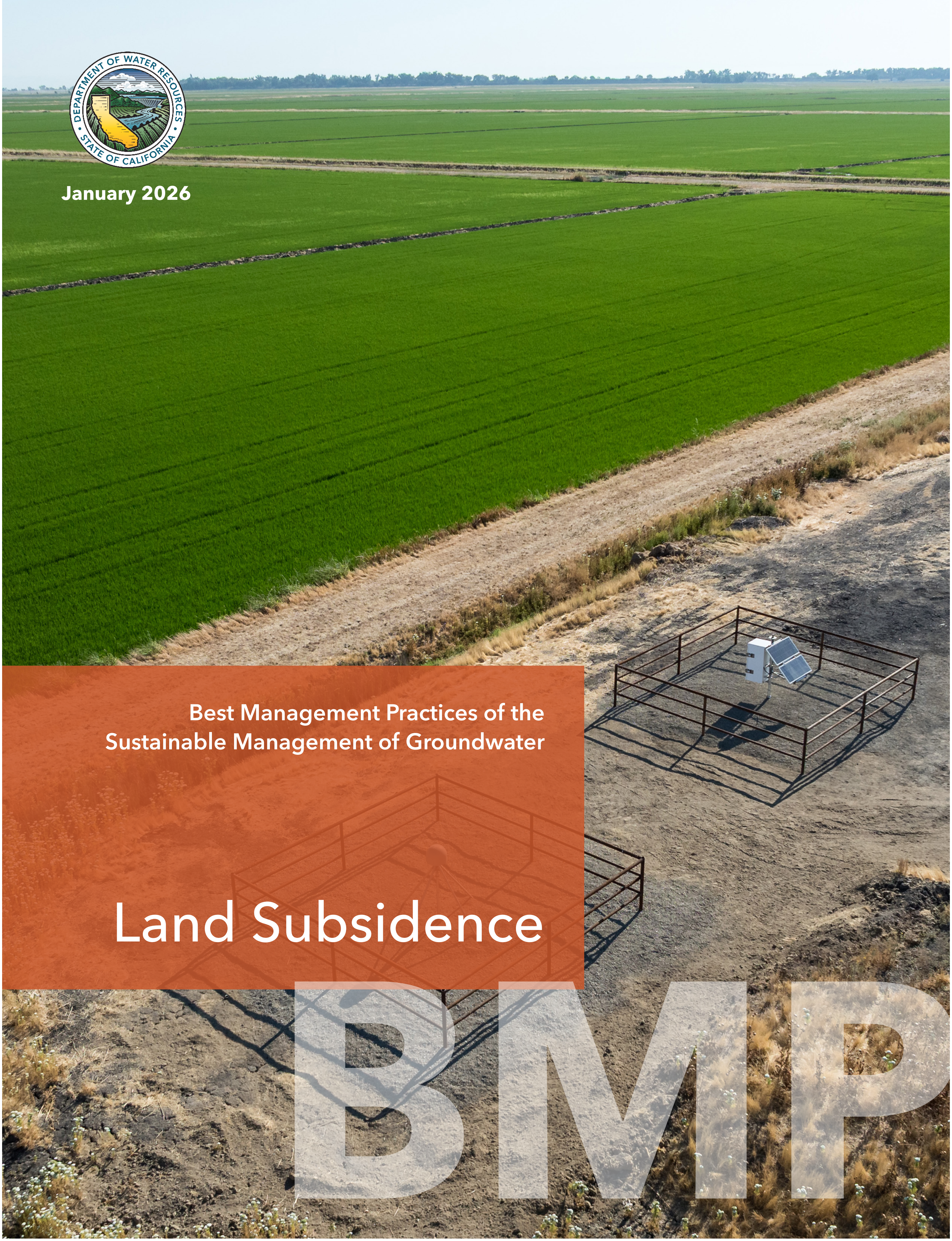

January 2026

Best Management Practices of the
Sustainable Management of Groundwater

Land Subsidence

BMP

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Executive Summary

The Subsidence Best Management Practices document (Subsidence BMP) provides a guide on the fundamentals of land surface subsidence (also called “land subsidence” or “subsidence”), technical assistance related to subsidence, and best practices for managing subsidence. The Subsidence BMP also provides specific information about subsidence in California and how it must be considered within the structure of the Sustainable Groundwater Management Act (SGMA). Subsidence is one of the six sustainability indicators required to be managed under SGMA. The Subsidence BMP does not supersede or replace any existing local, state, or federal regulations. Rather, it is meant to help groundwater managers, especially Groundwater Sustainability Agencies and the public, better understand land subsidence and how it can be managed.

Land subsidence, or the sinking of the land surface, can be caused by multiple factors, including the dewatering of fine-grained sediments, including clay layers, within an aquifer due to groundwater pumping. Aside from impacting the structure of the aquifer itself, subsidence can also significantly impact infrastructure, including water conveyance facilities, pipelines, levees, building foundations, railways, highways, well casings, and bridges. Subsidence from groundwater pumping has severely impacted land surfaces and infrastructure in parts of California. Rates of subsidence and its associated impacts have increased in some areas of California due to unsustainable groundwater pumping. The effects are costing Californians hundreds of millions of dollars annually in damage repairs, reducing water supply reliability, and jeopardizing public safety. It is imperative that existing subsidence is minimized as quickly as possible and that the emergence of new subsiding areas is avoided.

Fortunately, well-established scientific principles, modeling data, and measured historic evidence demonstrate that subsidence can be minimized or avoided. The Subsidence BMP provides technical assistance on the scientific fundamentals and facts. With the scientific foundation established, the Subsidence BMP provides specific guidance on how subsidence management fits within the framework of SGMA. For example, Groundwater Sustainability Agencies (GSAs) will be tasked with establishing subsidence monitoring, identifying affected or at-risk infrastructure, and refining subsidence sustainable management criteria. Finally, the Subsidence BMP outlines a number of general management actions that can help a basin determine subsidence sustainable management criteria.

Successfully addressing subsidence under SGMA involves evaluating all available information, educating the local community, coordinating with entities responsible for the operation and maintenance of infrastructure, understanding other potential impacts to surface and land uses (e.g., changes in flood risk, depth, or flow pattern), stabilizing and potentially raising groundwater levels, and adaptively managing a basin as conditions change.

The Department encourages GSAs and other groundwater managers to utilize this Subsidence BMP to successfully address the challenging issue of subsidence management to avoid costly and unintended impacts to land surface uses and infrastructure and achieve the legislative intent of SGMA to avoid or minimize subsidence.

This BMP includes the following chapters:

- **Chapter 1, Objective.** A description of the objectives of the BMP and a brief overview of the contents of this BMP.
- **Chapter 2, Uses and Limitations.** A brief description of the use and limitations of this BMP.
- **Chapter 3, Relationship of Subsidence BMP to other BMPs.** A description of how the Subsidence BMP relates to other BMPs and Groundwater Sustainability Plan requirements.
- **Chapter 4, Land Subsidence Fundamentals.** A description of fundamental concepts of subsidence, causes of land subsidence and its processes. Discusses the properties of fine-grained sediments that compress during subsidence and introduces critical head. This chapter also discusses California's subsidence history, damage resulting from subsidence, and how to limit subsidence.
- **Chapter 5, Technical Assistance.** Provides technical content with guidance for how to monitor subsidence and how to monitor groundwater levels and groundwater pumping with consideration of their relationship with subsidence. Discusses identification of infrastructure and methods used to estimate critical head.
- **Chapter 6, Land Subsidence and SGMA.** Discusses best practices for monitoring and establishing sustainable management criteria under SGMA.
- **Chapter 7, Land Subsidence Management.** A discussion of actions to limit land subsidence, regional subsidence management, guidance for GSAs on engaging with interested parties, and scenario-based subsidence management strategies.
- **Chapter 8, References.** References and other materials that provide supporting information related to subsidence.

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Key Terms

Subsidence is a complex technical subject, and its discussion requires the use of many technical terms. This section provides working definitions of terms not defined by SGMA, legal definitions of terms used in this document that are defined in SGMA code or regulations, and a list of acronyms.

Working Definitions

This section offers working definitions of certain key terms used in this BMP and offers context for their use. These definitions are not intended to be used in other contexts, are not legally binding, and are subject to change or further clarification.

Coarse-grained sediments	Generally include sands and gravels and clasts larger than 0.0625 millimeters
Compaction	Compression of fine-grained sediments resulting in decreased aquifer-system thickness
Confining Units	Laterally extensive fine-grained sediments
Critical Head	Groundwater elevation in fine-grained units below which permanent compaction of fine-grained sediments may occur
Effective Stress	Relationship of the weight of the overlying rock and water balanced by the pore-fluid pressure and intergranular stress on the aquifer-system skeleton
Elastic Compaction	Occurs when the effective stress is less than the preconsolidation stress and is reversible if groundwater levels are raised
Fine-grained sediments	Consist of silt and clay with grain size less than 0.0625 millimeters (too small for individual grains to be recognized by the human eye). Laboratory tests are used to evaluate the grain size distribution of a soil sample
Fine-grained units	Generally include two classes of low permeability deposits: laterally discontinuous fine-grained sediments (interbeds) within the aquifers, and laterally extensive fine-grained sediments (confining units) separating individual aquifers in the aquifer system
Groundwater level	For the purposes of this document, the term “groundwater level” is synonymous with a groundwater level elevation measured in feet above a vertical datum
Inelastic Compaction	Occurs when effective stress exceeds the preconsolidation stress, and the skeletal structure of fine-grained sediments undergoes significant, permanent rearrangement
Infrastructure	Any land use or property interest that has been or is likely to be affected by land subsidence

Integrated Model	A model that couples groundwater flow, surface water flow, landscape and vadose zone processes, and subsidence
Interbeds	Laterally discontinuous fine-grained sediments
Land Subsidence	The lowering of the land surface elevation due the compression of fine-grained sediments (also called “land surface subsidence” or “subsidence”)
Low permeability sediments	Characterized by high porosity (percentage of void space) and low permeability (measure of the interconnectedness of the pores). Clays have high storage of water in the pore space, but the pores are poorly connected, limiting flow of water
Overburden	Weight of the overlying sediments and water
Preconsolidation Stress	Greatest historical effective stress imposed on the aquifer system before fine-grained sediments permanently compact
Preconsolidation Head	The lowest groundwater level (elevation) in the fine-grained sediments that corresponds to the preconsolidation stress
Residual Subsidence	The continued decrease in land surface elevation after the primary cause of subsidence (response to groundwater level declines) has ceased
Skeletal specific storage	The compressibility and porosity of subsurface sediment (abbreviated S_{sk})
Vertical hydraulic conductivity	The rate at which water moves vertically through subsurface sediment (abbreviated K_v)

Legal Definitions

California Code, WAT 10721.

View Document - California Code of Regulations (westlaw.com)

https://govt.westlaw.com/calregs/Document/IB3BC39345B6E11EC9451000D3A7C4BC3?viewType=FullText&originationContext=documenttoc&transitionType=CategoryPageItem&contextData=(sc.Default)

Acronyms

Term	Abbreviation
1D	one-dimensional
ASR	aquifer storage and recovery
BMP	best management practice
C2VSim	California Central Valley Groundwater-Surface Water Simulation Model
CalGEM	California Geologic Energy Management Division
CCR	California Code of Regulations
CNRA	California Natural Resources Agency
CSUB	Skeletal Storage, Compaction, and Subsidence package for MODFLOW 6
CVHM2	Central Valley Hydrologic Model Version 2
DWR	California Department of Water Resources
σ_e	Effective stress
ft	foot / feet
ft/year	feet per year
σ_T	Geostatic stress
GPS	global positioning system
GSA	Groundwater Sustainability Agency
GSP	Groundwater Sustainability Plan
ρ	Hydrostatic stress
IBS	interbed-storage package
InSAR	interferometric synthetic aperture radar
IWFM	integrated water flow model
km^2	square kilometers
K_v	vertical hydraulic conductivity
MAR	managed aquifer recharge
MODFLOW	Modular Finite-Difference Flow Model
PMAs	Projects and Management Actions
SGMA	Sustainable Groundwater Management Act
S_{sk}	skeletal specific storage
S_{se}	elastic skeletal specific storage
S_{sv}	Inelastic skeletal specific storage
SUB	Subsidence and Aquifer-System Compaction package for MODFLOW-2005 and MODFLOW One-Water Hydrologic Flow Model
SUB-WT	subsidence and aquifer-system compaction package for water-table aquifers for MODFLOW-2005 and MODFLOW One-Water Hydrologic Flow Model
TSS	Technical Support Services
USGS	U.S. Geological Survey

1 Objective

The Department of Water Resources (DWR, Department) developed this Subsidence Best Management Practice (BMP) document to describe the activities, practices, and procedures that are recognized as effective methods for the quantification and prediction of land subsidence. The BMP also provides guidance that Groundwater Sustainability Agencies (GSAs) may employ to sustainably manage land subsidence as required by the Sustainable Groundwater Management Act (SGMA) and the Groundwater Sustainability Plan (GSP) Regulations.

The objectives of this BMP are to guide groundwater managers in collecting sufficient information and undertaking suitably detailed studies, as appropriate, to reach a better understanding of the magnitude of subsidence under various groundwater level conditions and more precisely describe the potential impacts of that subsidence, and to guide GSAs in their determination of what level of subsidence would lead to undesirable results.

This BMP provides details about the mechanics of subsidence and why the best management practice of raising groundwater level elevations (expressed in this BMP as a "groundwater level") as high and as quickly as possible is the most effective way to avoid or minimize subsidence. This BMP explains critical head and how to estimate it, how to identify infrastructure, and what aspects of impacts to that infrastructure to consider. This BMP provides details about how to estimate correlated amounts of subsidence that may occur with groundwater level changes so that impacts to infrastructure may be avoided.

This BMP also provides guidance for GSAs regarding the establishment of sustainable management criteria for subsidence in a manner that supports the basin reaching sustainability and supports discussion of how corresponding criteria for the chronic lowering of groundwater levels align with avoiding or minimizing subsidence or limiting impacts to infrastructure. The implementation of project and management actions to assist in managing subsidence is also discussed in further detail.

2 Uses and Limitations

This document provides the best practices for the management of subsidence to assist in meeting the intent and requirements of the SGMA and the GSP Regulations.[1]

2.1 Legal Disclaimer

This BMP document provides technical guidance to GSAs and other interested parties. Although the BMP references and discusses provisions and concepts from SGMA and the GSP Regulations, it does not create new requirements or obligations for the GSAs or other interested parties and is not a substitute for compliance with SGMA and the GSP Regulations. This BMP does not prescribe specific methods that GSAs or other interested parties must use but rather discusses approaches to avoid or minimize land subsidence induced by groundwater pumping that are the most widely and generally adopted practices and are recognized among professionals involved in the study and management of subsidence to be the best or preferred management practices in most cases when feasible. Using this BMP document to develop and periodically evaluate a GSP (or Plan) or a Plan Amendment does not equate to agreement by the Department that the chosen practice is the most appropriate in any specific case, nor does conformance with specific approaches in this document guarantee the Department's approval of a Plan or its implementation or compliance with SGMA. SGMA in its entirety can be found in Division 6, Part 2.74, of the California Water Code Section 10720. The GSP Regulations are in Subchapter 2 of Chapter 1.5, Division 2 of Title 23 of the California Code of Regulations (CCR).

[1] CWC § 10720 [e].

3 Relationship of Subsidence BMP to other BMPs

This Subsidence BMP builds on existing BMPs that describe best management practices for satisfying the requirements of SGMA and the GSP Regulations. This Subsidence BMP provides an in-depth discussion of subsidence processes and the relationship between groundwater levels and subsidence. This BMP also describes best management practices for avoiding subsidence in susceptible areas and minimizing subsidence in areas that are subsiding. For these areas, this Subsidence BMP should be considered an extension of other BMPs, including but not limited to these specific sections:

- BMP 1—Monitoring Protocols, Standards, and Sites
  - 5. Technical Assistance
    - Protocols for measuring subsidence
- BMP 2—Monitoring Networks and Identification of Data Gaps
  - 5. Technical Assistance
    - General Monitoring Networks
    - Specific Monitoring Networks
      - — A. Chronic Lowering of Groundwater Levels
      - — E. Land Subsidence
    - Representative Monitoring Points
    - Network Assessment and Improvements
- BMP 5—Modeling
  - 5. Technical Assistance
    - Modeling Considerations
      - — Land Subsidence
- BMP 6—Sustainable Management Criteria (Draft)
  - 4. Setting Sustainable Management Criteria

4 Land Subsidence Fundamentals

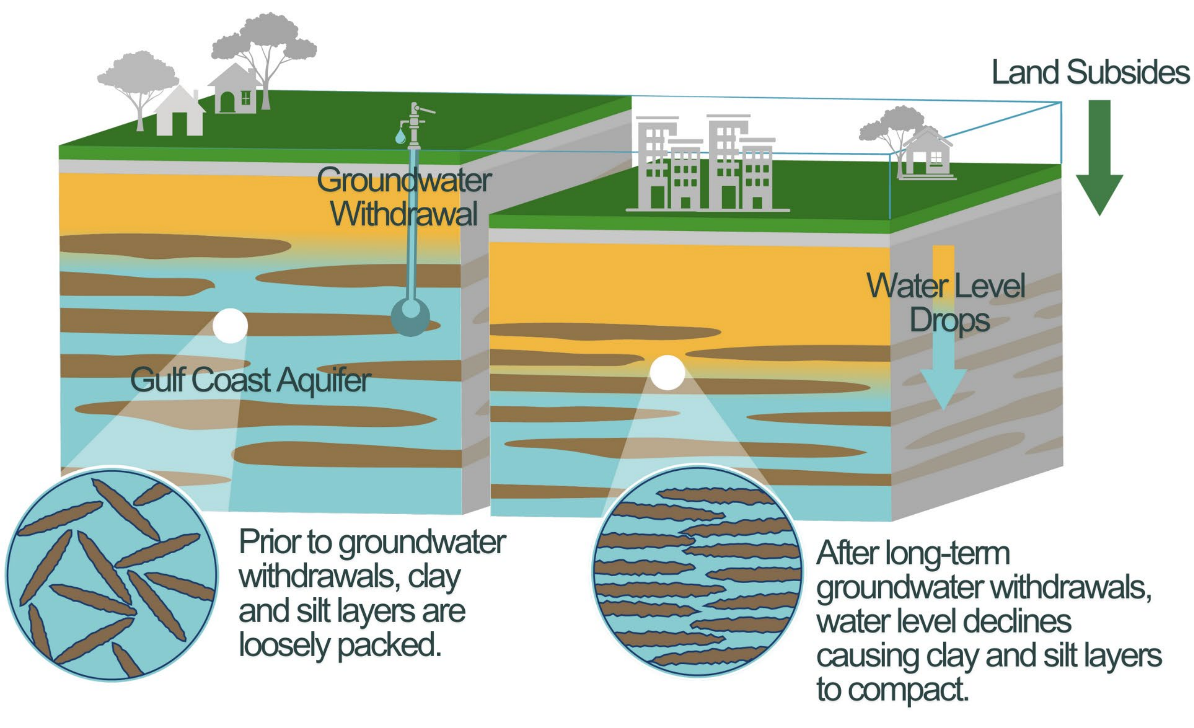
This section of the Subsidence BMP provides discussions on subsidence processes, management actions to limit subsidence, and subsidence in California. Definitions of key terms used in this discussion are provided in Key Terms.

4.1 Land Subsidence Overview

Land subsidence happens because different types of sediments are present below ground. **Fine-grained sediments** like clays and silts are made of tiny, flat, plate-like particles. Water sits in the small spaces between these "plates" and separates them. When groundwater is pumped, and the **groundwater level** declines, the support for the "plates" decreases, and they become packed closer together, causing the layer to become thinner and the ground above it to sink. This compaction of fine-grained sediments in response to declines in groundwater levels is shown in Figure 4-1.

In contrast, **coarse-grained sediments** like sands and gravels are made of larger, rounded grains. These rounded grains don't rearrange when the groundwater level is lowered because they are already packed as tightly as their shape allows. When groundwater is pumped, the water between the sand and gravel grains drains out, but the grains themselves don't move closer together, meaning these layers don't compress and don't cause appreciable subsidence.

Figure 4-1. Illustration of Subsidence Concepts



*Subsidence illustration courtesy of Harris-Galveston Subsidence District.

4.2 What Causes Land Subsidence

When groundwater pumping exceeds recharge, groundwater levels can decline. This lowering of groundwater levels reduces groundwater pore pressure (depressurization) of subsurface formations (in particular, low permeability fine-grained sediments), which leads to vertical decreases in aquifer-system thickness (**compaction**) in many areas. This compaction of subsurface fine-grained sediments is manifested at the surface as **land subsidence**, the lowering of the land surface elevation. While the dominant mechanism in California that results in land subsidence is related to groundwater pumping, subsidence can also result from oil and gas operations (extraction of water and oil), tectonic and volcanic activity, hydrocompaction of historically dry sediment that becomes saturated and oxidation of organic matter such as peat soil.[2,3] This Subsidence BMP focuses on the management of compaction due to declines in groundwater levels.

In California, unconsolidated alluvial or basin-fill aquifer systems that contain **fine-grained units**, or layers, that have undergone extensive groundwater pumping are typically the regions most susceptible to subsidence.[4,] The fine-grained units generally include two classes of low permeability deposits: laterally discontinuous fine-grained sediments (**interbeds**) within the aquifers and laterally extensive fine-grained sediments (**confining units**) separating individual aquifers in the aquifer system. The interbeds and confining units, typically comprised of clay and silt, create confining conditions by impeding the vertical flow of water within the aquifer system and are often several orders of magnitude more compressible than the coarse-grained sediments constituting the aquifers.[5,6,7]

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[2] Borchers, J. W., Carpenter, M., Kretsinger Grabert, V., Dalgish, B., & Cannon, D. (2014). Prepared By Full Report of Findings / Land Subsidence from Groundwater Use in California Land Subsidence from Groundwater Use in California Contributing Authors. http://www.californiawaterfoundation.org.

[3] Galloway, D. L., Jones, D. R., & Ingebritsen, S. E. (1999). *Land subsidence in the United States* (Vol. 1182). Geological Survey (USGS).

[4] Galloway, D. L., & Burbey, T. J. (2011). Regional land subsidence accompanying groundwater extraction. Hydrogeology Journal, 19(8), 1459.

[5] Freeze, R. A., & Cherry, J. A. (1979). Groundwater. Prentice Hall, Inc.

[6] Kelley, V., Deeds, N., Young, S., & Pinkard, J. (2018). Subsidence Risk Assessment and Regulatory Considerations for the Brackish Jasper Aquifer.

[7] Poland, J. F., Lofgren, B. E., Ireland, R. L., & Pugh, R. G. (1975). Land subsidence in the San Joaquin Valley, California, as of 1972.

Subsidence due to groundwater pumping is related to changes in pore-fluid pressure (expressed in terms of an equivalent **hydraulic [groundwater] head** or a "groundwater level" for this BMP) and the compressibility of the aquifer system (where the "aquifer system" includes a combination of the aquifer units, confining units, and interbeds). This relationship is based on the principle of **effective stress** (Figure 4-2), where stress from the weight of the overlying rock and water (σ_T, geostatic stress, or "**overburden"**), is balanced by the pore-fluid pressure (ρ, hydrostatic stress) and intergranular stress on the aquifer-system skeleton (σ_e, effective stress) (Part A of Figure 4-2).[8,9]

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

Figure 4-2. Illustration of Subsidence Mechanics

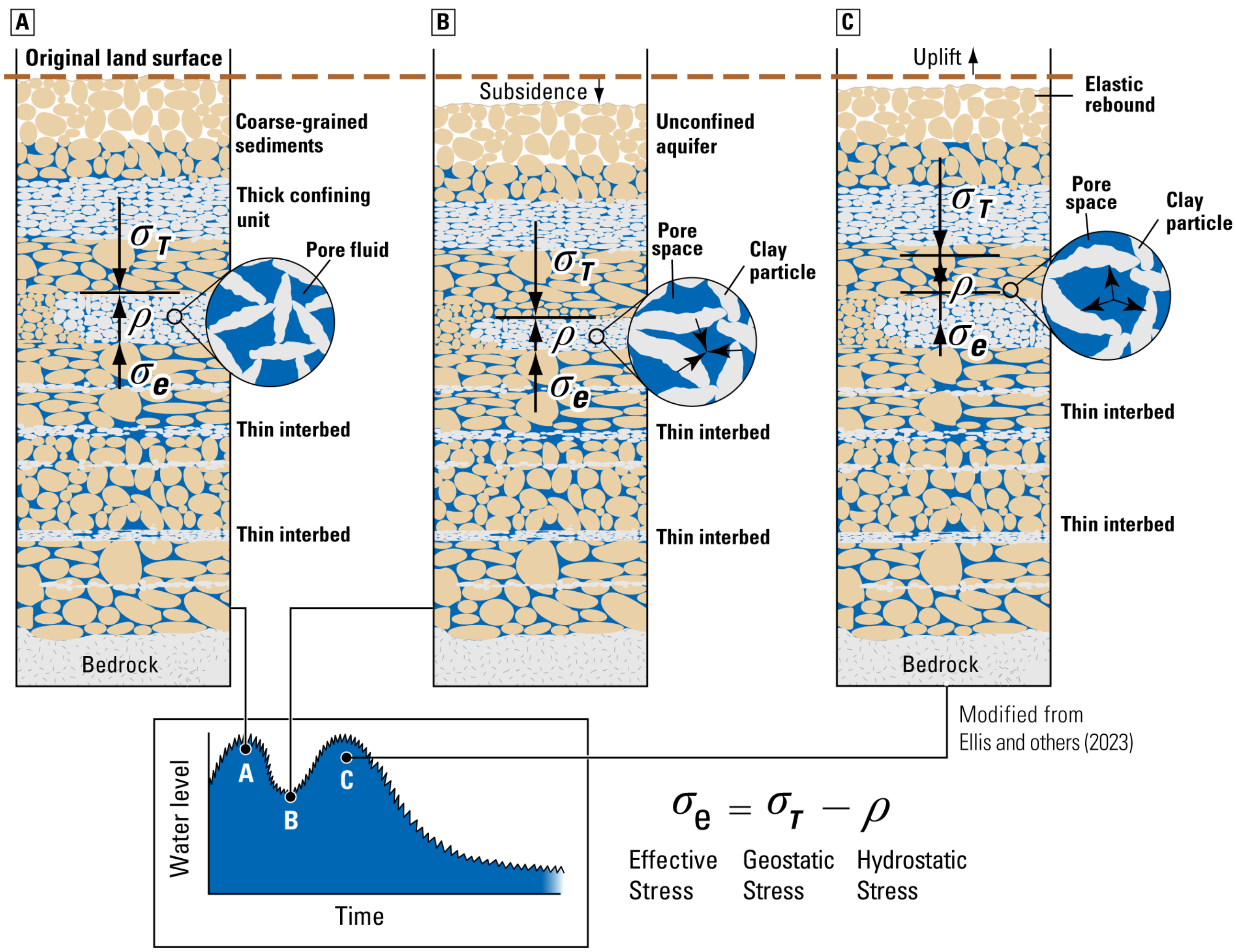

Figure Notes: This figure shows the mechanics of subsidence and visually illustrates effective stress (σ_e) and its relationship to total stress (σ_T) and fluid pressure (ρ) during times of changing hydraulic [groundwater] head or "groundwater level".

8 Terzaghi, K. (1925). Principles of soil mechanics. IV. Settlement and consolidation of clay. Engineering News-Record, 95, 874.

9 Meinzer, O.E., 1928, Compressibility and elasticity of artesian aquifers: Economic Geology, v. 23, no. 3, p. 263–291. https://doi.org/10.2113/gsecongeo.23.3.263.

As the groundwater level is lowered (i.e., a reduction in pore-fluid pressure) due to groundwater use, the overburden stress (weight of overlying sediments) is increasingly transferred to the granular skeleton of the aquifer system, leading to an increase in effective stress that compresses the skeleton (Part B of Figure 4-2). Conversely, when the groundwater level is raised, the increased pore-fluid pressure reduces the effective stress, allowing the aquifer-system skeleton to expand (Part C of). **Preconsolidation stress** is the greatest historical effective stress imposed on the aquifer system, which occurs at the lowest groundwater level that can occur before fine-grained sediments start to compress. The corresponding lowest groundwater level (in the fine-grained sediment) is referred to as the **preconsolidation head**.[10]

If the effective stress is less than the preconsolidation stress throughout the aquifer system, changes in groundwater level will result in **elastic** (or reversible) compaction of both the coarse- and fine-grained sediments in the aquifer system. Fine-grained sediments are **low permeability sediments** (clay and silt), through which water moves more slowly than coarse-grained sediments (sands and gravels). Short term fluctuations in groundwater levels, such as seasonal or daily variations, can lead to elastic compaction.[11] When the effective stress exceeds the preconsolidation stress, the skeletal structure of interbeds and confining units may undergo significant, permanent rearrangement, resulting in **inelastic** (or irreversible) compaction. Part C of Figure 4-2 shows a land surface that is lower than the original land surface in Part A due to inelastic compaction. However, it is higher than the land surface in Part B, demonstrating that some of the compaction was elastic. Due to the high compressibility of fine-grained, low permeability sediments, elastic and inelastic compaction and resulting subsidence is orders of magnitude higher in these sediments relative to coarse-grained material.

The change in effective stress and resulting compaction process in fine-grained sediments is not instantaneous; the low hydraulic conductivity (measure of a sediment's capability to conduct water) of these fine grained sediments results in depressurizing that can occur for many years, until equilibration occurs between the coarse- and fine-grained sediments (discussed further in Section 4.3.1).

During this depressurizing process, the preconsolidation head decreases to a new value when the groundwater level drops below the preconsolidation head; this new value is referred to in this BMP as the **critical head**. Critical head is identified for fine-grained sediments, not coarse-grained sediments. Depending on the stress history of the aquifer system, the critical head can differ between sequences of fine-grained sediments in the subsurface. This critical head value is the "new" preconsolidation head for the fine-grained sediments. Critical Head is discussed in Section 4.3.2, and recommendations to estimate critical head are discussed in Section 5.3.

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10 Leake, S. A., & Prudic, D. E. (1991). Documentation of a computer program to simulate aquifer-system compaction using the modular finite-difference ground-water flow model. US Government Printing Office.

11 Galloway, D. L., Jones, D. R., & Ingebritsen, S. E. (1999). Land subsidence in the United States (Vol. 1182). Geological Survey (USGS).

4.3 Subsidence Processes Summary

Fine-grained sediments within or adjacent to unconsolidated aquifers that undergo groundwater level declines related to groundwater pumping are susceptible to aquifer-system compaction.[12] Compaction of large amounts of fine-grained sediments can result in appreciable subsidence.[13] The compaction of these susceptible aquifer sediments, and thereby subsidence, is largely dependent on the various characteristics of the interbeds and confining units present in the aquifer system and the change in aquifer stress.[14] A full description of the technical components of subsidence processes is presented in Appendix A.

The extent of compaction largely depends on the characteristics and arrangement of layers of fine-grained sediments and on the magnitude, duration, and history of the groundwater level declines. The hydrogeological structure (number and thicknesses of interbeds and confining units) and fine-grained sediment properties control the total compaction possible for the aquifer system.[15] Fine-grained sediments that are thinner and have higher **vertical hydraulic conductivity** values will equilibrate to groundwater level changes more quickly, resulting in more immediate subsidence. Thicker layers of fine-grained sediments that have lower vertical hydraulic conductivity values will take longer to equilibrate to groundwater level changes. The time required for equilibration results in the delayed compaction of clay layers, potentially for years to decades or centuries in clays with low hydraulic conductivity, after an initial groundwater level decline occurred.[16,17] The sinking of the land surface due to the delayed compaction of clay layers is referred to as **residual subsidence**. Although vertical drainage typically governs consolidation, fine-grained units can exhibit moderate anisotropy, with horizonal conductivity a few times greater than vertical).[18] This anisotropy may cause limited lateral flow under non-equilibrated conditions but is generally a secondary factor relative to vertical drainage. This change in the amount of subsidence laterally is known as differential subsidence. Additional details of fine-grained unit properties are included in Appendix A.

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12 Hughes, J. D., Leake, S. A., Galloway, D. L., & White, J. T. (2022). Documentation for the Skeletal Storage, Compaction, and Subsidence (CSUB) Package of MODFLOW 6. US Geological Survey.

13 Kasmarek, M. C., & Robinson, J. L. (2004). Hydrogeology and simulation of ground-water flow and land-surface subsidence in the northern part of the Gulf Coast aquifer system, Texas (Issue 2004). US Geological Survey.

14 Kelley, V., Deeds, N., Young, S., & Pinkard, J. (2018). Subsidence Risk Assessment and Regulatory Considerations for the Brackish Jasper Aquifer.

15 Kelley, V., Deeds, N., Young, S., & Pinkard, J. (2018). Subsidence Risk Assessment and Regulatory Considerations for the Brackish Jasper Aquifer.

16 Hoffmann, J., Leake, S. A., Galloway, D. L., Wilson, A. M., & Survey, U. S. G. (2003). MODFLOW-2000 ground-water model-user guide to the Subsidence and Aquifer-System Compaction (SUB) Package. In Open-File Report. https://doi.org/10.3133/ofr03233.

17 Lees, M., Knight, R., & Smith, R. (2022). Development and Application of a 1D Compaction Model to Understand 65 Years of Subsidence in the San Joaquin Valley. Water Resources Research, 58(6). https://doi.org/10.1029/2021WR031390.

18 Freeze, R. A., & Cherry, J. A. (1979). Groundwater. Prentice Hall, Inc.

4.3.1 Residual Subsidence

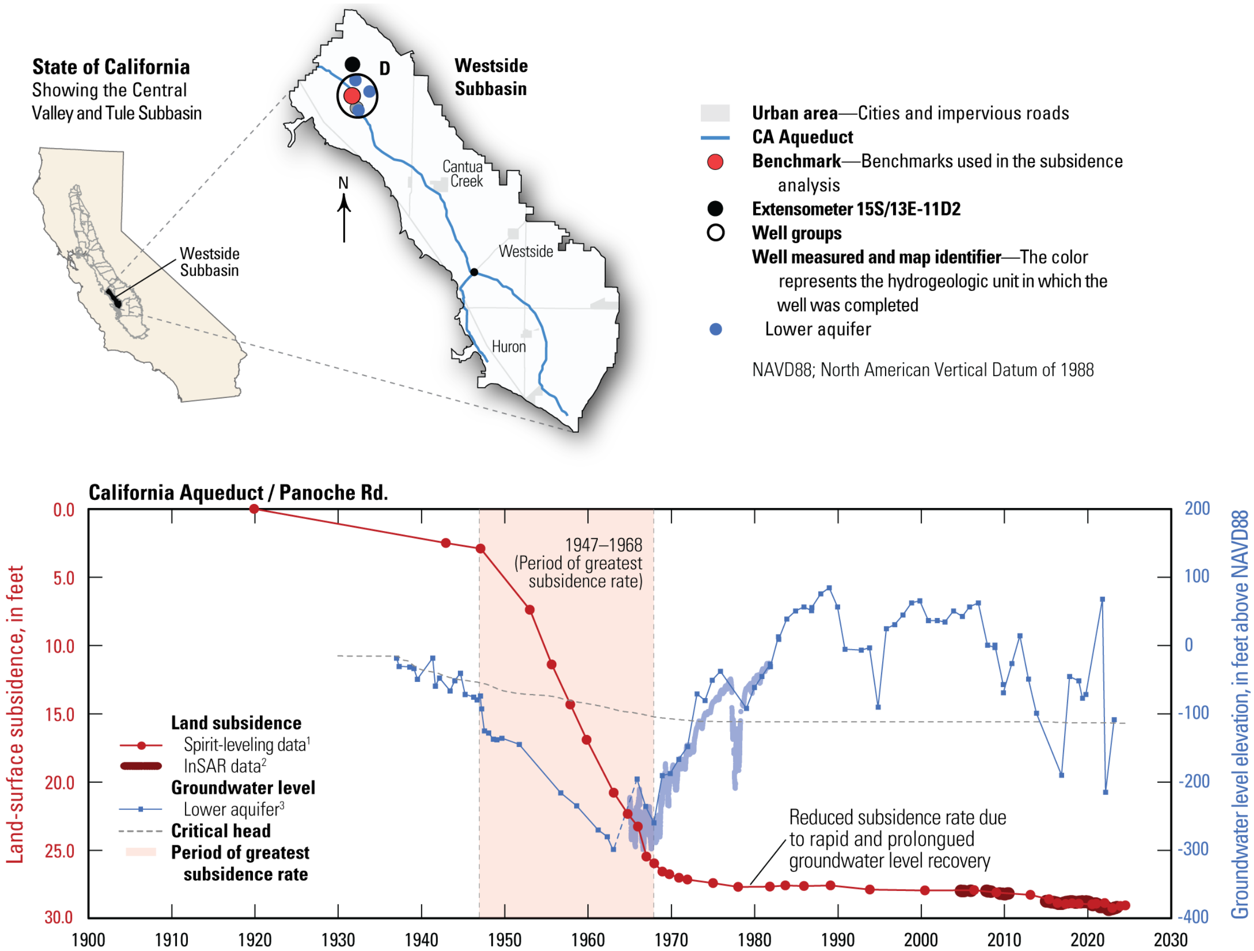
Residual subsidence is the continued compaction of fine-grained sediments, resulting in a decrease in land surface elevation over time after the primary cause of subsidence (response to groundwater level declines) has ceased. In an equilibrated aquifer system, the groundwater levels in the fine- and coarse-grained sediments are effectively equal. During groundwater pumping, the groundwater levels do not decline at the same rate for both sediment types; rather, groundwater levels in layers of coarse-grained sediments with higher permeability (sands and gravels) decline first and more rapidly than in layers of fine-grained sediments with lower permeability. While these coarse-grained sediments have negligible compaction, the groundwater level decline generates a pressure gradient between the coarse-grained and fine-grained units. At the boundaries between these sediments, the water in the fine-grained sediments will drain into the coarse-grained sediments under an increase in effective stress.

