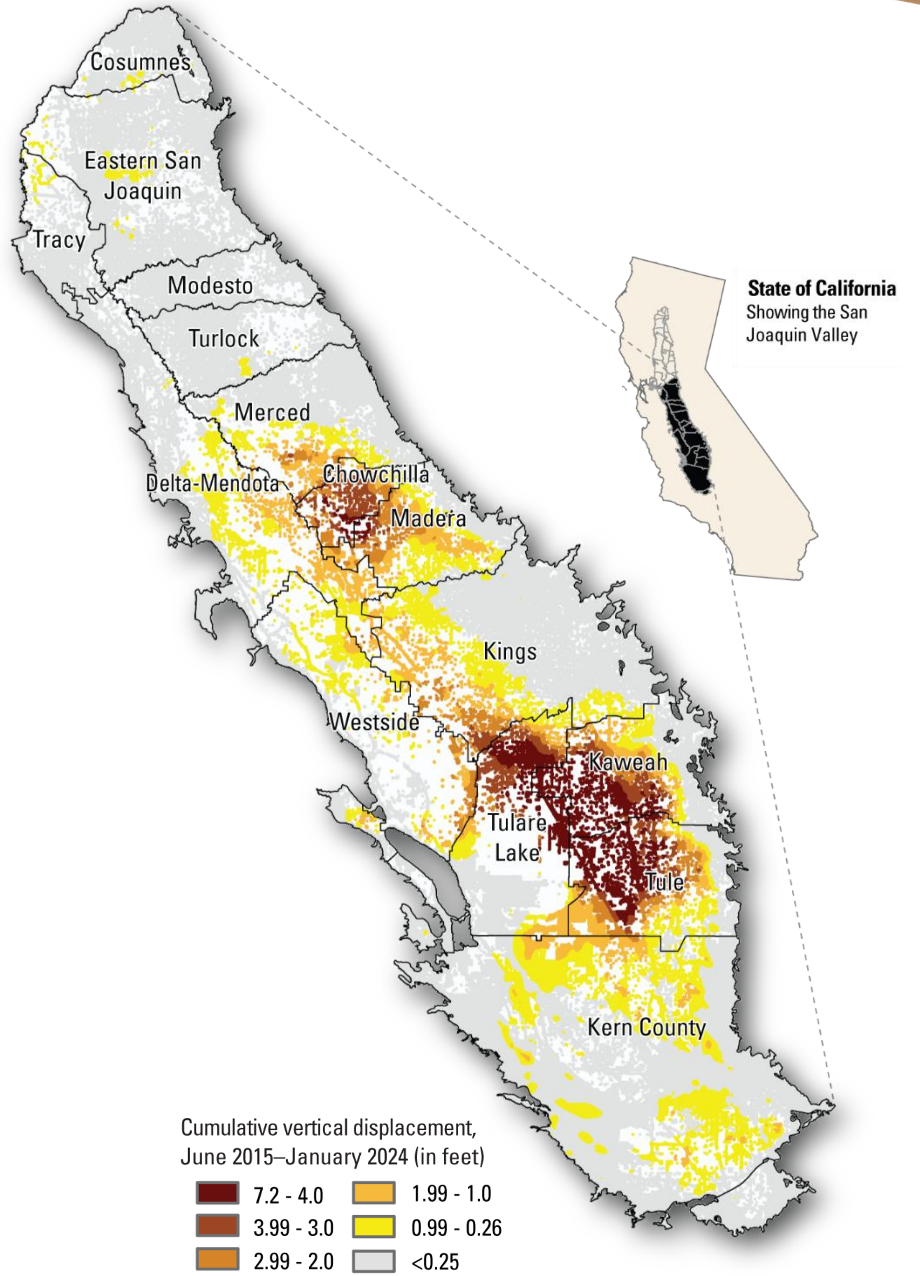
INTERA

Integrating Multi-Source Subsidence Data for 1D Subsidence Modeling



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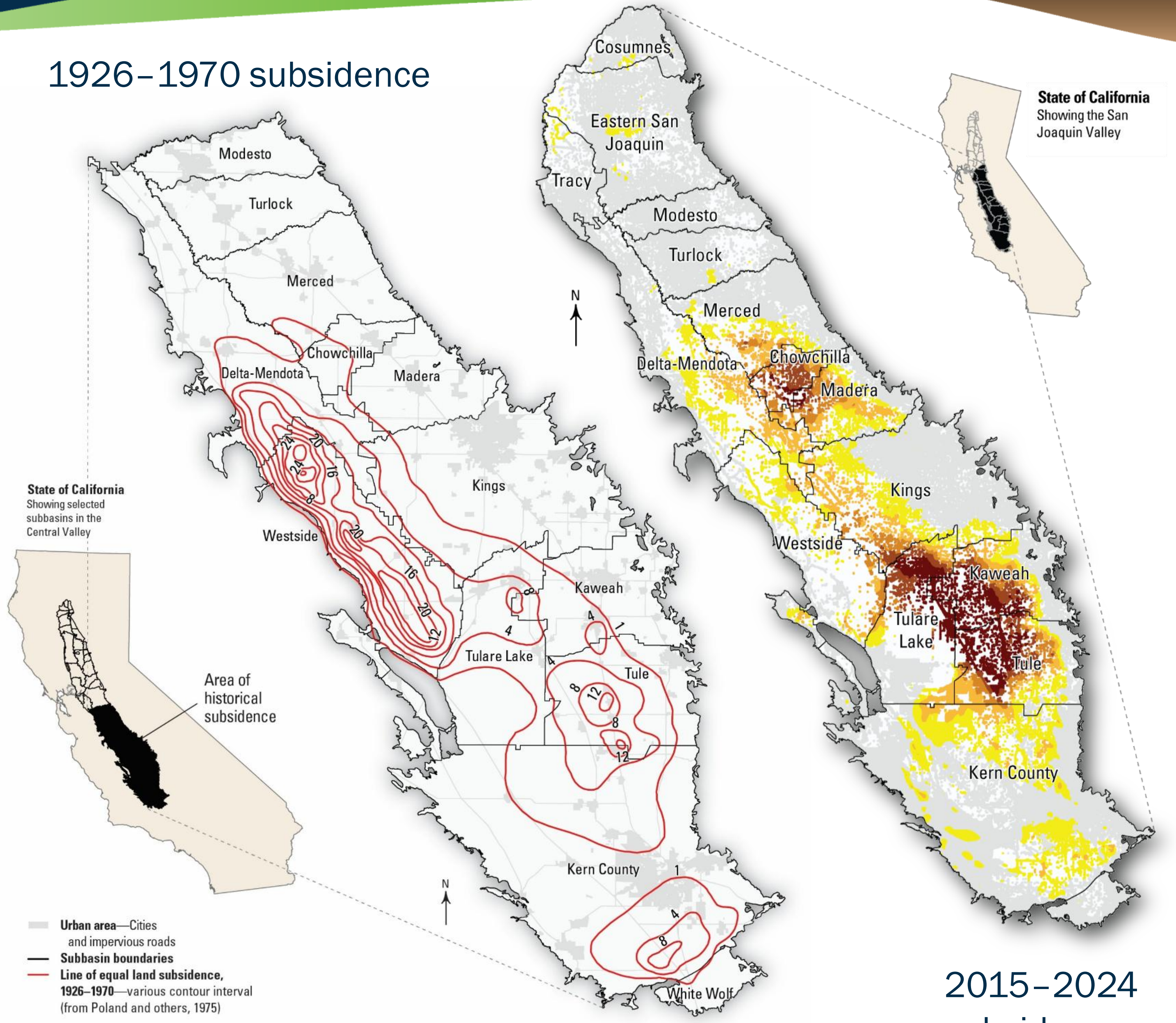
with collaborators John Ellis, Wesley Nealy, Spencer Jordan

The subsidence problem

California's San Joaquin Valley

- Land subsidence, driven predominantly by groundwater extraction, presents complex challenges for many areas of California.
- Largest alteration of land surface elevation in the U.S.
- 28+ feet of subsidence from 1926–1970 in some locations
- 7.0+ feet of subsidence since 2015 in some locations

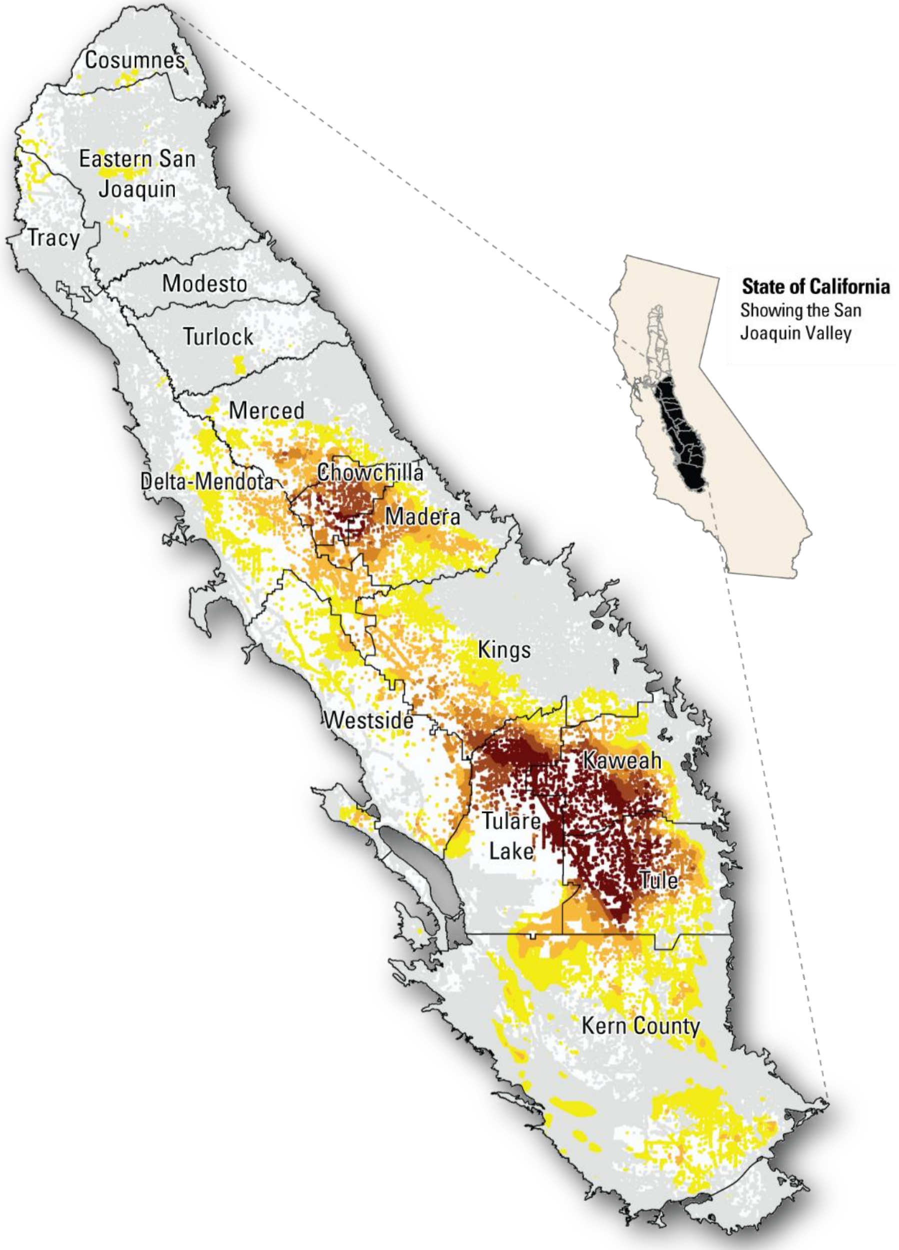
1926–1970 subsidence



2015–2024 subsidence

SGMA and subsidence

- Sustainable Groundwater Management Act's legislative intent (CWC § 10720 [e]) to "avoid and minimize subsidence"
- How do we accomplish this?
- What tools do we use?

