CALIFORNIA DEPARTMENT OF WATER RESOURCES
SUSTAINABLE GROUNDWATER MANAGEMENT OFFICE

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Image: NASA/JPL-Caltech

Subsidence Monitoring and Analysis

Monitoring changes in groundwater level and land surface elevation is important to the management of subsidence. Monitoring land surface elevations, groundwater levels, and groundwater pumping is the best practice for groundwater managers to use to identify relationships and manage subsidence.

Land Surface Elevation Monitoring

Subsidence monitoring networks should incorporate all available subsidence data and data collection approaches including, but not limited to: Spirit-leveling surveys, Extensometers, GPS stations, and InSAR.

- ***Spirit leveling:*** These surveys for measuring land surface elevations were the primary means of measuring subsidence through most of the 20th century.
- ***Extensometers:*** Borehole extensometers are a stable benchmark installed at a depth that is used to measure the 1D thickness of a specified depth interval of an aquifer system.
- ***GPS stations:*** Sites that collect high-precision position measurements using satellites on regular intervals.
- ***InSAR:*** a satellite-based remote sensing technique that measures ground elevation change over large areas. InSAR data is available on SGMA data viewer.[1]

1 https://sgma.water.ca.gov/webgis/?appid=SGMADataViewer#landsub

Did You Know?

*The Sustainable Groundwater Management Act (SGMA) specifically outlines a goal to "avoid or minimize land subsidence.[2]" However, some areas of California have experienced over 6 feet of land subsidence since the passage of SGMA based on InSAR data (**Figure 1**).*

