There is no comprehensive land subsidence monitoring program in California. The land subsidence information presented in *California's Groundwater Update 2013* is an overview of local and regional investigations that include various monitoring efforts in the Central Valley. Some of these monitoring efforts include elevation surveys along the California Aqueduct, borehole extensometer monitoring, satellite remote sensing studies using interferometric synthetic aperture radar (InSAR), continuous and conventional global positioning system (GPS) measurements, and spirit-leveling surveying. In addition, land subsidence discussions in this report include data from the monitoring of ground surface elevations associated with non-land subsidence studies, such as periodic highway elevation surveys.

A comprehensive assessment of statewide land subsidence studies was not within the scope of *California's Groundwater Update 2013*. However, during preparation of the *California Water Plan Update 2013*, California experienced four of the driest water years on record (2011-2015), which dramatically increased the amount of groundwater extraction on an annual basis to meet statewide demands. As a result of increased groundwater pumping due to lack of precipitation and reduced surface water deliveries, groundwater levels in spring 2015 were found to be at all-time historical lows in many parts of California.

In response to the current drought, and because the existing land subsidence monitoring programs were reporting renewed occurrences and alarming rates of land subsidence, two significant land subsidence studies were initiated and completed in 2014. For up-to-date information on land subsidence caused by groundwater withdrawals, and for a determination of estimated potential for future land subsidence to occur, the following reports should be consulted. The first report provided here was prepared by DWR to provide a statewide a summary and analysis of recent, historical, and potential land subsidence. The second report from Luhdorff and Scalmanini Consulting Services is a comprehensive statewide land subsidence report that also looks at historical and current processes and the relationships between land subsidence and groundwater pumping. Links to these land subsidence reports can be found on DWR's Groundwater Information Center website http://www.water.ca.gov/groundwater/index.cfm.

State of California

Department of Water Resources

Summary of Recent, Historical, and Estimated Potential for Future Land Subsidence in California



2014

Executive Summary

Inelastic land subsidence (subsidence) caused by groundwater extraction is a major problem in California and is exacerbated by additional pressure on groundwater resources during periods of drought. The purpose of this document is to summarize recent and historical subsidence and estimate the potential for future subsidence. Specifically, the following documentation and associated maps are intended to be used as a screening tool to identify areas where the potential for subsidence due to groundwater extraction may persist and to act as a guide to focus future site-specific subsidence studies. The results of this study consist of a summary map (Figure ES-1) and data compilation (Appendix A) of recent, historical, and estimated potential for future subsidence within the DWR Bulletin 118-defined groundwater basins of California. This information is also available on an interactive web map (http://water.ca.gov/groundwater/GIC_MapApp_Intro.cfm).

The key findings are:

- In general, the areas with a higher estimated potential for future subsidence are in the southern San Joaquin, Antelope, Coachella, and western Sacramento Valleys. These areas match well with the areas of subsidence documented by Luhdorff & Scalmanini Consulting Engineers (LSCE), Borchers and Carpenter (2014).
- Most of the groundwater basins with a higher estimated potential for future subsidence are also ranked as high or medium priority by the CASGEM Basin Prioritization Process.
- Subsidence is occurring in many groundwater basins in the state especially in the southern San Joaquin River (4 subbasins) and Tulare Lake (7 subbasins) Hydrologic Regions. Subsidence is also occurring in the South Lahontan (5 basins), South Coast (4 basins), Sacramento River (3 subbasins), Central Coast (2 basins), and Colorado River (2 basins) Hydrologic Regions.
- Since spring 2008, groundwater levels are at all-time historical lows (for period of record) in most areas of the state especially in the southern San Joaquin Valley, portions of the Sacramento Valley, and portions of the San Francisco Bay, South Lahontan, and South Coast Hydrologic Regions – these areas exhibit groundwater levels more than 50 feet below previous historical lows experienced sometime prior to 2000. There are many areas of the San Joaquin Valley where recent groundwater levels are more than 100 feet below previous historical lows and correspond to areas of recent subsidence.
- In the Central Valley, groundwater levels in 36% of the long-term wells (216 of 599) in the Sacramento Valley and 55% of the long-term wells (1,718 of 3,124) in the San Joaquin Valley are at or below the historical spring low levels.

Gaps in groundwater and subsidence monitoring include:

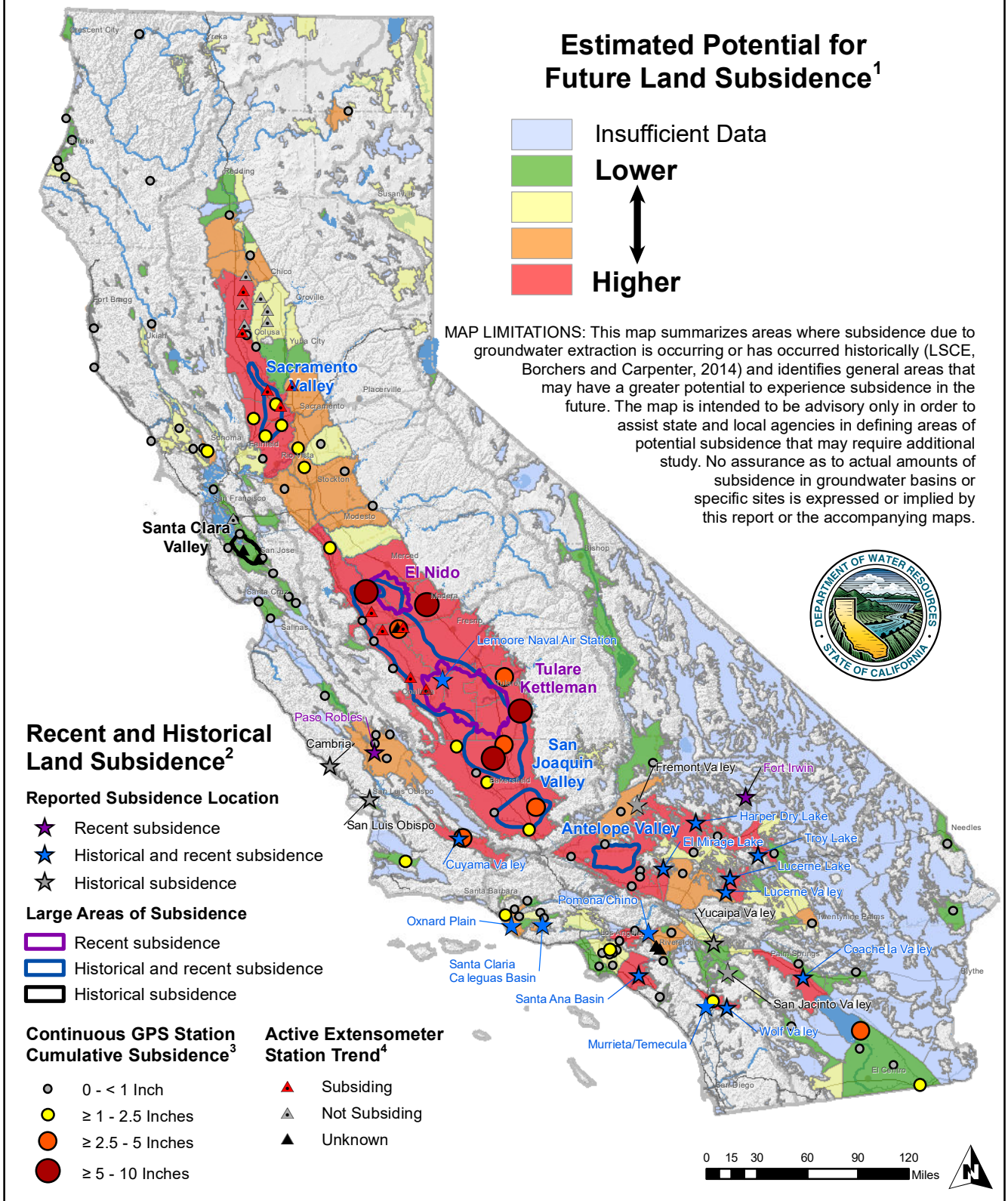
- Many high and medium priority basins do not have subsidence monitoring networks or long-term groundwater monitoring wells, most notably in the Central Coast Hydrologic Region.
- Large areas of recent subsidence in the San Joaquin Valley (El Nido and Tulare-Kettleman areas [LSCE, Borchers and Carpenter, 2014]) do not have continuous GPS or borehole extensometers in the areas of maximum subsidence.

Recommendations include:

- Future efforts should build off this initial work, incorporate the results of the planned NASA-JPL InSAR assessment of the Central Valley, integrate site-specific lithology data, and include updated groundwater level, extensometer, and continuous GPS data. The recommendations from the comprehensive review of subsidence completed by LSCE, Borchers and Carpenter (2014) should also be considered.

FIGURE ES-1

Summary of Recent, Historical, and Estimated Potential for Future Land Subsidence in California



[1]The estimated potential for land subsidence was calculated in each groundwater basin by combining the ranking values of groundwater levels, previous subsidence studies, borehole extensometer, and continuous GPS data (Appendix A). [2]Land subsidence data modified from LSCE, Borchers and Carpenter, 2014. [3]Continuous GPS data from UNAVCO.org. [4]Extensometer data from DWR (http://www.water.ca.gov/waterdatalibrary) and LSCE, Borchers and Carpenter, 2014

Introduction

Inelastic land subsidence (subsidence) caused by groundwater extraction is a major problem in California and is exacerbated by additional pressure on groundwater resources during periods of drought. Subsidence has occurred historically and is continuing in many areas in California, most notably in the San Joaquin, Antelope, Coachella, and Sacramento Valleys (Luhdorff & Scalmanini Consulting Engineers (LSCE), Borchers and Carpenter, 2014).

Purpose

The purpose of this document is to summarize recent and historical subsidence and estimate the potential for future subsidence. Specifically, the following documentation and associated maps are intended to be used as a screening tool to identify areas where the potential for subsidence due to groundwater extraction may persist and to act as a guide to focus future site-specific subsidence studies.

This study included an assessment of groundwater levels, review of previous subsidence studies, and compilation of borehole extensometer and continuous GPS station information. The results of this study consist of a summary map (Figure ES-1) and data compilation (Appendix A) of recent, historical, and estimated potential for future subsidence within the DWR Bulletin 118-defined groundwater basins of California. This information is also available on an interactive web map (http://water.ca.gov/groundwater/GIC_MapApp_Intro.cfm).

In addition to this study, the Department of Water Resources (DWR) is also contracting with the National Aeronautics and Space Administration (NASA) Jet Propulsion Laboratory (JPL) to use satellite-based Interferometric Synthetic Aperture Radar (InSAR) to measure relative changes in land surface elevation in the Central Valley from 2007 through 2014; this analysis is expected to be completed by summer 2015. A test area along the California Aqueduct is also being evaluated using aircraft-based InSAR; this work is expected to be completed in winter 2014-15.

Future efforts should build off of this initial work, incorporate the results of the NASA-JPL InSAR assessment in the Central Valley, integrate site-specific lithology data, and include updated groundwater level, extensometer, and continuous GPS data.

Data Sources and Methodology

This study is based on the evaluation of groundwater levels in wells (regardless of well depth or well use) with supporting information from previous subsidence studies (LSCE, Borchers and Carpenter, 2014), and data from borehole extensometers and continuous GPS stations. A description of the each data source is described as follows.

Groundwater Levels

Declining groundwater levels, as a result of groundwater extraction, is a major cause of subsidence especially when they decline past historical lows (Sneed and Others, 2013). Historical low groundwater level data, along with supporting information described below, were used to estimate the potential for future subsidence. Groundwater level data from wells were used only if the period of record was 10 years or more (long-term monitoring wells). Data from all types of wells (agricultural production, municipal and industrial production, and monitoring wells) regardless of depth were used. Groundwater level data were compiled and analyzed from the California Statewide Groundwater Elevation Monitoring (CASGEM) Program and the Water Data Library (WDL) groundwater level database as of May 19, 2014.

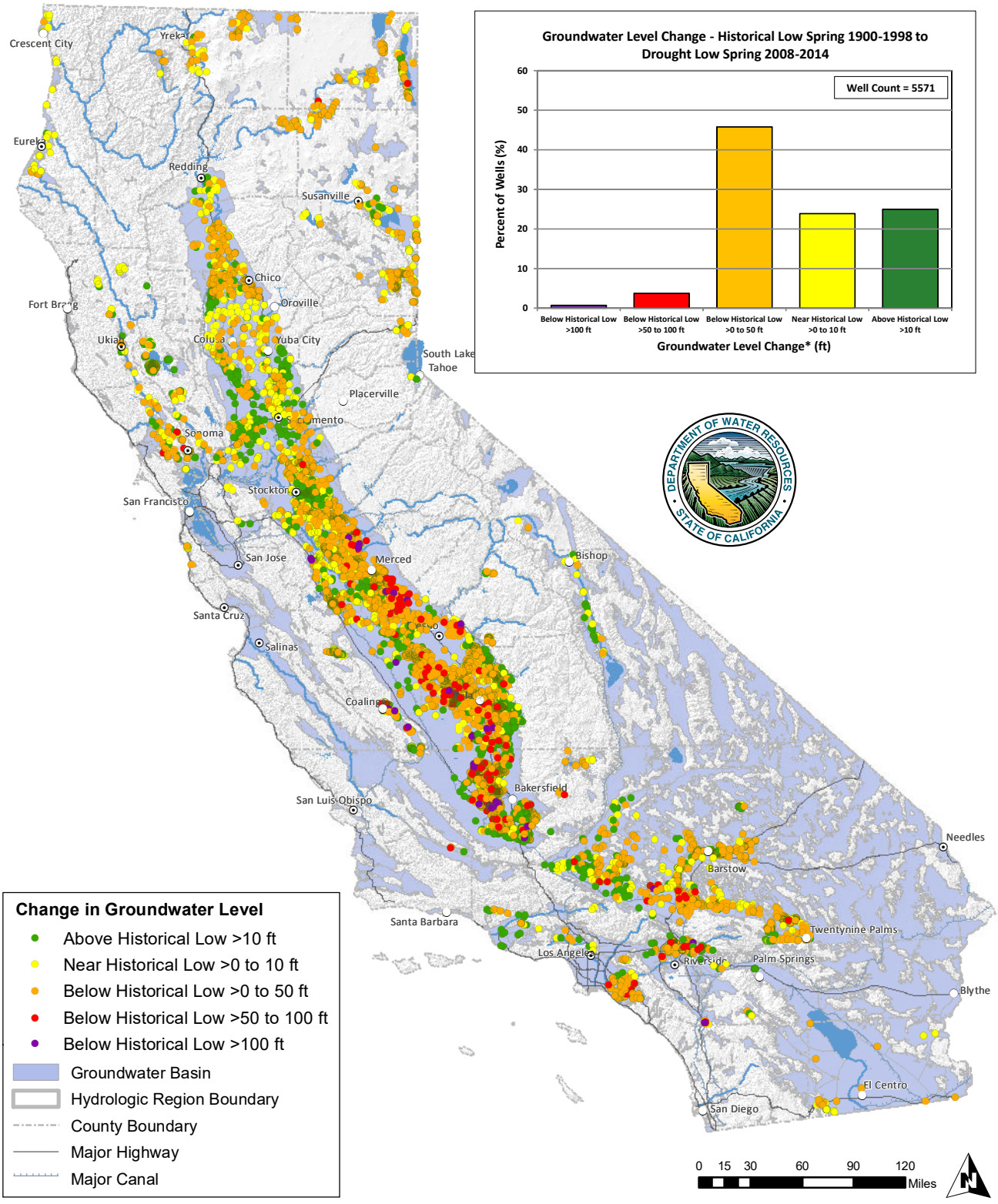
Plotting the difference between groundwater level measurements collected over a long time period at discrete locations is a simple way to depict changes in groundwater levels and evaluate long-term regional trends. These plots were used to estimate the potential for future subsidence. Figure 1 depicts the comparison of historical low spring groundwater levels between spring 1900 and 1998 to more recent low spring groundwater levels between spring 2008 and 2014. Maximum groundwater level declines, and potential for subsidence, are more likely to occur in the summer and fall, however, spring groundwater level measurements were used because the fall 2014 data is currently not available, and in general, spring groundwater level measurements are more numerous and more consistent throughout the state. It should also be noted that groundwater levels from wells only represent site-specific information and do not necessarily represent the conditions in entire groundwater basins. This highlights the importance of having sufficient long-term groundwater monitoring wells and subsidence monitoring stations in each groundwater basin.

The percentage of wells with current groundwater levels (2008-2014) at or below historical low spring levels was calculated for each groundwater basin. This was accomplished by dividing the wells currently at or below historical lows to all long-term wells in the groundwater basin. The results, displayed on Figure 2 and in Appendix A, were categorized into five ranks;

- $\geq$ 50% of groundwater levels at or below historical lows - 4
- $\geq$ 30% to < 50% of groundwater levels at or below historical lows - 3
- $\geq$ 10% to < 30% of groundwater levels at or below historical lows - 2
- < 10% of groundwater levels at or below historical lows - 1
- Insufficient data - 0

FIGURE 1

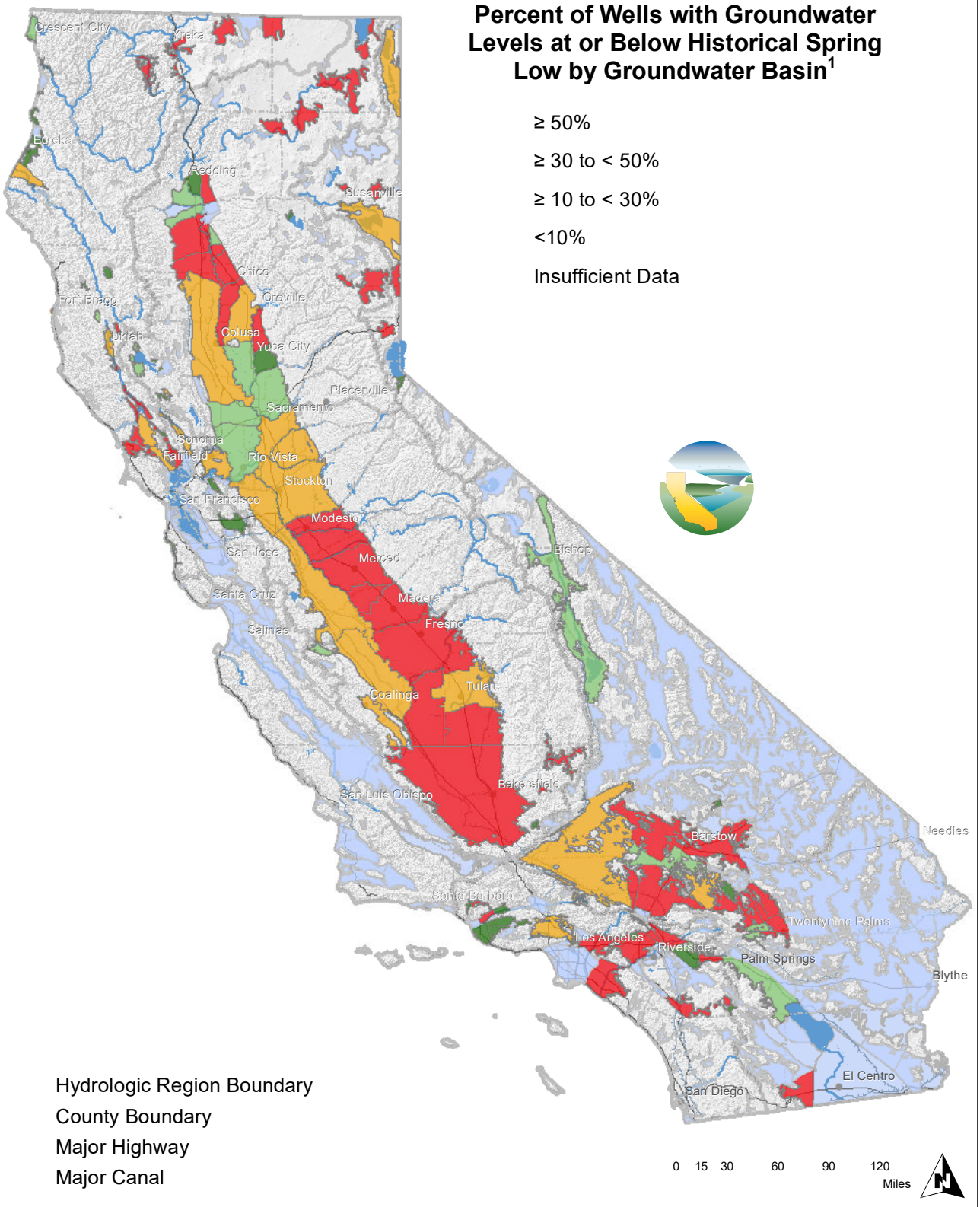
Groundwater Level Change[1]
Historical Low Spring 1900-1998 to Drought Low Spring 2008-2014



[1]Groundwater level change determined from water level measurements in wells. Map and chart based on available data from the DWR Water Data Library as of 05/19/2014. Data subject to change without notice.

FIGURE 2

Percent of Wells with Groundwater Levels at or Below Historical Spring Low by Groundwater Basin



[1]Wells with greater than or equal to 10 years of record were used for this analysis. Percentage based on wells at historical Spring low in current drought period 2008-2014 divided by total number of wells in each groundwater basin.
Map based on available data from the DWR Water Data Library (http://www.water.ca.gov/waterdatalibrary) as of 5/19/2014.

Basins without long-term groundwater monitoring wells or basins that have less than two wells per 100 square miles were classified as having insufficient data. Two wells per 100 square miles was used because that is the minimum monitoring well coverage recommended in the DWR Groundwater Elevation Monitoring Guidelines (DWR, 2010).

Previous Subsidence Studies

A comprehensive review of historical areas of subsidence as well as new areas experiencing subsidence was recently completed by LSCE, Borchers and Carpenter (2014). The information from this report was summarized by groundwater basin in Appendix A, and is displayed on Figure 3. Each groundwater basin was ranked based on information from previous studies;

- Recent and historical subsidence – 5
- Historical subsidence – 1
- No documented subsidence – 0
- Data gap – Blank

Borehole Extensometer Data

The approximate trends (subsiding or not subsiding) of 27 active extensometers, monitored by DWR, USGS, and local agencies, were summarized in Appendix A and are displayed on Figure 4. Borehole extensometer data in each groundwater basin was ranked as follows;

- Cumulative subsidence ≥ 0.1 feet (approximately 1 inch) – 2
- Cumulative subsidence < 0.1 feet (approximately 1 inch) – 1
- Cumulative subsidence unknown – 0
- Data gap - Blank

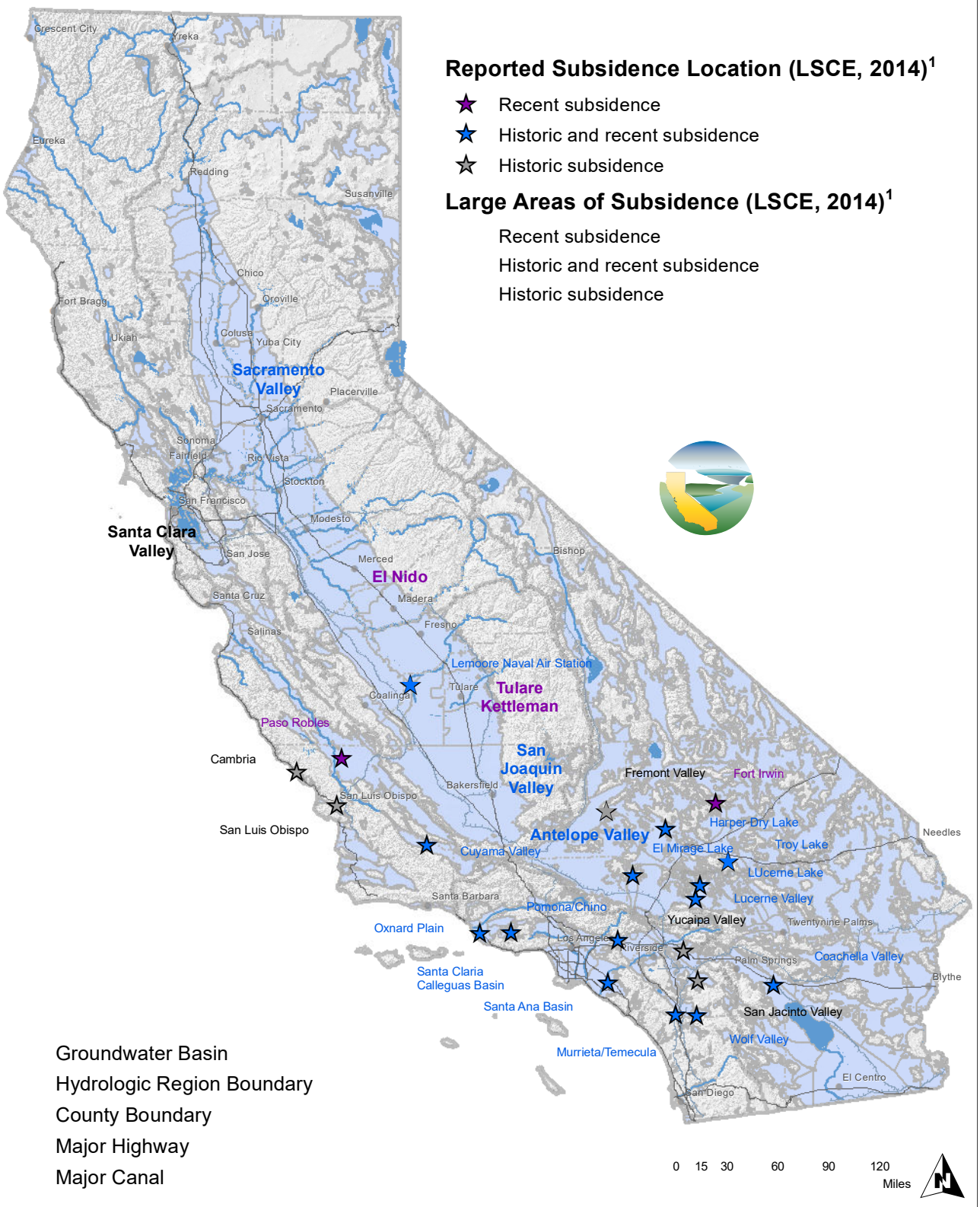
Continuous Global Positioning System (GPS) Data

Continuous GPS data from the UNAVCO (a non-profit university-governed consortium that facilitates geoscience research and education using geodesy) Plate Boundary Observatory (PBO) were used for this study. The approximate trend (subsiding or not subsiding) of the vertical displacement data from 319 continuous GPS stations within groundwater basins (Figure 4) were analyzed and summarized in Appendix A. (http://pbo.unavco.org/, accessed 4/30/2014). Figure 5 displays the cumulative subsidence at continuous GPS stations that have subsiding trends. Each groundwater basin with continuous GPS station(s) was ranked as follows;

- Cumulative subsidence ≥ 0.1 feet (approximately 1 inch) – 2
- Cumulative subsidence < 0.1 feet (approximately 1 inch) – 1
- No cumulative subsidence – 0
- Data gap - Blank

FIGURE 3

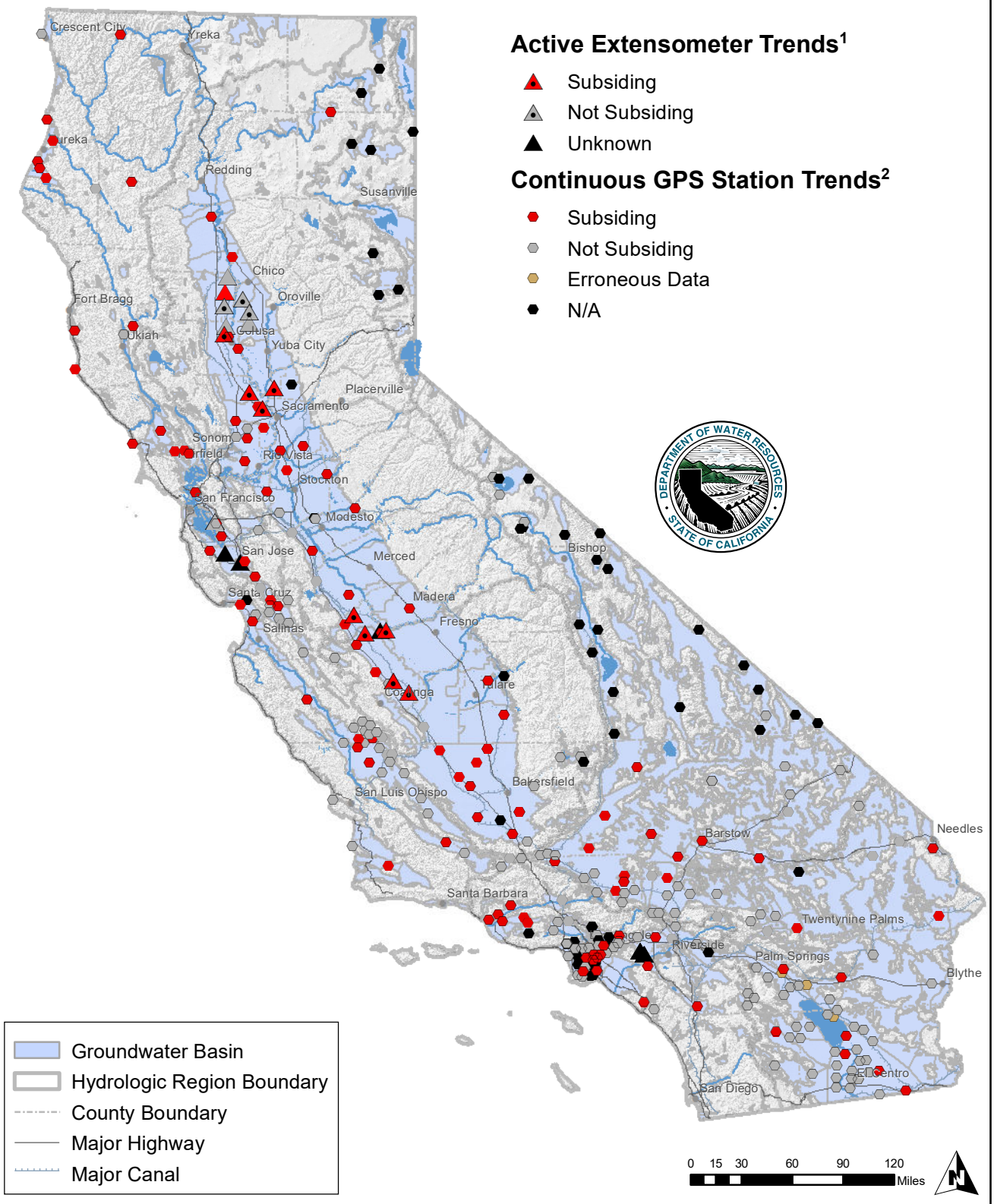
Land Subsidence from Groundwater Use in California
LSCE, Borchers and Carpenter, 2014[1]



[1]Land Subsidence data modified from LSCE, Borchers and Carpenter, 2014.

FIGURE 4

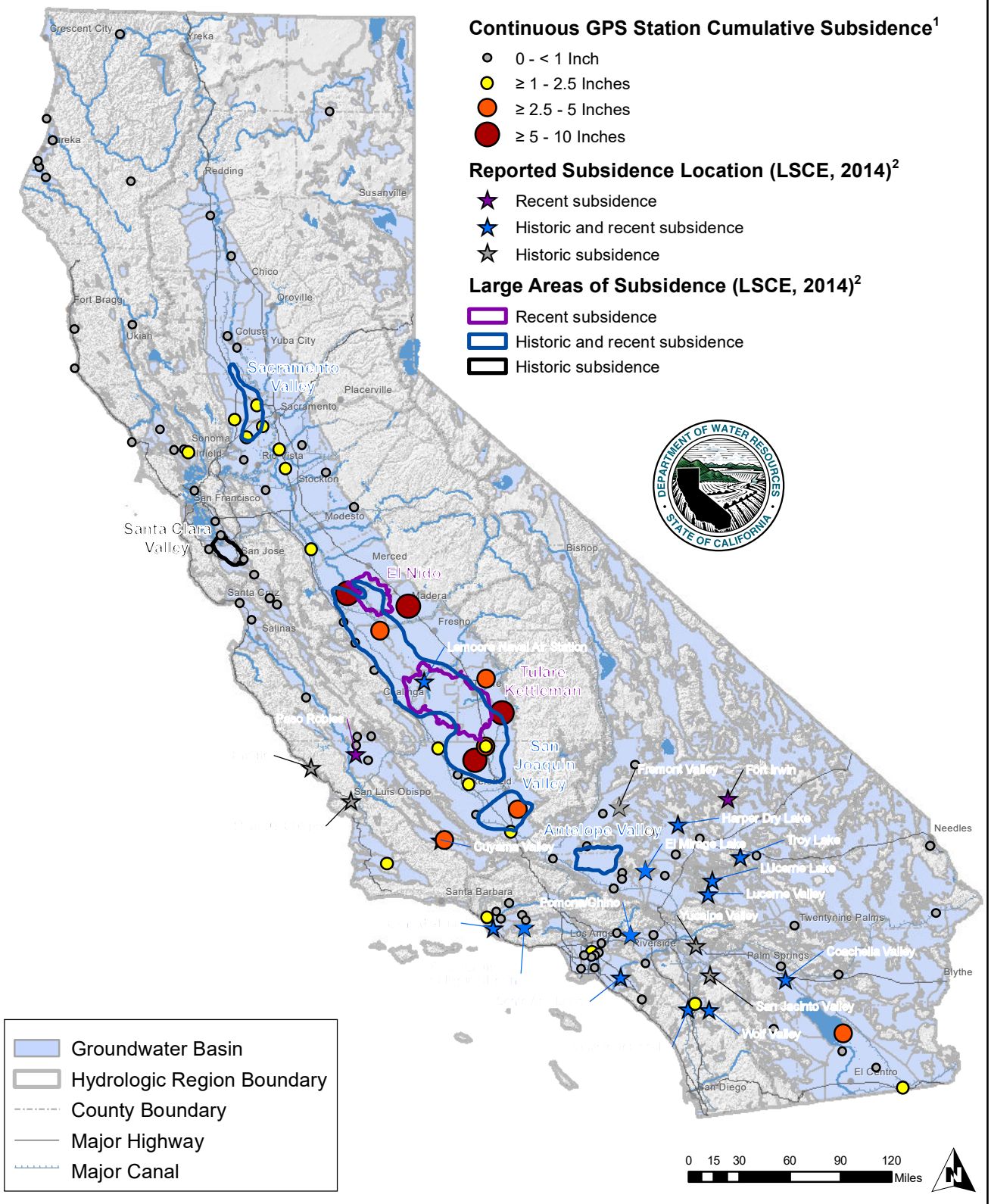
Active Extensometers and Continuous GPS Stations in California



[1]Extensometer data from DWR (http://www.water.ca.gov/waterdatalibrary), USGS (http://waterdata.usgs.gov/nwis), and LSCE, Borchers and Carpenter, 2014. [2]Continuous GPS data from UNAVCO.org.

FIGURE 5

Continuous GPS Station Cumulative Subsidence Compared to Areas of Recent and Historical Land Subsidence



[1]Continuous GPS data from UNAVCO.org. [2]Areas of Land Subsidence Modified from LSCE, Borchers and Carpenter, 2014.

Findings

The estimated potential for future subsidence was calculated in each groundwater basin by combining groundwater level, information from previous subsidence studies, and borehole extensometer and continuous GPS data (Figure 6). In general, the areas with a higher estimated potential for future subsidence are in the southern San Joaquin, Antelope, Coachella, and western Sacramento Valleys. These areas match well with the areas of subsidence documented by LSCE, Borchers and Carpenter (2014) (Figure ES-1).

Most of the basins with a higher estimated potential for future subsidence are also ranked as high or medium priority by the CASGEM Basin Prioritization Process.

Groundwater Basins with Recent Subsidence – Previous Studies

Based on the comprehensive review of subsidence by LSCE, Borchers and Carpenter (2014) the following number of groundwater basins in seven hydrologic regions are currently experiencing subsidence (Appendix A):

- Subsidence is occurring in many groundwater basins in the state and especially in the southern San Joaquin River (4 basins) and Tulare Lake (7 basins) Hydrologic Regions. Subsidence is also occurring in the South Lahontan (5 basins), South Coast (4 basins), Sacramento River (3 subbasins), Central Coast (2 basins), and Colorado River (2 basins) Hydrologic Regions.

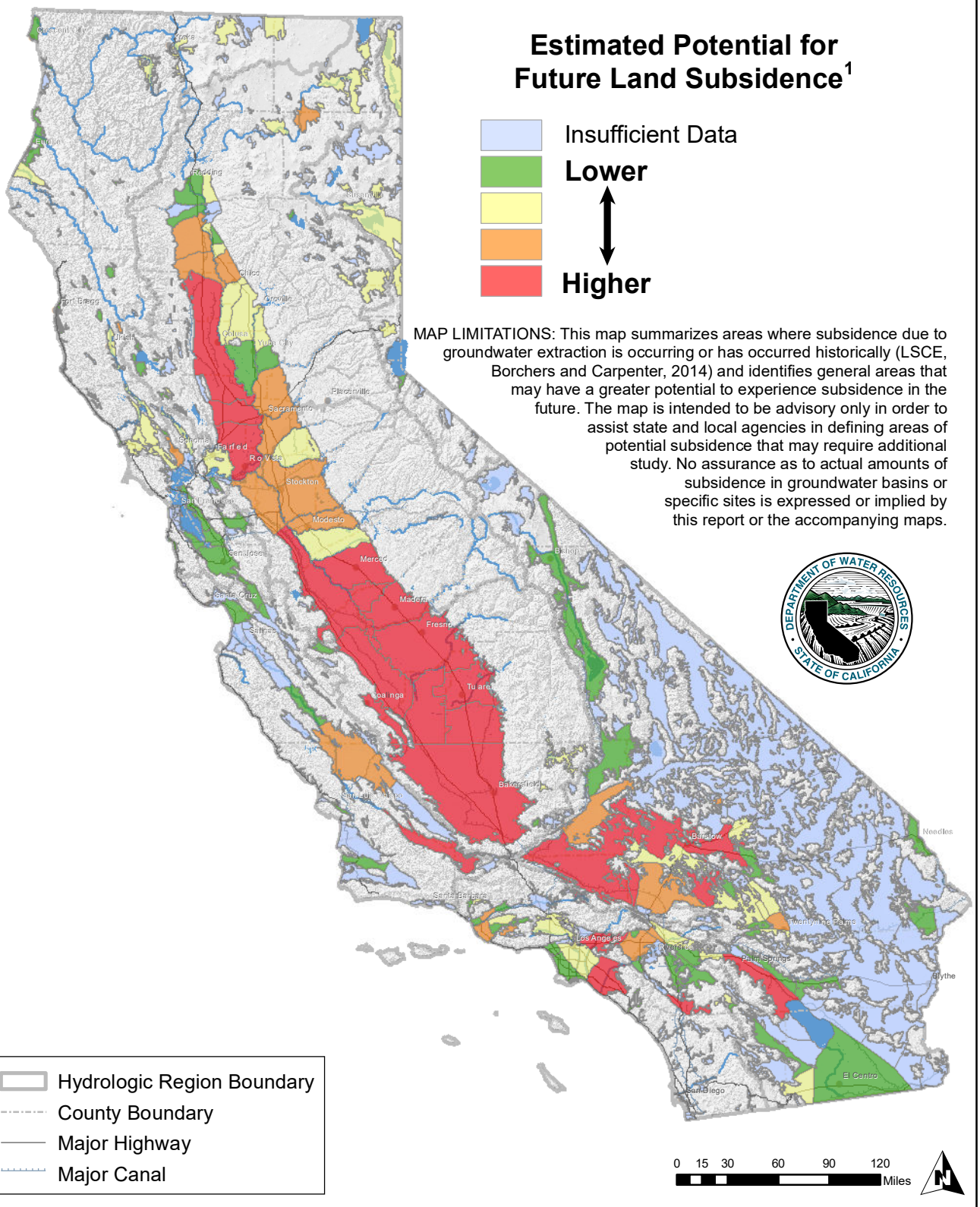
Groundwater Basins with Potential for Subsidence - Groundwater Level Data

Analysis of historical groundwater levels at discrete locations was completed to evaluate recent groundwater lows compared to historical lows. Figure 1 depicts the comparison of historical low spring levels between spring 1900 and 1998 to more recent low spring levels between spring 2008 and 2014. Since spring 2008, groundwater levels are at all-time historical lows (for the period of record) in most areas of the state especially in the southern San Joaquin Valley, portions of the Sacramento Valley, and portions of the San Francisco Bay, South Lahontan, and South Coast Hydrologic Regions – these areas exhibit groundwater levels more than 50 feet below previous historical lows experienced sometime prior to 2000. There are many areas of the San Joaquin Valley where recent groundwater levels are more than 100 feet below previous historical lows and correspond to areas of recent subsidence.

