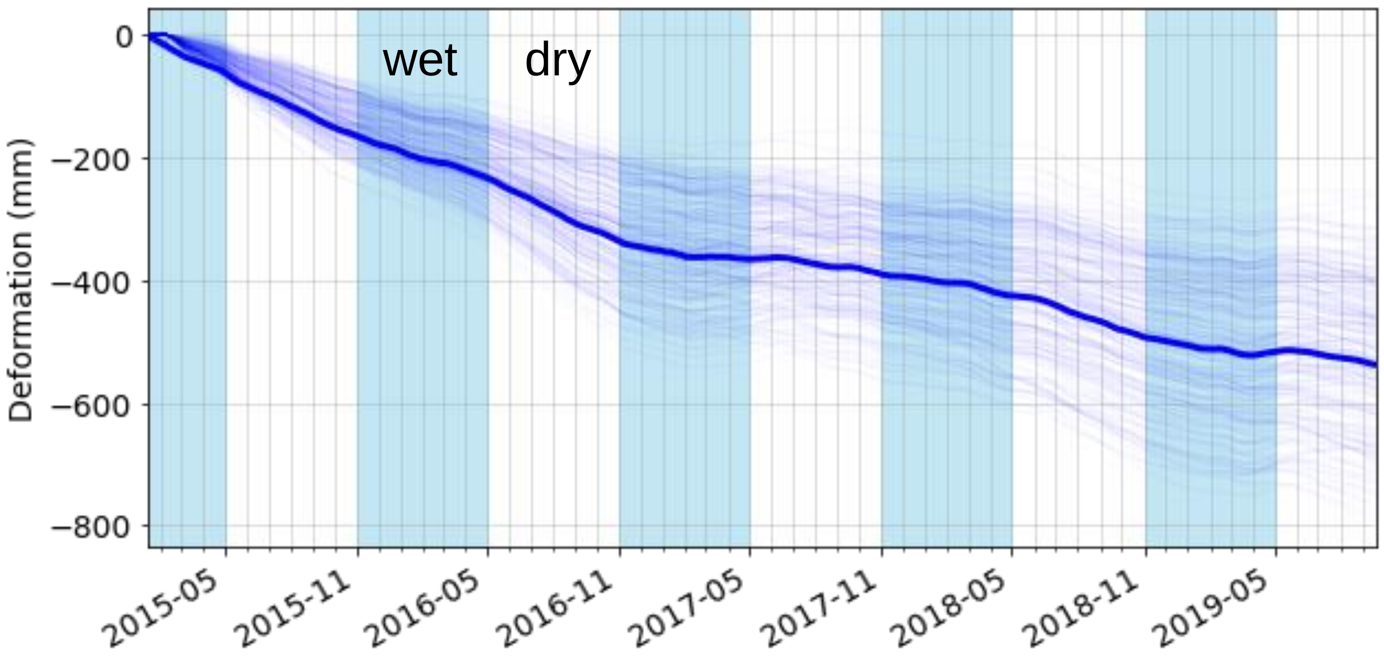
There is a regional response required to be either removed or taken into account.