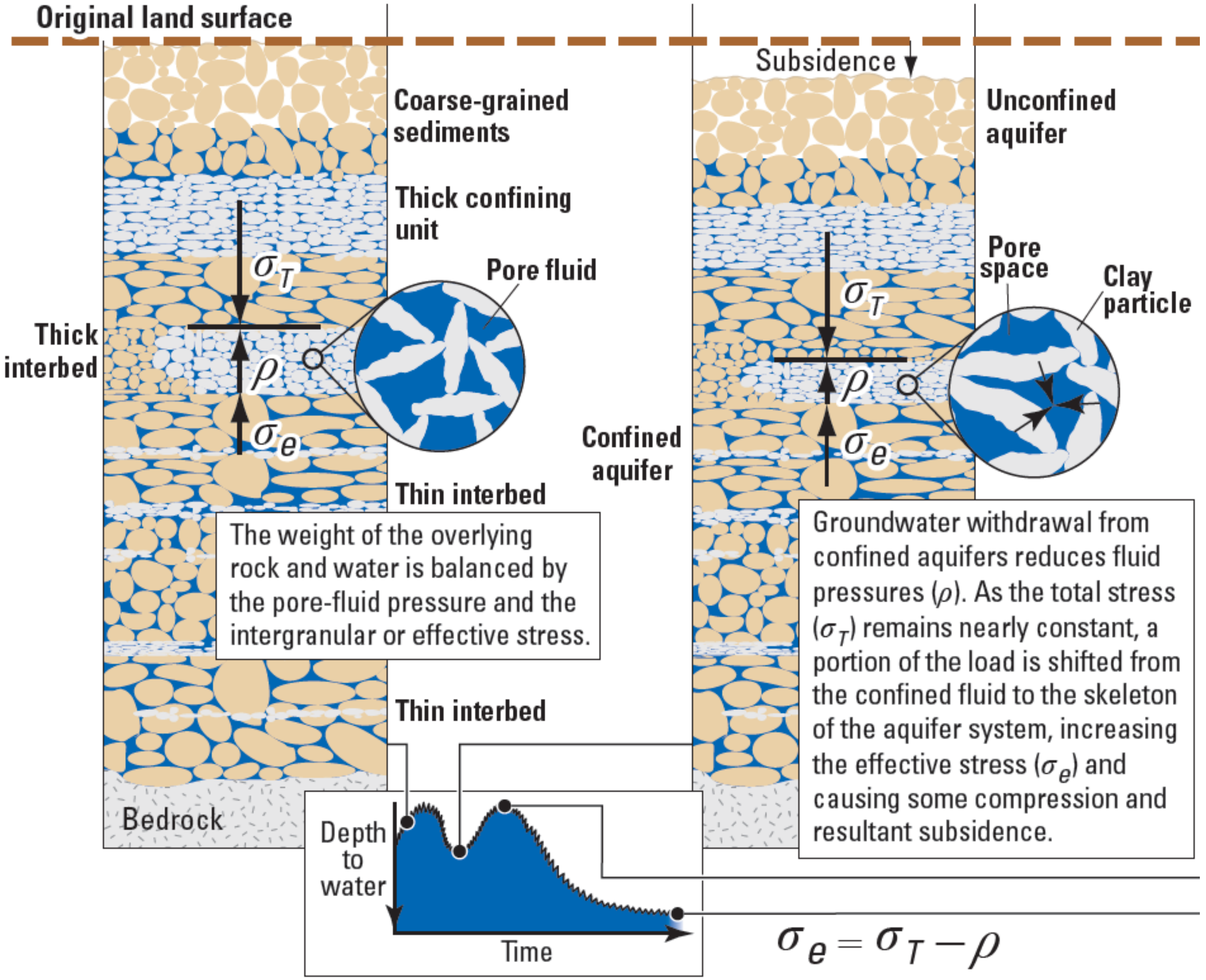


Subsidence Background

- Subsidence due to groundwater pumping is based on the principle of effective stress:
  - Stress from the overlying rock and water (overburden) is balanced by the pore-fluid pressure (hydrostatic stress) and intergranular stress on the aquifer skeleton (effective stress)
- As the groundwater level (head) is lowered, the overburden stress is increasingly transferred to the aquifer system skeleton, leading to an increase in effective stress that compresses the skeleton.

$$\sigma_e = \sigma_T - \rho$$

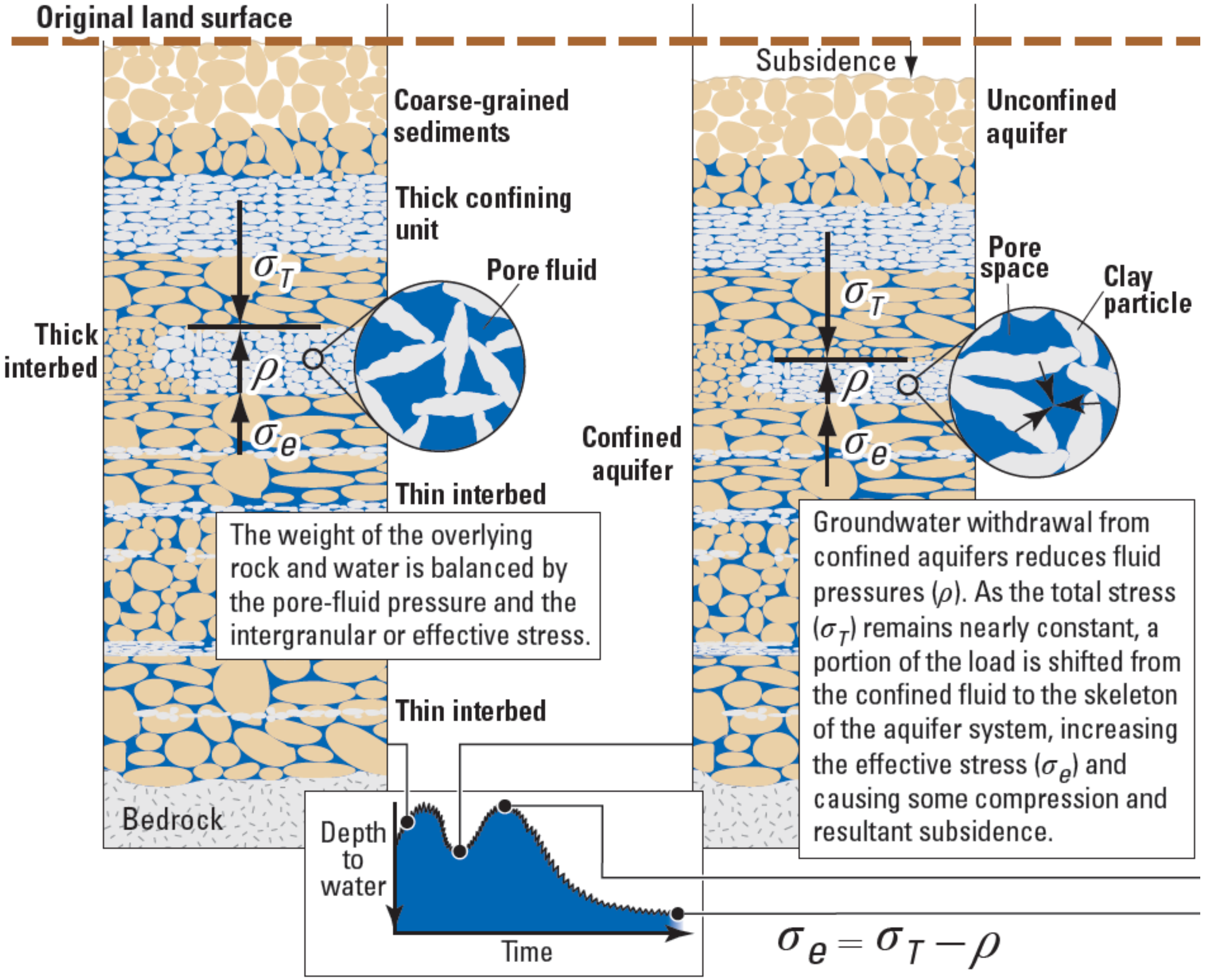
Effective stress — Overburden — Hydrostatic stress (equiv. water level)



From Ellis and others (2023)

Subsidence Background

- Conversely, as the groundwater level is raised, the effective stress is reduced, and the aquifer system skeleton expands
- Subsidence continues until the groundwater levels in the aquifer and the clay beds equilibrate.
- A rapid and prolonged recovery in aquifer groundwater levels reduces the time for equilibration
- Thin clay beds equilibrate faster; thicker beds can take many years to equilibrate with the aquifer groundwater levels

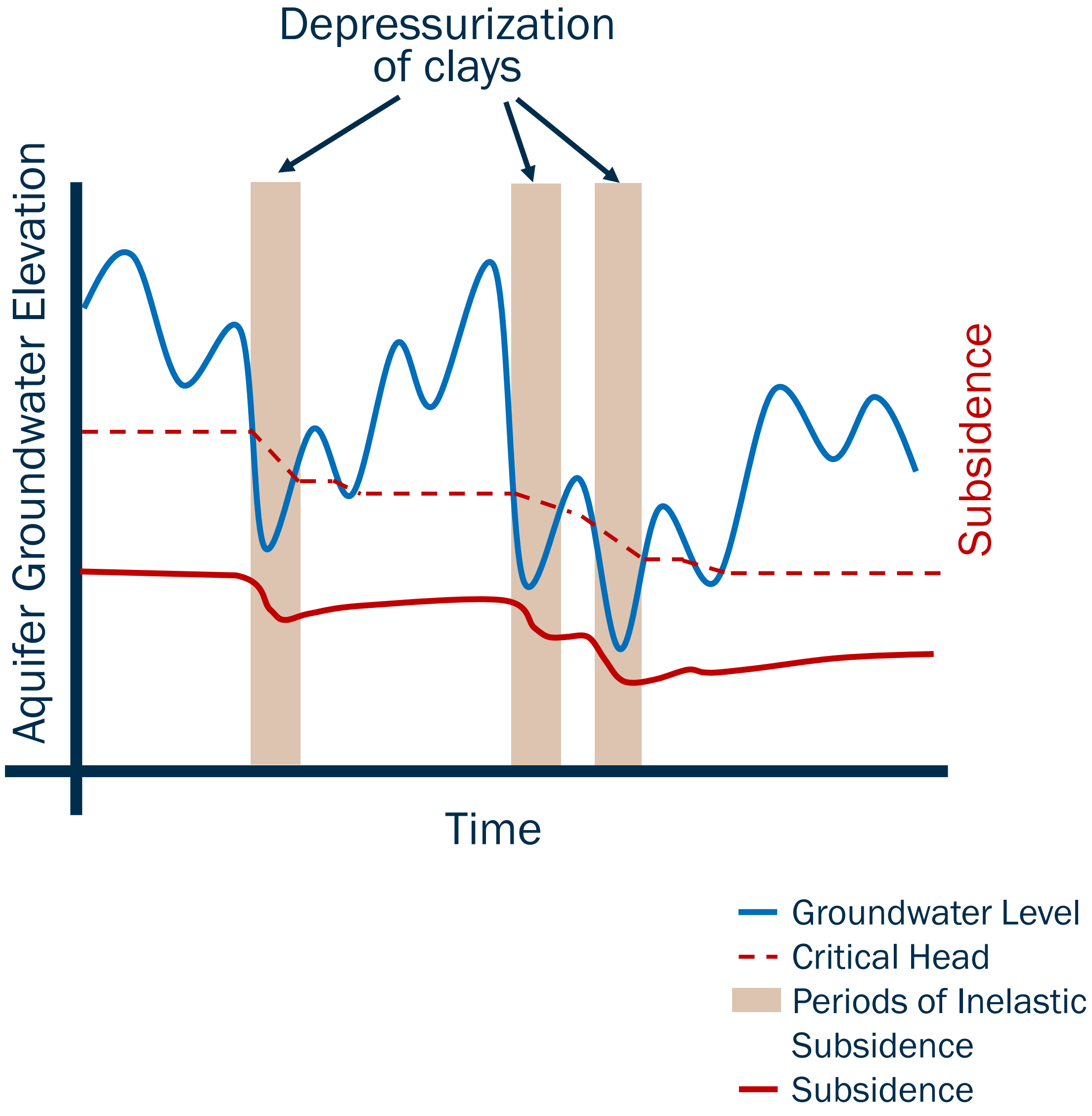


$$\sigma_e = \sigma_T - \rho$$

From Ellis and others (2023)

