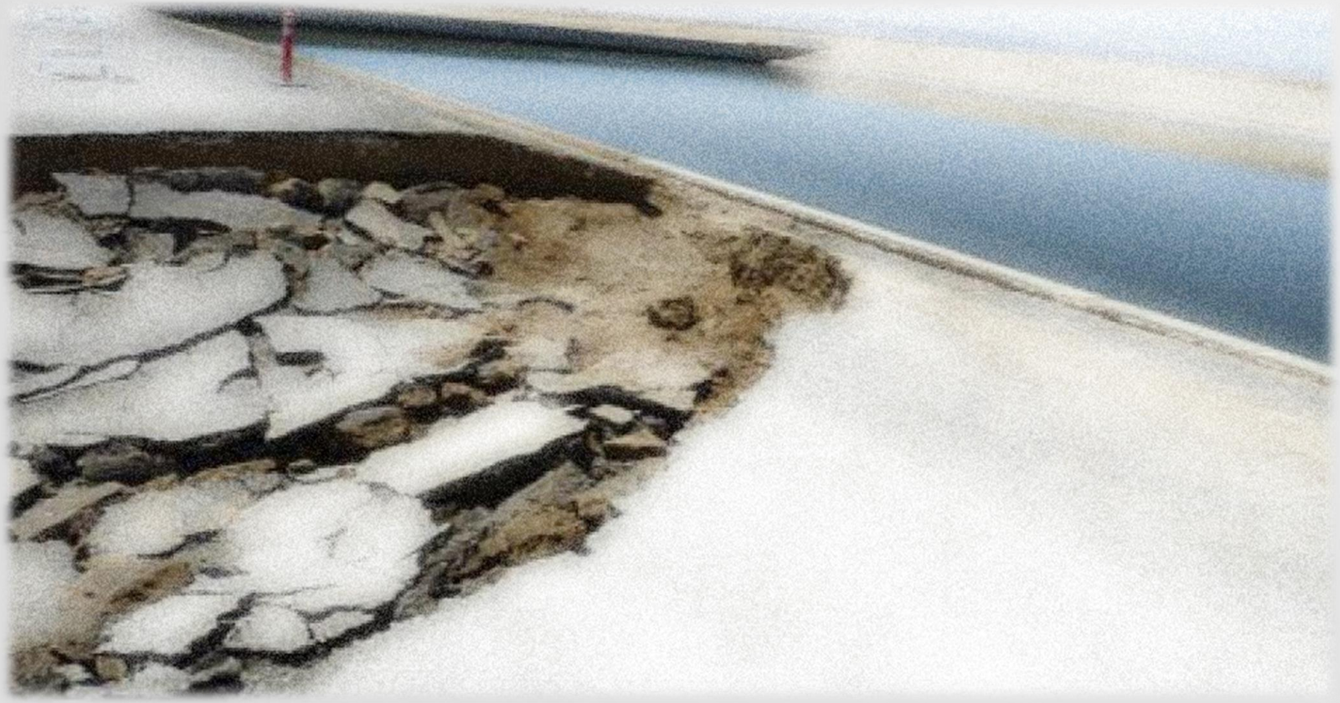
CALIFORNIA DEPARTMENT OF WATER RESOURCES

Modeling of Land Subsidence in C2VSimFG

Wednesday, April 19, 2023



Sustainable Groundwater Management Office

Overview

- Key terms and definitions
- Introduction
- Land Subsidence in IWFM
  - Land subsidence from the vertical compaction of aquifer interbeds
  - Effect of vertical compaction of aquifer interbeds effect on groundwater flow
- Land Subsidence in C2VSimFG
  - Subsidence Parameters
  - Model Calibration

Key Terms and Definitions

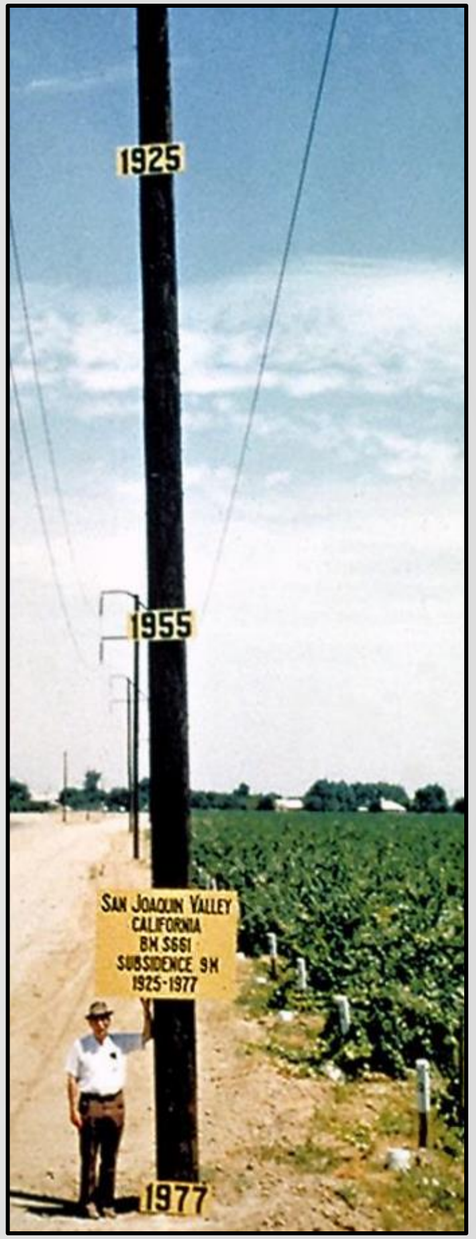
- **Aquifer interbeds** - lenses of low permeability within a relatively permeable aquifer
- **C2VSimFG** - Fine Grid Version of the California Central Valley Groundwater and Surface Water Simulation Model using the IWFM modeling platform
- **Central Valley** - California's Sacramento Valley and San Joaquin Valley
- **Elastic deformation** – temporary change in length, volume, and/or shape of material from a stress that is less than the elastic limit of the material
- **Inelastic deformation** – permanent change in length, volume, and/or shape of material from a stress that is greater than the elastic limit of the material
- **IWFM** – Integrated Water Flow Model; DWR's computer program for modeling groundwater and surface water related processes
- **Land subsidence** - gradual or sudden vertical displacement of ground surface due to deformation and/or removal of underlying stratum