Cluster 2

Classified time series on a map

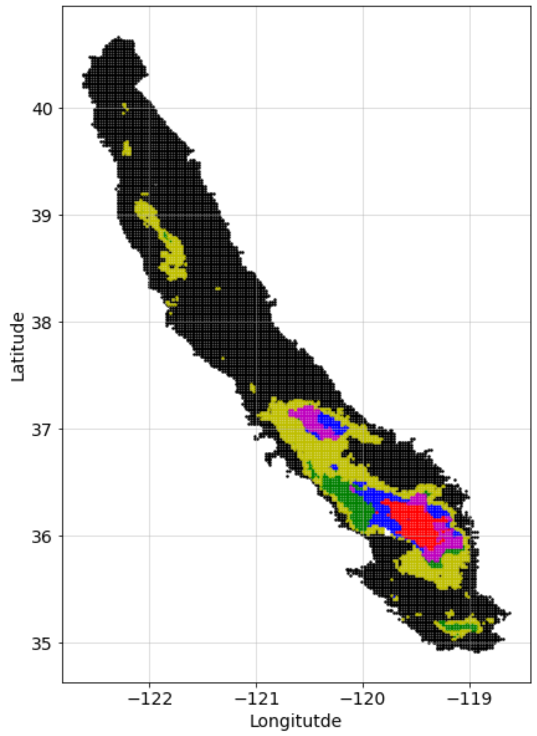


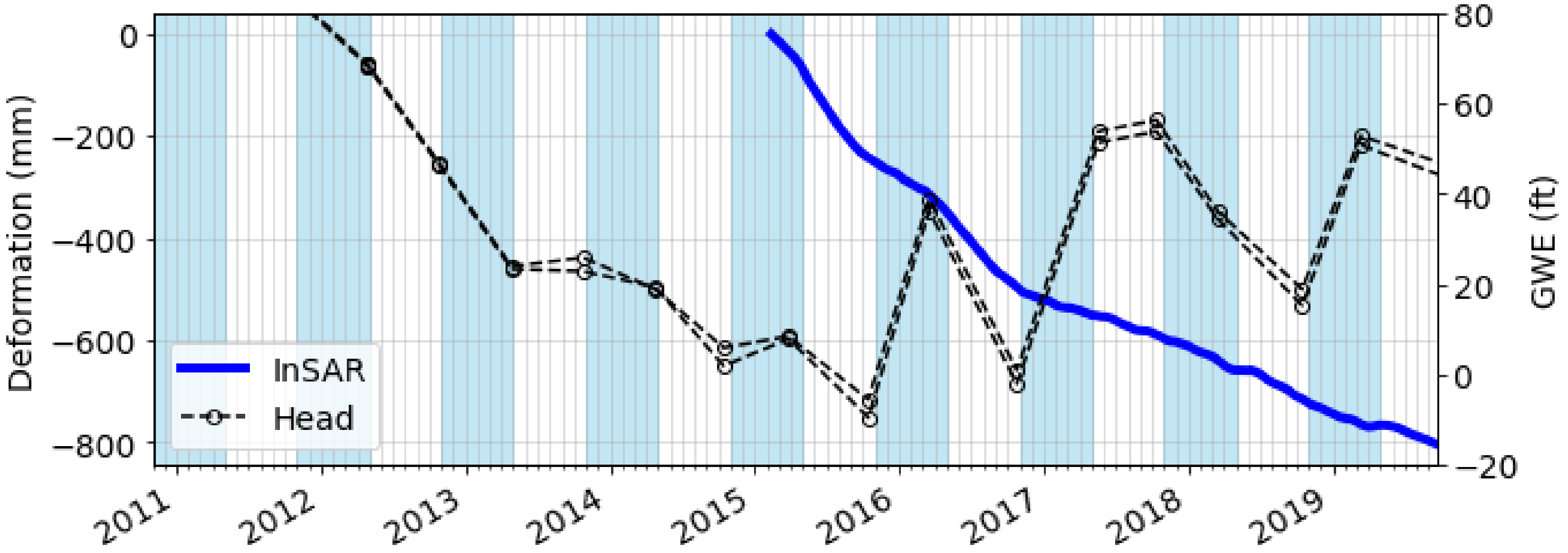
All time series for cluster 2



Cluster 2: co-located pair of deformation and head data

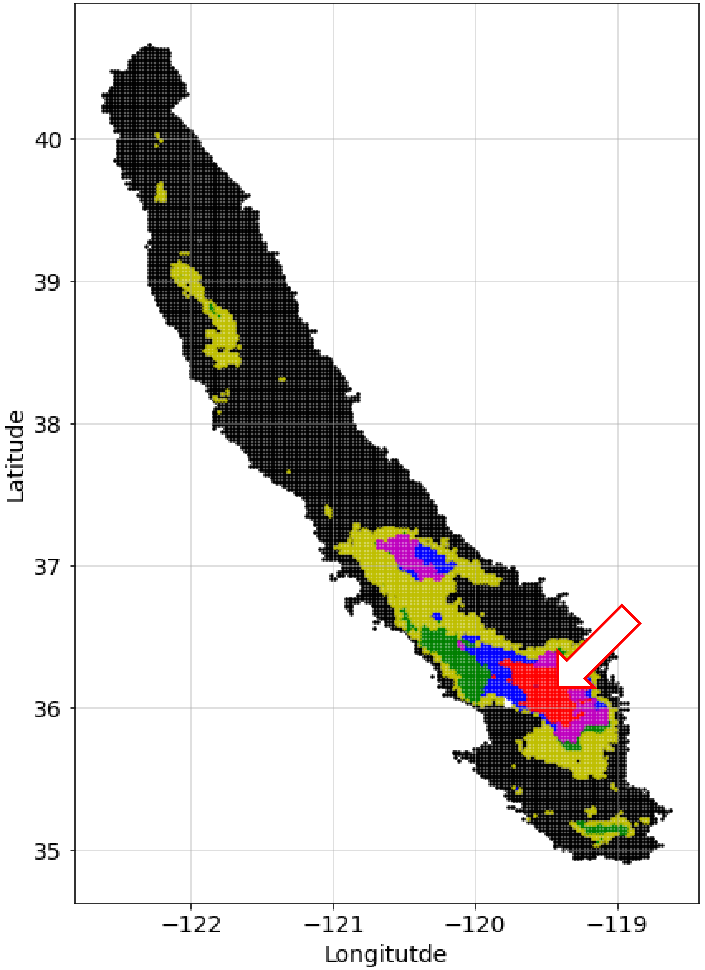
Location map



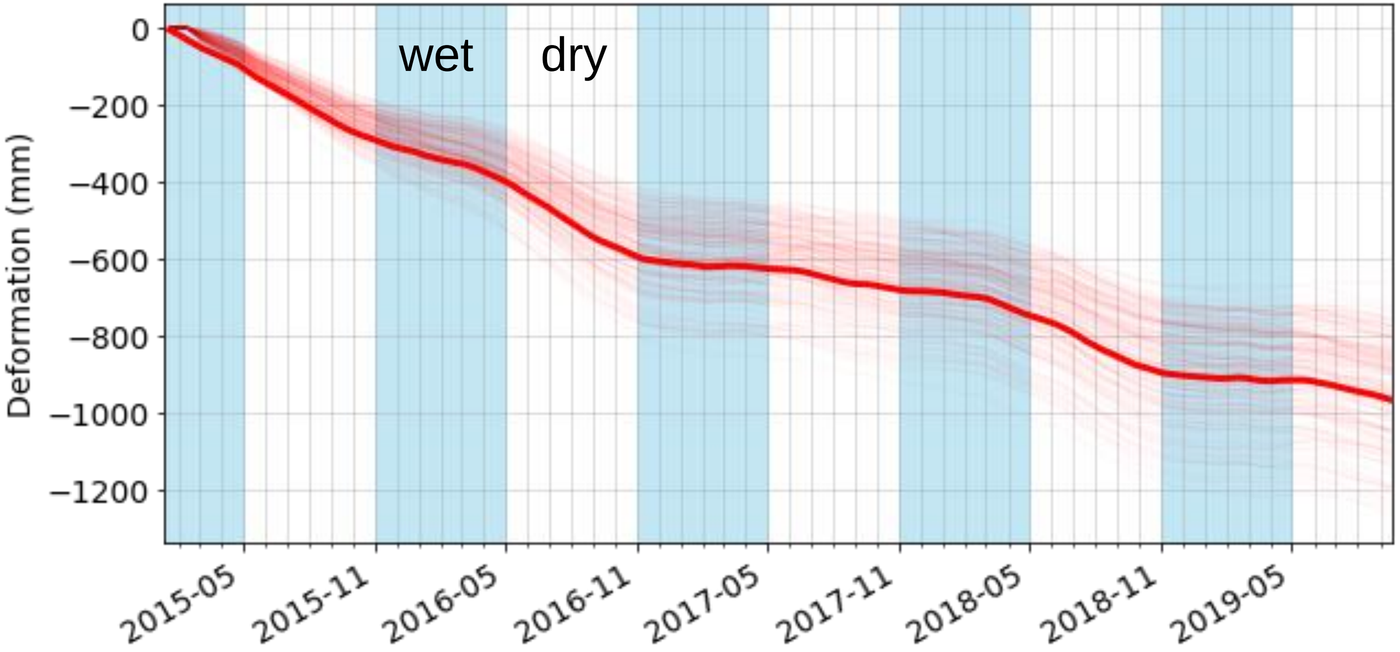


Cluster 3

Classified time series on a map