In the Central Valley, groundwater levels in 36% of the long-term wells (216 of 599) in the Sacramento Valley and 55% of the long-term wells (1,718 of 3,124) in the San Joaquin Valley are at or below the historical spring low levels.

FIGURE 6

Estimated Potential for Future Land Subsidence in California



[1]The estimated potential for land subsidence was calculated in each groundwater basin by combining the ranking values of groundwater levels, previous subsidence studies, borehole extensometer, and continuous GPS data (Appendix A).

The percentage of wells with groundwater levels currently (2008-2014) at or below historical spring low levels was calculated for each groundwater basin (Figure 2 and Appendix A). The following number of groundwater basins in each hydrologic region have greater than 50% of groundwater levels at or below historical spring low levels:

- Sacramento River (18 basins), South Coast (10 basins), North Coast (11), Colorado River (9 basins), Tulare Lake (6 basins), San Joaquin River (5 basins), South Lahontan (5 basins), Central Coast (2 basins), North Lahontan (4 basins), and San Francisco Bay (2 Basins)

Gaps in Groundwater and Subsidence Monitoring

A groundwater level and subsidence monitoring gap is an informal term indicative of insufficient data to reasonably assess and interpret groundwater and subsidence conditions in a basin and these gaps exist throughout the state. There are two primary gaps that exist in groundwater level or subsidence monitoring data; spatial and temporal. Spatial data gaps exist where there is inadequate horizontal and/or vertical distribution of groundwater level or subsidence monitoring to accurately represent or assess conditions within an area of interest (groundwater basin). Sufficient vertical distribution of data is important in groundwater basins having multiple aquifer systems at various depths, and that may also be characterized by varying levels of confinement (compressible clays and silts) or changing groundwater levels. A thorough understanding of a groundwater basin's hydrogeology is essential to assess whether or not the spatial distribution of groundwater level and subsidence monitoring data are adequate for a basin. Groundwater level and subsidence data collected at routine intervals can provide seasonal and long-term trends for a basin, which are essential for accurately estimating aquifer response and change in storage associated with changing hydrology, land use, total water supply, and effects of local groundwater management practices. Temporal data gaps exist when a consistent record of groundwater level and subsidence data, recorded over regular time intervals, is not available. Specific data gaps identified in this study include;

- Many high and medium priority basins do not have subsidence monitoring networks or long-term groundwater monitoring wells; this is most notable in the Central Coast Hydrologic Region.

- Large areas of recent subsidence in the San Joaquin Valley (El Nido and Tulare-Kettleman areas of LSCE, Borchers and Carpenter, 2014) do not have continuous GPS or borehole extensometers in the areas of maximum subsidence (Figure 5).

Usage and Limitations

This document and associated maps summarize areas where subsidence due to groundwater extraction is occurring or has occurred historically (LSCE, Borchers and Carpenter, 2014) and identifies general areas that may have a greater potential to experience subsidence in the future. The map is intended to be advisory only in order to assist state and local agencies in defining areas of potential subsidence that may require additional study. No assurance as to actual amounts of subsidence in groundwater basins or at specific sites is expressed or implied by this report or the accompanying maps.

Furthermore it is important to note the following:

- Maps do not provide a differentiation between the amounts of subsidence that is occurring (which can range from 0.1 feet to several feet).
- This analysis was completed on a groundwater basin scale, which could over or understate the potential for future subsidence on a more localized or site specific scale.
- The scope of this analysis was limited and relied on readily available high level published data. This analysis did not incorporate potentially available local knowledge and data to refine the areas of potential subsidence necessary to go from a groundwater basin scale to a more localized or site specific scale of subsidence.

Recommendations

Future efforts should build off of this initial work, incorporate the results of the NASA-JPL InSAR assessment in the Central Valley, integrate site-specific lithology data, and include updated groundwater level, extensometer, and continuous GPS data. Synthesis of this additional subsidence data should inform groundwater managers about areas of new or continuing subsidence that need site-specific monitoring data (CGPS and/or borehole extensometers). The recommendations from LSCE, Borchers and Carpenter, 2014 (see report for details) should also be considered in future subsidence work in California and include:

- Monitor land surface elevation changes and compaction
    - Remote surveillance and analysis: InSAR and continuous GPS
    - Ground surveillance and analysis: Surveying and borehole extensometry
- Characterize aquifer system and monitor groundwater levels
- Collect, store and disseminate data
- Evaluate and prioritize subsiding groundwater basins

References

DWR, 2010, Department of Water Resources Groundwater Elevation Monitoring Guidelines, http://www.water.ca.gov/groundwater/casgem/pdfs/CASGEM%20DWR%20GW%20Guidelines%20Final%20121510.pdf

LSCE, Borchers and Carpenter, 2014, Land Subsidence from Groundwater Use in California, report prepared by Luhdorff and Scalmanini consulting engineers with support by the California Water Foundation, http://www.californiawaterfoundation.org/uploads/1397858208- SUBSIDENCEFULLREPORT_FINAL.pdf

Sneed, Michelle, Brandt, Justin, and Solt, Mike, 2013, Land subsidence along the Delta-Mendota Canal in the northern part of the San Joaquin Valley, California, 2003–10: U.S. Geological Survey Scientific Investigations Report 2013–5142, 87 p., http://dx.doi.org/10.3133/sir20135142

Appendix A. Summary of Recent, Historical, and Estimated Potential for Future Land Subsidence in California

Appendix A. Summary of Recent, Historical, and Estimated Potential for Future Land Subsidence in California

CASGEM Groundwater Basin Prioritization Results											CASGEM Overall Basin Priority Ranking	B-118-80 Overdraft Designation (Critical Overdraft, Special Problems, Evidence of Overdraft, Not Analyzed)	Potential for Land Subsidence Estimated From Long-Term Groundwater Level Data							Summary of Recent and Historical Land Subsidence													Documented Subsidence Data Ranking Value	Summary of Recent, Historical, and Estimated Potential for Future Subsidence Ranking Value	Overall Estimated Potential For Future Subsidence
Basin Number	Basin Name	Sub-Basin Name	Hydrologic Region	DWR Region Office	Basin Area		Irrigated Acreage (Acres)	Estimated Groundwater Use (AF)	Total Wells	2010 Population			Number of Wells At or Below Historical Low	Total Number of Wells with Longterm record (> 10 yrs)	Percent of Wells At or Below Historical Low	Number of Wells with Longterm record (> 10 yrs) per Sq. Mile	Estimated Potential For Subsidence From Groundwater Levels Rank	Estimated Potential for Land Subsidence	Long Term (> 10 yrs) Groundwater Level Trends	Documented Subsidence (Yes/No)	Documented Subsidence Ranking (0 - None, 1 - Historical, 5 - Recent and Historical)	If Yes, during what period?	If Yes, maximum amount (feet)?	Active Extensometer Stations in Basin (Yes/No) and (#)	Period of record	Current station trend(s)? Max decrease (ft)	Borehole Extensometer Cumulative Subsidence Ranking (0 - unknown, 1 - Subsided < 0.1 ft, 2 - Subsided > 0.1 ft)	Active Continuous GPS Stations in Basin (Yes/No) and (#)	Current station trend?	Continuous GPS Cumulative Subsidence Ranking (0 - no subsidence or unknown, 1 - subsided < 0.1 ft , 2 - Subsided > 0.1 ft)	Max. Decrease (Ft)	Max Increase (ft)	Longest CGPS Period of record	Land Subsidence Comments			
					Acres	Sq. Mile																														
5-22.07	SAN JOAQUIN VALLEY	DELTA-MENDOTA	San Joaquin River	SCRO	746,697	1,166.7	470,500	509,687	7,132	107,879	High	Not Analyzed	84	189	44%	16	3	Medium-High	30 to 50% GWL at or Below Historical Low	Yes[1]	5	1926-1970 (Ireland, 1984) and 2007 to 2011 (CWF, 2014)	1.0-1.5 (2007-2011), 28.0 (1926-1970)	Yes (2)	2012 to Present	Subsiding (2), 0.17 USGS 365325120391501	2	Yes (6)	Subsiding (4), Not Subsiding(2)	2	0.66	0.02	2005 to Present	[1]Subsidence has been documented in adjacement groundwater basins (Merced, Chowchilla, Madera, Kings);	9	12	High
5-21.67	SACRAMENTO VALLEY	YOLO	Sacramento River	NCRO	225,718	352.7	128,860	200,000	7,329	194,158	High	Not Analyzed	3	18	17%	5	2	Low-Medium	10 to 30% GWL at or Below Historical Low	Yes	5	1926 to Present	0.40 (1992-Present), 5.4 (1926-1994)	Yes (1)	1992 to Present	Subsiding, 0.20 in one year	2	Yes (2)	Subsiding (2)	2	0.20	-	2004 to Present		9	11	High
5-22.06	SAN JOAQUIN VALLEY	MADERA	San Joaquin River	SCRO	393,429	614.7	238,070	375,800	9,100	116,919	High	Critical Overdraft	77	112	69%	18	4	High	>50% GWL at or Below Historical Low	Yes[1]	5	1926-1970 (Ireland, 1984) and 2007 to 2011 (CWF, 2014)	0.5 - 1.0 (2007-2011), >1.0 (1926-1970)	No	-	-		Yes (1)	Subsiding	2	0.57	-	2005-Present	[1]Subsidence has been documented in adjacement groundwater basins (Chowchilla, Delta-Mendota, Kings)	7	11	High
5-22.09	SAN JOAQUIN VALLEY	WESTSIDE	Tulare Lake	SCRO	640,504	1,000.8	513,759	411,534	3,790	27,285	High	Not Analyzed	9	27	33%	3	3	Medium-High	30 to 50% GWL at or Below Historical Low	Yes[1]	5	1926-1970 (Ireland, 1984) and 2007 to 2011 (CWF, 2014)	0.5-1.0 (2007-2011), 28.0 (1926-1970)	Yes (3)	2012 to Present	Subsiding (3), 0.25 ft USGS 363935120134501	2	Yes (4)	Subsiding (2), Not Subsiding (2)	1	0.08	0.03	2005 to Present	[1]Subsidence has been documented in adjacement groundwater basins (Delta-Mendota, Kings, Tulare Lake, Pleasant Valley)	8	11	High
5-22.13	SAN JOAQUIN VALLEY	TULE	Tulare Lake	SCRO	469,959	734.3	371,028	592,823	6,355	108,660	High	Critical Overdraft	109	207	53%	28	4	High	>50% GWL at or Below Historical Low	Yes[1]	5	1926-1970 (Ireland, 1984) and 2007 to 2011 (CWF, 2014)	3.0 - 4.0 (2007-2011), >12.0 (1926-1970)	No	-	-		Yes (1)	Subsiding	2	0.82	-	2006 to Present	[1]Subsidence has been documented in adjacement groundwater basins (Tulare Lake,Kern County, Kaweah)	7	11	High
5-22.14	SAN JOAQUIN VALLEY	KERN COUNTY	Tulare Lake	SCRO	1,950,113	3,047.1	919,821	1,041,462	15,015	700,323	High	Critical Overdraft	299	587	51%	19	4	High	>50% GWL at or Below Historical Low	Yes[1]	5	1926-1970 (Ireland, 1984) and 2007 to 2011 (CWF, 2014)	0-0.5 (2007-2011), 12.0 (1926-1970)	Yes (2)	Semitropic WSD 2010 to present, KWB 1994 to Present?	Unknown	0	Yes (12)	Subsiding (10), Not Subsiding (2)	2	0.44	0.07	2007 to Present	[1]Subsidence has been documented in adjacement groundwater basins (Tulare Lake, Tule, Pleasant Valley)	7	11	High
6-44	ANTELOPE VALLEY		South Lahontan	SRO	1,014,596	1,585.3	21	90,000	4,476	398,864	High	Evidence of Overdraft	56	151	37%	10	3	Medium-High	30 to 50% GWL at or Below Historical Low	Yes[1]	5	1930s to Present	>6.0 (CWF, 2014)	Yes (3)	See CWF, 2014	See CWF, 2014	2	Yes (15)	Not Subsiding (10), Subsiding (5)	1	0.03	0.07	2004 to Present	[1]Subsidence has been documented in adjacement groundwater basin (El Mirage)	8	11	High
4-13	SAN GABRIEL VALLEY		South Coast	SRO	127,278	198.9	0	218,696	1,587	1,275,187	High	Not Analyzed	3	5	60%	3	4	High	>50% GWL at or Below Historical Low	Yes[1]	5	Various (CWF, 2014)	Various (CWF, 2014)	No	-	-		Yes (6)	Not Subsiding (4), Subsiding (2)	1	0.08	0.07	2004 to Present	[1]Subsidence has been documented in adjacement groundwater basin (Chino)	6	10	High
5-21.52	SACRAMENTO VALLEY	COLUSA	Sacramento River	NRO	917,793	1,434.1	572,927	172,896	9,695	48,369	Medium	Not Analyzed	53	171	31%	12	3	Medium-High	30 to 50% GWL at or Below Historical Low	Yes	5	1926 to Present	5.4 (CWF, 2014)	Yes (5)	1988 to Present	Subsiding (3), Not Subsiding (2)	1	Yes (2)	Subsiding (2)	1	0.07	-	2005 to Present		7	10	High
5-22.11	SAN JOAQUIN VALLEY	KAWEAH	Tulare Lake	SCRO	446,283	697.3	380,311	453,226	12,092	271,700	High	Critical Overdraft	183	405	45%	58	3	Medium-High	30 to 50% GWL at or Below Historical Low	Yes[1]	5	1926-1970 (Ireland, 1984) and 2007 to 2011 (CWF, 2014)	3.0 - 4.0 (2007-2011), >8.0 (1926-1970)	No	-	-		Yes (1)	Subsiding	2	0.33	-	2005 to Present	[1]Subsidence has been documented in adjacement groundwater basins (Tulare Lake, Kings, Tule)	7	10	High
6-40	LOWER MOJAVE RIVER VALLEY		South Lahontan	SRO	287,563	449.3	6,126	31,374	63	32,938	Medium	Evidence of Overdraft	69	123	56%	27	4	High	>50% GWL at or Below Historical Low	Yes[1]	5	Various (CWF, 2014 and Sneed and others, 2003)	Various (CWF, 2014 and Sneed and others, 2003)	No	-	-		Yes (1)	Subsiding	1	0.03	-	2004 to Present	[1]Subsidence has been documented in adjacement groundwater basins (Harper Valley, Langford Valley)	6	10	High
6-47	HARPER VALLEY		South Lahontan	SRO	411,827	643.5	813	10,000	95	1,634	Low	Evidence of Overdraft	13	23	57%	4	4	High	>50% GWL at or Below Historical Low	Yes[1]	5	Various (CWF, 2014 and Sneed and others, 2003)	Various (CWF, 2014 and Sneed and others, 2003)	No	-	-		Yes (1)	Subsiding	1	0.02	-	2005 to Present	[1]Subsidence has been documented in adjacement groundwater basin (Antelope Valley)	6	10	High
5-21.66	SACRAMENTO VALLEY	SOLANO	Sacramento River	NCRO	424,832	663.8	258,208	69,149	6,790	119,263	Medium	Not Analyzed	16	65	25%	10	2	Low-Medium	10 to 30% GWL at or Below Historical Low	Yes[2]	5	1926 to Present	5.4 (1926-1994) CWF, 2014	No	-	-		Yes (5)	Subsiding (3), Not Subsiding (2)	2	0.13	0.02	2005 to Present	[1]Subsidence caused by oxidation of organic deposits has occurred	7	9	High
5-22.04	SAN JOAQUIN VALLEY	MERCED	San Joaquin River	SCRO	491,255	767.6	279,142	364,227	8,392	173,731	High	Not Analyzed	170	216	79%	28	4	High	>50% GWL at or Below Historical Low	Yes	5	1926-1970 (Ireland, 1984) and 2007 to 2011 (CWF, 2014)	0.5-1.0 (2007-2011), 28.0 (1926-1970)	No	-	-		No	-		-	-	-		5	9	High
5-22.05	SAN JOAQUIN VALLEY	CHOWCHILLA	San Joaquin River	SCRO	159,319	248.9	153,038	210,976	2,203	15,820	High	Critical Overdraft	83	109	76%	44	4	High	>50% GWL at or Below Historical Low	Yes	5	1926-1970 (Ireland, 1984) and 2007 to 2011 (CWF, 2014)	2.0 - 2.5 (2007-2011), >1.0 (1926-1970)	No	-	-		No	-		-	-	-		5	9	High
5-22.08	SAN JOAQUIN VALLEY	KINGS	Tulare Lake	SCRO	977,030	1,526.6	720,852	1,055,502	37,841	906,544	High	Critical Overdraft	229	368	62%	24	4	High	>50% GWL at or Below Historical Low	Yes	5	1926-1970 (Ireland, 1984) and 2007 to 2011 (CWF, 2014)	1.0-2.0 (CWF, 2014)	No	-	-		No	-		-	-	-		5	9	High
5-22.12	SAN JOAQUIN VALLEY	TULARE LAKE	Tulare Lake	SCRO	524,539	819.6	332,240	504,271	5,345	125,701	High	Critical Overdraft	81	113	72%	14	4	High	>50% GWL at or Below Historical Low	Yes	5	1926-1970 (Ireland, 1984) and 2007 to 2011 (CWF, 2014)	3.0-4.0 (2007-2011), >8.0 (1926-1970)	No	-	-		Yes (1)	Not Subsiding	0	-	0.02	2005 to Present	[1]Subsidence has been documented in adjacement groundwater basins (Westside, Kern County, Kaweah, Tule, Pleasant Valley)	5	9	High
6-43	EL MIRAGE VALLEY		South Lahontan	SRO	76,292	119.2	462	5,300	16	10,933	Medium	Not Analyzed	12	15	80%	13	4	High	>50% GWL at or Below Historical Low	Yes[1]	5	Various (CWF, 2014 and Sneed and others, 2003)	Various (CWF, 2014 and Sneed and others, 2003)	No	-	-		Yes (1)	Not Subsiding	0	-	-	2008 to Present	[1]Subsidence has been documented in adjacement groundwater basins (Antelope Valley, Upper Mojave River Valley)	5	9	High
8-1	COASTAL PLAIN OF ORANGE		South Coast	SRO	223,222	348.8	0	342,000	8,534	2,309,966	Medium	Not Analyzed	53	97	55%	28	4	High	>50% GWL at or Below Historical	Yes[1]	5	April 1998-May 1999 Bawden	0.1 (CWF, 2014)	No	-	-		No	-		-	-	-	[1]subsidence has been	5	9	High
5-22.10	SAN JOAQUIN VALLEY	PLEASANT VALLEY	Tulare Lake	SCRO	145,782	227.8	28,131	47,383	358	34,213	Low	Not Analyzed	27	74	36%	32	3	Medium-High	30 to 50% GWL at or Below Historical Low	Yes[1]	5	1926-1970 (Ireland, 1984) and 2007 to 2011 (CWF, 2014)	0-0.5 (2007-2011), 4.0 (1926-1970)	No	-	-		No	-		-	-	-	[1]Subsidence has been documented in adjacement groundwater basin (Westside, Tulare Lake, Kern County)	5	8	High
7-19	LUCERNE VALLEY		Colorado River	SRD	148,467	232.0	1,435	10,000	32	3,311	Low	Evidence of Overdraft	17	37	46%	16	3	Medium-High	30 to 50% GWL at or Below Historical Low	Yes[1]	5	Various (CWF, 2014 and Sneed and others, 2003)	Various (CWF, 2014 and Sneed and others, 2003)	No	-	-		Yes (1)	Not Subsiding	0	-	-	2005 to Present	[1]Subsidence has been documented in adjacement groundwater basin (Upper Mojave River Valley)	5	8	High
3-13	CUYAMA VALLEY		Central Coast	SRD	242,114	378.3	26,023	69,160	248	1,236	Medium	Evidence of Overdraft/Critical Overdraft	2	3	67%	1	0	Insufficient Data	Insufficient Data	Yes	5	2002 to 2008	0.21 (CWF, 2014)	No	-	-		Yes (2)	Subsiding (1), Not Subsiding (1)	2	0.25	0.02	2011 to Present		7	7	High
7-21.01	COACHELLA VALLEY	INDIO	Colorado River	SRD	299,784	468.4	74,268	200,979	224	368,855	Medium	Evidence of Overdraft	1	9	11%	2	2	Low-Medium	10 to 30% GWL at or Below Historical Low	Yes	5	1995-2010	1.97 (CWF, 2014)	No	-	-		Yes (4)	Not Subsiding (4)	0	-	0.05	2005 to Present		5	7	High
9-5	TEMECULA VALLEY		South Coast	SRO	88,338	138.0	4,800	3,365	1,556	219,431	High	Evidence of Overdraft	13	16	81%	12	4	High	>50% GWL at or Below Historical Low	Yes	1	Various (CWF, 2014)	Various (CWF, 2014)	No	-	-		Yes (1)	Subsiding	2	0.16	-	2005 to Present		3	7	High
2-2.02	NAPA-SONOMA VALLEY	SONOMA VALLEY	San Francisco Bay	NCRO	44,626	69.7	15,382	2,523	2,242	31,275	Medium	Not Analyzed	13	17	76%	24	4	High	>50% GWL at or Below Historical Low	No	0	-	-	No	-	-		Yes (2)	Subsiding (2)	2	0.11	-	2005 to Present		2	6	Medium to High
3-4.06	SALINAS VALLEY	PASO ROBLES AREA	Central Coast	SCRO	597,241	933.2	101,763	120,215	440	56,077	High	Evidence of Overdraft	0	0	0%	0	0	Insufficient Data	Insufficient Data	Yes	5	1997	0.17 (CWF, 2014)	No	-	-		Yes (16)	Not Subsiding (12), Subsiding (4)	1	0.03	0.03	2004 to Present		6	6	Medium to High
4-4.02	SANTA CLARA RIVER VALLEY	OXNARD	South Coast	SRD	58,200	90.9	49,616	77,036	147	235,973	High	Critical Overdraft	0	4	0%	4	1	Low	<10% GWL at or Below Historical Low	Yes	5	1939-2003	3.0 (CWF, 2014)	No	-	-		No	-		-	-	-		5	6	Medium to High
5-21.65	SACRAMENTO VALLEY	SOUTH AMERICAN	Sacramento River	NCRO	247,745	387.1	61,539	76,465	11,779	718,113	High	Not Analyzed	13	35	37%	9	3	Medium-High	30 to 50% GWL at or Below Historical Low	Yes[2]	1	-	-	No	-	-		Yes (1)	Subsiding	2	0.11	0.00	2005 to Present	[1]Subsidence caused by oxidation of organic deposits has occurred	3	6	Medium to High
6-36.02	LANGFORD VALLEY	IRWIN	South Lahontan	SRO	10,557	16.5	0	0	40	8,845	Very Low	Not Analyzed	0	6	0%	36	1	Low	<10% GWL at or Below Historical Low	Yes	5	1993-2006	.88 (CWF, 2014)	No	-	-		No	-		-	-	-		5	6	Medium to High
6-42	UPPER MOJAVE RIVER VALLEY		South Lahontan	SRO	415,295	648.9	1,183	66,748	163	355,338	High	Evidence of Overdraft	101	159	64%	25	4	High	>50% GWL at or Below Historical Low	Yes[1]	1	1969 to Present	2.0 (CWF, 2014)	No	-	-		Yes (5)	Not Subsiding (4), Subsiding (1)	1	0.02	0.03	2004 to Present	[1]Subsidence has been documented in adjacement groundwater basins (Lucerne Valley, El Mirage Valley)	2	6	Medium to High
8-2.01	UPPER SANTA ANA VALLEY	CHINO	South Coast	SRD	154,693	241.7	25,000	169,488	2,162	898,653	High	Not Analyzed	21	26	81%	11	4	High	>50% GWL at or Below Historical Low	Yes[1]	1	1986-1993	4.0 (CWF, 2014)	Yes (6)	2003 to Present	Unknown	0	Yes (1)	Subsiding	1	0.03	-	2004 to Present	[1]Subsidence has been documented in adjacement groundwater basin (San Gabriel Valley)	2	6	Medium to High
8-2.04	UPPER SANTA ANA VALLEY	RIALTO-COLTON	South Coast	SRD	30,224	47.2	32	12,000	265	145,832	Medium	Not Analyzed	35	41	85%	87	4	High	>50% GWL at or Below Historical Low	Yes[1]	1	-	-	No	-	-		Yes (1)	Not Subsiding	1	0.07	-	2011 to Present	[1]Subsidence has been documented in adjacement groundwater basins (Chino)	2	6	Medium to High
1-51	POTTER VALLEY		North Coast	NCRO	8,237	12.9	4,423	6,045	363	1,145	Very Low	Not Analyzed	2	2	100%	16	4	High	>50% GWL at or Below Historical Low	No	0	-	-	No	-	-		Yes (1)	Subsiding	3	0.02	-	2005 to Present		1	5	Medium to High
4-10	CONEJO		South Coast	SRD	18,848	29.4	1	2,029	103	96,704	Low	Not Analyzed	0	0	0%	0	0	Insufficient Data	Insufficient Data	Yes	5	See CWF, 2014	See CWF, 2014	No	-	-		No	-		-	-	-		5	5	Medium to High
4-4.04	SANTA CLARA RIVER VALLEY	SANTA PAULA	South Coast	SRD	22,899	35.8	12,014	25,940	79	46,816	Medium	Critical Overdraft	1	2	50%	6	4	High	>50% GWL at or Below Historical Low	No[1]	0	-	-	No	-	-		Yes (1)	Subsiding	1	0.03	-	2004 to Present	[1]Subsidence has been documented in adjacement groundwater basin (Oxnard)	1	5	Medium to High
5-21.50	SACRAMENTO VALLEY	RED BLUFF	Sacramento River	NRO	274,489	428.9	46,908	90,000	5,810	28,053	Medium	Not Analyzed	22	32	69%	7	4	High	>50% GWL at or Below Historical Low	No	0	-	-	No	-	-		Yes (1)	Subsiding	1	0.02	-	2005 to Present		1	5	Medium to High
5-21.51	SACRAMENTO VALLEY	CORNING	Sacramento River	NRO	205,473	321.1	72,909	160,000	4,125	18,852	Medium	Not Analyzed	17	27	63%	8	4	High	>50% GWL at or Below Historical Low	No	0	-	-	Yes (1)	2005 to Present	Not Subsiding, 0.05	1	No	-		-	-	-		1	5	Medium to High
5-21.57	SACRAMENTO VALLEY	VINA	Sacramento River	NRO	124,577	194.7	43,328	155,000	4,295	71,397	High	Not Analyzed	16	21	76%	11	4	High	>50% GWL at or Below Historical Low	No	0	-	-	No	-	-		Yes (1)	Subsiding	1	0.03	-	2006 to Present		1	5	Medium to High
5-21.64	SACRAMENTO VALLEY	NORTH AMERICAN	Sacramento River	NCRO	340,170	531.5	143,312	399,000	9,855	832,746	High	Not Analyzed	21	87	24%	16	2	Low-Medium	10 to 30% GWL at or Below Historical Low	Yes	1	1994 to Present	0.032	Yes (1)	1994 to Present	Subsiding	1	Yes (1)	Subsiding	1	0.07	-	2003 to Present		3	5	Medium to High
5-22.01	SAN JOAQUIN VALLEY	EASTERN SAN JOAQUIN	San Joaquin River	NCRO	707,073	1,104.8	410,810	491,297	19,176	582,662	High	Critical Overdraft	122	329	37%	30	3	Medium-High	30 to 50% GWL at or Below Historical Low	No[2]	0	-	-	No	-	-		Yes (2)	Subsiding (2)	2	0.11	-	2005 to Present	[1]Subsidence caused by oxidation of organic deposits has occurred	2	5	Medium to High
5-22.02	SAN JOAQUIN VALLEY	MODESTO	San Joaquin River	SCRO	246,518	385.2	116,709	226,000	6,122	294,872	High	Not Analyzed	79	128	62%	33	4	High	>50% GWL at or Below Historical Low	No	0	-	-	No	-	-		Yes (2)	Subsiding (1), Not Subsiding (1)	1	0.03	-	2006 to Present		1	5	Medium to High
5-22.15	SAN JOAQUIN VALLEY	TRACY	San Joaquin River	NCRO	344,884	538.9	224,284	19,198	7,267	268,175	Medium	Not Analyzed	8	26	31%	5	3	Medium-High	30 to 50% GWL at or Below Historical Low	Yes[2]	1	-	-	No	-	-		Yes (2)	Subsiding (1), Not Subsiding (1)	1	0.05	-	2005 to Present	[1]Subsidence caused by oxidation of organic deposits has occurred	2	5	Medium to High
5-4	BIG VALLEY		Sacramento River	NRO	92,050	143.8	34,129	35,000	610	1,046	Medium	Not Analyzed	16	19	84%	13	4	High	>50% GWL at or Below Historical Low	No	0	-	-	No	-	-		Yes (1)	Subsiding	1	0.02	-	2007 to Present		1	5	Medium to High
6-46	FREMONT VALLEY		South Lahontan	SRO	336,682	526.1	0	4,584	203	16,883	Low	Not Analyzed	11	27	41%	5	3	Medium-High	30 to 50% GWL at or Below Historical Low	Yes[1]	1	Various (CWF, 2014 and Sneed and others, 2003)	Various (CWF, 2014 and Sneed and others, 2003)	No	-	-		Yes (1)	Subsiding	1	0.02	-	2005 to Present	[1]Subsidence has been documented in adjacement groundwater basin (Antelope Valley)	2	5	Medium to High
7-10	TWENTYNINE PALMS VALLEY		Colorado River	SRD	62,829	98.2	13	4,026	154	22,113	Low	Evidence of Overdraft	16	28	57%	29	4	High	>50% GWL at or Below Historical Low	No	0	-	-	No	-	-		Yes (1)	Subsiding	1	0.02	-	2004 to Present		1	5	Medium to High