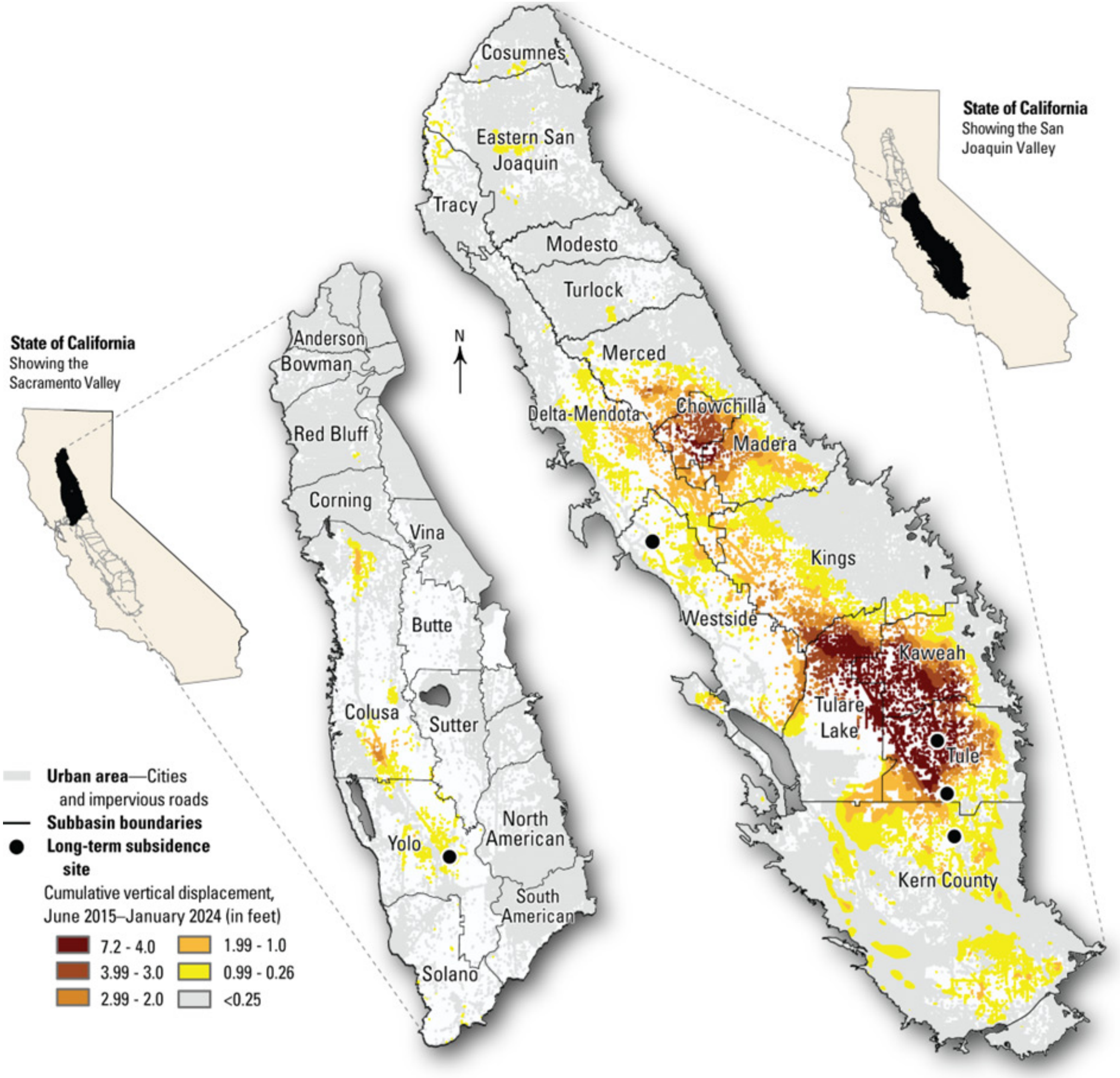

***Figure 1.** June 2015–March 2024 Subsidence from InSAR in the Central Valley.*

2 CWC 10721.1(e)

DWR InSAR Subsidence Dataset

Interferometric Synthetic Aperture Radar (InSAR) is a remote sensing technique used to estimate relative surface displacements. It functions by the repeat collection of synthetic aperture radar collected via satellite (***Figure 2***). InSAR estimates the relative motion of the ground surface by identifying the difference in signal phase between two visits, referred to as an interferogram.[3]

As part of the Department of Water Resources (DWR)'s technical assistance role to help Groundwater Sustainability Agencies (GSAs) develop and implement groundwater sustainability plans (GSPs), DWR provides regular releases of InSAR data that show the rate and extent of ongoing subsidence over California's groundwater basins. Currently, the InSAR dataset uses the European Space Agency (ESA) Sentinel-1 missions to generate monthly subsidence estimates spanning 2015 to present and with quarterly updates. DWR provides maps and time series of vertical surface displacements with data beginning in 2015. Included in this dataset are:

- Maps of the total vertical displacement relative to June 13, 2015, and
- Maps of annual vertical displacement rates with earlier coverage for some areas.

Separate historical datasets DWR provides include:

- Data from the ESA Envisat mission with monthly estimates of displacement spanning September 1, 2003, to October 1, 2010, and
- Displacement estimates from select time pairs using images collected by the Canadian Space Agency Radarsat-2 mission between 2011 and 2015.

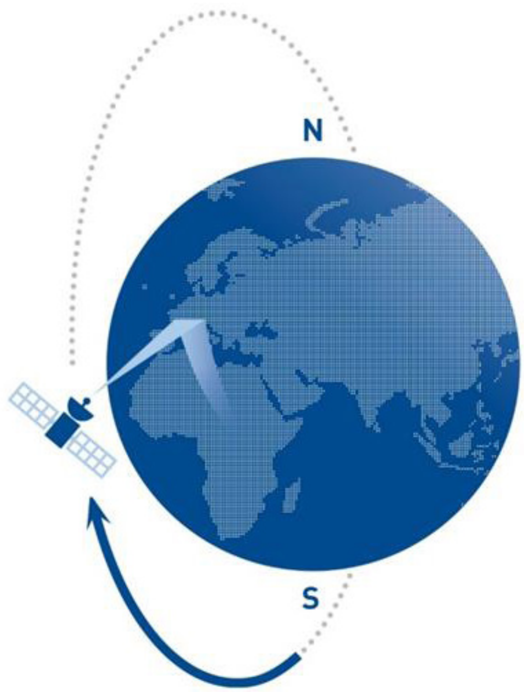

Figure 2. *Synthetic Aperture Radar (SAR) satellites image the ground from orbit.*

3 Massonnet, D., & Feigl, K. L. (1998). Radar interferometry and its application to changes in the Earth's surface. Reviews of Geophysics, 36(4), 441–500.