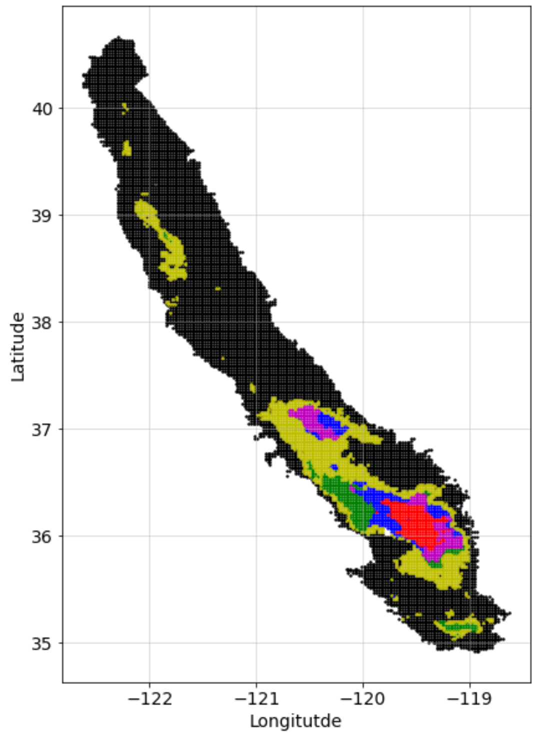


All time series for cluster 3

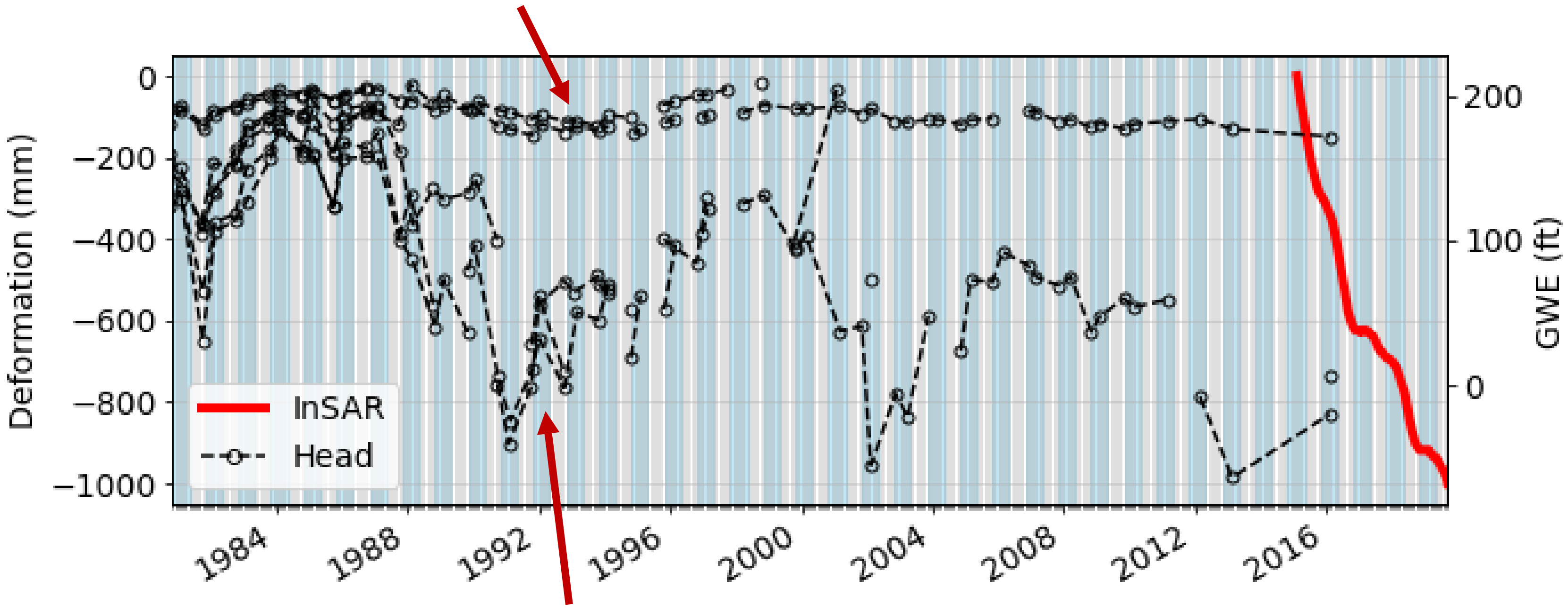


Cluster 3: co-located pair of deformation and head data

Location map



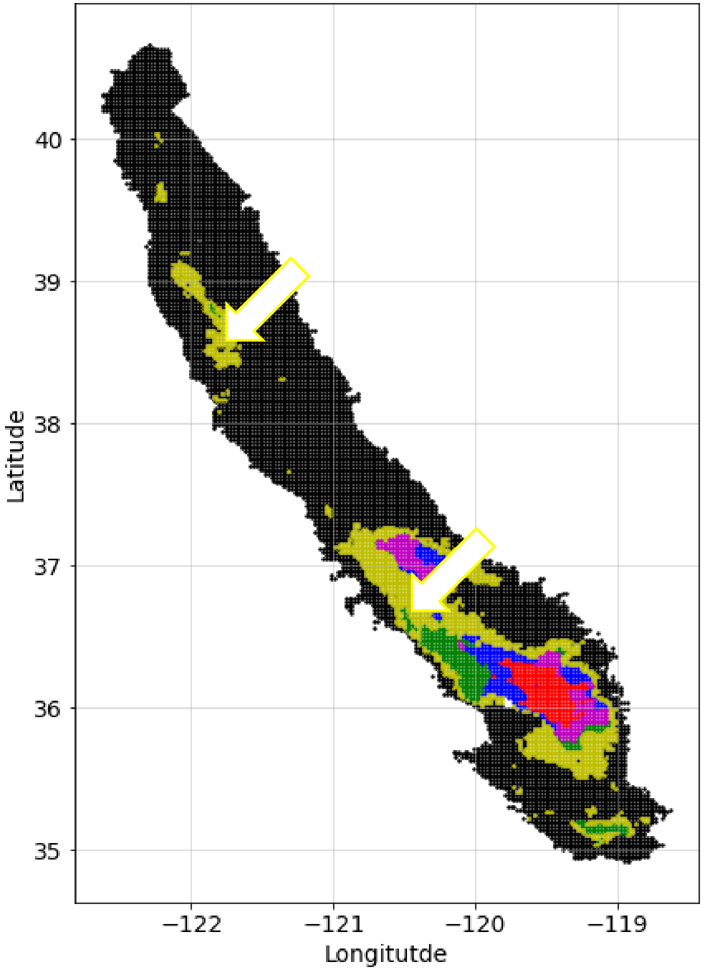
Unconfined aquifer



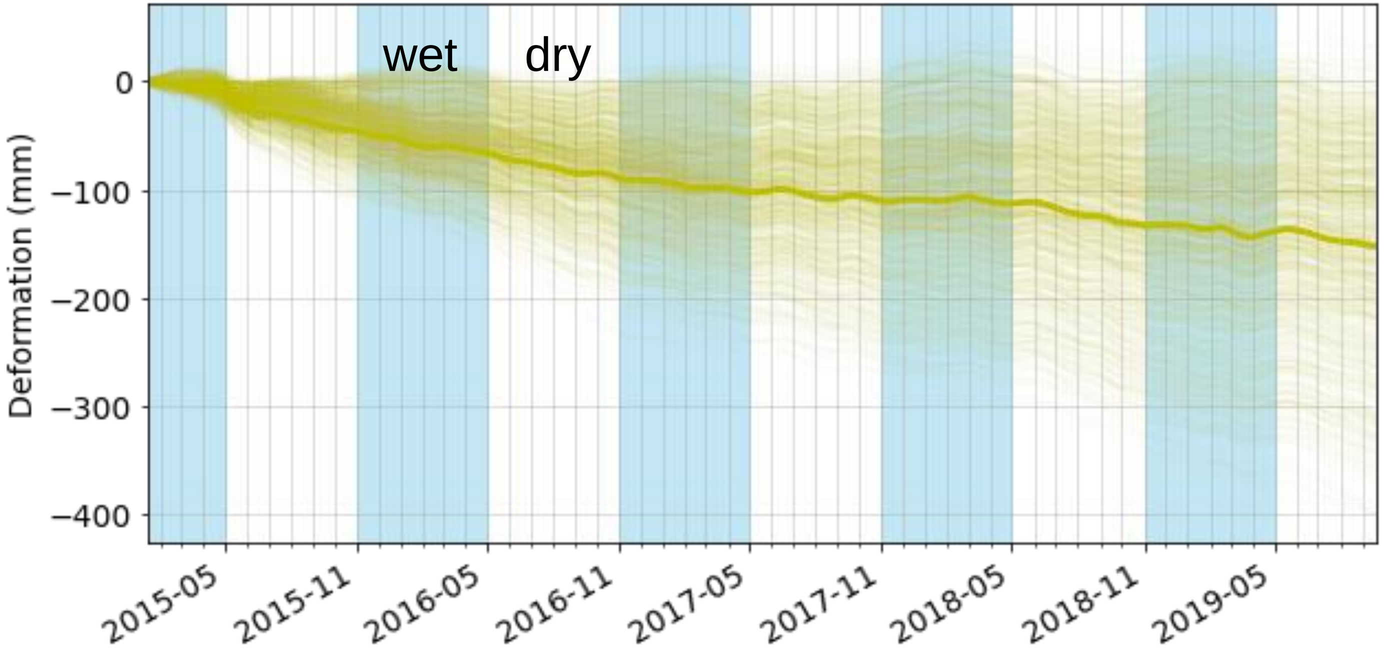
Confined aquifer

Cluster 4

Classified time series on a map