Due to the low permeability of fine-grained materials, depressurization causes a time-dependent increase in effective stress that progresses slowly through the unit. This gradual propagation of stress results in compaction of layers of fine-grained sediments over time and is seen at the surface as subsidence that occurs after the depressurizing event occurred. Historical modeling studies and recent one-dimensional (1D) compaction models show that delayed compaction of clay layers, and consequent residual subsidence, can occur over decades to centuries.[19] Additional details of residual subsidence are included in Appendix A, and empirical examples are provided in Appendix A.4. Details regarding the development and application of 1D models are included in Appendix C.

Residual subsidence can still occur during times after groundwater levels rebound above the critical head; however, raising groundwater levels as high and as quickly as possible above critical head minimizes residual subsidence. In the period from 1965 to 1975, shown in Figure 4-3, the groundwater level in the aquifer rose quickly and recovered above the critical head. The greatest sustained lower aquifer groundwater level decline and greatest subsidence rate since the first groundwater level measurements at this site occurred over the 1947-1968 period (shaded in red on the figure). At the onset of this recovery, subsidence rates remained relatively high (1963 to 1967) but decreased quickly as groundwater levels in the lower aquifer rose significantly above critical head (after 1968) due to the rapid and substantial groundwater level recovery, which resulted in a faster period of equilibration between the coarse- and fine-grained sediment than what would have occurred with a lesser groundwater level recovery. This site is located approximately one mile west of the well-known photo of Dr. Joseph F. Poland standing next to a telephone pole indicating about 30 feet of subsidence between 1925 and 1977 at benchmark S 661.

[19] Galloway, D. L., Jones, D. R., & Ingebritsen, S. E. (1999). Land subsidence in the United States (Vol. 1182). Geological Survey (USGS).

Figure 4-3. Groundwater Level and Land Subsidence Data in the Westside Subbasin Showing Groundwater Level Decline and Active Subsidence, then Recovery and Residual Subsidence



[1]Benchmarks GWM 14, 111.91 L, 111.93 L, and Z 1444 were used to determine cumulative subsidence from 1941 to 2024. From Ireland and others (1984), a total of 2.5 feet of subsidence was estimated from the 1920s to 1943 one mile east of this benchmark site. [2]The initial value for the InSAR vertical displacement is registered to the amount of cumulative subsidence determined from spirit leveling. Data obtained from CADWR and extracted at cells containing the benchmark. [3]1937–46: 364109120294101 (USGS); 1947–63: 364102120294101 (USGS); 1965–2009: 14S13E22A001M; 2010–23: 15S13E02P001M.

Continuous recorder well 15S13E11D002M located 1.8 miles to the south at historical extensometer 15S/13E-11D2 is also shown. This site is located approximately one mile west of a well-known photo of Dr. Joseph F. Poland standing next to a telephone pole indicating about 30 feet of subsidence between 1925 and 1977 at benchmark S 661 (at right). Note that the critical head shown on this figure is the representative critical head for the lower aquifer. Also note this is the same site shown on Figure A-4, which is also site GWM 14 in Bulletin 118.

4.3.2 Critical Head

Critical head is the groundwater level—or pressure threshold—within compressible sediments (e.g., fine-grained sediments like clays), below which permanent compaction, and therefore subsidence, begins (as discussed in Section 4.2). Because groundwater levels within fine-grained sediments are not typically monitored directly (i.e., through dedicated piezometers or monitoring wells in clay layers), analyses of subsidence records and groundwater level observations for wells screened in the aquifer unit may be used to help estimate the critical head, such as those described in Section 5.3. Estimates of critical head provide groundwater managers with a quantitative target for managing groundwater levels in the aquifer system to prevent or minimize subsidence. The critical head is site-specific and varies by location and depth, dependent on the spatial distribution and properties of fine-grained sediments and groundwater conditions.

Because it is often impractical to characterize the critical head for many sequences of fine-grained sediment within each aquifer unit, a representative critical head (referred to hereafter in this document simply as the "critical head") can be estimated for aquifer units, or vertical intervals of aquifer units, at specific locations to provide an operationally meaningful threshold for groundwater levels. This representative critical head can be determined in multiple ways and is further discussed in Section 5.3. Using a representative critical head provides a guide for maintaining groundwater levels high enough to avoid renewed inelastic compaction. This representative critical head has been estimated for five sites shown in Appendix A.3, and a total of 50 sites in Bulletin 118 Appendix I[20]. An in-depth discussion of critical head is provided in Appendix A.3.

Inelastic compaction occurs when groundwater levels drop below the critical head in fine-grained sediments. In areas currently unaffected by subsidence, maintaining aquifer groundwater levels above the critical head prevents permanent compaction. Conversely, allowing groundwater levels to fall below the critical head, even briefly in some cases, can initiate permanent subsidence. The magnitude of subsidence is directly related to how far and how long groundwater levels remain below the critical head.

Where subsidence is already occurring, a rapid and sustained recovery of aquifer groundwater levels well above the critical head is essential to minimize long-term subsidence effectively. Such recovery reduces the time required for groundwater levels within fine-grained sediments to reach a new equilibrium with conditions in the surrounding aquifer, thereby halting compaction—and thus, subsidence—sooner. In contrast, maintaining aquifer groundwater levels at or near the critical head following periods of decline will result in prolonged residual subsidence. Examples illustrating the relationships between groundwater recovery rates and delayed compaction are documented in the Long-Term Stress History analysis in Appendix A.4, featuring case studies from the San Joaquin and Sacramento Valleys.

Subsidence can be either elastic (temporary and recoverable) or inelastic (permanent) depending on whether groundwater levels decline below the critical head. Elastic compaction, such as the

[20] 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.

seasonal fluctuation observed in the San Joaquin Valley (peak-to-trough magnitudes up to approximately 3.0 inches[21,22]) does not permanently alter sediment properties. In contrast, inelastic compaction, triggered when groundwater levels drop below the critical head, permanently rearranges the skeletal structure of the fine-grained sediments. Additional details on short-term elastic compaction are described in Appendix A.5.

4.4 Limiting Subsidence

The key to minimizing ongoing subsidence and avoiding future subsidence is a recovery of groundwater levels to elevations above critical head in the fine-grained units as high and as quickly as possible. Raising groundwater levels in the aquifer can reduce the stress gradient between the aquifer and interbeds and confining units and slows the drainage of water out of and—reduces depressurization of—the fine-grained units. The rate and extent of inelastic compaction will depend on the magnitude and duration of time that groundwater levels are below the critical head, as well as the thicknesses, distribution, and hydraulic properties of the interbeds and confining units and the long-term stress history of the region. Most subsidence is related to stress propagation into interbeds and confining units.

As shown in Figure 4-3, a rapid groundwater level recovery in the lower aquifer between 1965 and 1975 resulted in a substantial decrease in the average subsidence rate from about 1 foot per year (ft/year) between 1947 and 1968 to 0.05 ft/year per year between 1969 and 1989. Rapidly raising groundwater levels greatly limited the amount of land subsidence observed at this location. More information about the modeled relationship between groundwater levels and land subsidence, including additional modeling sites, can be found in Appendix A.

Groundwater managers have the ability to limit future subsidence based on how they choose to manage groundwater levels. In general, the faster and higher groundwater levels rise, the less land subsidence will be observed based on observed historical conditions such as Figure 4-4 and various modeling scenarios. In association with this BMP, various modeling scenarios were conducted to simulate future land subsidence given different groundwater level thresholds. At each site, five groundwater levels were simulated: (historical low, critical head, critical head plus 20 feet, critical head plus 50 feet, and a rebound scenario, which represents raising groundwater levels as high and as quickly as possible). The results of modeling at one site are shown in Figure 4-4, and results at four additional sites are shown in Appendix C, along with additional sites in Bulletin 118 Appendix I.[23]

The results at this site (Figure 4-4) are clear: the higher the groundwater level, the less future subsidence occurs, often with differences ranging in feet of subsidence. Groundwater managers

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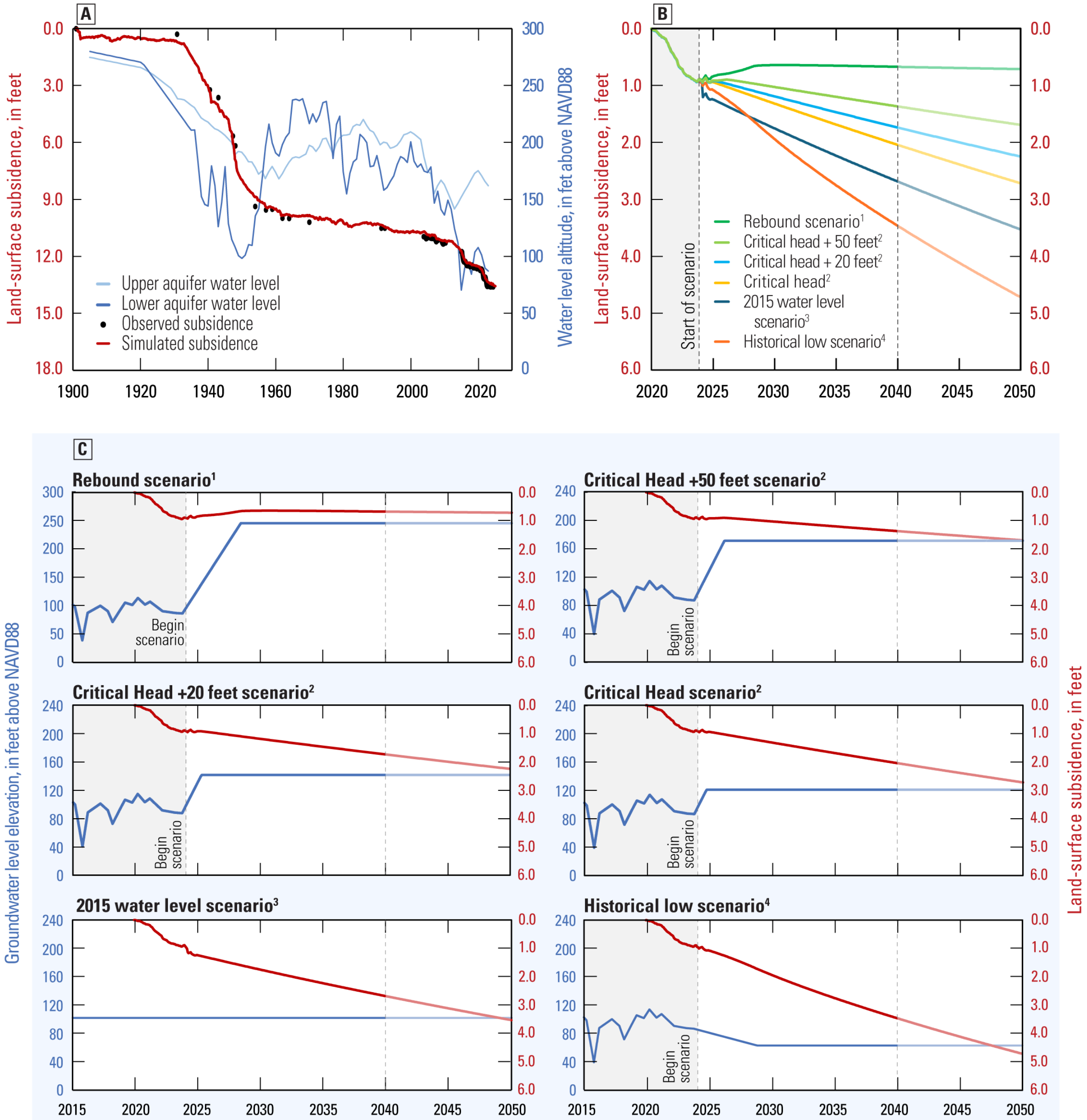
21 Chaussard, E., & Farr, T. G. (2019). A new method for isolating elastic from inelastic deformation in aquifer systems: Application to the San Joaquin Valley, CA. Geophysical Research Letters, 46(19), 10800–10809.

22 Neely, W. R., Borsa, A. A., Burney, J. A., Levy, M. C., Silverii, F., & Sneed, M. (2021). Characterization of groundwater recharge and flow in California's San Joaquin Valley from InSAR-observed surface deformation. Water Resources Research, 57(4), e2020WR028451.

23 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.

should be aware of this relationship and thoroughly discuss how their chosen thresholds may affect land subsidence and land uses, including infrastructure impacts.

Figure 4-4. Results of Modeling Scenarios to Simulate Future Land Subsidence Given Different Groundwater Level Thresholds



¹This scenario reflects a rapid rise in water levels to the highest historical groundwater elevation, approximating managed aquifer recovery. ²These scenarios uses the approximated critical head, the approximated critical head + 20 feet, and the approximated critical head + 50 feet for the duration of the simulation. ³This scenario uses the 2015 water level through the duration of the simulation. ⁴This scenario uses the average of the lowest three water levels recorded and approches this water level using the 2015–23 decline rate.

Figure Note: Part A shows subsidence and groundwater level (i.e., water level) data; Part B shows estimated subsidence from numerical modeling methods described in Appendix C for six scenarios; Part C shows input water levels and estimated subsidence for each of the scenarios shown in Part B.

4.5 Subsidence in California

Subsidence has been documented throughout the last century in many parts of California and continues today. Groundwater satisfies around 40% of California's annual water demand and serves agricultural, municipal, industrial, and domestic purposes.[24,25] Many areas are 100% reliant on groundwater to meet demands. Due to the extensive use of groundwater, decades of groundwater pumping in excess of natural recharge have caused widespread groundwater level declines, and the resulting subsidence has been documented in many parts of California.

Subsidence in California has led to significant impacts to infrastructure in different areas over the last century. In fact, a 2014 study found that subsidence in California has caused billions of dollars of damage to water conveyance, flood control, transportation infrastructure, and groundwater wells.[26] Water Conveyance facilities such as the California Aqueduct and Friant-Kern Canal have lost up to 46% and 60% of their respective conveyance capacities in certain areas due to subsidence.[27,28] Flood infrastructure such as the Corcoran Levee has been raised multiple times in just the past 10 years due to subsidence impacts,[29] and portions of San Jose require protection because subsidence has lowered these portions below sea level.[30] These are just a few of the many subsidence impacts that have occurred throughout California.

From 1926 to 1970, an area in the Central Valley southwest of Mendota had documented subsidence of more than 28 feet (Figure 4-3).[31] Construction of the Central Valley Project began in the late 1930s to address water supply and distribution in California's Central Valley.[32] The introduction of Central Valley Project surface water imports via the Friant-Kern and Delta-Mendota Canals in the 1950s, and Central Valley Project and State Water Project surface water imports via the California Aqueduct in the 1970s, significantly reduced groundwater reliance, initiated groundwater level recoveries, and slowed and even stopped subsidence in some areas of the San

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[24] Borchers, J. W., Carpenter, M., Kretsinger Grabert, V., Dalgish, B., & Cannon, D. (2014). Prepared By Full Report of Findings / Land Subsidence from Groundwater Use in California Land Subsidence from Groundwater Use in California Contributing Authors. http://www.californiawaterfoundation.org.

[25] California Department of Water Resources. (2024c, July 24). Groundwater. Https://Water.ca.Gov/Water-Basics/Groundwater.

[26] Borchers, J. W., Carpenter, M., Kretsinger Grabert, V., Dalgish, B., & Cannon, D. (2014). Prepared By Full Report of Findings/Land Subsidence from Groundwater Use in California Land Subsidence from Groundwater Use in California Contributing Authors. http://www.californiawaterfoundation.org.

[27] California Natural Resources Agency, Department of Water Resources. (2023). The State Water Project Delivery Capability Report 2023. Sacramento, CA: California Department of Water Resources. Published July 2024.

[28] California Department of Water Resources. (2022c) DWR Releases Funds for Repairs of the Friant-Kern Canal.

[29] California Governor's Office. Governor Newsom Announces New Flood Investment Proposals. https://www.gov.ca.gov/2023/05/11/governor-newsom-announces-new-flood-investment-proposals/ May 11, 2023.

[30] Santa Clara Valley Water District. (2025). Subsidence. https://www.valleywater.org/your-water/groundwater/subsidence.

[31] Poland, J. F., & Ireland, R. L. (1988). Land subsidence in the Santa Clara Valley, California, as of 1982 (Vol. 497). US Government Printing Office.

[32] Stene, E. A. (2015). The Central Valley Project. Available at https://www.usbr.gov/history/cvpintro.html.

Joaquin Valley.[33] As subsidence abated due to this influx of surface water and reduced groundwater pumping, statewide monitoring efforts of subsidence declined due to an assumption of stabilization of groundwater levels through surface water imports. However, expansions of agricultural acreage and drought periods between 2000 and 2023 coincided with reduced surface water availability, resulting in increased groundwater pumping, which resulted in accelerated subsidence rates of more than 1.0 ft/year in parts of the San Joaquin Valley and more than 0.5 ft/year in parts of the Sacramento Valley.[34,35] Recent land subsidence rates have decreased following the wetter, higher precipitation 2023 water year and subsequent reductions in groundwater pumping. However, subsidence rates may increase again during future dry periods unless groundwater pumping is reduced in certain areas.

Subsidence was measured from 1915 through 1970 in Santa Clara County, with maximum subsidence of about 14 feet occurring under downtown San Jose. This subsidence cost over $1 billion in today's dollars to remedy, as the subsidence lowered communities and treatment facilities below sea level.[36] Subsidence is now prevented in Santa Clara County by managing groundwater levels above thresholds that avoid subsidence, supported by ongoing land surface monitoring.

Spirit leveling surveys for measuring land surface elevations were the primary means of measuring subsidence through most of the 20th century. However, since the early 2000s, there has been significant improvements and a shift in the State's subsidence monitoring network and methods. This includes the installation of continuous Global Positioning System (GPS) stations, the installation/refurbishment of extensometers, and—most notably—the State-supported processing and reporting of satellite-based Interferometric Synthetic Aperture Radar (InSAR) data across many groundwater basins. DWR publishes these statewide InSAR subsidence data on the California Natural Resources Agency (CNRA) Open Data Portal[37] and the SGMA Data Viewer with quarterly updates.[38] Areas that have subsided more than 0.5 foot since October 1, 2015 are shown in Figure 4-5. Subsidence monitoring in California has been regularly conducted using InSAR data since January 2015[39] and is discussed in Section 5.1.1.

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[33] Sneed, M., Brandt, J. T., & Solt, M. (2013). Land subsidence along the Delta-Mendota Canal in the northern part of the San Joaquin Valley, California, 2003-10 (No. 2013-5142). US Geological Survey.

[34] California Department of Water Resources. (2021). Groundwater Conditions Report 2021. https://water.ca.gov/-/media/DWR-WebSite/Web-Pages/Programs/Groundwater-Management/Data-and-Tools/Files/Statewide-Reports/Groundwater-Conditions-Report-Fall-2021.pdf.

[35] California Department of Water Resources. (2022b, February 22). New Data Shows Subsidence Continued in Water Year 2021; Pace Slower than Previous Droughts. https://water.ca.gov/News/News-Releases/2022/Feb-22/New-Data-Shows-Subsidence-Continued-in-Water-Year-2021-Pace-Slower-than-Previous-Droughts.

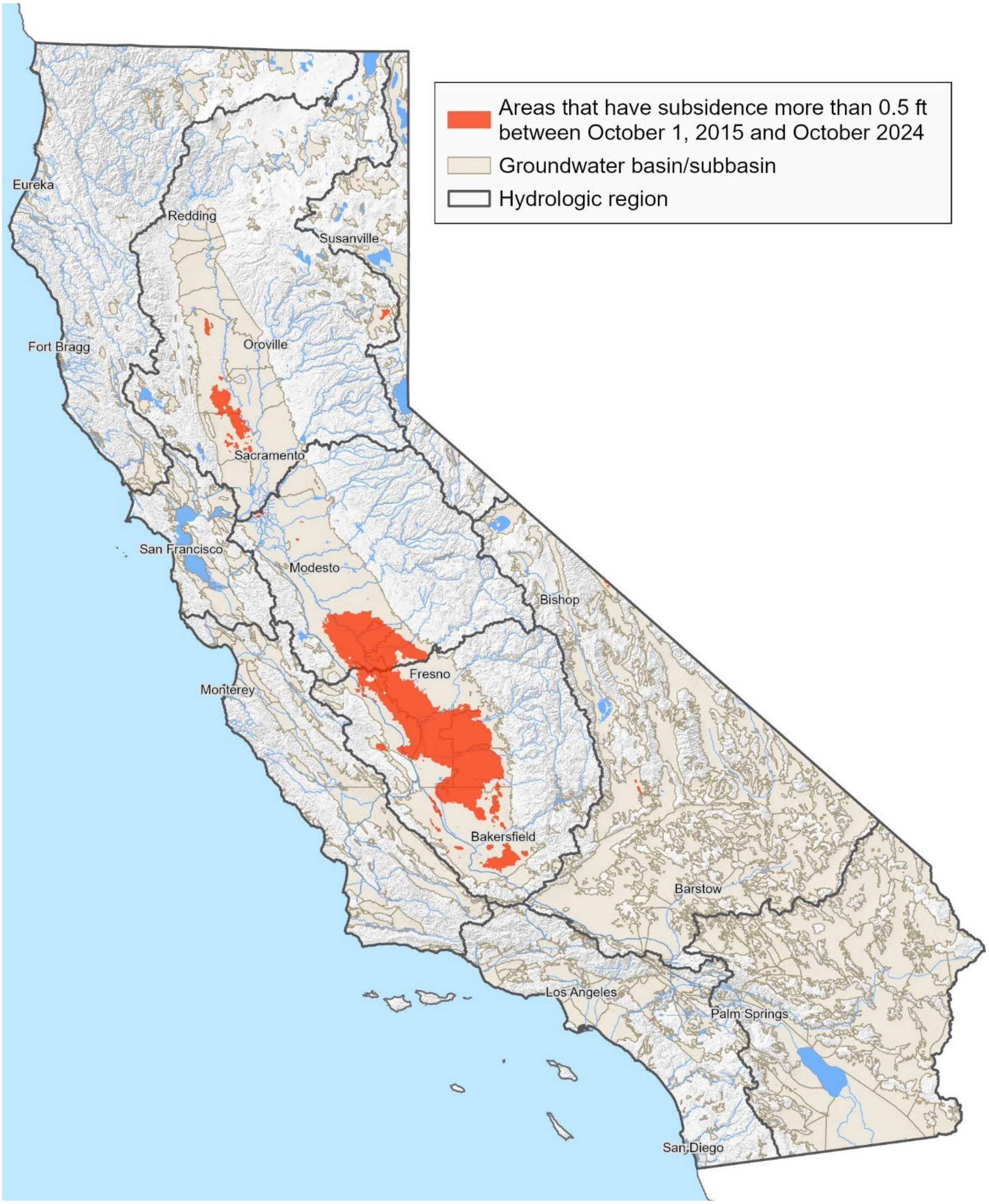
[36] Santa Clara Valley Water District. (2025). Subsidence. https://www.valleywater.org/your-water/groundwater/subsidence.

[37] California Natural Resources Agency. (2024). California Natural Resources Agency Open Data. https://data.cnra.ca.gov.

[38] California Department of Water Resources. (2024a). SGMA Data Viewer. https://sgma.water.ca.gov/webgis/?appid=SGMADataViewer#currentconditions.

[39] California Natural Resources Agency. (2025). TRE ALTAMIRA InSAR Subsidence Data. https://data.cnra.ca.gov/dataset/tre-altamira-insar-subsidence.

Figure 4-5. Areas that Have Subsided More than 0.5 foot between October 2015 and October 2024



Local, State, and federal entities will continue to work to address the cause, damage, and costs associated with land subsidence in California. Each time repairs are made to infrastructure, should land subsidence in that area continue, there is a risk that the repairs themselves will become stranded or ineffective, and even more additional costs must be expended on yet more repairs. The key to minimizing damage and costs associated with land subsidence is managing the basin to avoid or minimize land subsidence, not simply repairing the damage without addressing the root cause.

Although general public funds and specific infrastructure owners and their ratepayers have in the past paid to repair damage caused by subsidence, under California law, groundwater pumpers may also be liable for damages caused by subsidence from their groundwater pumping. For example, in *Los Osos Valley Associates v. City of San Luis Obispo* (1994) 30 Cal.App.4th 1670, the owner of a shopping mall sued the city for structural damage caused by subsidence from the city's increased groundwater pumping during a drought. The court announced: "The rule, as it pertains to subterranean water, is stated in the Restatement Second of Torts section 818: 'One who is privileged to withdraw subterranean water, oil, minerals, or other substances from under the land of another is not for that reason privileged to cause a subsidence of the other's land by the withdrawal.'" Accordingly, the court held that "the City may not … avoid compensation for the physical destruction of [plaintiffs'] buildings due to its groundwater pumping operations," and affirmed that the city was liable for physical damage to the buildings owned by plaintiff. The potential for liability should further incentivize efforts to avoid or minimize subsidence in basins where costly infrastructure damage or other risks could occur.

Subsidence, and its associated impacts, have been an ongoing issue in California, which may have influenced the passage of the first law in state history to present a statewide framework to regulate groundwater: SGMA. Subsidence is mentioned in the first page of SGMA, stating "it is the intent of the Legislature…to avoid or minimize subsidence."[40] Under SGMA, new local agencies—called Groundwater Sustainability Agencies—have been established and are now required to manage land subsidence by setting standards of what would constitute significant and unreasonable conditions in a Groundwater Sustainability Plan (GSP). GSPs can be found on the Department's SGMA Portal. For more information on Land Subsidence and SGMA, please see Chapter 6.

[40] CWC § 10720.1(e).

5 Technical Assistance

This section provides assistance and tools to monitor conditions related to subsidence, identify at-risk and affected infrastructure, estimate critical head groundwater level, and conduct numerical modeling.

5.1 Land Subsidence Monitoring

Monitoring land surface elevations, groundwater levels, and groundwater pumping is the best practice for groundwater managers to use to identify and manage subsidence. Given the diverse conditions under which subsidence occurs and the various infrastructure vulnerable to it, designing monitoring networks requires tailored solutions rather than a one-size-fits-all approach. The monitoring techniques and datasets to evaluate changes in land surface elevation each have strengths and deficiencies. Further, their utility can be greatly improved by comparing the results of other monitoring datasets and monitoring networks.

5.1.1 Land Surface Elevation Monitoring

Monitoring changes in land surface elevation is important to the management of subsidence. The evaluation, measurement, and monitoring of subsidence should rely on multiple data sources. These data types include, but are not limited to, leveling surveys referenced to known stable benchmarks; borehole extensometers anchored below compacting sediments; continuous GPS stations and/or static and Realtime Kinematic Global Navigation Satellite System/GPS surveys and installations; and displacement estimates from InSAR.

The land surface monitoring network should be capable of identifying the spatial extent and magnitude of land subsidence, including the ability to evaluate temporal changes and efficacy of management strategies. The network should include enough spatial coverage to evaluate conditions near land uses and infrastructure that may be affected by subsidence and be measured at a regular frequency that supports groundwater managers' efforts to understand the occurrence of subsidence and its management.

Land subsidence due to groundwater pumping can vary in magnitude and occur on a wide range of time and spatial scales. Each monitoring method has unique limitations of monitoring frequency and may be influenced by different kinds of uncertainties, as discussed in Appendix B. Because of the variability of the different monitoring methods, subsidence monitoring networks should incorporate all available subsidence data and data collection approaches including, but not limited to:

1. Spirit-leveling surveys (or "**leveling**") of benchmarks (historical subsidence measured using spirit leveling is shown in Figure 5-1);
2. Borehole extensometers (or "**extensometers**"), a stable benchmark installed at a depth that is used to measure the 1D thickness of a specified depth interval of an aquifer system (locations of known extensometers are shown in Figure 5-2);
3. **GPS** stations, which are sites that collect high-precision position measurements on regular intervals (locations of known GPS stations are shown in Figure 5-2); and

4. **InSAR**, a satellite-based remote sensing technique that measures ground elevation change over large areas. (InSAR measured subsidence from June 2015 to March 2024 is shown in Figure 5-3.)

Each subsidence measurement type is useful when used exclusively; however, integrating the four subsidence measurement types leverages their various temporal and spatial scales to improve the understanding of compaction and subsidence processes. Details regarding subsidence monitoring datasets and methodologies, how they are used independently and with each other, and their general limitations are described in Appendix B. Examples of using these datasets to build long-term time series of subsidence are discussed in Appendix A.4 and in California's Groundwater Update 2025 (Bulletin 118) Appendix I: Land Subsidence.[41]

Elastic and inelastic compaction can occur over short time intervals (as discussed in Appendix A.5). Frequent and routine evaluation of subsidence data allows groundwater managers to detect changes, especially sudden or unexpected ones, and to take actions in a timely manner to avoid or minimize the amount of inelastic compaction that occurs. Subsidence monitoring data should be reviewed as often as is feasible to reduce the time between when subsidence occurs and management to reduce subsidence.

[41] 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.

Figure 5-1. 1926–1970 Land Subsidence in the Central Valley from Spirit Leveling

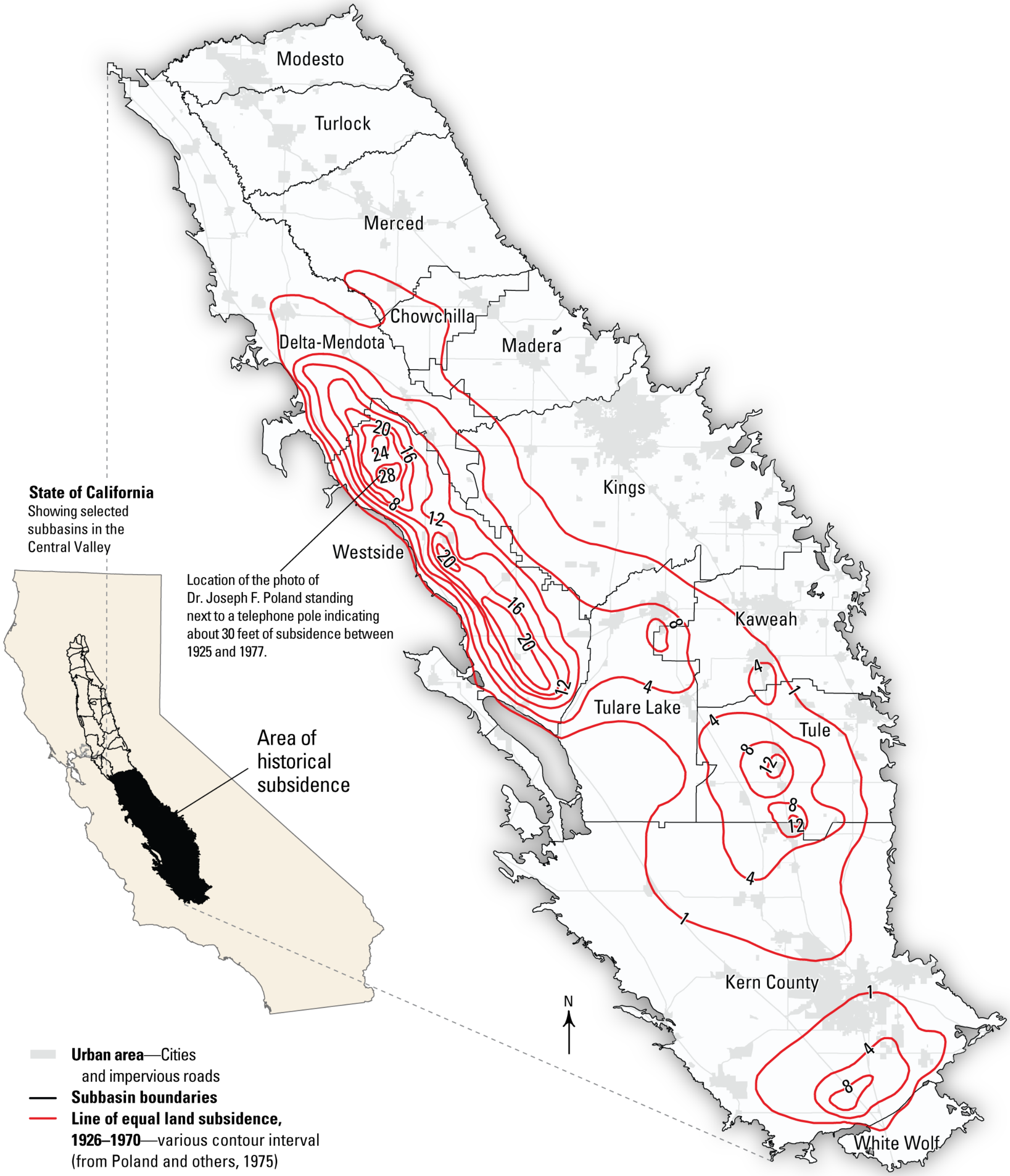


Figure 5-2. Locations of Borehole Extensometers and Global Positioning System Stations in the Central Valley.

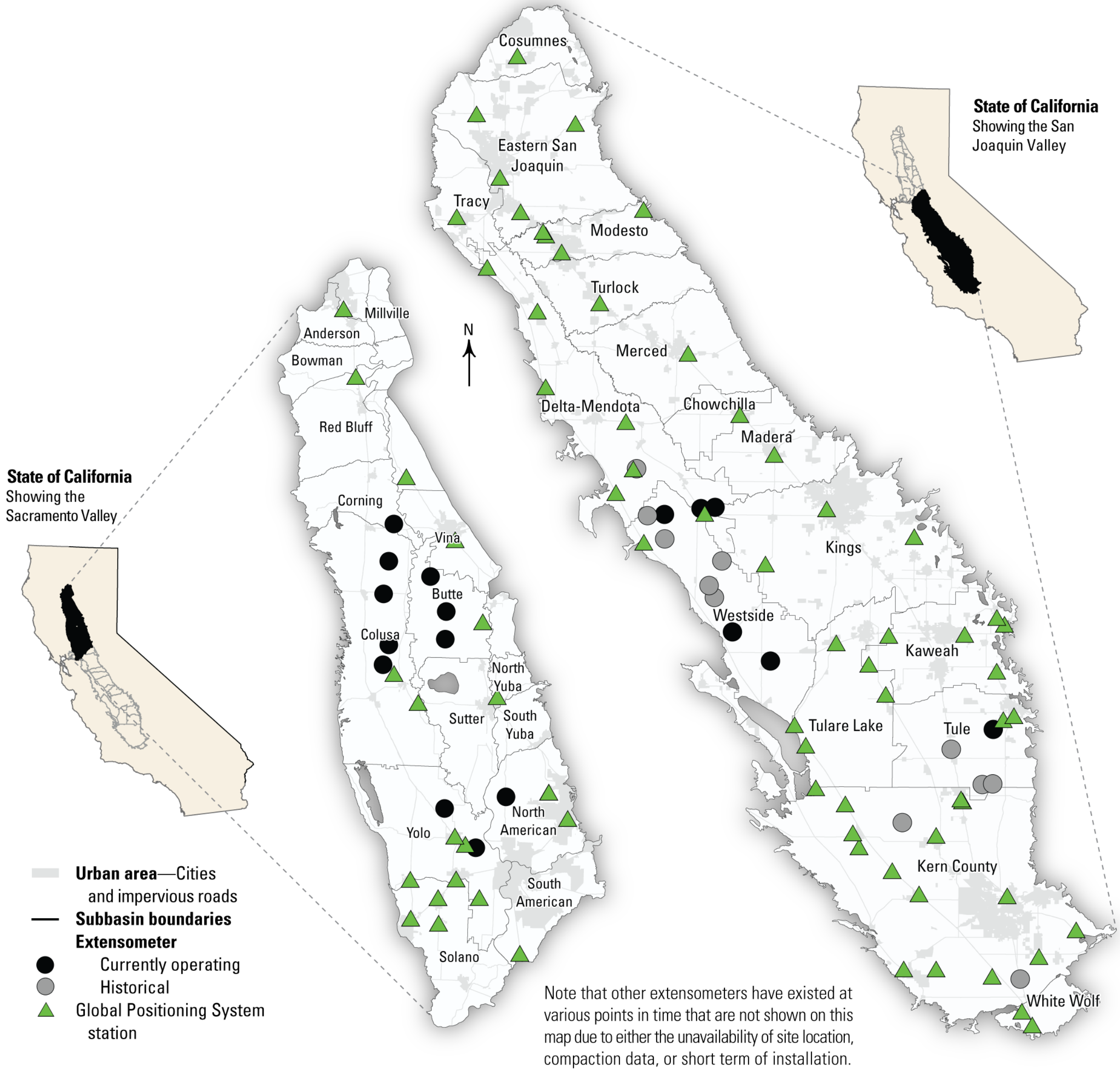
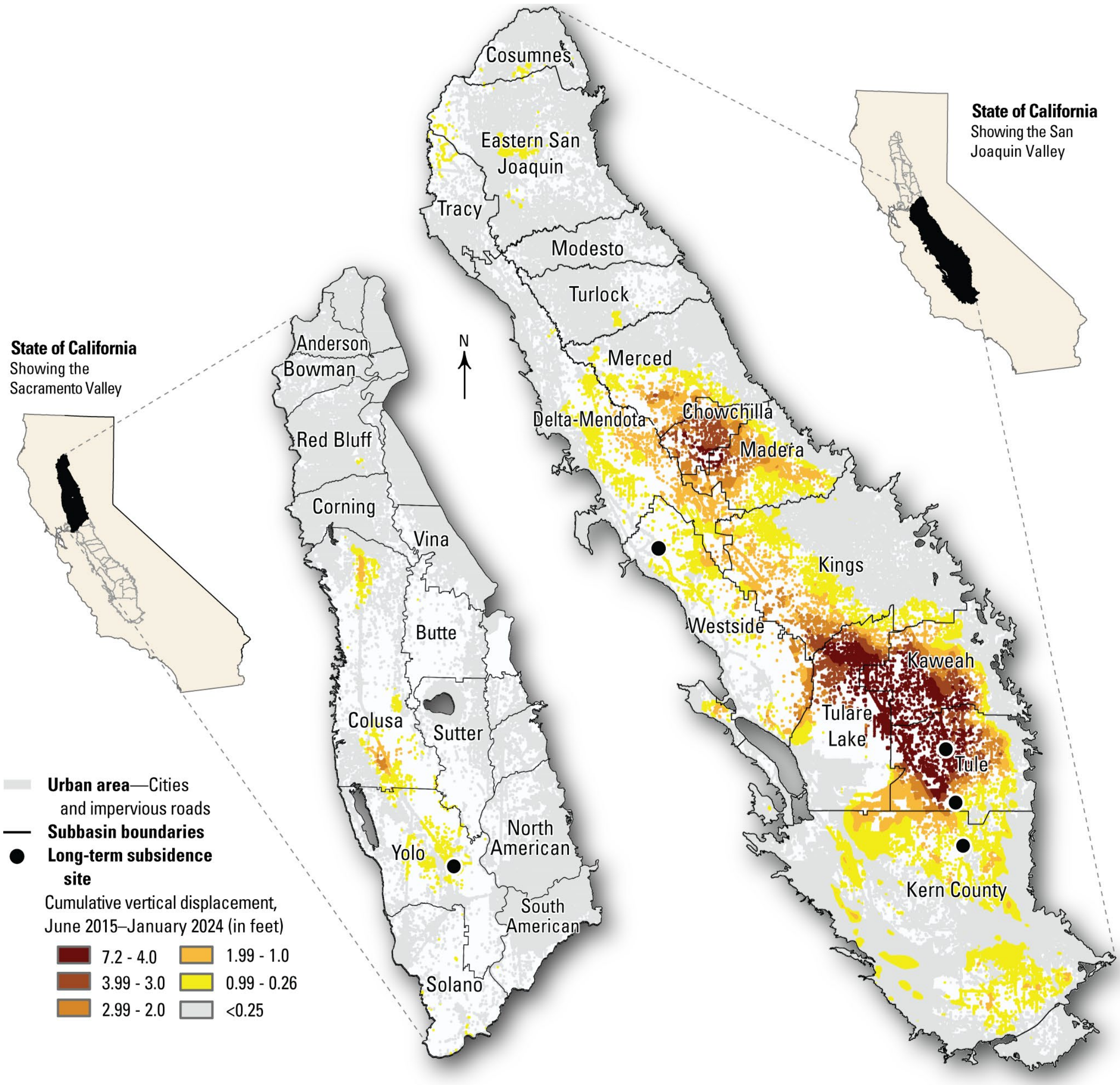


Figure 5-3. June 2015–March 2024 Subsidence from InSAR in the Central Valley



5.1.2 Groundwater Level Monitoring with Consideration of Subsidence

Robust groundwater level monitoring networks are essential for responsive and adaptive management, as lowering of groundwater levels is the primary driver of subsidence in California. This direct connection between declines in groundwater levels due to pumping and subsidence is discussed in Chapter 4. To manage groundwater levels to avoid impacts from subsidence, groundwater managers should monitor groundwater levels with a spatial density of sites and with a measurement frequency sufficient to evaluate the connection between groundwater levels and subsidence in their basin. How subsidence data and groundwater level data can be used in conjunction with numerical models to estimate the critical head in fine-grained units is discussed in Section 5.3.