Subsidence Data Resources

GIS services and data reports:
https://data.cnra.ca.gov/dataset/tre-altamira-insar-subsidence

GIS image services of vertical displacement rasters for the current InSAR subsidence dataset:
https://gis.water.ca.gov/arcgisimg/rest/services/SAR

Current InSAR subsidence dataset is viewable on the SGMA Data Viewer:
https://sgma.water.ca.gov/webgis/?appid=SGMADataViewer#landsub

More information on the SGMA Data Viewer is available at it's "readme" file:
https://sgma.water.ca.gov/webgis/config/custom/html/SGMADataViewer/doc/

Raster maps for total subsidence since 2015 or annual subsidence maps can be selected in monthly timesteps, as shown in ***Figure 3***.

GSAs can choose any number of subsidence monitoring sites from available InSAR subsidence data. Monitoring sites that utilize DWR's InSAR subsidence data can be specified in GSPs and annual reports by referencing the dataset at https://data.cnra.ca.gov/dataset/tre-altamira-insar-subsidence and listing the monitoring site coordinates. GSAs can enter monitoring sites that utilize DWR's InSAR subsidence data in the SGMA Monitoring Network Module as an existing site, and by entering the site-specific data report URL from the SGMA data viewer.

DWR increased reporting frequency of InSAR subsidence data in 2022 from annually to quarterly. The monthly data is being updated four times a year to help local, state and federal agencies make informed management

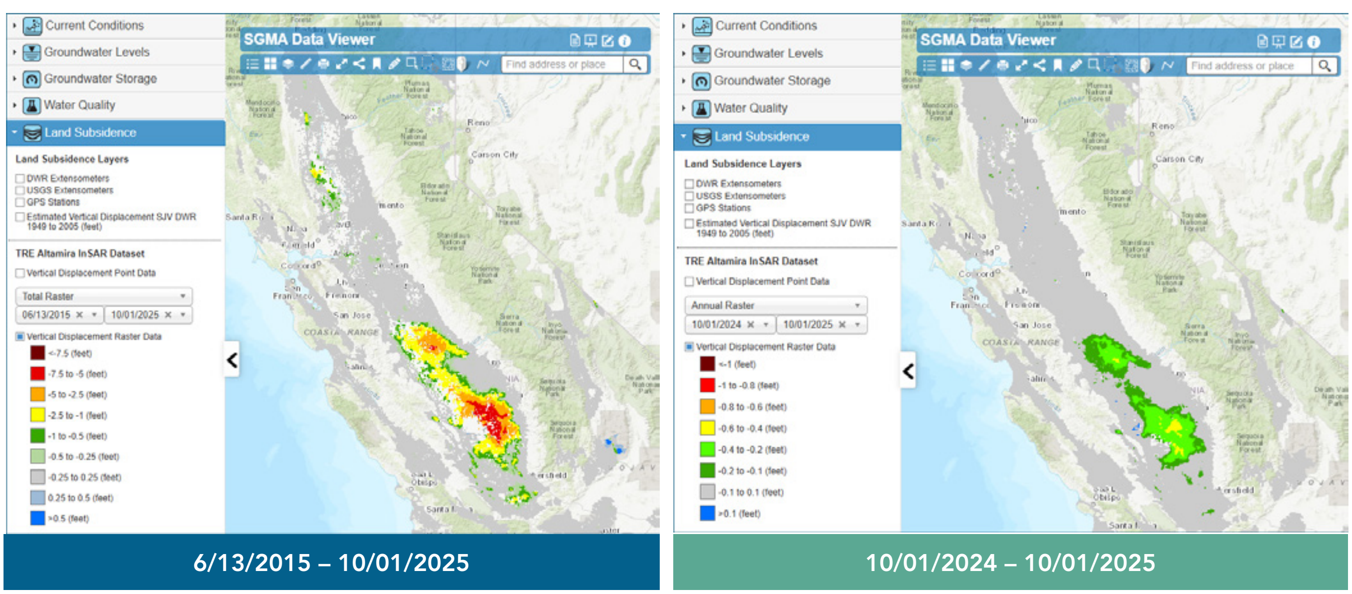

Figure 3. *Image of SGMA Data Viewer showing InSAR measured subsidence from 6/13/2015 to 10/01/2025 (left) and from 10/01/2024 to 10/01/2025 (right).*

decisions backed by science-based data. Beginning with the last quarterly update in 2025, spatial coverage of the annual subsidence raster data has been improved to reduce data gaps. The increase in coverage applies to the May 1, 2024 to May 1, 2025 annual raster map and beyond.