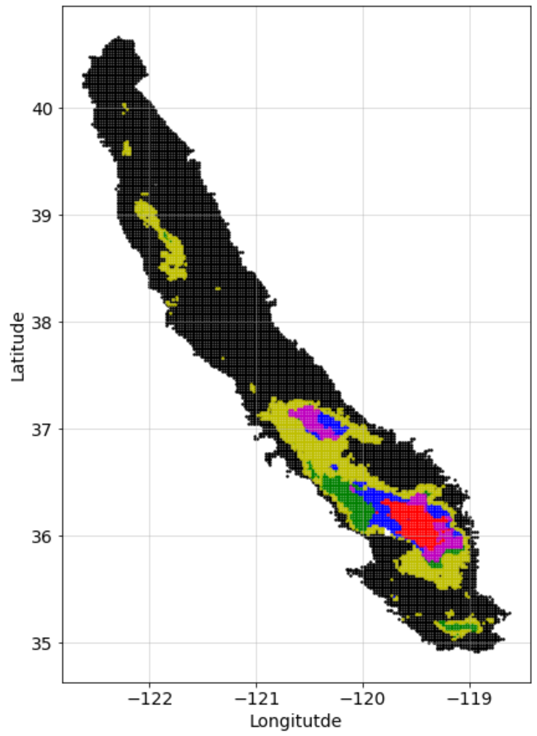


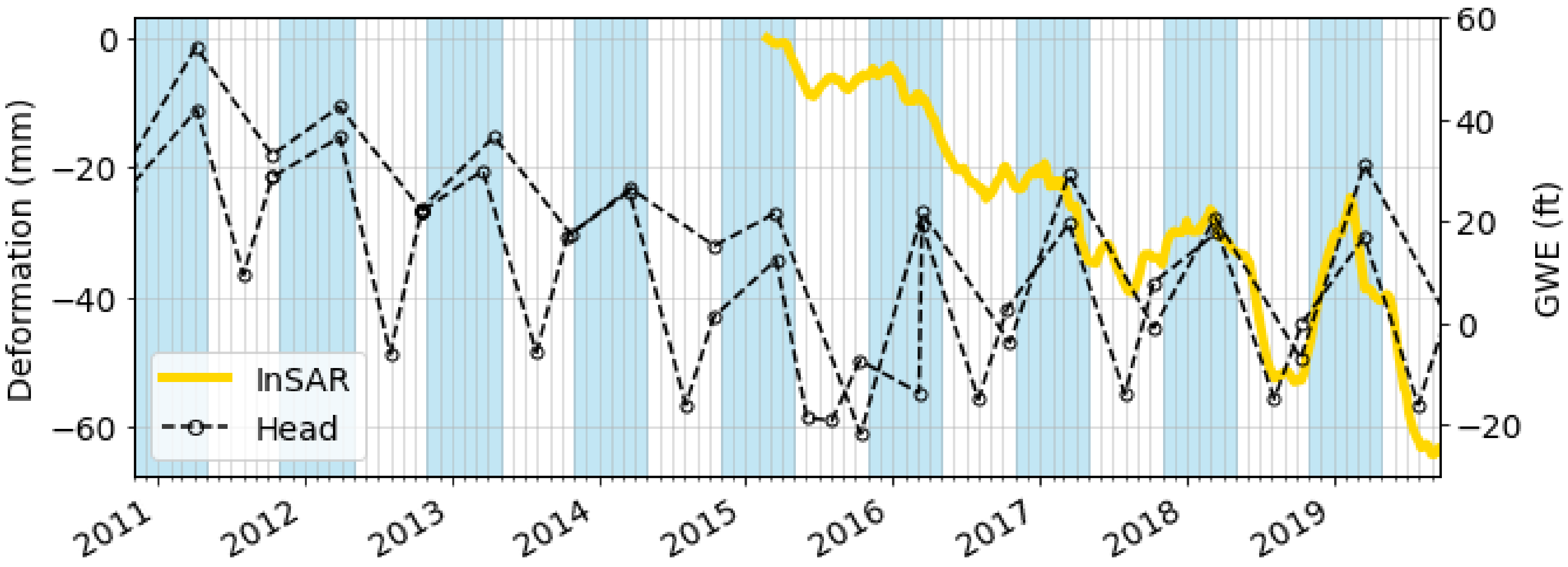
All time series for cluster 3



Cluster 4: co-located pair of deformation and head data

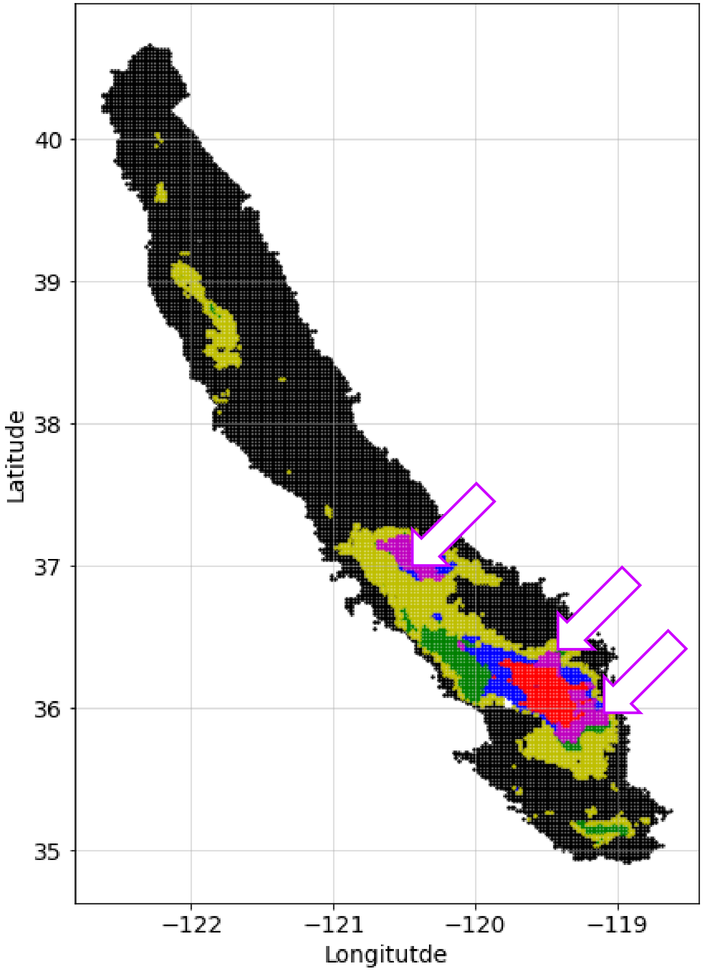
Location map



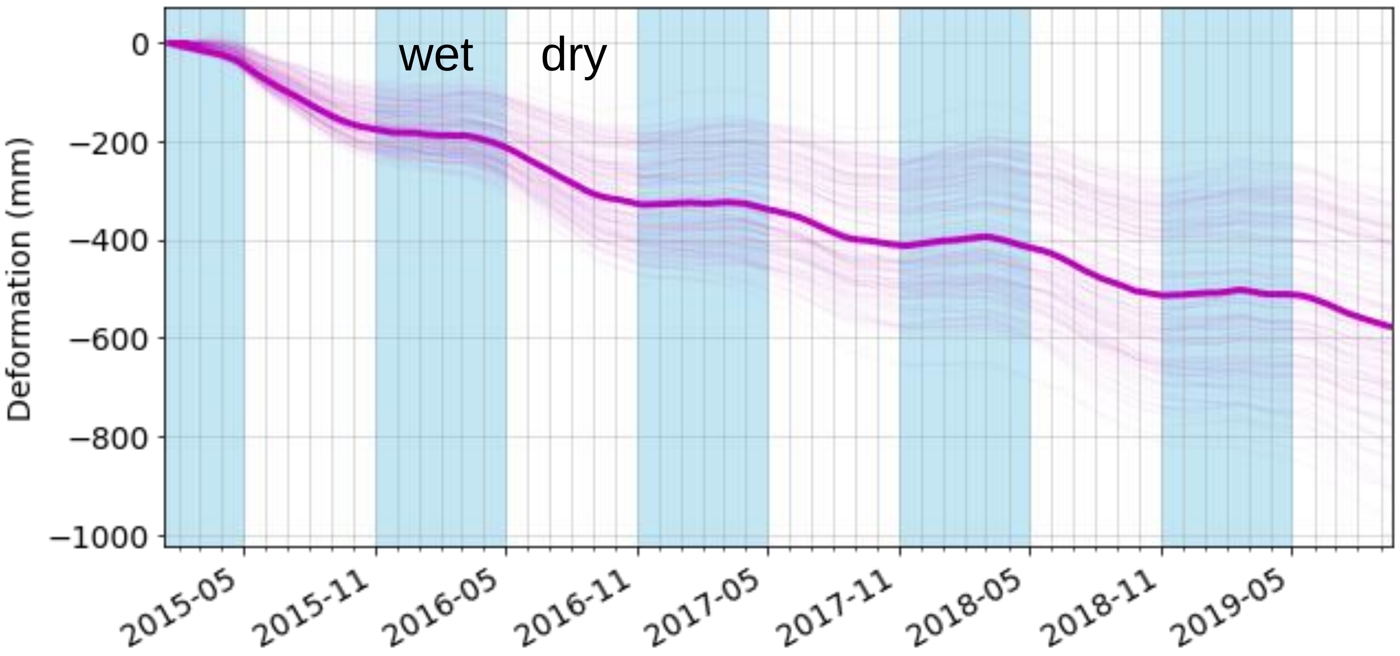


Cluster 5

Classified time series on a map

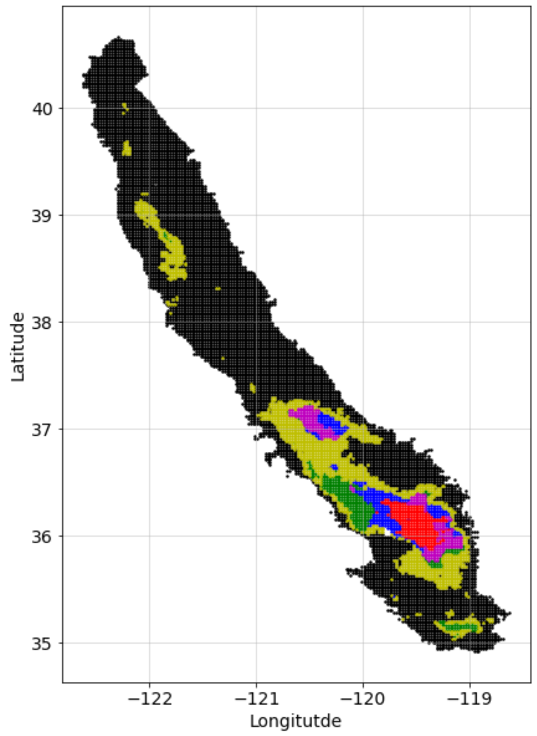