Introduction

- Land subsidence has been a longtime occurrence within the Central Valley:
  - Largely attributed to the effects of groundwater pumping:
    - Pumping lowers groundwater head and removes pore water from soil matrices
    - Hydrostatic pressures dissipate, stresses transfer to soil matrix solids, and effective stresses increase
    - Elastic and/or plastic deformations develop over varying degrees of time
    - Deformations are observed as vertical displacements of the land surface
  - Land subsidence has been linked to:
    - Damage to critical infrastructure and/or facilities
    - Temporary and/or permanent changes to groundwater storage

- Land subsidence is a critical feature of modeling physical groundwater processes

- C2VSimFG leverages IWFM's subsidence module to simulate elastic and inelastic land subsidence throughout the Central Valley



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Land Subsidence in IWFM

- The IWFM subsidence module accounts for changes in groundwater storage due to land subsidence from the vertical compaction of aquifer interbeds

- Aquifer interbeds are identified using the following criteria:
  - Hydraulic conductivity of the interbed is significantly lower than the hydraulic conductivity of the aquifer material
  - Lateral extent of the interbed must be sufficiently small that it is not considered a confining bed which separates adjacent aquifers
  - Small interbed thickness relative to its lateral extent

- IWFM's simulation of land subsidence from the vertical compaction of aquifer interbeds
  - IWFM expresses the vertical compaction of aquifer interbeds (Δb_{se}) as:

$$\Delta b_s = \frac{\Delta p' S_s b_o}{\gamma_w} = -\Delta h S_s b_o$$

Where:
- $\Delta p'$ is the change in effective stress, defined as $\Delta p' = -\gamma_w \Delta h$ while geostatic pressure is assumed constant
- S_s is the elastic (S_{se}) or inelastic (S_{si}) specific storage
- b_o is the initial aquifer interbed thickness
- γ_w is the unit weight of water

Land Subsidence in IWFM (continued)

- IWFM's simulation of the effect of the vertical compaction of aquifer interbeds on groundwater flow
  - The groundwater flow equation used in IWFM, the partial differential equation for unsteady groundwater flow in a multi-layer aquifer system that consists of confined and/or unconfined layers, accounts for the effect on groundwater flow from land subsidence (q_{sd}):

$$0 = \frac{\partial S_s h}{\partial t} - \vec{\nabla}\left(T\,\vec{\nabla}h\right) + I_u L_u \Delta h^u + I_d L_d \Delta h^d - q_o + q_{sd} + q_{et} - \delta(x - x_s, y - y_s)\frac{Q_{sint}}{A_s} - \delta(x - x_{lk}, y - y_{lk})\frac{Q_{lkint}}{A_{lk}} - \delta(x - x_{td}, y - y_{td})\frac{Q_{td}}{A_{td}}$$

  - Specifically, the rate of groundwater flow into groundwater storage due to the vertical compaction of aquitard interbeds is expressed as:

$$q_{sd} = S_s' \frac{\partial h}{\partial t}$$

    Where:
    - S_s' is the skeletal storativity of interbeds which varies between the elastic (S_{se}) and inelastic (S_{si}) specific storage values multiplied by the interbed thickness, depending on the relation of the head (h) to the pre-consolidation head (h_c):

$$S_s' = \begin{cases} S_{se} b_o \; if \; h > h_c \\ S_{si} b_o \; if \; h \le h_c \end{cases}$$

    - $\frac{\partial h}{\partial t}$ is the rate of change of groundwater head

Land Subsidence in C2VSimFG v1.01

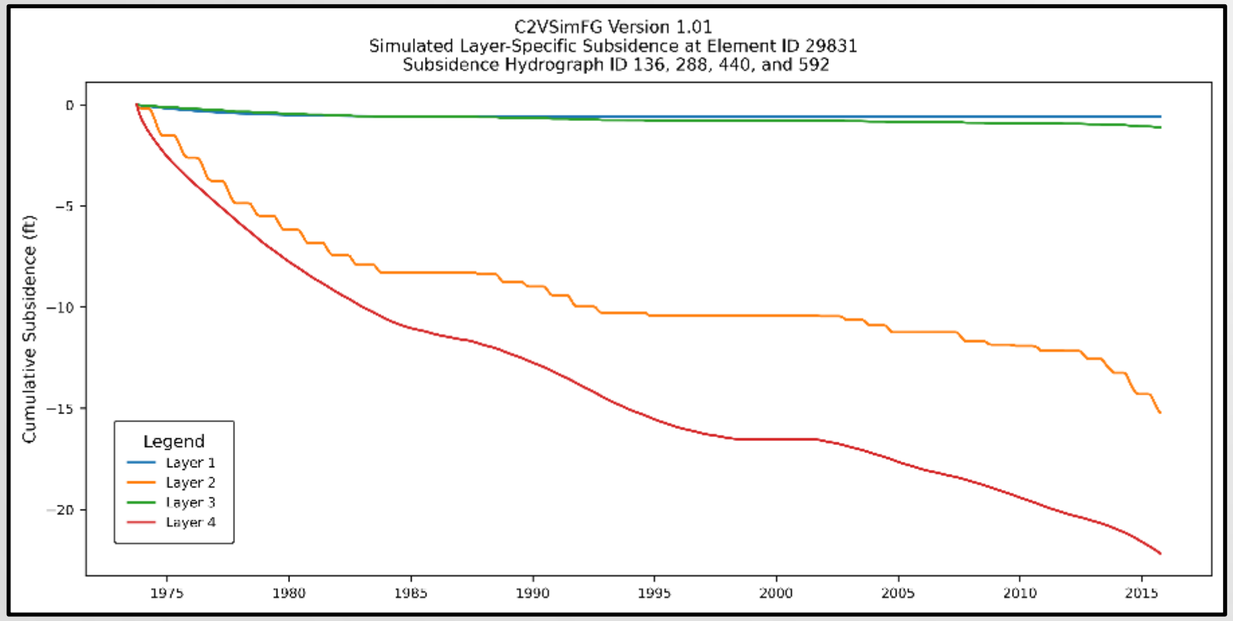
- Uses Version 4.0 of the IWFM Subsidence module (no delayed subsidence)