1-10	EEL RIVER VALLEY		North Coast	NRO	73,701	115.2	33,309	55,000	763	21,558	Medium	Not Analyzed	3	8	38%	7	3	Medium-High	30 to 50% GWL at or Below Historical Low	No	0	-	-	No	-	-		Yes (2)	Subsiding (2)	1	0.05	-	2005 to Present		1	4	Medium to Low
1-2.01	KLAMATH RIVER VALLEY	TULELAKE	North Coast	NRO	85,934	134.3	56,139	75,000	164	2,261	Medium	Not Analyzed	4	4	100%	3	4	High	>50% GWL at or Below Historical Low	No	0	-	-	No	-	-		No	-		-	-	-		0	4	Medium to Low
1-3	BUTTE VALLEY		North Coast	NRO	79,689	124.5	29,324	72,403	417	1,464	Medium	Not Analyzed	16	19	84%	15	4	High	>50% GWL at or Below Historical Low	No	0	-	-	No	-	-		No	-		-	-	-		0	4	Medium to Low
1-4	SHASTA VALLEY	SHASTA VALLEY	North Coast	NRO	52,589	82.2	26,842	55,000	750	5,333	Medium	Not Analyzed	4	8	50%	10	4	High	>50% GWL at or Below Historical Low	No	0	-	-	No	-	-		No	-		-	-	-		0	4	Medium to Low
1-5	SCOTT RIVER VALLEY		North Coast	NRO	63,780	99.7	34,540	50,285	885	3,520	Medium	Not Analyzed	4	5	80%	5	4	High	>50% GWL at or Below Historical Low	No	0	-	-	No	-	-		No	-		-	-	-		0	4	Medium to Low
1-53	SANEL VALLEY		North Coast	NCRO	5,568	8.7	2,258	1,247	104	698	Very Low	Not Analyzed	1	1	100%	11	4	High	>50% GWL at or Below Historical Low	No	0	-	-	No	-	-		No	-		-	-	-		0	4	Medium to Low
1-54.01	ALEXANDER VALLEY	ALEXANDER AREA	North Coast	NCRO	24,464	38.2	9,636	642	1,099	2,098	Very Low	Not Analyzed	4	6	67%	16	4	High	>50% GWL at or Below Historical Low	No	0	-	-	No	-	-		No	-		-	-	-		0	4	Medium to Low
1-54.02	ALEXANDER VALLEY	CLOVERDALE AREA	North Coast	NCRO	6,525	10.2	2,339	759	592	8,297	Very Low	Not Analyzed	1	2	50%	20	4	High	>50% GWL at or Below Historical Low	No	0	-	-	No	-	-		No	-		-	-	-		0	4	Medium to Low
1-55.01	SANTA ROSA VALLEY	SANTA ROSA PLAIN	North Coast	NCRO	80,059	125.1	17,727	13,698	10,983	250,375	Medium	Not Analyzed	9	22	41%	18	3	Medium-High	30 to 50% GWL at or Below Historical Low	No	0	-	-	No	-	-		Yes (1)	Subsiding	1	0.02	-	2005 to Present		1	4	Medium to Low
1-55.02	SANTA ROSA VALLEY	HEALDSBURG AREA	North Coast	NCRO	15,400	24.1	7,973	3,281	1,383	10,515	Very Low	Not Analyzed	2	4	50%	17	4	High	>50% GWL at or Below Historical Low	No	0	-	-	No	-	-		No	-		-	-	-		0	4	Medium to Low
1-55.03	SANTA ROSA VALLEY	RINCON VALLEY	North Coast	NCRO	5,549	8.7	67	577	919	21,787	Very Low	Not Analyzed	1	2	50%	23	4	High	>50% GWL at or Below Historical Low	No	0	-	-	No	-	-		No	-		-	-	-		0	4	Medium to Low
1-59	WILSON GROVE FORMATION HIGHLANDS		North Coast	NCRO	86,400	135.0	10,404	3,417	8,422	37,799	Very Low	Not Analyzed	7	9	78%	7	4	High	>50% GWL at or Below Historical Low	No	0	-	-	No	-	-		No	-		-	-	-		0	4	Medium to Low
2-1	PETALUMA VALLEY		San Francisco Bay	NCRO	46,043	71.9	9,270	2,689	1,870	49,915	Medium	Not Analyzed	7	15	47%	21	3	Medium-High	30 to 50% GWL at or Below Historical Low	No	0	-	-	No	-	-		Yes (1)	Subsiding	1	0.07	-	2004 to Present		1	4	Medium to Low
2-24	SAN GREGORIO VALLEY		San Francisco Bay	NCRO	1,074	1.7	247	0	14	66	Very Low	Not Analyzed	1	1	100%	60	4	High	>50% GWL at or Below Historical Low	No	0	-	-	No	-	-		No	-		-	-	-		0	4	Medium to Low
4-1	UPPER OJAI VALLEY		South Coast	SRO	3,815	6.0	1,043	13	7	616	Very Low	Not Analyzed	1	2	50%	34	4	High	>50% GWL at or Below Historical Low	No	0	-	-	No	-	-		No	-		-	-	-		0	4	Medium to Low
4-2	OJAI VALLEY		South Coast	SRO	6,851	10.7	2,614	5,873	50	8,268	Medium	Not Analyzed	1	1	100%	9	4	High	>50% GWL at or Below Historical Low	No	0	-	-	No	-	-		No	-		-	-	-		0	4	Medium to Low
5-1.01	GOOSE LAKE	GOOSE VALLEY	Sacramento River	NRO	35,966	56.2	14,360	8,512	86	57	Very Low	Not Analyzed	10	10	100%	18	4	High	>50% GWL at or Below Historical Low	No	0	-	-	No	-	-		No	-		-	-	-		0	4	Medium to Low
5-1.02	GOOSE LAKE	FANDANGO VALLEY	Sacramento River	NRO	18,439	28.8	6,830	4,025	73	124	Very Low	Not Analyzed	2	3	67%	10	4	High	>50% GWL at or Below Historical Low	No	0	-	-	No	-	-		No	-		-	-	-		0	4	Medium to Low
5-11	MOHAWK VALLEY		Sacramento River	NRO	18,987	29.7	1,469	607	344	1,375	Very Low	Not Analyzed	1	1	100%	3	4	High	>50% GWL at or Below Historical Low	No	0	-	-	No	-	-		No	-		-	-	-		0	4	Medium to Low
5-12.01	SIERRA VALLEY	SIERRA VALLEY	Sacramento River	NRO	117,680	183.9	81,465	68,188	561	2,196	Medium	Special Problems	29	38	76%	21	4	High	>50% GWL at or Below Historical Low	No	0	-	-	No	-	-		No	-		-	-	-		0	4	Medium to Low
5-12.02	SIERRA VALLEY	CHILCOOT	Sacramento River	NRO	7,551	11.8	2,059	300	125	308	Very Low	Not Analyzed	4	8	50%	68	4	High	>50% GWL at or Below Historical Low	No	0	-	-	No	-	-		No	-		-	-	-		0	4	Medium to Low
5-2.01	ALTURAS AREA	SOUTH FORK PITT RIVER	Sacramento River	NRO	114,164	178.4	35,874	13,260	714	4,429	Low	Not Analyzed	7	12	58%	7	4	High	>50% GWL at or Below Historical Low	No	0	-	-	No	-	-		No	-		-	-	-		0	4	Medium to Low
5-2.02	ALTURAS AREA	WARM SPRINGS VALLEY	Sacramento River	NRO	68,009	106.3	15,365	8,097	257	964	Low	Not Analyzed	4	7	57%	7	4	High	>50% GWL at or Below Historical Low	No	0	-	-	No	-	-		No	-		-	-	-		0	4	Medium to Low
5-21.54	SACRAMENTO VALLEY	ANTELOPE	Sacramento River	NRO	18,696	29.2	8,770	20,000	979	6,124	Medium	Not Analyzed	10	13	77%	45	4	High	>50% GWL at or Below Historical Low	No	0	-	-	No	-	-		No	-		-	-	-		0	4	Medium to Low
5-21.56	SACRAMENTO VALLEY	LOS MOLINOS	Sacramento River	NRO	33,148	51.8	6,204	5,000	489	2,220	Medium	Not Analyzed	2	3	67%	6	4	High	>50% GWL at or Below Historical Low	No	0	-	-	No	-	-		No	-		-	-	-		0	4	Medium to Low
5-21.58	SACRAMENTO VALLEY	WEST BUTTE	Sacramento River	NRO	181,479	283.6	116,582	150,000	3,660	36,152	High	Not Analyzed	19	28	68%	10	4	High	>50% GWL at or Below Historical Low	No	0	-	-	Yes (1)	2005 to Present	Not Subsiding	0	No	-		-	-	-		0	4	Medium to Low
5-21.59	SACRAMENTO VALLEY	EAST BUTTE	Sacramento River	NRO	265,312	414.6	144,305	186,000	4,436	38,465	Medium	Not Analyzed	16	48	33%	12	3	Medium-High	30 to 50% GWL at or Below Historical Low	No	0	-	-	Yes (2)	2005 to Present	Not Subsiding (2), 0.010)	1	No	-		-	-	-		1	4	Medium to Low
5-21.60	SACRAMENTO VALLEY	NORTH YUBA	Sacramento River	NCRO	103,152	161.2	53,387	70,000	1,334	14,667	Medium	Not Analyzed	4	8	50%	5	4	High	>50% GWL at or Below Historical Low	No	0	-	-	No	-	-		No	-		-	-	-		0	4	Medium to Low
5-22.03	SAN JOAQUIN VALLEY	TURLOCK	San Joaquin River	SCRO	347,146	542.4	250,852	450,000	9,758	197,605	High	Not Analyzed	130	196	66%	36	4	High	>50% GWL at or Below Historical Low	No	0	-	-	No	-	-		No	-		-	-	-		0	4	Medium to Low
5-22.16	SAN JOAQUIN VALLEY	COSUMNES	San Joaquin River	NCRO	280,490	438.3	82,534	155,475	5,539	59,163	Medium	Not Analyzed	17	38	45%	9	3	Medium-High	30 to 50% GWL at or Below Historical Low	No	0	-	-	No	-	-		Yes (1)	Subsiding	1	0.07	-	2006 to Present		1	4	Medium to Low
5-25	KERN RIVER VALLEY		Tulare Lake	SCRO	79,678	124.5	2,391	8,068	843	10,364	Very Low	Not Analyzed	6	10	60%	8	4	High	>50% GWL at or Below Historical Low	No	0	-	-	No	-	-		Yes (2)	Not Subsiding (2)	0	-	0.02	2004 to Present		0	4	Medium to Low
5-26	WALKER BASIN CREEK VALLEY		Tulare Lake	SCRO	7,693	12.0	348	3	134	249	Very Low	Not Analyzed	3	5	60%	42	4	High	>50% GWL at or Below Historical Low	No	0	-	-	No	-	-		No	-		-	-	-		0	4	Medium to Low
5-36	ROUND VALLEY		Sacramento River	NRO	7,266	11.4	2,981	2,811	33	27	Very Low	Not Analyzed	2	2	100%	18	4	High	>50% GWL at or Below Historical Low	No	0	-	-	No	-	-		No	-		-	-	-		0	4	Medium to Low
5-5	FALL RIVER VALLEY		Sacramento River	NRO	54,803	85.6	31,850	22,722	659	1,629	Low	Not Analyzed	13	15	87%	18	4	High	>50% GWL at or Below Historical Low	No	0	-	-	No	-	-		No	-		-	-	-		0	4	Medium to Low
5-6.05	REDDING AREA	MILLVILLE	Sacramento River	NRO	65,226	101.9	6,548	6,842	807	2,640	Very Low	Not Analyzed	2	4	50%	4	4	High	>50% GWL at or Below Historical Low	No	0	-	-	No	-	-		No	-		-	-	-		0	4	Medium to Low
6-100	SECRET VALLEY		North Lahontan	NRO	33,680	52.6	2,813	5,406	31	26	Very Low	Not Analyzed	1	2	50%	4	4	High	>50% GWL at or Below Historical Low	No	0	-	-	No	-	-		No	-		-	-	-		0	4	Medium to Low
6-104	LONG VALLEY		North Lahontan	NRO	46,836	73.2	1,085	423	128	141	Very Low	Special Problems	17	26	65%	36	4	High	>50% GWL at or Below Historical Low	No	0	-	-	No	-	-		No	-		-	-	-		0	4	Medium to Low
6-3	WILLOW CREEK VALLEY		North Lahontan	NRO	11,698	18.3	4,946	6,914	48	62	Very Low	Not Analyzed	3	5	60%	27	4	High	>50% GWL at or Below Historical Low	No	0	-	-	No	-	-		No	-		-	-	-		0	4	Medium to Low
6-38	CAVES CANYON VALLEY		South Lahontan	SRO	73,542	114.9	0	0	2	88	Very Low	Not Analyzed	3	4	75%	3	4	High	>50% GWL at or Below Historical Low	No	0	-	-	No	-	-		No	-		-	-	-		0	4	Medium to Low
6-67	MARTIS VALLEY		North Lahontan	NCRO	36,381	56.8	0	9,300	686	14,743	Medium	Not Analyzed	14	24	58%	42	4	High	>50% GWL at or Below Historical Low	No	0	-	-	No	-	-		No	-		-	-	-		0	4	Medium to Low
7-13.01	DEADMAN LAKE	DEADMAN LAKE	Colorado River	SRO	89,793	140.3	0	4	12	22	Very Low	Not Analyzed	18	32	56%	23	4	High	>50% GWL at or Below Historical Low	No	0	-	-	No	-	-		No	-		-	-	-		0	4	Medium to Low
7-13.02	DEADMAN VALLEY	SURPRISE SPRING	Colorado River	SRO	29,507	46.1	0	31	0	179	Very Low	Not Analyzed	23	27	85%	59	4	High	>50% GWL at or Below Historical Low	No	0	-	-	No	-	-		Yes (1)	Not Subsiding	0	-	0.03	2004 to Present			4	Medium to Low
7-16	AMES VALLEY		Colorado River	SRO	109,340	170.8	0	713	26	4,540	Very Low	Not Analyzed	24	26	92%	15	4	High	>50% GWL at or Below Historical Low	No	0	-	-	No	-	-		Yes (2)	Not Subsiding	0	-	0.05	2004 to Present		0	4	Medium to Low
7-17	MEANS VALLEY		Colorado River	SRO	15,061	23.5	0	26	0	46	Very Low	Not Analyzed	1	1	100%	4	4	High	>50% GWL at or Below Historical Low	No	0	-	-	No	-	-		No	-		-	-	-		0	4	Medium to Low
7-18.01	JOHNSON VALLEY	SOGGY LAKE	Colorado River	SRO	77,865	121.7	0	248	4	354	Very Low	Not Analyzed	7	14	50%	12	4	High	>50% GWL at or Below Historical Low	No[1]	0	-	-	No	-	-		No	-		-	-	-	[1]Subsidence has been documented in adjacement groundwater basin (Lucerne Valley)	0	4	Medium to Low
7-21.04	COACHELLA VALLEY	SAN GORGONIO PASS	Colorado River	SRO	38,823	60.7	138	15,909	31	29,540	Medium	Evidence of Overdraft	1	2	50%	3	4	High	>50% GWL at or Below Historical Low	No	0	-	-	No	-	-		No	-		-	-	-		0	4	Medium to Low
7-29	COYOTE WELLS VALLEY		Colorado River	SRO	147,088	229.8	0	92	5	374	Very Low	Not Analyzed	7	14	50%	6	4	High	>50% GWL at or Below Historical Low	No	0	-	-	No	-	-		No	-		-	-	-		0	4	Medium to Low
7-62	JOSHUA TREE		Colorado River	SRO	27,422	42.8	0	773	29	4,951	Very Low	Not Analyzed	15	17	88%	40	4	High	>50% GWL at or Below Historical Low	No	0	-	-	No	-	-		No	-		-	-	-		0	4	Medium to Low
8-2.06	UPPER SANTA ANA VALLEY	BUNKER HILL	South Coast	SRO	80,972	126.5	3,257	32,550	1,247	363,394	High	Not Analyzed	14	20	70%	16	4	High	>50% GWL at or Below Historical Low	No[1]	0	-	-	No	-	-		Yes (1)	Not Subsiding	0	-	-	2005 to Present	[1]Subsidence has been documented in adjacement groundwater basin (Yucaipa)	0	4	Medium to Low
9-6	CAHUILLA VALLEY		South Coast	SRO	18,342	28.7	1,849	2,115	406	1,993	Medium	Not Analyzed	1	2	50%	7	4	High	>50% GWL at or Below Historical Low	No	0	-	-	No	-	-		No	-		-	-	-		0	4	Medium to Low
1-52	UKIAH VALLEY		North Coast	NCRO	37,508	58.6	9,361	7,500	1,689	32,761	Medium	Not Analyzed	1	3	33%	5	3	Medium-High	30 to 50% GWL at or Below Historical Low	No	0	-	-	No	-	-		Yes (1)	Not Subsiding	0	-	-	2005 to Present		0	3	Medium to Low
2-2.01	NAPA-SONOMA VALLEY	NAPA VALLEY	San Francisco Bay	NCRO	45,895	71.7	20,510	20,000	3,960	91,234	Medium	Not Analyzed	3	9	33%	13	3	Medium-High	30 to 50% GWL at or Below Historical Low	No	0	-	-	No	-	-		No	-		-	-	-		0	3	Medium to Low
2-3	SUISUN-FAIRFIELD VALLEY		San Francisco Bay	NCRO	133,505	208.6	11,899	6,655	1,613	136,754	Very Low	Not Analyzed	5	15	33%	7	3	Medium-High	30 to 50% GWL at or Below Historical Low	No	0	-	-	No	-	-		No	-		-	-	-		0	3	Medium to Low
4-11.04	COASTAL PLAIN OF LOS ANGELES	CENTRAL	South Coast	SRO	180,357	281.8	0	197,387	6,752	3,052,303	High	Not Analyzed	0	0	0%	0	0	Insufficient Data	Insufficient Data	Yes[1]	1	April 1998-May 1999 Bawden and others, 2001, 2003		0.07 (CWF, 2014)	No	-	-		Yes (11)	Subsiding (6), Not Subsiding (5)	2	0.10	0.05	2004 to Present	[1]Subsidence has been documented in adjacement groundwater basins (Coastal Plain of Orange County, West Coast)	3	3	Medium to Low
4-12	SAN FERNANDO VALLEY		South Coast	SRO	145,354	227.1	0	108,500	1,909	1,745,338	Medium	Not Analyzed	4	12	33%	5	3	Medium-High	30 to 50% GWL at or Below Historical Low	No	0	-	-	No	-	-		Yes (3)	Not Subsiding (3)	0	-	0.08	2004 to Present		0	3	Medium to Low
4-8	LAS POSAS VALLEY		South Coast	SRO	42,353	66.2	23,416	38,000	600	39,835	High	Critical Overdraft	0	6	0%	9	1	Low	<10% GWL at or Below Historical Low	Yes[1]	1	1939-2003 (CWF, 2014)		5.0 (Hanson, 2003)	No	-	-		Yes (2)	Subsiding (2)	1	0.08	-	2004 to Present	[1]Subsidence has been documented in adjacement groundwater basin (Oxnard)	2	3	Medium to Low
5-18	COYOTE VALLEY		Sacramento River	NRO	6,528	10.2	700	2,464	138	2,252	Very Low	Not Analyzed	2	5	40%	49	3	Medium-High	30 to 50% GWL at or Below Historical Low	No	0	-	-	No	-	-		No	-		-	-	-		0	3	Medium to Low
6-1	SURPRISE VALLEY		North Lahontan	NRO	228,460	357.0	49,199	33,307	557	1,127	Low	Special Problems	21	44	48%	12	3	Medium-High	30 to 50% GWL at or Below Historical Low	No	0	-	-	No	-	-		No	-		-	-	-		0	3	Medium to Low
6-4	HONEY LAKE VALLEY		North Lahontan	NRO	311,741	487.1	42,746	50,721	2,661	23,566	Low	Not Analyzed	19	52	37%	11	3	Medium-High	30 to 50% GWL at or Below Historical Low	No	0	-	-	No	-	-		No	-		-	-	-		0	3	Medium to Low
6-41	MIDDLE MOJAVE RIVER VALLEY		South Lahontan	SRO	212,595	332.2	685	30,000	15	6,654	Low	Evidence of Overdraft	9	40	23%	12	2	Low-Medium	10 to 30% GWL at or Below Historical Low	No[1]	0	-	-	No	-	-		Yes (1)	Subsiding	1	0.02	-	2004 to Present	[1]Subsidence has been documented in adjacement groundwater basins (Harper Valley, Lower Mojave River Valley)	1	3	Medium to Low
8-2.07	UPPER SANTA ANA VALLEY	YUCAIPA	South Coast	SRO	25,410	39.7	1,272	8,270	220	65,180	Medium	Not Analyzed	1	6	17%	15	2	Low-Medium	10 to 30% GWL at or Below Historical Low	Yes	1	1950's		See CWF, 2014	No	-	-		Yes (1)	Not Subsiding	0	-	0.05	2011 to Present		1	3	Medium to Low
1-1	SMITH RIVER PLAIN		North Coast	NRO	40,446	63.2	8,383	10,000	1,462	24,588	Medium	Not Analyzed	1	6	17%	9	2	Low-Medium	10 to 30% GWL at or Below Historical Low	No	0	-	-	No	-	-		Yes (1)	Not Subsiding	0	-	0.05	2004 to Present		0	2	Low
1-13	LITTLE LAKE VALLEY		North Coast	NRO	10,018	15.7	4,190	2,000	629	5,993	Very Low	Not Analyzed	1	5	20%	32	2	Low-Medium	10 to 30% GWL at or Below Historical Low	No	0	-	-	No	-	-		No	-		-	-	-		0	2	Low
1-27	BIG LAGOON AREA		North Coast	NRO	13,343	20.8	6	313	138	2,465	Very Low	Not Analyzed	0	1	0%	5	1	Low	<10% GWL at or Below Historical Low	No	0	-	-	No	-	-		Yes (1)	Subsiding	1	0.03	-	2004 to Present		1	2	Low
1-9	EUREKA PLAIN		North Coast	NRO	37,405	58.4	6,811	4,600	878	50,231	Very Low	Not Analyzed	0	4	0%	7	1	Low	<10% GWL at or Below Historical Low	No	0	-	-	No	-	-		Yes (1)	Subsiding	1	0.08	-	2004 to Present		1	2	Low
2-22	HALF MOON BAY TERRACE		San Francisco Bay	NCRO	9,189	14.4	1,739	603	1,031	19,825	Very Low	Not Analyzed	1	5	20%	35	2	Low-Medium	10 to 30% GWL at or Below Historical Low	No	0	-	-	No	-	-		No	-		-	-	-		0	2	Low
2-9.01	SANTA CLARA VALLEY	NILES CONE	San Francisco Bay	NCRO	57,906	90.5	914	29,600	6,051	321,494	Medium	Evidence of Overdraft	0	0	0%	0	0	Insufficient Data	Insufficient Data	Yes[1]	1	1920's - 1969 (CWF, 2014)		See (CWF, 2014)	No	-	-		Yes (1)	Subsiding	1	0.07	-	2004 to Present	[1]Subsidence has been documented in adjacement groundwater basin (Pleasant Valley)	2	2	Low
2-9.02	SANTA CLARA VALLEY	SANTA CLARA	San Francisco Bay	NCRO	190,235	297.2	3	150,000	46,423	1,633,190	Medium	Not Analyzed	0	0	0%	0	0	Insufficient Data	Insufficient Data	Yes	1	1920's - 1969 (CWF, 2014)		14.0 (CWF, 2014)	Yes (2)	1960 to Present	Unknown	0	Yes (2)	Subsiding (2)	1	0.08	-	2005 to Present		2	2	Low
2-9.03	SANTA CLARA VALLEY	SAN MATEO PLAIN	San Francisco Bay	NCRO	37,708	58.9	97	1,987	2,611	291,899	Very Low	Not Analyzed	0	0	0%	0	0	Insufficient Data	Insufficient Data	Yes	1	1920's - 1969 (CWF, 2014)		See (CWF, 2014)	-	-	-		Yes (1)	Subsiding	1	0.02	-	2004 to Present		2	2	Low
3-14	SAN ANTONIO CREEK VALLEY		Central Coast	SRO	81,941	128.0	11,614	16,000	362	2,279	Medium	Evidence of Overdraft	0	0	0%	0	0	Insufficient Data	Insufficient Data	No	0	-	-	-	No	-	-		Yes (1)	Subsiding	2	0.20	-	2004 to Present		2	2	Low
3-3.01	GILROY-HOLLISTER VALLEY	LLAGAS AREA	Central Coast	SCRO	55,967	87.4	36,140	44,000	5,537	91,706	High	Evidence of Overdraft	0	0	0%	0	0	Insufficient Data	Insufficient Data	Yes	1	See CWF, 2014		See CWF, 2014	No	-	-		Yes (3)	Not Subsiding (2), Subsiding (1)	1	0.02	0.03	2005 to Present		2	2	Low
4-11.03	COASTAL PLAIN OF LOS ANGELES	WEST COAST	South Coast	SRO	93,795	146.6	0	43,920	4,221	1,195,195	Medium	Not Analyzed	0	0	0%	0	0	Insufficient Data	Insufficient Data	Yes[1]	1	Various (CWF, 2014)		Various (CWF, 2014)	No	-	-		Yes (5)	Not Subsiding (4), Subsiding (1)	1	0.03	0.07	2004 to Present	[1]Subsidence has been documented in adjacement groundwater basin (Coastal Plain of Los Angeles)	2	2	Low
4-4.03	SANTA CLARA RIVER VALLEY	MOUND	South Coast	SRO	14,846	23.2	3,487	7,330	126	77,886	Medium	Critical Overdraft	0	0	0%	0	0	Insufficient Data	Insufficient Data	No[1]	0	-	-	-	No	-	-		Yes (1)	Subsiding	2	0.16	-	2004 to Present	[1]Subsidence has been documented in adjacement groundwater basin (Oxnard)	2	2	Low
4-4.05	SANTA CLARA RIVER VALLEY	FILLMORE	South Coast	SRO	20,842	32.6	12,720	44,350	56	16,417	Medium	Critical Overdraft	0	3	0%	9	1	Low	<10% GWL at or Below Historical Low	No	0	-	-	-	No	-	-		Yes (1)	Subsiding	1	0.03	-	2004 to Present		1	2	Low
4-6	PLEASANT VALLEY		South Coast	SRO	21,654	33.8	17,309	18,000	71	69,392	High	Critical Overdraft	0	1	0%	3	1	Low	<10% GWL at or Below Historical Low	Yes[1]	1	See CWF, 2014		See CWF, 2014	No	-	-		No	-		-	-	-	[1]Subsidence has been documented in adjacement groundwater basin (Oxnard)	1	2	Low
5-13	UPPER LAKE VALLEY		Sacramento River	NRO	7,260	11.3	2,880	5,400	367	2,055	Very Low	Not Analyzed	1	9	11%	79	2	Low-Medium	10 to 30% GWL at or Below Historical Low	No	0	-	-	No	-	-		No	-		-	-	-		0	2	Low
5-14	SCOTTS VALLEY		Sacramento River	NRO	7,320	11.4	1,525	5,124	647	6,553	Medium	Evidence of Overdraft	1	4	25%	35	2	Low-Medium	10 to 30% GWL at or Below Historical Low	No	0	-	-	No	-	-		No	-		-	-	-		0	2	Low
5-15	BIG VALLEY		Sacramento River	NRO	24,212	37.8	6,800	12,832	1,091	6,344	Medium	Not Analyzed	7	61	11%	161	2	Low-Medium	10 to 30% GWL at or Below Historical Low	No	0	-	-	No	-	-		No	-		-	-	-		0	2	Low
5-21.55	SACRAMENTO VALLEY	DYE CREEK	Sacramento River	NRO	27,709	43.3	6,097	39,000	371	1,626	Medium	Not Analyzed	2	8	25%	18	2	Low-Medium	10 to 30% GWL at or Below Historical Low	No	0	-	-	No	-	-		No	-		-	-	-		0	2	Low
5-21.62	SACRAMENTO VALLEY	SUTTER	Sacramento River	NCRO	234,264	366.0	187,530	175,300	5,999	82,125	Medium	Not Analyzed	4	20	20%	5	2	Low-Medium	10 to 30% GWL at or Below Historical Low	No	0	-	-	No	-	-		No	-		-	-	-		0	2	Low
5-23	PANOCHE VALLEY		Tulare Lake	SCRO	33,090	51.7	122	200	26	41	Very Low	Not Analyzed	4	34	12%	66	2	Low-Medium	10 to 30% GWL at or Below Historical Low	No	0	-	-	No	-	-		No	-		-	-	-		0	2	Low
5-6.01	REDDING AREA	BOWMAN	Sacramento River	NRO	78,426	122.5	3,384	16,500	1,498	7,165	Medium	Not Analyzed	1	6	17%	5	2	Low-Medium	10 to 30% GWL at or Below Historical Low	No	0	-	-	No	-	-		No	-		-	-	-		0	2	Low

5-6.03	REDDING AREA	ANDERSON	Sacramento River	NRO	96,857	151.3	12,473	63,572	3,430	52,937	Medium	Not Analyzed	1	8	13%	5	2	Low-Medium	10 to 30% GWL at or Below Historical Low	No	0	-	-	No	-	-		No	-			-	-	-		0	2	Low
6-12	OWENS VALLEY		South Lahontan	SRD	663,458	1,036.7	25,560	140,000	1,279	17,664	Medium	Special Problems	3	28	11%	3	2	Low-Medium	10 to 30% GWL at or Below Historical Low	No	0	-	-	No	-	-		No	-			-	-	-		0	2	Low
7-11	COPPER MOUNTAIN VALLEY		Colorado River	SRD	30,540	47.7	11	561	4	6,085	Very Low	Not Analyzed	1	4	25%	8	2	Low-Medium	10 to 30% GWL at or Below Historical Low	No	0	-	-	No	-	-		No	-			-	-	-		0	2	Low
7-12	WARREN VALLEY		Colorado River	SRD	23,952	37.4	0	3,180	3	22,860	Medium	Evidence of Overdraft	4	27	15%	72	2	Low-Medium	10 to 30% GWL at or Below Historical Low	No	0	-	-	No	-	-		Yes (1)	Not Subsiding	0		-	-	2004 to Present		0	2	Low
7-30	IMPERIAL VALLEY		Colorado River	SRD	969,017	1,514.1	621,898	0	111	164,037	Very Low	Not Analyzed	3	3	100%	0	0	Insufficient Data	Insufficient Data	No	0	-	-	No	-	-		Yes (17)	Not Subsiding (13), Subsiding (4)	2	0.33	0.23	2004 to Present		2	2	Low
8-2.08	UPPER SANTA ANA VALLEY	SAN TIMOTEO	South Coast	SRD	73,541	114.9	1,155	6,310	460	54,169	Medium	Not Analyzed	0	4	0%	3	1	Low	<10% GWL at or Below Historical Low	Yes[1]	1	Various (CWF, 2014)	Various (CWF, 2014)	No	-	-		No	-			-	-	-	[1]subsidence has been documented in adjacement groundwater basin (Yucaipa)	1	2	Low
1-11	COVELO ROUND VALLEY		North Coast	NRO	16,396	25.6	8,561	918	305	1,968	Very Low	Not Analyzed	0	6	0%	23	1	Low	<10% GWL at or Below Historical Low	No	0	-	-	No	-	-		No	-			-	-	-		0	1	Low
1-12	LAYTONVILLE VALLEY		North Coast	NRO	5,020	7.8	1,329	415	170	1,167	Very Low	Not Analyzed	0	4	0%	51	1	Low	<10% GWL at or Below Historical Low	No	0	-	-	No	-	-		No	-			-	-	-		0	1	Low
1-14	LOWER KLAMATH RIVER VALLEY		North Coast	NRO	7,026	11.0	428	450	48	806	Very Low	Not Analyzed	0	1	0%	9	1	Low	<10% GWL at or Below Historical Low	No	0	-	-	No	-	-		No	-			-	-	-		0	1	Low
1-15	HAPPY CAMP TOWN AREA		North Coast	NRO	2,771	4.3	1	450	30	759	Very Low	Not Analyzed	0	0	0%	0	0	Insufficient Data	Insufficient Data	No	0	-	-	No	-	-		Yes (1)	Subsiding	1	0.02	-	2007 to Present		1	1	Low
1-21	FORT BRAGG TERRACE AREA		North Coast	NCRO	24,085	37.6	1,240	447	1,997	12,517	Very Low	Not Analyzed	0	0	0%	0	0	Insufficient Data	Insufficient Data	No	0	-	-	No	-	-		Yes (1)	Subsiding	1	0.05	-	2006 to Present		1	1	Low
1-26	REDWOOD CREEK AREA		North Coast	NRO	1,996	3.1	676	739	9	234	Very Low	Not Analyzed	0	1	0%	32	1	Low	<10% GWL at or Below Historical Low	No	0	-	-	No	-	-		No	-			-	-	-		0	1	Low
1-57	BODEGA BAY AREA		North Coast	NCRO	2,676	4.2	0	410	58	719	Very Low	Not Analyzed	0	0	0%	0	0	Insufficient Data	Insufficient Data	No	0	-	-	No	-	-		Yes (1)	Subsiding	1	0.05	-	2006 to Present		1	1	Low
1-6	HAYFORK VALLEY		North Coast	NRO	3,295	5.1	337	1,019	67	814	Very Low	Not Analyzed	0	0	0%	0	0	Insufficient Data	Insufficient Data	No	0	-	-	No	-	-		Yes (1)	Subsiding	1	0.03	-	2005 to Present		1	1	Low
1-61	FORT ROSS TERRACE DEPOSITS		North Coast	NCRO	8,483	13.3	0	37	176	1,075	Very Low	Not Analyzed	0	0	0%	0	0	Insufficient Data	Insufficient Data	No	0	-	-	No	-	-		Yes (1)	Subsiding	1	0.03	-	2006 to Present		1	1	Low
1-8.01	MAD RIVER VALLEY	MAD RIVER LOWLAND	North Coast	NRO	13,981	21.8	1,162	6,400	375	14,204	Very Low	Not Analyzed	0	0	0%	0	0	Insufficient Data	Insufficient Data	No	0	-	-	No	-	-		Yes (1)	Subsiding	1	0.02	-	2005 to Present		1	1	Low
1-8.02	MAD RIVER VALLEY	DOWS PRAIRIE SCHOOL AREA	North Coast	NRO	25,570	40.0	8,347	2,200	555	23,086	Very Low	Not Analyzed	0	4	0%	10	1	Low	<10% GWL at or Below Historical Low	No	0	-	-	No	-	-		No	-			-	-	-		0	1	Low
2-10	LIVERMORE VALLEY		San Francisco Bay	NCRO	69,531	108.6	6,347	5,692	4,632	196,658	Medium	Not Analyzed	0	4	0%	4	1	Low	<10% GWL at or Below Historical Low	No	0	-	-	No	-	-		Yes (1)	Not Subsiding	0		-	-	2005 to Present		0	1	Low
2-19	KENWOOD VALLEY		San Francisco Bay	NCRO	5,135	8.0	1,093	136	424	6,057	Very Low	Not Analyzed	0	2	0%	25	1	Low	<10% GWL at or Below Historical Low	No	0	-	-	No	-	-		No	-			-	-	-		0	1	Low
2-5	CLAYTON VALLEY		San Francisco Bay	NCRO	17,836	27.9	29	189	828	73,287	Very Low	Not Analyzed	0	4	0%	14	1	Low	<10% GWL at or Below Historical Low	No	0	-	-	No	-	-		No	-			-	-	-		0	1	Low
2-9.04	SANTA CLARA VALLEY	EAST BAY PLAIN	San Francisco Bay	NCRO	77,292	120.8	68	3,350	9,892	881,718	Medium	Evidence of Overdraft	0	0	0%	0	0	Insufficient Data	Insufficient Data	No[1]	0	-	-	Yes (2)	2008 to Present	Not Subsiding	0	Yes (3)	Subsiding (2), Not Subsiding (1)	1	0.05	-	2005 to Present	[1]subsidence has been documented in adjacement groundwater basin (Niles Cone)	1	1	Low
3-2	PAJARO VALLEY		Central Coast	SCRO	88,062	137.6	29,650	67,000	3,523	114,282	High	Critical Overdraft	0	0	0%	0	0	Insufficient Data	Insufficient Data	No	0	-	-	No	-	-		Yes (3)	Subsiding (2), Not Subsiding (1)	1	0.02	0.02	2005 to Present		1	1	Low
3-3.02	GILROY-HOLLISTER VALLEY	BOLSA AREA	Central Coast	SCRO	20,912	32.7	13,051	2,200	229	2,935	Medium	Not Analyzed	0	0	0%	0	0	Insufficient Data	Insufficient Data	No	0	-	-	No	-	-		Yes (1)	Subsiding	1	0.07	-	2004 to Present		1	1	Low
3-36	SANTA ROSA VALLEY		Central Coast	SRO	3,525	5.5	1,196	5,900	0	920	Very Low	Not Analyzed	0	0	0%	0	0	Insufficient Data	Insufficient Data	Yes	1	1976-1977	Unknown	No	-	-		No	-			-	-	-		1	1	Low
3-4.05	SALINAS VALLEY	UPPER VALLEY AQUIFER	Central Coast	SCRO	98,164	153.4	51,574	125,000	525	15,862	Medium	Evidence of Overdraft	0	0	0%	0	0	Insufficient Data	Insufficient Data	No	0	-	-	No	-	-		Yes (2)	Subsiding (1), Not Subsiding (1)	1	0.03	-	2006 to Present		1	1	Low
3-9	SAN LUIS OBISPO VALLEY		Central Coast	SCRO	12,724	19.9	5,211	5,000	0	18,834	Medium	Not Analyzed	0	0	0%	0	0	Insufficient Data	Insufficient Data	Yes	1	1989-1991 (CWF, 2014)	1.0 (CWF, 2014)	No	-	-		No	-			-	-	-		1	1	Low
4-11.01	COASTAL PLAIN OF LOS ANGELES	SANTA MONICA	South Coast	SRO	31,846	49.8	0	3,500	1,586	465,606	Medium	Not Analyzed	0	0	0%	0	0	Insufficient Data	Insufficient Data	Yes	1	See CWF, 2014	See, CWF, 2014	No	-	-		Yes (1)	Not Subsiding	0		-	0.03	2011 to Present		1	1	Low
4-15	TIERRA REJADA		South Coast	SRO	4,611	7.2	1,598	77	3	3,673	Very Low	Not Analyzed	0	0	0%	0	0	Insufficient Data	Insufficient Data	No	0	-	-	No	-	-		Yes (1)	Subsiding	1	0.08	-	2004 to Present		1	1	Low
4-3.01	VENTURA RIVER VALLEY	UPPER VENTURA RIVER	South Coast	SRO	7,430	11.6	1,125	4,000	20	15,961	Medium	Not Analyzed	0	2	0%	17	1	Low	<10% GWL at or Below Historical Low	No	0	-	-	No	-	-		No	-			-	-	-		0	1	Low
4-7	ARROYO SANTA ROSA VALLEY		South Coast	SRO	3,747	5.9	2,368	4,246	6	2,211	Medium	Critical Overdraft	0	1	0%	17	1	Low	<10% GWL at or Below Historical Low	No[1]	0	-	-	No	-	-		No	-			-	-	-	[1]subsidence has been documented in adjacement groundwater basin	0	1	Low
4-9	SIMI VALLEY		South Coast	SRO	12,192	19.0	96	2,069	10	98,625	Low	Not Analyzed	0	1	0%	5	1	Low	<10% GWL at or Below Historical Low	No	0	-	-	No	-	-		No	-			-	-	-		0	1	Low
5-16	HIGH VALLEY		Sacramento River	NRO	2,356	3.7	490	94	32	34	Very Low	Not Analyzed	0	5	0%	136	1	Low	<10% GWL at or Below Historical Low	No	0	-	-	No	-	-		No	-			-	-	-		0	1	Low
5-17	BURNS VALLEY		Sacramento River	NRO	2,873	4.5	81	160	151	2,691	Very Low	Not Analyzed	0	1	0%	22	1	Low	<10% GWL at or Below Historical Low	No	0	-	-	No	-	-		No	-			-	-	-		0	1	Low
5-19	COLLAYOMI VALLEY		Sacramento River	NRO	6,497	10.2	240	649	178	1,513	Very Low	Not Analyzed	1	11	9%	108	1	Low	<10% GWL at or Below Historical Low	No	0	-	-	No	-	-		No	-			-	-	-		0	1	Low
5-21.61	SACRAMENTO VALLEY	SOUTH YUBA	Sacramento River	NCRO	104,486	163.3	47,048	17,206	2,086	45,014	Medium	Not Analyzed	0	15	0%	9	1	Low	<10% GWL at or Below Historical Low	No	0	-	-	No	-	-		No	-			-	-	-		0	1	Low
5-27	CUMMINGS VALLEY		Tulare Lake	SCRO	10,051	15.7	2,925	3,000	171	7,665	High	Not Analyzed	0	1	0%	6	1	Low	<10% GWL at or Below Historical Low	No	0	-	-	No	-	-		No	-			-	-	-		0	1	Low
5-6.04	REDDING AREA	ENTERPRISE	Sacramento River	NRO	60,862	95.1	7,010	8,576	2,768	68,627	Medium	Not Analyzed	1	11	9%	12	1	Low	<10% GWL at or Below Historical Low	No	0	-	-	No	-	-		No	-			-	-	-		0	1	Low
5-7	LAKE ALMANOR VALLEY		Sacramento River	NRO	7,152	11.2	247	810	49	2,121	Very Low	Not Analyzed	0	4	0%	36	1	Low	<10% GWL at or Below Historical Low	No	0	-	-	No	-	-		No	-			-	-	-		0	1	Low
6-5.01	TAHOE VALLEY	TAHOE SOUTH	North Lahontan	NCRO	14,814	23.1	0	10,000	680	25,967	Medium	Not Analyzed	0	6	0%	26	1	Low	<10% GWL at or Below Historical Low	No	0	-	-	No	-	-		No	-			-	-	-		0	1	Low
6-54	INDIAN WELLS VALLEY		South Lahontan	SRO	383,492	599.2	0	24,000	231	34,837	Medium	Evidence of Overdraft	0	0	0%	0	0	Insufficient Data	Insufficient Data	No[1]	0	-	-	No	-	-		Yes (1)	Subsiding	1	0.03	-	2004 to Present	[1]subsidence has been documented in adjacement groundwater basin (Antelope Valley)	1	1	Low
7-14	LAVIC VALLEY		Colorado River	SRO	103,132	161.1	0	0	12	0	Very Low	Not Analyzed	0	0	0%	0	0	Insufficient Data	Insufficient Data	No[1]	0	-	-	No	-	-		Yes (1)	Subsiding	1	0.02	-	-	[1]subsidence has been documented in adjacement groundwater basin (Lower Mojave River Valley)	1	1	Low
7-18.02	JOHNSON VALLEY	UPPER JOHNSON VALLEY	Colorado River	SRO	35,050	54.8	0	0	0	0	Very Low	Not Analyzed	0	1	0%	2	1	Low	<10% GWL at or Below Historical Low	No	0	-	-	No	-	-		No	-			-	-	-		0	1	Low
7-21.03	COACHELLA VALLEY	DESERT HOT SPRINGS	Colorado River	SRD	101,862	159.2	896	2,500	46	22,568	Low	Evidence of Overdraft	0	0	0%	0	0	Insufficient Data	Insufficient Data	No[1]	0	-	-	No	-	-		Yes (2)	Subsiding (1), Not Subsiding (1)	1	0.05	0.03	2012 to Present	[1]subsidence has been documented in adjacement groundwater basin (Indio)	1	1	Low
7-24	BORREGO VALLEY		Colorado River	SRD	153,978	240.6	4,041	20,000	446	3,853	Medium	Evidence of Overdraft	0	0	0%	0	0	Insufficient Data	Insufficient Data	No	0	-	-	No	-	-		Yes (2)	Subsiding (1), Not Subsiding (1)	1	0.08	0.07	2004 to Present		1	1	Low
7-26	TERWILLIGER VALLEY		Colorado River	SRD	8,081	12.6	229	2,000	188	1,085	Very Low	Not Analyzed	0	1	0%	8	1	Low	<10% GWL at or Below Historical Low	No	0	-	-	No	-	-		Yes (1)	Not Subsiding	0		-	0.02	2006 to Present		0	1	Low
7-31	OROCOPIA VALLEY		Colorado River	SRD	97,214	151.9	0	957	4	2,243	Very Low	Not Analyzed	0	0	0%	0	0	Insufficient Data	Insufficient Data	No	0	-	-	No	-	-		Yes (1)	Subsiding	1	0.02	-	2004 to Present		1	1	Low
7-42	VIDAL VALLEY		Colorado River	SRD	139,577	218.1	0	6	2	10	Very Low	Not Analyzed	0	0	0%	0	0	Insufficient Data	Insufficient Data	No	0	-	-	No	-	-		Yes (1)	Subsiding	1	0.02	-	2005 to Present		1	1	Low
7-44	NEEDLES VALLEY		Colorado River	SRD	89,101	139.2	3,470	2,500	207	4,902	Low	Evidence of Overdraft	0	0	0%	0	0	Insufficient Data	Insufficient Data	No	0	-	-	No	-	-		Yes (1)	Subsiding	1	0.02	-	2006 to Present		1	1	Low
8-2.02	UPPER SANTA ANA VALLEY	CUCAMONGA	South Coast	SRD	9,574	15.0	11	14,400	26	51,001	Medium	Not Analyzed	0	7	0%	47	1	Low	<10% GWL at or Below Historical Low	No[1]	0	-	-	No	-	-		No	-			-	-	-	[1]subsidence has been documented in adjacement groundwater basin	0	1	Low
8-2.09	UPPER SANTA ANA VALLEY	TEMESCAL	South Coast	SRD	23,654	37.0	831	22,024	445	141,436	Medium	Not Analyzed	0	0	0%	0	0	Insufficient Data	Insufficient Data	No[1]	0	-	-	No	-	-		Yes (1)	Subsiding	1	0.02	-	2004 to Present	[1]subsidence has been documented in adjacement groundwater basin (Chino)	1	1	Low
8-5	SAN JACINTO		South Coast	SRD	188,623	294.7	30,430	91,842	2,181	474,317	High	Evidence of Overdraft	0	0	0%	0	0	Insufficient Data	Insufficient Data	Yes	1	1950s to 1970's	2.34 (CWF, 2014)	No	-	-		No	-			-	-	-		1	1	Low
9-1	SAN JUAN VALLEY		South Coast	SRD	16,797	26.2	0	5,500	194	61,131	Low	Not Analyzed	0	0	0%	0	0	Insufficient Data	Insufficient Data	No	0	-	-	No	-	-		Yes (1)	Subsiding	1	0.03	-	2004 to Present		1	1	Low
1-16	SEIAD VALLEY		North Coast	NRO	2,243	3.5	50	21	7	132	Very Low	Not Analyzed	0	0	0%	0	0	Insufficient Data	Insufficient Data	No	0	-	-	No	-	-		No	-			-	-	-		0	0	Insufficient Data
1-17	BRAY TOWN AREA		North Coast	NRO	8,027	12.5	1,281	6	3	0	Very Low	Not Analyzed	0	0	0%	0	0	Insufficient Data	Insufficient Data	No	0	-	-	No	-	-		No	-			-	-	-		0	0	Insufficient Data
1-18	RED ROCK VALLEY		North Coast	NRO	8,996	14.1	5,355	14,109	30	23	Low	Not Analyzed	0	0	0%	0	0	Insufficient Data	Insufficient Data	No	0	-	-	No	-	-		No	-			-	-	-		0	0	Insufficient Data
1-19	ANDERSON VALLEY		North Coast	NCRO	4,969	7.8	1,094	225	393	1,297	Very Low	Not Analyzed	0	0	0%	0	0	Insufficient Data	Insufficient Data	No	0	-	-	No	-	-		No	-			-	-	-		0	0	Insufficient Data
1-2.02	KLAMATH RIVER VALLEY	LOWER KLAMATH	North Coast	NRO	75,333	117.7	18,926	21,424	17	41	Low	Not Analyzed	0	0	0%	0	0	Insufficient Data	Insufficient Data	No	0	-	-	No	-	-		No	-			-	-	-		0	0	Insufficient Data
1-20	GARCIA RIVER VALLEY		North Coast	NCRO	2,242	3.5	588	302	21	119	Very Low	Not Analyzed	0	0	0%	0	0	Insufficient Data	Insufficient Data	No	0	-	-	No	-	-		No	-			-	-	-		0	0	Insufficient Data
1-22	FAIRCHILD SWAMP VALLEY		North Coast	NRO	3,278	5.1	0	0	0	0	Very Low	Not Analyzed	0	0	0%	0	0	Insufficient Data	Insufficient Data	No	0	-	-	No	-	-		No	-			-	-	-		0	0	Insufficient Data
1-25	PRAIRIE CREEK AREA		North Coast	NRO	20,013	31.3	0	2	4	4	Very Low	Not Analyzed	0	0	0%	0	0	Insufficient Data	Insufficient Data	No	0	-	-	No	-	-		No	-			-	-	-		0	0	Insufficient Data
1-28	MATTOLE RIVER VALLEY		North Coast	NRO	3,150	4.9	0	150	8	72	Very Low	Not Analyzed	0	0	0%	0	0	Insufficient Data	Insufficient Data	No	0	-	-	No	-	-		No	-			-	-	-		0	0	Insufficient Data
1-29	HONEYDEW TOWN AREA		North Coast	NRO	2,369	3.7	0	1	3	19	Very Low	Not Analyzed	0	0	0%	0	0	Insufficient Data	Insufficient Data	No	0	-	-	No	-	-		No	-			-	-	-		0	0	Insufficient Data
1-30	PEPPERWOOD TOWN AREA		North Coast	NRO	6,288	9.8	1,010	1,000	15	315	Very Low	Not Analyzed	0	0	0%	0	0	Insufficient Data	Insufficient Data	No	0	-	-	No	-	-		No	-			-	-	-		0	0	Insufficient Data
1-31	WEOTT TOWN AREA		North Coast	NRO	3,653	5.7	154	135	11	364	Very Low	Not Analyzed	0	0	0%	0	0	Insufficient Data	Insufficient Data	No	0	-	-	No	-	-		No	-			-	-	-		0	0	Insufficient Data
1-32	GARBERVILLE TOWN AREA		North Coast	NRO	2,112	3.3	20	117	77	1,391	Very Low	Not Analyzed	0	0	0%	0	0	Insufficient Data	Insufficient Data	No	0	-	-	No	-	-		No	-			-	-	-		0	0	Insufficient Data
1-33	LARABEE VALLEY		North Coast	NRO	967	1.5	0	0	0	9	Very Low	Not Analyzed	0	0	0%	0	0	Insufficient Data	Insufficient Data	No	0	-	-	No	-	-		No	-			-	-	-		0	0	Insufficient Data
1-34	DINSMORES TOWN AREA		North Coast	NRO	2,276	3.6	8	125	9	183	Very Low	Not Analyzed	0	0	0%	0	0	Insufficient Data	Insufficient Data	No	0	-	-	No	-	-		Yes (2)	Not Subsiding (2)	0		-	0.02	2008 to Present		0	0	Insufficient Data
1-35	HYAMPOM VALLEY		North Coast	NRO	1,354	2.1	72	201	12	52	Very Low	Not Analyzed	0	0	0%	0	0	Insufficient Data	Insufficient Data	No	0	-	-	No	-	-		No	-			-	-	-		0	0	Insufficient Data
1-36	HETTENSHAW VALLEY		North Coast	NRO	846	1.3	680	1	6	5	Very Low	Not Analyzed	0	0	0%	0	0	Insufficient Data	Insufficient Data	No	0	-	-	No	-	-		No	-			-	-	-		0	0	Insufficient Data
1-37	COTTONEVA CREEK VALLEY		North Coast	NCRO	763	1.2	0	0	3	1	Very Low	Not Analyzed	0	0	0%	0	0	Insufficient Data	Insufficient Data	No	0	-	-	No	-	-		No	-			-	-	-		0	0	Insufficient Data
1-38	LOWER LAYTONVILLE VALLEY		North Coast	NCRO	2,152	3.4	150	2	32	107	Very Low	Not Analyzed	0	0	0%	0	0	Insufficient Data	Insufficient Data	No	0	-	-	No	-	-		No	-			-	-	-		0	0	Insufficient Data
1-39	BRANSCOMB TOWN AREA		North Coast	NCRO	1,381	2.2	23	1	22	95	Very Low	Not Analyzed	0	0	0%	0	0	Insufficient Data	Insufficient Data	No	0	-	-	No	-	-		No	-			-	-	-		0	0	Insufficient Data
1-40	TEN MILE RIVER VALLEY		North Coast	NCRO	1,491	2.3	0	0	46	61	Very Low	Not Analyzed	0	0	0%	0	0	Insufficient Data	Insufficient Data	No	0	-	-	No	-	-		No	-			-	-	-		0	0	Insufficient Data
1-41	LITTLE VALLEY		North Coast	NCRO	812	1.3	36	0	3	11	Very Low	Not Analyzed	0	0	0%	0	0	Insufficient Data	Insufficient Data	No	0	-	-	No	-	-		No	-			-	-	-		0	0	Insufficient Data
1-42	SHERWOOD VALLEY		North Coast	NCRO	1,150	1.8	0	0	7	13	Very Low	Not Analyzed	0	0	0%	0	0	Insufficient Data	Insufficient Data	No	0	-	-	No	-	-		No	-			-	-	-		0	0	Insufficient Data
1-43	WILLIAMS VALLEY		North Coast	NCRO	1,642	2.6	128	0	16	2	Very Low	Not Analyzed	0	0	0%	0	0	Insufficient Data	Insufficient Data	No	0	-	-	No	-	-		No	-			-	-	-		0	0	Insufficient Data
1-44	EDEN VALLEY		North Coast	NCRO	1,376	2.2	381	600	0	0	Very Low	Not Analyzed	0	0	0%	0	0	Insufficient Data	Insufficient Data	No	0	-	-	No	-	-		No	-			-	-	-		0	0	Insufficient Data
1-45	BIG RIVER VALLEY		North Coast	NCRO	1,685	2.6	0	0	7	29	Very Low	Not Analyzed	0	0	0%	0	0	Insufficient Data	Insufficient Data	No	0	-	-	No	-	-		No	-			-	-	-		0	0	Insufficient Data
1-46	NAVARRO RIVER VALLEY		North Coast	NCRO	770	1.2	0	0	5	36	Very Low	Not Analyzed	0	0	0%	0	0	Insufficient Data	Insufficient Data	No	0	-	-	No	-	-		No	-			-	-	-		0	0	Insufficient Data
1-48	GRAVELLY VALLEY		North Coast	NRO	2,974	4.6	0	3	18	6	Very Low	Not Analyzed	0	0	0%	0	0	Insufficient Data	Insufficient Data	No	0	-	-	No	-	-		No	-			-	-	-		0	0	Insufficient Data
1-49	ANNAPOLIS OHLSON RANCH FM HIGHLANDS		North Coast	NCRO	8,646	13.5	138	3	76	233	Very Low	Not Analyzed	0	0	0%	0	0	Insufficient Data	Insufficient Data	No	0	-	-	No	-	-		No	-			-	-	-		0	0	Insufficient Data
1-50	KNIGHTS VALLEY		North Coast	NCRO	4,086	6.4	1,727	502	62	102	Very Low	Not Analyzed	0	0	0%	0	0	Insufficient Data	Insufficient Data	No	0	-	-	No	-	-		No	-			-	-	-		0	0	Insufficient Data
1-56	McDOWELL VALLEY		North Coast	NCRO	1,486	2.3	664	307	48	106	Very Low	Not Analyzed	0	0	0%	0	0	Insufficient Data	Insufficient Data	No	0	-	-	No	-	-		No	-			-	-	-		0	0	Insufficient Data
1-60	LOWER RUSSIAN RIVER VALLEY		North Coast	NCRO	6,640	10.4	1,219	106	188	3,754	Very Low	Not Analyzed	0	0	0%	0	0	Insufficient Data	Insufficient Data	No	0	-	-	No	-	-		No	-			-	-	-		0	0	Insufficient Data
1-62	WILSON POINT AREA		North Coast	NRO	709	1.1	36	100	0	14	Very Low	Not Analyzed	0	0	0%	0	0	Insufficient Data	Insufficient Data	No	0	-	-	No	-	-		No	-			-	-	-		0	0	Insufficient Data
1-7	HOOPA VALLEY		North Coast	NRO	3,894	6.1	302	338	42	1,797	Very Low	Not Analyzed	0	0	0%	0	0	Insufficient Data	Insufficient Data	No	0	-	-	No	-	-		No	-			-	-	-		0	0	Insufficient Data
2-11	SUNOL VALLEY		San Francisco Bay	NCRO	16,623	26.0	405	509	213	808	Very Low	Not Analyzed	0	0	0%	0	0	Insufficient Data	Insufficient Data	No	0	-	-	No	-	-		No	-			-	-	-		0	0	Insufficient Data
2-2.03	NAPA-SONOMA VALLEY	NAPA-SONOMA LOWLANDS	San Francisco Bay	NCRO	40,455	63.2	5,159	1,062	1,127	58,367	Very Low	Not Analyzed	0	0	0%	0	0	Insufficient Data	Insufficient Data	No	0	-	-	No	-	-		No	-			-	-	-		0	0	Insufficient Data
2-26	PESCADERO VALLEY		San Francisco Bay	NCRO	2,904	4.5	473	0	76	571	Very Low	Special Problems	0	0	0%	0	0	Insufficient Data	Insufficient Data	No	0	-	-	No	-	-		No	-			-	-	-		0	0	Insufficient Data
2-27	SAND POINT AREA		San Francisco Bay	NCRO	1,405	2.2	0	2	2	43	Very Low	Not Analyzed	0	0	0%	0	0	Insufficient Data	Insufficient Data	No	0	-	-	No	-	-		No	-			-	-	-		0	0	Insufficient Data
2-28	ROSS VALLEY		San Francisco Bay	NCRO	1,763	2.8	6	0	36	7,194	Very Low	Not Analyzed	0	0	0%	0	0	Insufficient Data	Insufficient Data	No	0	-	-	No	-	-		No	-			-	-	-		0	0	Insufficient Data
2-29	SAN RAFAEL VALLEY		San Francisco Bay	NCRO	874	1.4	0	0	155	10,153	Very Low	Not Analyzed	0	0	0%	0	0	Insufficient Data	Insufficient Data	No	0	-	-	No	-	-		No	-			-	-	-		0	0	Insufficient Data
2-30	NOVATO VALLEY		San Francisco Bay	NCRO	20,519	32.1	3,642	2,700	844	42,516	Very Low	Not Analyzed	0	0	0%	0	0	Insufficient Data	Insufficient Data	No	0	-	-	No	-	-		No	-			-	-	-		0	0	Insufficient Data
2-31	ARROYO DEL HAMBRE VALL