All time series for cluster 3

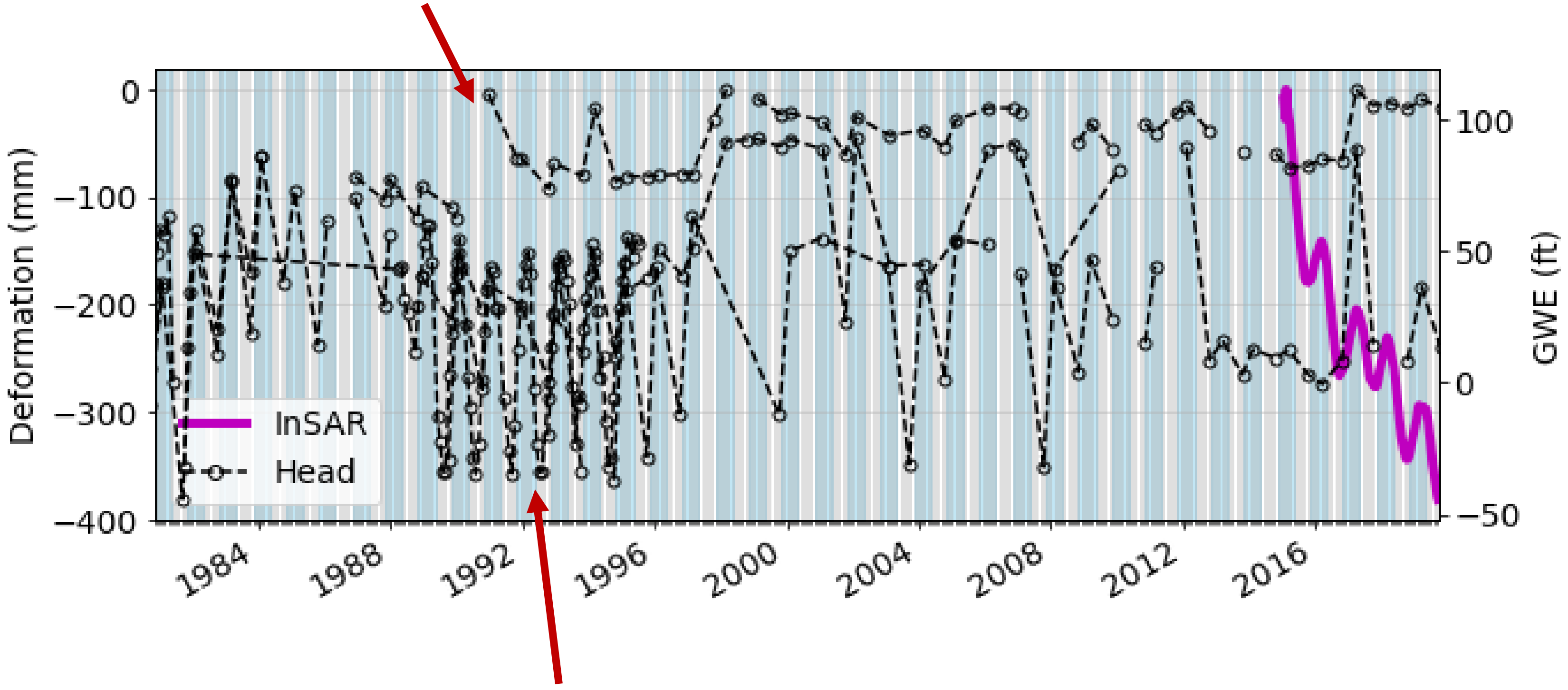


Cluster 5: co-located pair of deformation and head data

Location map



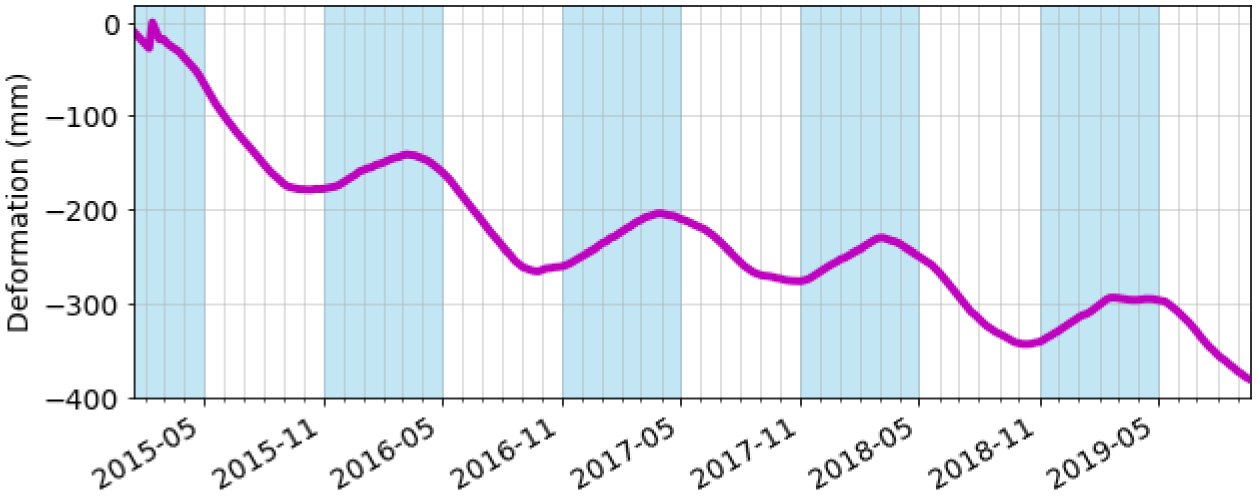
Unconfined aquifer



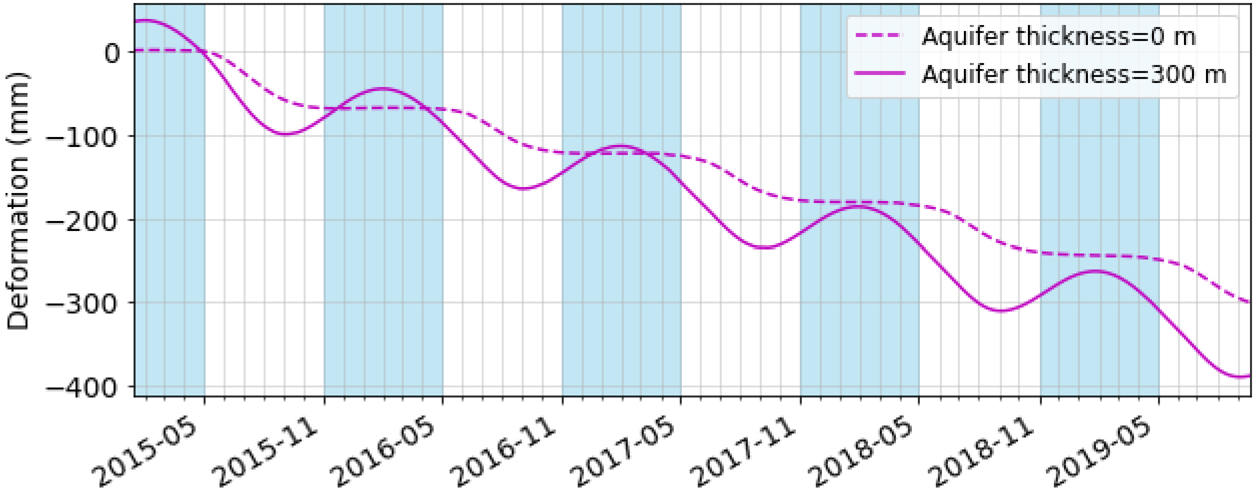
Confined aquifer

What can cause these large oscillations?

Measured:



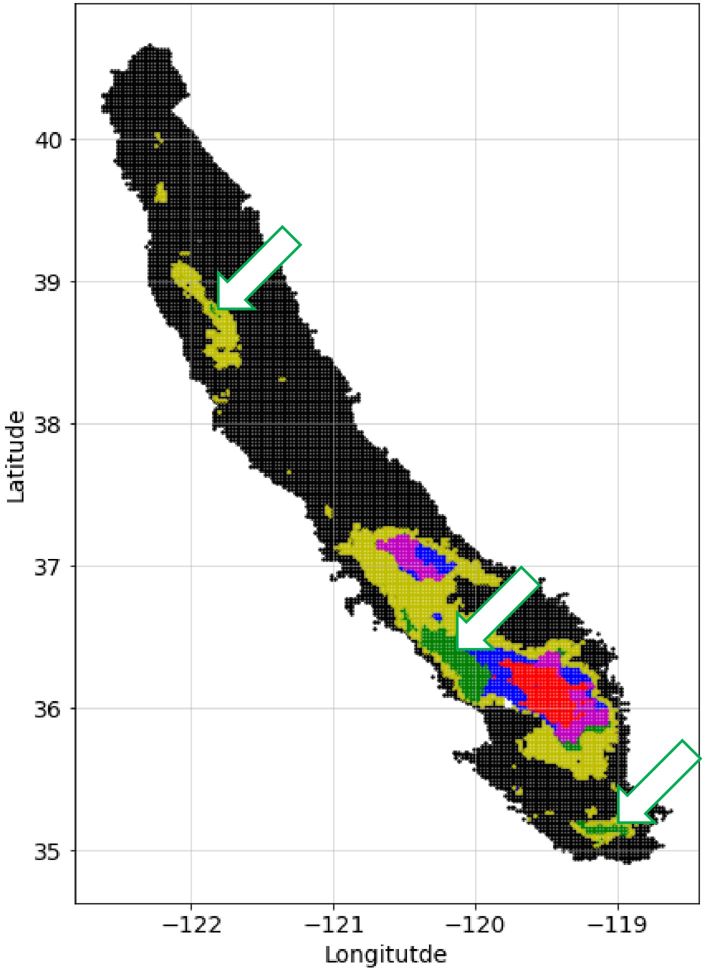
Simulated:



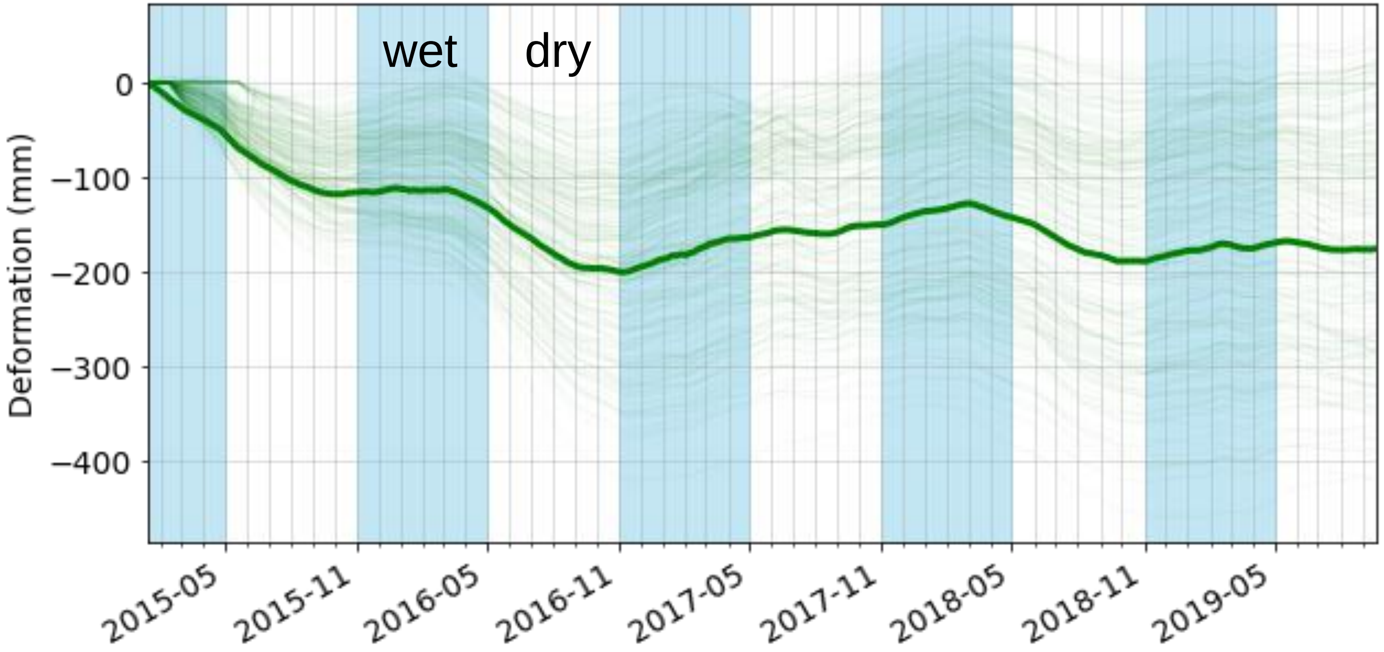
Increasing aquifer thickness
→ Increasing oscillations