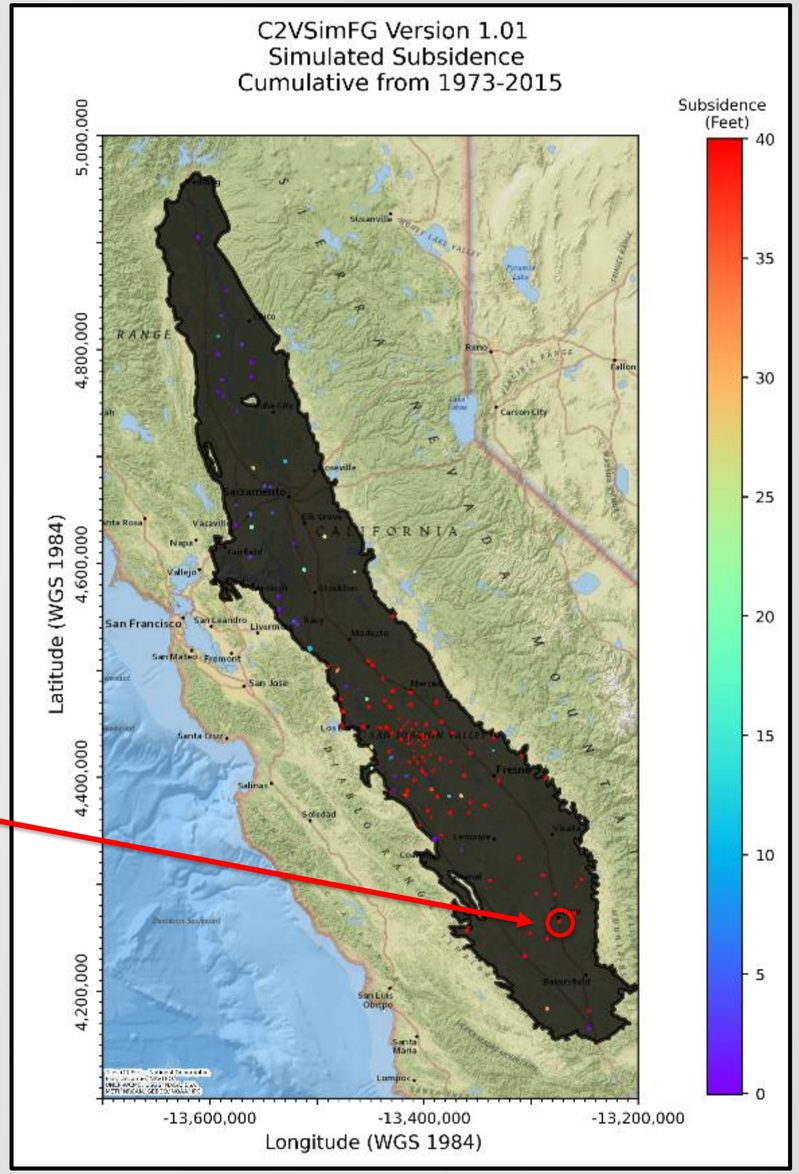
- Each groundwater node in each layer is assigned aquifer interbed thicknesses, elastic and inelastic storage coefficients, and pre-consolidation groundwater heads

Parameter	Units	Data Source	Average	Range
Aquifer Interbed Thickness for C2VSimFG Layer 1	ft	Texture Analysis	233.70	2.70 to 1123.50
Aquifer Interbed Thickness for C2VSimFG Layer 2	ft	Texture Analysis	282.50	0.70 to 1179.60
Aquifer Interbed Thickness for C2VSimFG Layer 3	ft	Texture Analysis	441.90	0.50 to 2733.10
Aquifer Interbed Thickness for C2VSimFG Layer 4	ft	Texture Analysis	749.30	1.50 to 5081.90
Elastic Storage Coefficient	ft^{-1}	Texture Analysis	1.27E-07	9.90E-09 to 1.90E-07
Inelastic Storage Coefficient	ft^{-1}	Texture Analysis	4.85E-05	1.20E-06 to 1.40E-04
Pre-consolidation head	Internal IWFM calculation using initial condition groundwater levels			

Land Subsidence in C2VSimFG v1.01

- Subsidence observations over time:
  - 164 measurement locations from DWR and USGS (map may not have all)
  - USGS InSAR
  - Restore SJR GPS stations
  - UNAVCO PBO GPS dataset
- Qualitative Review with minimal adjustment





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Known limitations of subsidence simulation in C2VSimFG

- Subsurface information
  - Heavily relies on subsurface information which can be very difficult to sufficiently collect (e.g., aquifer interbed thickness, specific storage)

- Immediate vs. delayed subsidence
  - C2VSimFG currently uses version 4.0 of the IWFM subsidence module – simulates subsidence as an instant response to stress changes
  - Vertical compaction of clays and silts occurs over varying degrees of time, not immediate
  - As a result, C2VSimFG should try emulate long-term subsidence in addition to immediate subsidence to better simulate the development of subsurface stresses
  - Incorporate version 5.0 of the IWFM subsidence module?