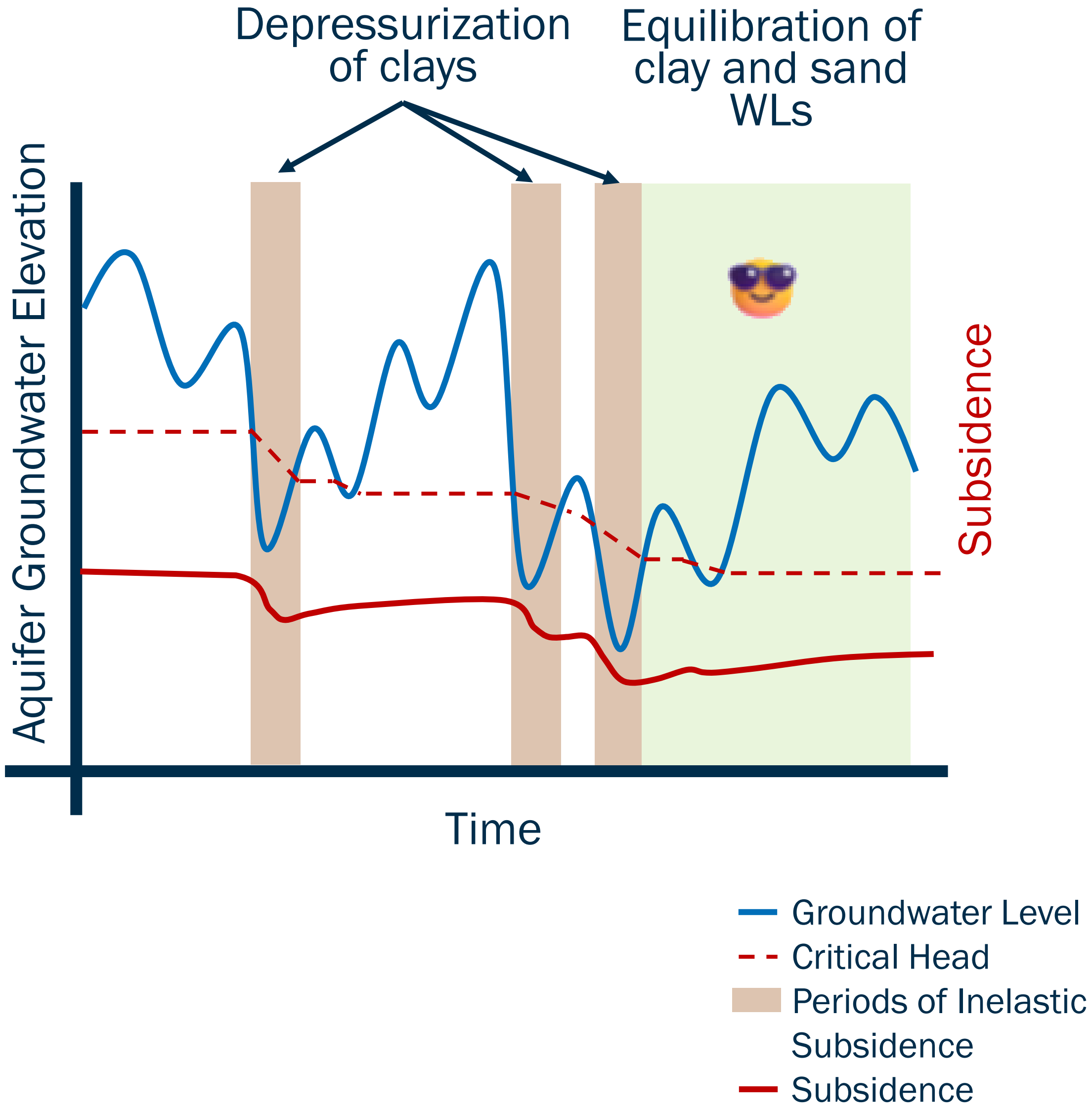
Subsidence and Critical Head

- The clay beds in an aquifer system retain the memory of past groundwater level declines
  - This is the "Preconsolidation Stress," the greatest maximum effective stress imposed
  - This stress expressed as a water level is the "Preconsolidation Head"
- When aquifer groundwater levels decline, they can result in an increase in the effective stress of the clay beds. This stress, expressed as a water level, is called the "Critical Head".
- The Critical Head changes in response to aquifer groundwater level declines (magnitude and duration).



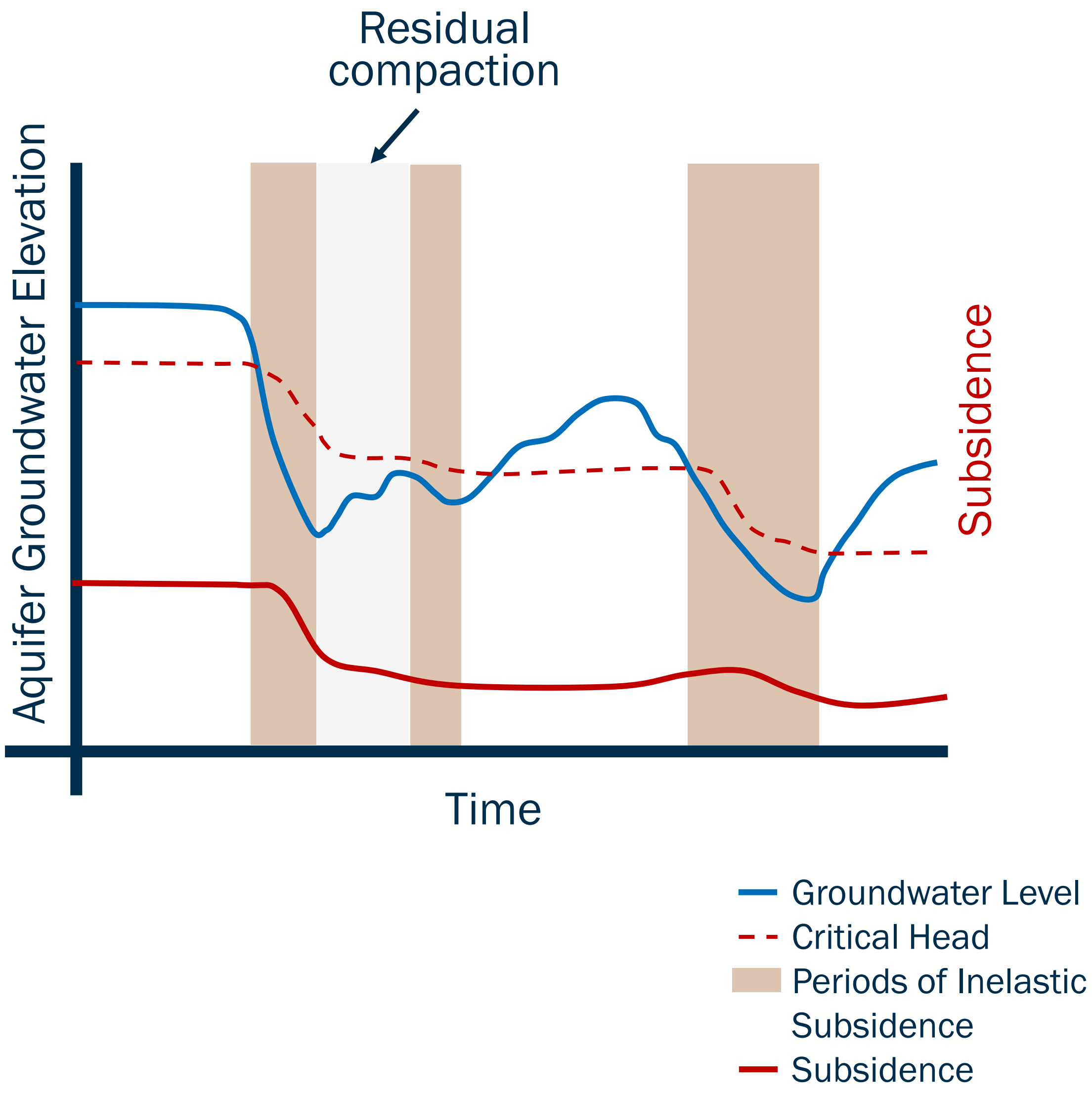
Critical Head

- The historical low in the aquifer is not the same as the Critical Head. The Critical Head is in the clay beds, not the aquifer.
- The relationship between the aquifer groundwater level and the critical head determines the type of subsidence (elastic vs inelastic).
- A rapid and prolonged recovery in aquifer groundwater levels provides the best possibility at reducing subsidence.



Residual Subsidence

- Residual subsidence: continued subsidence after the cessation of aquifer groundwater level declines but before the groundwater level in the clay and aquifer equilibrate.
- Want to raise groundwater levels as rapidly and high as long as possible to reduce residual subsidence.
- Once equilibration occurs, subsidence ceases



Residual Subsidence

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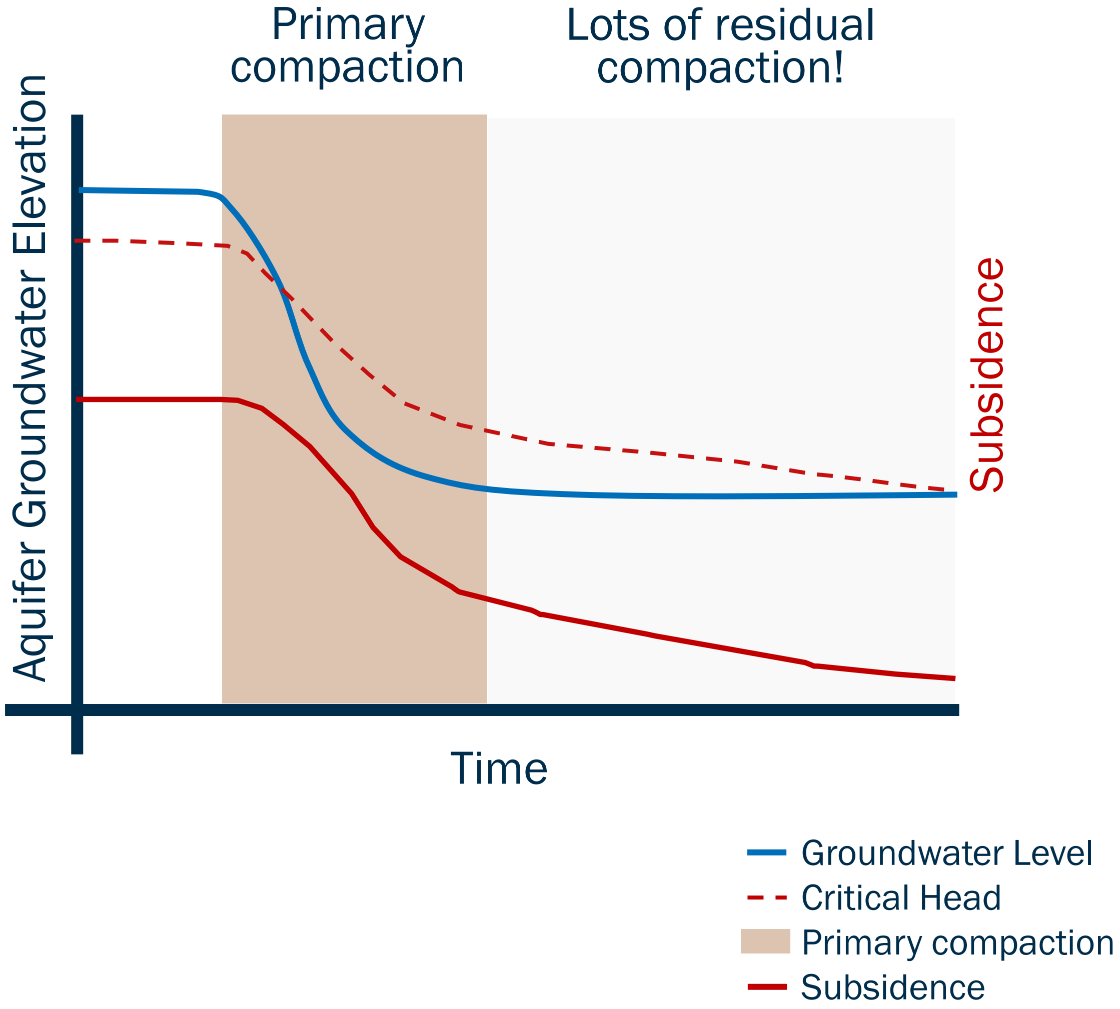
- Over a long enough time, if the aquifer water level is held at the same level, the water level (pressure) in the clay will decline to the water level (pressure) in the aquifer
  - This results in more subsidence than raising the aquifer groundwater level to (or preferably above) the level of the critical head
  - Once equilibration occurs, subsidence ceases