Cluster 6

Classified time series on a map

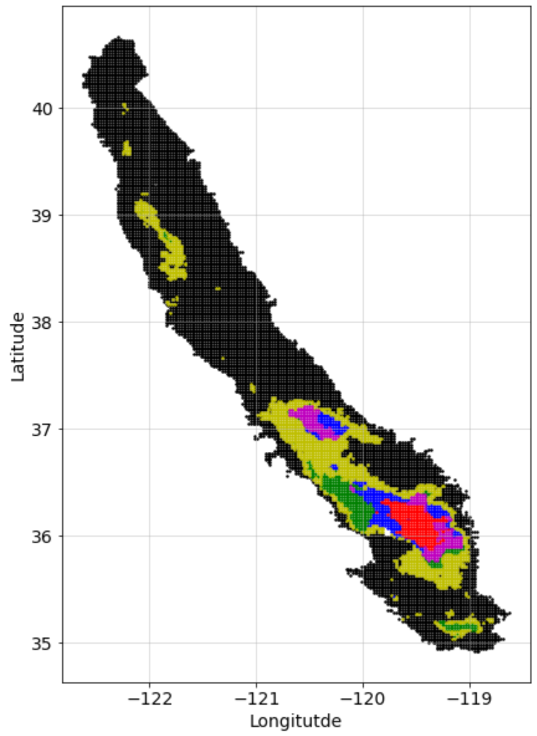


Mean time series for cluster 3

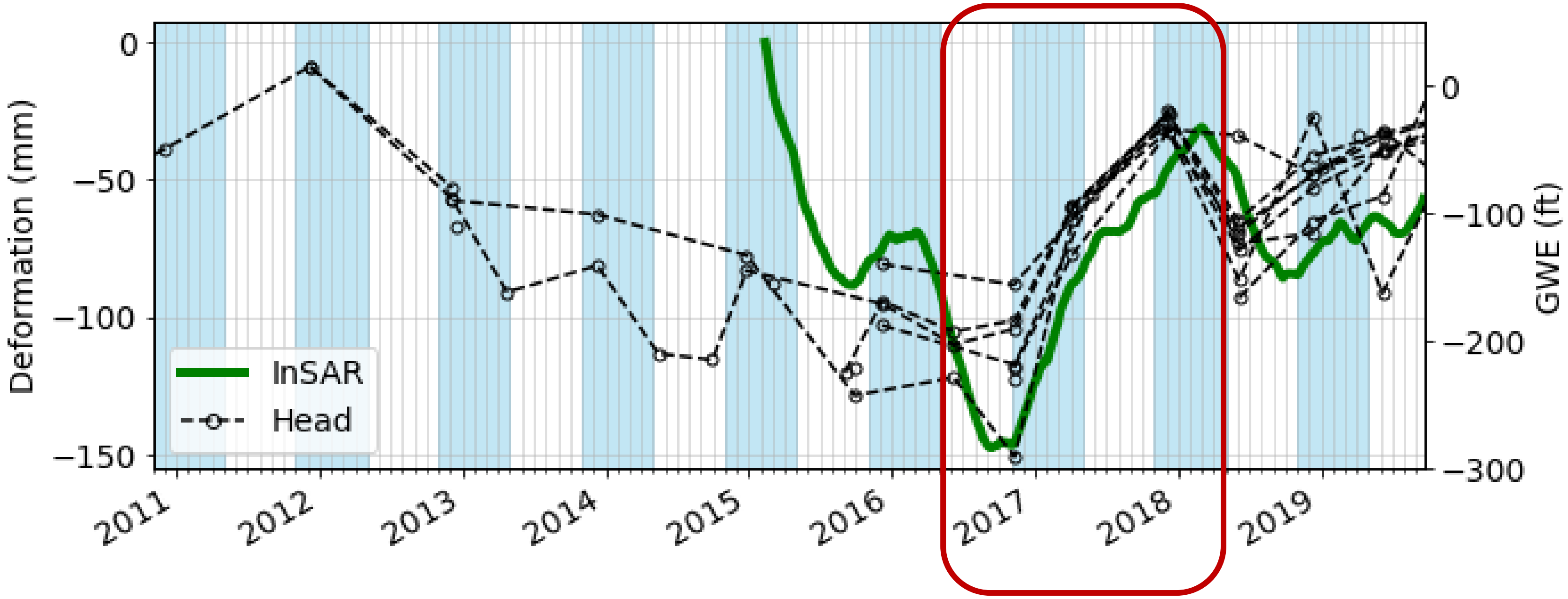


Cluster 5: co-located pair of deformation and head data

Location map

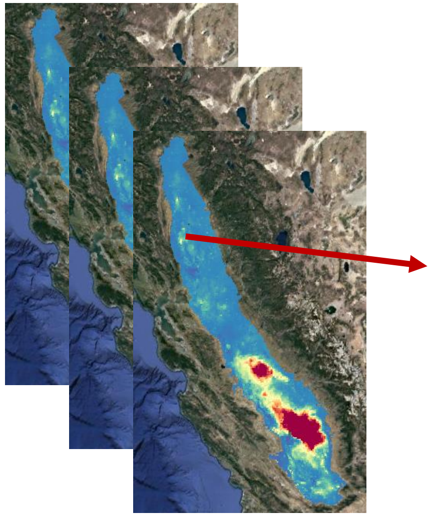


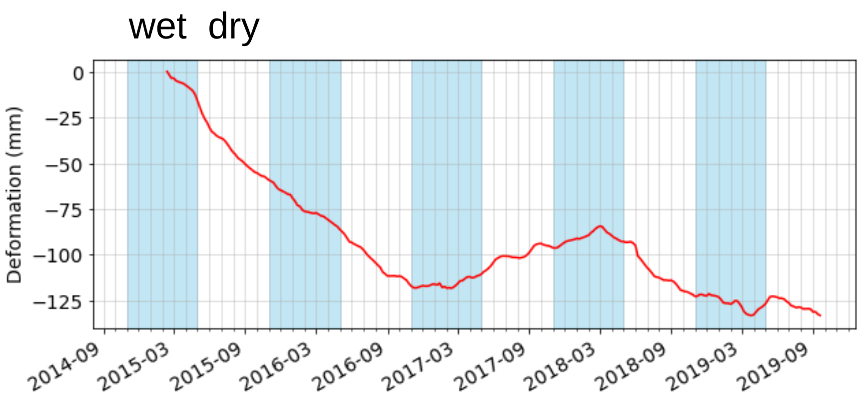
Due to a recharge project



“Can we recover water head from the satellite ground deformation data?”

Deformation data





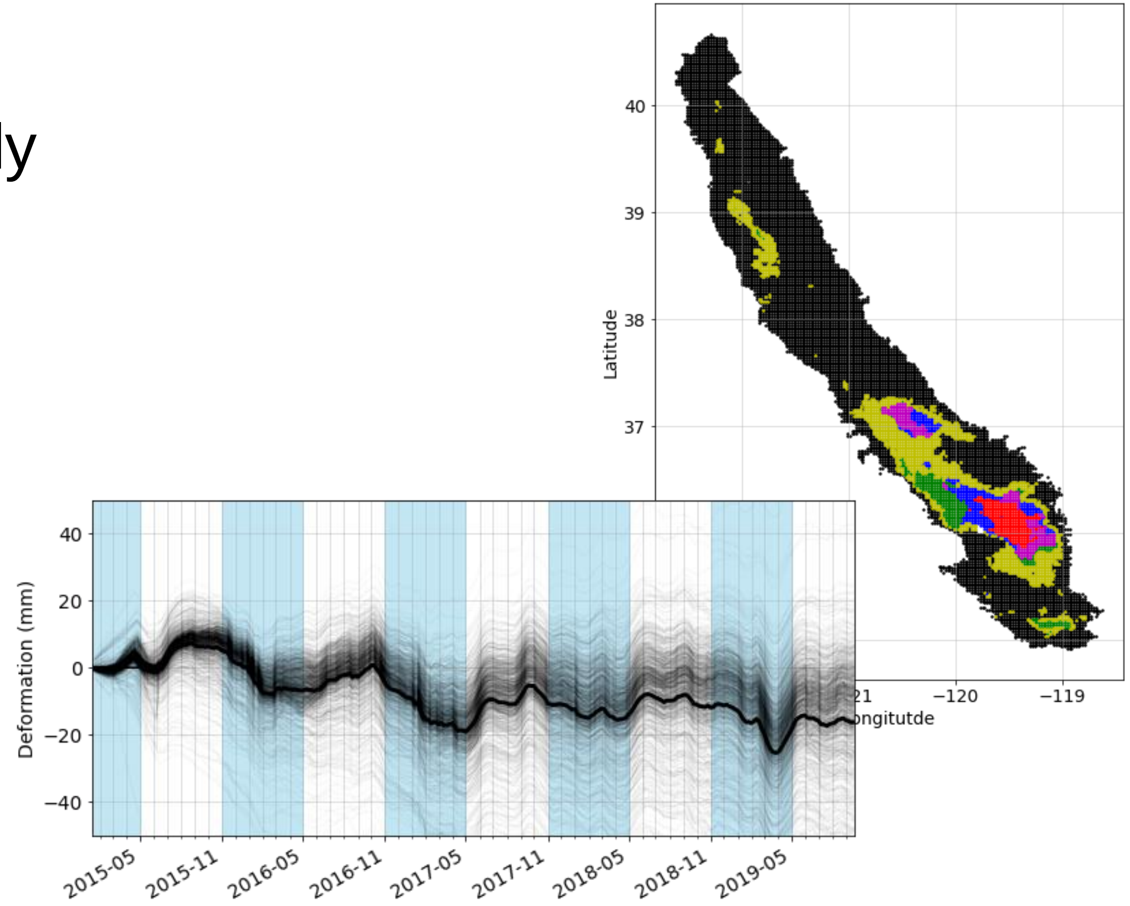
Water head

?

Expected challenges for the inverse problem

Deformation response less than ∓ 20 mm likely affected by loading/unloading signals.

→ Still provides information (e.g., upper bound)

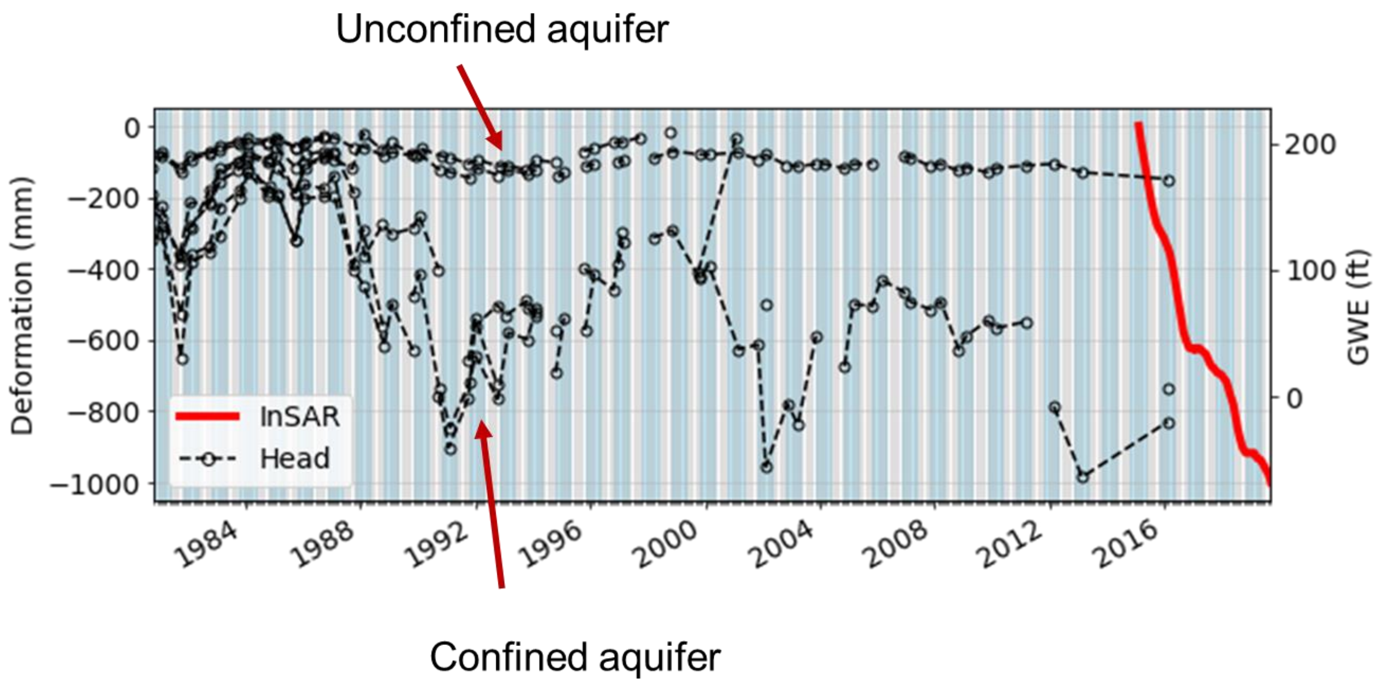


Expected challenges for the inverse problem

Deformation response less than ∓ 20 mm likely affected by loading/unloading signals.