Monitoring wells should be distributed spatially, both vertically and laterally, to capture groundwater level changes throughout the aquifer system. Monitoring wells should be placed in all aquifer units (for example: the upper and lower aquifers in California's Central Valley) to (1) evaluate the aquifer response to natural factors such as precipitation and anthropogenic factors such as groundwater pumping and managed aquifer recharge[42] and (2) to provide groundwater level data to estimate critical head, given that aquifer groundwater levels are used because fine-grained sediments are not typically monitored directly.

Vertically distributed monitoring is especially important in areas where pumping occurs at different depths across an aquifer system. The shallower aquifers may show seasonal effects of recharge and groundwater levels that are generally stable, whereas groundwater levels in the deeper layers may be declining due to pumping exceeding recharge. The long-term groundwater level data across different aquifers and depths are useful for modeling three-dimensional groundwater flow systems.[43] Monitoring all aquifers present in a given area is valuable for understanding groundwater dynamics and the impact of pumping, natural and augmented recharge, and supplemental water supplies on the groundwater level conditions.

Monitoring wells at various depths are valuable for groundwater managers to understand groundwater conditions, especially in water production zones, in areas experiencing significant subsidence or groundwater development. Monitoring wells should be present near GPS, benchmark, or extensometer sites to allow groundwater managers to evaluate the connection between groundwater levels and subsidence.

Installation of new monitoring wells and frequent monitoring of groundwater levels in and near subsidence monitoring sites will reduce the uncertainty of estimated critical head in interbeds and confining units. Complex aquifer systems often include multiple coarse-grain and fine-grained units; installing multi-depth monitoring wells or nested well sites allows the logging of the sediment types encountered during drilling, provides important data on the hydrogeology of complex basins,[44] and provides groundwater level measurements at various depths. Improvements to groundwater monitoring networks should focus on strategically placing wells that represent diverse geological conditions, as lithology data are often a limiting factor in developing accurate numerical models of complex aquifer systems.[45] Borehole lithology provides essential information about subsurface composition, structure, and properties, helping to characterize the distribution and thickness of fine-grained interbeds and confining units. These data are important for defining hydraulic properties and determining the horizontal extent and vertical thickness of lithology layers

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[42] Borchers, J. W., Carpenter, M., Kretsinger Grabert, V., Dalgish, B., & Cannon, D. (2014). Prepared By Full Report of Findings / Land Subsidence from Groundwater Use in California Land Subsidence from Groundwater Use in California Contributing Authors. http://www.californiawaterfoundation.org.

[43] Taylor, C. J., & Alley, W. M. (2001). Ground-water-level monitoring and the importance of long-term water-level data (Vol. 1217). US Geological Survey Denver, CO, USA.

[44] Hanson, R. T., Martin, P., & Koczot, K. M. (2003). Simulation of ground-water/surface-water flow in the Santa Clara-Calleguas ground-water basin, Ventura County, California. Water-Resources Investigations Report, 02–4136, 157.

[45] Galloway, D. L., & Burbey, T. J. (2011). Regional land subsidence accompanying groundwater extraction. Hydrogeology Journal, 19(8), 1459.

in regional models, which are important for predicting groundwater movement and identifying compaction-prone units, estimating critical head, and predicting subsidence.

Frequent monitoring and reporting of groundwater levels to inform timely management actions is a best practice for avoiding and minimizing subsidence. Poor data quality and spatial and temporal gaps in data can result in incorrect assumptions and biases. In highly managed basins, diverse sources of supplemental water and variations in the timing of water deliveries or the addition of new projects can significantly impact groundwater levels. As a result, seasonal low groundwater levels may not occur at consistent times each year, and 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. Figure 5-4 shows an example of continual, monthly, and biannual groundwater level measurement frequency.

Figure 5-4. Continual, Monthly, and Biannual Recording Interval Comparison of Groundwater Levels.

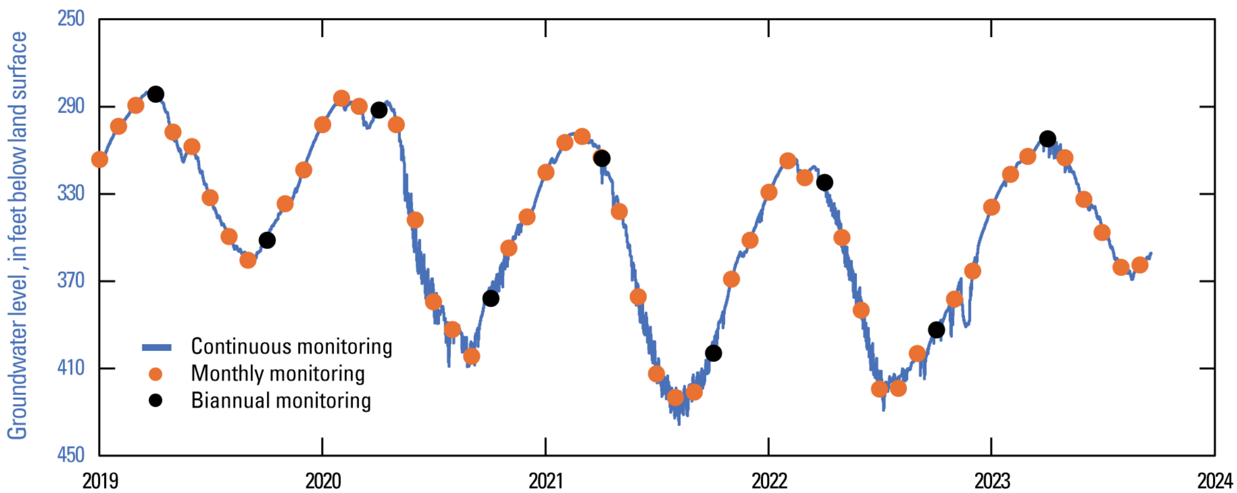

Fig. 14 Bi-annual, monthly, and continuous recording interval comparison of groundwater levels

The lowest seasonal groundwater level is an essential metric for predicting aquifer compaction and managing land subsidence. Monthly or more frequent measurements are the best practice for monitoring, as the seasonal lows are the times when groundwater levels may first fall below critical head, and inelastic compaction may occur. Critical head is discussed in Section 4.3.2. Measurements taken only twice annually may not capture the lowest groundwater levels and thereby miss the seasonal low, which limits the ability to identify the connection between groundwater levels and subsidence.

Long-term, frequent groundwater level data are useful for calibrating numerical models to capture regional flow patterns, enabling effective trend and risk analysis as well as predictive modeling of groundwater dynamics and aquifer-system compaction. Instrumentation of monitoring wells with pressure transducers that record continuous measurements by dataloggers is a best practice to acquire high-quality, high-frequency groundwater data that can be used to evaluate changing conditions. High-frequency monitoring is also needed to identify elastic compaction. The mechanics of elastic compaction are discussed in Chapter 4.

To identify the critical head, long-term stress histories can be identified using monthly groundwater levels that are compared with subsidence measurements from extensometers, leveling surveys, GPS, and InSAR. Methods used to estimate critical head are discussed in Section 5.3.

Figure 5-5 shows an example of a multi-depth monitoring well arrangement. Multi-depth monitoring wells help identify transitions between unconfined and confined conditions and track groundwater level changes, offering valuable insights into groundwater level variability[46] and its relationship to subsidence. Lithology recorded during drilling is useful to identify aquifers and groundwater level measurements over time that are associated with different depths and is useful to understand changes in groundwater conditions corresponding with depth. In this figure, little groundwater level fluctuation occurs from the shallowest intervals (wells A and B, with screens of 80–90 and 140–150 feet below land surface, respectively). As a result, little compaction likely occurs from this depth range due to the minimal groundwater level fluctuations and relatively small amount of overburden compared to deeper intervals. Although only one extensometer is installed at this site, a site in Pixley located in the Tule subbasin—with four collocated extensometers—showed that only three percent of subsidence occurred in the depth interval of 0–255 feet.[47] Greater groundwater level fluctuations occur in wells C and D (screens of 260–280 and 535–545 feet below land surface, respectively), which indicates more subsidence likely occurs in the vicinity of these depth intervals.

[46] Ellis, J. H., Knight, J. E., White, J. T., Sneed, M. I., Hughes, J. D., Ramage, J. K., Braun, C. L., Teeple, A., Foster, L., Rendon, S. H., & Brandt, J. (2023). Hydrogeology, Land-Surface Subsidence, and Documentation of the Gulf Coast Land Subsidence and Groundwater-Flow (GULF) Model, Southeast Texas, 1897–2018.

[47] Lofgren, B.E., Klausing, R.L. (1969) Land subsidence due to ground-water withdrawal, Tulare-Wasco area, California. Professional Paper 437b. US Geological Survey doi:10.3133/pp437b.

Figure 5-5. Example Collocated Well Showing Lithology and Changes in Groundwater Level by Depth

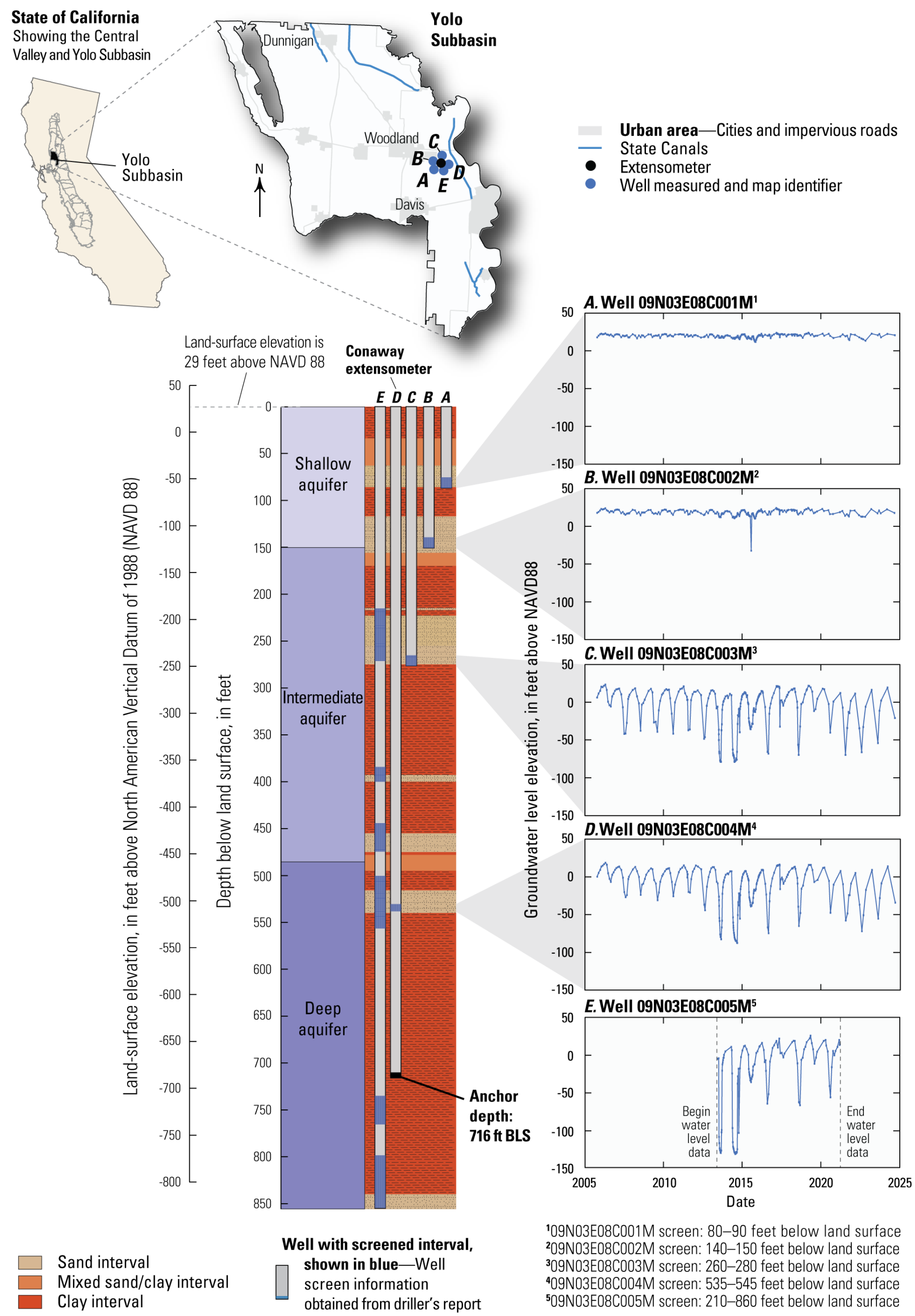

Figure Note: Diagram showing the information collected from the installation and monitoring of a multi-depth monitoring arrangement. Lithology and groundwater levels were measured for different subsurface depths provides valuable information.

5.1.3 Groundwater Pumping Monitoring

In areas experiencing land subsidence near infrastructure, the best management practice is to establish pumping reporting. Groundwater pumping reporting provides spatial and temporal data that groundwater managers may use to understand better the relationship between pumping, groundwater levels, and their effects on land surface conditions. 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. The measured pumping data can be combined with groundwater level data to help identify intervals where the compaction is originating, which allows managers to adjust practices to avoid or mitigate subsidence. Metered pumping data are important for identifying both regional and local responses to groundwater levels and subsidence and for the aquifer-system response across the basin. Metered pumping also helps groundwater managers account for different sources and movement of supplemental water and can improve estimates of conjunctive use by land use type, which is useful for predicting future pumping.

5.2 Identifying Infrastructure

Infrastructure, as the term is used in this BMP, refers to any land use or property interest that has been or is likely to be affected by land subsidence in the basin, as discussed in the GSP Regulations.[48] An essential part of subsidence management under SGMA is the review and identification of infrastructure within a basin as well as determining the amount of subsidence that may interfere with these surface land uses.[49] Investigations should broadly encompass any infrastructure, land use, and property interest (current and future) that may be impaired by changes in land elevation and areas around them where groundwater pumping may affect subsidence. General categories are listed in Table 5-1 (on the following page); however, GSAs should also consider additional infrastructure based on local conditions, infrastructure dependencies, stakeholder input, and public health and safety concerns.

When identifying infrastructure, groundwater managers should assess specific impact criteria that may limit functionality or performance, including:

- Physical damage
- Perturbation of designed operating conditions
- Increased maintenance due to reduced operational flexibility
- Reduced capacity to convey water or control flooding
- Broader impacts to the basin or other basins reliant upon that infrastructure

[48] 23 CCR § 354.28 (c)(5(A)).

[49] 23 CCR § 354.28 (c)(5).

Table 5-1. List of Infrastructure Types and Potential Impacts of Subsidence.

Infrastructure or Land Use Type	Infrastructure	Potential Impacts of Subsidence
Cities and Communities	- Property drainage - Power systems - Municipal water systems - Sewer systems	- Physical damage - Reduced service reliability - Increased maintenance
Pipelines and Other Utilities	- Natural gas - Water - Underground cables and overhead powerline utilities	- Cracking or joint failure - Over-pressurization - Reduced capacity - Pinch-points and un-alignment of transmission poles, towers, and lines
Railroads	- Private rail - High-speed rail	- Track deformation, instability, or loss of use during flooding - Safety hazards
Roads	- Drainage systems - Highways - Bridges	- Surface cracking - Drainage failure - Structural instability - Loss of use due to flooding
Canals	- State canals - Federal canals - Local canals	- Reduced conveyance, freeboard - Lining damage - Altered slope - Erosion and sedimentation of unlined channels
Flood Control & Drainage	- Federal, State, and Local flood facilities (e.g., levees, bypasses, and dams)	- Loss of grade - Structural failure - Reduced flood capacity - Levee overtopping or breach
Groundwater Pumping Facilities	- Domestic, agricultural, and public supply wells	- Casing collapse - Reduced capacity - Operational inefficiencies - Sand and gravel damaging pump bowls

Consultation and coordination with local, regional, state, and federal agencies is the best management practice to identify infrastructure and potential impacts and risks of subsidence. These entities include power and water utilities, canal and dam operators (e.g., Friant Water Authority, State Water Project, Central Valley Project and the U.S. Army Corps of Engineers), DWR, State Water Resources Control Board, and U.S. Bureau of Reclamation. Through this coordination, infrastructure may be prioritized for subsidence monitoring and management strategies according to the interests of beneficial uses and users and those that rely upon the function of the infrastructure that the lowered land surface is affecting.

Groundwater managers should not discount or dismiss impacts that could interfere with land uses or property interests as minimal or insubstantial without sufficient supporting evidence. GSAs will often lack the expertise or information to make an informed decision and must also recognize that different kinds of land uses and property interests will likely have different tolerances for interference. In some cases, even the same kind of property or surface use, like a water conveyance canal, may have different tolerances because of different design or construction specifications or different operational protocols or purposes. Accordingly, in many cases, 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.

For instance, if existing or future projected subsidence has reduced or will reduce a levee's height, then the groundwater manager should consult the relevant flood control agency or entity—or the local emergency services office—regarding the impacts or risks from the potential levee diminishment. Information obtained during these consultations should be documented and disclosed to ensure that it represents the official position of the agency or entity and so that potentially affected and interested members of the public are informed about these decisions. Depending on the infrastructure, the social, economic, and safety implications and importance of some of these determinations may be high; therefore, the Department considers thorough documentation and official correspondence to be the best management practice in many circumstances, especially if a groundwater manager intends to take the position that potential impacts from subsidence under its groundwater management program will not substantially interfere with infrastructure or is not significant and unreasonable.

When identifying infrastructure areas, groundwater managers should consider that groundwater pumping in areas susceptible to subsidence may cause subsidence not only near pumping sites but also in the surrounding areas. The areal extent that may experience increased subsidence related to lowered groundwater levels due to groundwater pumping varies by region and local conditions. Groundwater managers should work to understand the relationship between groundwater pumping and the spatial extent of subsidence. This Subsidence BMP recommends identifying an expanded area around infrastructure that should be managed to avoid or minimize subsidence and/or avoid impacts to infrastructure.

Groundwater managers should carefully manage pumping in areas around infrastructure and use their understanding of the relationship between groundwater pumping and the vertical and lateral extent of subsidence to inform management of pumping or projects that may be affecting subsidence. Estimates of critical head should be made, and groundwater levels should be managed above critical head in these areas. Recommendations on land subsidence management and considerations of infrastructure can be found in Chapter 6.

5.3 Estimating Critical Head

Critical head is a quantitative value representing the specific groundwater level (pressure) in compressible sediment below which permanent compaction begins, discussed in Section 4.1. Groundwater level changes occurring above the critical head result in recoverable (elastic) deformation (both subsidence and rebound) while declines of groundwater level below the critical head result in permanent (inelastic) subsidence. Therefore, the estimated critical head provides a numerical target for managing groundwater levels in the aquifer system. Critical head estimates carry inherent uncertainty and limitations; reliable estimation typically requires routinely measured, site-specific groundwater level and subsidence data. Critical head should be communicated as a relative indicator with associated uncertainty conveyed to stakeholders. In areas susceptible to subsidence, the best management practice is to develop an understanding of the critical head, because it enables proactive management strategies to address ongoing and future subsidence, as discussed in Section 7.4.

Three methods for estimating the critical head are described in this BMP, in order of increasing time required and complexity to implement. Groundwater managers should use time-efficient methods to gain an initial estimate of the critical head and support that analysis with the more robust methods, as appropriate, to refine their estimates of critical head. By using multiple methods, GSAs can begin management of subsidence as soon as possible rather than waiting an extended period for modeling results before developing or taking management actions. The methods are:

- **Trend-based Analysis**: This method 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, as described in Section 5.3.1. Nevertheless, 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 and then perform empirical analysis and/or modeling analysis, so that the initial estimate can be refined.
- **Empirical Analysis**: This method 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, as described in Section 5.3.2.
- **Modeling Analysis**: This method uses groundwater level and subsidence data to develop compaction models and requires technical expertise and familiarity with numerical modeling. More data are required to use this method than the trend-based and empirical analyses. 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, as discussed in Section 5.3.3. An example of the application of a modeling analysis is provided in a Technical Memorandum[50] which is summarized in Appendix E and in Bulletin 118 Appendix I.[51]

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[50] Ellis, J., White, J., Saberi, L., Earll, M., Neely, W., & Hughes, J. (2025). Documentation of subsidence modeling for the Central Valley (Technical Memorandum). INTERA Incorporated. https://data.cnra.ca.gov/dataset/cv-1d-subsidence-models-and-tech-memo.

[51] 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.

5.3.1 Trend-based Analysis

The trend-based analysis is based on relating time series records of subsidence and groundwater level data. Subsidence is largely correlated with changes in groundwater levels; therefore, the absence of subsidence during a sustained period indicates that groundwater levels are likely at or above the critical head. Ideally, these groundwater level values would be associated with a multi-year period of minimal subsidence, as shown in Figure 5-6. Figure 5-6 presents a hypothetical example of the trend-based analysis. In this example, the groundwater level measurements are shown as blue symbols, and subsidence is shown as a solid red line. As shown in the figure, subsidence occurs during a period of groundwater level decline but is minimized as groundwater levels recover during the subsequent period. During the period where subsidence is minimal (shaded gray), groundwater levels generally increase. Selection of a groundwater level during this period—provided this period is more recent versus a historical period—may be reasonable for estimating critical head levels and establishing sustainable management criteria for subsidence that would likely prevent future inelastic compaction. Note in Figure 5-6 that, after the fourth groundwater level measurement, subsidence continues even though groundwater levels in the aquifer recovered above the critical head. This illustrates the phenomenon of residual subsidence. Due to the approximate nature of this analysis, groundwater levels and subsidence should continue to be monitored, and critical head reevaluated, as more data are collected. In many cases, provided that a sufficient period of minimal subsidence or rebound is present, a trend-based analysis can be completed quickly due to the relatively low data requirements compared with the empirical and modeling analyses.

Figure 5-6. Hypothetical Example of the Trend-based Analysis Between Groundwater Levels and Subsidence

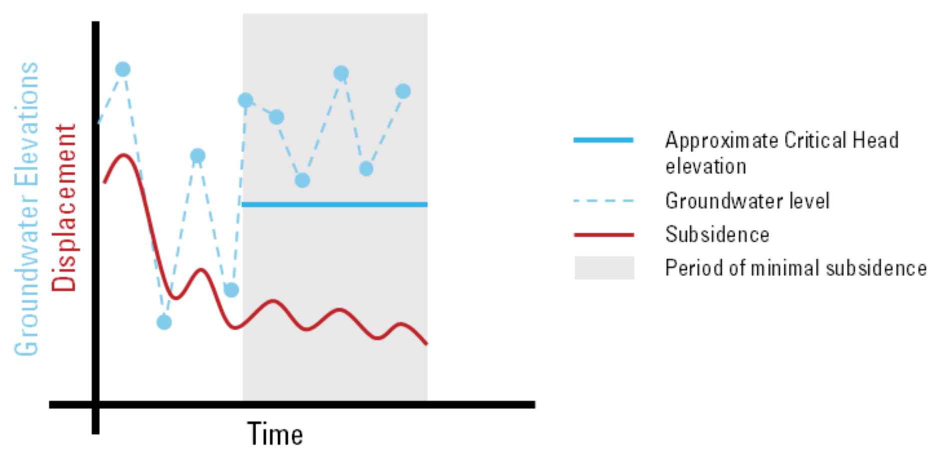

Figure Note: This figure shows that critical head can be estimated based on groundwater levels (i.e., groundwater elevations) that occur when the rate of subsidence substantially decreases.

5.3.2 Empirical Analysis

The empirical analysis approach uses estimates of critical head that can be made using time series of displacement and groundwater level measurements. This empirical method identifies periods where displacement is elastic (recoverable) and identifies the groundwater level during these times. This analysis is performed in a two-step procedure described below:

- **Identifying Time Periods with Sufficient Rebound.** An indicator of groundwater levels recovering above the critical head is the occurrence of land surface rebound (aquifer system expansion), which demonstrates elastic deformation. To determine the periods of rebound, the maximum subsidence for each period should first be estimated. This maximum subsidence is shown in the red line in part (a) of Figure 5-7. Then, the periods associated with sufficient land surface rebound should be identified, shown as shaded gray areas and areas above the purple line in part (b) of Figure 5-7. Here, "sufficient rebound" refers to a level of rebound that the user of this method has confidence in (i.e., the accuracy of the displacement dataset). Visually, the purple line represents this "sufficient rebound" above the maximum subsidence. In the case of the InSAR time series dataset provided by DWR,[52] a "sufficient rebound" level may be selected as the reported accuracy (0.067 ft).[53]
- **Identifying Groundwater Levels during Rebound Periods.** Using the identified periods of rebound, all groundwater levels during those periods are analyzed, shown in part (c) of Figure 5-7. Ideally, groundwater level measurements should be relatively frequent (monthly or more frequent) to ensure that there are sufficient observations during the times of rebound. Otherwise, semi-annual groundwater level measurements, or measurements that capture seasonal highs and lows, may be interpolated to estimate groundwater levels during sufficient rebound periods. For each period of sufficient rebound, the lowest groundwater level (observed or interpolated) is recorded. A time series of the lowest groundwater level during periods of rebound can then be constructed, which can be used as an estimation of the critical head, shown in part (d) of Figure 5-7 as a green line.

Implementation of this method to real data involves the collection and identification of collocated groundwater level and displacement records and the development of code to compute the critical head estimate. The groundwater level records should be representative of the groundwater level conditions driving the compaction of fine-grained sediments. This applies not only to lateral distance away from the displacement but also the depth. For example, if compaction is suspected as occurring at depth, selecting a collocated groundwater level record representative of shallow depths would be inappropriate. While data formatting and the one-time cost of developing code to perform the analysis may take some time, the relatively simple approach to the empirical estimate should result in fast computation of critical head (seconds to minutes). The accuracy of the critical head estimate will depend on the quality of input datasets (including frequency of measurements), how representative the groundwater levels are of the conditions driving displacements, and the site-specific relationship between displacement, groundwater levels, and critical head.

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52 California Natural Resources Agency. (2025). TRE ALTAMIRA InSAR Subsidence Data https://data.cnra.ca.gov/dataset/tre-altamira-insar-subsidence.

53 Towill. (2024). InSAR Data Accuracy for California Groundwater Basins: CGPS Data Comparative Analysis, January 2015 to October 2023. Task Order Report for the California Department of Water Resources, Contract 4600013876 TO#1. February 22, 2024.

Figure 5-7. Example Steps to an Empirical Estimation of Critical Head

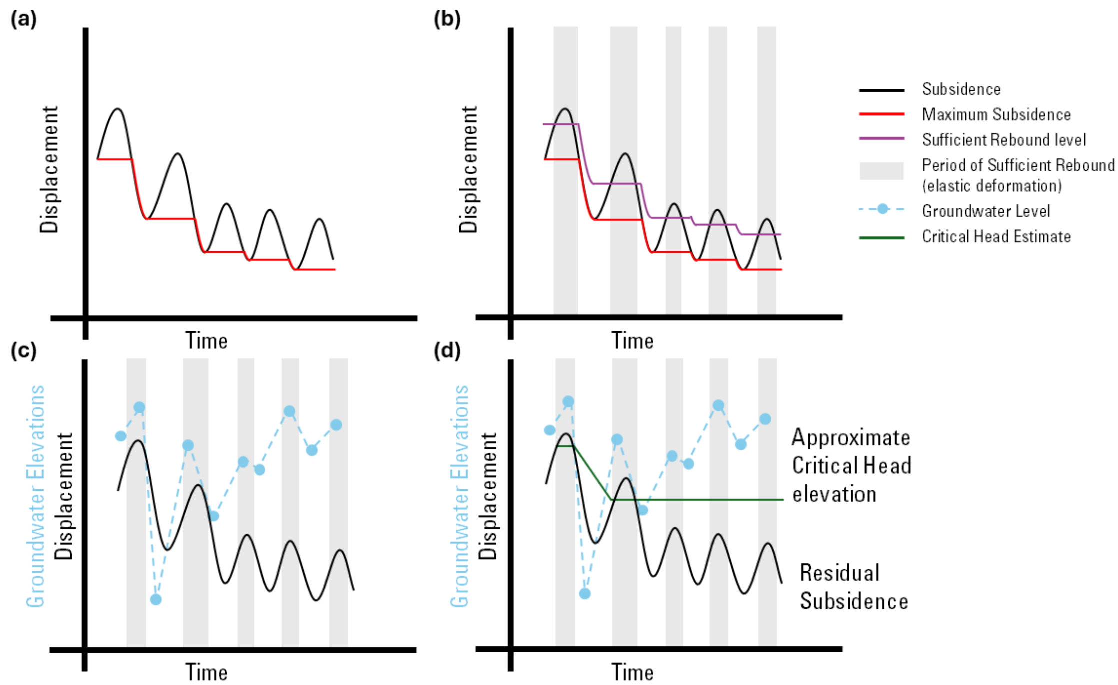

Figure Note: This figure shows hypothetical input subsidence and groundwater level (i.e., groundwater elevation) time series for the empirical critical head estimation method. Magnitude and behavior of signals are exaggerated to demonstrate clearly the methodological workflow. (a) shows a displacement 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". Note that, even after groundwater levels have risen above estimated critical head values, residual subsidence may occur.

5.3.3 Modeling Analysis

Numerical models can be used to provide robust estimates of critical head. These models (refer to Section 5.4, Appendix C, and in a Technical Memorandum[54] for more details) make use of reasonably long time series of groundwater levels in applicable aquifer units, subsidence information from historical and contemporary sources, and lithology records to capture the aquifer response to aquifer system stresses. By integrating these datasets, the models simulate temporal changes in critical head across different aquifer layers in response to changing stresses.

A representative critical head can be made by extracting the lowest simulated groundwater level in model cells containing an interbed in each model layer for each model stress period. The preconsolidation head, which is the lowest historical interbed groundwater level that corresponds

[54] Ellis, J., White, J., Saberi, L., Earll, M., Neely, W., & Hughes, J. (2025). Documentation of subsidence modeling for the Central Valley (Technical Memorandum). INTERA Incorporated. https://data.cnra.ca.gov/dataset/cv-1d-subsidence-models-and-tech-memo.

to the maximum effective stress, is tracked as a model parameter. Each time the interbed groundwater level drops below this previous minimum, a new critical head is established, signifying the onset of additional inelastic compaction. When interbed groundwater levels recover above the current critical head, the system reverts to elastic behavior; however, residual compaction will persist until pore pressures fully equilibrate. The difference between the aquifer and interbed groundwater level in each stress period reflects the degree of disequilibrium and delayed drainage across interbeds. Tracking both through time provides insight into how pressure equilibration controls the rate and persistence of compaction. An example of 1D critical head modeling is provided in Appendix E. Further, following the development and calibration of these models, subsidence under various groundwater level projections can be predicted (details discussed in Appendix C.5).

Although these models provide a powerful tool for understanding and predicting subsidence, they are also computationally intensive and, like any numerical model, are subject to uncertainty stemming from parameter estimation, data quality, and simplifications in representing natural heterogeneity. To address these challenges, the modeling framework described in Appendix C and a Technical Memorandum,[55] employs the PEST-IES (Iterative Ensemble Smoother) data-assimilation approach. Rather than relying on a single calibrated solution, PEST-IES generates an ensemble of plausible parameter sets that collectively represent the uncertainty in the system. This enables explicit quantification of predictive uncertainty, allowing modelers to express critical head estimates and subsidence forecasts in probabilistic terms. The ability to evaluate uncertainty in this way improves confidence in management decisions and provides a transparent basis for evaluating subsidence-related risk under different groundwater management scenarios.

5.3.4 Considerations and Limitations

Raising groundwater levels as high and as quickly as possible above the critical head is the best management practice to minimize ongoing subsidence and avoid future impacts. Estimation of critical head should begin with either the trend-based analysis or empirical analysis while more comprehensive estimates are developed through the modeling analysis. In areas where subsidence is ongoing and land surface rebound has not been observed, the use of the trend-based analysis and empirical analysis may not yield an estimate of critical head; therefore, a modeling approach is suggested.

These approaches demonstrate that critical head is often not the same as the lowest recorded groundwater level unless sufficient time has elapsed to allow for the equilibration of groundwater levels in fine- and coarse-grained sediments—a process that can take many years. Therefore, managing to the lowest recorded groundwater level may result in ongoing subsidence, because the critical head may be at a greater value than the lowest measured groundwater level in the aquifer system. Residual subsidence is discussed in Section 4.3.1. Further, estimates of critical head should be made spatially across basins where sufficient data are available due to the heterogeneity

[55] Ellis, J., White, J., Saberi, L., Earll, M., Neely, W., & Hughes, J. (2025). Documentation of subsidence modeling for the Central Valley (Technical Memorandum). INTERA Incorporated. https://data.cnra.ca.gov/dataset/cv-1d-subsidence-models-and-tech-memo.

of hydrogeologic conditions, water use, and infrastructure, as different regions have differing subsurface strata and conditions.

5.4 Land Subsidence Numerical Modeling

Numerical models are decision-support tools for understanding groundwater systems and evaluating management strategies to avoid or minimize subsidence in subsidence-prone basins. Models are simplified representations of complex systems that integrate diverse data types, conceptual understanding, and science in a hydrogeologically consistent framework. Various modeling approaches and software exist, each with specific assumptions, limitations, and uncertainties. Depending on the basin hydrogeology, data availability, and management objectives, GSAs may use simpler 1D models or more complex three-dimensional groundwater flow models, some of which integrate land surface and surface water processes, to simulate groundwater level response and aquifer system compaction. Information about modeling methods is provided in Appendix C.

GSAs should select modeling methods in consideration of data availability, hydrogeologic complexities in their basin, and regional management complexity. As conditions change and as more robust datasets are obtained, such as longer-term and higher frequency groundwater level and subsidence measurements collected during periods of critical stresses and with improved spatial coverage, GSAs should consider improving the tools and methods used. For subsidence, this could include incorporating better data on the properties of the fine-grained units that are susceptible to compaction or incorporating more complex numerical methods such as those that account for the delayed drainage (equilibration) of fine-grained units, which can improve estimates of future subsidence.

A primary consideration for model development is the availability of long-term, high-frequency observation data. Identifying locations with long-term groundwater level and subsidence data is important for developing and calibrating a subsidence model. During model calibration, estimated model parameters are adjusted so that simulated results match observed measurements within an acceptable tolerance, improving the model's ability to represent key aspects of the physical system being modeled. The quantity and quality of measurement data directly affect the reliability and accuracy of the calibration and thus affect the accuracy of predicted results. Using long-term stress data with higher frequency measurements can improve model calibration by better capturing system dynamics, which reduces uncertainty and increases confidence in model predictions. Models should be updated as new data become available.