2-6	YGNACIO VALLEY		San Francisco Bay	NCRO	15,459	24.2	6	131	3,607	107,878	Very Low	Not Analyzed	0	0	0%	0	0	Insufficient Data	Insufficient Data	No	0	-	-	No	-	-		No	-			-	-	-		0	0	Insufficient Data
2-7	SAN RAMON VALLEY		San Francisco Bay	NCRO	7,053	11.0	26	33	351	30,112	Very Low	Not Analyzed	0	0	0%	0	0	Insufficient Data	Insufficient Data	No	0	-	-	No	-	-		No	-			-	-	-		0	0	Insufficient Data
2-8	CASTRO VALLEY		San Francisco Bay	NCRO	1,821	2.8	0	39	244	24,486	Very Low	Not Analyzed	0	0	0%	0	0	Insufficient Data	Insufficient Data	No	0	-	-	No	-	-		No	-			-	-	-		0	0	Insufficient Data
3-1	SOQUEL VALLEY		Central Coast	SCRO	2,515	3.9	26	6,890	172	18,634	High	Critical Overdraft	0	0	0%	0	0	Insufficient Data	Insufficient Data	No	0	-	-	No	-	-		No	-			-	-	-		0	0	Insufficient Data
3-12	SANTA MARIA		Central Coast	SRO	184,248	287.9	115,386	138,510	1,234	201,759	High	Evidence of Overdraft	0	0	0%	0	0	Insufficient Data	Insufficient Data	No	0	-	-	No	-	-		Yes (1)	Not Subsiding	0		-	-	2007 to Present		0	0	Insufficient Data
3-15	SANTA YNEZ RIVER VALLEY		Central Coast	SRO	204,642	319.8	38,242	77,114	1,854	75,460	Medium	Evidence of Overdraft	0	0	0%	0	0	Insufficient Data	Insufficient Data	No	0	-	-	No	-	-		No	-			-	-	-		0	0	Insufficient Data
3-16	GOLETA		Central Coast	SRO	9,229	14.4	1,083	3,000	366	47,252	Medium	Evidence of Overdraft	0	0	0%	0	0	Insufficient Data	Insufficient Data	No	0	-	-	No	-	-		No	-			-	-	-		0	0	Insufficient Data
3-17	SANTA BARBARA		Central Coast	SRO	6,173	9.6	23	1,162	425	63,966	Very Low	Not Analyzed	0	0	0%	0	0	Insufficient Data	Insufficient Data	No	0	-	-	No	-	-		No	-			-	-	-		0	0	Insufficient Data
3-18	CARPINTERIA		Central Coast	SRO	8,140	12.7	4,565	1,387	98	14,561	Very Low	Not Analyzed	0	0	0%	0	0	Insufficient Data	Insufficient Data	No	0	-	-	No	-	-		No	-			-	-	-		0	0	Insufficient Data
3-19	CARRIZO PLAIN		Central Coast	SRO	210,896	329.5	18,500	91	18	440	Very Low	Not Analyzed	0	0	0%	0	0	Insufficient Data	Insufficient Data	No	0	-	-	No	-	-		Yes (2)	Not Subsiding (2)	0		-	0.03	2006 to Present		0	0	Insufficient Data
3-20	ANO NUEVO AREA		Central Coast	SCRO	2,030	3.2	399	100	12	46	Very Low	Not Analyzed	0	0	0%	0	0	Insufficient Data	Insufficient Data	No	0	-	-	No	-	-		No	-			-	-	-		0	0	Insufficient Data
3-21	SANTA CRUZ PURISIMA FORMATION		Central Coast	SCRO	40,166	62.8	531	15,000	1,399	17,693	Medium	Critical Overdraft	0	0	0%	0	0	Insufficient Data	Insufficient Data	No	0	-	-	No	-	-		No	-			-	-	-		0	0	Insufficient Data
3-22	SANTA ANA VALLEY		Central Coast	SCRO	2,724	4.3	1,486	1,623	25	76	Very Low	Not Analyzed	0	0	0%	0	0	Insufficient Data	Insufficient Data	No	0	-	-	No	-	-		No	-			-	-	-		0	0	Insufficient Data
3-23	UPPER SANTA ANA VALLEY		Central Coast	SCRO	1,431	2.2	0	2	0	5	Very Low	Not Analyzed	0	0	0%	0	0	Insufficient Data	Insufficient Data	No	0	-	-	No	-	-		No	-			-	-	-		0	0	Insufficient Data
3-24	QUIEN SABE VALLEY		Central Coast	SCRO	4,706	7.4	1,342	1	0	5	Very Low	Not Analyzed	0	0	0%	0	0	Insufficient Data	Insufficient Data	No	0	-	-	No	-	-		No	-			-	-	-		0	0	Insufficient Data
3-25	TRES PINOS VALLEY		Central Coast	SCRO	3,385	5.3	1,519	1,806	34	48	Very Low	Not Analyzed	0	0	0%	0	0	Insufficient Data	Insufficient Data	No	0	-	-	No	-	-		No	-			-	-	-		0	0	Insufficient Data
3-26	WEST SANTA CRUZ TERRACE		Central Coast	SCRO	7,863	12.3	221	4,036	419	70,336	Medium	Critical Overdraft	0	0	0%	0	0	Insufficient Data	Insufficient Data	No	0	-	-	No	-	-		No	-			-	-	-		0	0	Insufficient Data
3-27	SCOTTS VALLEY		Central Coast	SCRO	773	1.2	0	285	337	3,875	Very Low	Not Analyzed	0	0	0%	0	0	Insufficient Data	Insufficient Data	No	0	-	-	No	-	-		No	-			-	-	-		0	0	Insufficient Data
3-28	SAN BENITO RIVER VALLEY		Central Coast	SCRO	24,223	37.8	795	946	46	101	Very Low	Not Analyzed	0	0	0%	0	0	Insufficient Data	Insufficient Data	No	0	-	-	No	-	-		Yes (1)	Not Subsiding	0		-	-	2006 to Present		0	0	Insufficient Data
3-29	DRY LAKE VALLEY		Central Coast	SCRO	1,416	2.2	125	201	0	8	Very Low	Not Analyzed	0	0	0%	0	0	Insufficient Data	Insufficient Data	No	0	-	-	No	-	-		No	-			-	-	-		0	0	Insufficient Data
3-3.03	GILROY-HOLLISTER VALLEY	HOLLISTER AREA	Central Coast	SCRO	32,729	51.1	14,342	14,299	731	22,013	Medium	Not Analyzed	0	0	0%	0	0	Insufficient Data	Insufficient Data	No	0	-	-	No	-	-		Yes (1)	Not Subsiding	0		-	0.02	2005 to Present		0	0	Insufficient Data
3-3.04	GILROY-HOLLISTER VALLEY	SAN JUAN BAUTISTA AREA	Central Coast	SCRO	74,305	116.1	11,313	13,530	790	26,150	Medium	Not Analyzed	0	0	0%	0	0	Insufficient Data	Insufficient Data	No	0	-	-	No	-	-		Yes (4)	Not Subsiding (4)	0		-	0.03	2005 to Present		0	0	Insufficient Data
3-30	BITTER WATER VALLEY		Central Coast	SCRO	32,222	50.3	2,557	3,023	18	38	Very Low	Not Analyzed	0	0	0%	0	0	Insufficient Data	Insufficient Data	No	0	-	-	No	-	-		No	-			-	-	-		0	0	Insufficient Data
3-31	HERNANDEZ VALLEY		Central Coast	SCRO	2,865	4.5	0	0	10	3	Very Low	Not Analyzed	0	0	0%	0	0	Insufficient Data	Insufficient Data	No	0	-	-	No	-	-		No	-			-	-	-		0	0	Insufficient Data
3-32	PEACH TREE VALLEY		Central Coast	SCRO	9,791	15.3	1,193	902	3	7	Very Low	Not Analyzed	0	0	0%	0	0	Insufficient Data	Insufficient Data	No	0	-	-	No	-	-		No	-			-	-	-		0	0	Insufficient Data
3-33	SAN CARPOFORO VALLEY		Central Coast	SRO	1,054	1.6	0	0	0	4	Very Low	Not Analyzed	0	0	0%	0	0	Insufficient Data	Insufficient Data	No	0	-	-	No	-	-		No	-			-	-	-		0	0	Insufficient Data
3-34	ARROYO DE LA CRUZ VALLEY		Central Coast	SRO	1,028	1.6	252	0	0	1	Very Low	Not Analyzed	0	0	0%	0	0	Insufficient Data	Insufficient Data	No	0	-	-	No	-	-		No	-			-	-	-		0	0	Insufficient Data
3-35	SAN SIMEON VALLEY		Central Coast	SRO	560	0.9	158	1,010	0	9	Very Low	Not Analyzed	0	0	0%	0	0	Insufficient Data	Insufficient Data	No	0	-	-	No	-	-		No	-			-	-	-		0	0	Insufficient Data
3-37	VILLA VALLEY		Central Coast	SRO	1,358	2.1	461	0	0	21	Very Low	Not Analyzed	0	0	0%	0	0	Insufficient Data	Insufficient Data	No	0	-	-	No	-	-		No	-			-	-	-		0	0	Insufficient Data
3-38	CAYUCOS VALLEY		Central Coast	SRO	336	0.5	15	0	0	3	Very Low	Not Analyzed	0	0	0%	0	0	Insufficient Data	Insufficient Data	No	0	-	-	No	-	-		No	-			-	-	-		0	0	Insufficient Data
3-39	OLD VALLEY		Central Coast	SRO	1,179	1.8	58	0	0	217	Very Low	Not Analyzed	0	0	0%	0	0	Insufficient Data	Insufficient Data	No	0	-	-	No	-	-		No	-			-	-	-		0	0	Insufficient Data
3-4.01	SALINAS VALLEY	180/400 FOOT AQUIFER	Central Coast	SCRO	84,321	131.8	57,746	130,000	2,443	55,740	High	Evidence of Overdraft	0	0	0%	0	0	Insufficient Data	Insufficient Data	No	0	-	-	No	-	-		No	-			-	-	-		0	0	Insufficient Data
3-4.02	SALINAS VALLEY	EAST SIDE AQUIFER	Central Coast	SCRO	57,452	89.8	35,445	86,000	1,587	128,646	High	Evidence of Overdraft	0	0	0%	0	0	Insufficient Data	Insufficient Data	No	0	-	-	No	-	-		No	-			-	-	-		0	0	Insufficient Data
3-4.04	SALINAS VALLEY	FOREBAY AQUIFER	Central Coast	SCRO	94,025	146.9	60,146	160,000	935	43,867	Medium	Evidence of Overdraft	0	0	0%	0	0	Insufficient Data	Insufficient Data	No	0	-	-	No	-	-		No	-			-	-	-		0	0	Insufficient Data
3-4.08	SALINAS VALLEY	SEASIDE AREA	Central Coast	SCRO	25,903	40.5	758	11,135	902	65,899	Medium	Evidence of Overdraft	0	0	0%	0	0	Insufficient Data	Insufficient Data	No	0	-	-	No	-	-		No	-			-	-	-		0	0	Insufficient Data
3-4.09	SALINAS VALLEY	LANGLEY AREA	Central Coast	SCRO	15,344	24.0	2,084	13,000	1,136	9,833	Medium	Evidence of Overdraft	0	0	0%	0	0	Insufficient Data	Insufficient Data	No	0	-	-	No	-	-		No	-			-	-	-		0	0	Insufficient Data
3-4.10	SALINAS VALLEY	CORRAL DE TIERRA AREA	Central Coast	SCRO	22,274	34.8	0	10,000	449	7,831	Medium	Evidence of Overdraft	0	0	0%	0	0	Insufficient Data	Insufficient Data	No	0	-	-	No	-	-		No	-			-	-	-		0	0	Insufficient Data
3-40	TORO VALLEY		Central Coast	SRO	722	1.1	166	0	0	8	Very Low	Not Analyzed	0	0	0%	0	0	Insufficient Data	Insufficient Data	No	0	-	-	No	-	-		No	-			-	-	-		0	0	Insufficient Data
3-41	MORRO VALLEY		Central Coast	SRO	646	1.0	749	0	0	399	Very Low	Not Analyzed	0	0	0%	0	0	Insufficient Data	Insufficient Data	No	0	-	-	No	-	-		No	-			-	-	-		0	0	Insufficient Data
3-42	CHORRO VALLEY		Central Coast	SRO	1,547	2.4	1,121	0	0	247	Very Low	Not Analyzed	0	0	0%	0	0	Insufficient Data	Insufficient Data	No	0	-	-	No	-	-		No	-			-	-	-		0	0	Insufficient Data
3-43	RINCONADA VALLEY		Central Coast	SRO	2,579	4.0	973	2	0	11	Very Low	Not Analyzed	0	0	0%	0	0	Insufficient Data	Insufficient Data	No	0	-	-	No	-	-		No	-			-	-	-		0	0	Insufficient Data
3-44	POZO VALLEY		Central Coast	SRO	6,852	10.7	504	11	0	52	Very Low	Not Analyzed	0	0	0%	0	0	Insufficient Data	Insufficient Data	No	0	-	-	No	-	-		No	-			-	-	-		0	0	Insufficient Data
3-45	HUASNA VALLEY		Central Coast	SRO	4,706	7.4	580	14	2	55	Very Low	Not Analyzed	0	0	0%	0	0	Insufficient Data	Insufficient Data	No	0	-	-	No	-	-		No	-			-	-	-		0	0	Insufficient Data
3-46	RAFAEL VALLEY		Central Coast	SRO	2,996	4.7	0	0	0	0	Very Low	Not Analyzed	0	0	0%	0	0	Insufficient Data	Insufficient Data	No	0	-	-	No	-	-		No	-			-	-	-		0	0	Insufficient Data
3-47	BIG SPRING AREA		Central Coast	SRO	7,332	11.5	1,435	0	0	0	Very Low	Not Analyzed	0	0	0%	0	0	Insufficient Data	Insufficient Data	No	0	-	-	No	-	-		No	-			-	-	-		0	0	Insufficient Data
3-49	MONTECITO		Central Coast	SRO	6,286	9.8	236	300	476	9,885	Very Low	Not Analyzed	0	0	0%	0	0	Insufficient Data	Insufficient Data	No	0	-	-	No	-	-		No	-			-	-	-		0	0	Insufficient Data
3-5	CHOLAME VALLEY		Central Coast	SCRO	39,847	62.3	3,541	5,011	32	48	Very Low	Not Analyzed	0	0	0%	0	0	Insufficient Data	Insufficient Data	No	0	-	-	No	-	-		Yes (6)	Not Subsiding (6)	0		-	0.03	2006 to Present		0	0	Insufficient Data
3-50	FELTON AREA		Central Coast	SCRO	1,155	1.8	0	165	41	3,024	Very Low	Not Analyzed	0	0	0%	0	0	Insufficient Data	Insufficient Data	No	0	-	-	No	-	-		No	-			-	-	-		0	0	Insufficient Data
3-51	MAJORS CREEK		Central Coast	SCRO	364	0.6	229	200	2	53	Very Low	Not Analyzed	0	0	0%	0	0	Insufficient Data	Insufficient Data	No	0	-	-	No	-	-		No	-			-	-	-		0	0	Insufficient Data
3-52	NEEDLE ROCK POINT		Central Coast	SCRO	479	0.7	283	200	33	66	Very Low	Not Analyzed	0	0	0%	0	0	Insufficient Data	Insufficient Data	No	0	-	-	No	-	-		No	-			-	-	-		0	0	Insufficient Data
3-53	FOOTHILL		Central Coast	SRO	3,123	4.9	1	1,255	129	17,543	Very Low	Not Analyzed	0	0	0%	0	0	Insufficient Data	Insufficient Data	No	0	-	-	No	-	-		No	-			-	-	-		0	0	Insufficient Data
3-6	LOCKWOOD VALLEY		Central Coast	SCRO	59,933	93.6	3,677	4,565	446	1,171	Very Low	Not Analyzed	0	0	0%	0	0	Insufficient Data	Insufficient Data	No	0	-	-	No	-	-		No	-			-	-	-		0	0	Insufficient Data
3-7	CARMEL VALLEY		Central Coast	SCRO	5,151	8.0	557	9,500	331	5,086	High	Not Analyzed	0	0	0%	0	0	Insufficient Data	Insufficient Data	No	0	-	-	No	-	-		No	-			-	-	-		0	0	Insufficient Data
3-8	LOS OSOS VALLEY		Central Coast	SCRO	6,994	10.9	2,215	2,100	0	13,948	High	Not Analyzed	0	0	0%	0	0	Insufficient Data	Insufficient Data	No[1]	0	-	-	No	-	-		Yes (1)	Not Subsiding	0		-	-	2006 to Present	[1]Subsidence has been documented in adjacement groundwater basin (San Luis Obispo Valley)	0	0	Insufficient Data
4-11.02	COASTAL PLAIN OF LOS ANGELES	HOLLYWOOD	South Coast	SRO	10,108	15.8	0	1,800	505	250,649	Very Low	Not Analyzed	0	0	0%	0	0	Insufficient Data	Insufficient Data	No[1]	0	-	-	No	-	-		No	-			-	-	-	[1]Subsidence has been documented in adjacement groundwater basin (Coastal Plain of Los Angeles)	0	0	Insufficient Data
4-16	HIDDEN VALLEY		South Coast	SRO	2,217	3.5	1,271	11	15	503	Very Low	Not Analyzed	0	0	0%	0	0	Insufficient Data	Insufficient Data	No	0	-	-	No	-	-		No	-			-	-	-		0	0	Insufficient Data
4-17	LOCKWOOD VALLEY		South Coast	SRO	21,841	34.1	0	3,500	35	241	Low	Not Analyzed	0	0	0%	0	0	Insufficient Data	Insufficient Data	No	0	-	-	No	-	-		Yes (1)	Not Subsiding	0		-	-	2011 to Present		0	0	Insufficient Data
4-18	HUNGRY VALLEY		South Coast	SRO	5,324	8.3	0	0	0	2	Very Low	Not Analyzed	0	0	0%	0	0	Insufficient Data	Insufficient Data	No	0	-	-	No	-	-		No	-			-	-	-		0	0	Insufficient Data
4-19	THOUSAND OAKS AREA		South Coast	SRO	3,115	4.9	0	242	41	17,202	Very Low	Not Analyzed	0	0	0%	0	0	Insufficient Data	Insufficient Data	No	0	-	-	No	-	-		No	-			-	-	-		0	0	Insufficient Data
4-20	RUSSELL VALLEY		South Coast	SRO	3,087	4.8	0	600	12	18,860	Very Low	Not Analyzed	0	0	0%	0	0	Insufficient Data	Insufficient Data	No	0	-	-	No	-	-		No	-			-	-	-		0	0	Insufficient Data
4-22	MALIBU VALLEY		South Coast	SRO	615	1.0	0	0	34	563	Very Low	Not Analyzed	0	0	0%	0	0	Insufficient Data	Insufficient Data	No	0	-	-	No	-	-		No	-			-	-	-		0	0	Insufficient Data
4-23	RAYMOND		South Coast	SRO	26,310	41.1	0	59,000	33	223,100	Medium	Not Analyzed	0	0	0%	0	0	Insufficient Data	Insufficient Data	No	0	-	-	No	-	-		Yes (1)	Not Subsiding	0		-	0.05	2011 to Present		0	0	Insufficient Data
4-3.02	VENTURA RIVER VALLEY	LOWER VENTURA RIVER PIRU	South Coast	SRO	5,312	8.3	379	331	45	15,920	Very Low	Not Analyzed	0	0	0%	0	0	Insufficient Data	Insufficient Data	No	0	-	-	No	-	-		No	-			-	-	-		0	0	Insufficient Data
4-4.06	SANTA CLARA RIVER VALLEY		South Coast	SRO	8,915	13.9	4,977	12,490	20	2,666	High	Critical Overdraft	0	0	0%	0	0	Insufficient Data	Insufficient Data	No	0	-	-	No	-	-		No	-			-	-	-		0	0	Insufficient Data
4-4.07	SANTA CLARA RIVER VALLEY	SANTA CLARA RIVER VALLEY EAST	South Coast	SRO	66,417	103.8	63	35,000	527	221,204	High	Not Analyzed	0	0	0%	0	0	Insufficient Data	Insufficient Data	No	0	-	-	No	-	-		Yes (1)	Not Subsiding	0		-	0.03	2006 to Present		0	0	Insufficient Data
4-5	ACTON VALLEY		South Coast	SRO	8,300	13.0	0	1,540	230	2,280	Very Low	Not Analyzed	0	0	0%	0	0	Insufficient Data	Insufficient Data	No	0	-	-	No	-	-		No	-			-	-	-		0	0	Insufficient Data
5-10	AMERICAN VALLEY		Sacramento River	NRO	6,799	10.6	2,802	1,501	348	3,931	Very Low	Not Analyzed	0	0	0%	0	0	Insufficient Data	Insufficient Data	No	0	-	-	No	-	-		No	-			-	-	-		0	0	Insufficient Data
5-20	BERRYESSA VALLEY		Sacramento River	NCRO	1,375	2.1	0	0	2	0	Very Low	Not Analyzed	0	0	0%	0	0	Insufficient Data	Insufficient Data	No	0	-	-	No	-	-		No	-			-	-	-		0	0	Insufficient Data
5-21.53	SACRAMENTO VALLEY	BEND	Sacramento River	NRO	21,748	34.0	649	1,008	227	554	Very Low	Not Analyzed	0	0	0%	0	0	Insufficient Data	Insufficient Data	No	0	-	-	No	-	-		No	-			-	-	-		0	0	Insufficient Data
5-21.68	SACRAMENTO VALLEY	CAPAY VALLEY	Sacramento River	NCRO	24,970	39.0	6,066	5,500	501	550	Low	Not Analyzed	0	0	0%	0	0	Insufficient Data	Insufficient Data	No	0	-	-	No	-	-		No	-			-	-	-		0	0	Insufficient Data
5-28	TEHACHAPI VALLEY WEST		Tulare Lake	SCRO	14,854	23.2	348	3,500	533	17,313	Medium	Not Analyzed	0	0	0%	0	0	Insufficient Data	Insufficient Data	No	0	-	-	No	-	-		No	-			-	-	-		0	0	Insufficient Data
5-29	CASTAC LAKE VALLEY		Tulare Lake	SCRO	3,573	5.6	19	87	8	366	Very Low	Not Analyzed	0	0	0%	0	0	Insufficient Data	Insufficient Data	No	0	-	-	No	-	-		No	-			-	-	-		0	0	Insufficient Data
5-3	JESS VALLEY		Sacramento River	NRO	6,708	10.5	3,947	3	4	13	Very Low	Not Analyzed	0	0	0%	0	0	Insufficient Data	Insufficient Data	No	0	-	-	No	-	-		No	-			-	-	-		0	0	Insufficient Data
5-30	LOWER LAKE VALLEY		Sacramento River	NRO	2,404	3.8	70	577	33	2,694	Very Low	Not Analyzed	0	0	0%	0	0	Insufficient Data	Insufficient Data	No	0	-	-	No	-	-		No	-			-	-	-		0	0	Insufficient Data
5-31	LONG VALLEY		Sacramento River	NRO	2,799	4.4	450	532	40	194	Very Low	Not Analyzed	0	0	0%	0	0	Insufficient Data	Insufficient Data	No	0	-	-	No	-	-		No	-			-	-	-		0	0	Insufficient Data
5-35	MCCLOUD AREA		Sacramento River	NRO	21,320	33.3	37	2,000	131	822	Very Low	Not Analyzed	0	0	0%	0	0	Insufficient Data	Insufficient Data	No	0	-	-	No	-	-		No	-			-	-	-		0	0	Insufficient Data
5-37	TOAD WELL AREA		Sacramento River	NRO	3,356	5.2	0	0	0	0	Very Low	Not Analyzed	0	0	0%	0	0	Insufficient Data	Insufficient Data	No	0	-	-	No	-	-		No	-			-	-	-		0	0	Insufficient Data
5-38	PONDOSA TOWN AREA		Sacramento River	NRO	2,082	3.3	305	0	0	0	Very Low	Not Analyzed	0	0	0%	0	0	Insufficient Data	Insufficient Data	No	0	-	-	No	-	-		No	-			-	-	-		0	0	Insufficient Data
5-40	HOT SPRINGS VALLEY		Sacramento River	NRO	2,404	3.8	1,036	300	11	12	Very Low	Not Analyzed	0	0	0%	0	0	Insufficient Data	Insufficient Data	No	0	-	-	No	-	-		No	-			-	-	-		0	0	Insufficient Data
5-41	EGG LAKE VALLEY		Sacramento River	NRO	4,101	6.4	0	0	2	0	Very Low	Not Analyzed	0	0	0%	0	0	Insufficient Data	Insufficient Data	No	0	-	-	No	-	-		No	-			-	-	-		0	0	Insufficient Data
5-43	ROCK PRAIRIE VALLEY		Sacramento River	NRO	5,740	9.0	0	0	0	0	Very Low	Not Analyzed	0	0	0%	0	0	Insufficient Data	Insufficient Data	No	0	-	-	No	-	-		No	-			-	-	-		0	0	Insufficient Data
5-44	LONG VALLEY		Sacramento River	NRO	1,088	1.7	0	0	0	0	Very Low	Not Analyzed	0	0	0%	0	0	Insufficient Data	Insufficient Data	No	0	-	-	No	-	-		No	-			-	-	-		0	0	Insufficient Data
5-45	CAYTON VALLEY		Sacramento River	NRO	1,306	2.0	1,100	5	10	2	Very Low	Not Analyzed	0	0	0%	0	0	Insufficient Data	Insufficient Data	No	0	-	-	No	-	-		No	-			-	-	-		0	0	Insufficient Data
5-46	LAKE BRITTON AREA		Sacramento River	NRO	14,055	22.0	55	43	30	84	Very Low	Not Analyzed	0	0	0%	0	0	Insufficient Data	Insufficient Data	No	0	-	-	No	-	-		No	-			-	-	-		0	0	Insufficient Data
5-47	GOOSE VALLEY		Sacramento River	NRO	4,208	6.6	3,269	405	7	10	Very Low	Not Analyzed	0	0	0%	0	0	Insufficient Data	Insufficient Data	No	0	-	-	No	-	-		No	-			-	-	-		0	0	Insufficient Data
5-48	BURNEY CREEK VALLEY		Sacramento River	NRO	2,352	3.7	1,690	849	25	1,466	Very Low	Not Analyzed	0	0	0%	0	0	Insufficient Data	Insufficient Data	No	0	-	-	No	-	-		No	-			-	-	-		0	0	Insufficient Data
5-49	DRY BURNEY CREEK VALLEY		Sacramento River	NRO	3,074	4.8	0	0	0	0	Very Low	Not Analyzed	0	0	0%	0	0	Insufficient Data	Insufficient Data	No	0	-	-	No	-	-		No	-			-	-	-		0	0	Insufficient Data
5-50	NORTH FORK BATTLE CREEK		Sacramento River	NRO	12,755	19.9	997	3	312	528	Very Low	Not Analyzed	0	0	0%	0	0	Insufficient Data	Insufficient Data	No	0	-	-	No	-	-		No	-			-	-	-		0	0	Insufficient Data
5-51	BUTTE CREEK VALLEY		Sacramento River	NRO	3,227	5.0	155	0	2	0	Very Low	Not Analyzed	0	0	0%	0	0	Insufficient Data	Insufficient Data	No	0	-	-	No	-	-		No	-			-	-	-		0	0	Insufficient Data
5-52	GRAYS VALLEY		Sacramento River	NRO	5,440	8.5	0	0	0	0	Very Low	Not Analyzed	0	0	0%	0	0	Insufficient Data	Insufficient Data	No	0	-	-	No	-	-		No	-			-	-	-		0	0	Insufficient Data
5-53	DIXIE VALLEY		Sacramento River	NRO	4,866	7.6	2,796	0	0	6	Very Low	Not Analyzed	0	0	0%	0	0	Insufficient Data	Insufficient Data	No	0	-	-	No	-	-		No	-			-	-	-		0	0	Insufficient Data
5-54	ASH VALLEY		Sacramento River	NRO	6,008	9.4	945	2	11	3	Very Low	Not Analyzed	0	0	0%	0	0	Insufficient Data	Insufficient Data	No	0	-	-	No	-	-		No	-			-	-	-		0	0	Insufficient Data
5-56	YELLOW CREEK VALLEY		Sacramento River	NRO	2,311	3.6	1,377	1	0	2	Very Low	Not Analyzed	0	0	0%	0	0	Insufficient Data	Insufficient Data	No	0	-	-	No	-	-		No	-			-	-	-		0	0	Insufficient Data
5-57	LAST CHANCE CREEK VALLEY		Sacramento River	NRO	4,659	7.3	0	0	0	0	Very Low	Not Analyzed	0	0	0%	0	0	Insufficient Data	Insufficient Data	No	0	-	-	No	-	-		No	-			-	-	-		0	0	Insufficient Data
5-58	CLOVER VALLEY		Sacramento River	NRO	16,784	26.2	7,324	5	9	0	Very Low	Not Analyzed	0	0	0%	0	0	Insufficient Data	Insufficient Data	No	0	-	-	No	-	-		No	-			-	-	-		0	0	Insufficient Data
5-59	GRIZZLY VALLEY		Sacramento River	NRO	13,441	21.0	0	0	8	0	Very Low	Not Analyzed	0	0	0%	0	0	Insufficient Data	Insufficient Data	No	0	-	-	No	-	-		No	-			-	-	-		0	0	Insufficient Data
5-6.02	REDDING AREA	ROSEWOOD	Sacramento River	NRO	46,455	72.6	2,395	1,450	442	1,009	Very Low	Not Analyzed	1	1	100%	1	0	Insufficient Data	Insufficient Data	No	0	-	-	No	-	-		No	-			-	-	-		0	0	Insufficient Data
5-6.06	REDDING AREA	SOUTH BATTLE CREEK	Sacramento River	NRO	33,835	52.9	1,444	908	48	48	Very Low	Not