C2VSimFG Extension

- Extend observation data for refinement of subsidence parameters through calibration

- Process:
  - Data QA/QC
  - Spatial sampling at discrete locations (e.g., point data)
  - Temporal aggregation to monthly time-steps
  - Update C2VSimFG_Subsidence.dat input file (Subsidence Output Data)

- Data sources:
  - CGPS
  - Extensometer data
    - DWR
    - USGS
  - TRE ALTAMIRA InSAR Dataset

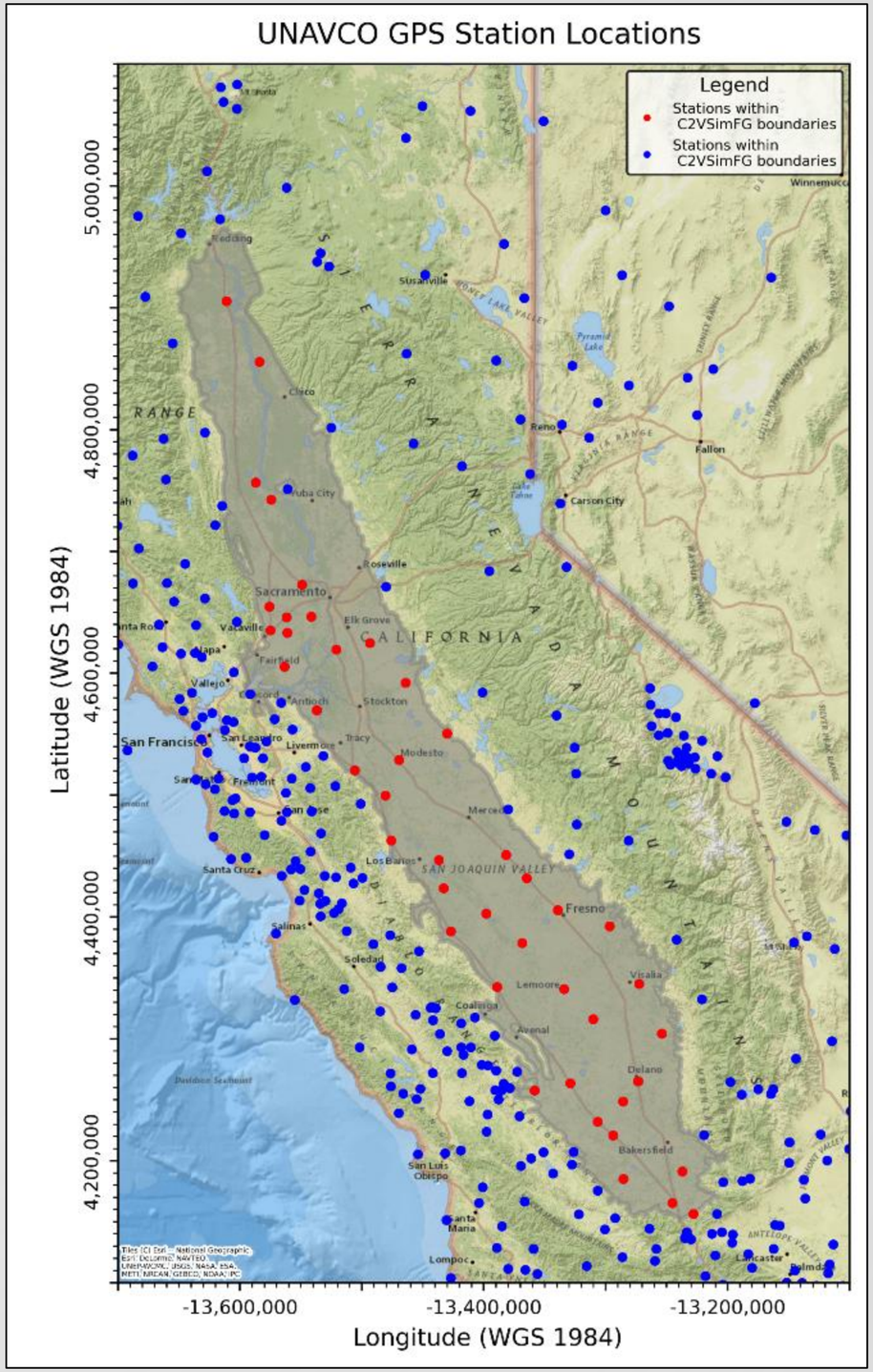
Continuous GPS

- Sources:
  - Scripps SOPAC
  - UNAVCO GPS Data

- Time series data of horizontal and vertical ground surface displacement

- Spatial Coverage
  - 47 potential GPS stations (UNAVCO) offer coverage within the C2VSimFG model boundaries