6 Land Subsidence and the Sustainable Groundwater Management Act

This section discusses land subsidence management and SGMA, including monitoring, sustainable management criteria, the relationship with sustainable management criteria for the chronic lowering of groundwater levels, and the use of management areas and groundwater levels as a proxy.

Subsidence sustainable management criteria should be identified to guide a GSA's management of the basin to avoid significant and unreasonable conditions. Developing sustainable management criteria for land subsidence differs from other sustainability indicators under SGMA in that subsidence can be irreversible (i.e., inelastic compaction). The criteria will vary among groundwater sustainability plans based on the basin conditions, the location of infrastructure, and decisions made at the local level. GSAs are required to set criteria based on a rate and/or cumulative amount of land subsidence that may represent significant and unreasonable conditions.[56]

SGMA and GSP Regulations require GSAs to evaluate their GSPs periodically and provide a written assessment at least every five years.[57] In those assessments, "elements of the Plan, including the basin setting, management areas, or the identification of undesirable results and the setting of minimum thresholds and measurable objectives, shall be reconsidered and revisions proposed, if necessary".[58] This is especially important for the land subsidence sustainability indicator. GSAs must evaluate the amount of subsidence and groundwater level decline that has recently occurred in a basin and continuously evaluate whether the sustainable management criteria for groundwater levels will avoid causing undesirable results for land subsidence.[59] If it is determined that management criteria for groundwater levels may lead to undesirable results for land subsidence, this indicates the Plan may not reach sustainability for the basin and the sustainable management criteria should be updated.

6.1 Subsidence Monitoring for Sustainable Management under SGMA

Subsidence monitoring under SGMA is an important component of land subsidence management. Collecting and analyzing high-quality, representative data is fundamental to managing subsidence and understanding changing conditions. This section describes the specific requirements for monitoring related to land subsidence required under SGMA and provides general recommendations GSAs should consider related to monitoring for land subsidence.

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56 23 CCR § 355.4(c).

57 CWC § 10728.2; 23 CCR § 356.4.

58 23 CCR § 355.4(c).

59 23 CCR § 354.28 (b)(3).

6.1.1 Monitoring Protocols

DWR has previously published the Monitoring Protocols, Standards, and Sites BMP,[60] the Monitoring BMP,[61] and the Monitoring Networks and Identification of Data Gaps BMP.[62] These BMPs provide guidance for the development of subsidence monitoring networks and provide standards for several monitoring methods. GSAs should follow the guidance in these BMPs. This includes reference to surveying standards, appropriate methods, equipment installation and calibration, and additional upcoming resources.

6.1.2 Land Surface Elevation Monitoring for Sustainable Management

Representative monitoring sites and InSAR measurements for subsidence should be selected throughout all subsiding areas at a distribution and density sufficient to monitor representatively the causes, rate, and extent of subsidence throughout the basin, as discussed in Section 5.1.1. The distribution and density of sites should be increased and specially tailored in subsiding areas with infrastructure as identified by the GSA. Identifying infrastructure is discussed in Section 5.2.

Elastic and inelastic compaction can occur over short time intervals (as discussed in Appendix A.5). The best practice to detect inelastic compaction is to perform frequent and routine evaluation of subsidence data. This allows GSAs to detect changes, especially sudden or unexpected ones, and implement PMAs in a timely manner so that GSAs may understand conditions early enough to implement management strategies to avoid undesirable results and adjust the GSA's PMAs as soon as possible to avoid permanent inelastic compaction. Subsidence monitoring data should therefore be reviewed at least quarterly to evaluate the relationship between groundwater level changes and the occurrence of subsidence, whether groundwater level sustainable management criteria need to be revised, and if the implementation of additional Projects and Management Actions (PMAs) is warranted to avoid undesirable results occurring from subsidence. GSAs should include the results of quarterly subsidence monitoring and any changes to sustainable management criteria or PMAs in their annual reports as part of describing progress towards implementing their plans (e.g. GSP Regulations 356.2(c)).

6.1.3 Groundwater Level Monitoring with Consideration of Subsidence for Sustainable Management Criteria

Groundwater level monitoring should be conducted in a manner that supports the GSA's ability to evaluate the potential effects of groundwater level management on other sustainability

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60 California Department of Water Resources. (2016d). Best Management Practices: Monitoring Protocols, Standards, and Sites. https://water.ca.gov/Programs/Groundwater-Management/SGMA-Groundwater-Management/Best-Management-Practices-and-Guidance-Documents.

61 California Department of Water Resources. (2016b). Best Management Practices: Monitoring. https://water.ca.gov/Programs/Groundwater-Management/SGMA-Groundwater-Management/Best-Management-Practices-and-Guidance-Documents.

62 California Department of Water Resources. (2016c). Best Management Practices: Monitoring Networks and Identification of Data Gaps. https://water.ca.gov/Programs/Groundwater-Management/SGMA-Groundwater-Management/Best-Management-Practices-and-Guidance-Documents.

indicators.[63] The best practice for monitoring groundwater levels with consideration of subsidence sustainable management criteria includes monitoring these levels at an appropriate spatial, vertical, and temporal density. This allows GSAs to understand the amount of subsidence that may occur based on the groundwater levels to which the GSA plans to manage. As discussed in Section 5.1.2, the best practices include monitoring groundwater levels near locations of subsidence monitoring, performing groundwater level monitoring in aquifers at a spatial density that allows for an understanding of subsidence, and using a monthly monitoring frequency to understand seasonal lows. Groundwater level data should be reported to the GSA's Data Management System with minimal lag and reported promptly to DWR through the SGMA Portal.

6.1.4 Groundwater Pumping Monitoring with Consideration of Sustainable Management

In areas experiencing land subsidence near infrastructure, the best management practice is to establish pumping reporting, as discussed in Section 5.1.3. Groundwater pumping should be monitored to provide measurements of where pumping occurs, so GSAs may better understand the relationship between pumping, groundwater levels, and their effects on land surface conditions. In areas experiencing land subsidence near infrastructure, GSAs should consider requiring groundwater pumping to be reported to the GSA's Data Management System with minimal lag and reported promptly to DWR through the SGMA Portal.

GSAs are authorized by SGMA to inventory wells and require meters. SGMA grants wide-ranging authority to GSAs to establish rules, regulations, and management actions that support the implementation of a GSA's GSP for the basin, including requiring registration of groundwater pumping facilities[64] and requiring water-measuring devices (meters).[65] GSAs, in coordination with counties and other local well-permitting agencies, should develop and maintain an inventory of pumping wells and collect pumping reports by well or parcel to support the management of the volume, timing, and distribution of pumping in subsiding areas with infrastructure. GSAs should communicate their planned pumping monitoring approach with groundwater extractors and entities responsible for the operation and maintenance of infrastructure in the basin.

6.2 Land Subsidence Undesirable Results

The best practice for the establishment of undesirable results for subsidence includes two components: (1) a qualitative description of the conditions the GSA has identified where subsidence may substantially interfere with surface land uses, including the potential effects on infrastructure, land uses, and property interests,[66] and (2) a quantitative combination of minimum threshold exceedances[67] that represents when it is significant and unreasonable to cause subsidence that substantially interferes with land uses.

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[63] 23 CCR § 354.28 (c)(1)(B).

[64] CWC § 10725.6 *et seq*.

[65] CWC § 10725.6 *et seq*.

[66] 23 CCR § 354.26 (b)(3).

[67] 23 CCR § 354. 26 (b)(2).

Each GSP that has proposed to lower groundwater levels below recent low levels should establish undesirable results and provide clear qualitative and quantitative definitions. This qualitative definition should clearly describe what constitutes significant and unreasonable conditions (e.g., damage to infrastructure, collapsed well casings, etc.) the GSA is managing the basin to avoid. Each GSP should also include a quantitative description of undesirable results that represent a specific numerical value when subsidence that is substantially interfering with land uses becomes significant and unreasonable. Considering impacts to infrastructure often occur at a specific location, the quantitative definition of undesirable results may be based on as little as a single exceedance of a minimum threshold if an exceedance at that location leads to the significant and unreasonable conditions (e.g., damage to infrastructure, collapsed well casings, etc.) the GSA is managing the basin to avoid. The definition of undesirable results for land subsidence should be made in conjunction with entities responsible for the operation and maintenance of the infrastructure and the specific tolerance of that infrastructure or any mitigation efforts that are agreed upon by the GSA and the infrastructure manager.

In areas where inelastic compaction has not occurred, it is recommended that the quantitative description be set to disallow the onset of subsidence, so that inelastic compaction in the basin will be prevented. In areas where subsidence has recently occurred, the general conditions the GSA is managing the basin to avoid should be clearly described.

GSAs should evaluate and refine undesirable results for land subsidence—based on all available data and public input with each periodic evaluation—and should consider and evaluate multiple groundwater level and subsidence scenarios; their economic impacts on all land uses, including infrastructure; and the ability of the GSA to remediate those impacts while refining undesirable results.[68]

6.3 Land Subsidence Minimum Thresholds

The best practices for establishing minimum thresholds for subsidence reflect the intent of SGMA to avoid or minimize subsidence.[69] The GSP Regulations identify that minimum thresholds for land subsidence shall be the rate and extent of subsidence that substantially interferes with surface land uses and may lead to undesirable results.[70]

The minimum threshold for subsidence should be reflective of local conditions. In areas that have not recently experienced land subsidence, the minimum threshold should be set to disallow the onset of subsidence. This could be zero or the measurement error of the monitoring equipment. If the GSA elects to account for the measurement error when setting the minimum threshold, it should also specify a cumulative amount of subsidence to prevent small amounts of subsidence that occur regularly from being mistaken as measurement error.

In areas where land subsidence has occurred, the minimum threshold should be the amount of subsidence that does not substantially interfere with surface land uses, with an emphasis on infrastructure. The minimum threshold values for these areas should be made based on specific

[68] 23 CCR § 354.26 (b)(3) and § 354.28 (c)(5)(A).

[69] CWC § 10720 (e).

[70] 23 CCR § 354.28 (c)(5).

tolerance levels described by the entities responsible for the operation and maintenance of the infrastructure. If substantial interference has already occurred to land uses from subsidence, the GSA should be actively communicating with the entity responsible for the operation and maintenance of these land uses to understand the costs of repairs due to subsidence. The GSA should then set the minimum threshold as the amount of additional subsidence that does not cause further substantial interference with land uses.

When developing or evaluating minimum thresholds for land subsidence, it is important that GSAs identify the cumulative amount of subsidence, in addition to a periodic rate, that substantially interferes with land uses. It is recommended that GSAs understand and consider how the cumulative extent of subsidence may impact infrastructure and land uses. The cumulative amount of subsidence that substantially interferes with land uses likely varies in a basin depending on the presence of areas susceptible to subsidence and the presence and type of infrastructure.

Minimum thresholds should be set using all available subsidence monitoring data. Each subsidence monitoring method has limitations and advantages, and the best practice establishes minimum thresholds using all available monitoring methods in a basin. Subsidence monitoring methods are discussed in Section 5.1.1, and the details of the four monitoring methods—including leveling surveys, extensometers, Global Navigation Satellite System/GPS, and InSAR—are discussed in Appendix B.

In conjunction with entities responsible for the operation and maintenance of infrastructure, GSAs should define the amount and location of subsidence that would substantially interfere with infrastructure. Specific effects from subsidence on infrastructure that should be considered include, but are not limited to, the following items:

- Physical damage,
- Perturbation of designed operating conditions,
- Additional maintenance requirements due to reduced operating flexibility,
- Impacts from the reduced capacity of infrastructure to convey water or prevent flooding,
- Impacts of this loss of function of infrastructure on implementation of the basin's or other basins' GSPs that are reliant upon that infrastructure.

GSAs should evaluate the effects from subsidence on infrastructure and other land uses using a variety of methods. Potential avenues to consider aspects of impacts include, but are not limited to, the following:

- Targeted communication with agencies that manage infrastructure in the basin; GSAs should provide documentation of the nature of that consultation[71] and should articulate how all land uses and property interests that may be affected were included in the discussion.[72]
- Public forums discussing subsidence impacts
- Economic impact assessments

[71] 23 CCR § 354.10(a) and § 354.10(d)(4).

[72] 23 CCR § 354.28 (c)(5)(A).

- Subsidence impact cost-sharing agreements

GSAs should document their processes used to evaluate the specific aspects that impact the functions of infrastructure in the basin that were used to establish minimum thresholds. GSAs should document communication, impact assessments, and exploration of potential repair costs to fix damage caused by subsidence. Where possible, GSAs should obtain communication from interested parties or agencies that manage potentially impacted infrastructure in written form demonstrating the proposed minimum thresholds will avoid impacts to infrastructure.

It is recommended that GSAs evaluate and refine minimum thresholds for land subsidence based on all available data and public input with each periodic evaluation and should consider and evaluate multiple groundwater level and subsidence scenarios; their economic impacts on all land uses, including infrastructure; and the ability of the GSA to remediate those impacts while refining minimum thresholds.

6.3.1 Residual Subsidence and Minimum Thresholds

Residual subsidence is subsidence that occurs while fine-grained sediment layers equilibrate to increased stresses from depressurizing. Residual subsidence is an inelastic component of subsidence that can be minimized in areas where it is occurring by raising groundwater levels above the critical head as high and as quickly as possible. The mechanics of residual subsidence are discussed in Section 4.3.1.

GSAs should include and consider residual subsidence while evaluating aspects of subsidence sustainable management criteria, including minimum thresholds, during each periodic review. When groundwater levels have stabilized or risen above recent lows, it is recognized that any ongoing subsidence is residual subsidence. GSAs may try to predict the amount of residual subsidence that may occur; however, this modeled value should not be used to set the minimum threshold, as it is an estimate. As previously discussed, the minimum threshold should be the rate and extent of subsidence that substantially interferes with surface land uses and may lead to undesirable results,[73] absent of the consideration of the type of subsidence.

6.4 Land Subsidence Measurable Objective

The best practice for establishing measurable objectives for land subsidence is to set them at a level to avoid or minimize subsidence.[74] In basins that have not experienced land subsidence, the measurable objective should be set at zero. In basins that have experienced subsidence, the measurable objective should be set at the minimal amount of subsidence possible, based on groundwater level management above critical head in the basin.

6.5 Land Subsidence Interim Milestones

The best management practice for establishing interim milestones for land subsidence is to describe a path of management that avoids undesirable results. The GSP Regulations state that interim milestones should describe a reasonable path to achieve the sustainability goal for the

[73] 23 CCR § 354.28 (c)(5).

[74] CWC § 10720 (e).

basin.[75] Interim milestones should be reflective of when PMAs are implemented, and benefits are realized, and outline a path that avoids undesirable results. In areas that have not experienced subsidence and the measurable objective has been set at zero, the establishment of interim milestones is not necessary.

In areas experiencing land subsidence, interim milestones should be established to show progress toward achieving sustainability. Interim milestones for subsidence should be identified as an amount of cumulative subsidence that, if exceeded over that period, still allows time for GSAs to implement additional PMAs to reduce subsidence rates so that the minimum threshold values are avoided. Interim milestones in areas near infrastructure should be developed in conjunction with entities responsible for the operation and maintenance of the infrastructure. All interim milestones in areas experiencing subsidence should be set at levels that are less than current land subsidence rates and lessen over time to show clearly that progress toward the sustainability goal is being made.

6.6 Management Areas

Subsidence often occurs in specific areas of the basin; therefore, the management approach should focus on the subsiding area(s) rather than on a basin-wide approach. The GSP Regulations provide for the use of one or more management areas within a basin if the GSA has determined that the creation of management areas will facilitate the implementation of the Plan.[76] It is the best management practice to utilize management areas to manage subsidence effectively. Minimum thresholds and measurable objectives may vary between management areas or portions of the basin outside management areas.[77] While impacts from subsidence often occur at the local level, undesirable results are required to be established at the basin level and should mention specific management areas. For example, the undesirable result could be defined as impacts to specific infrastructure and the quantitative exceedance of thresholds within any management area.

For each management area for subsidence, the GSA should identify:

- **Reason for Area**: The reason for the creation of each management area.[78]
- **Conditions:** Include descriptions, maps, and other information sufficient to describe conditions in management areas.[79]
- **Monitoring:** An explanation of how the monitoring network is appropriate.[80] As discussed in Section 5.1.1, the best practice is to use all available monitoring techniques.
- **Minimum Thresholds:** This includes the rate and extent of cumulative subsidence across each management area as discussed in Section 6.3.

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[75] 23 CCR § 354.30 (e).

[76] 23 CCR § 354.20 (a).

[77] 23 CCR § 354.20 (a).

[78] 23 CCR § 354.20 (b)(1).

[79] 23 CCR § 354.20 (c).

[80] 23 CCR § 354.20 (b)(3).

- **Measurable Objectives:** In basins that have not experienced land subsidence, the measurable objective should be set at zero. In basins that have experienced subsidence, the measurable objective should be set at the minimal level of subsidence possible based groundwater level management above critical head in the basin, as discussed in Section 6.4.
- **Interim Milestones:** This should be identified as an amount of cumulative subsidence that, if exceeded, allows time for GSAs to implement additional PMAs to reduce subsidence rates so that the minimum thresholds are avoided, as discussed in Section 6.5.
- **Effects on Other Management Areas:** An explanation of how the management area can operate under different minimum thresholds and measurable objectives without causing impacts outside the management area.[81] GSAs should thoroughly explain any technical analysis they conduct to support this explanation. Tools such as numerical models may be useful for evaluating how conditions in one management area could affect conditions in adjacent areas.

Any GSA that utilizes management areas for subsidence in areas near infrastructure should develop the management criteria in conjunction with entities responsible for the operation and maintenance of the infrastructure.

6.7 Groundwater Level Sustainable Management Criteria with Consideration of Subsidence

Regardless of how a GSA has defined undesirable results, to avoid or minimize further subsidence, the best management practice for groundwater level management in areas experiencing subsidence is to raise groundwater levels above the critical head as high and as quickly as possible. This will minimize subsidence because it limits the amount of time the clay is subjected to a high effective stress, which is the driving force for compaction. Managing groundwater to levels that avoid creating that high effective stress thus avoids or minimizes subsidence, while managing to levels below critical head is less proactive. Adoption of groundwater level sustainable management criteria that are preventative of inelastic compaction, specifically groundwater levels above the critical head, will provide opportunities for management strategies that are adaptive and proactive to avoid or minimize inelastic compaction, including the longer lasting residual subsidence.

Understanding the relationship between groundwater levels and land subsidence is an important component of sustainability that GSAs must consider. As shown in Chapter 4, groundwater level management is strongly correlated to the amount of inelastic compaction and residual subsidence a basin may experience. Understanding the relationship between groundwater level changes and land subsidence is not just recommended; it is required by the GSP Regulations. The GSP Regulations require a GSA to describe the relationship between the minimum thresholds for each sustainability indicator, including an explanation of how the Agency has determined that basin conditions at each minimum threshold will avoid undesirable results for each of the sustainability indicators.[82] Each GSP must include a description of how managing groundwater levels to the defined thresholds will avoid undesirable results for each of the sustainability indicators, including

[81] 23 CCR § 354.20 (b)(4).

[82] 23 CCR § 354.28 (b)(2).

subsidence. This description should be updated with each periodic evaluation of the Plan, and the setting of minimum thresholds and measurable objectives for groundwater levels shall be reconsidered and revisions proposed, if necessary, to avoid causing undesirable results for subsidence.[83]

In areas without recent subsidence that are managing groundwater levels below recent lows, the GSA should monitor land subsidence and have PMAs ready to implement if subsidence is detected. Once subsidence is detected, the GSA should implement these PMAs and raise groundwater level thresholds and any associated sustainable management criteria, as the presence of new subsidence indicates groundwater levels have dropped below the critical head.

In areas experiencing land subsidence, groundwater levels may currently be below critical head levels, and inelastic compaction is likely to increase if groundwater levels decline further. In this situation, GSAs should revise the groundwater level sustainable management criteria to be set at or above the critical head level. If the GSA cannot feasibly manage groundwater levels to the critical head level that corresponds to conditions that would avoid undesirable results caused by subsidence, the GSA must still perform an analysis to understand and quantify the relationship between groundwater levels and subsidence. This is important for the GSA to understand how managing groundwater to different levels will impact ongoing and future subsidence. Based on estimates of future land subsidence, the GSA should revise groundwater level sustainable management criteria to ensure it will continue to avoid causing undesirable results for subsidence. The analysis of the relationship between groundwater levels and subsidence, as well as clear evidence that the proposed groundwater level management will avoid undesirable results for land subsidence, should be clearly described in the GSP. The groundwater level minimum threshold values should be revised in conjunction with the entities responsible for the operation and maintenance of infrastructure that exists in the basin.

The relationship between groundwater levels and subsidence often includes uncertainties. Uncertainties may be present due to limitations of data for analysis, lack of knowledge of the location and physical properties of subsurface fine-grained units, and other factors. When data and knowledge of conditions are limited, GSAs can also use additional analyses to improve understanding. GSAs can compare long-term groundwater level and subsidence rate data, which is discussed in the long-term stress history analysis in Appendix A.4, or look at high-frequency, shorter-term data, which is discussed in short-term stress history analysis in Appendix A.5. GSAs should consider the margin of error in all analysis approaches, including modeling, and select the highest groundwater levels within the margin of error where possible.

A discussion of modeling tools that can be used to improve understanding of the relationship between groundwater levels and subsidence is included in Appendix C.

GSAs should consider the following regarding sustainable management criteria for groundwater levels with consideration of subsidence:

- **Undesirable Results:** GSAs should use the understanding of the relationship between groundwater levels and subsidence to identify the quantitative combination of minimum

[83] 23 CCR § 356.4 (c).

threshold exceedances that define an undesirable result condition that avoids the amount of subsidence that is identified as an undesirable results for subsidence.

- **Minimum Thresholds:** Minimum thresholds for groundwater levels should be set so that they prevent undesirable results for land subsidence. In areas experiencing subsidence, clear documentation should be provided as evidence to support where groundwater level thresholds have been established.
- **Measurable Objectives:** Measurable objectives for groundwater levels with consideration of subsidence should be set above the critical head groundwater level.
- **Interim Milestones:** Interim milestones for groundwater levels with consideration of subsidence should describe a reasonable path to achieve the measurable objective.

6.8 Groundwater Levels as a Proxy for Subsidence

The GSP Regulations allow GSAs to use groundwater levels as a proxy when it is possible to "demonstrate that the representative value is a reasonable proxy for multiple individual minimum thresholds as supported by adequate evidence."[84] When developing minimum thresholds where groundwater levels are desired to be used as a proxy for subsidence because land uses would be affected, it is necessary to evaluate the correlative relationship of groundwater levels in specific aquifers relative to rates and total extent of subsidence (including any anticipated residual subsidence) to support and justify the use of groundwater levels as a proxy. However, because subsidence can be measured directly, it is important to continue to calibrate the proxy relationship to support its use due to the inherent uncertainty caused by heterogeneity in the distribution of fine-grained units throughout the subsurface.

While the GSP Regulations allow the use of groundwater levels as a proxy, GSAs should consider that, as described in Section 6.2, the best practice for the establishment of undesirable results for subsidence includes a qualitative description of the conditions the GSA has identified where subsidence may substantially interfere with land uses, and a quantitative combination of minimum threshold exceedances that represents when it is significant and unreasonable to cause subsidence that substantially interferes with land uses.

Use of groundwater levels as a proxy may be appropriate in basins that have not experienced subsidence and where groundwater managers have selected groundwater level minimum thresholds that remain above historical lows. This is appropriate because subsidence is unlikely to occur, based on the evidence that it has not occurred at these levels previously at historical lows and groundwater will be managed above those historical lows.

In basins that have experienced subsidence, the use of groundwater levels as a proxy is not appropriate because subsidence can be measured and monitored directly. Undesirable results and minimum thresholds should be established using measurable subsidence metrics and not groundwater levels.

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[84] 23 CCR § 354.28(d).

7 Land Subsidence Management

Analysis, research, and data presented in this BMP show that subsidence, where it is occurring, is effectively minimized or avoided only when groundwater levels are allowed to rise above the critical head as high and as quickly as possible. This key concept drives the best management practices for subsidence. While achieving immediate stabilization of, or a rise, in groundwater levels may be difficult and requires the implementation of PMAs, raising groundwater levels as high and as quickly as possible is the best practice to avoid or minimize land subsidence.[85]

The reality is that many groundwater managers, who are required to manage a basin for various beneficial users and uses, may be unable to immediately manage to avoid or minimize subsidence. These managers should weigh the risk of future subsidence, and the potential revenue associated with that groundwater pumping, with the potential costs to repair infrastructure impacted by subsidence. As explained in this BMP, the actual cost-benefit analysis of achieving sustainability—when all factors are considered—is not simple and can reveal that it is in the long-term interests of a basin to achieve sustainable groundwater management, which includes addressing subsidence. Nevertheless, these management decisions, as well as educating interested parties about the costs and benefits, are challenging for groundwater managers who must sometimes confront decades of unsustainable groundwater pumping and the desire for short-term profits and gains against the longer-term costs and losses of current pumping and groundwater use practices. This section aims to assist groundwater managers by presenting the best management practices for limiting subsidence, discussing different land subsidence scenarios, and general ways a GSA may choose to revise sustainable management criteria developed under a GSP as required by SGMA.

7.1 Actions to Limit Land Subsidence

Land subsidence can be minimized and avoided through the management of groundwater levels as discussed in Section 4.4. On a technical level, the best management practice for limiting subsidence is to raise groundwater levels above the critical head as high and as quickly as possible in areas experiencing subsidence. This section presents some PMAs a groundwater manager should consider when managing land subsidence. Some actions should likely be taken across the entire basin, while others may only apply in areas actively experiencing subsidence. The choice of how to consider, select, and utilize these actions is at the discretion of the groundwater manager.

Actions to understand, manage, and limit land subsidence include:

- Utilizing all available subsidence monitoring data to evaluate land subsidence
- Using existing, improved, or new tools, such as numerical models, to understand historical and potential future subsidence
- Increasing the frequency of groundwater level monitoring in areas where subsidence has recently occurred, or where groundwater levels are declining rapidly
- Conducting enhanced (increased density) groundwater level and land subsidence monitoring near infrastructure

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85 CWC § 10720.1 (e).

- Considering requiring groundwater pumping monitoring in areas experiencing land subsidence
- Identifying infrastructure in areas experiencing land subsidence
- Coordinating with the managers of infrastructure to understand the impacts and cost to repair impacts from subsidence
- Modeling future subsidence based on groundwater level management
- Ceasing further groundwater level declines if land subsidence is observed
- Managing groundwater levels at or above recent groundwater levels
- Raising groundwater levels to the critical head level if land subsidence is observed
- Reducing groundwater demand in areas experiencing land subsidence
- Shifting pumping from an aquifer susceptible to land subsidence to other aquifers less susceptible to land subsidence
- Shifting pumping from areas experiencing subsidence to other areas within a basin less susceptible to land subsidence
- Coordinating with local land use and well permitting agencies to ensure their land use/permitting decisions do not exacerbate recent subsidence
- Identifying specific PMAs to manage subsidence
- Setting triggers to implement specific PMAs to limit subsidence
- Coordinating with groundwater managers in adjacent basins to execute regional subsidence management strategies

These are just some of the many actions that groundwater managers can implement to manage and limit subsidence. Regardless of the actions a groundwater manager chooses to implement, they should clearly explain how they are managing the basin for land subsidence, as timely implementation of actions is important to managing subsidence successfully. Detailed discussion of potential actions are included in Appendix D.

SGMA grants GSAs the authority to perform a wide range of management actions after the adoption and submission to DWR of their GSPs.[86] These authorities include, but are not limited to:

- Adopting rules, regulations, ordinances, and resolutions[87]
- Performing investigations to prepare regulations, adopt or update fees, and monitor compliance and enforcement, including water rights and inspection of property [88]
- Requiring registration of groundwater pumping facilities[89]
- Requiring water-measuring devices (meters)[90]

[86] CWC § 10725 and 10726 *et seq.*

[87] CWC § 10725.2 *et seq*.

[88] CWC § 10725.4 *et seq*.

[89] CWC § 10725.6 *et seq*.

[90] CWC § 10725.6 *et seq*.

- Purchasing property and water rights and performing any acts necessary to purchase, transfer, deliver, or exchange water or water rights [91]
- Imposing well spacing requirements[92]
- Controlling, regulating, limiting, or suspending groundwater pumping[93]
- Establishing accounting rules, allocations, and transfers of groundwater[94]
- Entering into written agreements and funding (contracts) with private parties to assist or facilitate the implementation of a GSP[95]

GSAs should use these authorities to implement PMAs to minimize subsidence and avoid undesirable results. The GSP should clearly show how the proposed PMAs are focused on areas where subsidence is occurring, areas where infrastructure that could be affected by subsidence is present, and how they collectively address subsidence. PMAs should be regularly reviewed by the GSA for effectiveness alongside quarterly review of subsidence monitoring and should be modified if they have not been effective. GSAs should report on the effectiveness of their PMAs as part of their annual reports and periodic evaluations to the Department. As part of periodic evaluations, GSAs may need to adjust their PMAs to ensure the basin reaches sustainability.

Effective subsidence management requires challenging decisions that necessitate communication with groundwater pumpers and owners and operators of infrastructure in the basin that may be affected. GSAs should communicate their planned PMAs, including discussions of pumping reduction with discrete pumping allocations directly with those that may be affected by them. Additional discussion of communication is included in Section 7.3.

7.2 Regional Subsidence Management

Due in part to groundwater flow, both within a basin and across subbasin boundaries, groundwater activity in one GSA or basin may affect groundwater conditions in adjacent GSAs or subbasins. Because groundwater moves freely across subbasin boundaries, although the rate and magnitude can vary widely, groundwater level declines in one GSA can lower groundwater levels in adjacent GSAs and subbasins, potentially causing subsidence beyond the source region. To prevent undesirable results and ensure the success of sustainability goals for all GSAs, the establishment of sustainable management criteria for subsidence and groundwater levels should seek to understand and account for these interconnected dynamics.

The best practice for subsidence management includes GSAs coordinating with neighboring subbasins to ensure individual basin management is not negatively affecting an adjacent basin. Regional coordination may include discussions in meetings of GSAs and public forums, supported by documentation such as memoranda of understanding, legal contracts, interbasin agreements, or other forms of cooperation. Such coordination is essential, as infrastructure like canals, levees, and roads often span multiple basins, and unchecked subsidence in one area can disrupt the

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[91] CWC § 10726.2 *et seq*.

[92] CWC § 10726.4 (a)(1).

[93] CWC § 10726.4 (a)(2).

[94] CWC § 10726.4 (a)(3) and 10726.4 (a)(4).

[95] CWC § 10726.5.

functioning of this infrastructure in others. Proactive approaches ensure that all GSAs work toward a shared goal of sustainable groundwater management while minimizing the risk of subsidence affecting regional infrastructure and water resources.

While SGMA and the GSP Regulations generally focus on local groundwater management and the avoidance of adverse conditions that may occur within a GSA's respective subbasin, it is important to consider that not all pumping-related depletions will necessarily occur within a given basin's boundaries. Groundwater level declines and subsidence can result from local pumping or groundwater level declines in nearby or adjacent management areas, GSAs, or subbasins.

GSAs should seek regional coordination beyond individual groundwater subbasins to establish sustainable management criteria and implement management actions to halt the decline of groundwater levels, or—where needed—raise groundwater levels to avoid or minimize subsidence. GSAs should compare and coordinate sustainable management criteria for groundwater levels and land subsidence across jurisdictional boundaries within and across subbasins to ensure regional and local groundwater trends are not adversely impacting subsidence in management areas, GSAs, or subbasins.

To enhance inter-basin coordination, Department staff recommend GSAs consider utilizing existing regional coordination efforts such as DWR's facilitation support services and Technical Support Services (TSS). The goal of facilitation support services is to promote discussions among diverse water management interests and jurisdictions to work through challenging issues and differences to meet the objectives of SGMA. Through the TSS, GSAs can request monitoring and other technical assistance. More information on facilitation support services and TSS can be found on DWR's Assistance and Engagement webpage.[96]

Successful regional coordination is imperative for successful land subsidence management and compliance with the SGMA. The Department is required by the CWC to evaluate whether a groundwater sustainability plan adversely affects the ability of an adjacent basin to implement their groundwater sustainability plan or impedes achievement of sustainability goals in an adjacent basin,[97] and is required to consider as part of its regulatory review whether the Plan will adversely affect the ability of an adjacent basin to implement its Plan or impede achievement of its sustainability goal.[98] Providing examples of regional coordination in annual reports and periodic evaluations will be critical to demonstrate to the Department adjacent basins are working together to manage subsidence.

7.3 Engaging with Interested Parties Regarding Subsidence

GSAs are required to explain their decision-making processes and the method they will follow to inform the public about the progress of implementing the Plan. This is especially important for subsidence management as effects are often irreversible and can result in significant damage to infrastructure and the associated costs for repairs. GSAs in areas experiencing subsidence should

[96] https://water.ca.gov/programs/groundwater-management/assistance-and-engagement.

[97] CWC § 10733 (c).

[98] 23 CCR § 355.4 (b)(7).

actively engage with entities responsible for the operation and maintenance of the infrastructure and consider their input when making management decisions in the basin for land subsidence.

The GSP Regulations require that GSAs document, in the communication section of the GSP, the opportunities for public engagement and active involvement of diverse social, cultural, and economic elements of the population within the basin.[99] GSAs should consider engaging and collaborating with relevant interested parties; subject matter experts; and entities representing beneficial uses and users, land uses, and property interests that may be impacted by subsidence. These entities may include federal and State agencies; flood control agencies; Tribal representatives; water masters (where rights have been adjudicated); irrigators; non-governmental and community-based organizations including environmental groups, relevant academic institutions, and programs; and the managers of infrastructure. Incorporating the expertise of entities representing beneficial uses and users and land uses and property interests increases the likelihood that GSAs are using the best available information and best available science for the development of subsidence sustainable management criteria.[100] Further discussion about how to identify and consider infrastructure is included in Section 5.2.

When engaging with interested parties, GSAs are not obligated to achieve consensus from competing interests when making the local determination of what is, or is not, an undesirable result, but it will help (where possible) to demonstrate to the Department when consensus was achieved. In areas where subsidence is occurring and infrastructure is present, the GSA should coordinate with entities responsible for the operation and maintenance of infrastructure and define the amount and location of subsidence that would substantially interfere with the infrastructure. Ultimately, GSAs are responsible for explaining their decision-making processes in annual reports and periodic evaluations and should demonstrate how public input was used in developing and periodically evaluating their GSPs.

Public awareness and education about subsidence impacts, water conservation, and available resources are also important to mitigate and prevent subsidence. Outreach efforts targeting farmers, residents, and policymakers that focus on water conservation practices and diversifying water resource portfolios can help mitigate the overuse of groundwater and reduce the risk of subsidence. These initiatives and techniques—as outlined here—can promote the importance of groundwater management to prevent further subsidence and damage to infrastructure.[101,102]

Successful coordination with interested parties is imperative for successful land subsidence management. Providing examples of coordination with interested parties, including responses to public comments in annual reports and periodic evaluations, will be critical to demonstrate to the Department that the groundwater manager is working with entities responsible for operation and maintenance of infrastructure to manage subsidence.

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[99] 23 CCR § 354.10(d)(2-3).

[100] 23 CCR § 355.4(b)(1).

[101] California Department of Water Resources. (2023d). Status of 2020 Agricultural Water Management Plans and Implementation of Efficient Water Management Practices Report. https://water.ca.gov/Programs/Water-Use-And-Efficiency/Agricultural-Water-Use-Efficiency.

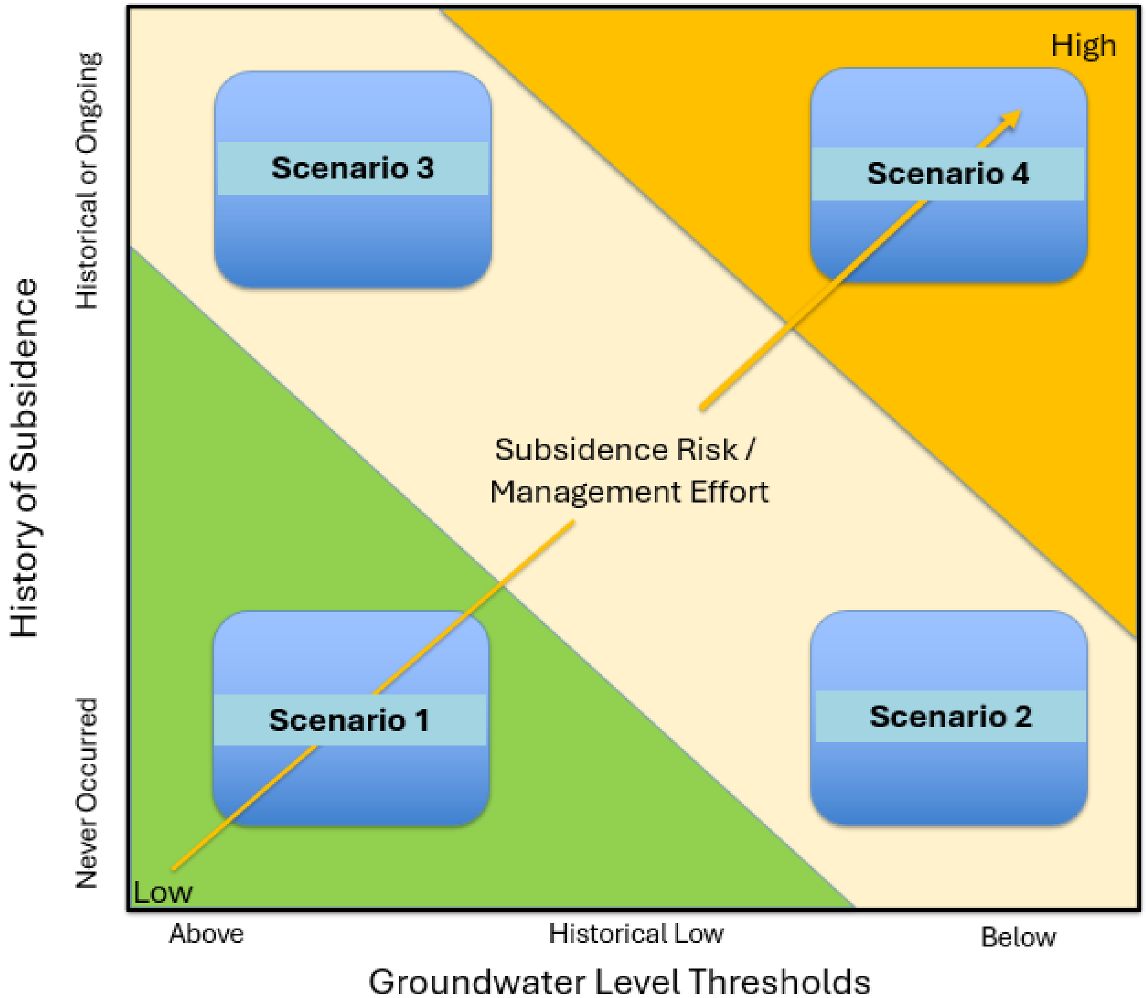
[102] California Natural Resources Agency. (2020). California Water Resilience Portfolio 2020. https://resources.ca.gov/Initiatives/Building-Water-Resilience/portfolio.