The National Aeronautics and Space Administration (NASA), in partnership with the Indian Space Research Organization (ISRO), launched the NASA-ISRO SAR (NISAR) mission in the summer of 2025. While NISAR will have similar repeat acquisition of data as the Sentinel-1 mission (12-day repeats), it will operate in longer wavelength radar bands (L- and S-bands) which should help to minimize the effects of spatial data loss due to decorrelation and to reduce data gaps. Going forward, DWR will work with external InSAR processing resources to evaluate and incorporate data from the NISAR mission. DWR has secured baseline funding to provide ongoing subsidence data assistance.

Groundwater Level Monitoring with Consideration of Subsidence

Groundwater managers should monitor groundwater levels with a sufficient spatial density of sites in all aquifer units. Frequent monitoring and reporting assists groundwater managers in understanding the timing of each year's seasonal low, which is when the highest likelihood of subsidence occurs. Monthly or more frequent measurements are the best practice for monitoring levels, as the seasonal lows are the times when groundwater levels may first fall below critical head, and inelastic compaction may occur. ***Figure 4*** shows how more frequent monitoring more accurately measures the seasonal low. Biannual measurements may miss the seasonal low in many years.

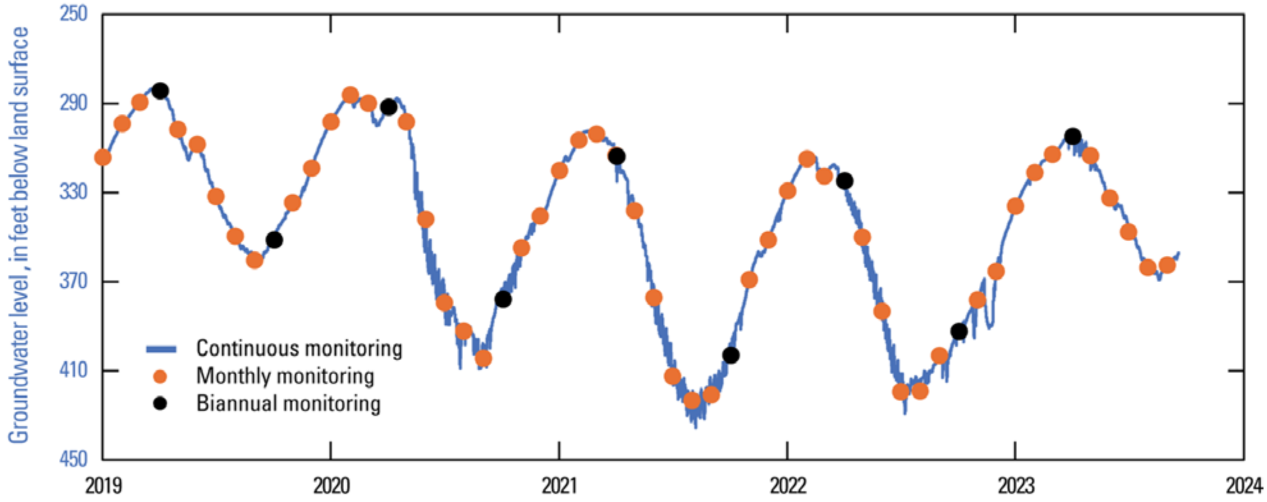

Figure 4. *Bi-annual, monthly, and continuous recording interval comparison of groundwater levels.*

Groundwater Pumping Monitoring

In areas experiencing land subsidence near infrastructure, the best management practice is to establish pumping reporting using spatial and temporal data that groundwater managers may use to understand better the relationship between pumping, groundwater levels, and their effects on subsidence. The most accurate way to gain local scale understanding of pumping is to use meters. Accurate interpretation of measured pumping requires well construction information such as well depth and screened intervals so that withdrawals can be linked to the hydrostratigraphic units being pumped.

Identifying Infrastructure

The best practice to determine if and how infrastructure will be impacted by subsidence is to consult or coordinate with the most knowledgeable persons or entities, which usually will be the owner, operator, or agency with jurisdiction over the infrastructure that will be affected. ***Thorough documentation and official correspondence is the best management practice.*** GSAs should consider the following kinds of infrastructure, and any additional infrastructure based on local conditions, infrastructure dependencies, stakeholder input, and public health and safety concerns:

- ***Cities and Communities:*** property drainage, power systems, municipal water systems, and sewer systems
- ***Pipelines and Other Utilities:*** natural gas, water, underground cables and overhead powerlines
- ***Railroads:*** private rail, high-speed rail
- ***Roads:*** drainage systems, highways, bridges
- ***Canals:*** state, federal, and local canals
- ***Flood Control & Drainage:*** state, federal, and local flood facilities (levees, bypasses, dams)
- ***Groundwater Pumping Facilities:*** domestic, agricultural, and public supply wells

Critical Head: The Groundwater Level to Minimize Subsidence

Critical head is the groundwater level within compressible sediments (like clays), below which permanent compaction, and therefore subsidence, begins. Estimates of critical head provide groundwater managers with a quantitative target for managing groundwater levels in the aquifer system to prevent or minimize subsidence. Critical head can be estimated using several methods. Because understanding critical head is an essential part of the best management practices for managing subsidence in subsidence prone areas, groundwater managers should at least perform a trend-based analysis as a first step to gain initial understanding and then perform empirical analysis and/or modeling analysis, so that the initial estimate can be refined.

Trend-based Analysis

Trend-based analysis uses general trends in groundwater levels and subsidence data to identify groundwater levels during periods of minimal to no subsidence. This is a comparatively rapid method to estimate critical head. This method can also result in greater uncertainty in the critical head results compared with the other methods because it relies on a general inspection of trends versus a more quantitative analysis.

Figure 5 shows that critical head can be estimated based on groundwater levels (i.e., groundwater elevations) that occur when the rate of subsidence substantially decreases.

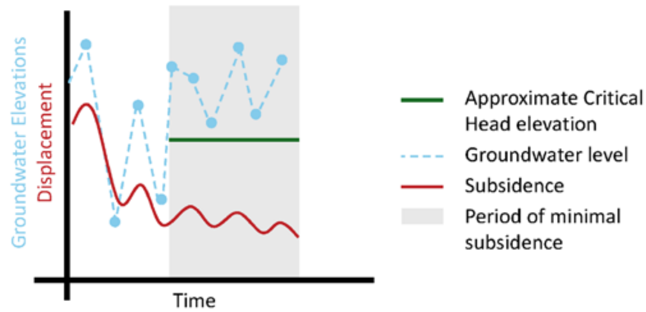

Figure 5. *Hypothetical Example of the Trend-based Analysis Between Groundwater Levels and Subsidence.*

Empirical Analysis

Empirical analysis uses an empirical relationship between groundwater levels and subsidence data to estimate critical head values. The empirical analysis approach requires additional time and data to develop and interpret than the trend-based analysis; however, it provides a more quantitative estimate of critical head. Additionally, if a structured workflow is developed for the empirical analysis, it can be quickly implemented in multiple locations.

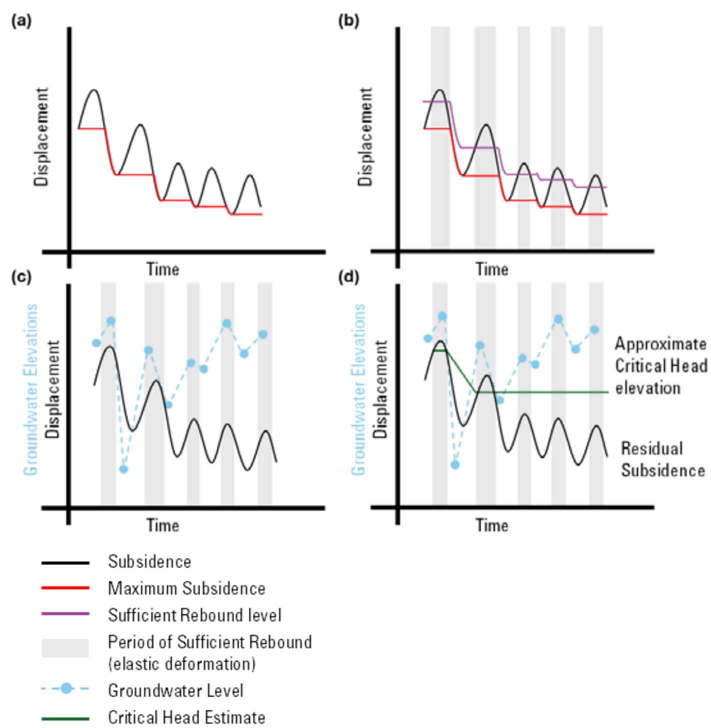

Figure 6. *Example Steps to an Empirical Estimation of Critical Head.*

Figure 6 shows hypothetical input subsidence and groundwater level (i.e., groundwater elevation) time series for the empirical critical head estimation method. (a) shows a displacement time series described by a subsidence signal superimposed with seasonal oscillations (black) and the maximum subsidence with time (red). (b) shows the "sufficient rebound" level (purple) and the associated time periods of sufficient rebound (shaded gray), which can be interpreted as periods of elastic deformation. (c) shows the corresponding interpolated groundwater level time series (dash blue) with observation marked as blue circle. (d) shows the estimated critical head (green) based on the interpolated groundwater levels during periods of "sufficient rebound."