- Temporal Coverage
  - Daily timestep



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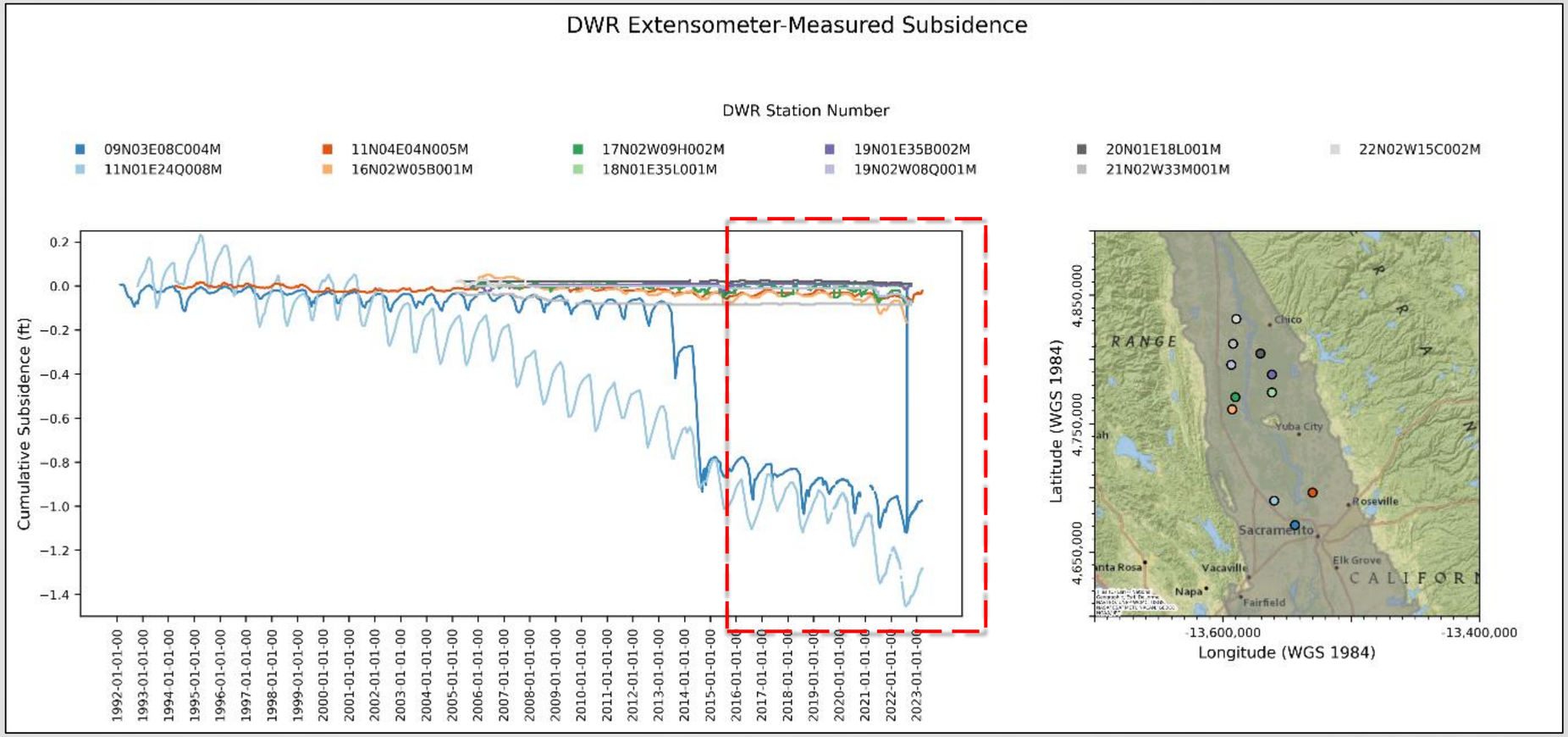
Extensometers - DWR

- https://data.cnra.ca.gov/dataset/wdl-ground-surface-displacement-
- Capable of detecting changes in land surface elevation to 1/100th of a foot

- Spatial Coverage
  - 11 sites
  - Limited to Sacramento Valley

- Temporal Coverage
  - Hourly data



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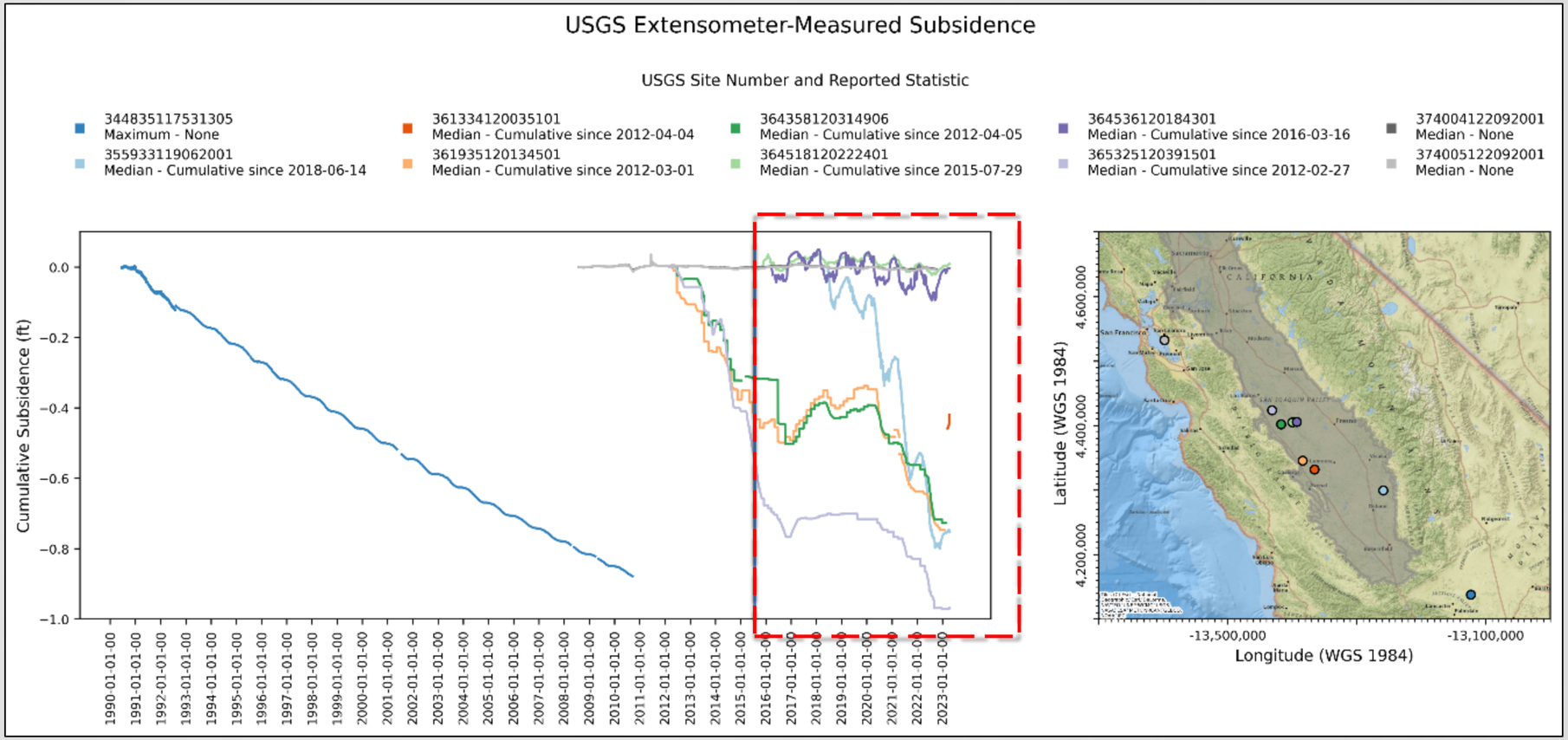
Extension Period