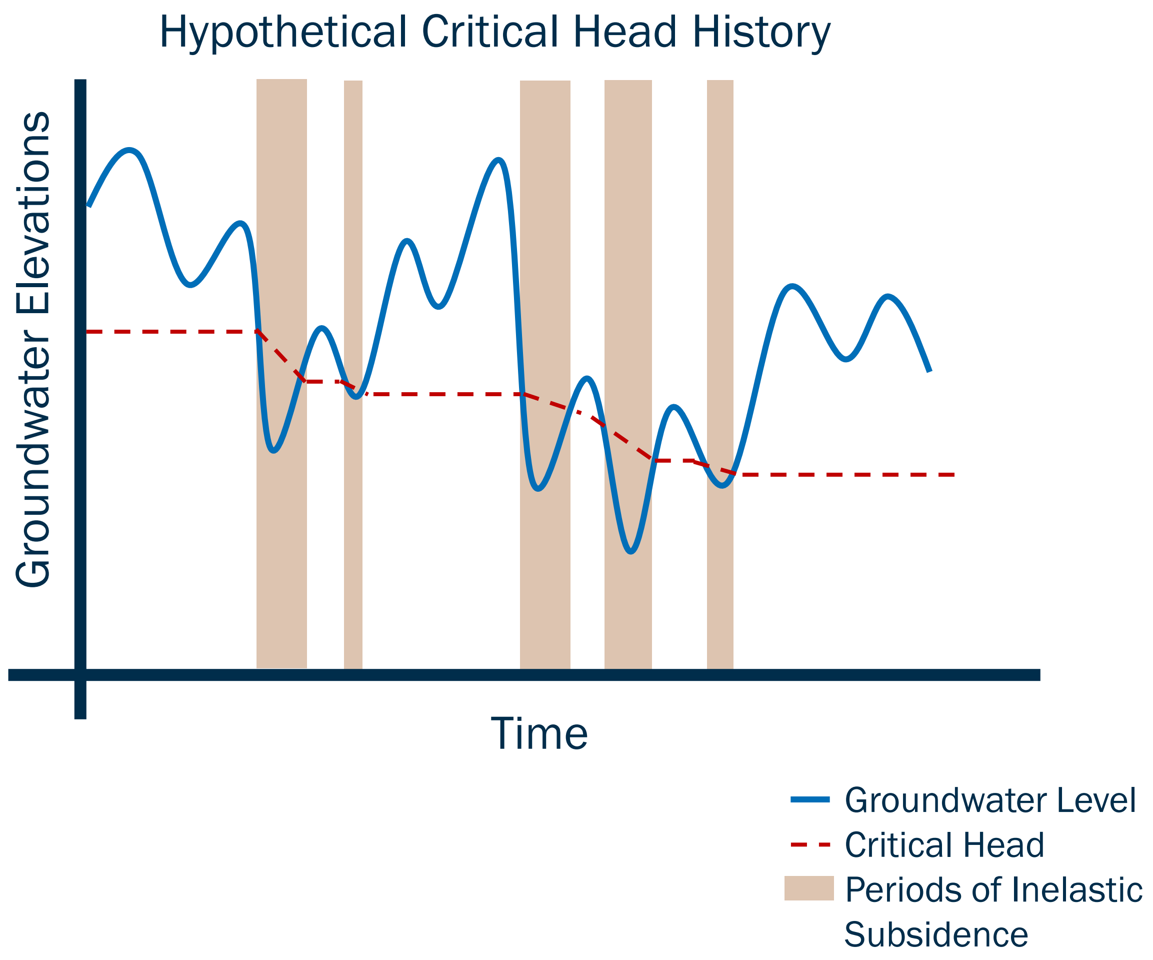
Critical Head Estimation

Empirical

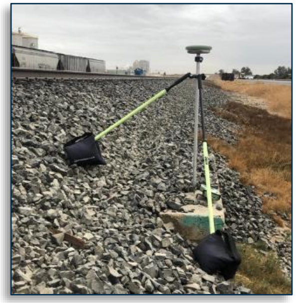
- Can estimate using shorter periods of data
- Compare groundwater levels to periods of time with no subsidence or uplift

Modeling

- Prefer a relatively **long history of groundwater and subsidence data,** although can use shorter period of data
- Use MODFLOW subsidence packages to track critical head (center of delay beds)



Data Approaches

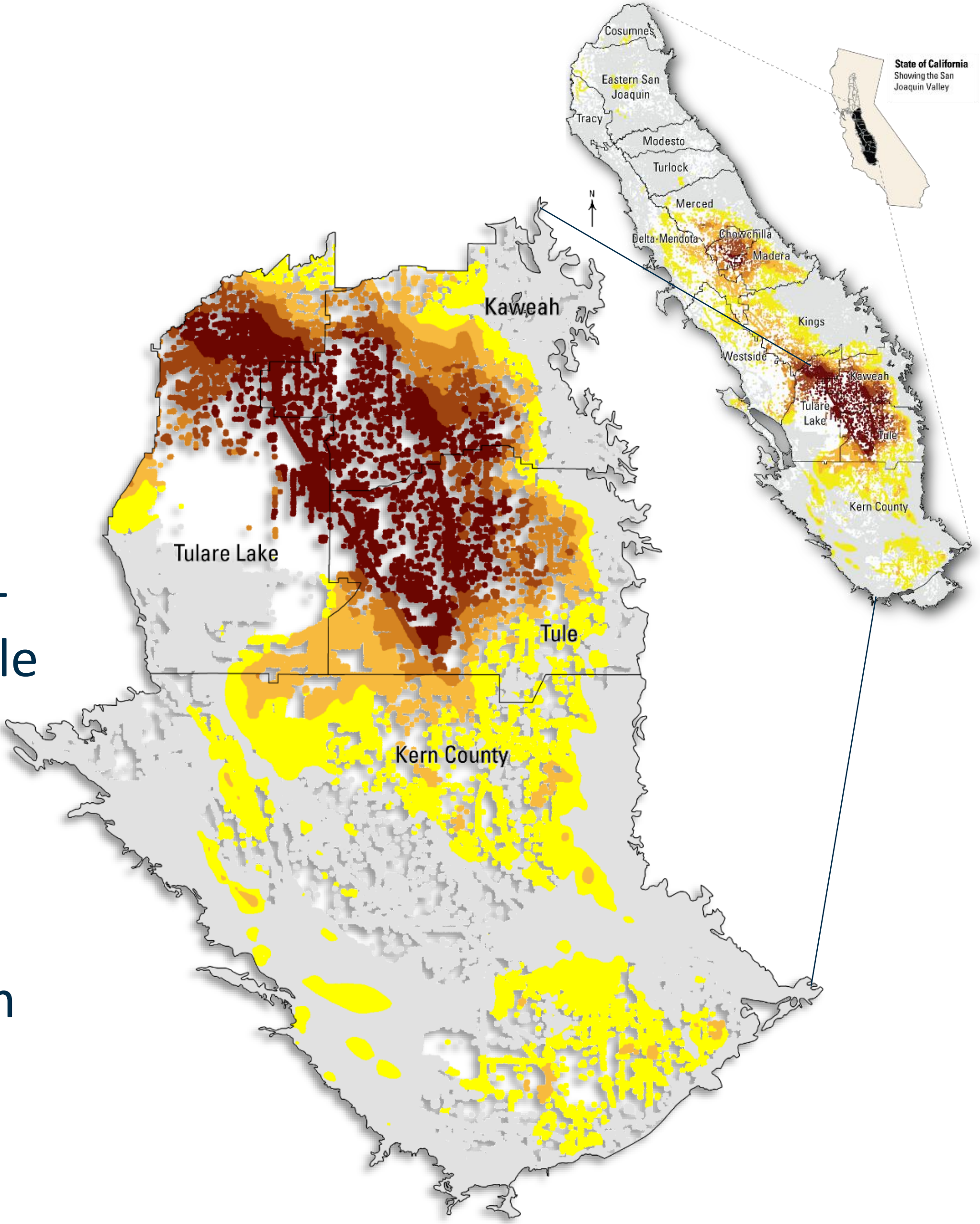


Long-term Data

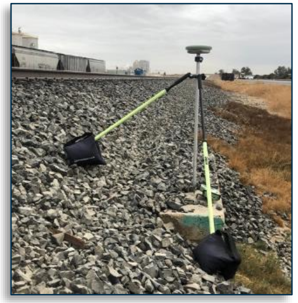
- Leveling Data
- InSAR, GPS, Extensometer Data
- Water level data

Data Analysis

- Process water levels from wells within a ~3-mile radius of long-term sites across multiple depth intervals
- Combine leveling, GPS, InSAR tied to water level data into a long-term time series
- Characterize interbeds: Average clay % from nearby DWR well completion reports