7.4 Management of Land Subsidence Scenarios

This section presents theoretical scenarios of how subsidence could be managed given different circumstances and discusses considerations for land subsidence management under SGMA. Each scenario is based on two simple factors: (1) whether the area has experienced subsidence (historically or currently) and (2) how the GSA has locally chosen to manage groundwater levels.

Figure 7-1 shows the four subsidence management scenarios and overall subsidence risk. Based on the Land Subsidence Fundamentals section (Chapter 4), the farther groundwater levels are allowed to decline below the critical head, the greater the risk of subsidence. In this section, to simplify the discussion, the scenarios are described by whether the groundwater level thresholds are above or below the historical low, and whether subsidence has occurred or has never occurred. These scenarios do not represent actual locations or conditions in any basin and are presented for informational purposes only.

Figure 7-1. Subsidence Risk and Management Effort Based on History of Subsidence and Groundwater Level Thresholds. The Four Land Subsidence Management Scenarios are shown based on these Factors.



As subsidence conditions and groundwater level thresholds change within a basin, the area is likely to switch from one scenario to another. For example, a basin with no history of subsidence that sets groundwater level thresholds below historical low (Scenario 2) and begins to experience declining groundwater levels will transition to a Scenario 4 as soon as subsidence is observed. The amount of subsidence that occurs in this example is insignificant, as the basin manager should begin considering the actions under Scenario 4 to manage land subsidence.

Similarly, a basin currently experiencing land subsidence that set thresholds below historical low (Scenario 4) may decide to revise groundwater level thresholds to be above historical low, which would transition the area to a Scenario 3.

7.4.1 Scenario 1: Area with No History of Subsidence, Managing Groundwater Levels Above Historical Low

Scenario 1 involves an area within a basin that has no history of land subsidence, and the groundwater manager has set minimum thresholds that do not allow groundwater levels to drop below the historical low. Based on the Land Subsidence Fundamentals (Chapter 4), the likelihood of land subsidence in this scenario is very low. The groundwater manager should monitor groundwater levels and readily available land subsidence data as part of monitoring basin conditions to ensure they do not change. Given the low likelihood of land subsidence and the availability of public monitoring sources such as InSAR, devoting significant resources to develop a locally maintained, dedicated land subsidence monitoring network and/or performing modeling related to future land subsidence is likely not warranted. The groundwater manager may consider the following actions to manage subsidence in this scenario:

Monitoring and Analysis Actions:

- Utilize all available monitoring data to evaluate whether land subsidence is occurring

Infrastructure-Related Actions:

- None

Management Actions:

- Continue to manage groundwater levels at or above recent groundwater levels

7.4.2 Scenario 2: Area with No History of Subsidence, Managing Groundwater Levels Below Historical Low

Scenario 2 involves an area within a basin that has not experienced land subsidence, and the groundwater manager has set thresholds that allow groundwater levels to fall below the historical lows. Based on the fundamentals of land subsidence (Chapter 4), there is the potential that the decline in groundwater levels could cause the onset of land subsidence in this scenario. The groundwater manager should review the lithology of the aquifer where groundwater levels will be allowed to decline to identify if fine-grained sediments susceptible to land subsidence exist. For more information on the definition of fine-grained sediments, please see Section 4.3. The groundwater manager should be aware of infrastructure in the area that could be impacted by land subsidence, set thresholds to identify the onset of land subsidence, and monitor basin conditions using readily available land elevation data.

In this scenario, the further basin groundwater levels decline and the greater the abundance of fine-grained units, the higher the likelihood that land subsidence will occur. The groundwater manager may consider the following actions to manage subsidence in this scenario:

Monitoring and Analysis Actions:

- Review the lithology of the aquifer
- Utilize all available monitoring data and increase the frequency of monitoring data (groundwater levels and subsidence) to evaluate whether land subsidence is occurring

Infrastructure-Related Actions:

- Coordinate with the managers of infrastructure to understand the potential impacts of subsidence

Sustainable Management Criteria Actions:

- Set sustainable management criteria for land subsidence

Subsidence Management Actions:

- Cease further groundwater level declines if land subsidence is observed
- Raise groundwater levels to the critical head level if land subsidence is observed

7.4.3 Scenario 3: Area with Historical or Ongoing Subsidence, Managing Groundwater Levels Above Historical Low

Scenario 3 involves an area within the basin that has experienced, or is currently experiencing, land subsidence, but the groundwater manager has set thresholds that prevent declines in the groundwater level beneath the historical low. Based on the Fundamentals of Land Subsidence (Chapter 4), subsidence will be minimized once groundwater level declines cease compared with a scenario where continued declines in groundwater levels occur.

If the area is currently experiencing subsidence, the first task is to stabilize and begin raising groundwater levels as soon as possible so the groundwater manager is only managing residual subsidence. Once groundwater levels are stabilized, residual subsidence may continue to occur; however, the total amount can be managed based on how high and how quickly groundwater levels are raised above the critical head level by the groundwater manager, as discussed in Section 4.4.

The groundwater manager should continue to be aware of where subsidence is occurring in the basin and perform analysis to understand if and how much active and residual subsidence may occur. The manager should set and reevaluate minimum thresholds to identify the amount of land subsidence that would be significant and unreasonable for surface land uses and monitor basin conditions using readily available land elevation data. The groundwater manager may consider the following actions to manage subsidence in this scenario:

Analysis and Monitoring Actions:

- Review the lithology of the aquifer
- Utilize all available monitoring data and increase the frequency of monitoring data (groundwater levels and subsidence)
- Determine the critical head level
- Model future residual subsidence based on groundwater level management

Infrastructure-Related Actions:

- Coordinate with the managers of infrastructure to understand the potential impacts of residual subsidence
- Set thresholds based on the tolerance of infrastructure to subsidence

Sustainable Management Criteria Actions:

- Reevaluate the sustainable management criteria for land subsidence and groundwater levels at each periodic evaluation

Subsidence Management Actions:

- Cease further groundwater level declines if land subsidence is observed
- Raise groundwater levels to the critical head level if land subsidence is observed
- Initiate PMAs to raise groundwater levels to the critical head level. The schedule and scope of the PMAs should be established as soon as possible.
- Set triggers to implement specific PMAs to limit residual subsidence if impacts to infrastructure occur
- Coordinate with local land use and well permitting agencies
- If the subsidence is occurring in adjacent basins, coordinate with groundwater managers in adjacent basins to understand regional subsidence management strategies

7.4.4 Scenario 4: Area with Historical or Ongoing Subsidence, Managing Groundwater Levels Below Historical Low

Scenario 4 involves an area within a basin that has experienced, or is currently experiencing, land subsidence, and the groundwater manager has set minimum thresholds that allow groundwater levels to continue to decline below historical lows. Based on the Fundamentals of Land Subsidence (Chapter 4), this scenario presents the highest risk for subsidence. In this scenario, subsidence is likely to continue and is not being minimized by the groundwater manager. The groundwater manager should be aware of where subsidence is occurring in the basin and understand how much future subsidence could occur based on the allowable groundwater level declines. The groundwater manager should be actively coordinating with the entities responsible for infrastructure, set and reevaluate minimum thresholds, ensure the amount of land subsidence that would be significant and unreasonable for land uses is not occurring, implement projects to minimize land subsidence, and monitor basin conditions using a dedicated land subsidence monitoring network. The groundwater manager may consider the following actions to manage subsidence in this scenario:

Analysis and Monitoring

- Review the lithology of the aquifer
- Utilize all available monitoring data and increase the frequency of monitoring data (groundwater levels and subsidence)
- Determine the critical head level
- Conduct enhanced groundwater level, groundwater pumping, and land subsidence monitoring near infrastructure
- Model future subsidence based on groundwater level management

Sustainable Management Criteria

- Reevaluate the sustainable management criteria for land subsidence and groundwater levels at each periodic evaluation

Infrastructure-Related Actions:

- Coordinate with the managers of infrastructure to understand the potential impacts of active subsidence
- Set thresholds based on the tolerance of infrastructure to subsidence
- Estimate impacts and potential costs to repair infrastructure from land subsidence

Projects and Management Actions

- Initiate PMAs to raise groundwater levels to the critical head level. The schedule, scope and initiation of the PMAs should occur as soon as possible.
- Immediately reduce groundwater demand in areas experiencing land subsidence
- Shift pumping from an aquifer susceptible to subsidence to areas not susceptible to subsidence
- Increase density and frequency of monitoring in areas where pumping is increased
- Set triggers to implement specific PMAs to limit subsidence and avoid undesirable results if impacts to infrastructure occur
- Coordinate with local land use and well permitting agencies
- If the subsidence is occurring in adjacent basins, coordinate with groundwater managers in adjacent basins to understand regional subsidence management strategies

Note: These scenarios do not represent actual locations or conditions within any basin and are presented for informational purposes only.

8 References

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A Subsidence Processes

This appendix provides more information on fine-grained unit properties, residual subsidence, critical head, long-term and short-term stress history analysis, and subsidence related to oil, gas, and geothermal activities.

A.1 Fine-Grained Unit Properties

Fine-grained units, including interbeds and confining units, within or adjacent to unconsolidated aquifers that undergo groundwater level declines related to groundwater pumping are susceptible to aquifer-system compaction.[103] Compaction of large amounts of fine-grained sediments can result in appreciable subsidence.[104] The compaction of this susceptible material, and thereby subsidence, is largely dependent on the various characteristics of the interbeds and confining units present in the aquifer system and the change in aquifer stress.[105]

The extent of compaction largely depends on: the characteristics and arrangement of the fine-grained units, specifically clay layers, and the magnitude, duration, and history of the groundwater level declines. The hydrogeological structure (number and thicknesses of interbeds and confining units) and material properties control the total compaction possible for the aquifer system.[106]

The magnitude and duration of compaction given a decline in groundwater level depends on individual fine-grained unit thickness, vertical hydraulic conductivity (K_v), and skeletal specific storage (S_{sk}), the latter of which can be related to compressibility. K_v measures the ease with which water can move vertically through subsurface sediment. Low K_v values for fine-grained units result in slow depressurization, leading to delayed compaction as groundwater levels inside the clay layers slowly equilibrate to the decline in the groundwater level in the adjacent aquifer. S_{sk} is related to the compressibility and porosity of the sediment and represents the volume of water a unit volume of sediment can release or absorb per unit change in groundwater level. This water exchange primarily occurs from the expansion or compaction of sediment due to changes in effective stress. S_{sk} varies depending on whether the groundwater level has declined below critical head. For the case where the groundwater level is below the critical head, compaction may be inelastic (permanent), which is represented by the inelastic skeletal specific storage (S_{sv}), which is generally several orders of magnitude larger than the elastic skeletal specific storage (S_{se}). Clay layers that are thicker have higher S_{sk} values, have lower K_v values, and will take longer to equilibrate to groundwater level changes. These equilibration times result in the delayed compaction of clay

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103 Hughes, J. D., Leake, S. A., Galloway, D. L., & White, J. T. (2022). Documentation for the Skeletal Storage, Compaction, and Subsidence (CSUB) Package of MODFLOW 6. US Geological Survey.

104 Kasmarek, M. C., & Robinson, J. L. (2004). Hydrogeology and simulation of ground-water flow and land-surface subsidence in the northern part of the Gulf Coast aquifer system, Texas (Issue 2004). US Geological Survey.

105 Kelley, V., Deeds, N., Young, S., & Pinkard, J. (2018). Subsidence Risk Assessment and Regulatory Considerations for the Brackish Jasper Aquifer.

106 Kelley, V., Deeds, N., Young, S., & Pinkard, J. (2018). Subsidence Risk Assessment and Regulatory Considerations for the Brackish Jasper Aquifer.

layers, potentially for years to decades after an initial groundwater level decline occurred.[107,108] The surface response due to the delayed compaction of fine-grained units is referred to as residual subsidence, described in the next section.

Whether or not compaction is elastic (recoverable) or inelastic (permanent) depends on if groundwater levels decline below the critical head. Examples of elastic deformation include seasonal (and daily) subsidence and rebound, described in the "Short-Term Stress History Analysis" section (Appendix A.5). These deformations do not permanently alter an aquifer-system's water storage properties, though they have been shown to have seasonal magnitudes as high as 3.0 inches (peak-to-trough) in the San Joaquin Valley.[109,110] Inelastic compaction leads to a permanent rearrangement of the interbed and/or confining unit skeletal structure.

A.2 Residual Subsidence

Residual subsidence is the continued decrease in land surface elevation after the primary cause of subsidence (generally groundwater level declines) has stabilized or ceased. In an equilibrated aquifer system, ignoring any vertical heterogeneity that could lead to differences in confining conditions with depth, the groundwater levels in the fine- and coarse-grained sediments are effectively equal. During groundwater pumping, the groundwater levels do not simultaneously decline for both sediment types; rather, groundwater levels in the higher permeability sediments (sands and gravels) decline first and more rapidly. While these coarse-grained sediments have negligible compaction, the groundwater level decline generates a stress gradient between the coarse-grained and fine-grained units. At the boundaries between these sediments, the water in the fine-grained units will drain into the coarse-grained sediment under an increase in effective stress. The change in effective stress gradually propagates through the fine-grained unit as it is depressurized. Over time, drainage from the clay and confining units can become the predominant water source, potentially leading to inelastic aquifer-system compaction and residual subsidence.

Groundwater levels in thinner, fine-grained units can equilibrate relatively quickly to a groundwater level decline in the surrounding coarse-grained material. However, changes in the groundwater level in the middle of a thicker fine-grained unit may result in a delayed response that is more

[107] Hoffmann, J., Leake, S. A., Galloway, D. L., Wilson, A. M., & Survey, U. S. G. (2003). MODFLOW-2000 ground-water model-user guide to the Subsidence and Aquifer-System Compaction (SUB) Package. In Open-File Report. https://doi.org/10.3133/ofr03233.

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[109] Chaussard, E., & Farr, T. G. (2019). A new method for isolating elastic from inelastic deformation in aquifer systems: Application to the San Joaquin Valley, CA. Geophysical Research Letters, 46(19), 10800–10809.

[110] Neely, W. R., Borsa, A. A., Burney, J. A., Levy, M. C., Silverii, F., & Sneed, M. (2021). Characterization of groundwater recharge and flow in California's San Joaquin Valley from InSAR - observed surface deformation. Water Resources Research, 57(4), e2020WR028451.

influenced by longer duration groundwater trends than by seasonal fluctuations.[111,112,113] Residual subsidence can occur years to centuries after the preconsolidation stress was exceeded and can persist even after groundwater levels recover above the critical head.[114,115,116] The factors that influence this time-dependence are the fine-grained unit thickness, the hydraulic properties of the fine-grained unit, and the magnitude and duration of the groundwater level decline. Thicker fine-grained units require longer to equilibrate than thinner fine-grained units, as there is a greater thickness (and distance) of material through which the stress will propagate and from which water will drain. The rate at which fine-grained units can equilibrate is determined by hydraulic conductivity—a quality that is determined by sediment permeability. Sediments with lower hydraulic conductivity values will require more time to equilibrate.

A.3 Critical Head

The stress history of an aquifer system influences the potential for and rate of future subsidence, making it key information for accurate subsidence forecasting.[117] Knowledge of the critical head level is needed to determine when groundwater level declines will result in permanent subsidence. Paired analyses of subsidence (and/or compaction) records and groundwater level observations may be used to help estimate the critical head, as well as improve the understanding of the aquifer-system response to changing groundwater levels and to calculate aquifer-system storage properties. This information is also beneficial to the calibration of groundwater models and to the establishment of sustainable management criteria for preventing further subsidence.

Critical head exceedances that are large in magnitude (such as groundwater levels that are substantially lower than the critical head in the interbeds or confining units) and duration will result in greater residual subsidence. A recovery of groundwater levels to the level of the critical head will reduce the equilibration time (and the amount of delayed compaction) compared with stabilizing groundwater levels below the critical head. However, the needed time for equilibration when raising groundwater levels only to the critical head can be substantial in some cases. Therefore, to minimize residual subsidence, a rapid and sustained recovery of groundwater levels to a level

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111 Borchers, J. W., Carpenter, M., Kretsinger Grabert, V., Dalgish, B., & Cannon, D. (2014). Prepared By Full Report of Findings / Land Subsidence from Groundwater Use in California Land Subsidence from Groundwater Use in California Contributing Authors. http://www.californiawaterfoundation.org.

112 Galloway, D. L., Jones, D. R., & Ingebritsen, S. E. (1999). Land subsidence in the United States (Vol. 1182). Geological Survey (USGS).

113 Kelley, V., Deeds, N., Young, S., & Pinkard, J. (2018). Subsidence Risk Assessment and Regulatory Considerations for the Brackish Jasper Aquifer.

114 Helm, D. C. (1978). Field verification of a one-dimensional mathematical model for transient compaction and expansion of a confined aquifer system.

115 Ireland, R. L., Poland, J. F., & Riley, F. S. (1984). Land Subsidence in the San Joaquin Valley, California as of 1980.

116 Lees, M., Knight, R., & Smith, R. (2022). Development and Application of a 1D Compaction Model to Understand 65 Years of Subsidence in the San Joaquin Valley. Water Resources Research, 58(6). https://doi.org/10.1029/2021WR031390.

117 Galloway, D. L., Jones, D. R., & Ingebritsen, S. E. (1999). Land subsidence in the United States (Vol. 1182). Geological Survey (USGS).

above the critical head may be required. Examples of various groundwater level recoveries compared with delayed compaction are discussed in the next section.

A.4 Long-Term Stress History Analysis

Here, examples of the long-term stress history at select sites in California's Central Valley are discussed. Similar analyses throughout the Central Valley and other basins that are prone to subsidence are needed to understand the long-term stress history at other locations. DWR, as a part of the California's Groundwater (Bulletin 118) Update 2025[118], released long-term subsidence and water level data compilations and numerical models for 50 sites throughout the Central Valley, including the fiveexamples provided in this BMP[119]. Details of the analysis summarized in this section, and the modeling performed in the Technical Memorandum[120] is summarized in Appendix E.

Figures A-1 through A-5 show long-term subsidence and groundwater levels at five sites: four in the San Joaquin Valley (Sites A–D) and one in the Sacramento Valley (Site E). At Sites A and B (Tule Subbasin) and Site D (Westside Subbasin), the upper and lower aquifer designation denotes the position above and below the Corcoran Clay, respectively. Subsidence in the San Joaquin Valley was first observed in the 1930s and was attributed to the intensive agricultural development that heavily relied on groundwater for irrigation.[121] Much of the subsidence in the southern San Joaquin Valley is linked to groundwater level declines in the deeper aquifer system, confined by the Corcoran Clay, a laterally extensive lacustrine deposit up to 160 feet thick.[122]

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[118] 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.

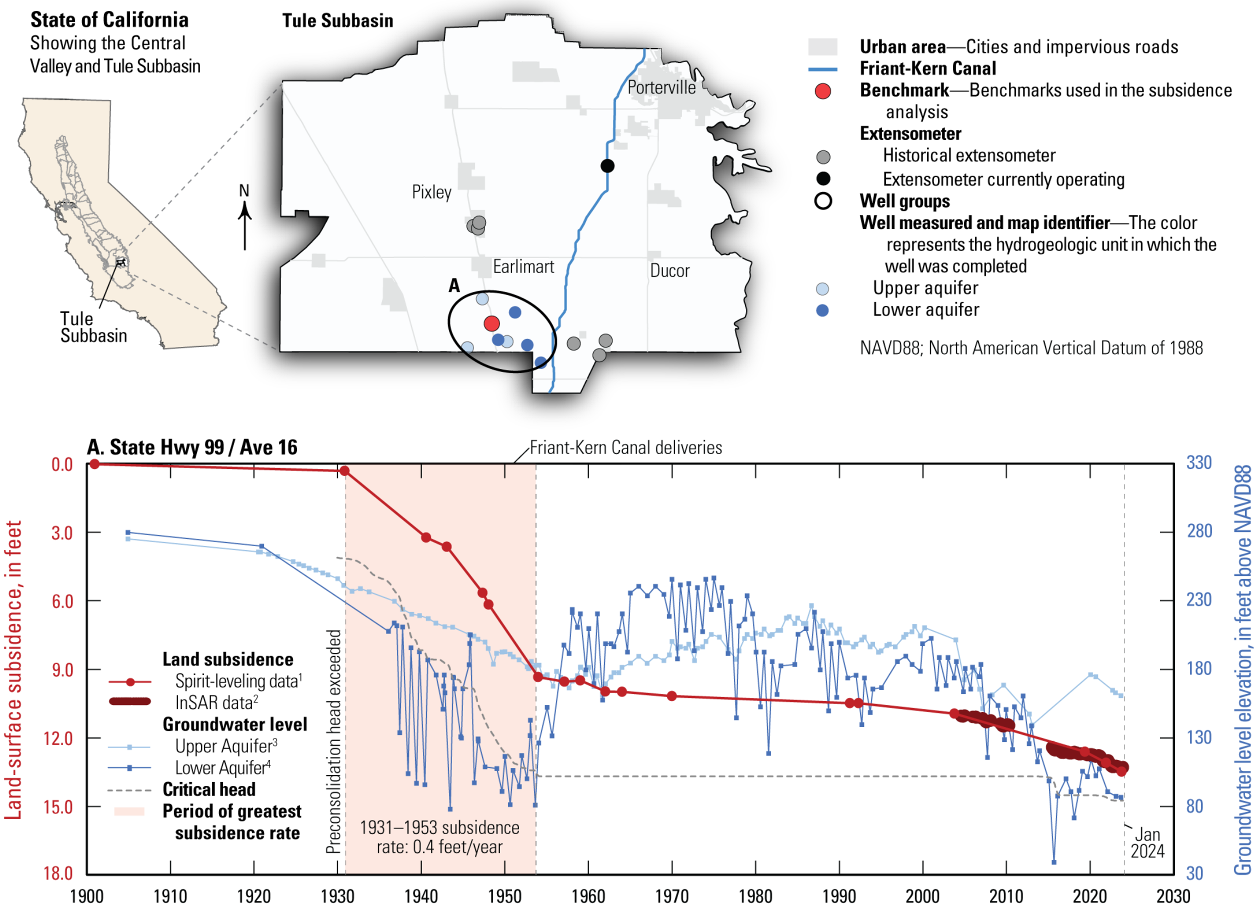
[119] Ellis, J., White, J., Saberi, L., Earll, M., Neely, W., & Hughes, J. (2025). *Documentation of subsidence modeling for the Central Valley* (Technical Memorandum). INTERA Incorporated. https://data.cnra.ca.gov/dataset/cv-1d-subsidence-models-and-tech-memo.

[120] Ellis, J., White, J., Saberi, L., Earll, M., Neely, W., & Hughes, J. (2025). *Documentation of subsidence modeling for the Central Valley* (Technical Memorandum). INTERA Incorporated. https://data.cnra.ca.gov/dataset/cv-1d-subsidence-models-and-tech-memo.

[121] Poland, J. F., Lofgren, B. E., Ireland, R. L., & Pugh, R. G. (1975). Land subsidence in the San Joaquin Valley, California, as of 1972.

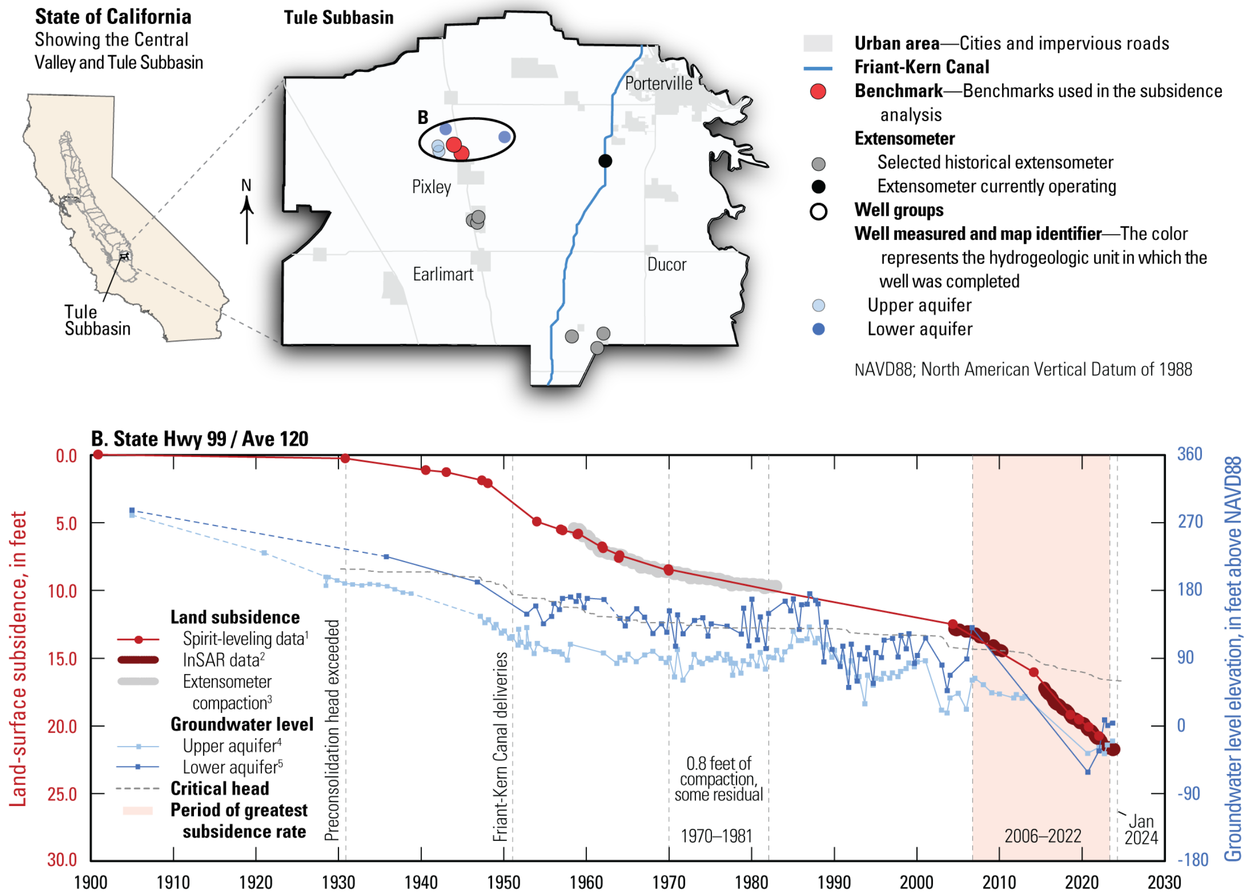
[122] Galloway, D. L., Jones, D. R., & Ingebritsen, S. E. (1999). Land subsidence in the United States (Vol. 1182). Geological Survey (USGS).

Figure A-1. Long-term site at State Hwy 99 / Ave 16



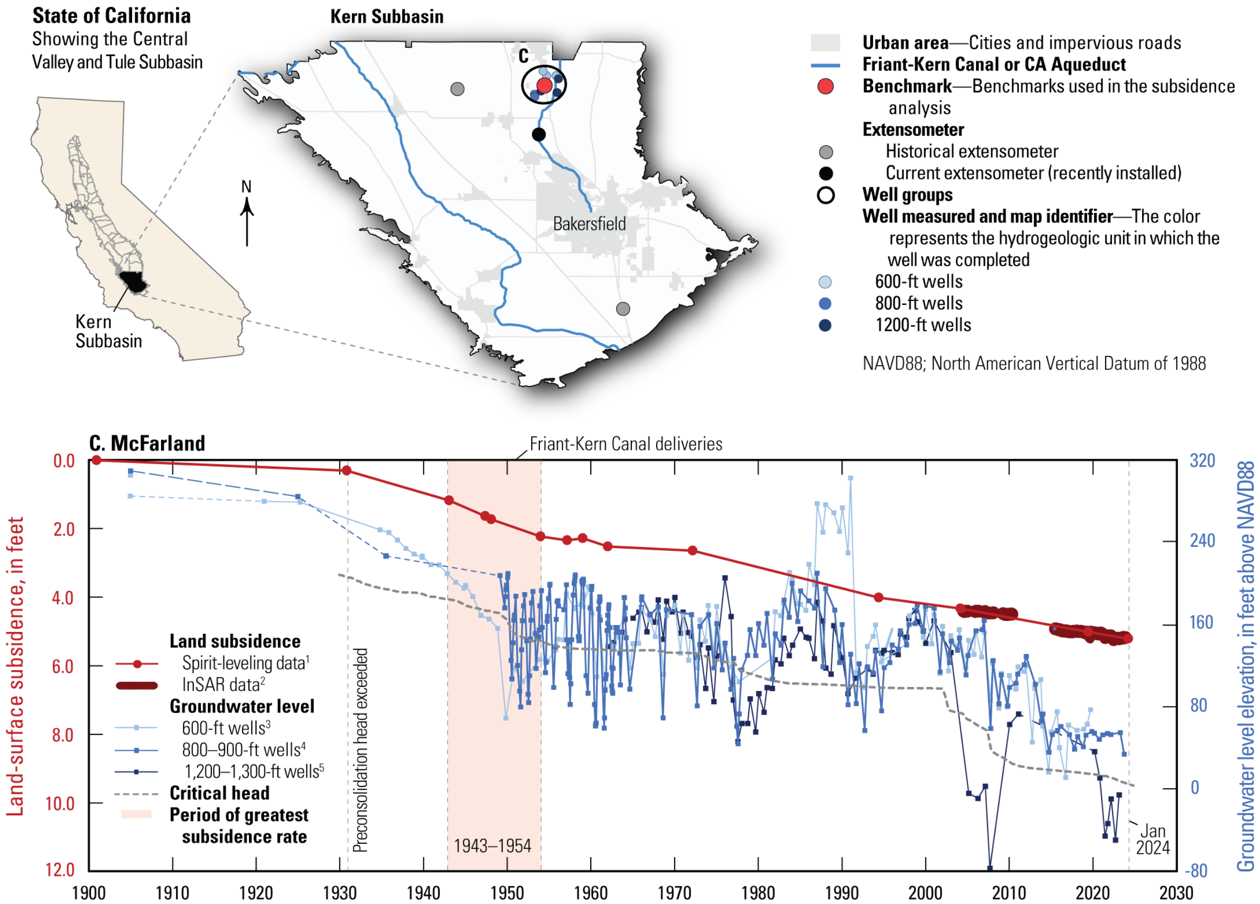
[1]Benchmarks 302.847, T 88, and HPGN CA 06 13 were used to determine cumulative subsidence from 1901 to 2021. [2]The initial value for the InSAR vertical displacement is registered to the amount of cumulative subsidence determined from spirit leveling. Data obtained from the California Department of Water Resources and extracted at cells containing the benchmark. [3]The 1905 and 1921 estimated water levels are from Lofgren and Klausing (1969); 1920–57: 25S25E04C001M; 1957–2013: 24S25E16B001M; 2020–23: 24S25E35H001M. [4]The 1905 and 1921 estimated water levels are from Lofgren and Klausing (1969); 1935–44: 24S25E36H001M; 1945–55: 25S26E08A001M; 1955–2000: 24S25E35D001M; 2000–24: 24S25E13F001M. Note that the critical head shown on this figure is the representative critical head for the lower aquifer. Much greater drawdown was observed to the northwest of this site during the period between 1945 and 1955 that is shown in Figure 68 of Lofgren and Klausing (1969) and Figure 23 of Poland and others (1975). This is site T 88 in Bulletin 118.

Figure A-2. Long-term site at State Hwy 99 / Ave 120



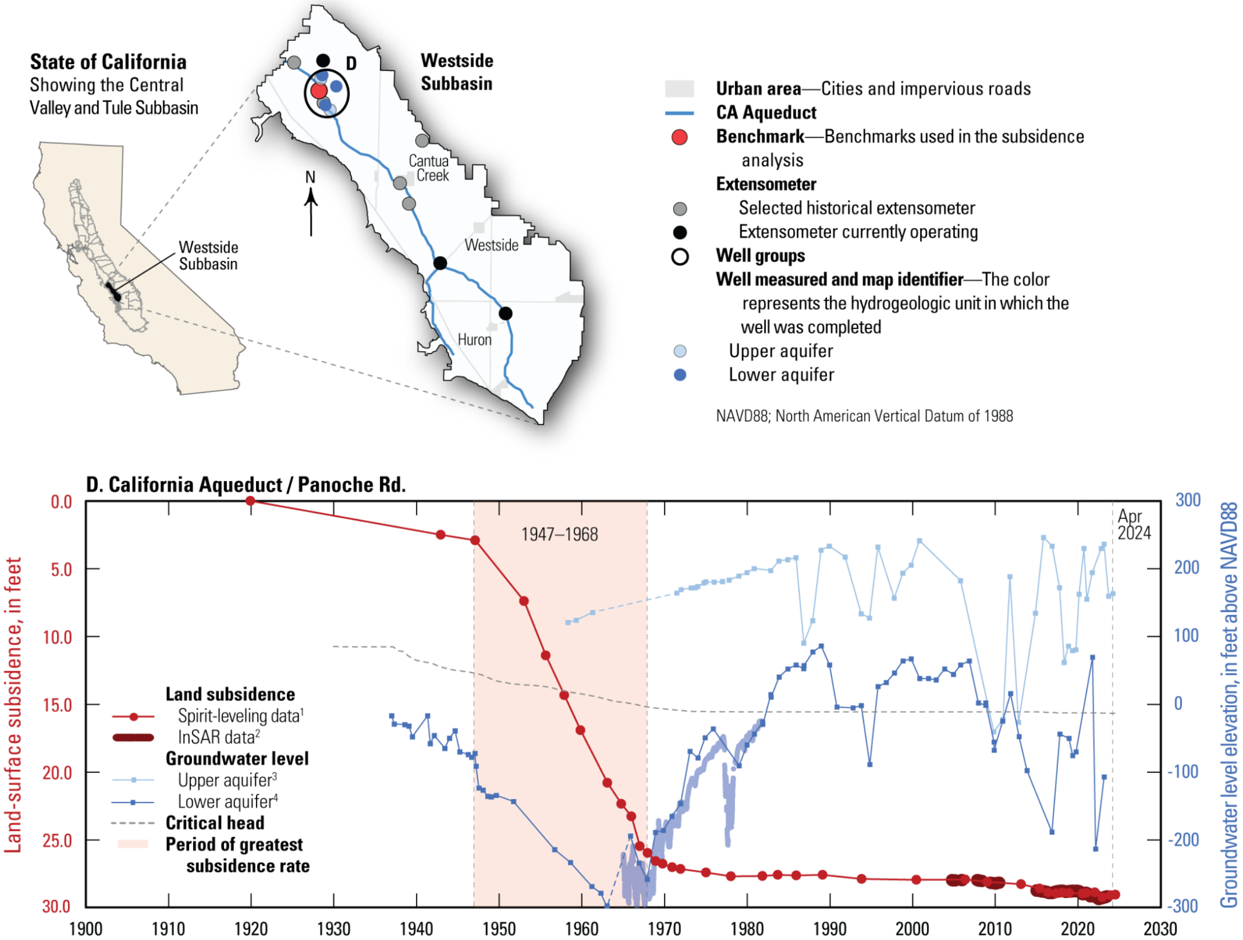
[1]Benchmarks 272.394, J 88, and QUAIL were used to determine cumulative subsidence from 1901 to 2021. [2]The initial value for the InSAR vertical displacement is registered to the amount of cumulative subsidence determined from spirit leveling. Data obtained from the California Department of Water Resources and extracted at cells containing the benchmark. [3]Extensometer data from extensometer 23S/25E-16N1 operational from 1958 to 1983 located in Pixley. [4]The 1905 and 1921 estimated water levels are from Lofgren and Klausing (1969); 1928–38: 22S24E23A001M; 1947–2023: 22S24E23J001M. [5]The 1905 estimated water level from Lofgren and Klausing (1969); 1935–62: 22S25E14J002M; 1964–2023: RMS well 22S24E01Q001M. Note that the critical head shown on this figure is the representative critical head for the lower aquifer. This is site J 88 in Bulletin 118.