→ Still provides information (e.g., upper bound)

Band-limited deformation data



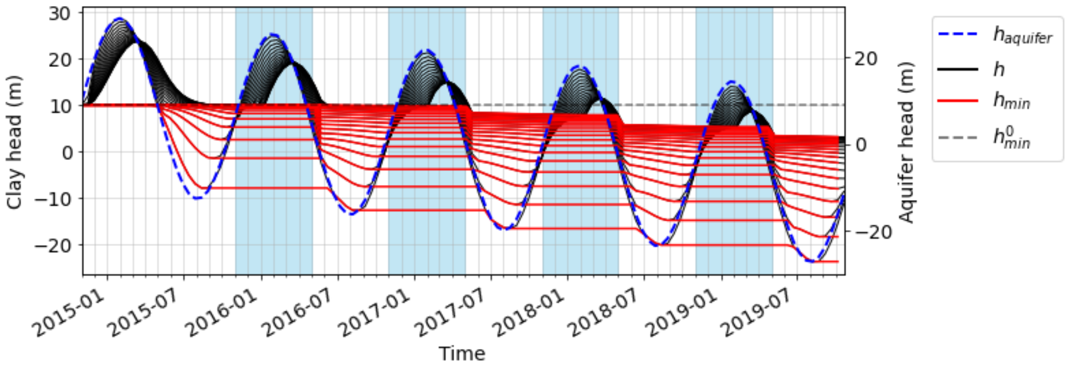
Expected challenges for the inverse problem

Deformation response less than ∓ 20 mm likely affected by loading/unloading signals.

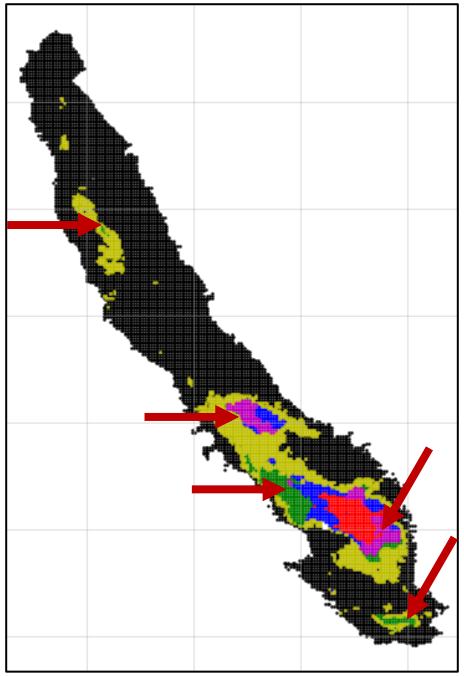
→ Still provides information (e.g., upper bound)

Band-limited deformation data

For highly subsiding region, deformation response is not sensitive to the peaks, but troughs



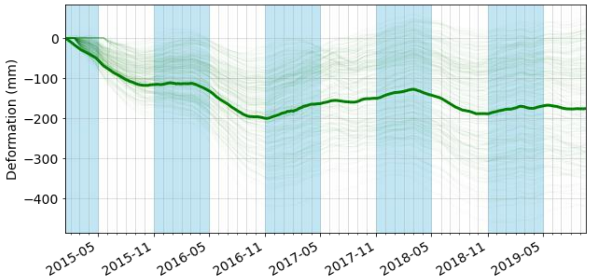
Expected challenges for the inverse problem



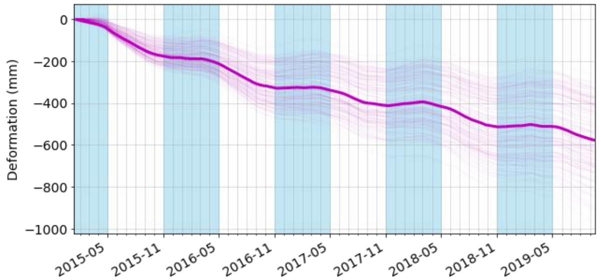
Deformation response less than ∓ 20 mm likely affected by loading/unloading signals.

→ Still provides information (e.g., upper bound)

Band-limited deformation data



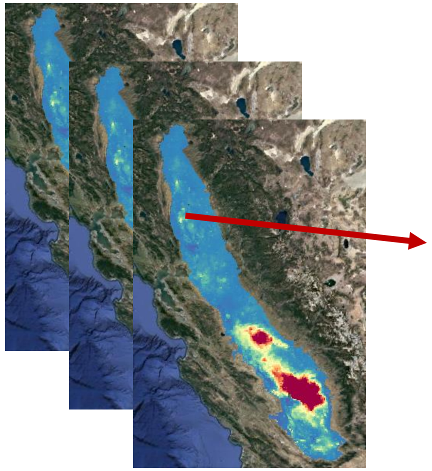
For highly subsiding region, deformation response is not sensitive to the peaks, but troughs

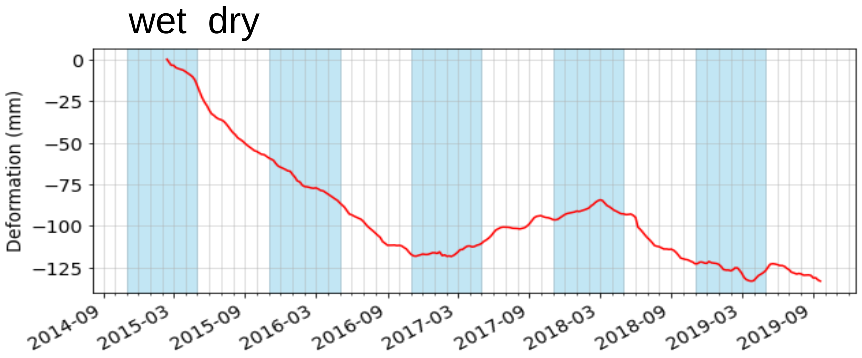


High level of oscillations contains information about the peaks

Outlook: Invert for all InSAR time series

InSAR deformation data





Water head
Aquifer properties

?

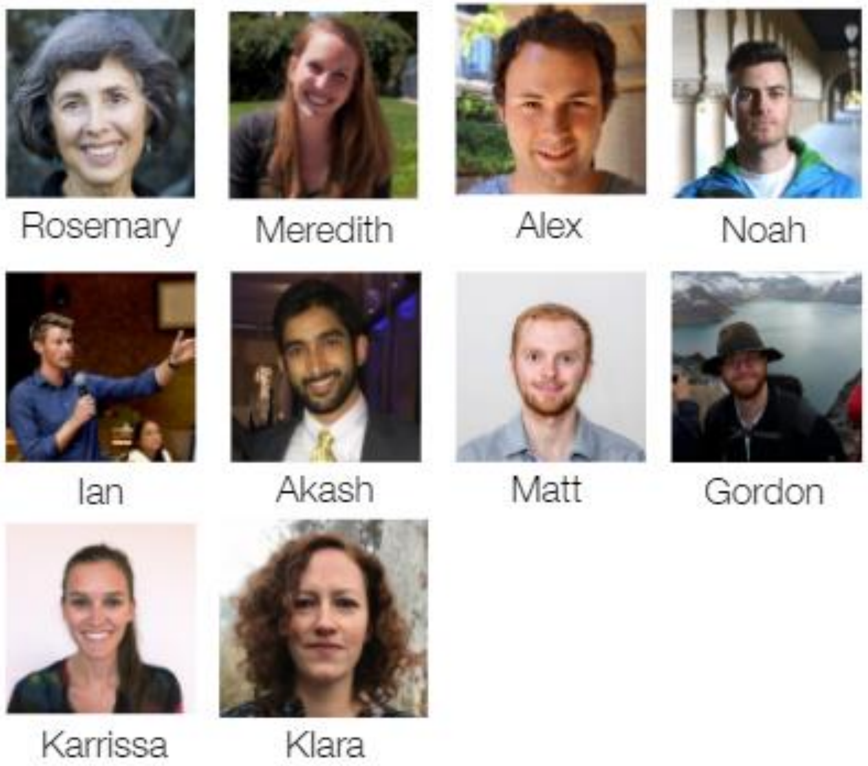
Integrate other available data:

- Head data from wells
- Aquifer properties
  (from existing groundwater model and geophysical data)

Thank you!

simpeg

Stanford University



@sgkang

sgkang09@stanford.edu

The end