5-84	CUDDY VALLEY		Tulare Lake	SCRO	3,474	5.4	0	186	38	779	Very Low	Not Analyzed	0	0	0%	0	0	Insufficient Data	Insufficient Data	No	0	-	-	-	No	-	-		No	-		-	-	-		0	0	Insufficient Data
5-85	MIL POTRERO AREA		Tulare Lake	SCRO	2,314	3.6	0	307	13	1,288	Very Low	Not Analyzed	0	0	0%	0	0	Insufficient Data	Insufficient Data	No	0	-	-	-	No	-	-		No	-		-	-	-		0	0	Insufficient Data
5-86	JOSEPH CREEK		Sacramento River	NRO	4,458	7.0	1,074	1,103	22	13	Very Low	Not Analyzed	0	0	0%	0	0	Insufficient Data	Insufficient Data	No	0	-	-	-	No	-	-		No	-		-	-	-		0	0	Insufficient Data
5-87	MIDDLE FORK FEATHER RIVER		Sacramento River	NRO	4,342	6.8	132	68	101	177	Very Low	Not Analyzed	0	0	0%	0	0	Insufficient Data	Insufficient Data	No	0	-	-	-	No	-	-		No	-		-	-	-		0	0	Insufficient Data
5-88	STONY GORGE RESERVOIR		Sacramento River	NRO	1,065	1.7	310	10	0	0	Very Low	Not Analyzed	0	0	0%	0	0	Insufficient Data	Insufficient Data	No	0	-	-	-	No	-	-		No	-		-	-	-		0	0	Insufficient Data
5-89	SQUAW FLAT		Sacramento River	NRO	1,294	2.0	0	0	0	0	Very Low	Not Analyzed	0	0	0%	0	0	Insufficient Data	Insufficient Data	No	0	-	-	-	No	-	-		No	-		-	-	-		0	0	Insufficient Data
5-9	INDIAN VALLEY		Sacramento River	NRO	29,413	46.0	11,535	100	487	1,718	Very Low	Not Analyzed	0	0	0%	0	0	Insufficient Data	Insufficient Data	No	0	-	-	-	No	-	-		No	-		-	-	-		0	0	Insufficient Data
5-90	FUNKS CREEK		Sacramento River	NRO	3,012	4.7	109	0	4	0	Very Low	Not Analyzed	0	0	0%	0	0	Insufficient Data	Insufficient Data	No	0	-	-	-	No	-	-		No	-		-	-	-		0	0	Insufficient Data
5-91	ANTELOPE CREEK		Sacramento River	NRO	2,040	3.2	339	1	3	3	Very Low	Not Analyzed	0	0	0%	0	0	Insufficient Data	Insufficient Data	No	0	-	-	-	No	-	-		No	-		-	-	-		0	0	Insufficient Data
5-92	BLANCHARD VALLEY		Sacramento River	NRO	2,221	3.5	138	1	2	0	Very Low	Not Analyzed	0	0	0%	0	0	Insufficient Data	Insufficient Data	No	0	-	-	-	No	-	-		No	-		-	-	-		0	0	Insufficient Data
5-93	NORTH FORK CACHE CREEK		Sacramento River	NRO	3,474	5.4	0	0	1	0	Very Low	Not Analyzed	0	0	0%	0	0	Insufficient Data	Insufficient Data	No	0	-	-	-	No	-	-		No	-		-	-	-		0	0	Insufficient Data
5-94	MIDDLE CREEK		Sacramento River	NRO	705	1.1	96	402	16	10	Very Low	Not Analyzed	0	0	0%	0	0	Insufficient Data	Insufficient Data	No	0	-	-	-	No	-	-		No	-		-	-	-		0	0	Insufficient Data
5-95	MEADOW VALLEY		Sacramento River	NRO	5,734	9.0	344	148	176	387	Very Low	Not Analyzed	0	0	0%	0	0	Insufficient Data	Insufficient Data	No	0	-	-	-	No	-	-		No	-		-	-	-		0	0	Insufficient Data
6-10	ADOBE LAKE VALLEY		South Lahontan	SRO	39,978	62.5	0	200	2	4	Very Low	Not Analyzed	0	0	0%	0	0	Insufficient Data	Insufficient Data	No	0	-	-	-	No	-	-		No	-		-	-	-		0	0	Insufficient Data
6-103	BULL FLAT		North Lahontan	NRO	18,151	28.4	0	0	0	2	Very Low	Not Analyzed	0	0	0%	0	0	Insufficient Data	Insufficient Data	No	0	-	-	-	No	-	-		No	-		-	-	-		0	0	Insufficient Data
6-101	BULL FLAT		North Lahontan	NRO	18,151	28.4	0	0	0	2	Very Low	Not Analyzed	0	0	0%	0	0	Insufficient Data	Insufficient Data	No	0	-	-	-	No	-	-		No	-		-	-	-		0	0	Insufficient Data
6-105	SLINKARD VALLEY		North Lahontan	NCRO	4,517	7.1	0	0	0	0	Very Low	Not Analyzed	0	0	0%	0	0	Insufficient Data	Insufficient Data	No	0	-	-	-	No	-	-		No	-		-	-	-		0	0	Insufficient Data
6-106	LITTLE ANTELOPE VALLEY		North Lahontan	NCRO	2,491	3.9	658	0	3	0	Very Low	Not Analyzed	0	0	0%	0	0	Insufficient Data	Insufficient Data	No	0	-	-	-	No	-	-		No	-		-	-	-		0	0	Insufficient Data
6-107	SWEETWATER FLAT		North Lahontan	NCRO	4,747	7.4	89	0	0	0	Very Low	Not Analyzed	0	0	0%	0	0	Insufficient Data	Insufficient Data	No	0	-	-	-	No	-	-		No	-		-	-	-		0	0	Insufficient Data
6-108	OLYMPIC VALLEY		North Lahontan	NCRO	702	1.1	0	0	8	471	Very Low	Not Analyzed	0	0	0%	0	0	Insufficient Data	Insufficient Data	No	0	-	-	-	No	-	-		No	-		-	-	-		0	0	Insufficient Data
6-11	LONG VALLEY		South Lahontan	SRO	72,028	112.5	6,898	87	20	800	Very Low	Not Analyzed	0	0	0%	0	0	Insufficient Data	Insufficient Data	No	0	-	-	-	Yes (1)	Not Subsiding	0	-	-	0.07	2006 to Present			0	0	Insufficient Data
6-13	BLACKSPRINGS VALLEY		South Lahontan	SRO	30,911	48.3	0	0	3	0	Very Low	Not Analyzed	0	0	0%	0	0	Insufficient Data	Insufficient Data	No	0	-	-	-	No	-	-		No	-		-	-	-		0	0	Insufficient Data
6-14	FISH LAKE VALLEY		South Lahontan	SRO	48,333	75.5	3,487	19,857	10	36	Low	Not Analyzed	0	0	0%	0	0	Insufficient Data	Insufficient Data	No	0	-	-	-	No	-	-		No	-		-	-	-		0	0	Insufficient Data
6-15	DEEP SPRINGS VALLEY		South Lahontan	SRO	30,048	47.0	149	912	1	5	Very Low	Not Analyzed	0	0	0%	0	0	Insufficient Data	Insufficient Data	No	0	-	-	-	No	-	-		No	-		-	-	-		0	0	Insufficient Data
6-16	EUREKA VALLEY		South Lahontan	SRO	129,329	202.1	0	0	0	10	Very Low	Not Analyzed	0	0	0%	0	0	Insufficient Data	Insufficient Data	No	0	-	-	-	No	-	-		No	-		-	-	-		0	0	Insufficient Data
6-17	SALINE VALLEY		South Lahontan	SRO	146,850	229.5	0	0	0	0	Very Low	Not Analyzed	0	0	0%	0	0	Insufficient Data	Insufficient Data	No	0	-	-	-	No	-	-		No	-		-	-	-		0	0	Insufficient Data
6-18	DEATH VALLEY		South Lahontan	SRO	926,496	1,447.7	17	1,060	52	190	Very Low	Not Analyzed	0	0	0%	0	0	Insufficient Data	Insufficient Data	No	0	-	-	-	No	-	-		No	-		-	-	-		0	0	Insufficient Data
6-19	WINGATE VALLEY		South Lahontan	SRO	71,755	112.1	0	0	0	0	Very Low	Not Analyzed	0	0	0%	0	0	Insufficient Data	Insufficient Data	No	0	-	-	-	No	-	-		No	-		-	-	-		0	0	Insufficient Data
6-2	MADELINE PLAINS		North Lahontan	NRO	156,152	244.0	25,052	42,400	231	151	Low	Not Analyzed	1	1	100%	0	0	Insufficient Data	Insufficient Data	No	0	-	-	-	No	-	-		No	-		-	-	-		0	0	Insufficient Data
6-20	MIDDLE AMARGOSA VALLEY		South Lahontan	SRO	392,862	613.8	0	120	64	230	Very Low	Not Analyzed	0	0	0%	0	0	Insufficient Data	Insufficient Data	No	0	-	-	-	Yes (1)	Not Subsiding	0	-	-	0.02	2004 to Present			0	0	Insufficient Data
6-21	LOWER KINGSTON VALLEY		South Lahontan	SRO	241,892	378.0	0	0	0	0	Very Low	Not Analyzed	0	0	0%	0	0	Insufficient Data	Insufficient Data	No	0	-	-	-	Yes (1)	Not Subsiding	0	-	-	0.03	2008 to Present			0	0	Insufficient Data
6-22	UPPER KINGSTON VALLEY		South Lahontan	SRO	178,533	279.0	0	87	26	37	Very Low	Not Analyzed	0	0	0%	0	0	Insufficient Data	Insufficient Data	No	0	-	-	-	Yes (1)	Not Subsiding	0	-	-	-	2008 to Present			0	0	Insufficient Data
6-23	RIGGS VALLEY		South Lahontan	SRO	88,274	137.9	0	0	0	0	Very Low	Not Analyzed	0	0	0%	0	0	Insufficient Data	Insufficient Data	No	0	-	-	-	No	-	-		No	-		-	-	-		0	0	Insufficient Data
6-24	RED PASS VALLEY		South Lahontan	SRO	97,088	151.7	0	0	0	0	Very Low	Not Analyzed	0	0	0%	0	0	Insufficient Data	Insufficient Data	No	0	-	-	-	No	-	-		No	-		-	-	-		0	0	Insufficient Data
6-25	BICYCLE VALLEY		South Lahontan	SRO	90,100	140.8	0	0	2	0	Very Low	Not Analyzed	1	2	50%	1	0	Insufficient Data	Insufficient Data	No[1]	0	-	-	-	No	-	-		No	-		-	-	-	[1]Subsidence has been documented in adjacement groundwater basin (Irwin)		0	0	Insufficient Data
6-26	AVAWATZ VALLEY		South Lahontan	SRO	27,826	43.5	0	0	0	0	Very Low	Not Analyzed	0	0	0%	0	0	Insufficient Data	Insufficient Data	No	0	-	-	-	No	-	-		No	-		-	-	-		0	0	Insufficient Data
6-27	LEACH VALLEY		South Lahontan	SRO	61,620	96.3	0	0	0	99	Very Low	Not Analyzed	0	0	0%	0	0	Insufficient Data	Insufficient Data	No	0	-	-	-	No	-	-		No	-		-	-	-		0	0	Insufficient Data
6-28	PAHRUMP VALLEY		South Lahontan	SRO	93,747	146.5	0	101	55	99	Very Low	Evidence of Overdraft	0	0	0%	0	0	Insufficient Data	Insufficient Data	No	0	-	-	-	No	-	-		No	-		-	-	-		0	0	Insufficient Data
6-29	MESQUITE VALLEY		South Lahontan	SRO	89,012	139.1	1,626	1,675	58	64	Very Low	Not Analyzed	0	0	0%	0	0	Insufficient Data	Insufficient Data	No	0	-	-	-	No	-	-		No	-		-	-	-		0	0	Insufficient Data
6-30	IVANPAH VALLEY		South Lahontan	SRO	200,155	312.7	0	89	54	40	Very Low	Not Analyzed	0	0	0%	0	0	Insufficient Data	Insufficient Data	No	0	-	-	-	No	-	-		No	-		-	-	-		0	0	Insufficient Data
6-31	KELSO VALLEY		South Lahontan	SRO	257,279	402.0	0	83	16	20	Very Low	Not Analyzed	0	0	0%	0	0	Insufficient Data	Insufficient Data	No	0	-	-	-	No	-	-		No	-		-	-	-		0	0	Insufficient Data
6-32	BROADWELL VALLEY		South Lahontan	SRO	92,688	144.8	0	65	30	8	Very Low	Not Analyzed	0	0	0%	0	0	Insufficient Data	Insufficient Data	No	0	-	-	-	No	-	-		No	-		-	-	-		0	0	Insufficient Data
6-33	SODA LAKE VALLEY		South Lahontan	SRO	383,560	599.3	0	94	159	750	Very Low	Not Analyzed	0	0	0%	0	0	Insufficient Data	Insufficient Data	No	0	-	-	-	Yes (1)	Not Subsiding	0	-	-	0.03	2006 to Present			0	0	Insufficient Data
6-34	SILVER LAKE VALLEY		South Lahontan	SRO	35,519	55.5	0	0	2	0	Very Low	Not Analyzed	0	0	0%	0	0	Insufficient Data	Insufficient Data	No	0	-	-	-	Yes (1)	Not Subsiding	0	-	-	2004 to Present				0	0	Insufficient Data
6-35	CRONISE VALLEY		South Lahontan	SRO	127,313	198.9	0	0	4	2	Very Low	Not Analyzed	0	0	0%	0	0	Insufficient Data	Insufficient Data	No	0	-	-	-	No	-	-		No	-		-	-	-		0	0	Insufficient Data
6-36.01	LANGFORD VALLEY	LANGFORD WELL LAKE	South Lahontan	SRO	19,457	30.4	0	0	0	0	Very Low	Not Analyzed	0	0	0%	0	0	Insufficient Data	Insufficient Data	No	0	-	-	-	No	-	-		No	-		-	-	-		0	0	Insufficient Data
6-37	COYOTE LAKE VALLEY		South Lahontan	SRO	88,735	138.6	0	102	3	99	Very Low	Not Analyzed	1	1	100%	1	0	Insufficient Data	Insufficient Data	No	0	-	-	-	No	-	-		No	-		-	-	-		0	0	Insufficient Data
6-45	TEHACHAPI VALLEY EAST		South Lahontan	SRO	24,055	37.6	96	101	228	480	Very Low	Not Analyzed	0	0	0%	0	0	Insufficient Data	Insufficient Data	No	0	-	-	-	No	-	-		No	-		-	-	-		0	0	Insufficient Data
6-48	GOLDSTONE VALLEY		South Lahontan	SRO	28,287	44.2	0	0	6	0	Very Low	Not Analyzed	0	0	0%	0	0	Insufficient Data	Insufficient Data	No	0	-	-	-	No	-	-		No	-		-	-	-		0	0	Insufficient Data
6-49	SUPERIOR VALLEY		South Lahontan	SRO	121,084	189.2	0	0	1	0	Very Low	Not Analyzed	0	0	0%	0	0	Insufficient Data	Insufficient Data	No	0	-	-	-	No	-	-		No	-		-	-	-		0	0	Insufficient Data
6-5.02	TAHOE VALLEY	TAHOE WEST	North Lahontan	NCRO	6,173	9.6	0	591	208	3,110	Very Low	Not Analyzed	0	0	0%	0	0	Insufficient Data	Insufficient Data	No	0	-	-	-	No	-	-		No	-		-	-	-		0	0	Insufficient Data
6-5.03	TAHOE VALLEY	TAHOE NORTH	North Lahontan	NCRO	1,931	3.0	0	575	45	3,410	Very Low	Not Analyzed	0	0	0%	0	0	Insufficient Data	Insufficient Data	No	0	-	-	-	No	-	-		No	-		-	-	-		0	0	Insufficient Data
6-50	CUDDEBACK VALLEY		South Lahontan	SRO	95,418	149.1	0	240	0	97	Very Low	Not Analyzed	0	0	0%	0	0	Insufficient Data	Insufficient Data	No	0	-	-	-	No	-	-		No	-		-	-	-		0	0	Insufficient Data
6-51	PILOT KNOB VALLEY		South Lahontan	SRO	139,460	217.9	0	0	3	0	Very Low	Not Analyzed	0	0	0%	0	0	Insufficient Data	Insufficient Data	No	0	-	-	-	No	-	-		No	-		-	-	-		0	0	Insufficient Data
6-52	SEARLES VALLEY		South Lahontan	SRO	198,115	309.6	0	400	81	1,651	Very Low	Not Analyzed	0	0	0%	0	0	Insufficient Data	Insufficient Data	No	0	-	-	-	No	-	-		No	-		-	-	-		0	0	Insufficient Data
6-53	SALT WELLS VALLEY		South Lahontan	SRO	29,629	46.3	0	0	1	0	Very Low	Not Analyzed	0	0	0%	0	0	Insufficient Data	Insufficient Data	No	0	-	-	-	No	-	-		No	-		-	-	-		0	0	Insufficient Data
6-55	COSO VALLEY		South Lahontan	SRO	25,684	40.1	0	0	0	0	Very Low	Not Analyzed	0	0	0%	0	0	Insufficient Data	Insufficient Data	No	0	-	-	-	No	-	-		No	-		-	-	-		0	0	Insufficient Data
6-56	ROSE VALLEY		South Lahontan	SRO	42,709	66.7	0	16	10	10	Very Low	Not Analyzed	0	0	0%	0	0	Insufficient Data	Insufficient Data	No	0	-	-	-	No	-	-		No	-		-	-	-		0	0	Insufficient Data
6-57	DARWIN VALLEY		South Lahontan	SRO	44,386	69.4	0	54	7	39	Very Low	Not Analyzed	0	0	0%	0	0	Insufficient Data	Insufficient Data	No	0	-	-	-	No	-	-		No	-		-	-	-		0	0	Insufficient Data
6-58	PANAMINT VALLEY		South Lahontan	SRO	260,754	407.4	0	10	11	7	Very Low	Not Analyzed	0	0	0%	0	0	Insufficient Data	Insufficient Data	No	0	-	-	-	No	-	-		No	-		-	-	-		0	0	Insufficient Data
6-6	CARSON VALLEY		North Lahontan	NCRO	10,716	16.7	2,990	0	114	328	Very Low	Not Analyzed	0	0	0%	0	0	Insufficient Data	Insufficient Data	No	0	-	-	-	No	-	-		No	-		-	-	-		0	0	Insufficient Data
6-61	CAMEO AREA		South Lahontan	SRO	9,349	14.6	0	0	0	0	Very Low	Not Analyzed	0	0	0%	0	0	Insufficient Data	Insufficient Data	No	0	-	-	-	No	-	-		No	-		-	-	-		0	0	Insufficient Data
6-62	RACE TRACK VALLEY		South Lahontan	SRO	14,184	22.2	0	0	0	0	Very Low	Not Analyzed	0	0	0%	0	0	Insufficient Data	Insufficient Data	No	0	-	-	-	No	-	-		No	-		-	-	-		0	0	Insufficient Data
6-63	HIDDEN VALLEY		South Lahontan	SRO	18,037	28.2	0	0	0	0	Very Low	Not Analyzed	0	0	0%	0	0	Insufficient Data	Insufficient Data	No	0	-	-	-	No	-	-		No	-		-	-	-		0	0	Insufficient Data
6-64	MARBLE CANYON AREA		South Lahontan	SRO	10,422	16.3	0	0	0	0	Very Low	Not Analyzed	0	0	0%	0	0	Insufficient Data	Insufficient Data	No	0	-	-	-	No	-	-		No	-		-	-	-		0	0	Insufficient Data
6-65	COTTONWOOD SPRING AREA		South Lahontan	SRO	3,918	6.1	0	0	0	0	Very Low	Not Analyzed	0	0	0%	0	0	Insufficient Data	Insufficient Data	No	0	-	-	-	No	-	-		No	-		-	-	-		0	0	Insufficient Data
6-66	LEE FLAT		South Lahontan	SRO	20,380	31.8	0	0	4	0	Very Low	Not Analyzed	0	0	0%	0	0	Insufficient Data	Insufficient Data	No	0	-	-	-	No	-	-		No	-		-	-	-		0	0	Insufficient Data
6-68	SANTA ROSA FLAT		South Lahontan	SRO	16,861	26.3	0	0	0	0	Very Low	Not Analyzed	0	0	0%	0	0	Insufficient Data	Insufficient Data	No	0	-	-	-	No	-	-		No	-		-	-	-		0	0	Insufficient Data
6-69	KELSO LANDER VALLEY		South Lahontan	SRO	11,208	17.5	0	0	8	0	Very Low	Not Analyzed	0	0	0%	0	0	Insufficient Data	Insufficient Data	No	0	-	-	-	No	-	-		No	-		-	-	-		0	0	Insufficient Data
6-7	ANTELOPE VALLEY		North Lahontan	NCRO	20,125	31.4	11,375	64	191	876	Very Low	Not Analyzed	0	0	0%	0	0	Insufficient Data	Insufficient Data	No	0	-	-	-	No	-	-		No	-		-	-	-		0	0	Insufficient Data
6-70	CACTUS FLAT		South Lahontan	SRO	7,056	11.0	0	0	0	0	Very Low	Not Analyzed	0	0	0%	0	0	Insufficient Data	Insufficient Data	No	0	-	-	-	No	-	-		No	-		-	-	-		0	0	Insufficient Data
6-71	LOST LAKE VALLEY		South Lahontan	SRO	23,414	36.6	0	0	0	0	Very Low	Not Analyzed	0	0	0%	0	0	Insufficient Data	Insufficient Data	No	0	-	-	-	No	-	-		No	-		-	-	-		0	0	Insufficient Data
6-72	COLES FLAT		South Lahontan	SRO	2,961	4.6	0	0	0	0	Very Low	Not Analyzed	0	0	0%	0	0	Insufficient Data	Insufficient Data	No	0	-	-	-	No	-	-		No	-		-	-	-		0	0	Insufficient Data
6-73	WILD HORSE MESA AREA		South Lahontan	SRO	3,337	5.2	0	0	0	0	Very Low	Not Analyzed	0	0	0%	0	0	Insufficient Data	Insufficient Data	No	0	-	-	-	No	-	-		No	-		-	-	-		0	0	Insufficient Data
6-74	HARRISBURG FLATS		South Lahontan	SRO	25,077	39.2	0	4	0	1	Very Low	Not Analyzed	0	0	0%	0	0	Insufficient Data	Insufficient Data	No	0	-	-	-	No	-	-		No	-		-	-	-		0	0	Insufficient Data
6-75	WILDROSE CANYON		South Lahontan	SRO	5,182	8.1	0	1	0	1	Very Low	Not Analyzed	0	0	0%	0	0	Insufficient Data	Insufficient Data	No	0	-	-	-	No	-	-		No	-		-	-	-		0	0	Insufficient Data
6-76	BROWN MOUNTAIN VALLEY		South Lahontan	SRO	21,862	34.2	0	0	0	0	Very Low	Not Analyzed	0	0	0%	0	0	Insufficient Data	Insufficient Data	No	0	-	-	-	No	-	-		No	-		-	-	-		0	0	Insufficient Data
6-77	GRASS VALLEY		South Lahontan	SRO	10,034	15.7	0	0	0	0	Very Low	Not Analyzed	0	0	0%	0	0	Insufficient Data	Insufficient Data	No	0	-	-	-	No	-	-		No	-		-	-	-		0	0	Insufficient Data
6-78	DENNING SPRING VALLEY		South Lahontan	SRO	7,289	11.4	0	0	0	0	Very Low	Not Analyzed	0	0	0%	0	0	Insufficient Data	Insufficient Data	No	0	-	-	-	No	-	-		No	-		-	-	-		0	0	Insufficient Data
6-79	CALIFORNIA VALLEY		South Lahontan	SRO	58,639	91.6	0	0	0	0	Very Low	Not Analyzed	0	0	0%	0	0	Insufficient Data	Insufficient Data	No	0	-	-	-	No	-	-		No	-		-	-	-		0	0	Insufficient Data
6-8	BRIDGEPORT VALLEY		North Lahontan	NCRO	32,545	50.9	16,618	43	68	586	Very Low	Not Analyzed	0	0	0%	0	0	Insufficient Data	Insufficient Data	No	0	-	-	-	No	-	-		No	-		-	-	-		0	0	Insufficient Data
6-80	MIDDLE PARK CANYON		South Lahontan	SRO	1,752	2.7	0	0	0	0	Very Low	Not Analyzed	0	0	0%	0	0	Insufficient Data	Insufficient Data	No	0	-	-	-	No	-	-		No	-		-	-	-		0	0	Insufficient Data
6-81	BUTTE VALLEY		South Lahontan	SRO	8,853	13.8	0	0	0	0	Very Low	Not Analyzed	0	0	0%	0	0	Insufficient Data	Insufficient Data	No	0	-	-	-	No	-	-		No	-		-	-	-		0	0	Insufficient Data
6-82	SPRING CANYON VALLEY		South Lahontan	SRO	4,832	7.5	0	0	0	0	Very Low	Not Analyzed	0	0	0%	0	0	Insufficient Data	Insufficient Data	No	0	-	-	-	No	-	-		No	-		-	-	-		0	0	Insufficient Data
6-84	GREENWATER VALLEY		South Lahontan	SRO	60,260	94.2	0	0	0	0	Very Low	Not Analyzed	0	0	0%	0	0	Insufficient Data	Insufficient Data	No	0	-	-	-	No	-	-		No	-		-	-	-		0	0	Insufficient Data
6-85	GOLD VALLEY		South Lahontan	SRO	3,234	5.1	0	0	0	0	Very Low	Not Analyzed	0	0	0%	0	0	Insufficient Data	Insufficient Data	No	0	-	-	-	No	-	-		No	-		-	-	-		0	0	Insufficient Data
6-86	RHODES HILL AREA		South Lahontan	SRO	15,697	24.5	0	0	0	0	Very Low	Not Analyzed	0	0	0%	0	0	Insufficient Data	Insufficient Data	No	0	-	-	-	No	-	-		No	-		-	-	-		0	0	Insufficient Data
6-88	OWL LAKE VALLEY		South Lahontan	SRO	22,402	35.0	0	0	0	0	Very Low	Not Analyzed	0	0	0%	0	0	Insufficient Data	Insufficient Data	No	0	-	-	-	No	-	-		No	-		-	-	-		0	0	Insufficient Data
6-89	KANE WASH AREA		South Lahontan	SRO	5,997	9.4	0	0	0	0	Very Low	Not Analyzed	0	0	0%	0	0	Insufficient Data	Insufficient Data	No[1]	0	-	-	-	No	-	-		No	-		-	-	-	[1]Subsidence has been documented in adjacement groundwater basin (Lucerne Valley)		0	0	Insufficient Data
6-9	MONO VALLEY		South Lahontan	SRO	173,299	270.8	0	338	13	385	Very Low	Not Analyzed	0	0	0%	0	0	Insufficient Data	Insufficient Data	No	0	-	-	-	No	-	-		Yes (2)	Not Subsiding (2)	0	-	-	0.03	2008 to Present			0	0	Insufficient Data
6-90	CADY FAULT AREA		South Lahontan	SRO	8,015	12.5	0	0	0	6	Very Low	Not Analyzed	0	0	0%	0	0	Insufficient Data	Insufficient Data	No	0	-	-	-	No	-	-		No	-		-	-	-		0	0	Insufficient Data
6-91	COW HEAD LAKE VALLEY		North Lahontan	NRO	5,625	8.8	3,287	0	2	0	Very Low	Not Analyzed	0	0	0%	0	0	Insufficient Data	Insufficient Data	No	0	-	-	-	No	-	-		No	-		-	-	-		0	0	Insufficient Data
6-92	PINE CREEK VALLEY		North Lahontan	NRO	9,526	14.9	0	0	0	0	Very Low	Not Analyzed	0	0	0%	0	0	Insufficient Data	Insufficient Data	No	0	-	-	-	No	-	-		No	-		-	-	-		0	0	Insufficient Data
6-93	HARVEY VALLEY		North Lahontan	NRO	4,503	7.0	0	0	0	0	Very Low	Not Analyzed	0	0	0%	0	0	Insufficient Data	Insufficient Data	No	0	-	-	-	No	-	-		No	-		-	-	-		0	0	Insufficient Data
6-94	GRASSHOPPER VALLEY		North Lahontan	NRO	17,665	27.6	250	300	4	0	Very Low	Not Analyzed	0	0	0%	0	0	Insufficient Data	Insufficient Data	No	0	-	-	-	No	-	-		No	-		-	-	-		0	0	Insufficient Data
6-95	DRY VALLEY		North Lahontan	NRO	6,498	10.2	104	0	4	2	Very Low	Not Analyzed	0	0	0%	0	0	Insufficient Data	Insufficient Data	No	0	-	-	-	No	-	-		No	-		-	-	-		0	0	Insufficient Data
6-96	EAGLE LAKE AREA		North Lahontan	NRO	12,700	19.8	0	10	177	41	Very Low	Not Analyzed	0	0	0%	0	0	Insufficient Data	Insufficient Data	No	0	-	-	-	No	-	-		No	-		-	-	-		0	0	Insufficient Data
6-97	HORSE LAKE VALLEY		North Lahontan	NRO	3,827	6.0	1,563	0	0	0	Very Low	Not Analyzed	0	0	0%	0	0	Insufficient Data	Insufficient Data	No	0	-	-	-	No	-	-		No	-		-	-	-		0	0	Insufficient Data
6-97	HORSE LAKE VALLEY		North Lahontan	NRO	3,827	6.0	1,563	0	0	0	Very Low	Not Analyzed	0	0	0%	0	0	Insufficient Data	Insufficient Data	No	0	-	-	-	No	-	-		No	-		-	-	-		0	0	Insufficient Data
6-98	HORSE LAKE VALLEY		North Lahontan	NRO	3,827	6.0	1,563	0	0	0	Very Low	Not Analyzed	0	0	0%	0	0	Insufficient Data

7-59	MASON VALLEY		Colorado River	SRO	5,567	8.7	0	19	6	23	Very Low	Not Analyzed	0	0	0%	0	0	Insufficient Data	Insufficient Data	No	0	-	-	No	-	-		No	-		-	-	-		0	0	Insufficient Data
7-6	PINTO VALLEY		Colorado River	SRO	184,377	288.1	0	0	2	7	Very Low	Not Analyzed	0	0	0%	0	0	Insufficient Data	Insufficient Data	No	0	-	-	No	-	-		No	-		-	-	-		0	0	Insufficient Data
7-61	DAVIES VALLEY		Colorado River	SRO	3,600	5.6	0	0	0	0	Very Low	Not Analyzed	0	0	0%	0	0	Insufficient Data	Insufficient Data	No	0	-	-	No	-	-		No	-		-	-	-		0	0	Insufficient Data
7-63	VANDEVENTER FLAT		Colorado River	SRO	6,787	10.6	0	16	6	50	Very Low	Not Analyzed	0	0	0%	0	0	Insufficient Data	Insufficient Data	No	0	-	-	No	-	-		Yes (1)	Not Subsiding	0	-	-	2006 to Present		0	0	Insufficient Data
7-7	CADIZ VALLEY		Colorado River	SRO	272,931	426.5	0	58	6	10	Very Low	Not Analyzed	0	0	0%	0	0	Insufficient Data	Insufficient Data	No	0	-	-	No	-	-		No	-		-	-	-		0	0	Insufficient Data
7-8	BRISTOL VALLEY		Colorado River	SRO	501,834	784.1	943	5,000	63	27	Low	Not Analyzed	0	0	0%	0	0	Insufficient Data	Insufficient Data	No	0	-	-	No	-	-		No	-		-	-	-		0	0	Insufficient Data
7-9	DALE VALLEY		Colorado River	SRO	214,650	335.4	18	1,500	178	1,197	Very Low	Not Analyzed	0	0	0%	0	0	Insufficient Data	Insufficient Data	No	0	-	-	No	-	-		No	-		-	-	-		0	0	Insufficient Data
8-2.03	UPPER SANTA ANA VALLEY	RIVERSIDE-ARLINGTON	South Coast	SRO	58,903	92.0	3,583	49,148	1,397	336,884	High	Not Analyzed	1	1	100%	1	0	Insufficient Data	Insufficient Data	No	0	-	-	No	-	-		No	-		-	-	-		0	0	Insufficient Data
8-2.05	UPPER SANTA ANA VALLEY	CAJON	South Coast	SRO	23,306	36.4	60	33	68	520	Very Low	Not Analyzed	0	0	0%	0	0	Insufficient Data	Insufficient Data	No	0	-	-	No	-	-		Yes (2)	Not Subsiding	0	-	0.03	2011 to Present		0	0	Insufficient Data
8-4	ELSINORE		South Coast	SRO	25,873	40.4	286	5,872	375	60,946	High	Evidence of Overdraft	0	0	0%	0	0	Insufficient Data	Insufficient Data	No[1]	0	-	-	No	-	-		No	-		-	-	-	[1]Subsidence has been documented in adjacement groundwater basin (Temecula Valley)	0	0	Insufficient Data
8-6	HEMET LAKE VALLEY		South Coast	SRO	16,811	26.3	84	5	47	464	Very Low	Not Analyzed	0	0	0%	0	0	Insufficient Data	Insufficient Data	No	0	-	-	No	-	-		Yes (1)	Not Subsiding	0	-	0.03	2006 to Present		0	0	Insufficient Data
8-7	BIG MEADOWS VALLEY		South Coast	SRO	14,263	22.3	0	3	23	51	Very Low	Not Analyzed	0	0	0%	0	0	Insufficient Data	Insufficient Data	No	0	-	-	No	-	-		No	-		-	-	-		0	0	Insufficient Data
8-8	SELVEN OAKS VALLEY		South Coast	SRO	4,103	6.4	0	0	0	7	Very Low	Not Analyzed	0	0	0%	0	0	Insufficient Data	Insufficient Data	No	0	-	-	No	-	-		No	-		-	-	-		0	0	Insufficient Data
8-9	BEAR VALLEY		South Coast	SRO	19,667	30.7	0	3,500	496	16,866	Medium	Not Analyzed	0	0	0%	0	0	Insufficient Data	Insufficient Data	No	0	-	-	No	-	-		Yes (1)	Not Subsiding	0	-	0.03	2004 to Present		0	0	Insufficient Data
9-10	SAN PASQUAL VALLEY		South Coast	SRO	4,563	7.1	1,963	8,800	110	968	Medium	Not Analyzed	0	0	0%	0	0	Insufficient Data	Insufficient Data	No	0	-	-	No	-	-		No	-		-	-	-		0	0	Insufficient Data
9-11	SANTA MARIA VALLEY		South Coast	SRO	12,379	19.3	624	4	542	16,695	Very Low	Not Analyzed	0	0	0%	0	0	Insufficient Data	Insufficient Data	No	0	-	-	No	-	-		No	-		-	-	-		0	0	Insufficient Data
9-12	SAN DIEGUITO CREEK		South Coast	SRO	3,578	5.6	976	1	89	3,135	Very Low	Not Analyzed	0	0	0%	0	0	Insufficient Data	Insufficient Data	No	0	-	-	No	-	-		No	-		-	-	-		0	0	Insufficient Data
9-13	POWAY VALLEY		South Coast	SRO	2,485	3.9	3	4	89	16,450	Very Low	Not Analyzed	0	0	0%	0	0	Insufficient Data	Insufficient Data	No	0	-	-	No	-	-		No	-		-	-	-		0	0	Insufficient Data
9-14	MISSION VALLEY		South Coast	SRO	7,387	11.5	0	9	307	37,066	Very Low	Not Analyzed	0	0	0%	0	0	Insufficient Data	Insufficient Data	No	0	-	-	No	-	-		No	-		-	-	-		0	0	Insufficient Data
9-15	SAN DIEGO RIVER VALLEY		South Coast	SRO	9,944	15.5	215	4,000	339	45,800	Medium	Not Analyzed	0	0	0%	0	0	Insufficient Data	Insufficient Data	No	0	-	-	No	-	-		No	-		-	-	-		0	0	Insufficient Data
9-16	EL CAJON VALLEY		South Coast	SRO	7,203	11.3	11	25	369	92,314	Very Low	Not Analyzed	0	0	0%	0	0	Insufficient Data	Insufficient Data	No	0	-	-	No	-	-		No	-		-	-	-		0	0	Insufficient Data
9-17	SWEETWATER VALLEY		South Coast	SRO	5,949	9.3	0	9	509	35,277	Very Low	Not Analyzed	0	0	0%	0	0	Insufficient Data	Insufficient Data	No	0	-	-	No	-	-		No	-		-	-	-		0	0	Insufficient Data
9-18	OTAY VALLEY		South Coast	SRO	6,869	10.7	83	10	204	39,191	Very Low	Not Analyzed	0	0	0%	0	0	Insufficient Data	Insufficient Data	No	0	-	-	No	-	-		No	-		-	-	-		0	0	Insufficient Data
9-19	TIA JUANA		South Coast	SRO	7,448	11.6	305	14	87	50,694	Very Low	Evidence of Overdraft	0	0	0%	0	0	Insufficient Data	Insufficient Data	No	0	-	-	No	-	-		No	-		-	-	-		0	0	Insufficient Data
9-2	SAN MATEO VALLEY		South Coast	SRO	3,009	4.7	515	0	21	554	Very Low	Not Analyzed	0	0	0%	0	0	Insufficient Data	Insufficient Data	No	0	-	-	No	-	-		Yes (1)	Not Subsiding	0	-	0.02	2012 to Present		0	0	Insufficient Data
9-22	BATIQUITOS LAGOON VALLEY		South Coast	SRO	745	1.2	6	0	5	2,109	Very Low	Not Analyzed	0	0	0%	0	0	Insufficient Data	Insufficient Data	No	0	-	-	No	-	-		No	-		-	-	-		0	0	Insufficient Data
9-23	SAN ELIJO VALLEY		South Coast	SRO	888	1.4	8	0	25	1,125	Very Low	Not Analyzed	0	0	0%	0	0	Insufficient Data	Insufficient Data	No	0	-	-	No	-	-		No	-		-	-	-		0	0	Insufficient Data
9-24	PAMO VALLEY		South Coast	SRO	1,514	2.4	0	0	0	0	Very Low	Not Analyzed	0	0	0%	0	0	Insufficient Data	Insufficient Data	No	0	-	-	No	-	-		No	-		-	-	-		0	0	Insufficient Data
9-25	RANCHITA TOWN AREA		South Coast	SRO	3,146	4.9	29	0	78	168	Very Low	Not Analyzed	0	0	0%	0	0	Insufficient Data	Insufficient Data	No	0	-	-	No	-	-		No	-		-	-	-		0	0	Insufficient Data
9-27	COTTONWOOD VALLEY		South Coast	SRO	3,871	6.0	148	0	17	44	Very Low	Not Analyzed	0	0	0%	0	0	Insufficient Data	Insufficient Data	No	0	-	-	No	-	-		No	-		-	-	-		0	0	Insufficient Data
9-28	CAMPO VALLEY		South Coast	SRO	3,569	5.6	310	0	55	985	Very Low	Not Analyzed	0	0	0%	0	0	Insufficient Data	Insufficient Data	No	0	-	-	No	-	-		No	-		-	-	-		0	0	Insufficient Data
9-29	POTRERO VALLEY		South Coast	SRO	2,035	3.2	131	0	62	475	Very Low	Not Analyzed	0	0	0%	0	0	Insufficient Data	Insufficient Data	No	0	-	-	No	-	-		No	-		-	-	-		0	0	Insufficient Data
9-3	SAN ONOFRE VALLEY		South Coast	SRO	1,261	2.0	0	1	2	3,133	Very Low	Not Analyzed	0	0	0%	0	0	Insufficient Data	Insufficient Data	No	0	-	-	No	-	-		No	-		-	-	-		0	0	Insufficient Data
9-32	SAN MARCOS AREA		South Coast	SRO	2,144	3.3	0	4	52	15,096	Very Low	Not Analyzed	0	0	0%	0	0	Insufficient Data	Insufficient Data	No	0	-	-	No	-	-		No	-		-	-	-		0	0	Insufficient Data
9-4	SANTA MARGARITA VALLEY		South Coast	SRO	7,998	12.5	157	5,800	111	4,121	Medium	Evidence of Overdraft	0	0	0%	0	0	Insufficient Data	Insufficient Data	No	0	-	-	No	-	-		No	-		-	-	-		0	0	Insufficient Data
9-7	SAN LUIS REY VALLEY		South Coast	SRO	29,865	46.7	7,830	14,400	500	43,942	Medium	Evidence of Overdraft	0	0	0%	0	0	Insufficient Data	Insufficient Data	No	0	-	-	No	-	-		No	-		-	-	-		0	0	Insufficient Data
9-8	WARNER VALLEY		South Coast	SRO	24,150	37.7	0	0	72	185	Very Low	Not Analyzed	0	0	0%	0	0	Insufficient Data	Insufficient Data	No	0	-	-	No	-	-		No	-		-	-	-		0	0	Insufficient Data
9-9	ESCONDIDO VALLEY		South Coast	SRO	2,906	4.5	40	10	221	38,593	Very Low	Not Analyzed	0	0	0%	0	0	Insufficient Data	Insufficient Data	No	0	-	-	No	-	-		No	-		-	-	-		0	0	Insufficient Data

Full Report of Findings / April 2014

Land Subsidence from Groundwater Use in California

Prepared By

LUHDORFF & SCALMANINI CONSULTING ENGINEERS

James W. Borchers • Michael Carpenter





With Support By

CALIFORNIA WATER FOUNDATION

Full Report of Findings / April 2014

Land Subsidence from Groundwater Use in California

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California Water Foundation

The California Water Foundation (CWF) seeks to transition California to a sustainable and resilient water future – a future in which water is managed as a natural resource, looking across all sources and uses to find the best solutions for social welfare, economic development, and environmental sustainability. CWF supports innovative projects and policies that address water challenges today, while achieving long-term, science-based solutions for the future. CWF is an initiative of Resources Legacy Fund, with primary funding from S.D. Bechtel, Jr. Foundation and Pisces Foundation, and additional support from David and Lucile Packard Foundation and others. Learn more at: http://www.californiawaterfoundation.org.