Figure A-3. Long-term site at McFarland



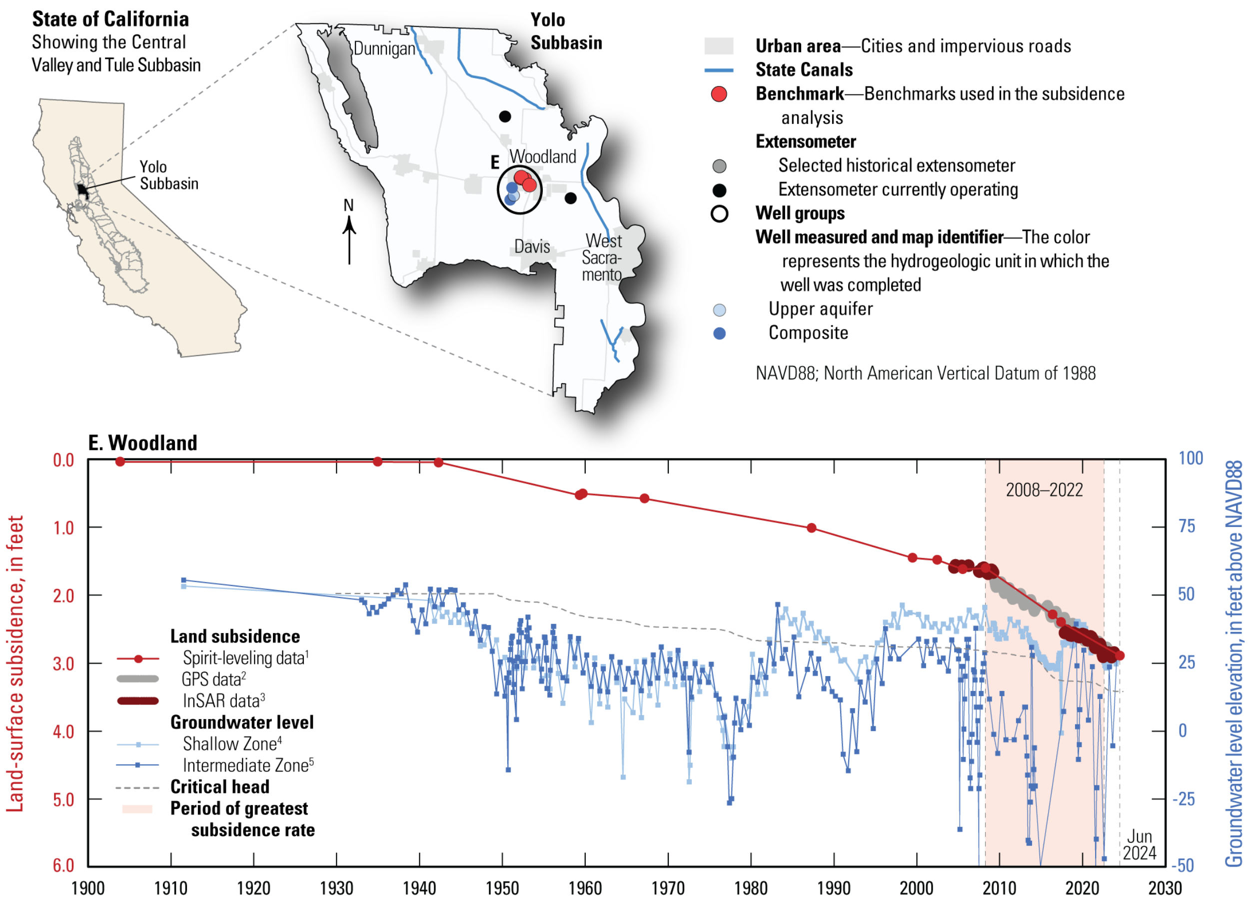
[1]Benchmarks 341.804, K 1206, R 454, and HPGN D CA 06 GK were used to determine cumulative subsidence from 1901 to 2021. [2]The initial value for the InSAR vertical displacement is registered to the amount of cumulative subsidence determined from spirit leveling. Data obtained from the California Department of Water Resources and extracted at cells containing the benchmark. [3]The 1905 and 1921 estimated water levels are from Lofgren and Klausing (1969); 1934–60: 25S26E32R001M; 1960–94: 25S25E36R002M; 1994–2019: 25S25E36C002. [4]The 1905, 1921, and 1934 estimated water levels are from Lofgren and Klausing (1969); 1949–1977: 26S25E15R001M; 1977–2023: 26S25E22H001M. Note that the sumer drawdown for 26S25E15R001M was filtered to improve readability. [5]1963–72: 26S26E05H001M; 1970–2011: 26S26E17J001M; 2020–23: 356675N1192402W001. Also note that the critical head shown on this figure is the representative critical head for the 800–900 ft wells interval. This is site 341.804 in Bulletin 118.

Figure A-4. Long-term site at California Aqueduct / Panoche Road



[1]Benchmarks GWM 14, 111.91 L, 111.93 L, and Z 1444 were used to determine cumulative subsidence from 1941 to 2024. From Ireland and others (1984), a total of 2.5 feet of subsidence was estimated from the 1920s to 1943 one mile east of this benchmark site. [2]The initial value for the InSAR vertical displacement is registered to the amount of cumulative subsidence determined from spirit leveling. Data obtained from the California Department of Water Resources and extracted at cells containing the benchmark. [3]1958–61: 14S13E23R001M; 1971–77: 15S13E12N004M; 1977–2024: 14S13E23E002M. [4]1937–46: 364109120294101 (USGS); 1947–63: 364102120294101 (USGS);1965–2009: 14S13E22A001M; 2010–23: 15S13E02P001M. Continuous recorder well 15S13E11D002M located 1.8 miles to the south at historical extensometer 15S/13E-11D2 is also shown. This is site GWM 14 in Bulletin 118.

Figure A-5. Long-term site at Woodland



[1]Benchmarks B 20, H 201, WOODLANDS RESET, LIBRARY, and Z 1444 were used to determine cumulative subsidence from 1941 to 2024. [2]GPS data from GPS station PLSB using data from JPL and SOPAC. [3]The initial value for the InSAR vertical displacement is registered to the amount of cumulative subsidence determined from spirit leveling. Data obtained from the California Department of Water Resources and extracted at cells containing the benchmark.[4]The 1913 estimated water level is from Bryan (1923); 1941–1984: 10N02E34M001M 1984–2024: 10N02E29A001M. [5]The 1913 estimated water level is from Bryan (1923); 1933–2005: 09N02E07L001M; 2005–2024: 09N02E06B001M. Note that the critical head shown on this figure is the representative critical head for the Intermediate Zone. This is site H 201 in Bulletin 118.

Sustained groundwater level declines in the Tule Subbasin (Sites A–B, Figures A-1 and A-2) led to some of the earliest recorded subsidence in the San Joaquin Valley. By 1931, the upper aquifer groundwater level at Site A (Figure A-1) had exceeded the preconsolidation head by an estimated 85 feet and the subsidence rate increased rapidly[123]; however the lower aquifer groundwater level for Figure A-1 was not available between 1921 and 1935. The increase in the subsidence rate once the preconsolidation head was exceeded at this site has been similarly documented in California, Texas, and Arizona by Holzer[124]. By the early 1950s, the importation of surface water from the Friant-Kern Canal resulted in a rapid groundwater level recovery, effectively minimizing all but a small amount of subsidence that occurred at Site A due to the previous rapid and sustained groundwater level recovery. Sustained groundwater level declines between 2007–2018 increased the subsidence

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[123] Holzer, T. L. (1981). Preconsolidation stress of aquifer systems in areas of induced land subsidence. Water Resources Research, 17(3), 693–704. https://doi.org/10.1029/WR017i003p00693.

[124] Holzer, T. L. (1981). Preconsolidation stress of aquifer systems in areas of induced land subsidence. Water Resources Research, 17(3), 693–704. https://doi.org/10.1029/WR017i003p00693.

rate to 0.13 ft/year. This subsidence rate (and total subsidence) was much less at Site A than at Site B due primarily to (1) the large recovery in groundwater levels between the early 1950s and 2013 prior to the more recent declines that provided for additional drawdown before reaching the critical head, and (2) substantial groundwater level declines in the 1930s to early 1950s that lowered the critical head.

During the early 1950s, the maximum subsidence area shifted northwards along Highway 99 to Site B (Figure A-2), located between Earlimart and Pixley (at the site of the historical Pixley extensometers). At Site B, groundwater levels had declined by more than 60 feet during 1931–1953, resulting in approximately five feet of subsidence (Figure A-2). Despite some periodic stabilization of groundwater levels through 1970, subsidence continued at a reduced rate. From 1970–1981, about 0.8 foot of (mostly) delayed compaction occurred due to the delayed drainage of the fine-grained interbeds of the lower aquifer beneath the Corcoran Clay based on the extensometer data. Beginning around 2007, groundwater levels at Site B rapidly declined, resulting in a subsidence rate of about 0.5 ft/year during 2006–2020 (Figure A-2).

By the early 1950s, subsidence extended southward to Site C, located in the northeastern part of the Kern Subbasin. Subsidence at Site C decreased to nearly zero until 1972 as groundwater levels stabilized and recovered (Figure A-3). Site C then experienced significant fluctuations in groundwater levels, with declines exceeding 50 feet in the deepest part of the aquifer. During 1977–1987 and 1991–1999, two periods of groundwater level recovery occurred across all sites, separated by intervals of groundwater level decline. Subsidence at Site C slowed to a rate of 0.06 ft/year between 1972–1994 and then slowed further to 0.03 ft/year from 1994–2005 (Figure A-3). Substantial groundwater level declines during 2001–2007 and 2012–2016 led to ongoing subsidence at Site C, driven largely by reduced surface water availability and increased groundwater pumping in the Kern Subbasin[125.] Although groundwater level declines at Site C have been similar to those in the Tule Subbasin (Sites A–B), the lower level of observed subsidence is likely due to the relatively lesser amount of fine-grained sediment content, resulting in less subsidence per foot of groundwater level decline (Figure A-3).

In the Westside Subbasin (Figure A-4), rapid lower aquifer groundwater level declines at Site D resulted in large annual increases in effective stress from the late 1940s to the mid 1960s. These groundwater level declines resulted in a sustained subsidence rate of about one foot per year between 1947 and 1968, for a total of 23 feet of subsidence during that same period (Figure A-4). This is the greatest sustained subsidence rate in California to the present day (2025). During the period between 1953 and 1955, the subsidence rate was greater than 1.5 feet per year (Figure A-4). This area remained the epicenter of subsidence in the San Joaquin Valley through the early 1970s. By the late 1960s, groundwater levels had began rising sharply, rapidly slowing subsidence in this area. Delayed compaction during 1970–1981 was similar to Site B. However, the compaction rate at Site D was more than three times the rate at Site B during the preceding 23 years (1947–1970). The rapid recovery of groundwater levels at Site D between 1967 and the early 1980s prevented many feet of delayed compaction. However, substantial groundwater level declines in the lower aquifer

[125] California Department of Water Resources. (2003). California's Groundwater: Bulletin 118 - Update 2003, Kern County Subbasin (5-022.14). Sacramento, CA. Retrieved from https://water.ca.gov/-/media/DWR-WebSite/Web-Pages/Programs/Groundwater-Management/Bulletin-118/Files/2003-Basin-Descriptions/5_022_14_KernCountySubbasin.pdf.

during the recent period have likely reached or exceeded the critical head, restarting some inelastic compaction (Figure A-4).

In Yolo County, some early subsidence beginning around 1943 occurred due to rapid declines in groundwater levels in the shallow and intermediate zones (Site E, Figure A-5). The groundwater level in both zones remained below the critical head between 1943 and the mid 1980s, resulting in about 1 foot of subsidence. In the mid-1990s, a rapid groundwater level recovery that reduced the subsidence rate to near zero averaged across the period of 1999 through 2008 (Site E, Figure A-5). However, groundwater pumping in the shallow and intermediate zones resulted in large seasonal declines in groundwater levels of as much as 80 feet, accelerating the rate of subsidence to 0.08 foot per year from 2008–2022 (Site E, Figure A-5). In 2008, DWR expanded the subsidence monitoring network in the Sacramento Valley, installing many new benchmarks and continuous GPS sites to monitor the ongoing subsidence as groundwater levels slowly recovered from the severe drought[126]. Continuous GPS data and InSAR for Site E (Figure A-5) show land subsidence of about 1.3 ft during the period 2008–2024.

A.5 Short-Term Stress History Analysis

While the vast majority of observed subsidence is due to the drainage of water out of fine-grained sediments, compaction/expansion processes may occur on a range of time scales. An example of these time scales for compaction/expansion processes can be demonstrated through an examination of collocated extensometer and monitoring well data (Tule Subbasin currently operating extensometer; location shown on Figures A-1 and A-2 and timeseries on Figure A-6). A comparison of these two records shows how they both capture the seasonal response each year. However, relative to their respective longer-term trends, the seasonal amplitudes for the groundwater level record are much larger than those for the compaction time series. During periods of time where groundwater level declines (red shaded regions), compaction occurs. In years where recorded groundwater levels decline to a new lowest level (such as 2020 and 2021) or approach the lowest recorded levels (such as 2022), the compaction rate is greater.. In the case where the groundwater level recovery exceeds the previous year's maximum level (such as 2023 compared to 2022), associated expansion does not fully counteract the compaction that previously occurred. This is evidence that some inelastic compaction has probably occurred. Simultaneously, the seasonal rebound (expansion) observed by the extensometer demonstrates elastic (recoverable) compaction.

[126] California Department of Water Resources. (2017). GPS Survey of the Sacramento Valley Subsidence Network. https://data.cnra.ca.gov/dataset/gps-survey-of-the-sacramento-valley-subsidence-network.

Figure A-6. Subsidence and Groundwater Level Time Series for the Extensometer (22S27E30D002M) in the Tule Subbasin

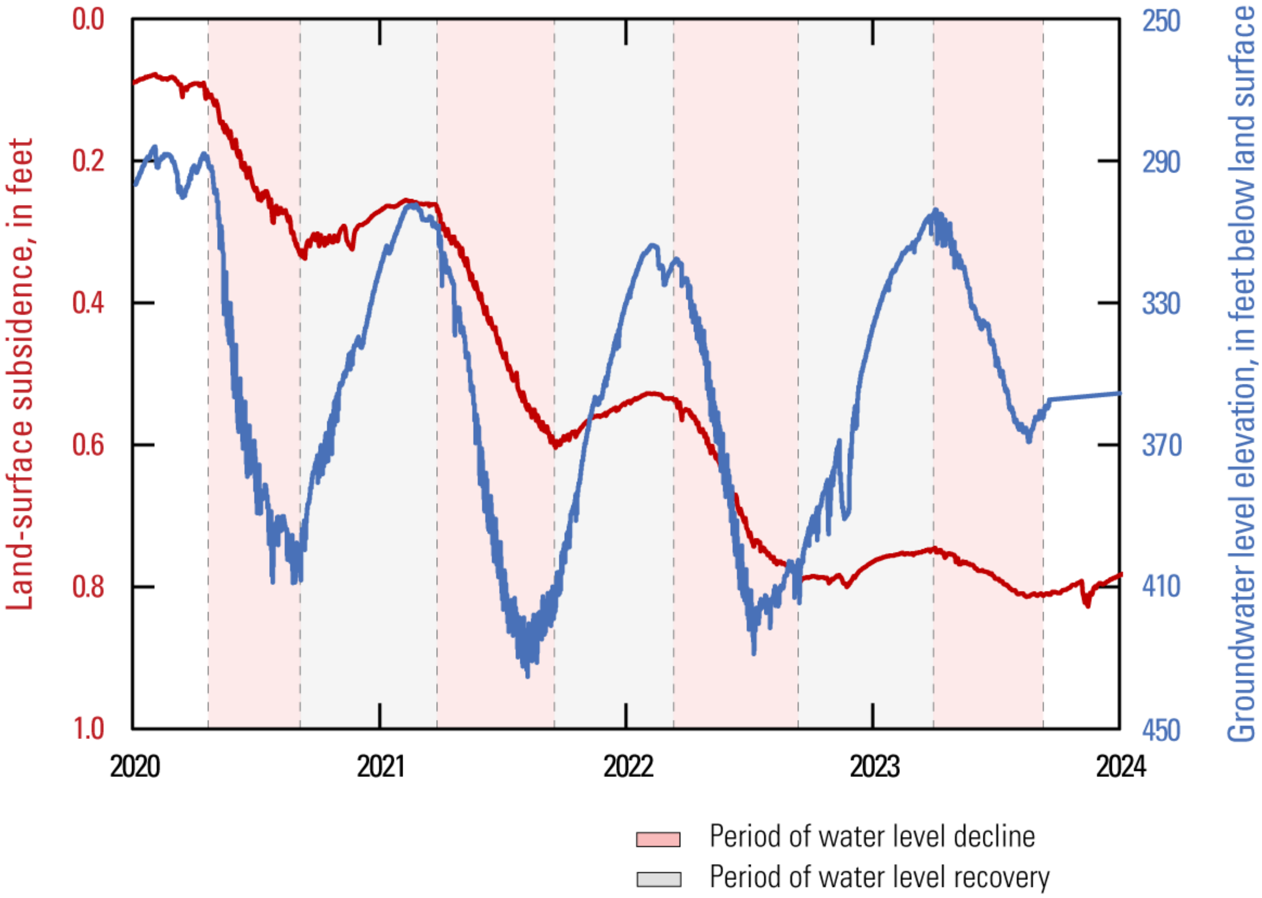

Figure Note: This figure shows the relationship between seasonal groundwater levels (i.e., water levels) and subsidence rates.

B Subsidence Monitoring Methods

This appendix presents the details of four subsidence monitoring methods, leveling surveys, extensometers, GPS, and InSAR. Table B-1 shows the methods, their time periods of use, and other considerations.

Table B-1 - Subsidence Monitoring Summary. Uncertainties for These Subsidence Methods is Available in Bawden et al., 2003.[127]

Method	Time Period	Spatial Coverage	Collection Frequency	Fundamental Observation	Major Noise Sources
Leveling Surveys	1900s - Present		Campaign	Relative Surface Elevation	User Error
Extensometers	1950s - Present	Station	< Daily	Subsurface Compaction	Calibration; Maintenance
Continuous GPS	1990s - Present	Station	< Daily	Timing to Satellite/Receiver	Antenna Offsets
GPS Surveys	2000s - Present		Campaign	Timing to Satellite/Receiver	User Error
InSAR	1990s - Present	Regional	Weeks - Months	Radar Reflection - Surface	Atmosphere, Orbits, Vegetation

B.1 Leveling Surveys

The use of leveling surveys for measuring land surface elevations in California dates back to the early 1900s. These surveys were the primary means for measuring subsidence through most of the twentieth century. Surveys were commonly performed along linear infrastructure, including roads and railroad tracks, as part of initial construction or ongoing maintenance.[128] The campaign installation of benchmarks (or “monumenting”) in California was generally first performed in 1901 by the U.S. Geological Survey (USGS) and in 1906 by the U.S. Coast and Geodetic Survey (predecessor to the National Geodetic Survey). The leveling technique allows the surveyor to carry an elevation from a known reference point (such as a benchmark) to other points by use of a precisely leveled telescope and a graduated rod resting vertically on temporary or permanent benchmarks. Repeated surveys of the same benchmarks over time yield a series of elevations from which elevation changes are calculated. While this surveying technique is not used as commonly today, the earliest surveys can still be tied to a contemporary or future survey, provided the historical data are adjusted.

Direct observations are limited to benchmark locations, and these measurements are often interpolated and contoured to determine changes between benchmarks (example of contouring shown in Figure 5-1). The spatial extent for an individual survey can be on the order of tens of miles,

[127] Bawden, G. W., Sneed, M., Stork, S. V., & Galloway, D. L. (2003). Measuring human-induced land subsidence from space: U.S. Geological Survey Fact Sheet 069–03.

[128] Sneed, M., Brandt, J. T., & Solt, M. (2018). SIR 2018 – 5144: Land Subsidence Along the California Aqueduct in West-Central San Joaquin Valley, California, 2003 – 10.

with 10-100 measurements collected (examples of survey designs shown in Figure B-1). Using a campaign style data collection process, repeat observations may not occur in regular intervals, with times between surveys ranging from years to decades. When surveyed according to best practices and in optimal conditions, this survey technique can achieve accuracies of 0.004-0.04 inch. Typical error sources may arise from the need to adjust the field-derived elevations due to surveys originating and traversing across areas of active subsidence, constraints used during the adjustment process, improper leveling of the telescope, surveying during extreme heat, and incorrect surveyor recording of measurements. Information on this survey type and measurement uncertainty is available in Federal Geodetic Control Committee.[129]

Leveling surveys form the basis of the subsidence maps published in many historical reports and allow for the construction of long-term subsidence time series (and with other subsidence datasets). However, as they are collected as points in a line-network, direct observations of elevation changes are limited to the locations of benchmarks. These locations are predominantly focused on important infrastructure (such as canals, pipelines, roads, and railways) at the time of data collection. While the contouring of data is useful, localized subsidence between benchmarks may not be observed. Conversely, benchmarks located in a localized subsidence feature may give the impression of a broader subsidence bowl when contoured. Further, leveling surveys can be labor intensive and are limited in their spatial extent as the line of sight between the instrument and location of interest needs to be maintained. As more modern surveying techniques have been developed, the use of leveling today is less prevalent.

[129] Bossler, J. D. (1984). Standards and specifications for geodetic control networks. Federal Geodetic Control Committee.

Figure B-1. Historical leveling in the Westside Subbasin

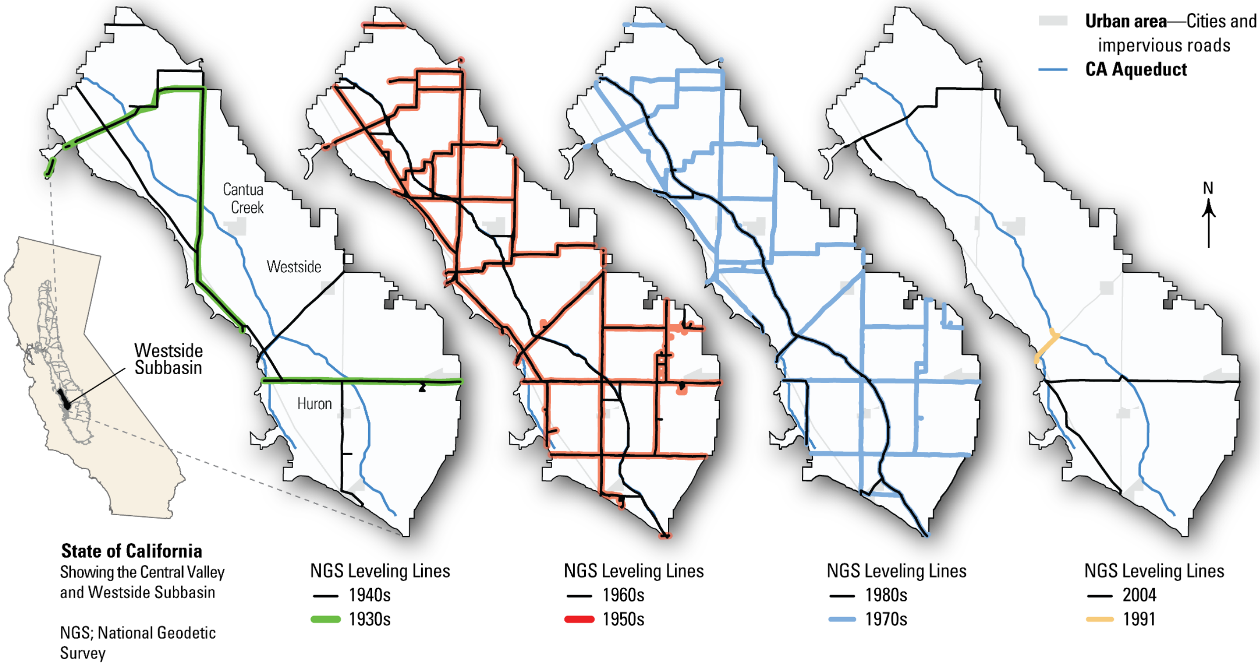

Figure Note: This figure shows the progression of spirit leveling lines run across the Westside subbasin between 1935 and 2004. After subsidence rates had slowed substantially by the early 1970s, little leveling was performed in the Westside Subbasin and the Central Valley.

B.2 Extensometers

A borehole extensometer measures the vertical compaction/expansion of subsurface materials over a specified depth interval(s) of an aquifer system. Whereas other methods described in this BMP measure ground surface elevation changes, extensometers are the only devices that directly measure the compaction or expansion of an aquifer system. A network of extensometers was installed across the Central Valley beginning in the late 1950s and early 1960s.[130,131] However, funding (and thus operation) at many of these instruments ceased during the 1980s. Since that time, some of these sites have been more recently refurbished in addition to the installation of newer extensometers.

An extensometer is often described as a deep benchmark in which changes in the vertical distance between the deep benchmark (anchor depth of the extensometer) and a surface reference point (a concrete pad at land surface or the depth of the extensometer concrete pad piers, typically about 20 ft below land surface) are measured. The earlier extensometers were typically built using a steel cable with an anchor weight at the bottom of the borehole and a counterweight at the surface to

[130] Borchers, J. W., Carpenter, M., Kretsinger Grabert, V., Dalgish, B., & Cannon, D. (2014). Prepared By Full Report of Findings / Land Subsidence from Groundwater Use in California Land Subsidence from Groundwater Use in California Contributing Authors. http://www.californiawaterfoundation.org.

[131] Ireland, R. L., Poland, J. F., & Riley, F. S. (1984). Land Subsidence in the San Joaquin Valley, California as of 1980.

keep the cable under tension.[132] More recently, the cable has been replaced by a continuous steel pipe that rests on the bottom of the borehole that is often counterweighted to keep the inner pipe stable and aligned within the borehole and maintain tension in the system. A conceptual extensometer design is shown in Figure B-2. Compaction and expansion measurements are taken using manual (dial gauge or tape) readings during periodic site visits and electronic (linear potentiometer) readings that are recorded on electronic data loggers capable of hourly measurements. When these instruments are properly calibrated and maintained, they can achieve accuracies of 0.0004-0.004 inch.[133] Compaction observations from extensometers are limited to their specific depth interval; however, measurements from these devices can be compared with InSAR or GPS subsidence data to assess compaction below the extensometer anchor depth. For steel-pipe style extensometers, a GPS antenna can be mounted to the top of the pipe to measure deep-seated compaction below the extensometer. Further, recent developments in extensometer design, such as the use of magnetic rings,[134] allow for greater detail of the specific depths at which compaction is occurring and enable improved understanding of subsidence processes at the instrumented sites.

When combined with groundwater level records, extensometer data are highly valuable for understanding subsidence processes. These instruments are often collocated with groundwater level recorders sampled at monthly or better time scales, which can be used to estimate the amount of compaction occurring in discrete subsurface zones at a fine temporal scale. The cost for installation of extensometers can be prohibitive, limiting the number of locations where these data are available. Extensometer data in California's Central Valley is available through the California Open Data Portal (https://data.ca.gov/dataset/wdl-ground-surface-displacement-land-subsidence-monitoring) and from the USGS.[135] Data can also be accessed through the SGMA Data Viewer.[136]

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[132] Lofgren, B. E. (1961). Measurement of compaction of aquifer systems in areas of land subsidence. US Geol. Surv. Prof. Pap, 424, 49 – 52.

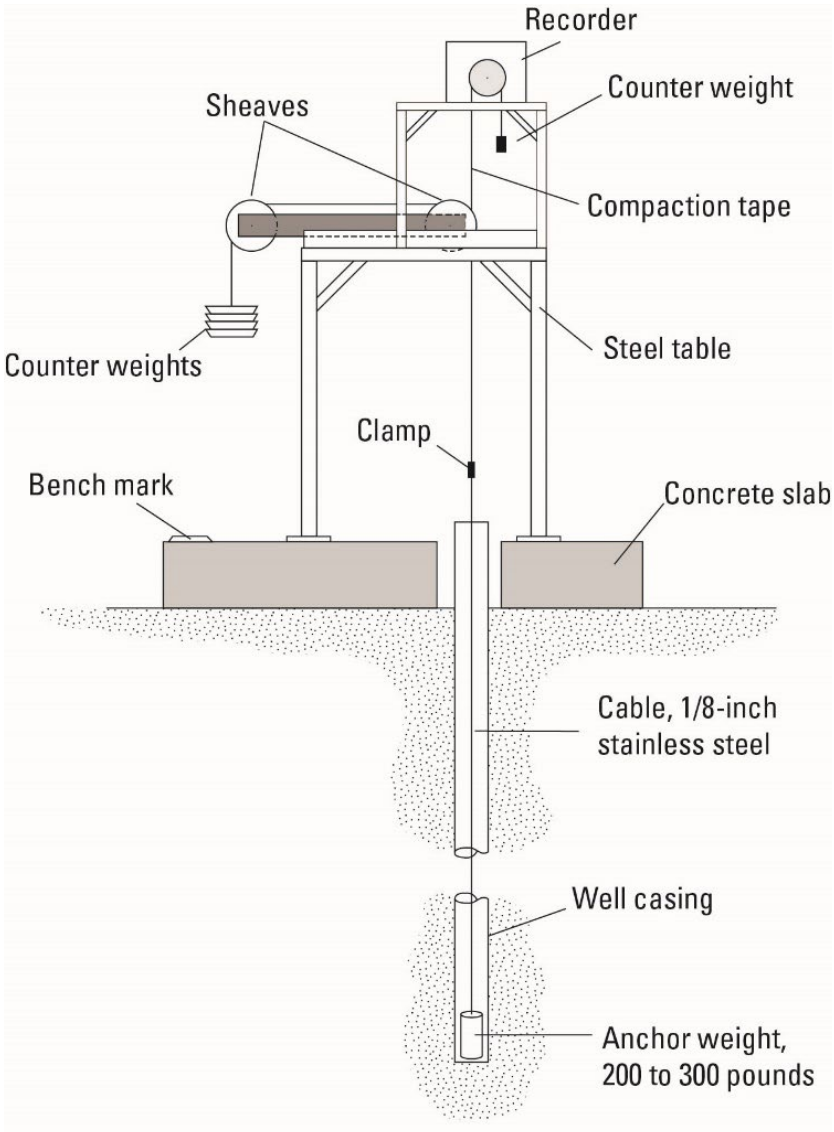
[133] Bawden, G. W., Sneed, M., Stork, S. V., & Galloway, D. L. (2003). Measuring human-induced land subsidence from space: U.S. Geological Survey Fact Sheet 069 – 03.

[134] Hung, W. C., Hwang, C., Sneed, M., Chen, Y. A., Chu, C. H., & Lin, S. H. (2021). Measuring and interpreting multilayer aquifer-system compactions for a sustainable groundwater-system development. *Water Resources Research*, *57*(4), e2020WR028194.

[135] Faunt, C. C., Traum, J. A., Boyce, S. E., Seymour, W. A., Jachens, E. R., Brandt, J. T., Sneed, M., Bond, S., & Marcelli, M. F. (2024). Groundwater Sustainability and Land Subsidence in California's Central Valley. Water (Switzerland), 16(8). https://doi.org/10.3390/w16081189.

[136] California Department of Water Resources. (2024a). SGMA Data Viewer. https://sgma.water.ca.gov/webgis/?appid=SGMADataViewer#currentconditions.

Figure B-2. Conceptual Diagram Illustrating a Borehole Cable Extensometer (from Sneed and others, 2013)



B.3 GPS

GPS surveying is a method that uses timing information for signals transmitted from a network of satellites and Earth-based receivers to determine accurately the position and ellipsoid height of geodetic monuments.[137] Using trilateration, the position can be determined precisely. The GPS technique allows the GPS surveyor to obtain elevations at specific locations autonomously rather than carrying an elevation from a known reference point to other points like the leveling technique requires. Repeated GPS surveys of the same points over time yield a series of elevations from which elevation changes are calculated.

[137] Sneed, M. (2001a). Hydraulic and Mechanical Properties Affecting Ground-Water Flow and Aquifer-System Compaction, San Joaquin Valley, California.

Receivers that are fixed to the ground at a station and continuously operated are called continuous GPS. Thousands of continuous GPS stations in the United States are operated by various scientific research consortiums, government agencies, private industries, or other groups. In California, networks of hundreds of continuous GPS stations are maintained by UNAVCO and the Scripps Orbit and Permanent Array Center, which began to expand in the early to mid-2000s for the observation of transient crustal deformation.[138] The network of stations was primarily designed with a focus on tectonic applications. Thus, many of the available stations in California are located near active fault systems, such as along the San Andreas Fault. As the utility of GPS positioning data for other applications increases, spatial data gaps have been increasingly filled. In the Central Valley, the spacing between continuous stations is on the order of tens of miles. The sampling frequency of data collection for these permanent stations are often set to 15-30 second intervals, with the observations averaged into daily estimates. The continuous calculation of the station position allows for the estimation of displacement time series at accuracies of 0.2 inch for the vertical component and 0.04 inch for the horizontal components.[139]

While data from continuous GPS stations provide highly precise and frequent observations of land surface displacements, errors and discontinuities in the GPS displacement time series include offsets due to equipment changes, processing strategies, orbital and clock errors, atmospheric errors, and multipath effects. It should be noted that most stations are often coupled at depth (~30 feet), resulting in an inability to capture shallow displacement processes using conventional methods. Due to the high frequency and moderate time window of data collection, GPS time series are often subsampled to match observational times of other displacement datasets for calibration and validation efforts. Vertical displacement records from GPS can be accessed through the SGMA Data Viewer.[140]

Additionally, with the introduction of GPS, technologies such as Real-Time Kinematic GPS are nowadays often used to measure subsidence in California rather than leveling surveys. These Real-Time Kinematic surveys will generally have one or more base stations occupying a location with a known elevation while a mobile receiver (rover) collects positional data at selected points. Positional rover data are corrected using information from the base station. For optimal data reliability, the locations of rover sites will have clear sky visibility, avoidance of reflective surfaces that can introduce multipath effects, avoidance of strong sources of radio frequency (such as cellular antennas), a stable ground surface during data collection, and proximity to a base station to maintain a constant communication link. Similarly, these surveys can be labor intensive and are used to collect data at point locations. The relative sparsity of GPS (both continuous and survey) may lead to potential aliasing effects if interpolated.

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[138] Herring, T. A., Melbourne, T. I., Murray, M. H., Floyd, M. A., Szeliga, W. M., King, R. W., Phillips, D. A., Puskas, C. M., Santillan, M., & Wang, L. (2016). Plate Boundary Observatory and related networks: GPS data analysis methods and geodetic products. Reviews of Geophysics, 54(4), 759 – 808.

[139] Herring, T. A., Melbourne, T. I., Murray, M. H., Floyd, M. A., Szeliga, W. M., King, R. W., Phillips, D. A., Puskas, C. M., Santillan, M., & Wang, L. (2016). Plate Boundary Observatory and related networks: GPS data analysis methods and geodetic products. Reviews of Geophysics, 54(4), 759 – 808.

[140] California Department of Water Resources. (2024a). SGMA Data Viewer. https://sgma.water.ca.gov/webgis/?appid=SGMADataViewer#currentconditions.

B.4 InSAR

InSAR is a remote sensing technique used to estimate relative surface displacements. It functions by the repeat collection of synthetic aperture radar, an active remote sensing dataset often collected via satellite. During each visit, the sensor transmits an electromagnetic signal towards the Earth's surface and then records the signal phase and amplitude of the reflected energy. Using the difference in signal phase between two visits, referred to as an interferogram, the relative motion of the ground surface can be estimated.[141] While interferometric methods have existed since the 1970s, it was not until the 1990s, with the launch of the European Space Agency's ERS-1/2 missions, that InSAR for displacement observations truly began. Using satellite radar, displacements over large regions (10s-100s miles in width) can be observed at the resolution of 10s of feet and often at near global coverage. Repeat visits over a particular location depend on the satellite mission and objective but typically range between 12-46 days. Often, displacement rates and time series are calibrated and referenced to GPS data. While formal uncertainties on InSAR time series can be challenging to quantify, assessment of calibrated InSAR data with continuous GPS data over California have suggested statewide Root Mean Square Error values of about 0.35 inch though comparison with individual GPS stations' range of about 0.04 to about 1.18 inches.[142] The largest sources of error in InSAR are related to atmospheric phase delay, ionospheric noise, changes in surface scattering properties, and processing and orbital errors.

InSAR has transformed how surface displacements can be observed. The near global coverage, high spatial resolution, and regular collection intervals make it an ideal dataset for regional monitoring efforts. Additionally, InSAR allows for observation in locations where in situ data collection would otherwise be challenging. However, many InSAR datasets are not freely available, and the available datasets require specialized skills for data processing. DWR provides processed InSAR data for utility by non-InSAR experts.[143] While there are several satellite missions that seemingly overlap, data from one mission is generally not compatible with another due to differences in radar wavelength and orbital geometries. Further, satellite specific radar properties and data collection strategies can necessitate differences in processing parameters, complicating the overlapping of multiple missions for a single time series. As interferograms represent observations that are relative to each radar image phase information, calibration with external data sources, such as GPS data, are often used to link interferograms together and force InSAR results into an absolute reference frame.

As a part of the SGMA Technical Assistance Program,[144] DWR provides regular releases of InSAR vertical surface displacement estimates over California's groundwater basins. Currently, the InSAR dataset available uses the European Space Agency Sentinel-1 missions to generate monthly estimates spanning 2015 to present and with quarterly updates. DWR also provides time series from the European Space Agency Envisat mission with monthly estimates of displacement

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[141] 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.

[142] Towill. (2024). InSAR Data Accuracy for California Groundwater Basins.

[143] Towill. (2024). InSAR Data Accuracy for California Groundwater Basins.

[144] California Department of Water Resources. (2024b). Technical Assistance Program. https://Water.ca.Gov/Work-With-Us/Technical-Assistance.

spanning September 1, 2003, to October 1, 2010, as well as displacement from select time pairs using images collected by the Canadian Space Agency Radarsat-2 mission for 2011-2015.