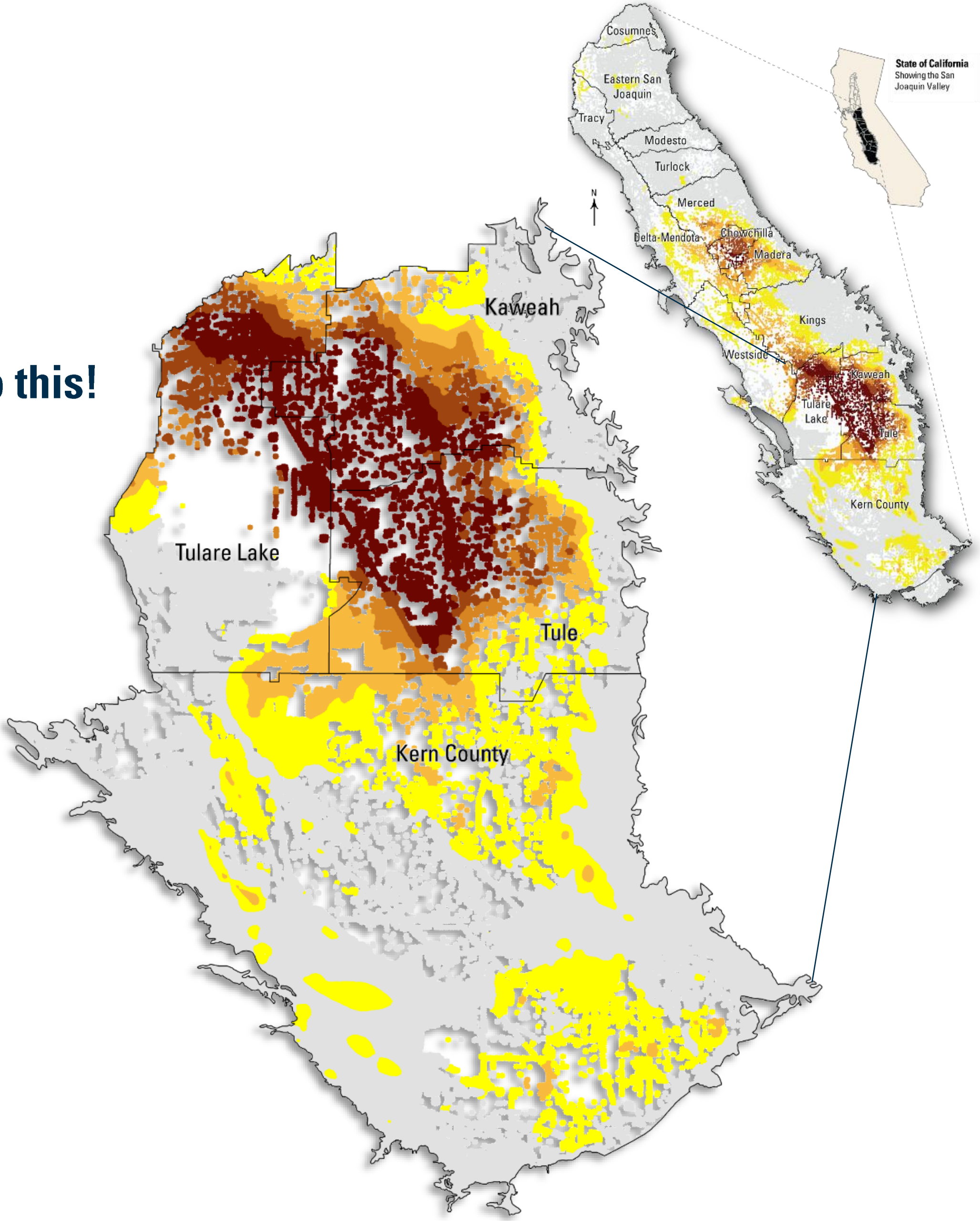
Long-Term Data



Why needed?

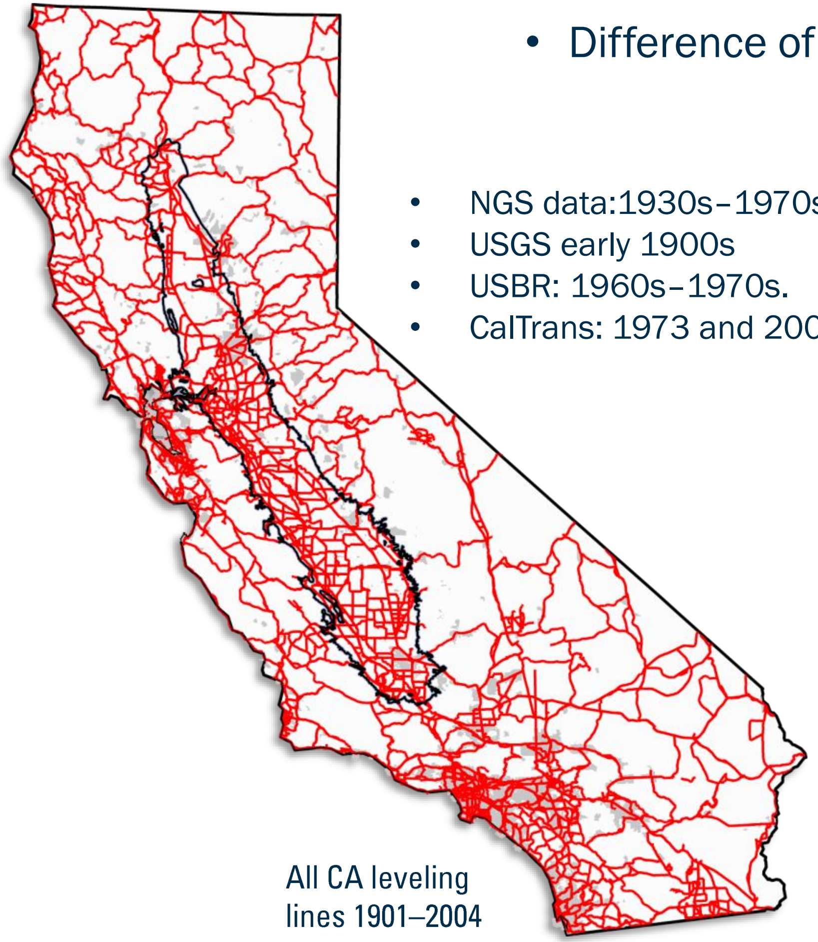
- Provide context for the 2015–present subsidence rates
- Better estimate **clay critical head** for empirical and modeling work
- Provide an estimate of residual compaction from previous periods
- Better constrain model parameters during calibration.
  Better data = better predictions

Manage to this!



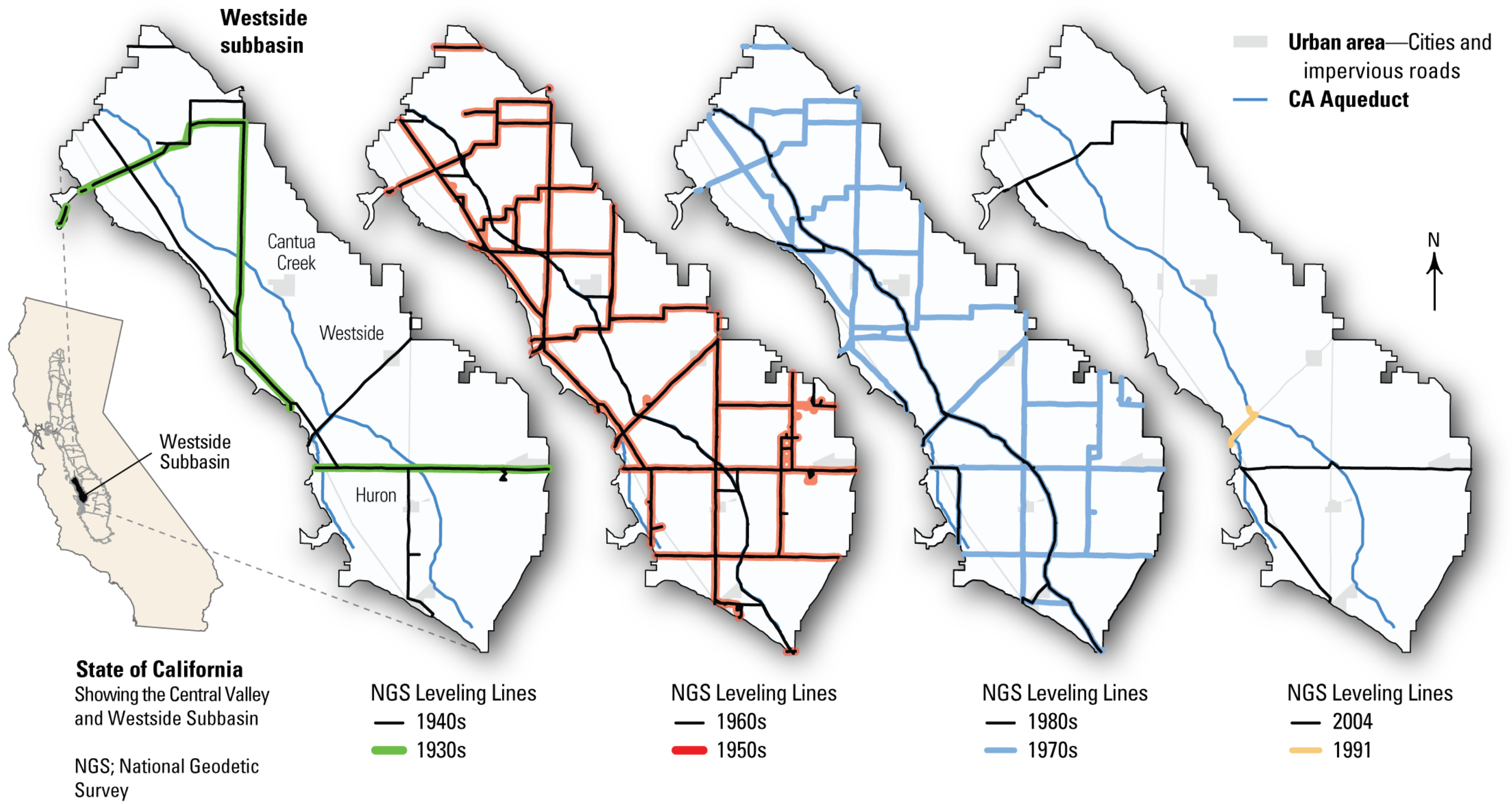
Leveling Data

- Forms the basis for the long-term subsidence record in California and other subsiding areas. Primarily available from the National Geodetic Survey (NGS).
- Carry elevation from a known reference point to other points using telescope and leveling rod.
- Difference of elevations at the same benchmark through time = subsidence record