CALIFORNIA WATER FOUNDATION

Land Subsidence from Groundwater Use in California

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The California Water Foundation Subsidence Resources Group was established on April 29, 2013 to act as advisors for this report and is made up of those persons most knowledgeable on the subject of subsidence. The group has provided general input and subsequent review of reference lists, data assessments, and descriptions of monitoring and research needs. CWF appreciates the contributions of the 22 members listed below:

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List of Acronyms

AISH	International Association of Hydrological Sciences
ASCII	American Standard Code for Information Interchange
ASR	Artificial Storage and Recovery
AVEK	Antelope Valley-East Kern Water Agency
BARD	Bay Area Regional Deformation
BM	Benchmarks
Caltrans	California Department of Transportation
CCID	Central California Irrigation District
CHSRA	California High-Speed Rail Authority
CGPS	Continuous GPS Sites
CORS	Continuously Operating Reference Station
CSRC	California Spatial Reference Center
CVFED	Central Valley Floodplain Evaluation and Delineation
CWF	California Water Foundation
DIXN	Dixon
DMC	Delta Mendota Canal
DWR	Department of Water Resources
EAFB	Edwards Air Force Base
EDM	Electronic Distance Measuring
EIS	Environmental Impact Statement
GPS	Global Positioning System
GRACE	Gravity Recovery and Climate Experiment
GWMP	Groundwater Management Plans
HARNS	High Accuracy Reference Network
IASH	International Association of Scientific Hydrology
IBS	Interbedded Storage
InSAR	Interferometric Synthetic Aperture Radar
LACDPW	Los Angeles County Department of Public Works
LiDAR	Light Detection and Ranging
LSCE	Luhdorff & Scalmanini, Consulting Engineers
MODFLOW	Modular Finite-Difference Flow Model
NAD83	North American Datum of 1983
NASA/JPL	Jet Propulsion Laboratory
NAVD88	North American Vertical Datum of 1988
NGS	National Geodetic Survey
NGVD29	National Geodetic Vertical Datum of 1929
NSF	National Science Foundation
NSRS	National Spatial Reference System
NTC	Fort Irwin National Training Center
PBO	Plate Boundary Observatory

PMT	Program Management Team
PS	Persistent Scatterer
SAR	Synthetic Aperture Radar
SCVWD	Santa Clara Valley Water District
SCWA	Solano County Water Agency
SJRRP	San Joaquin River Restoration Program
SLDMWA	San Luis Delta-Mendota Water Authority
SOPAC	Scripps Orbit and Permanent Array Center
SSC	Super-Conducting Super Collider
SUB	Subsidence and Aquifer System Compaction Package
SWSD	Semitropic Water Storage District
USACE	U.S. Army Corps of Engineers
UNAVCO	A Non-Profit University-Governed Consortium, Facilitates Geoscience Research and Education Using Geodesy
USBR	U.S. Bureau of Reclamation
USGS	U.S. Geological Survey
VCVL	Vacaville
WSD	Water Storage District

EXECUTIVE SUMMARY

California's groundwater is a vital resource for the state that provides water supplies for urban and rural areas, supports a large agricultural economy, and benefits fish and wildlife habitats and ecosystems. Groundwater meets about 40 percent of the state's water demands in an average year (DWR, 2014). During droughts when surface supplies are limited, groundwater offers a critical buffer, providing a higher percent of the state's water supply. In 2014, it is anticipated statewide groundwater use will be closer to 65 percent because of the critical nature of this year's drought.

Historically, groundwater has been pumped as needed in many areas of the state, often with little regard for the deleterious effects of over pumping. Over pumping is not sustainable in the long-term and can lead to a number of adverse consequences, including water-quality degradation; increased energy costs for groundwater pumping; costs for well deepening or replacement; impacts to nearby rivers and streams; and land subsidence. This report highlights the current and historical impacts of land subsidence in California due to groundwater pumping and makes recommendations for monitoring and assessment.

This report confirms that land subsidence in California is not just a historical occurrence, but that it is an ongoing problem in many regions. The report presents key examples of significant historical subsidence and current active occurrences of subsidence, including the impacts and costs.

There is no comprehensive land subsidence monitoring program in California. The information in this report was compiled from individual regional or local studies, which usually were initiated after substantial subsidence impacts had occurred. The most comprehensive evaluation of land subsidence in California occurred between 1954 and 1970, to assist with the construction of the state and federal water projects. Funding for this program ended when groundwater levels recovered after completion of the state and federal water projects. The lack of comprehensive subsidence monitoring has had costly consequences for the state.

The California Water Foundation's (CWF) vision is for California to meet its 21st century economic and ecological water needs sustainably. The CWF supports innovative projects and policies that address today's water challenges, bringing together experts, stakeholders, and the public to achieve long-term, science-based solutions for the future.

This report presents the following:

- Subsidence processes especially as related to groundwater extraction
- Locations of areas subsiding as a result of groundwater extraction in California

- Methods used to measure the magnitude of land subsidence and ground-surface deformation, and
- Recommendations related to sustainable groundwater management.

ES 1 Subsidence Resources Group

At the outset of the project, a Subsidence Resources Group was created to lend expertise and experience and provide input on document sources and this Report of Findings. The Subsidence Resources Group comprises 22 experts; 13 currently work for the U.S. Geological Survey, four work for the California Department of Water Resources (DWR), and five are retirees or former employees of these agencies. Most members of this group have contributed to articles and reports contained in the reference list.

ES 2 Major Areas of Subsidence

Land subsidence has been discovered in many areas of the state, causing billions of dollars of damage. Impacts from subsidence fall into the following categories:

- Loss of conveyance capacity in canals, streams and rivers, and flood bypass channels;
- Diminished effectiveness of levees;
- Damage to roads, bridges, building foundations, pipelines, and other surface and subsurface infrastructure; and
- Development of earth fissures, which can damage surface and subsurface structures and allow for contamination at the land surface to enter shallow aquifers.

In many of these regions subsidence continues today, sometimes at nearly historically high rates of more than 1 foot/year (ft/yr). This report provides examples of current and historical subsidence pieced together from local or regional studies that were conducted by state, federal, or local agencies after subsidence was discovered to have dramatically deformed the land surface and/or caused significant infrastructure problems. Six major areas of subsidence in California are summarized below; additional details on these and other areas are provided in **Section 4**.

Santa Clara Valley

- Subsidence in Santa Clara Valley, in the South San Francisco Bay Area, has required diking to prevent flooding from the bay; water well, and sanitary and storm sewer system repairs; modifications to roads, bridges, and stream channel levees, and other infrastructure construction and repair, translating to more than $756 million in damages.
- Between 1910 and 1995, downtown San Jose subsided 14 feet.
- Santa Clara Valley has been successful in halting subsidence in the region by implementing a monitoring program, importing surface water, artificially recharging groundwater, and regulating groundwater withdrawals.

San Joaquin Valley

- Subsidence from groundwater extraction in the San Joaquin Valley has been called the greatest human alteration of the Earth's surface.
- By 1970, subsidence of more than 1 foot had affected 5,200 mi^2—more than half of the valley — and in some areas it had reached 28 feet.
- Over the past decade, subsidence has been identified in two regions in the San Joaquin Valley, including 3.94 feet during a 3½ year period near Corcoran, California.
- Subsidence has caused major impacts to infrastructure and physical features, including the San Joaquin River, Delta Mendota Canal, Friant-Kern Canal and San Luis Canal, as well as numerous privately owned canals and related infrastructure such as turnouts, bridges, pipelines, and storm sewers.
- These costs, add up to a total estimated cost of more than $1.3 billion during 1955-1972 (2013 dollars). Subsequent cost data are mostly unavailable.

Sacramento Valley

- Subsidence in the Sacramento Valley has resulted in wide scale destructive failure of steel groundwater well casings, making wells sometimes unusable.
- From the locations of damaged wells during a drought in 1976-1977, the subsidence appears to stretch from central Colusa County, through Yolo County, to Dixon in Solano County.

Antelope Valley

- Subsidence in Antelope Valley, east of Los Angeles, has been occurring for over 80 years. Increased pumping in the last 30 years due to population growth has accelerated the groundwater level declines to as much as 300 feet in some areas.
- Subsidence has adversely affected runways at Edwards Air Force Base and caused other negative consequences such as increased flooding and erosion; failed well casings; and damage to roads, homes, and other structures.

Coachella Valley

- Subsidence in Coachella Valley, in Riverside County, paused after importation of surface water began in 1949, but resumed in the 1970s as population and groundwater pumping increased.
- Earth fissures formed in 1948 and again recently. A subsidence study of a portion of the Coachella Branch of the All American Canal showed that the canal subsided as much as 1.35 feet from 1995 to 2010.

Mojave River Basin Area

- In the Mojave River Basin area, groundwater pumping resulted in groundwater-level declines of more than 100 feet. Giant desiccation cracks, sink-like depressions, and earth fissures more than 3 feet wide and deep have made permanent scars on the landscape.
- A 1998 survey indicated 2 to 5 feet of subsidence occurred in Lucerne Valley.
- Recent groundwater adjudication developed actions to stabilize the water levels of the basin and manage groundwater pumping.

As indicated in this report, alarming rates of subsidence continue to occur throughout California, causing impacts that can have lasting effects to property and the environment. This information is only being collected after the impacts from subsidence have occurred. The lack of a coordinated subsidence monitoring program, uniform monitoring procedures, and an ongoing data repository is causing significant irreversible impacts and costs to many regions and the state.

ES 3 Recommendations

This report proposes recommendations to help California address the ongoing economic and environmental impacts associated with over extraction of groundwater and the resulting land subsidence. The recommendations are summarized below; a complete set of recommendations is contained in **Section 7**. Only by monitoring and evaluation of monitoring data can California avoid the potential costly impacts of land subsidence that have plagued the state in the past. This report presents the technically necessary and desirable measures.

ES 3.1 Monitor Land Surface Elevation Changes and Compaction

Remote Surveillance and Analysis: InSAR and Continuous GPS

Interferometric Synthetic Aperture Radar (InSAR) provides the most cost efficient method to generate high-resolution land surface deformation information over large areas with high spatial detail. InSAR products provide detailed monitoring data and imagery that facilitate communicating the magnitude and extent of subsidence to the general public. Although the United States does not have a civilian radar satellite that can provide data for InSAR analysis, NASA and the Indian Space Agency are cooperating to construct and launch a SAR satellite this decade.

All available SAR data covering unconsolidated aquifer systems in California should be acquired and analyzed to identify areas of potential aquifer compaction, especially in areas of critical infrastructure. Additionally, Continuous Global Positioning System (CGPS) data should be examined for likely deformation sources and correlated with InSAR results. New CGPS stations should be installed in areas of actual or potential subsidence.

Ground Surveillance and Analysis: Surveying and Borehole Extensometry

Ground surveillance techniques are a critical component in identifying areas of subsidence, and are an important complement to remote techniques. Therefore, geodetic surveys should be correlated with InSAR and CGPS data and with groundwater-level data. Geodetic networks should be improved by upgrading and protecting geodetic monuments.
Borehole extensometers provide important aquifer compaction data. The distribution of extensometers in groundwater basins and subbasins should undergo a comprehensive evaluation and abandoned extensometers should be refurbished in priority areas. New extensometers should be designed and installed to monitor likely compacting intervals in areas where InSAR, CGPS, surveying, or infrastructure effects indicate that subsidence is occurring, or where groundwater use is increasing. Extensometers should be paired with multi-depth monitoring wells (piezometers) and a CGPS installation. New and more economical methods of building extensometers should be tested and assessed.

ES 3.2 Characterize Aquifer System and Monitor Groundwater Levels

Declining groundwater levels can trigger permanent land subsidence; it is therefore important to monitor, compile, and interpret groundwater levels throughout the state. The collection and storage of groundwater-level data by all federal, state, and local entities should be coordinated and made publically available. The distribution of groundwater-level monitoring wells areally and vertically within the aquifer system should be assessed to identify locations where additional monitoring wells are needed to track changes in hydraulic head. In order to make groundwater level monitoring measurements meaningful, and to use these measurements to understand the response of the aquifer system to natural factors (e.g., precipitation and droughts), imposed factors (e.g., pumping and artificial recharge) and the potential for land subsidence, requires that the construction of monitored wells and the distribution of fine-grained sediments be understood in the context of the aquifer system.

Subsurface lithology used to characterize the aquifer system can be obtained from a variety of sources; the most prevalent form of this information is well completion reports submitted by drilling contractors. Although these reports vary greatly in the quality of information recorded, they capture subsurface information that is critical to understanding the relationships between measured groundwater levels and the subsurface location and thickness of clayey layers susceptible to compaction. Standards should be established for drillers to report well locations as GPS-determined latitude and longitude or other horizontal coordinate system.

ES 3.3 Collect, Store and Disseminate Data

Data collection related to subsidence, and the interpretation of such information, is fragmented. It is critical to develop a state repository for subsidence-related information. Currently,

collection, storage, dissemination, and reporting of the data required to monitor and evaluate land subsidence is dispersed among many federal, state, and local agencies. Coordinated data maintenance should be achieved to assure consistent procedures for the collection, storage, and availability of pertinent water-resources data. The Arizona Department of Water Resources (ADWR) has developed a land subsidence monitoring program (Conway, 2013) that could provide a model for implementing a statewide subsidence-monitoring program in California. Alternatively, regional coordination of these responsibilities and an ongoing repository for the storage and disbursement of these data would facilitate their efficient use by government agencies, water purveyors and their consultants, and the public.

ES 3.4 Evaluate and Prioritize Subsiding Groundwater Basins

If the above data were in available databases and archives, groundwater basins statewide could be more easily and consistently prioritized for subsidence-relevant planning. In priority basins, where subsidence has occurred or is likely to occur, a step-wise planning assessment and management program could proceed as follows:

- Evaluate historical groundwater-level monitoring information and establish augmented groundwater-level monitoring networks to fully characterize the aquifer system.
- Characterize land surface deformation in priority basins with InSAR techniques, follow-up with geodetic surveys in subsiding areas, and establish a network of CGPS stations to provide time-series data at critical points.
- Establish borehole extensometers and associated multi-level monitoring well arrays to measure compaction and hydraulic head in various depth intervals of the aquifer system and CGPS installations to measure total change in land surface elevation at each extensometer.
- Establish measurable basin management objectives (BMOs) that identify goals for groundwater levels, land-surface elevations, and rates of change of each to avoid amounts or rates of inelastic compaction judged to be inappropriate for efficient operation of local infrastructure. These BMOs could be implemented through pumping strategies, artificial recharge, conservation strategies, and other sustainable groundwater management alternatives.

1 INTRODUCTION

California's groundwater is a vital resource for municipal, rural residential, agricultural, and commercial water users, and for the health of ecosystems and biological habitats. California's groundwater resources are widespread and diverse. There are presently 431 delineated groundwater basins (24 of which are subdivided into a total of 108 subbasins to result in 515 groundwater systems) in ten hydrologic regions that underlie 40 percent of California. Groundwater meets about 40 percent of the state's water demands in an average year (DWR, 2014). During droughts when surface supplies are limited, groundwater offers a critical buffer, providing a higher percent of the state's water supply. In 2014, it is anticipated statewide groundwater use will be closer to 65 percent because of the critical nature of this year's drought. In many basins, groundwater is the principal source of supply, especially during droughts. In 2000, California accounted for approximately 18 percent of the total groundwater withdrawals in the United States (Hutson et al., 2004). Population projections estimate growth to about 48 million people in 2020, an increase of about 14 million people relative to 2000.

Groundwater overdraft currently is estimated to occur at the rate of about 1 to 2 million acre-feet per year (DWR, 2003). Nonetheless, a comprehensive assessment of overdraft in the state's groundwater basins has not been conducted since 1980, and "information is insufficient in many basins to quantify overdraft that has occurred, project future impacts on ground water in storage, and effectively manage ground water" (DWR, 2003). Essentially, future groundwater availability in the state is not well understood.

Chronically declining groundwater levels associated with depletion of groundwater resources can lead to a number of adverse consequences, including saltwater intrusion or other water quality degradation; reduced groundwater storage, availability and reliability; increased energy costs; facilities costs such as for well deepening or replacement; streamflow depletion; environmental effects; and land subsidence.

This Report of Findings focuses on land subsidence, and particularly on subsidence in California related to groundwater use. Land subsidence is a complex subject, and this report provides some background on the topic before presenting an overview of the processes, occurrence, measuring and monitoring, and broader implications of subsidence.

Managing aquifer systems requires understanding changes in groundwater storage in saturated sediments or rock. Key components of tracking and understanding changes in groundwater storage include monitoring changing water levels (or potentiometric elevations) over time and, in areas susceptible to permanent subsidence, changes in aquifer storage capacity resulting from the compaction of the aquifer system itself. Senate Bill 1938 added monitoring (including subsidence) to the components to be included in Groundwater Management Plans (GWMP)

(Water Code 10753.7(a)(1)); therefore, agencies seeking state funding must necessarily address monitoring for permanent and nonrecoverable (inelastic) land subsidence.

According to the U.S. Geological Survey, land subsidence is a phenomenon found across the United States, affecting the land surface of over 17,000 square miles in 45 states (Galloway et al., 1999). The principal causes of land subsidence in general are aquifer system compaction, drainage of organic soils, compaction of hydrocarbon reservoirs, underground mining, hydrocompaction, natural compaction, sinkholes, and thawing permafrost. Most subsidence in the United States is a result of groundwater exploitation, and the increasing development of land and water resources threatens to worsen existing land-subsidence issues and initiate new ones (Galloway et al., 1999). Land subsidence caused by compaction of aquifer systems is often overlooked as a potential hazard and an environmental consequence of groundwater withdrawal. Some of the more costly consequences include damage to engineered structures, including buildings, roadways, pipelines, aqueducts, levees, sewerages, and well casings (Hoffmann et al., 2003), as well as increases in flood risk and associated remediation. Land subsidence in California is commonly a result of fluid withdrawal (oil or groundwater). As described in this report, significant subsidence has occurred historically in the San Joaquin Valley and elsewhere in California. However, recent observations of subsidence in the San Joaquin Valley are unanticipated and alarming.

1.1 Report Organization and Resources

The California Water Foundation's (CWF) vision is for California to meet its 21st century economic and ecological water needs sustainably. The CWF supports innovative projects and policies that address today's water challenges, bringing together experts, stakeholders, and the public to achieve long-term, science-based solutions for the future. The CWF communicates science-based facts on issues related to groundwater extraction, including land subsidence.

This report presents the following:

- Subsidence processes especially as related to groundwater extraction
- Locations of areas subsiding as a result of groundwater extraction in California
- Methods used to measure the magnitude of land subsidence and ground-surface deformation, and
- Recommendations related to sustainable groundwater management.

The lack of a coordinated state-wide land subsidence monitoring program, and an accessible data repository, which are essential to the assessment of subsidence, and the lack of funding to support technical synthesis and evaluation of data and remotely sensed imagery, point to a real need to address an ongoing problem that has immense implications for the state of California.

Recommendations are presented relating to current and future land surface monitoring and assessment needs.

1.1.1 References

In support of several tasks associated with CWF's interests in land subsidence, Luhdorff & Scalmanini, Consulting Engineers in association with James Borchers and Michael Carpenter (LSCE Team) with contributions from our Subsidence Resources Group (described below) prepared the list of key references in this report, including the references cited as well as many others. During a preliminary review of published literature relating to subsidence, it was found that there is no single compilation of historical and active occurrences of subsidence in California. This report, although not an exhaustive detailing of every occurrence of groundwater extraction-related subsidence in California, brings together key examples of significant historical subsidence and active occurrences, including those reported in just-published reports by the U.S. Geological Survey. It also provides examples obtained through personal communications with others in the geotechnical community, including the specially assembled Subsidence Resources Group acknowledged in this report. The examples presented in this report identify the impacts and historical costs of such subsidence.

The reference list contains key citations for published and unpublished materials that describe the geographic locations of subsidence and processes that contribute to subsidence in California. Most citations relate to land subsidence resulting from withdrawal of groundwater from subsurface materials by water wells. Several citations describing other processes that cause land subsidence include: failure of natural or man-made underground cavities (solution voids, piping cavities, and engineered openings such as mines), tectonic activity, natural settling of sedimentary materials, oxidation of organic soils (peaty deposits), hydrocompaction (collapse of moisture deficient sediments upon wetting), energy development, and hydrocarbon extraction. Investigation of subsidence in areas where groundwater is pumped must also consider the potential contributions to land subsidence from these other processes.

The reference list comprises primarily articles and reports that have been published in government reports, scientific journals, and proceedings of technical meetings. Active web site links are included as available. A few reports by consultants or students are also listed. Published abstracts of oral presentations at technical meetings are included in the list where they address either geographic locations or subsidence processes that are not well-reported in the more traditional literature. Articles describing damage to infrastructure in subsiding areas and legal and regulatory issues are included.

1.1.2 Subsidence Resources Group

At the outset of the project, a Subsidence Resources Group was created to lend expertise and experience, provide input on document sources, and assist with subsequent tasks, including this Report of Findings. The Subsidence Resources Group comprises 22 experts; 13 currently work for the U.S. Geological Survey, four work for the California Department of Water Resources, and five are retirees or former employees of these agencies. Most members of this group have contributed to articles and reports contained in the reference list.

2 SUBSIDENCE PROCESSES IN CALIFORNIA

In California, land subsidence primarily occurs as a result of groundwater extraction, but can also result from collapse of underground cavities, tectonic activity, natural consolidation of sediment, oxidation and compaction of organic deposits, hydrocompaction of moisture deficient soil and sediments, development of geothermal energy, and extraction of hydrocarbons. Land subsidence resulting from groundwater extraction is the primary focus of this report. However, it is important to recognize the potential effect of other processes. Subsidence processes other than those related to groundwater extraction are described in **Appendix A**, and some examples of the significance of other contributing factors are provided below.

Tectonic forces influence all of California. Consequently, it is necessary to consider their effect on land surface elevation both in subsiding areas and in elevated bedrock areas used for reference elevations when evaluating subsidence in alluvial basins.

Gas and oil wells produce hydrocarbons and saline formation water from sedimentary rocks and deposits that are usually deep in the subsurface. Because aquifers that provide groundwater often overlie hydrocarbon reservoirs, distinguishing subsidence resulting from hydrocarbon extraction from that resulting from pumping groundwater can be difficult. Understanding the location and production history of both hydrocarbon reservoirs and aquifers, and obtaining measurements of compaction over discrete subsurface intervals, are important in order to evaluate the deformation caused by each source.

Lofgren (1975) evaluated land subsidence caused by groundwater extraction in areas underlain by oil and gas fields in the Arvin-Maricopa area of the southern San Joaquin Valley. Comparing the elevation changes at surveying monuments (bench marks) directly overlying the oil and gas fields to elevation changes noted in surrounding agricultural areas, he suggested that only the component of subsidence in the oil fields that exceeded subsidence in adjacent agricultural areas was caused by oil and gas extraction. He concluded that subsidence in oil fields was of little concern compared to subsidence related to groundwater extraction, although conceding that only a small part of the oil production, and therefore the consequent subsidence, occurred during the period of available leveling measurements. Subsidence caused by groundwater extraction has reportedly damaged the steel casings of oil and gas wells located near the San Joaquin River west from Fresno, California (Glenn Muggelberg, California Division of Oil, Gas, and Geothermal resources, oral commun., September 17, 2013). Measuring compaction over appropriate subsurface intervals is the only way to conclusively discriminate which compacting process has contributed to subsidence measured at the land surface.

3 EXTRACTION OF GROUNDWATER FROM THE SUBSURFACE

A balance occurs naturally in an undeveloped aquifer system where recharge mechanisms and discharge mechanisms of groundwater are equal (**Figure 3-1**). Pumping for urban or agricultural uses changes the balance of the system and may lead to land subsidence (Galloway et al., 1999). Aquifer systems experience some degree of deformation in response to changes in stress (additions such as recharge or withdrawals such as groundwater pumping). The seasonal cycle of discharge and recharge from unconsolidated heterogeneous aquifer systems like those underlying many locations in the Central and San Joaquin Valleys typically causes measurable elastic (recoverable) land subsidence and proportionate uplift (measured in millimeters to centimeters) of the land surface. Removing water from storage in fine-grained silts and clays that are interbedded in the aquifer system can cause these highly compressible sediments to compact inelastically and permanently. Land subsidence from inelastic (non-recoverable) compaction is a common consequence of the significant groundwater level changes that can result from developing groundwater as a water resource.

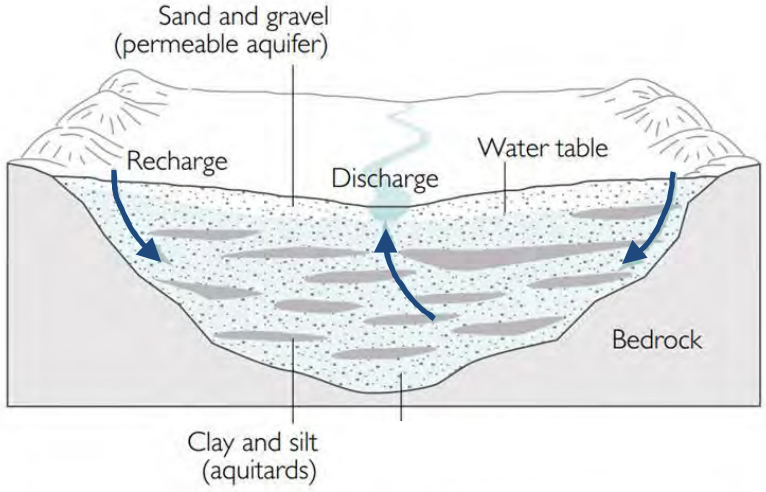


Figure 3-1. An undeveloped aquifer system in balance (adapted from Galloway et al., 1999)

When evaluating land subsidence from groundwater extraction it is important to understand the subsurface distribution and thickness of coarse (sand and gravel) and fine (silt and clay)-grained sediments and the aquifer units that are used by municipal, agricultural, and other wells for groundwater production. The geologic setting, combined with pumping records and the measured physical response of the aquifer system to pumping, are keys to analyzing subsidence.

Section 3.2 describes the mechanisms associated with land subsidence in response to groundwater extraction.

3.1 Unconsolidated Aquifer Systems

Aquifer-system compaction caused by groundwater pumping and extensive water-level declines is responsible for most subsidence in the state and has been observed for decades in the Santa Clara, San Joaquin, Sacramento, Antelope Valleys, and elsewhere. In other instances, it may be an unrecognized or overlooked consequence of groundwater development in alluvial basins. The reduction of fluid pressure in the pores and cracks of aquifer systems, especially unconsolidated sediments, is inevitably accompanied by some deformation of the aquifer system. The physical process is similar to that occurring in oil and gas fields (**Appendix A**).

Unconsolidated sediments composing an aquifer system in an alluvial basin often are sorted into layers of similarly sized particles, i.e., gravel, sand, silt, and clay (**Figure 3-2**). The degree of sorting and layer physical dimensions, from thick and extensive to thin and discontinuous, affect the ability of an aquifer system to store and transmit water. Water moves most easily through permeable coarse-grained deposits of sand and gravel and much more slowly through finer-grained deposits of silt and clay. The fine-grained silt, silty-clay, and clay units typically are "aquitards" that can confine and separate groundwater flowing through coarser-grained aquifers that underlie or overlie them. Thick and extensive aquitards are effective confining units within an aquifer system (**Figure 3-3**). Aquifers often contain thinner and discontinuous aquitards. The arrangement of these elements of an aquifer system determines the bulk hydraulic and mechanical properties that govern how it responds to stresses imposed by extraction of groundwater.

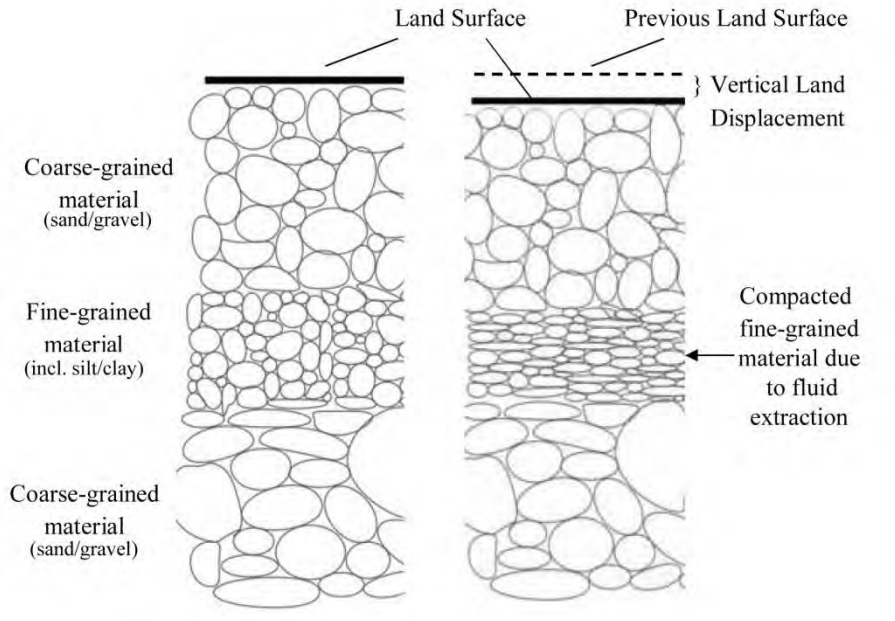


Figure 3-2. Land subsidence due to compaction of fine-grained material after fluid extraction. (adapted from Sneed and Galloway, 2000)

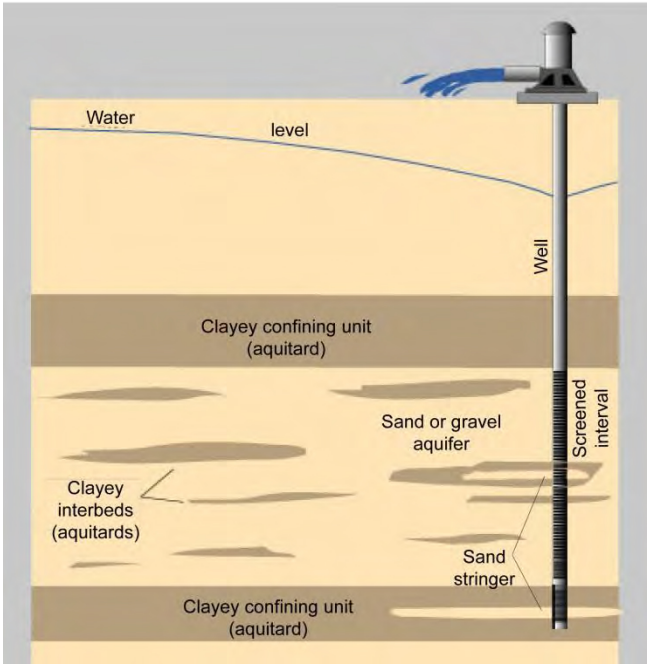


Figure 3-3. An aquifer system susceptible to compaction that results in land subsidence.
Release of water from aquitards, both clayey confining units and clayey interbeds, causes a reduction in thickness of these compressible sediments.

Water levels in wells screened in confined aquifers are higher than the upper surface of the aquifer (**Figure 3-3**).[1] If thin and sometimes discontinuous aquitard layers are numerous, confinement of water flowing through aquifer units increases with depth in the aquifer system. If saturated permeable deposits are not overlain by confining aquitards, they are termed unconfined and are open to the atmosphere via the unsaturated zone, and to direct infiltration from the land surface.

3.2 Elastic and Inelastic Deformation

The weight of materials overlying an aquifer (the rocks and sediments, water, soil, vegetation, and structures on the land surface) is borne within an aquifer system by both the water in the pore spaces and by the clay, silt, sand, and gravel that form the granular mineral skeleton of the aquifer. When pumping lowers groundwater levels and thus fluid pressure in the pores (pore pressure), the weight of overlying materials must be increasingly supported by the mineral skeleton of the aquifer.

Increased pressure or stress on the mineral grains (effective stress) exactly balances the support lost by decreased pore pressure. Increased effective stress causes some compression of the aquifer system skeleton and, if the stresses are large enough, some rearrangement of mineral grains and compaction of the aquifer system. The aggregate result of aquifer-system compaction

[1] The term artesian is sometimes used as an adjective to refer to a confined aquifer.

within the full thickness of the system is expressed as subsidence at the land surface. It is well known that extraction of groundwater by pumping wells causes a complex three-dimensional deformation of an aquifer system (Galloway and Burbey, 2011). However, because of its conceptual simplicity and wide application to accurately describe subsidence measured in in California and throughout the world, one-dimensional vertical compaction discussed here is used to illustrate land subsidence processes throughout this report.

Aquifer-system deformation can be fully reversible (elastic) or largely permanent (inelastic). Elastic deformation occurs when sediments compress as pore pressure decreases, and expand equally as pore pressure increases. The consequent cycles of subsidence and rebound of the land surface commonly occur seasonally, coincident with cyclic groundwater discharge and recharge. The elastic compressibility of clayey aquitards typically is several times larger than that of coarser-grained aquifers.

Elastic deformation does not permanently alter the water storage properties of an aquifer, that is, the same volume of water can be stored in an aquifer after many cycles of solely elastic compression and expansion. The magnitudes of elastic subsidence and rebound are equivalent and typically small, ranging from about 2×10^{-6} to 8×10^{-6} feet of subsidence (or rebound) per foot of aquifer-system thickness per foot of hydraulic head change (the terms “hydraulic head”, “water level” and “pore pressure” are used interchangeably here). For example, 0.25 feet of reversible subsidence would result from a hydraulic head decline of 100 feet in a 500-foot-thick aquifer system with an average elastic compressibility. If the water-level decline occurred over a large area a large but shallow (0.25 ft-deep) subsidence bowl would form at the land surface. The bowl would disappear when water-levels recovered and land surface rebounded. The rebound occurs because the aquifer system has not been permanently reconfigured into a denser, more closely packed arrangement. Neglecting the time it takes for water to drain from aquitards (Section 3.3), because they are more elastically compressible than coarser-grained parts of the aquifer system, they can elastically yield and then regain, should water levels rise, more groundwater than coarser-grained aquifer sand and gravel units.

Permanent compaction results only when the sediments are compressed inelastically beyond their previous maximum effective stress (preconsolidation stress). The preconsolidation stress, the effective stress threshold at which inelastic compaction begins, generally is exceeded when groundwater levels decline past historical low levels. In these stress ranges, the materials compress inelastically, and the inelastic compaction and consequent land subsidence are largely permanent and irreversible. Because clay (particularly montmorillonite) and diatomaceous deposits (materials that contain a high percentage of the siliceous skeletal remains, or frustules of phytoplankton) are often highly compressible and subject to rearrangement of the grains, depressurization results in more compaction and subsidence than depressurization of less compressible, coarser-grained deposits of sand and gravel. In fact, inelastic compaction of

coarse-grained sediment generally is negligible unless very large decreases in pore pressure increase effective stress to levels that fracture mineral grains or crush diatom frustules as sometimes occurs in oil and gas fields (**Appendix A**).

The inelastic compressibility of aquitards typically ranges from 20 to more than 100 times larger than their elastic compressibility. For example, in contrast to the earlier example for elastic subsidence, 20 feet of compaction and permanent land subsidence would ultimately result from 100 feet of hydraulic head decline beyond the preconsolidation stress in an aquifer system containing an aggregate 500-foot thickness of fine-grained, clay-rich sediments with a typical inelastic compressibility (4×10^{-4} feet of irreversible subsidence per foot of aquifer-system thickness per foot of head change). If the water-level decline occurred over a large area, a large 20 ft-deep subsidence bowl would form at the land surface. Except for a small amount of elastic subsidence and rebound (perhaps as much as 0.4 ft), the subsided area would remain a permanent feature of the land surface even when groundwater levels recovered to original values. The subsidence is permanent because clayey mineral grains in the aquifer system have been reconfigured into a denser, more closely packed arrangement.

3.3 Delayed Yield, Residual Compaction, and Water of Compaction

The relative timing of variations in hydraulic head and aquifer-system compaction is often complex. Because clay and other fine-grained sediments have low hydraulic conductivity (permeability), changes in hydraulic head are transmitted slowly through these materials. Typically, when pumping wells extract groundwater from aquifer systems, water in aquitards (confining units and clayey interbeds, **Figure 3-3**) moves slowly vertically outward toward adjacent depressured coarser-grained sediments that transport groundwater to wells. Although hydraulic heads in thin aquitards (1 to 3 feet) equilibrate relatively quickly to a pressure decline in adjacent aquifers, pore pressures in the middle of thick aquitards may take decades or centuries to equilibrate. The result of this delay is that the magnitude of subsidence is considerably less than would ultimately result if hydraulic head had equilibrated with the lowest water levels in adjacent aquifers. For example, if hydraulic head in thick aquitards at the area of maximum subsidence in the San Joaquin Valley had equilibrated with the lowest water levels in adjacent aquifers, it is likely that subsidence would be double the almost 30 feet measured (Riley, 1998). Compaction of thick aquitards can be hastened if the aquitards drain from both their upper and lower surface to depressured parts of the aquifer system, or if screened intervals in pumping wells intersect stringers of permeable sand that lie within them (**Figure 3-3**).

The delay in drainage or delayed yield of groundwater from the middle of thick aquitards results in residual compaction that may continue long after water levels have stabilized in the aquifers. The unequal distribution of hydraulic head in these low permeability confining units leads to a complex vertical distribution of preconsolidation stress within them. It is likely that unequal distribution of preconsolidation stress in aquitards accounts for the rapid re-initiation of inelastic

compaction in some areas of the Central Valley where temporarily recovered groundwater levels in permeable parts of the aquifer have more recently declined, though not below historical low levels (Borchers et al., 1999). Similarly, residual compaction measured during winters in the 1990s after water levels in wells at Edwards Air Force Base in Antelope Valley, California recovered from summer pumping is likely caused both by the lingering effects of seasonal drawdown on the aquifer system and the ongoing long-term effects of delayed yield from thick, slowly draining aquitards still responding to large water-level declines between 1950 and 1975 (Sneed and Galloway, 2000).

Confining units are often thicker than the permeable units of the aquifer system, so although the permeabilities of aquitards are low, their storage capacities can be very high. Freeze and Cherry (1979) provide important insight to the long-term relationship between pumping and the release of water from the aquifer and confining units (aquitards), which may result in inelastic compaction:

> "In the very early pumping history of a production well, most of the water comes from the depressurization of the aquifer in which the well is completed. As time proceeds the leakage properties of the aquitards are brought into play and at later times the majority of the water being produced by the well is aquitard leakage[2]. In many aquifer-aquitard systems, the *aquitards provide* the water and the *aquifers transmit* it to the wells. It is thus of considerable interest to be able to predict the response of aquitards as well as aquifers."

In overpumped, confined aquifer systems, water provided during inelastic compaction of aquitards (water of compaction) typically amounts to between 10 and 30 percent of the total volume of water pumped (Riley, 1969). The volume of the permanently subsided region is equal to the volume of storage space lost, which is equivalent to the volume of water of compaction.