Extensometers - USGS

- https://waterdata.usgs.gov/nwis

- Spatial Coverage
  - 10 sites measure vertical compaction of the underlying aquifer system
  - Limited to San Joaquin Valley

- Temporal Coverage
  - Daily data



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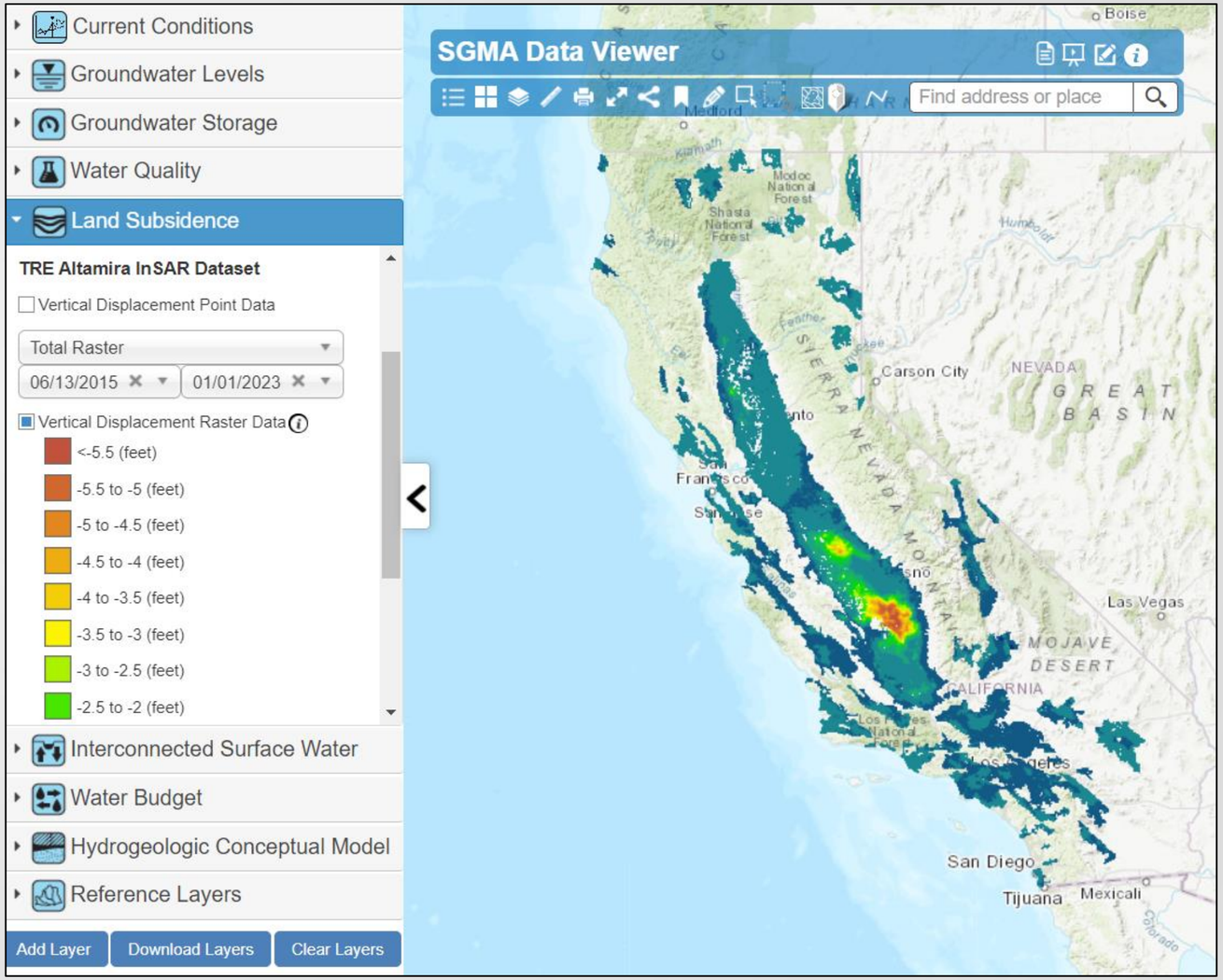
Extension Period