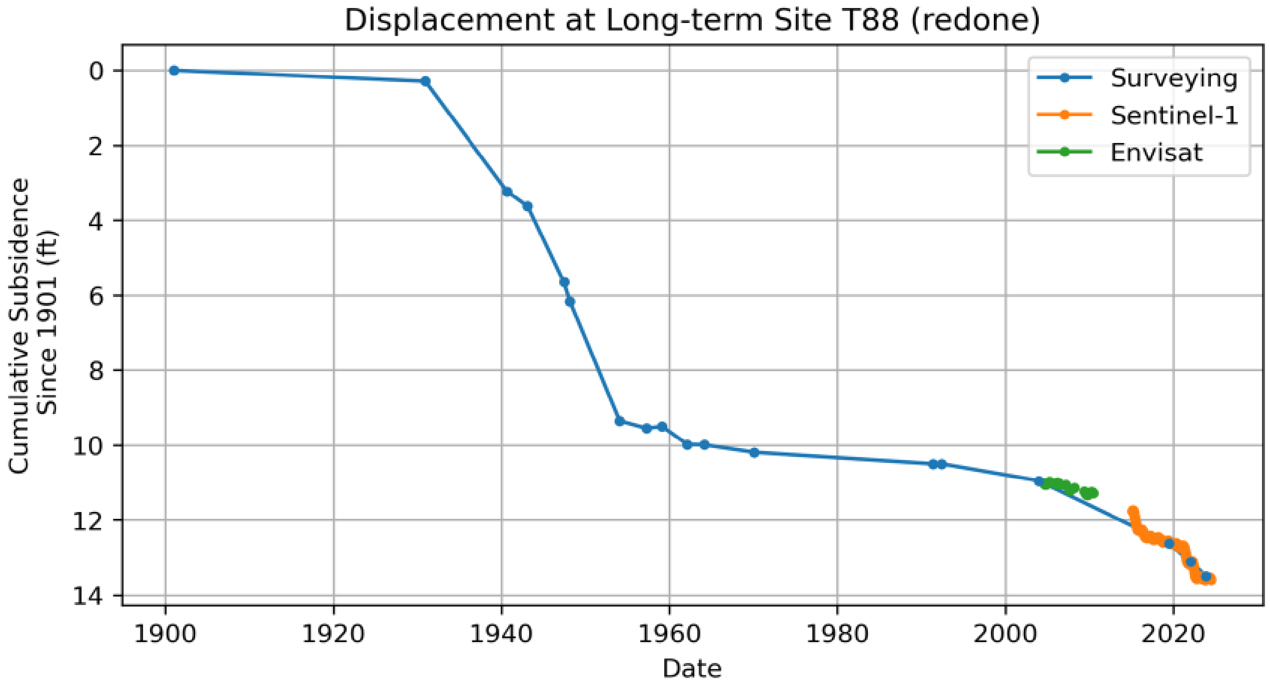
All CA leveling lines 1901–2004

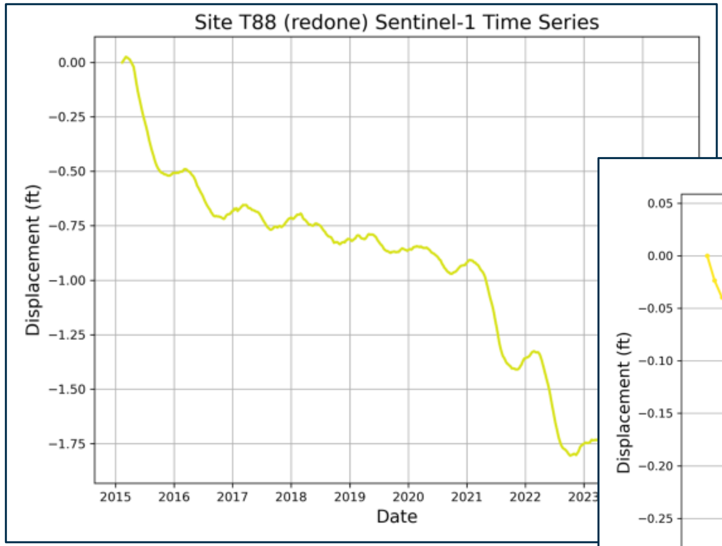
- NGS data:1930s–1970s
- USGS early 1900s
- USBR: 1960s–1970s.
- CalTrans: 1973 and 2004.

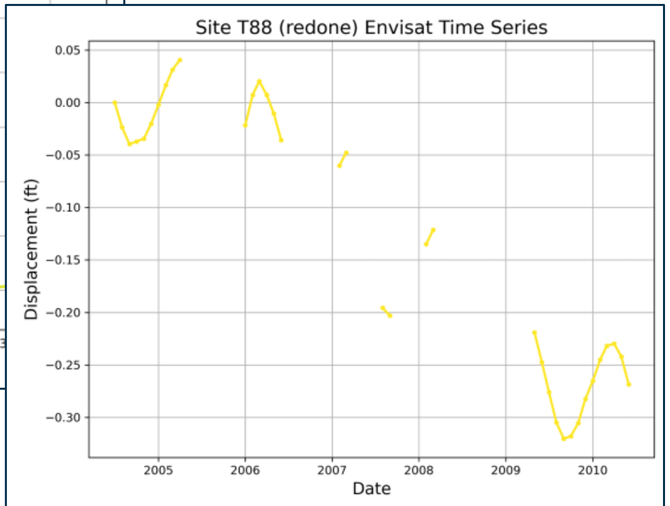


InSAR and GPS Data

- InSAR data from Sentinel-1 (2015-2024) and Envisat (2002-2012) are registered to cumulative subsidence at known leveling measurement. (TRE Altamira InSAR Subsidence data provided by DWR)
- Fill data gaps by estimating displacement rates or interpolating between known points. Back-project or forward-project displacement to ensure continuity across data gaps.
- Shift InSAR timeseries to align with interpolated or measured leveling values.
- Similar approach used to process GPS.