When water of compaction is removed, the pore space that it occupied is reduced. However, this does not mean that the nonrecoverable compaction constitutes substantial structural damage to an aquifer system. The hydraulic conductivity (permeability) of aquitards is reduced by inelastic compaction but the notion that subsidence collapses aquifers and destroys usable storage space for water is a misrepresentation of the physical process. This space in the aquitards was never available for cyclic storage of groundwater. A published quotation from Joseph Poland, in answer to a question raised about inelastic compaction after his presentation at the 1969 IASH/AISH land subsidence symposium in Tokyo, Japan, states this concept simply: "…as far as the aquifers themselves are concerned (the permeable beds), there has been very little compaction, so that the usable storage capacity of the aquifer system is affected very little by this actual subsidence" (Poland, 1969, p.294). A key aspect of Poland's statement is his use of the

[2] Leakage includes water derived from inelastic compaction in the aquitard and also water moving vertically through confining units from adjacent aquifers.

word ‘usable’, which is intended to describe cyclically reusable storage space in an aquifer system.

Water managers may need to take a long-term perspective with regard to economic issues created by inelastic compaction of thick confining units. For example, after an initial period of inelastic compaction and subsequent water-level recovery, extracting an identical amount of water during a second pumping cycle will result in lower water levels than during the first cycle of pumping. During the second pumping cycle, less water is stored in aquitards because of previous compaction. Additionally, previous compaction decreases the vertical hydraulic conductivity in the aquitard making it more difficult for water to be released. Lowering water levels further to produce the same volume of water initially retrieved will induce additional inelastic compaction and additional, permanent land subsidence. This pattern repeats until hydraulic head throughout the confining units equilibrates with that in more permeable parts of the aquifer system. Effectively though, in the lifetime of a water manager, there will be no equilibration for affected systems with thick confining units. The manager will have to contend with inelastic compaction each pumping cycle. The energy expended and the pumping costs to lift groundwater to the surface will increase as water levels drop farther during each pumping cycle. Wells with damaged casings will have to be repaired and most likely replaced. In California, loss of capacity in water conveyance facilities such as canals, streams and rivers, flood bypass channels and the loss of effectiveness of levees are other expensive consequences of subsidence that have to be remediated. Damage to roads, bridges, building foundations, pipelines, and other surface and subsurface infrastructure may result in exposure to liability claims. Moreover, the development of earth fissures can accompany the subsidence and damage surface and subsurface structures and also provide conduits for sources of contamination at the land surface to shallow aquifers, further degrading the resource.

Water of compaction is available only once – beginning when the aquifer system experiences historically low water levels. Riley (1998) described this as follows:

> “The water released by inelastic compaction represents ground-water mining in the truest sense of the term-- a one-time exploitation of a nonrenewable resource, unusable if not mined but accessible only at the cost of the significant and in some cases unacceptable environmental impact.”

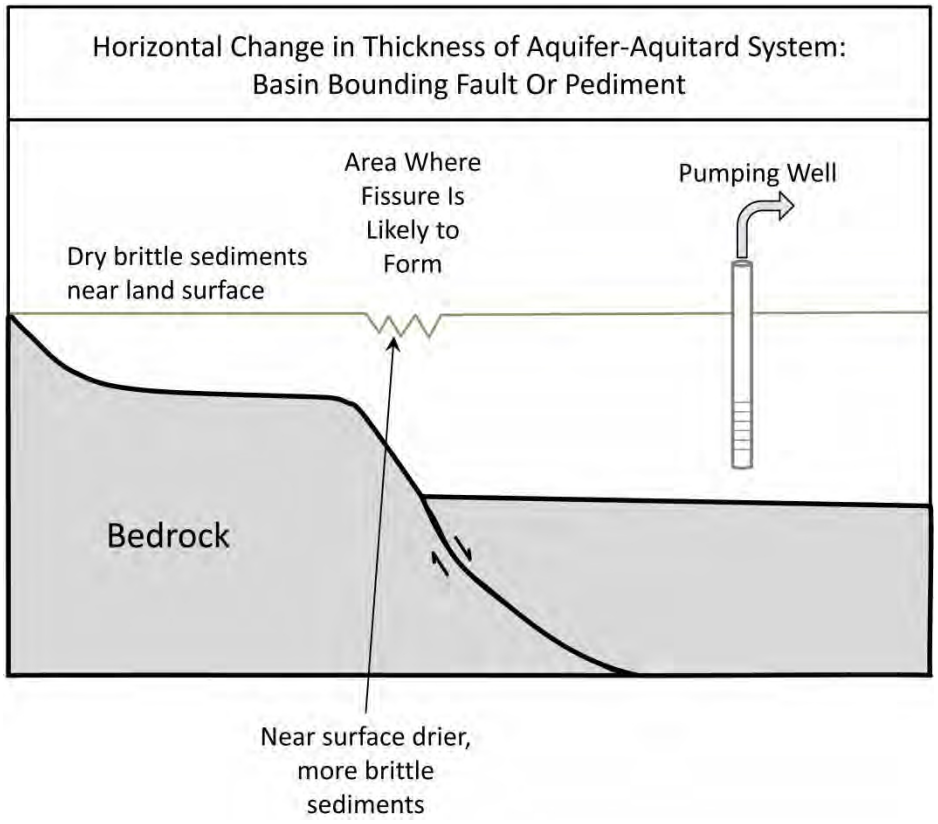
Water of compaction is akin to a sequestered inheritance, such as a chest of rare coins buried deeply out of sight. It is not invested, so it gathers no interest although its value can fluctuate with market forces and the costs to retrieve it. It is only available once, so its expenditure should be planned carefully. In California, water of compaction has supported a vibrant agricultural industry and expanding population. It can be argued, though, that its use has not been carefully planned; a legacy of aquifer-system compaction, land subsidence, and unanticipated deleterious

effects on surface and subsurface infrastructure has resulted. These impacts are discussed later in this report.

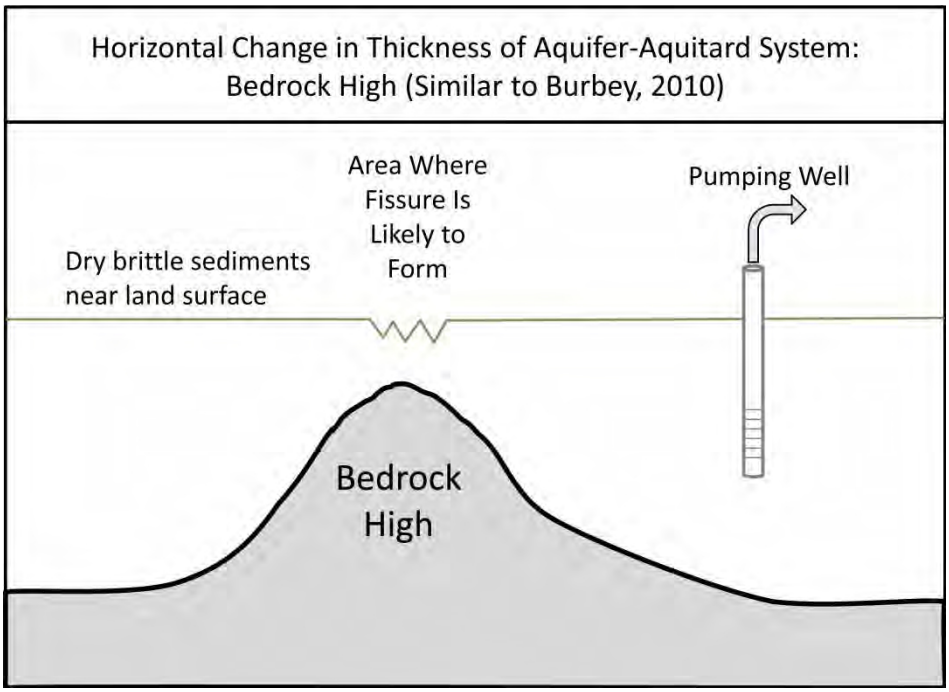
3.4 Earth Fissures

Earth fissures are long curvilinear cracks in unconsolidated alluvial basins that have undergone groundwater depletion. In the western United States, earth fissures have occurred predominantly in California, Arizona, Nevada, New Mexico, and Texas. Holzer (1980) distinguished between earth fissures, which exhibit little evidence of vertical offset, and surface faults, which exhibit mostly vertical movement and are associated with known tectonic faults at depth. Earth fissures commonly occur around the periphery of basins where thickness of the aquifer system subjected to water-level decline varies laterally, resulting in differential vertical compaction of the aquifer system (Jachens and Holzer, 1982). Differential compaction means that the amount of compaction within an aquifer system differs significantly with location. Differential compaction results in different magnitudes of subsidence over short distances on the land surface. Other causes of differential compaction may include shallow buried bedrock away from the periphery of a basin, faults within the basin-filling sediments (Burbey, 2010) and fault-plane barriers to groundwater flow (Holzer, 1980). Differential subsidence results from lateral differences in thickness, compressibility or the amount of water-level decline within an aquifer system. (**Figures 3-4A-D**). Differential compaction also produces horizontal deformation of the land surface as sediments overlying an aquifer system in a fissure-prone area bend (Holzer, 2010).

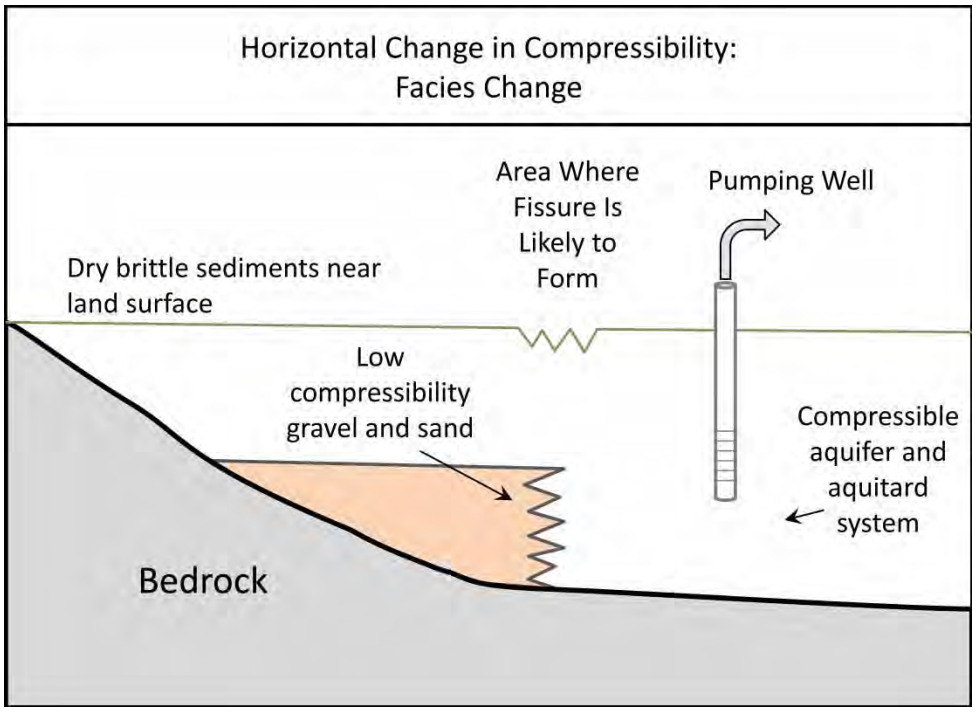
A


Horizontal Change in Thickness of Aquifer-Aquitard System:
Basin Bounding Fault Or Pediment
Area Where Fissure Is Likely to Form
Pumping Well
Dry brittle sediments near land surface
Bedrock
Near surface drier, more brittle sediments

B


Horizontal Change in Thickness of Aquifer-Aquitard System:
Bedrock High (Similar to Burbey, 2010)
Area Where Fissure Is Likely to Form
Pumping Well
Dry brittle sediments near land surface
Bedrock High

C



D

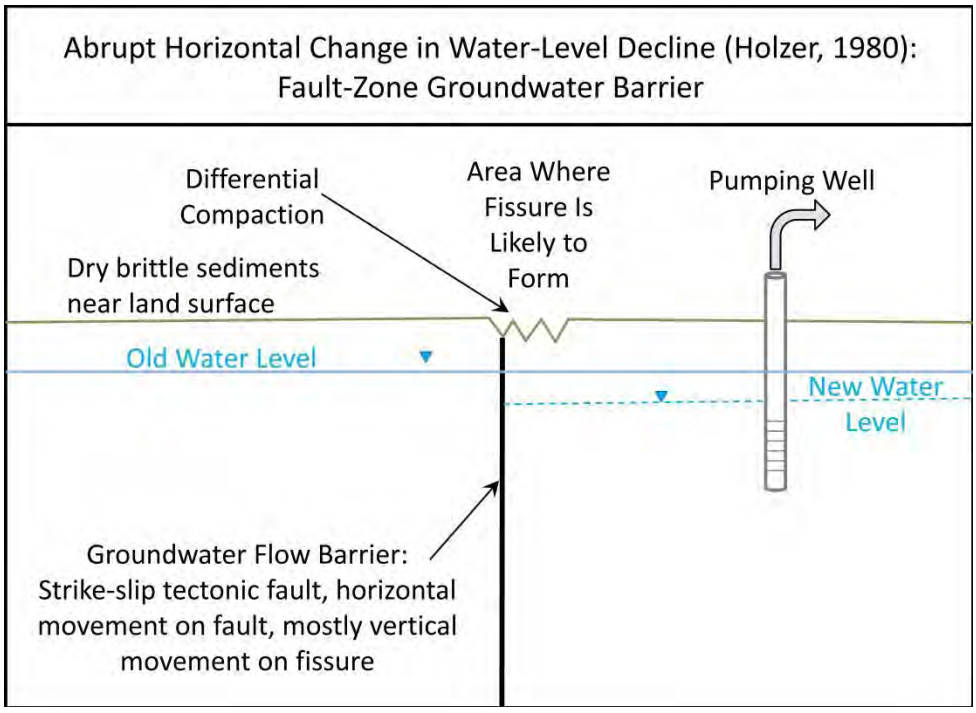


Figure 3-4 A-D. Schematic of differential compaction settings for earth fissures. A) Wells pumping near a substantial change in the thickness of compressible aquifer materials at a basin-bounding fault trigger fissuring. B) High total compaction in thick sediments triggers fissuring where sediments are thin over a buried bedrock high. C) Fissure forms where less compressible sand and gravel transition to highly compressible clay and silt. D) Sediments are uniformly compressible, but a fissure forms where a fault barrier prevents groundwater from flowing toward pumping wells.

Some earth fissures have occurred in the absence of measured differential compaction although differential compaction may or may not have been present. Other hypotheses include piping erosion (Fletcher et al., 1954), brittle vertical rupture of a rigid aquifer slab at the buried bedrock edge of a basin-bounding fault (Bouwer, 1977), horizontal seepage stresses (Lofgren, 1971), and an effective hydraulic stress (Helm, 1994a), that includes a total or bulk stress and the negative of Lofgren's seepage stress, which acts to move aquifer-system sediments horizontally toward pumping centers and which may not be associated with differential vertical compaction.

Earth fissure zones may be as much as 200 m (600 ft) wide and consist of multiple parallel, branching, or en echelon (stepped offset) fissures and graben (downdropped) blocks. Where fissure initiation has been observed, fissures formed first as hairline cracks on the land surface and widened during storms. Fissures may open by collapse to a width of as much as 6 m (20 ft) and depth of as much as 9 m (30 ft). Fissures may propagate by extension or may continue to widen without apparent lengthening. A continuous record of extensional movement across one fissure showed that more than 25 mm (1 in) of tensile opening occurred in less than 16 hr during the passage of the remnant of a hurricane. Several major fissure openings have occurred during severe storms as water floods into a crack at the land surface, dissolves cementing materials in the desert soils, erodes sediments, and builds up more than 10 to 20 m (30 to 60 ft) of hydraulic head (water level), causing hydraulic fracturing. Because of the paucity of information describing deformation of the sediments below land surface, it cannot be stated with certainty, whether fissures form at land surface and propagate downwards, form at depth and propagate upward or if propagation direction is dependent on the particular physical process causing fissuring (Holzer, U. S. Geological Survey, oral commun. January 17, 2014).

The Picacho earth fissure in south-central Arizona may be the most thoroughly studied fissure in the world. It was visible in the Super Bowl Chevrolet Cobalt commercial in 2012 (**Figure 3-5**). The fissure marks the location of a Basin and Range dip-slip (vertical movement) fault that horizontally juxtaposes alluvium of different compressibilities. The Picacho earth fissure opened after an earthquake in 1927, before major groundwater pumping began in that basin, but major vertical offset began with increased pumping after WWII. The fissure is 16 km (10 mi) long, has a depth of 300 m (1,000 ft) as a dip-slip (vertical displacement) fault, and exhibits parallel fissures 200 m (600 ft) apart in some sections. Since World War II, the fault has not been tectonically active; the fissure has experienced more than 0.6 m (2 ft) of vertical offset in many places due to differential compaction of aquifer sediments. During 1980-1984, seasonal movements of 4 mm opening and 2 mm closing were correlated with 16 m (52 ft) of water-level decline and recovery, respectively. During that time 20 mm (0.8 in) of vertical offset occurred, with the basinward side downthrown.

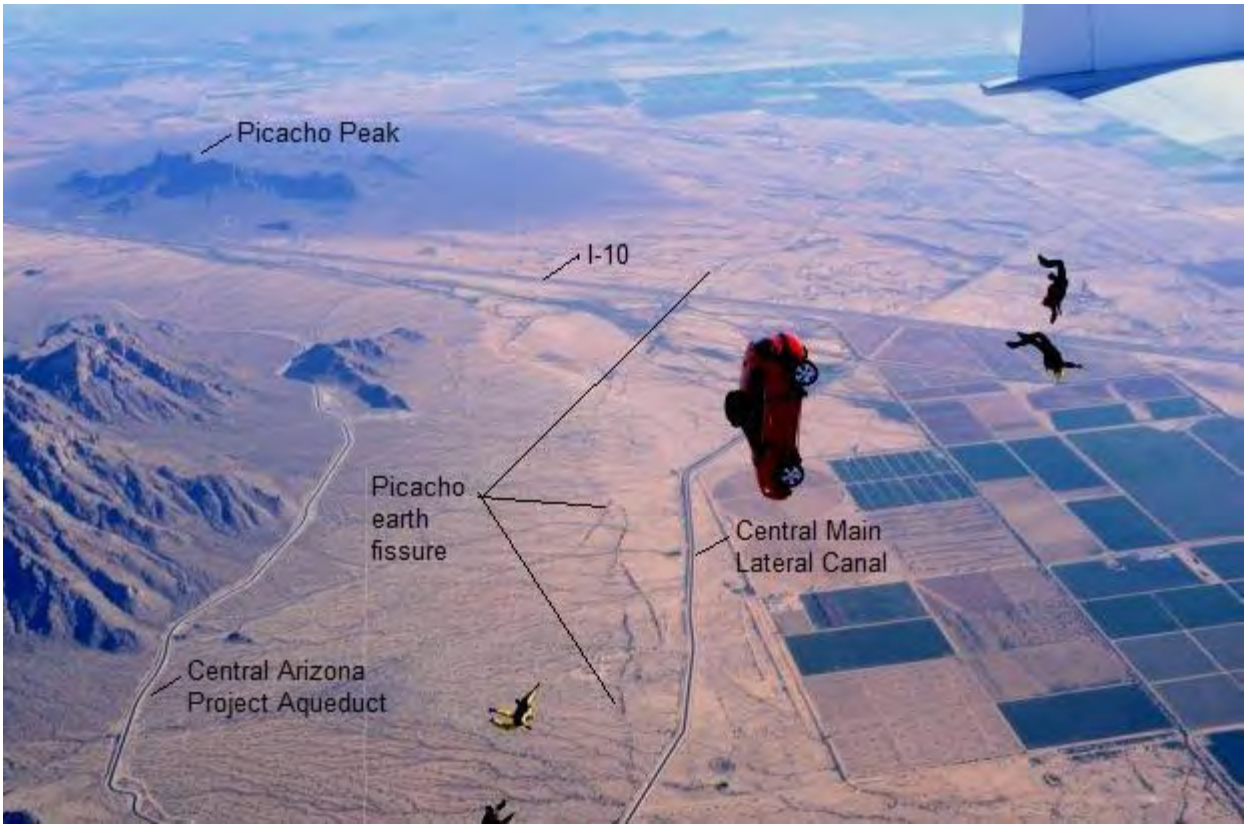


Figure 3-5. Picacho earth fissure in Superbowl 2012 Chevrolet Cobalt commercial. View is toward the south. Holes and cracks have occurred in the concrete lining and berm of the Central Main Lateral Canal where it crosses the fissure at the bottom of the photograph.

Damage from earth fissures includes (typical fissures shown in **Figure 3-6 and 3-7**):

- cracked and offset streets, highways, and airport runways
- railroad derailments
- loss of field irrigation
- erosional destruction and cracking of irrigation canals
- forced rerouting of an aqueduct
- cracked and condemned houses
- utility disruption
- groundwater contamination from surface pollutants.

Potential disasters from cracking include:

- explosions from cracked gas lines
- explosions in sewer lines when methane is trapped because of changes in gradients
- multi-car pileups on freeways because of a sudden, several centimeter (1 in) vertical crack opening during passage of a tropical storm.



Figure 3-6. Earth fissure, Harquahala Plain, Arizona, USA. (USGS photo)



Figure 3-7A. Earth fissure, Rogers Dry Lake at Edwards Air Force Base, California. (USGS photo)



Figure 3-7B. Earth fissure, Edwards Dry Lake at Edwards Air Force Base, California. (USGS photo)

4 SUBSIDENCE FROM GROUNDWATER EXTRACTION IN CALIFORNIA

Groundwater extraction from nearly any aquifer will cause some degree of subsidence as aquifer materials adjust to new stresses. In fact, any change of groundwater levels from any cause, natural or human induced, will move the land surface up or down in response to expansion or compression of aquifer materials. Substantial and damaging subsidence from groundwater extraction in California is nearly always related to inelastic compaction in an aquifer system, and sometimes to differences in the magnitude of compaction over short lateral distances (differential compaction and subsidence).

This section presents summaries of subsidence attributed to groundwater extraction (**Figure 4-1**). The summaries are organized by geographic location, and they range from an area that has been called the largest human alteration of the surface of the Earth's surface, described in scores of scientific reports and scholarly articles, to small areas of minor subsidence that may not have been previously described in the scholarly literature.

4.1 Santa Clara Valley

The northern Santa Clara Valley, an alluvial lowland at the southern end of the San Francisco Bay, was the first area in the United States where land subsidence due to groundwater overdraft was recognized and described (Tolman and Poland, 1940). It is also the first area where remedial action effectively halted the subsidence caused by massive withdrawals of groundwater that supplied water first for agricultural development and later primarily for domestic and industrial uses.

Ingebritsen and Jones (1999) described the history of water use and land development that precipitated land subsidence and later recovery of water levels in the aquifer system of the Santa Clara Valley. During the late 1800s, most wells in the central Santa Clara Valley between San Jose and the bay, and along the bay shore to the northeast and northwest, flowed freely; pumps were not needed in these wells. Wells produced water from an artesian aquifer as thick as 245 m (800 ft) that was confined beneath clayey deposits at about 18 m (60 ft) below land surface (Poland and Ireland, 1988). Agriculture developed rapidly in the early 1900s; two thirds of the valley was irrigated by 1920. By 1930, the groundwater level in a monitoring well in San Jose had fallen to 24 m (80 ft) below land surface. Subsidence was first noted in 1933, when bench marks installed in 1912 were found to have subsided more than 1.12 m (3.66 ft) (Fowler, 1981). Except for a few years in the early 1940s when higher than normal precipitation and stream runoff recharged aquifers, groundwater levels continued to decline. In 1964, the water level in the San Jose monitoring well had fallen to 72 m (235 ft) below land surface. Spirit-level surveys in 1967 identified subsidence of substantial magnitude and areal extent (**Figure 4-1 and 4-2**).



Figure 4-1. Location of areas of subsidence caused by groundwater extraction in California. (Historic subsidence is defined for convenience in this report as occurring before 1993.)

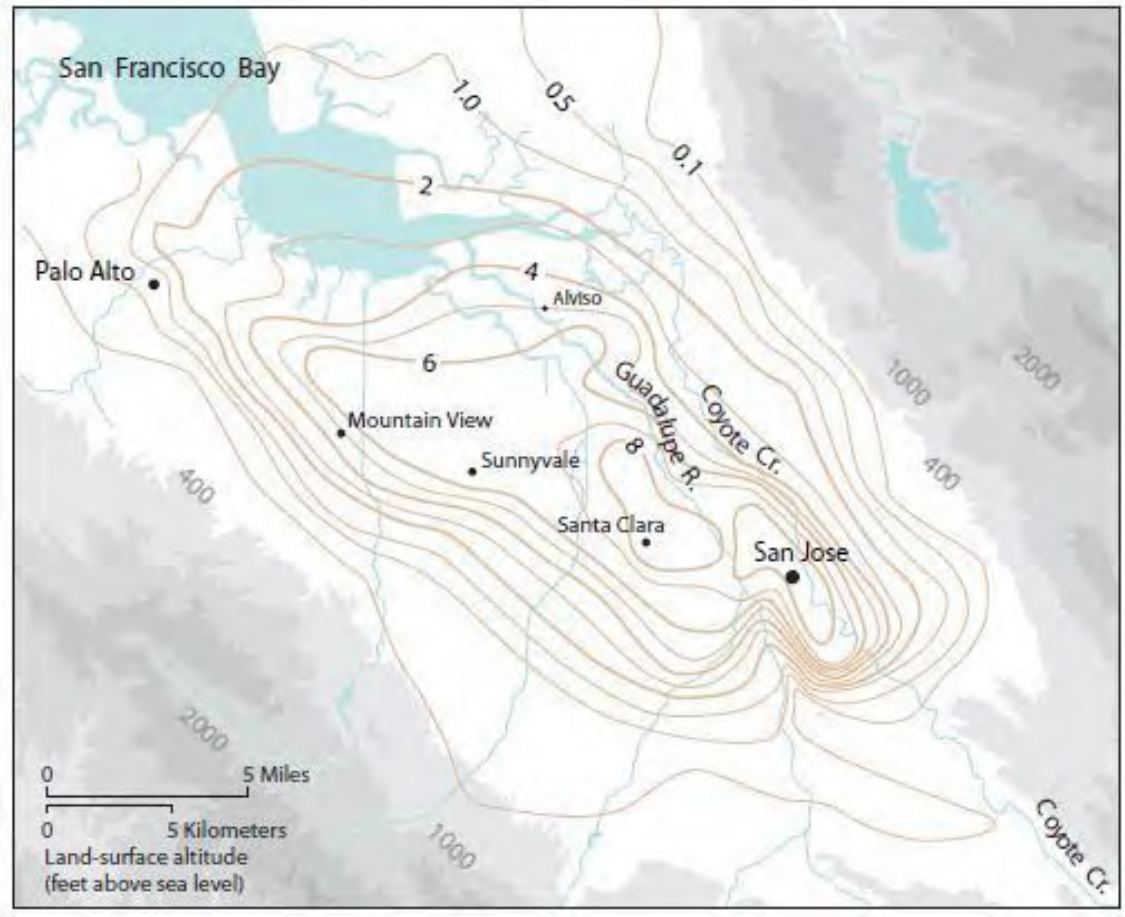


Figure 4-2. Contours of land subsidence in the northern Santa Clara Valley during 1934-1967, in feet (from Ingebritsen and Jones, 1999).

Between 1910 and 1995 subsidence was greatest, 4.2 m (14 ft), in downtown San Jose. About 260 km^2 (100 mi^2) of land had subsided by more than one foot.

In 1935 and 1936, the Santa Clara Valley Water District (SCVWD) built dams on local streams to retain flood flows for later release, in order to foster recharge of the aquifer system through stream beds. The SCVWD began to import water from the Hetch Hetchy reservoir in the Sierra Nevada in 1951, from the California State Water Project in 1965, and from the San Felipe Project of the Federal Central Valley Project in 1987. About 25 per cent of the imported water was used for groundwater recharge projects. Water imports for consumptive use and recharge projects proved successful; water levels in the confined aquifer system made a dramatic recovery. A pumping tax imposed in 1964 provided a disincentive to pump groundwater and thus contributed to groundwater-level recovery.

Subsequently, some abandoned and long-forgotten wells have begun flowing once again. Subsidence has been completely arrested. The SCVWD now manages the aquifer system within

tight water-level and subsidence tolerances designed to prevent the reoccurrence of land subsidence (see **Section 5**).

InSAR was used to evaluate seasonal and multi-year deformation patterns, understanding of which is critical for implementing appropriate water-management strategies such as subsidence mitigation. An 8-month interferogram (January - August 1997) shows seasonal subsidence of about 30 mm (1.2 in) near San Jose (**Figure 4-3A**) and corresponds to about a 10-m decline in water levels. A 5-year interferogram (September 1992 - August 1997) shows a small amount (15 mm, 0.6 in) of regional uplift (**Figure 4-3B**). The uplift corresponds to a sustained period of water-level recovery throughout the valley. The lack of subsidence between 1992-1997 indicates that the seasonal subsidence during 1997 was elastic (recoverable) (Galloway et al., 1999).

Interferograms prepared by Schmidt and Burgmann (2003) for September 1992-August 1999 indicate that uplift due to long-term elastic rebound of the aquifer system was most pronounced in two locations in the northern Santa Clara Valley— north of Sunnyvale and east of the Silver Creek Fault. The maximum uplift, 41 mm (1.6 in) north of Sunnyvale, was attributed to a greater amount of fine-grained sediment in this area. The elastic compressibility of fine-grained sediment is several times greater than that of coarser-grained materials.

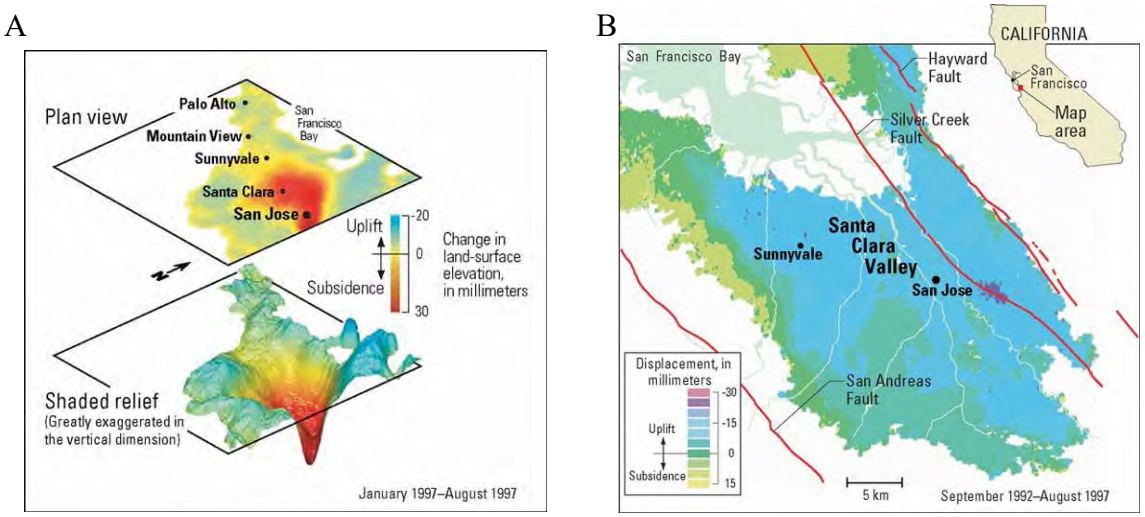


Figure 4-3. Interferograms showing A) seasonal subsidence during January 1997-August 1997, and B) small amounts of uplift over longer time period, 1992-1997 (from Galloway et al., 1999).

Despite the efficient and coordinated management of groundwater and surface-water supplies that allowed groundwater levels to return nearly to predevelopment levels in the Santa Clara Valley, aquifer compaction that occurred historically was almost completely inelastic and land subsidence permanent. The economic costs of this subsidence were substantial and continue today as a legacy of groundwater overdraft from the previous century.

The economic costs of subsidence in California are perhaps nowhere documented as thoroughly as in the Santa Clara Valley. Because the valley has a gentle topographic slope and borders the San Francisco Bay, the effects of subsidence on coastal flooding are dramatic. Were it not for levees at the bay shore and bordering the streams and drains that flow to the bay, about 50 km^2 (19 mi^2) of the Santa Clara Valley would be under water. Fowler (1981) wrote, "Once a person standing on the land near the bay could look down upon the waters. Now, a person standing on the same spot looks up at levees keeping the salt water off the land" (**Figure 4-4)**.



Figure 4-4. The South Bay Yacht Club at Alviso, California in A) 1914, before dikes were necessary to prevent flooding and B) 1978 after dikes were constructed to prevent bay water from flooding areas near the yacht club that had subsided to 10 feet below sea level. The yacht club headquarters stands on the right side of each photograph (photographs courtesy of Santa Clara Valley Water District).

Fowler (1981) described the direct costs for subsidence remediation activities in the Santa Clara Valley. Costs to repair 1,000 wells whose steel casing had been compressed and collapsed by subsidence were estimated to be $2 million dollars between 1960 and 1965. The cost for well replacement during 1960-1965, or repair and replacement in other years, is not included in the estimate. Roll (1967) estimated the cost for well repairs in the valley at $5 million for the same period. Using Roll's early-1960s estimate and 1967 as a base value, well replacement and repair costs amounted to $35 million in 2013 dollars. Where reductions in the design grade of sanitary sewers reduced their carrying capacity, larger sewer mains or parallel lines were constructed, and pumping stations had to be built to lift fluids to the bay at a cost of more than $8 million dollars in 1970 ($48 million in 2013 dollars), exclusive of the additional annual costs for electricity and maintenance of the pumping stations (Viets, et al., 1979). Viets and others (1979) estimated the

cost to operate the additional pumping facilities at the San Jose-Santa Clara Sewage Treatment Plant at $200,000 annually in 1970 ($28 million total through 2013 in 2013 dollars). Raising the grades of roads and bridges cost $2.8 million by 1975 ($12 million in 2013 dollars) not including the costs of repairs necessitated by flooding. The estimated cost of constructing bayfront levees was $58 million in 1973 ($305 million in 2013 dollars), and the initial cost of raising stream channel levees was more than $10 million in 1979 ($32.2 million in 2013 dollars). The initial capital outlay to build pumping stations to remove storm drainage was $2.7 million in 1975 ($12 million in 2013 dollars). Annual operation and maintenance costs for the pumping facilities were expected to exceed the total capital outlay for construction of the plants ($283 million in 2013 dollars). Raising a Southern Pacific Railroad bridge to align it to tracks that had to be moved to avoid flooding cost $100,000 in 1970 (0.6 million in 2013 dollars). Roll's (1967), Viets and others (1979), and Fowler's (1981) cost estimates translate to more than $756 million in 2013 dollars spent on subsidence remediation in the Santa Clara Valley. These costs did not include replacing destroyed wells or repairing wells at other times than 1960-1965, or the indirect costs of silted up stream channels in flood prone areas. Costs to the Southern Pacific Railroad (and its successors) to raise tracks are not included in these estimated costs, nor are the substantial costs to private industry to raise about 80 km (50 mi) of levees protecting 80 km^2 (30 mi^2) of salt evaporation ponds that fringe the bay. The decline in the property values resulting from obstructed views or by flood zone designation has also not been estimated.

Movement on a 0.56 km (0.35 mi) segment of the Busch fault north from Hollister, California, in what is sometimes referred to as the southern Santa Clara Valley, has been attributed to groundwater withdrawal (Holzer, 1984). Tectonic motion on the fault is predominantly right lateral, parallel to the surface trace of the fault, rather than vertical along on the steeply dipping fault plane. Yet measurements during 1970-1975 indicated only a slow, nearly vertical, creeping displacement averaging 8.6 mm/yr (0.34 in/yr) on the fault. The downward displacements on the steeply dipping fault plane were seasonal—coincident with the end of pumping for irrigation in the intensely farmed region. It is likely that seasonal lowering of groundwater levels by pumping wells caused the measured displacements.

4.2 San Joaquin Valley

Land subsidence from groundwater extraction in the San Joaquin Valley has been called the greatest human alteration of the Earth's surface (Galloway et al., 1999). It is inexorably linked to the development of agriculture and the availability of water. Because the valley is semi-arid, and streamflow into the east side of the valley varies substantially from year to year and is mostly not available on the west side, agriculture developed a reliance on the aquifer system. More than half of the thickness of the aquifer system is composed of fine-grained sediments, including clays, silts, and sandy or silty clays (Williamson et al., 1989), that are susceptible to compaction if depressured by pumping wells. Throughout most of the valley, a thick compressible clay, the Corcoran Clay member of the Tulare formation, confines and separates deep aquifer sediments

from a shallow unconfined or partly confined aquifer. Most of the chronic groundwater level decline, and compaction due to decline of hydraulic head, occurred in the deep confined aquifer (Ireland et al., 1984). Most subsidence probably resulted from compaction of relatively thin aquitards within the deep aquifer system rather than in the Corcoran Clay confining unit, because the Corcoran's large thickness and low permeability inhibited drainage of water from its interior (Faunt et al., 2009).

Subsidence related to groundwater withdrawal began in the mid-1920s. Subsidence rates increased as agricultural development intensified after World War II and more wells were drilled to supply water for irrigation; subsidence rates eventually exceeded 1 ft/yr in some places. In 1955, about one-fourth of all groundwater extracted for irrigation in the United States was pumped from the San Joaquin Valley (Galloway and Riley, 1999). Eventually groundwater levels in the deep aquifer system on the west side of the valley declined by more than 122 m (400 ft). By 1970, subsidence of more than 1 foot (**Figure 4-1**) had affected 5,200 square miles—more than half of the valley—and subsidence southwest of Mendota had exceeded 28 feet (Poland et al., 1975).

Despite early recognition of the relationship between groundwater-level decline and subsidence near Delano by I. H. Althouse (Ingerson, 1940), subsidence from groundwater overdraft was not investigated regionally until the early 1950s, when government agencies became concerned about a 30 percent reduction in the design capacity of the San Joaquin River, about the effect of subsidence on the Delta-Mendota Canal (then under construction), and on the California Aqueduct (then in the planning stages). Part of the reason for the delayed reaction to subsidence is that it occurred uniformly and over such a broad area that few residents or agencies realized that it had happened. As late as the mid-1950s, subsidence in the Arvin-Maricopa area was ascribed to tectonically uplifted survey control points in the Tehachapi Mountains south of the valley (Whitten, 1955) rather than to the actual causative agent, decline of groundwater levels (Lofgren, 1975).

In 1954, a Federal-State interagency committee and the USGS "Mechanics of Aquifers Project", headed by Joseph Poland, began studying land subsidence by conducting both field monitoring and research. The studies identified the magnitude and extent of subsidence and its quantitative relationship to groundwater overdraft, developed new monitoring methods and techniques for analysis of field data that allowed accurate computer models of aquifer system compaction to be built, and provided information that allowed optimal siting of the California Aqueduct which, along with the Delta-Mendota Canal and the Friant-Kern Canal, brought surface water into the valley to diminish reliance on groundwater.

Surface water imports allowed groundwater levels to recover by more than 61 m (200 ft) in some areas on the west side of the valley by 1974. Although increasing water levels slowed subsidence

by the early 1970s, subsidence continued due to delayed drainage of water from compacting clayey aquitards, particularly in three areas: the Los Banos-Kettleman City area on the west side of the mid-valley, the Wasco-Tulare area of the southern valley east from the Tulare Lake bed, and the Arvin-Maricopa area in the extreme southern end of the valley (**Figures 4-1 and 4-5**). For example, although no long-term water-level decline occurred at an extensometer installation near Pixley, California (23S25E16N1-4, in the Tulare-Wasco subsiding region) between January 1959 and February 1971, almost 1 m (3.2 ft) of aquifer-system compaction occurred during this period (Helm, 1975). Three fissures formed in the large subsiding area near Pixley, California (Wasco-Tulare area), about 40 km north from Wasco. The easternmost fissure which formed in 1969 was believed to be related to differential subsidence (Holzer, 1984) that probably was triggered by groundwater extraction. During the drought of 1976-1977, groundwater was used to make up for reductions in surface water deliveries. Movement during 1977-1978 on the northern end of the Pond-Poso Creek fault, an active tectonic fault located about 11 km (6.8 mi) north of Wasco was attributed to stresses imparted by declining groundwater levels (Holzer, 1977 and 1980).