InSAR – TRE ALTAMIRA

- https://data.cnra.ca.gov/dataset/tre-altamira-insar-subsidence
- Measurements of vertical ground surface displacement derived from InSAR data collected by the ESA Sentinel-1A satellite and processed by TRE ALTAMIRA Inc.
- Dataset includes:
  - Point data that represents average vertical displacement values for 100 meter by 100 meter areas
  - GIS rasters interpolated from the point data (monthly)
- Spatial Coverage
  - Study area covers large portion of state
- Temporal Coverage
  - Collection Began in late 2014
  - Full coverage of study area began June 13, 2015
  - Available January 1, 2015 through January 1, 2023



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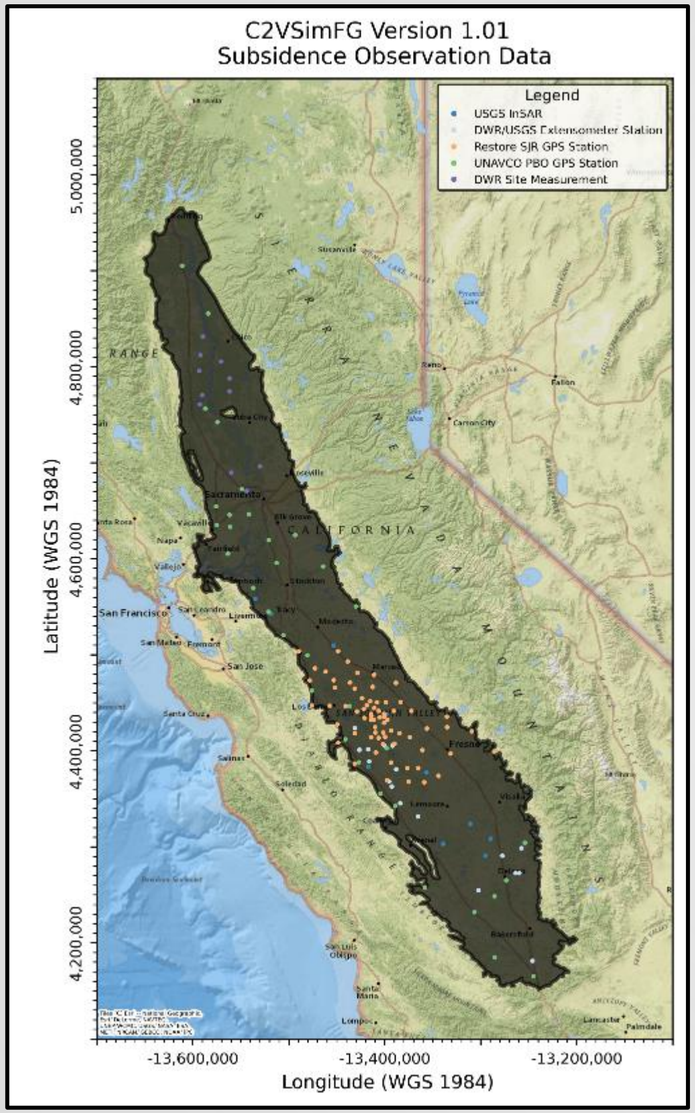
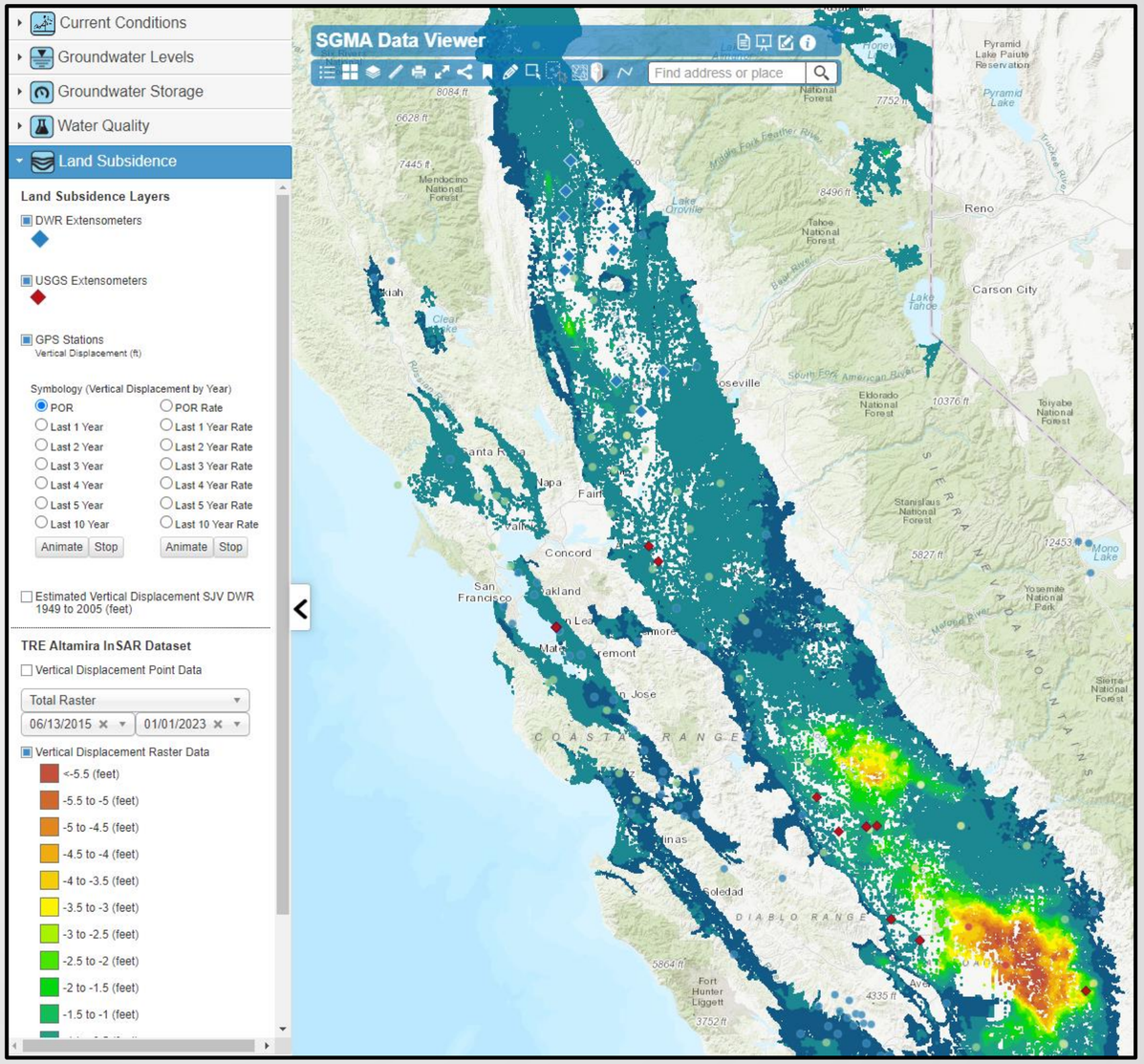
Potential Improvements