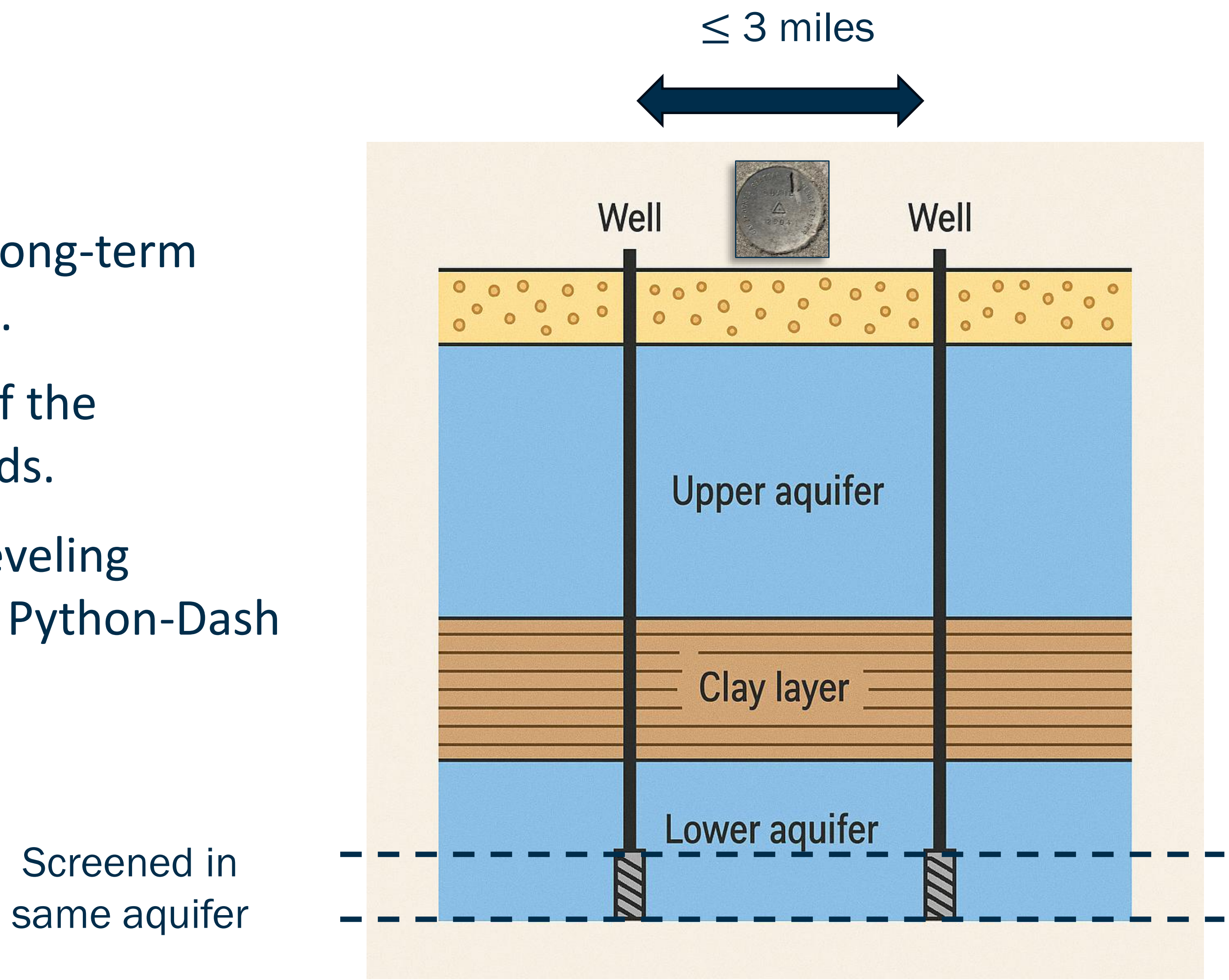






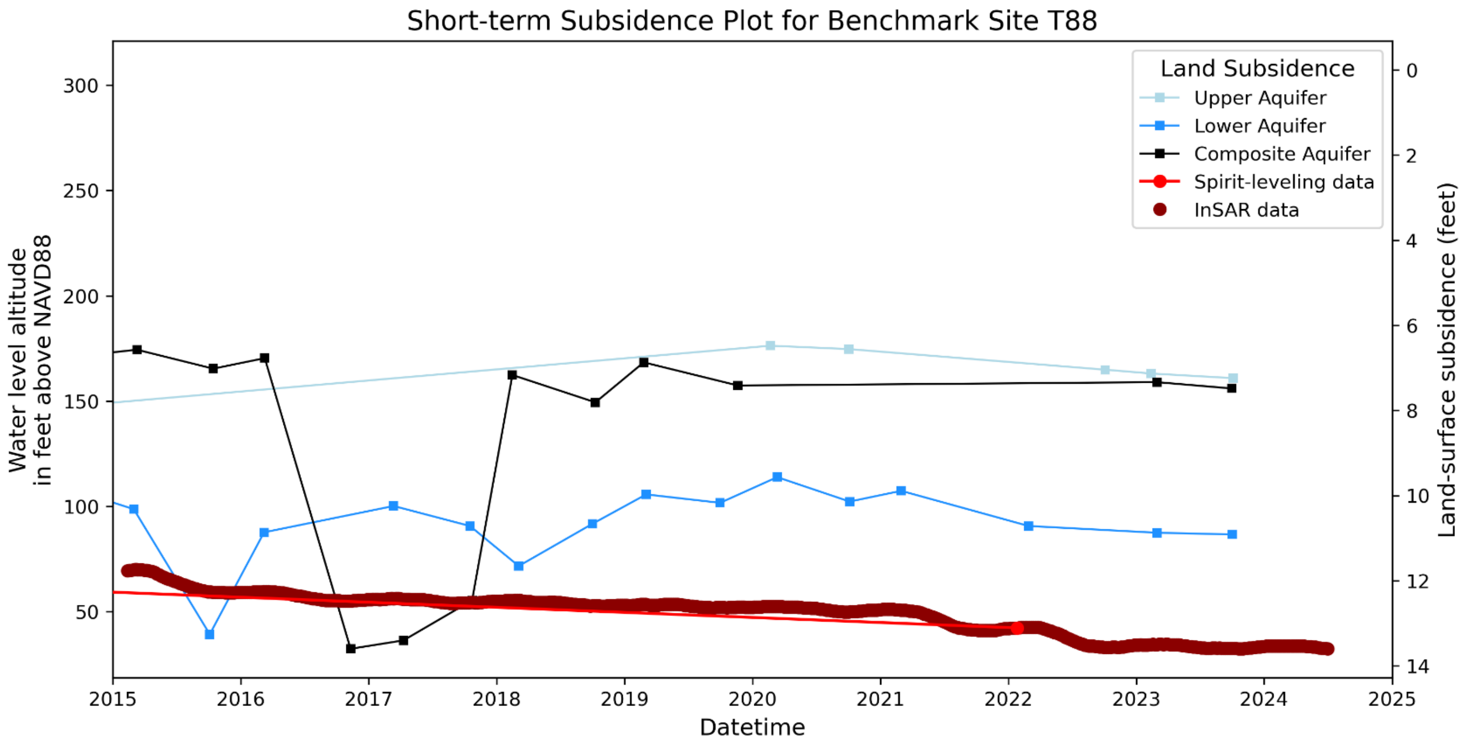
Water-Level Data

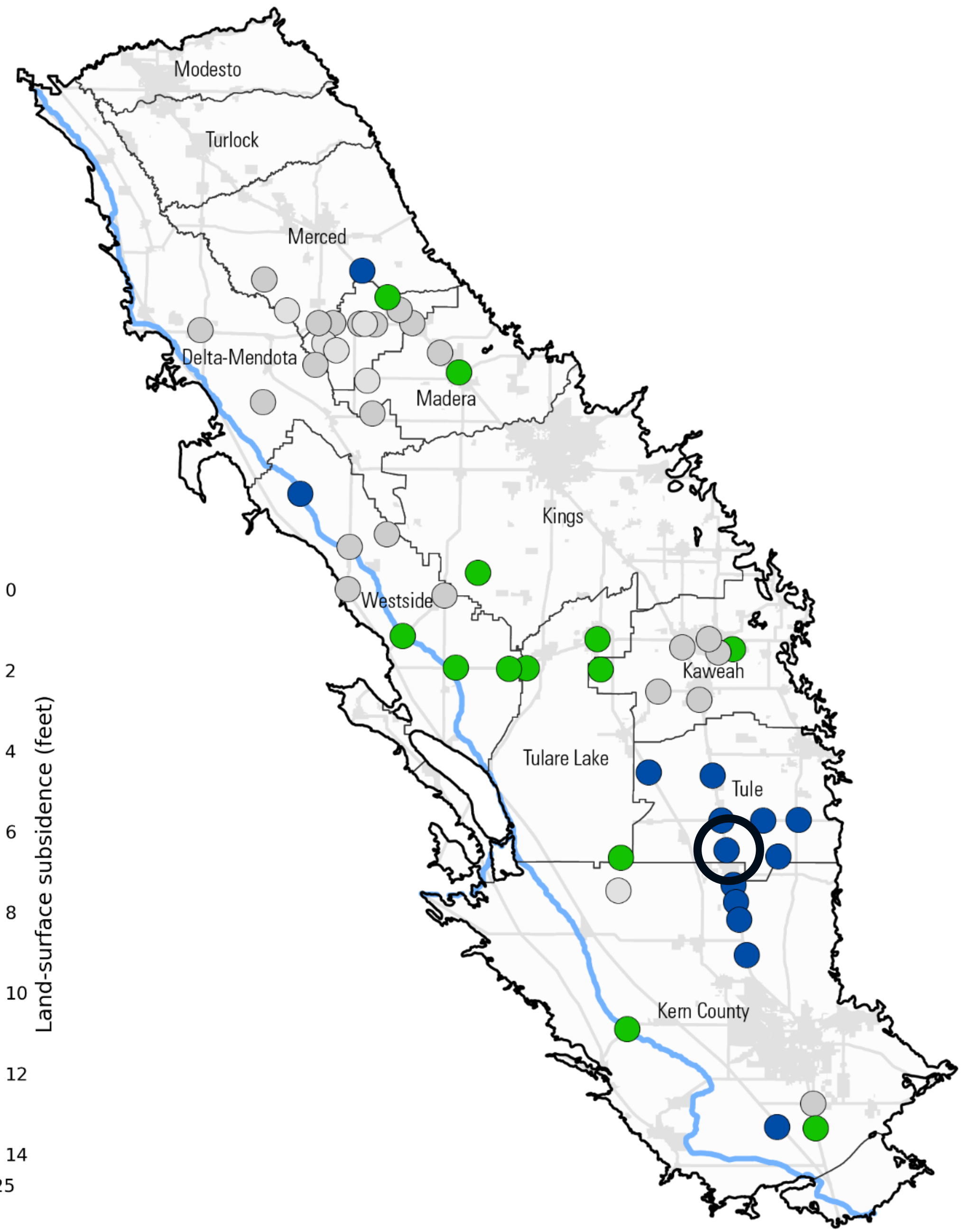
- Water level data were selected to create long-term timeseries across different aquifer depths.
- Each series of wells were within 3-miles of the benchmark sites, similar depths, and trends.
- Well completion data, water levels, and leveling surveys were compiled into database and Python-Dash framework.
- Dash



Subsidence Record (2015-2024)

- **Short-term subsidence record** may not fully capture subsidence processes:
  - What do the longer-term subsidence trends look like?
  - Are pre-2015 water level changes affecting 2015+ subsidence?

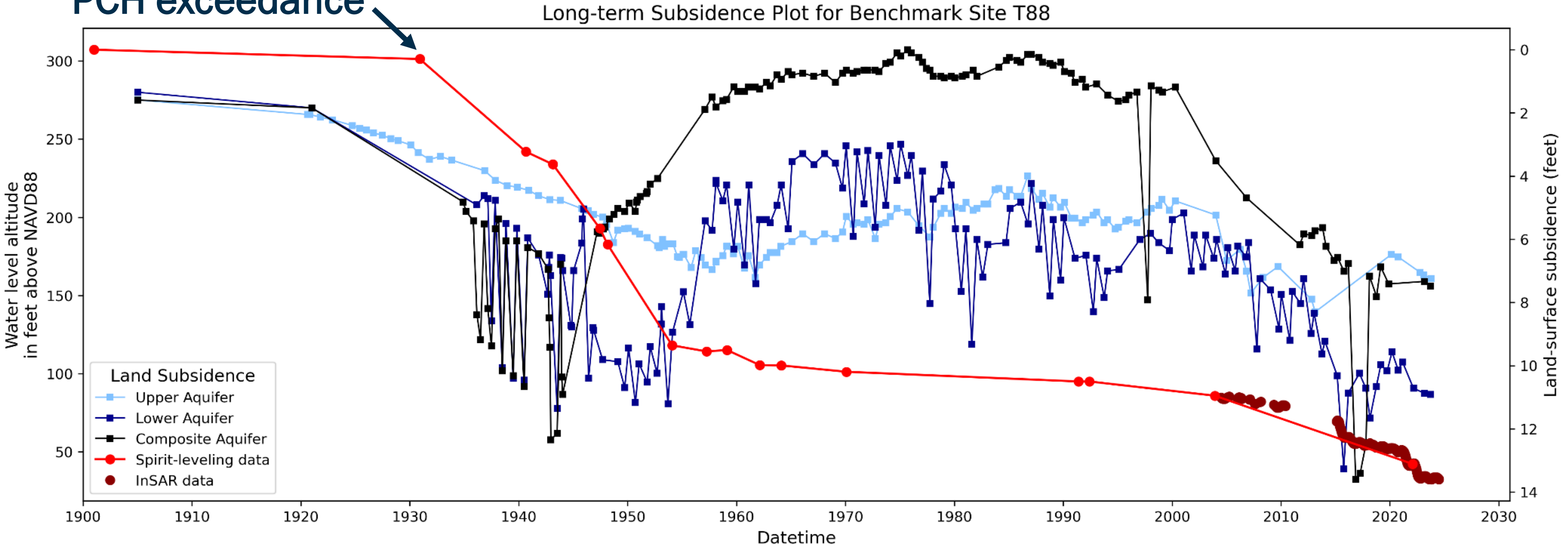


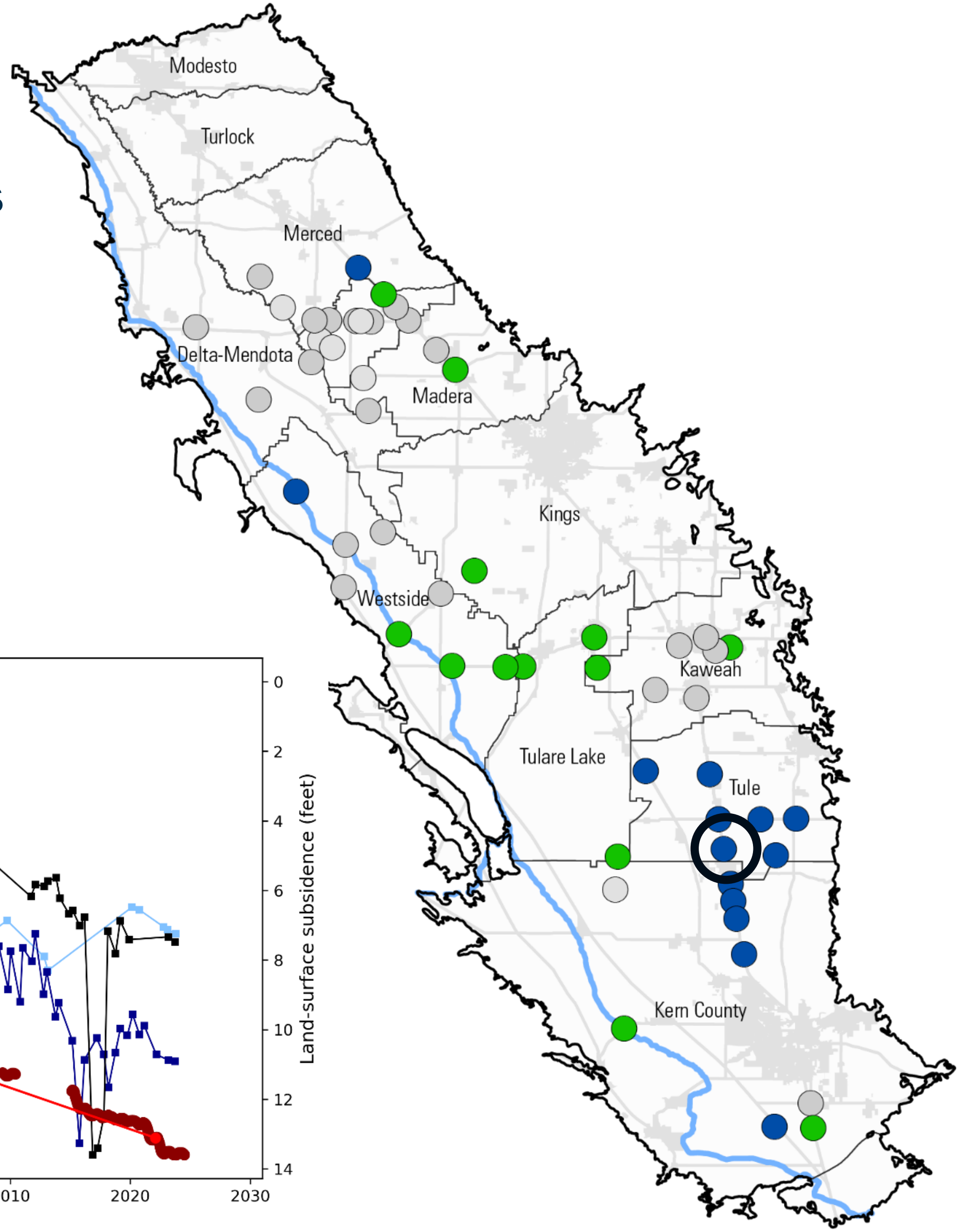


Subsidence Record (1901-2024)

- A **long-term subsidence record** informs development of SMCs for managing subsidence including:
  - Better estimation of clay critical head
  - Estimate residual compaction
  - Understand the relationship with groundwater levels SMCs