C Numerical Modeling

Numerical modeling can estimate the extent and timing of land subsidence, which can be used to assess risks to infrastructure and develop strategies for mitigating impacts due to groundwater pumping and understanding long-term subsidence trends. Numerical models are widely used as decision-support tools for understanding groundwater systems and evaluating management strategies aimed at mitigating and preventing subsidence while optimizing water availability.[145]

In groundwater basins with historical or active land subsidence due to pumping, GSAs should use models capable of simulating changes in groundwater level and the loss of storage from sediment compaction caused by drawdown from pumping. For basins with significant spatial variability in groundwater levels and historical subsidence, models that couple one-dimensional subsidence calculations with three-dimensional groundwater flow simulations can provide a more complete spatial representation of system response. However, the accuracy of any subsidence model ultimately depends on the availability and quality of site-specific data, including measurements of soil compressibility, groundwater levels, and subsidence.[146] The applicability and assumptions of each modeling strategy depend on the problem and hydrogeology of the aquifer system, as well as the availability of developed subsidence modeling tools. Each tool is subject to its own uncertainties, limitations, and assumptions.

C.1 Integrated Modeling

An **integrated model** typically refers to the coupling of groundwater flow, surface water flow, landscape and vadose zone processes, and aquifer system compaction and subsidence. Integrated models are particularly used in California, where subsidence is driven by issues related to water resource availability. There are two integrated modeling codes that are relevant to water resource planning and adaptive management in California: The Integrated Water Flow Model (IWFM),[147] maintained by the California Department of Water Resources, and the MODFLOW suite, maintained by the U.S. Geological Survey.

The IWFM and MODFLOW codes are capable of simulating steady state or transient conditions and confined and unconfined groundwater flow. They simulate the vertical displacement of the land surface from both recoverable (elastic) and permanent (inelastic) compaction of compressible fine-grained layers caused by changes in effective stress and its impact on water flow within the

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145 Faunt, C. C., Traum, J. A., Boyce, S. E., Seymour, W. A., Jachens, E. R., Brandt, J. T., Sneed, M., Bond, S., & Marcelli, M. F. (2024). Groundwater Sustainability and Land Subsidence in California’s Central Valley. Water (Switzerland), 16(8). https://doi.org/10.3390/w16081189.

146 California Department of Water Resources. (2016a). Best Management Practices for the Sustainable Management of Groundwater: Modeling. https://water.ca.gov/Programs/Groundwater-Management/SGMA-Groundwater-Management/Best-Management-Practices-and-Guidance-Documents.

147 California Department of Water Resources. (2024e). Integrated Water Flow Model (IWFM): Theoretical Documentation (Revision 1594). E. C. Dogrul & T. N. Kadir, Modeling Support Office, California Department of Water Resources. Sacramento, CA: California Department of Water Resources.

aquifer using a similar approach based on Terzaghi's[148] theory of 1D consolidation. Compaction is controlled by variations in groundwater levels or pore pressure and overburden stress from groundwater level fluctuations. Depending on the specific version used, IWFM and MODFLOW can simulate delayed compaction resulting from the release of groundwater from interbed storage, making them effective in areas with thick, slow-draining clay layers, such as the Corcoran Clay in the San Joaquin Valley.[149,150]

There are four modules that can simulate subsidence in MODFLOW. These are the Interbed-Storage package (IBS),[151] the Subsidence and Aquifer-System Compaction (SUB) Package,[152] the Subsidence and Aquifer-System Compaction Package for Water-Table Aquifers (SUB-WT),[153] and the Skeletal Storage, Compaction, and Subsidence (CSUB) package for MODFLOW 6.[154] The SUB package simulates both elastic (recoverable) and inelastic (permanent) compaction of compressible fine-grained interbeds. Groundwater level changes in the interbeds are modeled using a transient, 1D (vertical) diffusion equation accounting for the delayed release of water and reuptake of water in the interbeds. The SUB package simulates both time-delayed subsidence (delay interbeds) and instantaneous compaction (no-delay interbeds). The term "delay interbeds" refers to interbeds where equilibrium with the surrounding aquifer groundwater levels takes significantly longer than the simulation time step (thick interbeds). The term "no-delay interbeds" refers to interbeds where equilibrium occurs within the simulation time step (thinner interbeds). In practice, this is accomplished by subdividing each model layer into multiple interbeds, allowing delay and no-delay interbeds to be represented simultaneously within the same aquifer system. Additional reference materials for model inputs, outputs, and specialized SUB-package files can be found in the One-Water Hydrologic Flow Model repository.[155] The SUB package supersedes the IBS package by introducing a delayed-drainage formulation that allows simulation of thick interbeds

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[148] Terzaghi, K. (1925). Principles of soil mechanics. IV. Settlement and consolidation of clay. Engineering News - Record, 95, 874.

[149] Traum, J.A. Central Valley Hydrologic Model Version 2 (CVHM2): Subsidence Package; U.S. Geological Survey Data Release; U.S. Geological Survey: Reston, VA, USA, 2022.

[150] Faunt, C. C., Traum, J. A., Boyce, S. E., Seymour, W. A., Jachens, E. R., Brandt, J. T., Sneed, M., Bond, S., & Marcelli, M. F. (2024). Groundwater Sustainability and Land Subsidence in California's Central Valley. Water, 16(8), 1189.

[151] Leake, S. A., & Prudic, D. E. (1991). Documentation of a computer program to simulate aquifer-system compaction using the modular finite-difference ground-water flow model. US Government Printing Office.

[152] Hoffmann, J., Leake, S. A., Galloway, D. L., Wilson, A. M., & Survey, U. S. G. (2003). MODFLOW-2000 ground-water model-user guide to the Subsidence and Aquifer-System Compaction (SUB) Package. In Open-File Report. https://doi.org/10.3133/ofr03233.

[153] Leake, S. A., Galloway, D. L., & Survey, U. S. G. (2007). MODFLOW Ground-Water Model - User Guide to the Subsidence and Aquifer-System Compaction Package (SUB-WT) for Water-Table Aquifers. In Techniques and Methods. https://doi.org/10.3133/tm6A23.

[154] Langevin, C. D., Hughes, J. D., Banta, E. R., Niswonger, R. G., Panday, S., Provost, A. M., & Survey, U. S. G. (2017). Documentation for the MODFLOW 6 Groundwater Flow Model. In Techniques and Methods. https://doi.org/10.3133/tm6A55.

[155] https://code.usgs.gov/modflow/mf-owhm/-/tree/develop/doc/Option_Block_Cheatsheets?ref_type=heads.

with longer pore-pressure equilibration times. In contrast, the IBS package assumes instantaneous equilibration and is therefore suitable for thinner interbeds with short time constants.

In basins that lack deep, confined aquifers or thick clay layers, modeling delayed drainage may not be necessary. The SUB-WT package in MODFLOW, developed by Leake et al.,[156] is designed for shallow, unconfined flow systems. SUB-WT uses an effective-stress-based formulation with no-delay interbeds and can simulate geostatic stress based on groundwater level. Compaction is determined by changes in effective stress, and the thickness of compressible sediments is adjusted in proportion to the saturated thickness. This makes it particularly useful for simulating subsidence occurring in the unsaturated zone of the aquifer.

IWFM provides two options to simulate land subsidence: version 4.0 that assumes instantaneous compaction and version 5.0 that simulates delayed compaction. Version 4.0 assumes that any change in groundwater levels leads to compaction or expansion of the interbeds without any time delay (the interbed head reaches equilibrium instantaneously). This approach uses the same formulation based on Leake and Prudic (1991)[157] as is used in MODFLOW-SUB (when using no-delay interbeds) and SUB-WT and is applicable when the characteristic response time of the interbeds to changes in the aquifer head is shorter than the timesteps used in the IWFM simulation, such as simulating thin interbeds or unconfined conditions. Version 5.0 simulates the delayed change in the interbed groundwater levels and the resulting compaction or expansion of the interbed materials as a response to the change in the groundwater levels. Delay interbeds are simulated using the same finite difference approach as described by Hoffmann et al.[158] and Bedekar[159] in the MODFLOW-SUB using “delay interbeds”.

MODFLOW 6’s CSUB package expands upon the capabilities of the SUB[160] and SUB-WT[161] packages. The SUB package uses a head-based formulation coupled with no-delay or delay interbeds, and the SUB-WT package uses an effective-stress-based formulation coupled with no-delay interbeds; however, the CSUB package can couple either the head-based or effective-stress-based formulations with either delay or no-delay interbeds. Similar to earlier subsidence packages, subsidence simulated with CSUB does not affect the water table simulation relative to the top of a model cell where the subsidence occurred. The CSUB package does not perform

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156 Leake, S. A., Galloway, D. L., & Survey, U. S. G. (2007). MODFLOW Ground-Water Model - User Guide to the Subsidence and Aquifer-System Compaction Package (SUB-WT) for Water-Table Aquifers. In Techniques and Methods. https://doi.org/10.3133/tm6A23.

157 Leake, S. A., & Prudic, D. E. (1991). Documentation of a computer program to simulate aquifer-system compaction using the modular finite-difference ground-water flow model. US Government Printing Office.

158 Hoffmann, J., Leake, S. A., Galloway, D. L., Wilson, A. M., & Survey, U. S. G. (2003). MODFLOW-2000 ground-water model-user guide to the Subsidence and Aquifer-System Compaction (SUB) Package. In Open-File Report. https://doi.org/10.3133/ofr03233.

159 Bedekar, V. 2021. Technical memorandum: IWFM land subsidence module update, S. S. Papadopulos & Associates, Inc.

160 Hoffmann, J., Leake, S. A., Galloway, D. L., Wilson, A. M., & Survey, U. S. G. (2003). MODFLOW-2000 ground-water model-user guide to the Subsidence and Aquifer-System Compaction (SUB) Package. In Open-File Report. https://doi.org/10.3133/ofr03233.

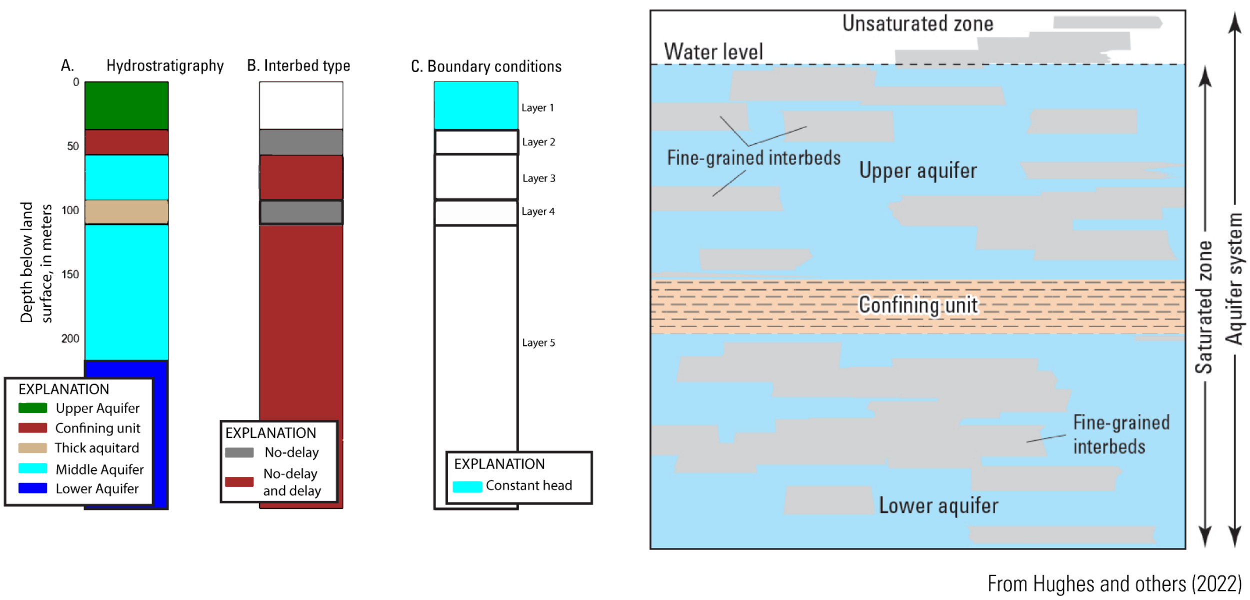
161 Leake, S. A., Galloway, D. L., & Survey, U. S. G. (2007). MODFLOW Ground-Water Model - User Guide to the Subsidence and Aquifer-System Compaction Package (SUB-WT) for Water-Table Aquifers. In Techniques and Methods. https://doi.org/10.3133/tm6A23.

calculations during steady-state periods but uses the heads from the steady-state period for subsequent transient calculations.[162,163] Although these models differ in complexity, all MODFLOW-based subsidence formulations are fundamentally one-dimensional in their mechanical representation of compaction, with three-dimensional groundwater flow providing the spatial context for stress distribution.

C.2 One-Dimensional Modeling

1D compaction models can be used when a more focused, vertical-only analysis is sufficient or when developing a regional flow model is not feasible. A localized 1D model simulates vertical compaction along a single column of the aquifer system (Figure C-1).

Figure C-1. Schematic Representation of Subsidence Using the CSUB Package (from Hughes et al., 2022)



In areas where data are only available from a single borehole, 1D models can be more appropriate to use as they provide a detailed understanding of subsidence at a specific location where subsidence is occurring. A 1D model operates under the assumption that horizontal groundwater flow is negligible compared with storage changes and other water budget components. This simplified approach may be advantageous in some situations where the heterogeneity of the aquifer or the lateral groundwater flow is not well understood. 1D modeling can be an effective tool for determining minimum thresholds based on simulated critical head approximations and assessing risk and measurable objectives for reducing the rate and extent of subsidence.

162 Hughes, J. D., Leake, S. A., Galloway, D. L., & White, J. T. (2022). Documentation for the Skeletal Storage, Compaction, and Subsidence (CSUB) Package of MODFLOW 6. US Geological Survey.

163 Langevin, C. D., Hughes, J. D., Banta, E. R., Niswonger, R. G., Panday, S., Provost, A. M., & Survey, U. S. G. (2017). Documentation for the MODFLOW 6 Groundwater Flow Model. In Techniques and Methods. https://doi.org/10.3133/tm6A55.

Additionally, 1D modeling offers computational simplicity, with shorter runtimes enabling faster iterations during calibration, uncertainty analysis, and scenario development.

An important consideration for 1D modeling is the availability of nearby subsidence and groundwater level data. The spatial representativeness of "nearby" monitoring data depends on local hydrogeologic conditions, particularly the lateral continuity and permeability of fine-grained units and the magnitude of imposed stresses. Therefore, in some areas, subsidence and groundwater level data within a multi-mile radius may be suitable; however, closer proximity (within hundreds of meters) is preferred in areas with strong vertical gradients or heterogeneous lithology to ensure that observed responses reflect the same stress regime simulated by the 1D model. Selecting a location with ample subsidence data (such as monthly InSAR data, a GPS station, or an extensometer) and continuous groundwater level measurements is important for developing and calibrating a compaction model.

Although 1D models offer detailed insight into vertical stress–strain behavior, they do not simulate the full spatial variability of groundwater flow or the distribution of pumping and recharge across a basin. Instead, they complement 3D groundwater flow models, which are used to simulate the hydrologic stresses that drive subsidence.

In practice, 3D flow models such as MODFLOW 6 or IWFM are used to simulate pumping and recharge scenarios under different management conditions. These scenarios generate groundwater-level time series at key monitoring locations or model cells. The simulated heads are then provided as input to 1D compaction models, which compute the resulting vertical deformation and time-dependent subsidence using local lithologic and mechanical properties.

This combined approach allows managers to use 3D models to test basin-scale water-management actions - such as reductions in pumping, redistribution of pumping, or managed aquifer recharge (MAR) - and to use 1D models to quantify the subsidence response at critical sites. For example, a 3D scenario might simulate the effects of a 20% reduction in deep pumping, while a 1D model at a nearby extensometer site predicts how much that change would reduce long-term compaction or raise the critical head margin.

By coupling 3D hydrologic simulations with 1D subsidence modeling, groundwater sustainability agencies can link management actions to physical outcomes—identifying how basin-wide recharge or pumping adjustments translate into reduced inelastic compaction. This complementary framework supports adaptive implementation of the SGMA and enables site-specific evaluation of measurable objectives and minimum thresholds for subsidence.

Because of their computational efficiency, 1D models can be rapidly recalibrated and rerun as new groundwater level or deformation data become available, allowing agencies to track subsidence risk in near real time. A consistent 1D workflow can also be applied across multiple monitoring sites within a Groundwater Sustainability Agency (GSA) area to develop a spatially distributed understanding of critical head conditions and subsidence response to management strategies.

An example of 1D subsidence modeling in MODFLOW 6 using CSUB and delay interbeds is available in MODFLOW 6 Examples*: One-Dimensional Compaction.*[164] Further detail on the

[164] https://modflow6-examples.readthedocs.io/en/master/ (Accessed October 1, 2024).

development and implementation of the 50 one-dimensional subsidence models (MODFLOW-6) can be found in the Technical Memorandum.[165]

Lees et al. (2022)[166] developed a 1D compaction model based on the aquitard-drainage model introduced by Helm[167] in 1975. The model assumes that groundwater level changes in coarse-grained aquifer sediments are known, either measured or simulated, and calculates the resulting compaction by modeling the gradual drainage of clay interbeds and confining layers. Like the SUB package, a time constant is used that represents the characteristic duration over which diffusion of effective stress occurs.[168] However, in this model, a gross time constant is used that is representative of the entire system. Based on Helm (1978),[169] the gross time constant represents the aggregate time over which delayed compaction occurs. However, because the model contains layers of variable thickness, significant compaction can still occur after the time constant is reached.[170]

C.3 Subsidence Modeling Parameters and Inputs

The MODFLOW subsidence packages and the Lees et al.[171] 1D compaction model simulate aquifer-system compaction and land subsidence based on the Terzaghi[172] theory of 1D vertical compaction and include the ability to simulate instantaneous or time-delayed compaction and subsidence. The selection of modeling code depends on the hydrogeology of the system. Vertical hydraulic conductivity (K_v), elastic (S_{se}) and inelastic (S_{skv}) skeletal specific storage, and interbed thickness control the timing of storage changes in the interbeds during model simulation. The variables used in this section are from the SUB package; however, parameter input variables for MODFLOW and IWFM model application are shown in Table C-1.

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165 Ellis, J., White, J., Saberi, L., Earll, M., Neely, W., & Hughes, J. (2025). *Documentation of subsidence modeling for the Central Valley* (Technical Memorandum). INTERA Incorporated. https://data.cnra.ca.gov/dataset/cv-1d-subsidence-models-and-tech-memo.

166 Lees, M., Knight, R., & Smith, R. (2022). Development and Application of a 1D Compaction Model to Understand 65 Years of Subsidence in the San Joaquin Valley. Water Resources Research, 58(6). https://doi.org/10.1029/2021WR031390.

167 Helm, D. C. (1975). One - dimensional simulation of aquifer system compaction near Pixley, California: 1. Constant parameters. Water Resources Research, 11(3), 465 – 478.

168 Lees, M., Knight, R., & Smith, R. (2022). Development and Application of a 1D Compaction Model to Understand 65 Years of Subsidence in the San Joaquin Valley. Water Resources Research, 58(6). https://doi.org/10.1029/2021WR031390.

169 Helm, D. C. (1978). Field verification of a one-dimensional mathematical model for transient compaction and expansion of a confined aquifer system.

170 Lees, M., Knight, R., & Smith, R. (2022). Development and Application of a 1D Compaction Model to Understand 65 Years of Subsidence in the San Joaquin Valley. Water Resources Research, 58(6). https://doi.org/10.1029/2021WR031390.

171 Lees, M., Knight, R., & Smith, R. (2022). Development and Application of a 1D Compaction Model to Understand 65 Years of Subsidence in the San Joaquin Valley. Water Resources Research, 58(6). https://doi.org/10.1029/2021WR031390.

172 Terzaghi, K. (1925). Principles of soil mechanics. IV. Settlement and consolidation of clay. Engineering News - Record, 95, 874.

K_v controls the ability of water to move vertically through the interbeds and governs the rate of compaction. K_v values can be estimated from aquifer tests, laboratory consolidation tests, analysis of stress-strain in borehole extensometer observations, and from previously calibrated compaction models such as C2VSim and CVHM (see Available Models for Subsidence Modeling in C.4).[173] The time for interbed heads to equilibrate with the aquifer groundwater level depends on interbed thickness, K_v, and skeletal specific storage (S_{se} and S_{sv}). Thin interbeds will equilibrate relatively quickly with the surrounding aquifer. These beds can be represented as no-delay interbeds that ignore the time delay of slow dissipation of groundwater level through the interbeds. In thick clay interbeds or confining units, low K_v values can be used to simulate the slow drainage and delayed compaction of fine-grained sediments.

The volume of water released or absorbed per unit volume of the aquifer per unit change in groundwater level is controlled by S_{se} under elastic conditions and by S_{sv} under inelastic conditions. These parameters are essential for simulating the timing and magnitude of subsidence, ensuring that groundwater management strategies account for both short-term and long-term compaction. In addition to vertical hydraulic conductivity and elastic and inelastic specific storage, the thickness of the interbeds is a primary factor in determining the extent and rate of aquifer-system compaction. To simulate delay interbeds, the time constant should be significantly longer than the time steps in the model simulated. For the interbeds, the slow dissipation of heads should be explicitly modeled in using delay interbeds. Due to the dependency of skeletal specific storage on stress history, a numerical method is used to solve the diffusion equation for each time step in the model. Because an aquifer may contain numerous interbeds of varying thickness, solving the 1D diffusion equation for each individual interbed becomes computationally impractical. To minimize the computational demand, delay interbeds within a single model layer that share the same K_v, S_{se}, and S_{sv} can be consolidated into a single system of delay interbeds. Helm[174] determined that the equivalent thickness of a system of individual delay interbeds with similar vertical hydraulic diffusivity can be calculated as

$$b_{equiv} = \sqrt{\frac{1}{\mathrm{N}} \sum_{i=1}^{N} b_i^2}$$

To accurately reproduce the total amount of interbed material and the correct compaction magnitude for the delay interbed system, the compaction and the volume of water exchanged with the surrounding aquifer must be multiplied by the factor

$$n_{equiv} = \frac{\sum_{i=1} b_i}{b_{equiv}}$$

By applying these equations, MODFLOW and IWFM calculate both the time history and the total magnitude of compaction of the interbed system. The diffusion equation is solved once for a single equivalent interbed of thickness b_{equiv} (b_{or} in IWFM), and the calculated compaction and flow

[173] Sneed, M. (2001b). Hydraulic and Mechanical Properties Affecting Ground-Water Flow and Aquifer-System Compaction, San Joaquin Valley, California.

[174] Helm, D. C. (1975). One - dimensional simulation of aquifer system compaction near Pixley, California: 1. Constant parameters. Water Resources Research, 11(3), 465 - 478.

across the interbed boundaries are multiplied by n_{equiv} (n in IWFM). A system of delay beds can be represented by assigning one or more equivalent delay interbeds to a single model layer. Lateral variability in interbed properties can then be represented using material zones, arrays, and cell-based assignments within that layer.

Table C-1 - Subsidence parameters for IWMF and MODFLOW packages.

Model/package	Reference	Vertical Hydraulic Conductivity	Interbed Elastic Specific Storage	Interbed Inelastic Specific Storage
MODFLOW-SUB	(Hoffmann et al., 2003)	K_v	SFE	SFV
MODFLOW 6-CSUB	(Hughes et al., 2022)	K_v	SSE_CR	SSV_CC
IWFM: Instantaneous Subsidence Component Version 4.0	(Dogrul, E. C., & Kadir, T. N., 2024)	N/A	SCE	SCI
IWFM: Delayed Subsidence Component Version 5.0	(Dogrul, E. C., & Kadir, T. N., 2024)	K_v	SCE	SCI

Abbreviations: K_v, vertical hydraulic conductivity of interbed; SFE, elastic skeletal storage coefficient for systems of no-delay interbeds; SFV, inelastic skeletal storage coefficient for systems of no-delay interbeds; SSE_CR, initial elastic coarse-grained of the interbed; SSV_CC, initial inelastic specific storage of the interbed; SCE, elastic storage coefficient; SCI, inelastic storage coefficient.

The selection of a subsidence modeling approach depends on lithology (thickness and arrangement of interbeds) and groundwater development. Many of California's aquifer systems are complex interbedded alluvial systems that are comprised of fine-grained clay layers of varying thickness. Reducing inelastic compaction requires not only stabilization but the recovery of groundwater levels above the critical head. Therefore, simulating the slow drainage of thick clay through use of delay interbeds is essential for understanding the short- and long-term impacts of groundwater pumping on subsidence and mitigating impacts to infrastructure.

The number of systems of delay interbeds used in a model determines how well the model can simulate the time-dependent compaction behavior of fine-grained sediment. A single delay system may not adequately capture both short-term and long-term subsidence patterns, while using too many (such as dozens) can become computationally expensive and unnecessarily complex. This concept is further described in the Technical Memo.[175]

When a subsidence model uses the interbeds approach described above (using n_equiv and b_equiv), whereby the complex sequence of many clay interbeds is represented by a smaller number of equivalent interbeds, the model simulates the aquifer system at an aggregated or "system" scale rather than at the level of individual interbeds. These equivalent interbeds are not meant to replicate each physical clay bed. Instead, they capture the overall timing and magnitude of compaction behavior for the compressible units.

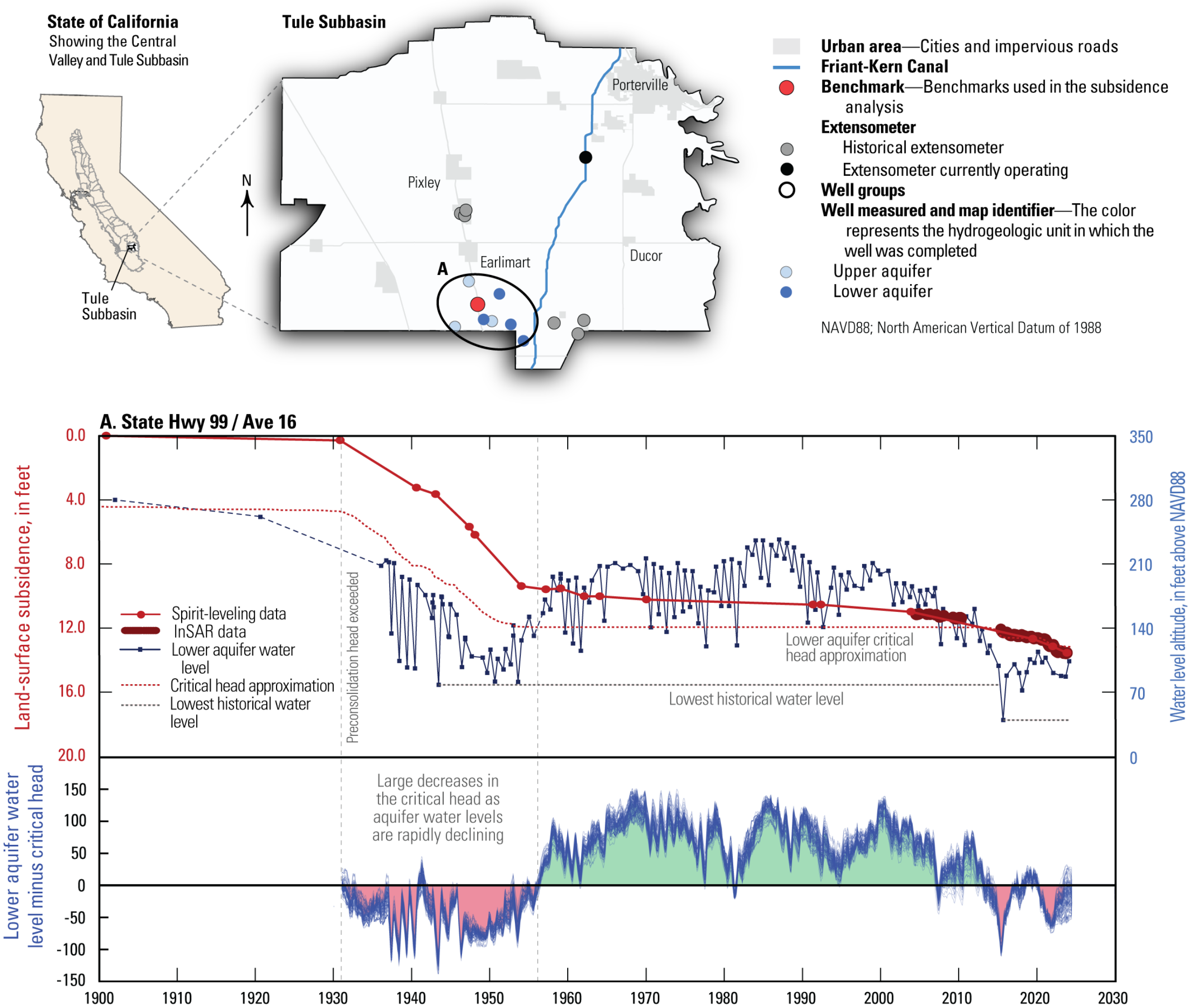
[175] Ellis, J., White, J., Saberi, L., Earll, M., Neely, W., & Hughes, J. (2025). Documentation of subsidence modeling for the Central Valley (Technical Memorandum). INTERA Incorporated. https://data.cnra.ca.gov/dataset/cv-1d-subsidence-models-and-tech-memo.

An approximation of the critical head can be made by extracting the lowest groundwater level in cells containing an interbed in each model layer for each model stress period. The critical head evolves through time as conditions change. Each time the simulated interbed groundwater level drops below the previous critical head, the model resets it to this new minimum, representing additional inelastic compaction and a new threshold for recovery. When groundwater levels in the aquifer and, consequently, the groundwater level in the clay interbed rise above the current critical head, the interbed returns to elastic behavior, although residual subsidence will continue until the pore pressures equilibrate. The difference of the groundwater flow cell groundwater level and the interbed lowest groundwater level in each stress period is the amount of groundwater level recovery or decline needed (in model units) to match the critical head value. For models that use multiple systems of delay interbeds, an average can be taken across each system of delay interbeds to provide a representative critical head.

Because the interbed approach described above groups interbeds into a simplified structure, it cannot yield interbed-specific critical heads. However, it can provide the threshold at which inelastic compaction occurs in the equivalent system. For this reason, using a representative (system-level) critical head aligns with the conceptual level at which the subsidence models operate. Both the model and the monitoring network (which often relies on long-screen wells that measure blended, system-averaged heads) function at a similar scale of hydraulic resolution. A system-level critical head therefore provides the appropriate linkage between the model's aggregated representation of the subsurface and the practical, observable water levels in wells.

GSAs are encouraged to explore the differences in critical head between interbeds, particularly if a bimodal distribution of fine-grained material exists, whereby most clay beds are either very thick or very thin. Figure C-2 illustrates this relationship by showing simulated groundwater levels in the lower aquifer together with the critical head, which corresponds to the lowest simulated head in the associated clay interbed. The difference between the aquifer groundwater level and the critical head indicates whether the system is undergoing elastic or inelastic compaction.

Figure C-2. Lower aquifer critical head at long-term site at State Hwy 99 / Ave 16



The critical head approximation shown on this figure was determined using a one-dimensional model where the groundwater level in the groundwater flow cell and the lowest groundwater level in the interbed delay cell are differenced. The critical head approximation is based on a model ensemble of about 200 realizations (individual models). Note the different y-axis scales for this figure than for figure A-1.

C.4 Available Models for Subsidence Modeling

The Central Valley Integrated Hydrologic Model, version 2.0 (CVHM2)[176] is a MODFLOW-OWHM[177]-based integrated hydrologic model of the Central Valley that simulates water years 1962 to 2019. The CVHM2 is discretized into 2.6 square kilometer (km^2) cells and 13 layers ranging in thickness from 3 – 550 meters across the Valley. CVHM2 simulates the magnitude of the change in storage

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[176] Faunt, C. C., Traum, J. A., Boyce, S. E., Seymour, W. A., Jachens, E. R., Brandt, J. T., Sneed, M., Bond, S., & Marcelli, M. F. (2024). Groundwater Sustainability and Land Subsidence in California's Central Valley. Water (Switzerland), 16(8). https://doi.org/10.3390/w16081189.

[177] Boyce, S.E., Hanson, R.T., Ferguson, I., Schmid, W., Henson, W., Reimann, T., Mehl, S.M., and Earll, M.M., 2020, One-Water Hydrologic Flow Model: A MODFLOW based conjunctive-use simulation software: U.S. Geological Survey Techniques and Methods 6 – A60, 435 p., https://doi.org/10.3133/tm6A60.

from the shallow aquifer system (layers 1–5), the Corcoran Clay (layers 6–8), and the lower aquifer system (layers 9–13) due to climatic variation, surface water availability, land use changes, and groundwater pumping.[178] Elastic and inelastic compaction and land subsidence are simulated by incorporating both delay and non-delay clay interbeds in the model framework using the MODFLOW SUB package[179] [180]. The CVHM2 used drillers' logs in three-dimensional space to develop a texture model of lithology to identify total thicknesses of coarse-grained and fine-grained deposits, thickness of delay and no-delay interbeds, number of equivalent interbeds, and the equivalent thickness of interbeds across the Central Valley. The model was calibrated to over 300,000 observations of groundwater levels, relative land surface elevation and compaction, and streamflow. Land subsidence from aquifer system compaction was measured using data from geodetic surveys, continuous GPS, and InSAR. Extensometers were used to calibrate to aquifer-system compaction.

The California Central Valley Groundwater-Surface Water Simulation Model (C2VSim)[181] is an IWFM-based regional model of the Central Valley released by the Department of Water Resources. The model has two versions: a coarse grid (C2VSim-CG) and a fine grid (C2VSim-FG). C2VSim-CG v1.0 uses 1,392 elements, while C2VSim-FG v1.01 offers more detailed modeling with over 32,500 elements for enhanced accuracy. Both versions simulate a long-term hydrologic period of water years 1974 through 2015 and are calibrated to historical land and water use datasets. C2VSim-FG uses the IWFM Version 4.0 subsidence formulation, which assumes instantaneous interbed storage change (analogous to the no-delay option in MODFLOW-SUB).[182] This approach does not simulate delayed drainage from thick clay layers such as the Corcoran Clay and therefore cannot represent time-delayed subsidence responses. C2VSimFG qualitatively assessed subsidence by comparing observed and simulated subsidence hydrographs at extensometers, along with maps and time series of cumulative subsidence using 14,500 observations of InSAR, GPS surveys, and continuous GPS. The model calibration focused on four primary subsidence parameters—elastic and inelastic storage, interbed thickness, and pre-consolidation head—but suggests that further calibration is necessary to assess the ranges and sensitivities of parameters, particularly interbed thickness and storage coefficients.[183]

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[178] Faunt, C. C., Traum, J. A., Boyce, S. E., Seymour, W. A., Jachens, E. R., Brandt, J. T., Sneed, M., Bond, S., & Marcelli, M. F. (2024). Groundwater Sustainability and Land Subsidence in California's Central Valley. Water (Switzerland), 16(8). https://doi.org/10.3390/w16081189.

[179] Boyce, S.E., Hanson, R.T., Ferguson, I., Schmid, W., Henson, W., Reimann, T., Mehl, S.M., and Earll, M.M., 2020, One-Water Hydrologic Flow Model: A MODFLOW based conjunctive-use simulation software: U.S. Geological Survey Techniques and Methods 6 – A60, 435 p., https://doi.org/10.3133/tm6A60.

[180] Hoffmann, J., Leake, S. A., Galloway, D. L., Wilson, A. M., & Survey, U. S. G. (2003). MODFLOW-2000 ground-water model-user guide to the Subsidence and Aquifer-System Compaction (SUB) Package. In Open-File Report. https://doi.org/10.3133/ofr03233.

[181] Brush, C. F., Dogrul, E. C., & Kadir, T. N. (2013). Development and calibration of the California Central Valley groundwater-surface water simulation model (C2VSim), version 3.02-CG. Citeseer.