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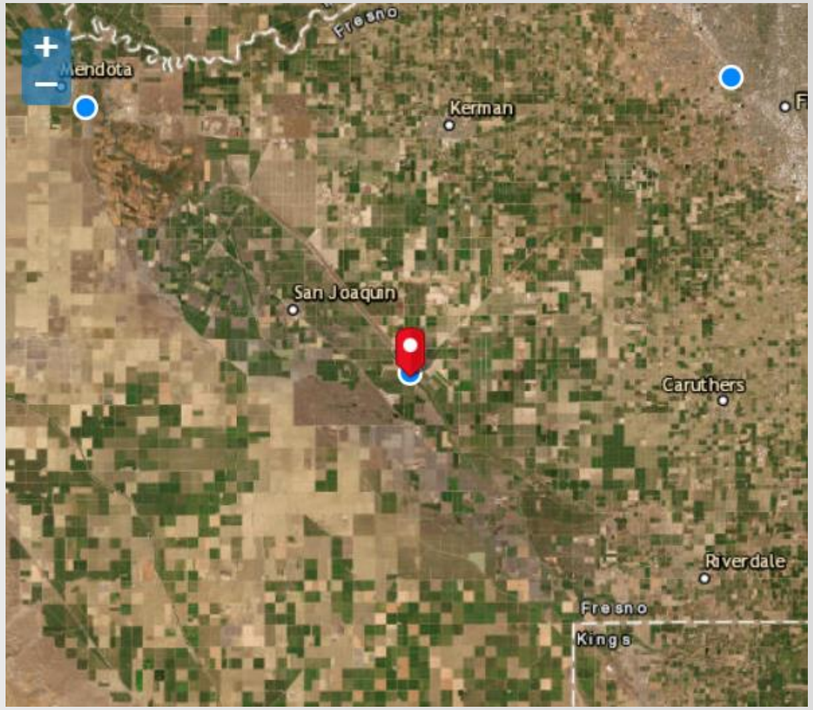
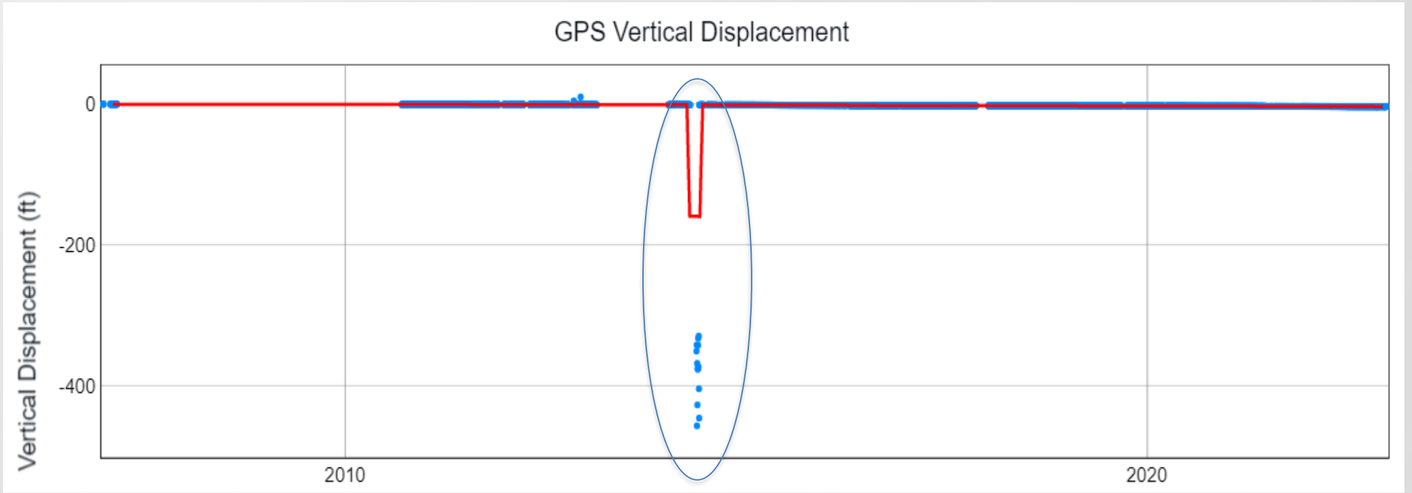
Data Selection Criteria

- Goal: Provide a complete coverage of land subsidence observations across the model over time
- QA
- Data de-densification
  - Use locations with consistent coverage over time.
  - May only need one observation within a particular model element
  - Aggregate to averages for the model time step (monthly rather than hourly or daily)





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Questions?

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