PCH exceedance





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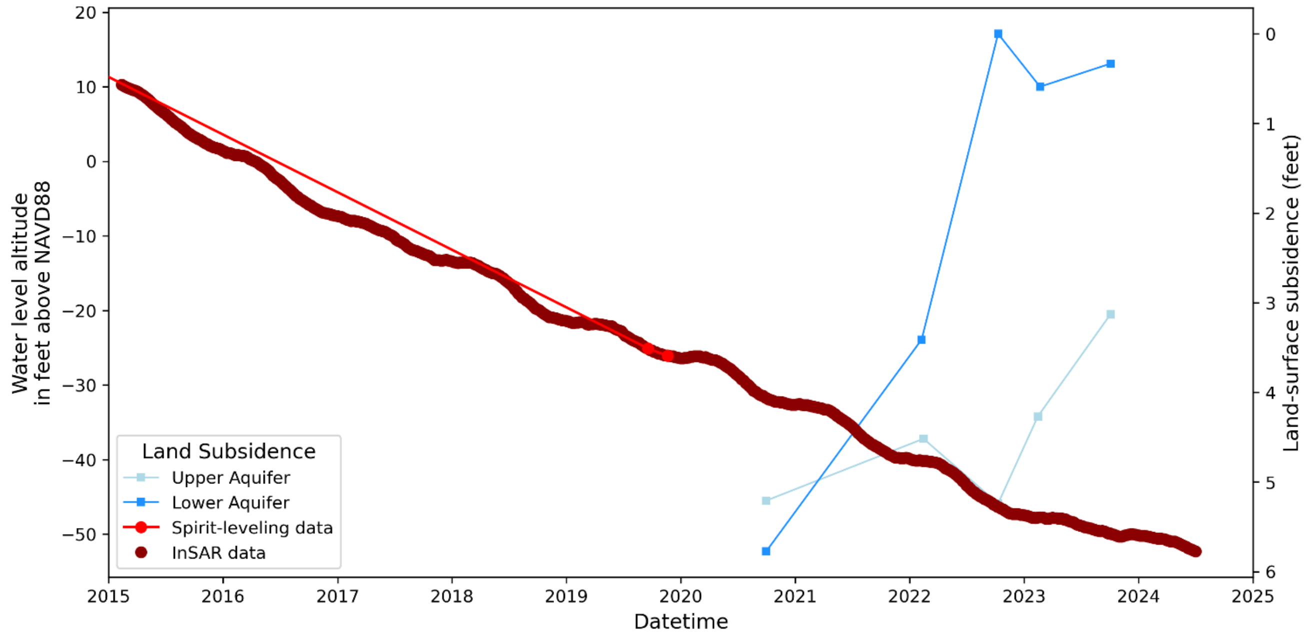

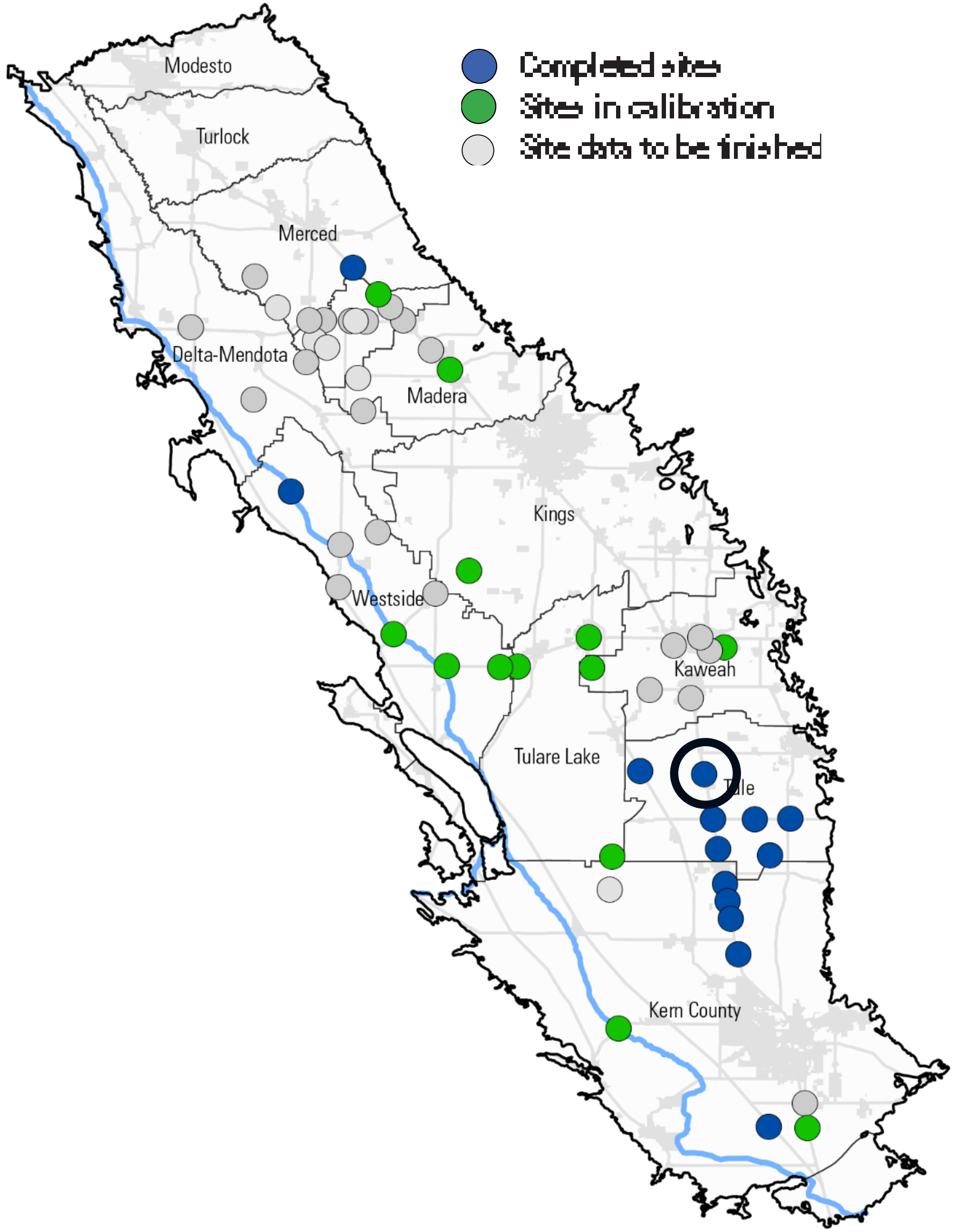

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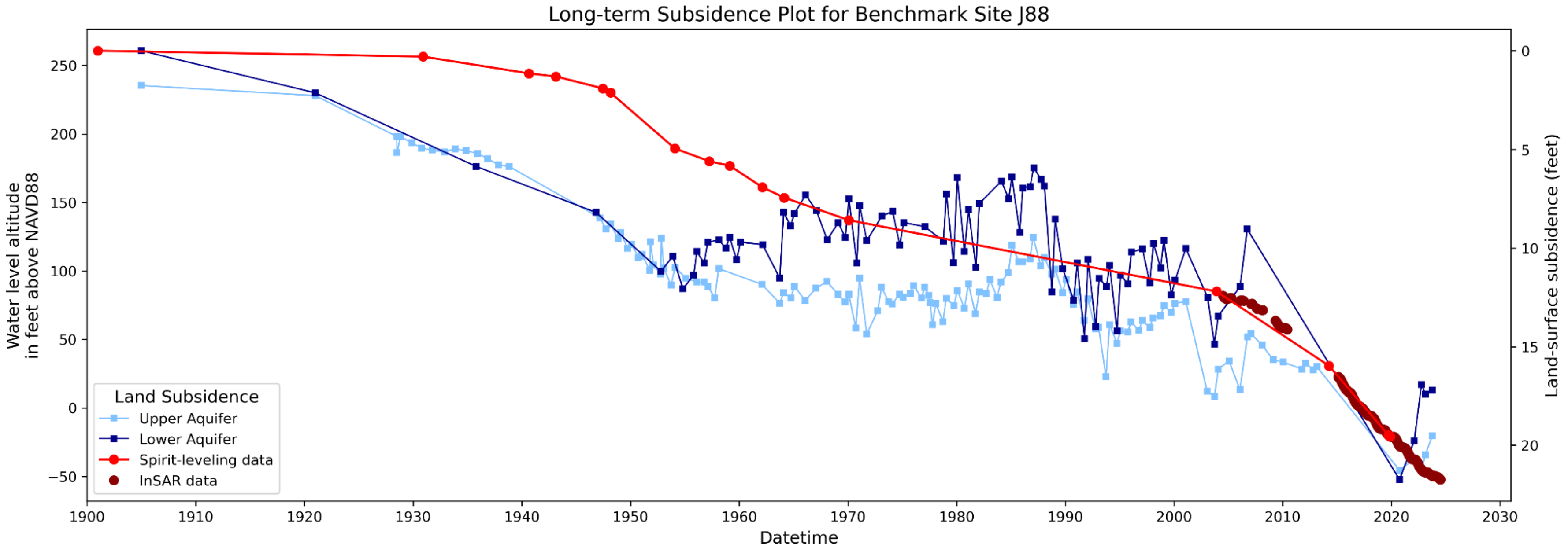

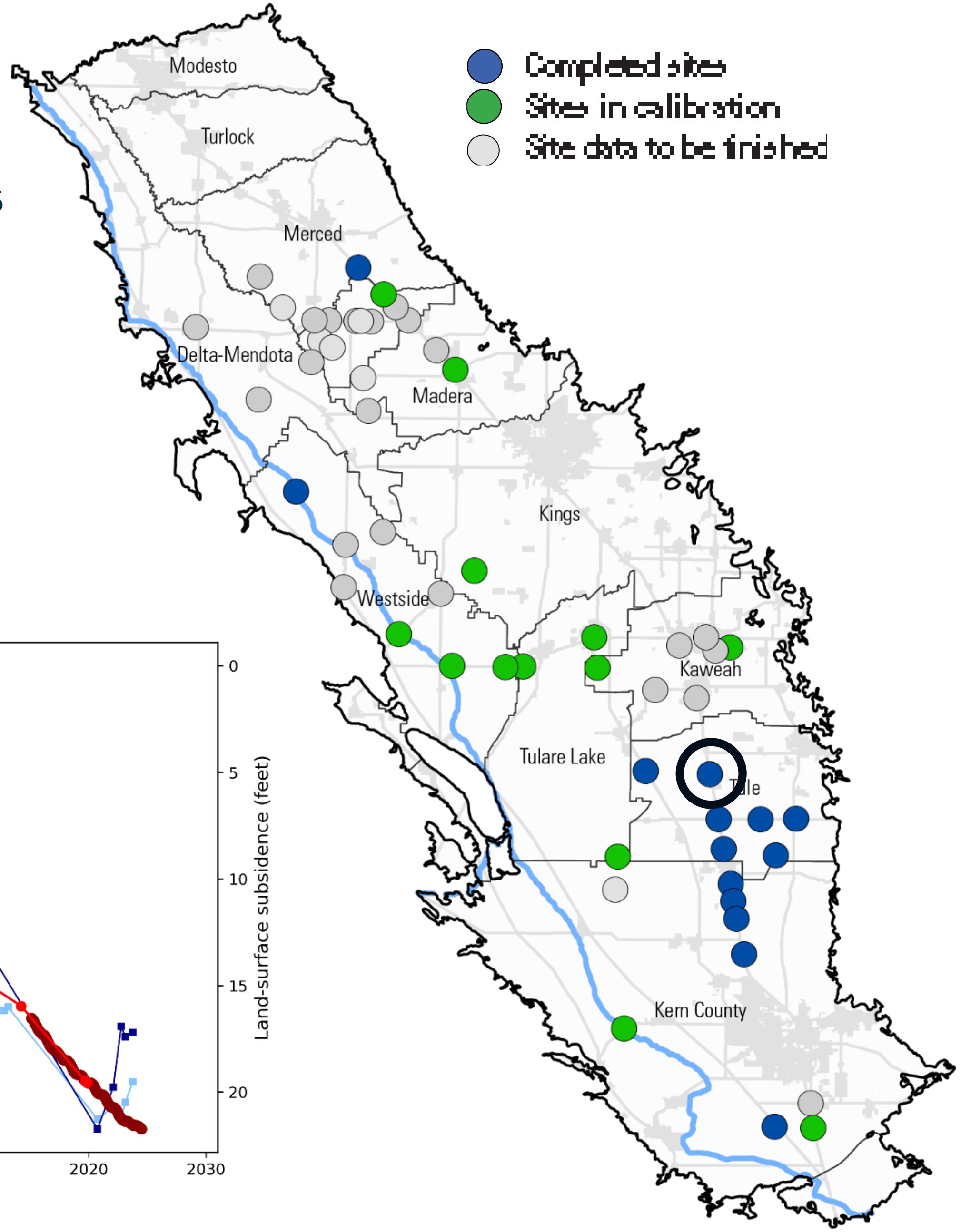

Thank You!

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