Modeling Analysis

Modeling analysis uses groundwater level and subsidence data to develop compaction models. More data are required to use this method than the trend-based and empirical analyses, including lithologic logs, records of groundwater levels across multiple aquifer units, and subsidence records. These models take time to develop and calibrate but can provide reasonable estimates of critical head, assuming a robust calibration to available groundwater level and subsidence data. An example of the application of a modeling analysis (***Figure 7***) is provided in Bulletin 118 Appendix I.[4]

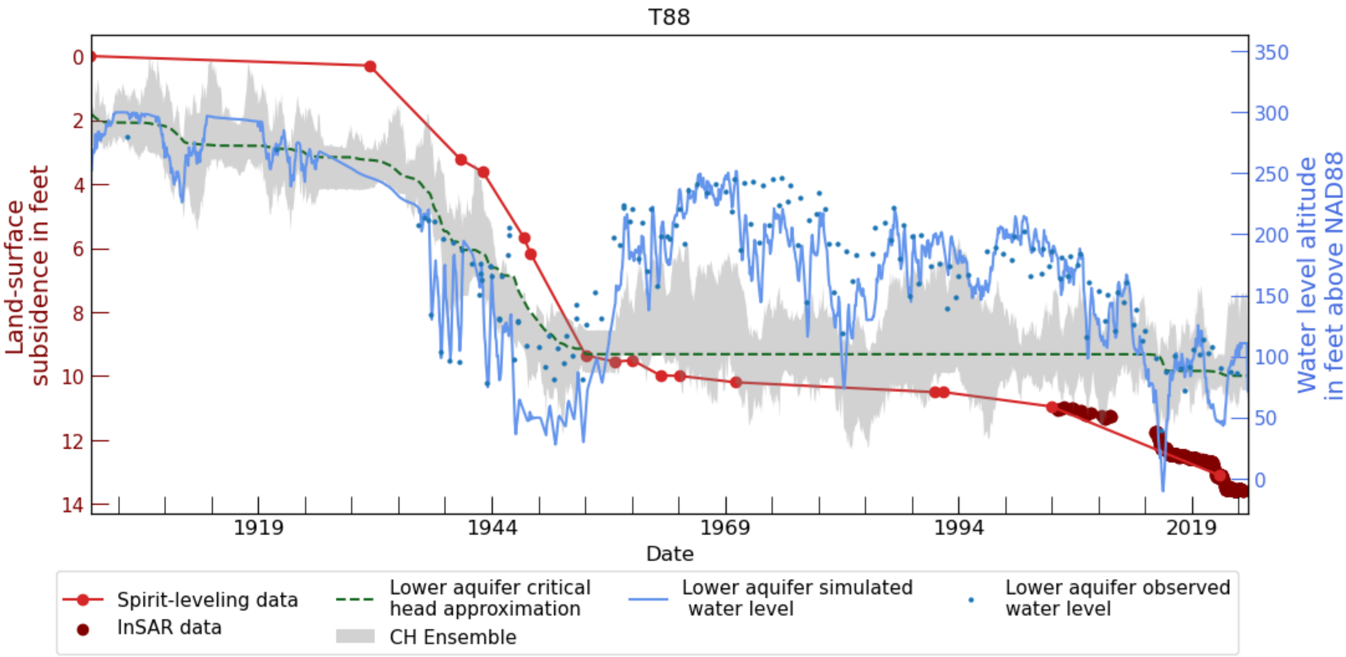

Figure 7. *Example Model Output showing estimates of critical head over time.*

4 California Department of Water Resources. (2025). Appendix I: Update on Land Subsidence in California. In: California's Groundwater: Bulletin 118 – Update 2025 (CalGW Update 2025). Sacramento, CA: California Department of Water Resources. Available at: https://water.ca.gov/programs/groundwater-management/bulletin-118