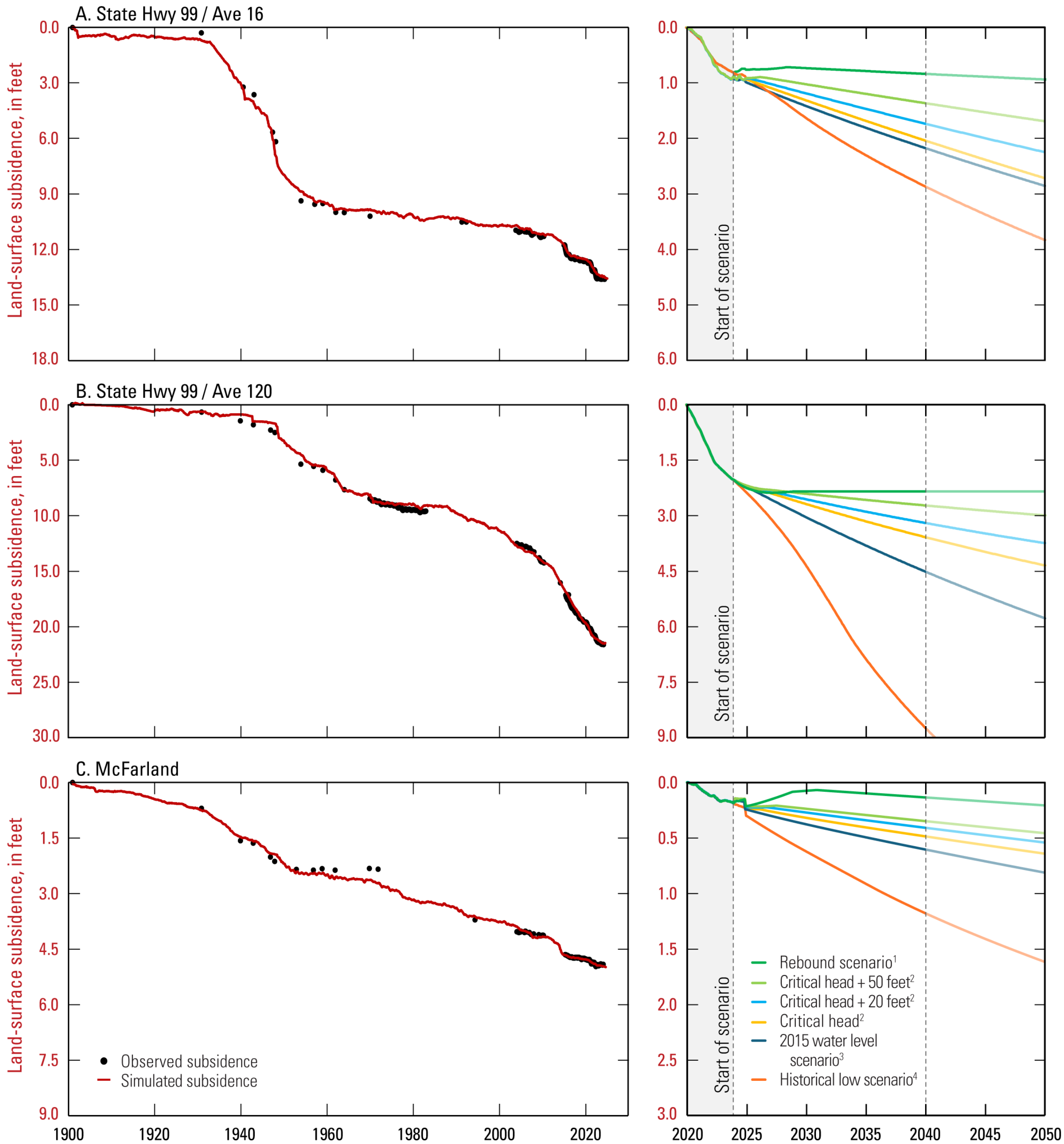
[182] Leake, S. A., & Prudic, D. E. (1991). Documentation of a computer program to simulate aquifer-system compaction using the modular finite-difference ground-water flow model. US Government Printing Office.

[183] California Department of Water Resources. (2023a). California Central Valley Groundwater-Surface Water Simulation Model-Fine Grid: C2VSimFG, version 1.01. https://data.ca.gov/dataset/california-central-valley-groundwater-surface-water-simulation-model-fine-grid-c2vsimfg.

C.5 Modeling of Management Scenarios

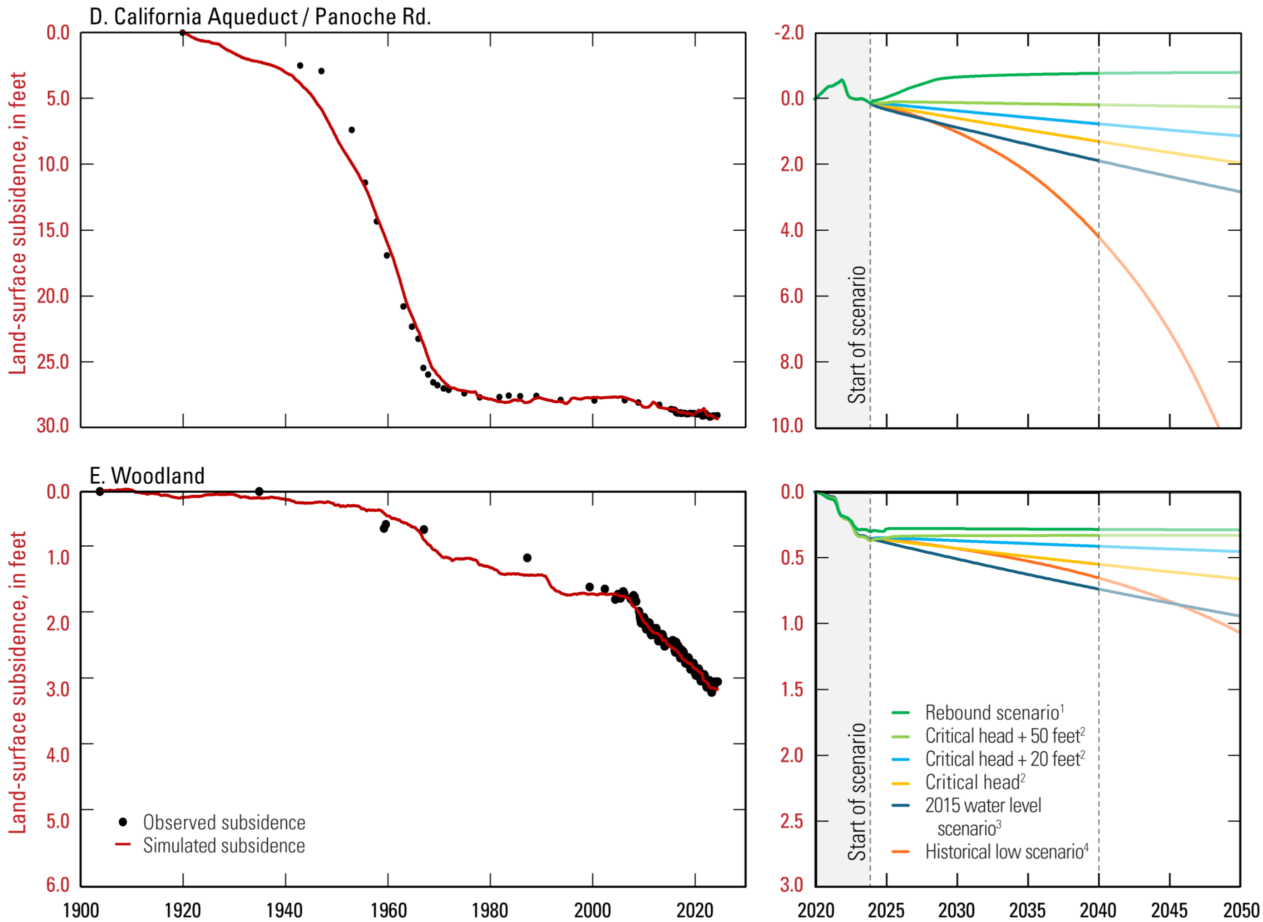
Adoption of one or more management strategies detailed in Section 6.1 will likely result in increases to groundwater levels. Using modeling approaches where available data allow for model calibration, scenarios of projected groundwater levels can be used to estimate future subsidence. Figure C-3 and Figure C-4 show examples of these calibrated models (corresponding to sites shown in Figures A-1 through A-5) and subsidence projections for six groundwater level scenarios: Historical Low, 2015 Water Level, Critical Head, 20 feet above Critical Head, 50 feet above Critical Head, and Rebound to the historical high groundwater level. These example scenarios use MODFLOW6 and the CSUB package and are initialized using the long-term groundwater level records shown in Figures A-1 through A-5. It's worth noting that the forecast simulations produced with PEST++ carry inherent uncertainty, and the deterministic plots shown here represent only the average behavior of the site under the specified management strategy.

Figure C-3. Scenario results for the 1D compaction models



[1]This scenario reflects a rapid rise in water levels to the highest historical groundwater elevation, approximating managed aquifer recovery. [2]These scenarios uses the approximated critical head, the approximated critical head + 20 feet, and the approximated critical head + 50 feet for the duration of the simulation. [3]This scenario uses the 2015 water level through the duration of the simulation. [4]This scenario uses the lowest average water level recorded and approches this water level using the 2015–23 decline rate.

Figure C-4. Scenario results for the 1D compaction models



[1]This scenario reflects a rapid rise in water levels to the highest historical groundwater elevation, approximating managed aquifer recovery. [2]These scenarios uses the approximated critical head, the approximated critical head + 20 feet, and the approximated critical head + 50 feet for the duration of the simulation. [3]This scenario uses the 2015 water level through the duration of the simulation. Note that at these sites (sites D and E) the 2015 water level is generally at or near the minimum water level observed since 2000. At Site E, the 2015 water level is near the historical low based on the water level data used at this site. [4]This scenario uses the lowest average water level recorded and approches this water level using the 2015–23 decline rate.

The Historical Low scenario represents a groundwater level time series that declines (following the 2015–2023 decline rate) to the lowest recorded groundwater level and then is held at that level for the remainder of the scenario. This demonstrates a case where groundwater levels are managed to the lowest groundwater level rather than the critical head. For the five sites shown, the lowest recorded groundwater level values can range from about 50 to 200 feet below 2024 groundwater levels. Scenario results suggest that an additional 1 to 6 feet of subsidence would occur during the implementation horizon (2024-2040) if managing to historical lows. The rates of subsidence for this scenario remain relatively high through 2040 and beyond. While Sites A, B, C, and E do show subtle declines in subsidence rates with time after an initial increase, site D shows an increase in subsidence rate with time for the Historical Low scenario. Site D is unique, as the historical low occurred in the 1960s and rebounded ~ 400 feet by the late 1980s. A return to the historical low at site D would result in a nearly 200-foot decline in the current groundwater level, with subsidence projections of about 6 feet through 2040 and an additional 4 feet between 2040–2045.

The 2015 Water Level scenario represents a groundwater level time series that returns groundwater levels to 2015 values and holds them constant into the future. This demonstrates a generalized estimate of subsidence due to pre-2015 groundwater activities. The 2015 Water Level scenario results in less subsidence than the historical low scenario (with the exception of site E, where the historical low occurred concurrently in 2015, thus producing identical results) with projected amounts of 0.5 to 3.5 feet of subsidence through 2040. Similar to the Historical Low scenario, the rates of subsidence for this scenario remain relatively high through 2040 and beyond with only subtle declines in subsidence rates with time.

The Critical Head scenario represents a groundwater level time series that returns groundwater levels to the estimated critical head values determined from the 1D models and are held constant into the future. The Critical Head scenario results in about 0.1 to 3 feet of subsidence through 2040. Three of the sites (sites C, D, and E) resulted in less 0.5 foot of subsidence through 2040. The subsidence rate at site C initially increases but is quickly followed by uplift until the 2030s, where it then remains relatively constant through 2040 and beyond. The subsidence rates at sites D and E remain relatively constant through 2040 and beyond. Sites A and B show that the Critical Head scenario results in more subsidence than the 2015 Water Level scenario, suggesting the critical head has fallen below those 2015 groundwater levels. Similar to the previous scenarios, the rates of subsidence for this scenario at these two sites remain relatively high through 2040 and beyond, with only subtle declines in subsidence rates with time.

The 20 feet above Critical Head scenario represents a groundwater level time series that returns groundwater levels to the estimated critical head values determined from the models, plus 20 feet, and held constant into the future. The 20 feet above Critical Head scenario results in less than about 0.1 to 2 feet of subsidence through 2040. These scenario results mirror the pattern of subsidence described by the Critical Head scenario, but with the total magnitude of subsidence reduced.

The 50 feet above Critical Head scenario represents a groundwater level time series that returns groundwater levels to the estimated critical head values determined from the models, plus 50 feet, and held constant into the future. The 50 feet above Critical Head scenario results in less than about 0.2 foot of uplift to about 1.25 feet of subsidence through 2040. The scenario results at sites A, B, and C are similar to the previous Critical Head scenario projections at these sites, but with the total magnitude of subsidence reduced. At site D, this scenario shows about 0.1 to 0.2 foot of uplift occurring between 2025 and 2030 before plateauing through 2040 and beyond. At site E, subsidence occurring prior to 2024 is halted within one year of the scenario start. A subtle rate (0.01 foot/year) of uplift persists through 2040 and beyond.

The Rebound (to Historical High) scenario represents a groundwater level time series that rapidly recovers (following the 2020–2022 recovery rate). This demonstrates a case where groundwater levels are managed to be highly protective, similar to the historical example shown for Long-Term Stress History Analysis Site D in the Westside Subbasin (Figure A-4). The Rebound to Historical High scenario results in less than about 0.1 foot of subsidence through 2040. The scenario results at sites B, D, and E show initial uplift rates followed by a plateau in rates through 2040 and beyond. The scenario results at sites A and C also show initial uplift rates but are then followed by subtle subsidence rates after 2030, continuing through 2040 and beyond.

These scenarios demonstrate the effects different approaches towards groundwater management have on subsidence. From these examples, the importance of managing groundwater levels to critical head rather than historically lowest groundwater level is highlighted. Further, models such as these can be important tools for determining sustainable management criteria that will ensure the avoidance and minimization of subsidence.

D Projects and Management Actions

This appendix includes descriptions of potential PMAs that GSAs may take to manage groundwater levels and subsidence sustainably.

D.1 Reduction in Groundwater Pumping, Demand Reduction, Land Repurposing

The most controllable subsidence management action for responsive management of groundwater levels is to reduce groundwater pumping. To minimize irreversible subsidence, reductions in groundwater pumping need to be significant and immediate and can only be dialed back when the relationship between subsidence, groundwater levels, and pumping rates are sufficiently understood, monitored, and controlled. Buffer zones can be established near impacted infrastructure where reduction of groundwater pumping should be prioritized first. For example, in 2024, the Westside District Water Authority GSA established the California Aqueduct Subsidence Program Buffer Zone that requires landowners include key management actions of mandatory well registration,[184] a net-zero well drilling moratorium,[185] and required reporting of well pumping volumes[186] in areas within proximity to infrastructure, defined as, "groundwater extraction wells within 2.5 miles of Mileposts 195-215 of the California Aqueduct."

These buffer zones are helpful in reducing subsidence; however, additional basin-wide or regional reduction in groundwater pumping may be necessary to stabilize groundwater levels above critical head given the regional nature of groundwater declines and resulting subsidence in the Central Valley. For example, in the Houston area, a location in Baytown, Texas, contains two extensometers: a shallow extensometer anchored below the water-production zone in the local area and a deep extensometer anchored at the base of the same unit from which water is produced in Pasadena, Texas. Differencing the compaction records from these two extensometers demonstrates that about 20 percent of the compaction that has occurred in Baytown is due to

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[184] California Department of Water Resources. (2023c). SGM Grant Program Requirements for Post-Performance Monitoring and Reporting: Aquifer Storage and Recovery (ASR) Monitoring Method. https://water.ca.gov/work-with-us/grants-and-loans

[185] Westside District Water Authority GSA. (2024a). Well Drilling Moratorium within Proximity to Critical Infrastructure Impacted by Subsidence Purpose. https://www.westsidedwa.org/files/18a48cda0/WDWA+GSA+Well+Drilling+Moratorium+Management+Action+-+Adopted+20240220.pdf

[186] Westside District Water Authority GSA. (2024b). Well Extraction Volume Reporting within Proximity to Critical Infrastructure Management Action Purpose. https://www.westsidedwa.org/files/23e198e83/WDWA+GSA+Well+Extraction+Volumes+Management+Action+with+Flowmeters+-+Adopted+20240220.pdf.

groundwater level declines from groundwater use in Pasadena, which is about eight miles distant.[187]

Land repurposing programs and land fallowing can have significant impact on industries and communities that depend on existing land uses. However, it is often the demand on groundwater of those land uses that also causes costly subsidence impacts on nearby infrastructure, including water conveyance infrastructure that the same industries rely on for surface water deliveries. Financial incentives may be targeted at small and mid-sized farms, with partnerships ensuring equitable participation and supporting compliance with SGMA.

D.2 Managed Aquifer Recharge

Improved water management practices such as Managed Aquifer Recharge (MAR) and Aquifer Storage and Recovery (ASR) are essential for addressing overdraft and managing subsidence. MAR involves establishing recharge basins to capture excess water — such as stormwater runoff or treated wastewater — that infiltrates into aquifers, replenishing depleted groundwater levels. MAR can help to stabilize areas affected by subsidence by replenishing the aquifer and provide a buffer against future dry years, droughts, and water shortages. Flood-Managed Aquifer Recharge (Flood-MAR) is an integrated management strategy that uses flood water resulting from rainfall or snowmelt for MAR on agricultural lands and landscapes such as refuges, floodplains, and flood bypasses.[188] Flood-MAR can be implemented at various scales, from individual landowners diverting flood water using existing infrastructure to large-scale efforts involving the development of recharge areas, upgrading levees, reservoirs, and drainage infrastructure to improve water capture and storage.[189] The Merced River Watershed Flood-MAR Reconnaissance Study is an example of how targeted recharge using Flood-MAR practices can reduce subsidence by replenishing groundwater levels.[190] Other basins facing similar subsidence challenges can utilize technical and funding resources from DWR to implement similar Flood-MAR strategies to address subsidence and improve water resource sustainability. This integrated approach enhances water supply reliability and drought resilience, reduces flood risks, and replenishes groundwater levels to prevent and mitigate subsidence.

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[187] Ellis, J. H., Knight, J. E., White, J. T., Sneed, M. I., Hughes, J. D., Ramage, J. K., Braun, C. L., Teeple, A., Foster, L., Rendon, S. H., & Brandt, J. (2023). Hydrogeology, Land-Surface Subsidence, and Documentation of the Gulf Coast Land Subsidence and Groundwater-Flow (GULF) Model, Southeast Texas, 1897 – 2018.

[188] California Department of Water Resources. (2023b). Coordinating Flood & Groundwater Management Considerations for Local Flood Managers. https://water.ca.gov/-/media/DWR-WebSite/Web-Pages/Programs/Flood-Management/Flood-MAR/Flood_GW_Brochure_Final.pdf.

[189] Marr, J., Arrate, D., Maendly, R., Guivetchi, K., Goyal, A., Wieking, J., Nordberg, M., Tsai, E., & Olivares, C. (2018). Flood-MAR: Using Flood Water for Managed Aquifer Recharge to Support Sustainable Water Resources (White Paper).

[190] California Department Water Resources. (2024d). Merced River Watershed Flood-MAR Reconnaissance Study: Study Report. https://water.ca.gov/-/media/DWR-WebSite/Web-Pages/Programs/Flood-Management/Flood-MAR/TM-4--Adaptation-Strategy-PerformanceFINAL.pdf.

ASR stores excess water supply in aquifers for later recovery by injecting water into an aquifer via wells.[191] The ASR wells are designed both to inject and extract water and can be paired with other pumping wells in the same wellfield. ASR replenishes groundwater levels by injecting surplus water — often highly treated or recycled water — into aquifers during wet periods, helping maintain groundwater levels and manage subsidence. The stored water can be recovered during droughts or peak demand periods using the same wells that injected the water, providing a reliable water source and offsetting pumping in subsidence-prone areas. These projects reduce over-pumping and help mitigate the risk of further subsidence. The State Water Resources Control Board has created a permitting process for ASR wells, which is outlined in the State Water Resources Control Board Water Quality Order 20212-0010. The United States Environmental Protection Agency also regulates injection wells through the Underground Injection Control Program, where ASR wells are classified as Class V injection wells, which indicate that they inject non-hazardous fluids into or above underground sources of drinking water.[192]

D.3 Conjunctive Use

Surface water is increasingly used in California as an alternative water source that can offset pumping to reduce overdraft and mitigate subsidence. Conjunctive management refers to the coordinated use of surface water and groundwater to maximize water availability and reliability. With the appropriate infrastructure, water districts and agencies can treat surface water and groundwater as an integrated system, using one to balance the other during periods of reduced availability. Periods of extreme weather – both dry and wet – place significant stress on California's water resources. As climate change intensifies these extremes, challenges to water supply reliability will also be exacerbated. By using surface water during wet periods to offset groundwater pumping and replenish aquifers via MAR, water agencies can maintain reliable water supplies during droughts and help mitigate subsidence by reducing the reliance on groundwater. Using and storing surface water supplies effectively requires infrastructure such as reservoirs and dams for storage, canals and pipelines for transporting water, ASR wells, and recharge basins. Diversion structures manage surface water flow from streams and rivers, while water treatment plants ensure the water meets safety standards. State and local agencies should focus on improving infrastructure, streamlining regulatory approvals, and providing incentives for improving conjunctive management of the basins' water resources. Expanding these practices statewide could help mitigate subsidence, reduce flood risk, and improve the long-term reliability of water supply in response to increasing climate variability.[193]

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[191] California Department of Water Resources. (2023c). SGM Grant Program Requirements for Post-Performance Monitoring and Reporting: Aquifer Storage and Recovery (ASR) Monitoring Method. https://water.ca.gov/work-with-us/grants-and-loans.

[192] State Water Resources Control Board. (2018). Water Recycling Criteria. Title 22, Division 4, Chapter 3, California Code of Regulations.

[193] Peterson, C., Hanak, E., & Joaquín Morales, Z. (2024). Replenishing Groundwater in the San Joaquin Valley: 2024 Update.

D.4 Alternative Water Sources

The development of alternative water sources, such as recycled water, desalination, and stormwater capture, plays an important role in alleviating the reliance on groundwater resources. By diversifying water supplies, these alternative sources can be used in lieu of groundwater pumping, help maintain groundwater levels, and prevent overdraft that may lead to subsidence. Effective October 1, 2024, California's new Direct Potable Reuse regulations enable the safe treatment of recycled water to potable standards, allowing it to be directly added to public water systems.[194] This regulatory framework supports water security by providing an alternative drinking water source. This important climate-resiliency strategy reduces reliance on surface water and groundwater resources, which is especially crucial during droughts.

California's Water Supply Strategy, adopted by the Newsom Administration in 2022, outlines key actions to enhance water supply reliability in response to climate change.[195] A primary goal is the development of new water supplies, including expanding brackish water desalination. The strategy includes investing in new infrastructure and upgrading existing facilities to meet production targets of 28,000 acre-feet per year of brackish water desalination by 2023 and 84,000 acre-feet per year by 2040. The program will involve partnerships with local water districts, utilities, and private entities to streamline the implementation of the operation of facilities. The additional water from desalination can help reduce groundwater demand and diversify water resource portfolios in areas prone to subsidence from overdraft.

D.5 Improved Irrigation Practices

Improving irrigation practices, such as implementing drip irrigation and water-saving technologies to optimize irrigation practices, is essential for reducing groundwater pumping in subsidence-prone areas while sustaining California's agricultural productivity amid growing water challenges.[196] Key strategies for optimizing irrigation practices include the use of soil moisture sensors that provide real-time data, enabling farmers to apply the right amount of water at the right time to crops. The State Water Efficiency and Enhancement Program provides grants of up to $200,000 to implement water-saving practices such as installing soil moisture sensors.[197] Enhanced irrigation techniques and management practices can boost crop yields without increasing water usage, reducing the need for excessive groundwater pumping. Key agricultural management strategies include precision irrigation technologies (sensors and automated systems), irrigation scheduling, cover cropping, efficient fertilization to maximize the benefits of irrigation, and utilizing supplemental

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[194] State Water Resources Control Board. (2024, August 12). Direct Potable Reuse Regulations (SBDDW-23-001).

[195] California Department of Water Resources. (2022a). Projected Brackish Water Desalination Projects in California. https://cawaterlibrary.net/document/projected-brackish-water-desalination-projects-in-california/.

[196] Morales, J., Roldan, J., Ko, S., Pombrol, M., Bailey, R., & Cook, S. (2023). Agricultural Water Use Efficiency Resource Management Strategy Agricultural Water Use Efficiency Resource Management Strategy Draft Memorandum.

[197] California Department of Food and Agriculture. (2023, December 7). State Water Efficiency and Enhancement Program (SWEEP). https://agcouncil.org/cdfa-accepting-sweep-grant-applications/.

water for irrigation.[198,199] These strategies help to reduce reliance on groundwater and mitigate land subsidence risks.[200]

D.6 Enhanced Monitoring

Establishing comprehensive monitoring plans around areas with infrastructure and in current and historical subsidence areas is also essential for managing subsidence. This is especially important for basins that rely on groundwater to support agricultural, industrial, and domestic practices. Monthly monitoring and reporting of groundwater levels, along with advanced subsidence monitoring technologies such as InSAR, ground-based continuous GPS stations, and installation of extensometers, allow water managers to assess the extent and impact of aquifer compaction and subsidence due to overdraft (see Monitoring section). These data allow for adaptive subsidence management, such as reducing groundwater pumping or providing supplemental water supplies to at-risk areas, preventing further compaction.

D.7 Well Inventories and Metering of Groundwater Pumping

The most controllable subsidence management action for responsive management of groundwater levels is to reduce groundwater pumping. GSAs, in coordination with Counties and other local Well Permitting Agencies, should develop and maintain an inventory of pumping wells and collect pumping reports by well or parcel to support management of the volume, timing, and distribution of groundwater pumping.

The success of management actions can be undermined and negated by additional groundwater pumping in the subsidence areas. The GSAs should coordinate with the Counties and local Well Permitting agencies to assure that no new groundwater pumping wells are permitted that are inconsistent with the management actions. For example, if taking efforts to phase out groundwater pumping, the GSA should encourage that no new wells are permitted. GSAs should consider how new groundwater pumping wells comply with their management actions.

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[198] California Department of Water Resources. (2023d). Status of 2020 Agricultural Water Management Plans and Implementation of Efficient Water Management Practices Report. https://water.ca.gov/Programs/Water-Use-And-Efficiency/Agricultural-Water-Use-Efficiency.

[199] Mcfadden, J., Njuki, E., & Griffin, T. (2023). Precision Agriculture in the Digital Era: Recent Adoption on U.S. Farms. https://www.ers.usda.gov/publications/pub-details?pubid=105893.

[200] Morales, J., Roldan, J., Ko, S., Pombrol, M., Bailey, R., & Cook, S. (2023). Agricultural Water Use Efficiency Resource Management Strategy Agricultural Water Use Efficiency Resource Management Strategy Draft Memorandum.

E Summary of Subsidence Modeling Technical Memorandum

This appendix summarizes the modeling efforts performed in support of the Subsidence BMP and provides links to additional information and data. To better understand the potential extent of subsidence, the DWR initiated efforts to monitor, analyze, and predict subsidence trends. This project is a collaborative effort between DWR's Sustainable Groundwater Management Office, the Division of Regional Assistance, and the Division of Flood Operations Hydrology and Flood Operations Branch, in cooperation with INTERA Incorporated (INTERA). The effort began with the compilation and analysis of historical data, which were then used to model future subsidence based on various groundwater level scenarios for 50 sites across California. The modeling results, which are referenced in the Subsidence BMP, are documented in a Technical Memorandum[201] that describes the project, including associated tasks, modeling assumptions, and modeling results. The Technical Memorandum and the model files used are publicly available and archived at https://data.cnra.ca.gov/dataset/cv-1d-subsidence-models-and-tech-memo.

The modeling framework integrated key hydrogeologic properties, including aquifer thickness, interbedded clay layers ("interbeds"), and historical groundwater level fluctuations. Well-log data were compiled for each site to estimate the number and thickness of clay interbeds, as well as the overall hydrostratigraphy for each location. Model parameters were derived from literature sources, subbasin-scale three-dimensional (3D) models such as Central Valley Hydrologic Model version 2 (CVHM2) and the California Central Valley Groundwater-Surface Water Simulation Model (C2VSim-FG), and other available regional datasets. Using these inputs, the models were calibrated against long-term subsidence records to refine predictive capabilities and ensure alignment with observed trends. The simulation results included instantaneous and delayed subsidence, elastic and inelastic deformation, and layer-specific compaction tracking.

E.1 Model Code

The project team selected MODFLOW 6-CSUB due to several key advantages this code provides with its ability to:

- Couple groundwater flow and subsidence processes; subsidence is computed dynamically based on changing groundwater levels rather than as a separate post-processing step.
- Incorporate site-specific interbed properties and track layer-specific compaction.
- Simulate both instantaneous and time-delayed compaction with an effective stress formulation (Terzaghi theory of 1D vertical compaction).

[201] Ellis, J., White, J., Saberi, L., Earll, M., Neely, W., & Hughes, J. (2025). Documentation of subsidence modeling for the Central Valley (Technical Memorandum). INTERA Incorporated. https://data.cnra.ca.gov/dataset/cv-1d-subsidence-models-and-tech-memo.

CSUB also offers flexibility in defining hydraulic conductivity (K_v), elastic (S_{se}) and inelastic (S_{sv}) skeletal specific storage, and interbed thickness, which are its primary input variables and control the timing of storage changes in the interbeds during model simulation. This flexibility makes CSUB suited for complex heterogeneous groundwater basins.

Vertical hydraulic conductivity controls the ability of water to move vertically through the interbeds and governs the rate of compaction. Vertical hydraulic conductivity values can be estimated from aquifer tests, laboratory consolidation tests, analysis of stress-strain in extensometer observations, and from previously calibrated compaction models such as C2VSim-FG and CVHM2. The time for interbed groundwater levels to equilibrate with the aquifer groundwater level depends primarily on interbed thickness and vertical hydraulic conductivity. Thin interbeds will equilibrate relatively quickly with the surrounding aquifer. These beds can be represented as no-delay interbeds that ignore the time delay of slow dissipation of the head through the interbeds. In thick clay interbeds or confining units, low vertical hydraulic conductivity values can be used to simulate the slow drainage and residual compaction of fine-grained sediments.

The modeling files are publicly available to offer transparency and reproducibility, allowing DWR and other interested parties to access, review, and build upon the modeling framework developed for this analysis. The shared files include configuration inputs for MODFLOW 6-CSUB, pre- and post-processing scripts, and documentation to facilitate implementation and further analysis. The complete set of model input files, along with the custom source codes used for data processing and simulation, are publicly available and archived (https://data.cnra.ca.gov/dataset/cv-1d-subsidence-models-and-tech-memo).

E.2 Modeling Critical Head

Numerical models are important for estimating critical head because these values cannot easily be directly measured in the field. Instead, they must often be inferred through simulation of the stress-strain behavior of interbeds in response to changing groundwater levels over time. The MODFLOW 6-CSUB models simulate critical head by resolving both the time-delayed and instantaneous compaction effects across different layers.

MODFLOW 6 CSUB can be used to approximate critical head by extracting the lowest groundwater level in cells containing an interbed in each model layer for each model stress period. The difference of the groundwater flow cell groundwater level and the interbed lowest groundwater level in each stress period is the amount of groundwater level recovery or decline needed (in model units) to match the critical head value. For models that use multiple systems of delay interbeds, an average can be taken across each system of delay interbeds to provide a representative critical head.

E.3 Results

This analysis provided a comprehensive assessment of subsidence dynamics in California's Central Valley at selected locations, integrating long-term observation data with predictive numerical modeling to improve subsidence forecasting and inform sustainable groundwater management strategies. The results highlight a correlation between groundwater level declines and subsidence, with inelastic compaction occurring when groundwater levels decline below the critical head.

Historical analysis confirms that past groundwater overdrafts have led to significant subsidence, underscoring the need for proactive management of water resources.

Future subsidence projections under different groundwater management scenarios indicate the potential for continued subsidence if groundwater levels are not stabilized or increased. Model results suggest maintaining groundwater levels above critical head would be necessary to minimize inelastic compaction. The results also indicate that MODFLOW 6-CSUB performs well in simulating subsidence processes.

E.4 Future Uses and Enhancements

Enhancing model calibration and uncertainty analysis is important to improving the accuracy of subsidence predictions. Additional calibration using newly acquired InSAR, extensometer, and groundwater level data will refine parameter estimates, particularly for interbed hydraulic conductivity and skeletal storage values. Incorporating additional geophysical data, such as borehole lithology logs, will further improve model resolution and predictive capabilities.

The critical head estimates from this analysis will also help inform sustainable management criteria, specifically minimum thresholds for groundwater levels with consideration of subsidence. This will assist groundwater managers with defining site-specific groundwater level thresholds to prevent further inelastic compaction and undesirable results. Groundwater managers can also integrate findings into Groundwater Sustainability Plans to align with regional groundwater management strategies. Additionally, scenario testing will help evaluate the impact of managed aquifer recharge, strategic pumping reductions, and land-use changes on future subsidence trends. This will provide insight into how seasonal and long-term groundwater level recovery strategies can mitigate subsidence in high-risk areas.

Identifying additional benchmark sites for long-term monitoring will improve spatial coverage in subsidence-prone areas. The integration of real-time GPS, extensometer, and InSAR data can provide near-continuous tracking of land surface deformation, allowing for early detection of subsidence trends. Establishing collaborative data-sharing frameworks with local agencies, water districts, and research institutions will further enhance subsidence monitoring efforts and facilitate informed decision-making.

The findings from this analysis underscore the need for proactive groundwater management to mitigate and prevent further subsidence in California's Central Valley. The integration of empirical data, numerical modeling, and real-time monitoring offers an effective framework for assessing subsidence risks and informing adaptive management strategies. Through continued monitoring, improved modeling, and evidence-based policy development, California can enhance its resilience to subsidence-related challenges while securing a sustainable water future for the region.

For more information on the modeling results, please read California's Groundwater Update 2025 (Bulletin 118) Appendix I: Land Subsidence.[202] More information on the modeling effort can be found in a Technical Memo.[203] The complete set of model input files, along with the custom source codes used for data processing and simulation, are publicly available and archived at https://data.cnra.ca.gov/dataset/cv-1d-subsidence-models-and-tech-memo.

[202] 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.

[203] Ellis, J., White, J., Saberi, L., Earll, M., Neely, W., & Hughes, J. (2025). Documentation of subsidence modeling for the Central Valley (Technical Memorandum). INTERA Incorporated. https://data.cnra.ca.gov/dataset/cv-1d-subsidence-models-and-tech-memo.

F Subsidence Related to Oil, Gas and Geothermal Activities

The California Geologic Energy Management Division (CalGEM) of the California Department of Conservation has broad authority over oil and gas production operations, and any possible damage to life, health, property, or natural resources resulting from those production operations is within the scope of CalGEM's regulatory authority (Pub. Resources Code, § 3106.) If oil and gas production results in subsidence that threatens damage, then responding to that subsidence would be within CalGEM's regulatory purview. GSAs should fully support any claims that subsidence is due to oil, gas, or geothermal activities with data, analysis, and evidence.

In support of this BMP, CalGEM developed the Best Management Practices (BMP) for Avoiding or Minimizing Subsidence Related to Oil, Gas and Geothermal Activities.

California
Department of Conservation
Geologic Energy Management Division

Gavin Newsom, Governor
Gabe Tiffany, Acting Director

Best Management Practices (BMP) for Avoiding or Minimizing Subsidence Related to Oil, Gas and Geothermal Activities

Oil, gas, and geothermal production can lead to subsidence by reducing subsurface pressure through fluid extraction, which may cause the land surface to sink. The following best practices outline methods typically used by operators to manage and mitigate subsidence risks, ensuring resource sustainability and infrastructure protection while aligning with the goals of SGMA. CalGEM has broad authority over oil and gas production operations, and any possible damage to life, health, property, or natural resources resulting from those production operations is within the scope of CalGEM's regulatory authority. (Pub. Resources Code, § 3106.) If oil and gas production results in subsidence that threatens damage, then responding to that subsidence would be within CalGEM's regulatory purview.

1. **Developing and Implementing Mitigation Plans**
   Mitigation plans are routinely developed to address subsidence risks as they arise. Typical mitigation strategies include:

   - **Controlled Production Rates:** Operators often manage the amount of fluid withdrawn from the subsurface to prevent rapid pressure depletion, allowing for a more stable underground environment and reducing the risk of subsidence.
   - **Reducing Extraction Rates:** When signs of subsidence are detected, operators may reduce extraction rates or temporarily halt operations to stabilize subsurface conditions.
   - **Reservoir Re-pressurization:** Reinjecting fluids (water or gas) to restore subsurface reservoir pressure is a common practice to counteract subsidence by sustaining the structural integrity of the geological formations and prevent further surface land deformation.
   - **Balanced Injection-to-Production Ratio:** Operators maintain a balanced injection-to-production ratio, which helps prevent fluid migration from damaged wellbores. This strategy is critical in mitigating subsidence by maintaining reservoir stability and reducing the risk of land subsidence due to fluid movement.

2. **Use of Geomechanical Modeling**
   Advanced geomechanical modeling is commonly used by operators to assess and mitigate subsidence risks.

   - **Modeling Subsurface Dynamics:** Operators use models to predict how fluid extraction impacts subsurface formations, helping to anticipate potential subsidence risks.
   - **Informed Production Decisions:** These models help guide operational decisions, such as extraction rates, pressure management strategies (e.g., location of injection), and other operational choices to help minimize subsidence. The models

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can also identify data gaps and guide monitoring strategies to improve data collection, thereby optimizing the model to better minimize subsidence.

3. **Establishing Comprehensive Monitoring Networks**
   Monitoring subsidence is a critical aspect of ongoing operations. Operators typically establish comprehensive monitoring systems to detect early signs of subsidence, and typically include:

   - **Ground-Based and Satellite Monitoring:** Operators use ground-based sensors such as tiltmeters and satellite technology such as InSAR (Interferometric Synthetic Aperture Radar) to monitor surface movement. These systems are designed to provide real-time data for detecting subtle changes in land elevation.
   - **Monitoring Groundwater and Reservoir Pressure:** Groundwater levels and reservoir pressure are regularly monitored to track conditions that may lead to subsidence, enabling timely adjustments to production practices.

Collaboration with Stakeholders

CalGEM plays a pivotal role in coordinating subsidence management, even though it does not directly manage or monitor subsidence, with the exception of geothermal areas where CalGEM is more actively involved. Operators are typically responsible for monitoring subsidence risks, and CalGEM can request relevant data from them, such as fluid extraction rates, reservoir pressure, and ground movement, when concerns arise. This data helps CalGEM assess whether oil, gas and geothermal activities are contributing to subsidence and determine appropriate mitigation actions.

CalGEM also serves as a key intermediary between operators, State and Local agencies. CalGEM has oversight regarding subsidence caused by oil and gas drilling operations and CalGEM coordinates efforts with agencies such as the Department of Water Resources (DWR) and the State Water Resources Control Board for broad subsidence issues that do not yet have direct cause data. Acting as a liaison, CalGEM facilitates the flow of data between operators and agencies, supporting subsidence evaluation and decision-making. This role ensures agencies have the information needed for thorough subsidence risk assessments and helps coordinate a unified response, protecting public health, safety, and the environment and promoting resource sustainability.