Figure 4-5. Primary areas of subsidence in the San Joaquin Valley (from Galloway et al., 1999). A, Los Banos-Kettleman City, B, Wasco-Tulare, C, Arvin Maricopa.

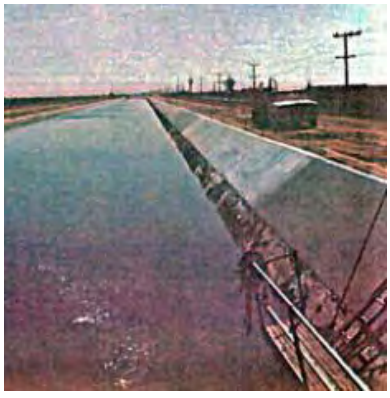
About 48 km (30 mi) of the Friant-Kern Canal, from 153 to 201 km (95 to 125 mi) downstream of the Friant Dam, was impacted by subsidence in the Tulare-Wasco area. Between the end of construction in 1951 and January 1975, parts of the affected reach of the canal subsided 5.5 ft, interfering with operations (Prokopovich, 1983). Measurements of water depth at closed check dams indicated that subsidence also affected parts of the canal farther south toward Bakersfield. During 1976-1980, a 26.67 km (16.67 mi) reach of the canal was rehabilitated. Canal berm materials were excavated and recompacted (**Figure 4-6 A**), concrete linings were extended upward (**Figure 4-6 B**), bridges were raised (**Figure 4-6 C, D**), canal turnout structures and drain inlets were modified, and three large pumping plants were raised on new foundations. Costs for the remedial activities in 2013 dollars totaled $15 million (calculated from 1976, 1977, and 1980 contract amounts provided in Prokopovich, 1983). Currently, a $25 million (2013 dollars) rehabilitation of upstream reaches of the Friant-Kern Canal is planned to improve flow capacity where original design limitations, increased canal roughness, and perhaps small amounts of land subsidence have reduced its intended capacity.

Although only about one-third of the peak annual groundwater volumes of the 1960s was pumped during the 1976-1977 drought, water levels fell more than 45.7 m (150 ft) over a large area on the west side of the valley, and subsidence rates increased. The droughts of 1987-1992 and droughts and regulatory reductions in surface water diversions during 2007-2010 had similar effects, despite the fact that water levels never approached the historically low levels of the 1960s.

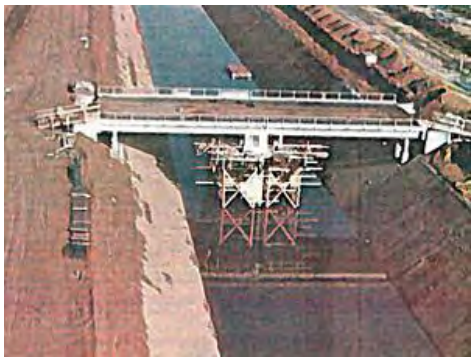
A



B



C



D



Figure 4-6. Remedial activities in subsidence-affected reaches of the Friant-Kern Canal. A) Excavating the canal berm for recompaction, and B) extension of concrete canal lining, C) cribbing emplaced to raise bridge higher, D) jacking operation in progress at Avenue 88 bridge, where only one workman is clearly visible in the photograph, but 21 more workman are under the bridge manning 50-ton jacks (from Prokopovich, 1983).

Increased use of the aquifer system during climactic and regulatory droughts is reflected in statistics on new well construction compiled by the California Department of Water Resources (**Figure 4-7**). At the end of the drought in the late 1970s, surface water availability increased and fewer wells were drilled until the drought of 1987-1992. New well construction peaked in 1991, when more that 1,100 new wells were drilled in the valley. After the 1987-1992 drought, fewer wells were constructed until the regulatory reductions in surface water diversions prompted additional well construction beginning in 2007.

The rapid decline of groundwater levels during post-1975 droughts in response to relatively small volumes of pumping (compared to those of the 1960s) results from a loss of storage space in the aquifer system—mostly from inelastic compaction of aquitards during the 1950s and 1960s— and from reduced hydraulic conductivity (permeability) of those compacted aquitards that restrict drainage of water to permeable parts of the aquifer system. Observations showed that water levels were considerably higher than during the 1960s, yet there was renewed land subsidence during droughts. This illustrates the complex effects of unequal distribution of preconsolidation stress within the aquitards and between the aquitards and more permeable units of the aquifer system (see **Section 3**).

Comprehensive leveling surveys of the valley ended in 1970 and, over time, funding for coordinated subsidence investigations also ended, and field installations such as borehole extensometers and water-level monitoring wells were decommissioned or fell into disrepair. DWR continued to collect compaction data from a few extensometers and from deep monitoring wells where available, and state, federal, and local water agencies continued to run surveys on

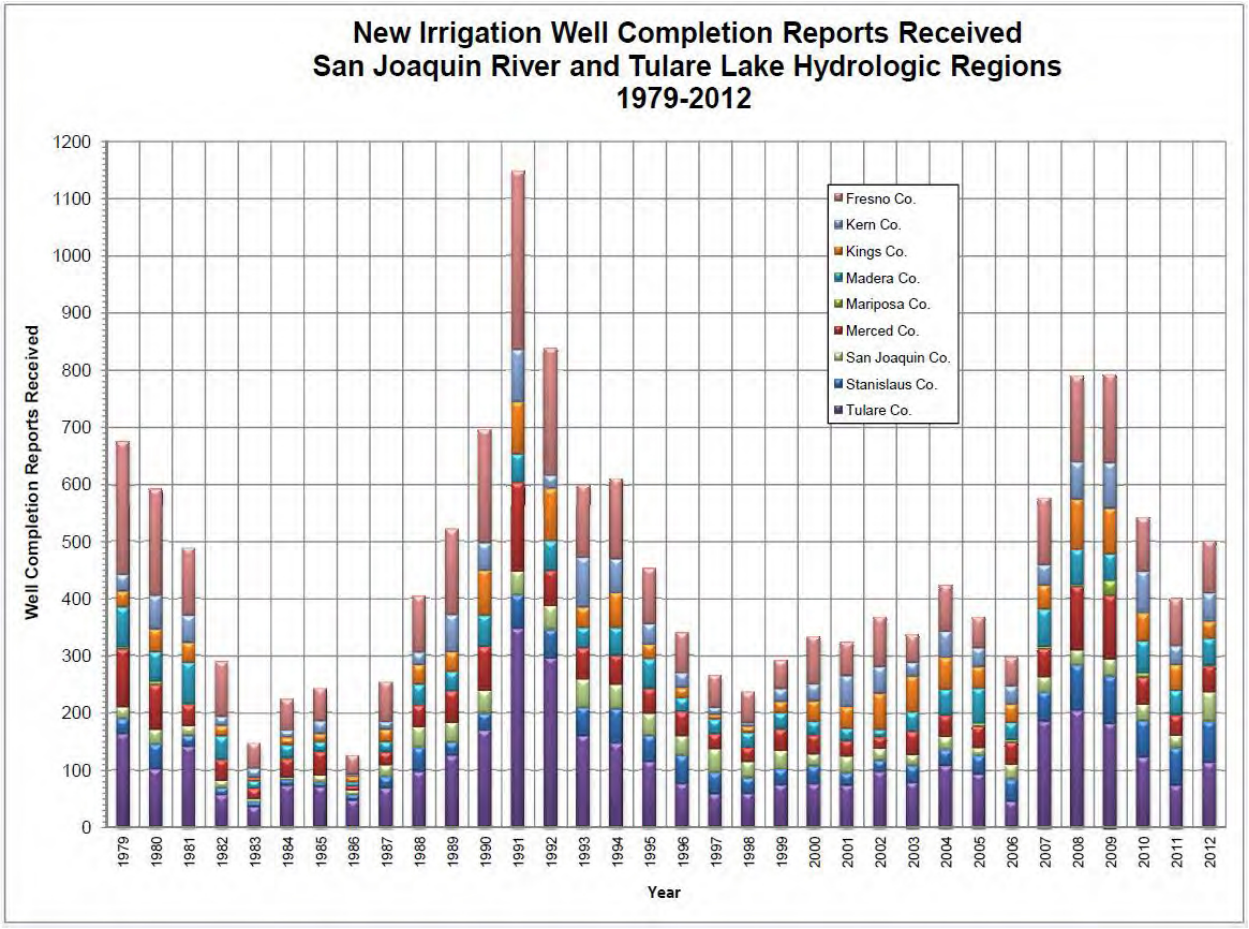


Figure 4-7. Number of well completion reports received by the California Department of Water Resources annually for counties within San Joaquin Valley. (courtesy of the California Department of Water Resources)

canal alignments intermittently, but analysis of this information was not centralized. Swanson (1998) presented a summary of land subsidence that occurred between 1970 and 1995. His information, gleaned from road, canal and levee surveys, documentation of canal and bridge infrastructure repairs, and reports of changing canal gradients from water agency managers, indicated that subsidence was continuing in each of the three main areas identified in the earlier comprehensive subsidence studies (Los Banos-Kettleman City, Tulare-Wasco, Arvin-Maricopa) and in an additional area near the San Joaquin River north of Mendota.

The current drought and cropping patterns that have changed from row crops and range land to tree and other permanent crops have again forced reliance on aquifer systems in the San Joaquin Valley for agricultural irrigation supplies. Recent Interferometric Synthetic Aperture Radar (InSAR) analyses show that two large areas in the San Joaquin Valley are currently subsiding substantially (Jessica Reeves, Stanford University, written commun., July 9, 2013;Thomas Farr, NASA-JPL, written commun., September, 2013; Sneed et al., 2013). These areas are a large, about 7,000 km^2 (2,700 mi^2) swath of subsidence west of Tulare and east of Kettleman City and

an area about half the size, 3,100 km^2 (1,200 mi^2), but still very large near El Nido (South of Merced and west of Madera; **Figure 4-8**). Currently subsiding areas are shifted substantially from the locales of major subsidence during 1926-1970 (**Figure 4-8**).

Figure 4-8 shows shaded contours of land subsidence in both subsiding areas that were derived from preliminary InSAR analysis (Thomas Farr, NASA-JPL, written commun. February 22, 2014). The large subsiding area in the southern San Joaquin Valley is shifted to the northwest from the Wasco-Tulare area where maximum subsidence during 1926-1970 was about 4 m (13 ft) (Ireland et al., 1984). More than 46 cm (1.5 ft) of subsidence occurred over a large part of the southern subsiding area during 2007-2011. In some places subsidence lowered the land surface 120 cm (3.9 ft). The maximum rate of recent subsidence is about twice the maximum rate that occurred historically in the area.

Caltrans surveys at bench marks along Hwy 198 corroborate the location of the subsidence and indicate that as much as 2.86 m (9.37 ft) of subsidence occurred between the 1960s and 2004 (**Figure 4-9**). Subsidence studies at the Lemoore Naval Air Station (LNAS), which lies in the northwest edge of this subsiding area (Cobett et al., 2011), indicate that total subsidence there between 1925 and 2010 exceeded 10 ft—considerably more than the Caltrans surveys indicated had occurred during the 1960s-2004, 1.0-1.2 m (3.5-4.0 ft). The difference in Corbett's estimate and the Caltrans surveys likely is due to subsidence that occurred prior to the 1960s and after 2004. Because the LNAS and Highway 198 are located on northern fringe of the subsiding area, neither Corbett's estimate or the Caltrans survey capture the maximum subsidence in this region. No independent surface measurements of land subsidence or aquifer-system compaction have been acquired to confirm the magnitude of subsidence represented on the **Figure 4-8** in the southern subsiding area.

The subsiding area reportedly is correlated with increased groundwater extraction needed for changing land use and cropping patterns; open land and seasonal crops have been supplanted by perennial crops and orchards that require irrigation year-round (John Kirk, California Department of Water Resources, oral commun., April 24, 2013). Planning for the effects of continued land subsidence in the area will be important for water conveyance agencies. Canals, rivers, and flood bypass channels sag in subsiding areas, losing freeboard and flow capacity. Historical photographs reportedly show the water surface in a full canal of the Angiola Water District (Corcoran, California, near the center of subsidence) lying 3.7-4.6 m (12-15 ft) below children fishing in the canal with their legs dangling over the canal embankment. 'If a person sat there in the spring of 2013, they would get wet up to their knees' (Matt Hurley, Angiola Water District, oral comm. June 25, 2013).

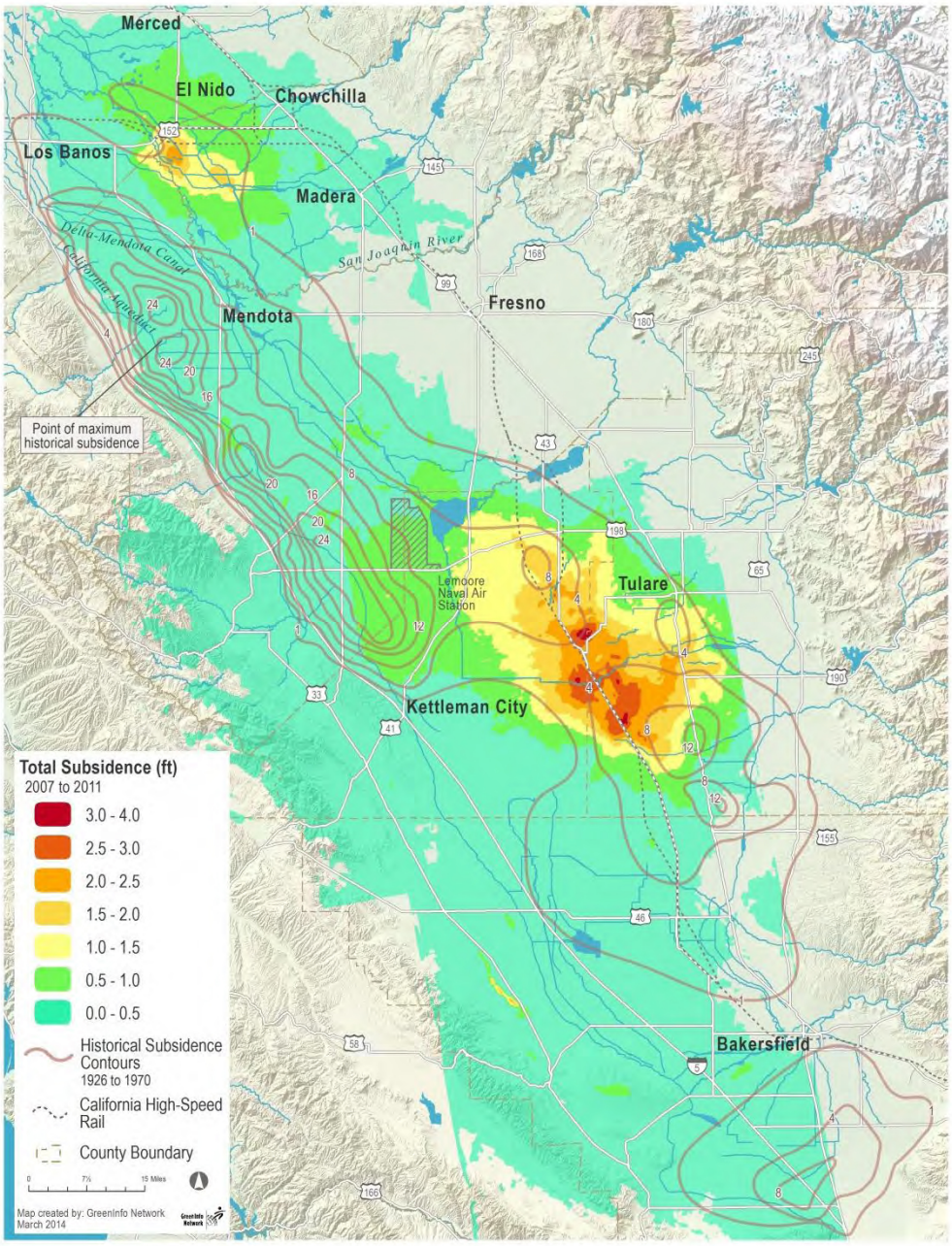


Figure 4-8. Recent subsidence in the in San Joaquin Valley January 2007-March 2011 shown as shaded regions compiled from Interferometric Synthetic Aperture Radar (InSAR) analysis. (InSAR derived subsidence data were provided as preliminary unpublished data courtesy of NASA-JPL.) Subsidence data were composited from three separate interferograms—eastern part of the area, 1/2007-7/2010; central part, 6/2007-6/2010; and western part, 1/2007-3/2011.). Brown contours are lines of equal magnitude of historical land subsidence, in feet, during 1926-1970 (Ireland et al., 1984). The proposed alternative alignments of the California High-Speed Rail system are shown as dotted lines.

A



B

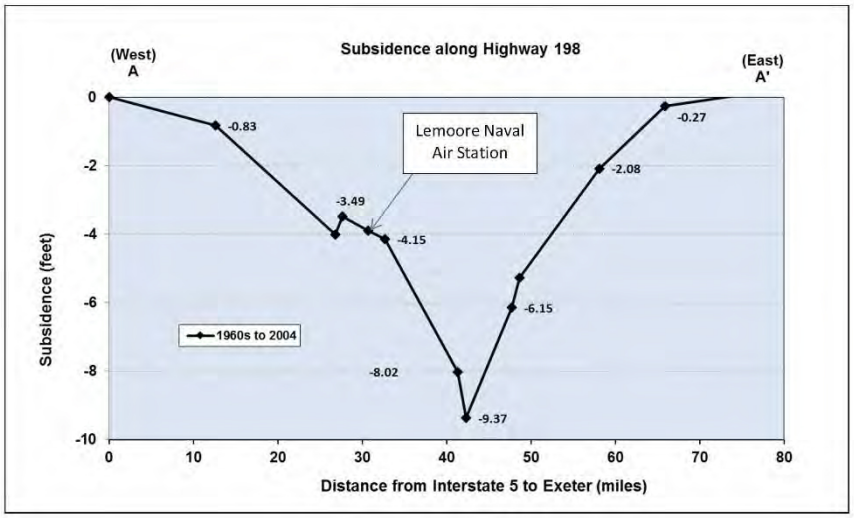


Figure 4-9. A) The location of Lemoore Naval Air Station and Caltrans subsidence profile A-A', and B) Elevation changes from between the 1960s-2004 computed from repeat geodetic surveys along Highway 198 (courtesy of California Department of Water Resources).

Plans for other infrastructure currently in the design stage can be adjusted to accommodate the expected continued subsidence. The California High-Speed Rail (CHSR) line is one such project. The dotted line (**Figure 4-8)** shows proposed alternative alignments of the CHSR. To confirm subsidence information obtained from NASA-JPL shown on **Figure 4-8**, the Program Management Team California High-Speed Rail Authority conducted limited GPS field surveys, contacted Caltrans regarding their experience with subsidence, and proposed to develop mitigations to be implemented during procurement, design, and construction (California High-Speed Rail Project Monthly Program Report, May 2013).

The area near El Nido (west of Madera and south of Merced) containing the northern subsidence feature (**Figure 4-8**) subsided between 0.3 m-1.2 m (1-4 ft) during 1926-1970, but subsidence was centered much further to the southwest at that time. In fact, the greatest subsidence during 1926-1970 was located 1.7 km (1.0 mi) northeast of the California Aqueduct on Panoche Road southwest from Mendota, California (**Figure 4-8**). This was the location of the well-known photograph of Joseph Poland of the U.S. Geological Survey standing next to a power pole signed to indicate the former height of land surface during 1925-1977 (**Figure 4-10**). Currently, subsidence occurs in a broad swath of the mid-valley area further to the northeast, in the focal area of the San Joaquin River Restoration Program (**Figure 4-11**), where it has affected water-conveyance structures, roads, and bridges. The subsiding area is apparently correlated with increased groundwater extraction needed for changing land uses and cropping patterns in areas east of the San Joaquin River that lie outside water district boundaries and have no access to surface water for irrigation. As is the case in the area of recent subsidence further south in the San Joaquin Valley, open land and seasonal crops have been supplanted by perennial crops and orchards that require irrigation year round. Farms have relied on extraction of water from the deep confined part of the aquifer system for irrigation (Chris White, Central California Irrigation District, oral commun., July 10, 2013).

The U. S. Army Corps of Engineers (2002) has predicted that 5.2 m (17 ft) of subsidence will occur during 2000-2060 where Route 152 crosses the San Joaquin River and the East Side Bypass **(Figure 4-11)** in the area identified by Swanson (1998) as an emerging subsidence problem. GPS surveying in 2010, done by contractors to DWR's Central Valley Floodplain Evaluation and Delineation (CVFED) Program to rectify vertical control for LiDAR surveys, identified discrepancies with historic elevations at survey monuments in this area. The discrepancies were attributed to subsidence that amounted to 0.18 m (0.6 ft) near Sack Dam during 2008-2010. Surveying campaigns by the USBR between 2011 and 2013 indicate that subsidence continues at about the same or a slightly greater rate (Gerald Davis, USBR, written commun., December 6, 2013). Preliminary InSAR analysis and later reporting by the USGS (Sneed et al., 2013, fig. 17) and NASA-JPL (Tom Farr, NASA-JPL, written commun., September 2013) showed substantial subsidence (**Figure 4-12 A, B, C**).



Figure 4-10. Joseph Poland standing near the location of greatest land subsidence during 1925-1977 in the San Joaquin Valley, southwest from Mendota, California. Bench mark S 661, to which subsidence at the power pole was referenced was located 31 ft southeast of the center line of Panoche Road, 2.3 ft southwest of San Joaquin Power and Light Corporation power line pole number 3/10 (replaced by a new Pacific Gas and Electric Company pole since the photograph) was not found in 1988 when NGS survey crews visited the area; it likely has been destroyed.

Sneed and others' (2013) investigation of subsidence along the Delta Mendota Canal **(Figure 4-12 C)** determined that the northern portion of the canal was relatively stable. Historical land-surface deformation measurements indicate that the southern portion of the canal (Checks 15–21) subsided substantially (Chris White, Central California Irrigation District (CCID), oral commun. July 10, 2013); more recently, slight subsidence has occurred, probably in response to the large subsidence feature south of the town of El Nido. Results of InSAR analysis indicated at least 54 cm (1.8 ft) of subsidence at rates of 43 cm/yr (11 in/yr) near the San Joaquin River and the Eastside Bypass during 2008-2010 (Sneed et al., 2013), within a 3,100 km^2 (~ 1,200 mi^2) area, including the southern part of the Delta-Mendota Canal, that was affected by 20 mm (0.07 ft) or more of subsidence during the same period. Water levels in many shallow and deep wells in this area declined during 2007-2010; in many deep wells, water levels reached historical lows, indicating that subsidence measured during this period was largely inelastic.

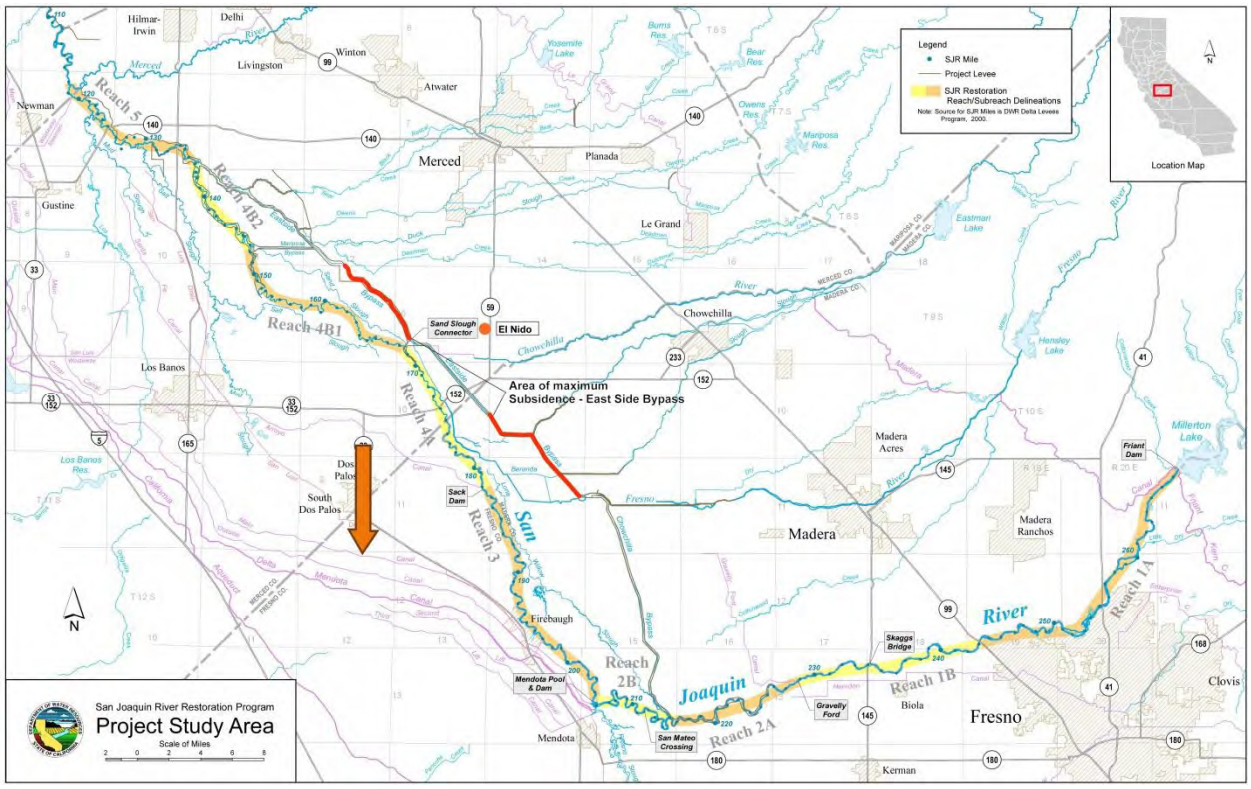


Figure 4-11. The San Joaquin River Restoration Program area. Land subsidence centered near the El Nido area has affected water conveyance facilities between Mendota and areas downstream from El Nido, including the Sack Dam and Arroyo Canal, the San Joaquin River and the Chowchilla and Eastside Bypasses. Red highlighting indicates those reaches of the Eastside Bypass that are most affected by recent subsidence according to the Lower San Joaquin Levee District. Canal reaches indicated by the orange arrow and the Arroyo Canal directly above the arrow were severely affected by subsidence historically, and are experiencing renewed occurrences (Chris White, Central California Irrigation District, oral commun. July 10, 2013). (Base map courtesy of DWR)

Recent surveying campaigns by DWR and USBR indicate that subsidence continues at about 0.15 m/yr (0.5 ft/yr) near the Sack Dam and 0.27 m/yr (0.9 ft/yr) near the Eastside Bypass (Gerald Davis, USBR, written commun., December 6, 2013). Discovery of subsidence in this area halted redesign efforts for Sack Dam as agencies considered how to adapt to the lowered land surface and prepare for likely continued subsidence. The design process was complicated by the need to build a taller dam to contain a deeper and broader pool of water that would result from continued subsidence; dams taller than 6 ft are regulated by more rigorous safety regulations and approvals. Results of further study by USBR and DWR will provide guidance for dam design and other subsidence issues revealed by recent investigations in the area.

A

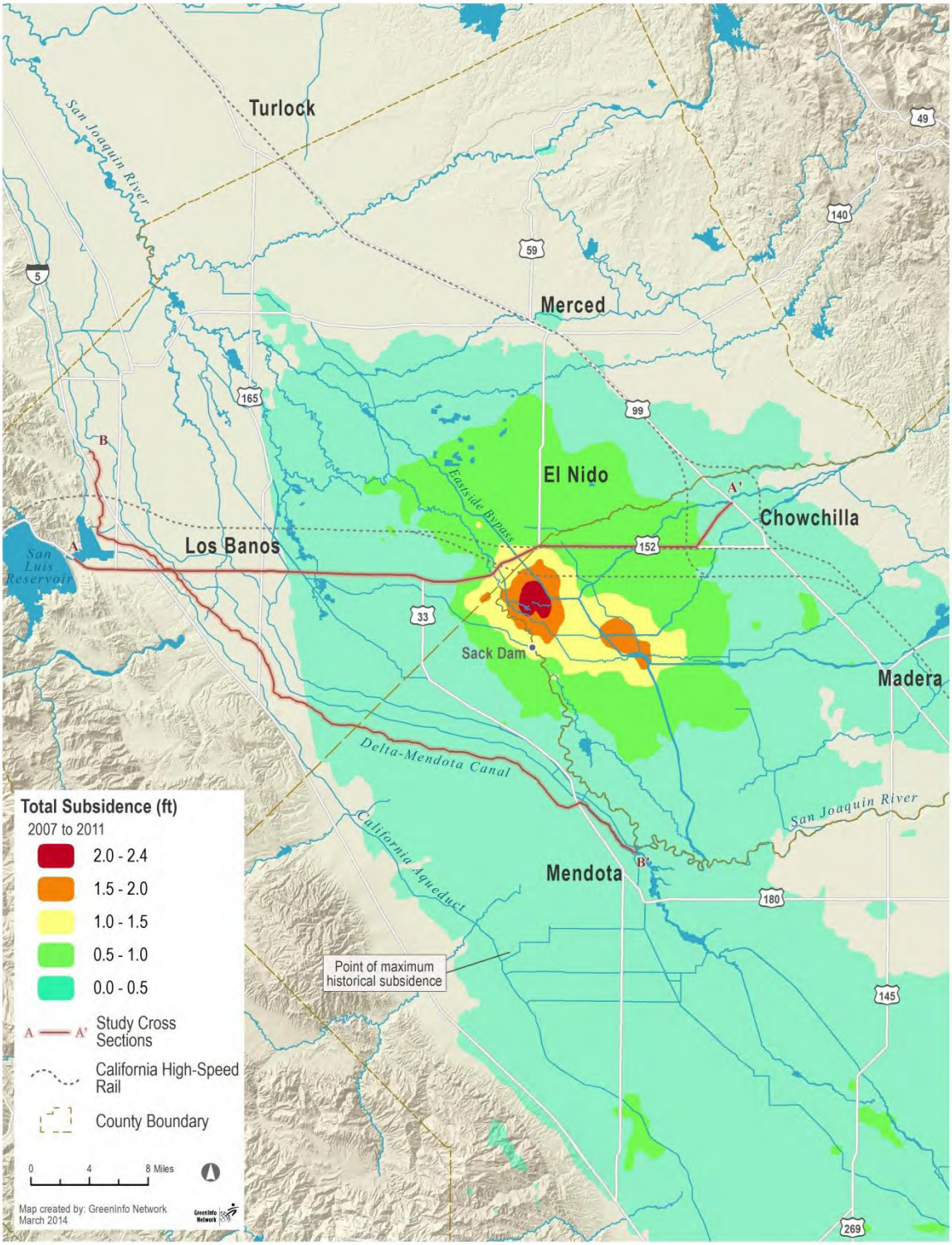
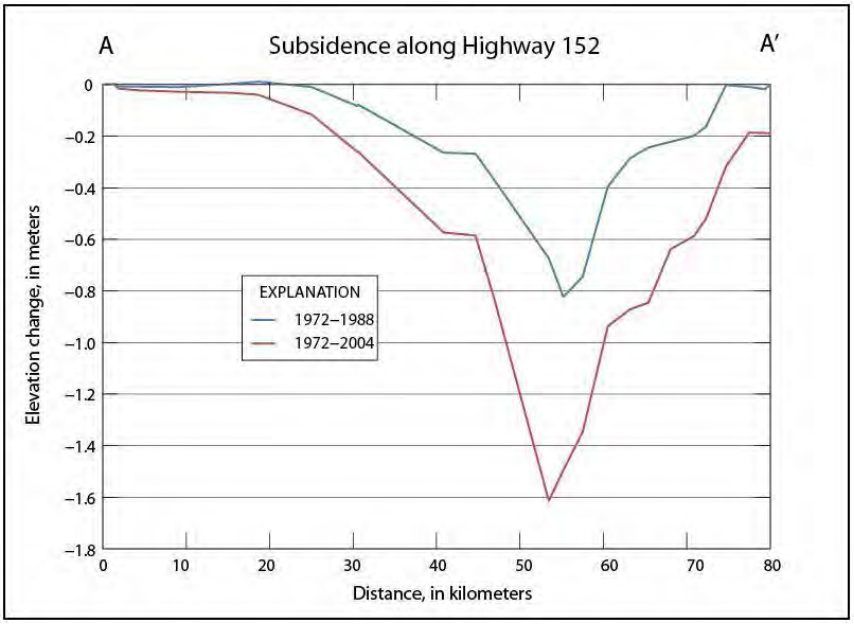


Figure 4-12 A. See full figure title on next page.

B



C

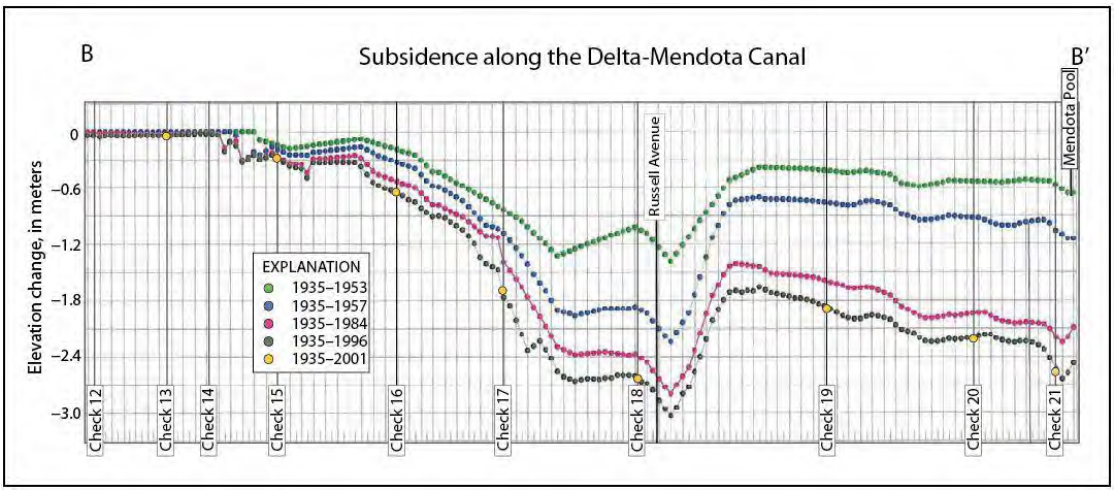


Figure 4-12. A) Recent subsidence in the central San Joaquin Valley near El Nido between January 2007 and March 2011. The location of proposed alignments for the Merced to San Jose rail line are shown in more detail and with additional points of geographic reference on Figure 4-13. B) Graph showing elevation changes computed from repeat geodetic surveys along Highway 152 for 1972–2004. C) Graph showing elevation changes computed from repeat geodetic surveys along the Delta-Mendota Canal for 1935–2001 (from Sneed et al., 2013, Fig. 17).

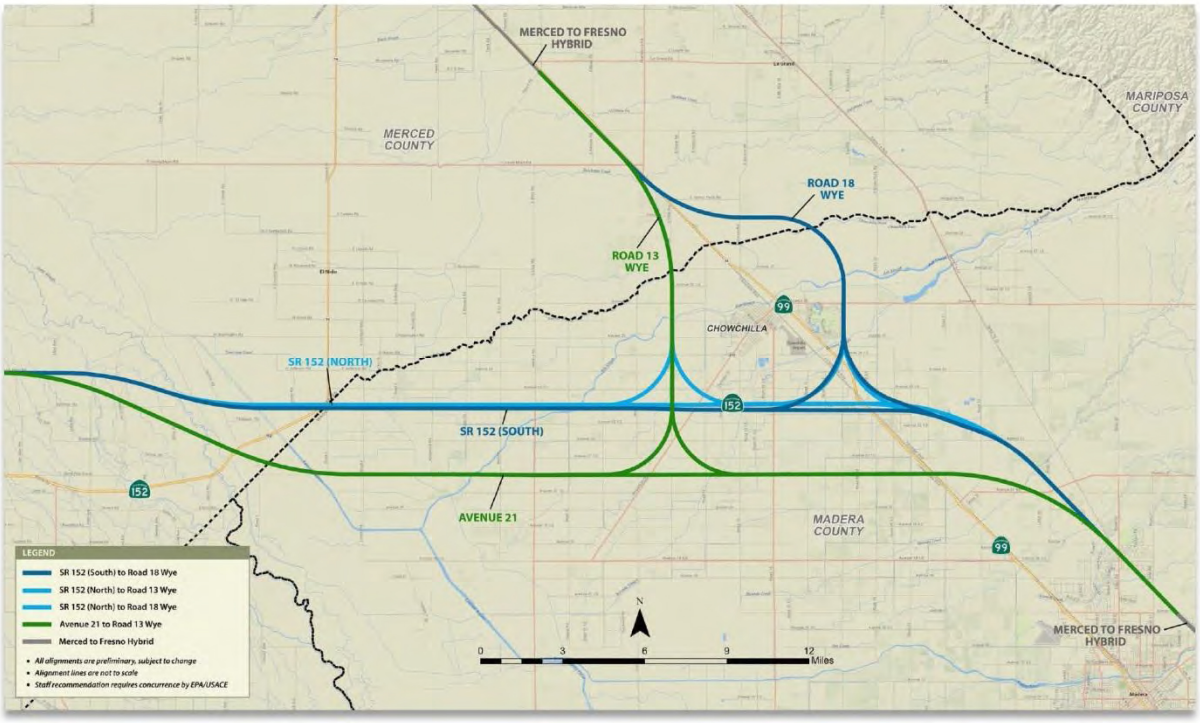


Figure 4-13. Proposed alternative alignments of the Merced to San Jose section of California high-speed rail line pass through the newly subsiding areas south of El Nido, near where Highway 152 crosses the San Joaquin River (from California High Speed Rail Authority, 2013).

Channel and levee surveys by DWR in 1983 and the U.S. Army Corps of Engineers (USACE) in 1984 indicated that one reach of the Eastside Bypass, west from El Nido California, downstream from the Sand Slough Connector (**Figure 4-11**) had subsided by about 0.46 m (1.5 ft) since it was constructed in 1964 (USACE, 1984). A flood breaching the west levee, which had subsided more than the east levee in this reach, would inundate at least 83 km^2 (32 mi^2) and possibly as much as 440 km^2 (170 mi^2) west from the bypass. This reach was originally designed to carry 4,672 m^3/s (16,500 ft^3/s) with a levee freeboard (the distance between the water surface and the top of the levees) of 1.22 m (4 ft). In 1984 the USACE removed 18,400 m^3 (650,000 yd^3) of sediment that had accumulated in 2.5 mi of the subsiding reach to improve the flow capacity. However, during a flood in 1995, flow in this reach was 340 m^3/s (12,000 ft^3/s) with only 0.46 m (1.5 ft) of freeboard—a substantial reduction of the design flow capacity (Reggie Hill, Lower San Joaquin Levee District (LSJLD), oral commun., December 11, 2013). In 1999, the LSJLD raised part of the west levee of the bypass 0.3 m (1ft) and in 2000 DWR raised both levees as much as 0.91 m (3 ft) (Reggie Hill, LSJLD, oral commun., December 11, 2013).

The reach upstream from the Sand Slough connector (between the reaches highlighted in red on **Figure 4-11**) may be more severely impacted by subsidence than the reaches immediately upstream and downstream. In 2008, the flow capacity of this reach of the bypass was 5,000 ft^3/s lower than the designed capacity of 17,500 ft^3/s. Modeling studies by DWR predict that

subsidence continuing at current rates will reduce levee freeboard by an additional 0.46 m (1.5 ft) between 2011 and 2016 reducing the flow capacity of this reach to 10,000 ft^3/s, only 57 percent of its design capacity.

Subsidence likely also has reduced the flow capacity of the San Joaquin River east of El Nido to less than half its design capacity of 42.5 m^3/s (1500 ft^3/s) (Reggie Hill, LSJLD, oral commun., December 11, 2013).

Subsidence near Sack Dam has decreased the flow capacity of the Arroyo Canal by 5 percent. The Arroyo Canal, which flows westerly from its point of diversion at Sack Dam, is the only source of surface water for irrigation in the service area of the San Luis Canal Company. Additional subsidence may necessitate construction of pumping facilities and a pipeline to deliver water for irrigation (Chase Hurley, San Luis Canal Company, oral comm., July 8, 2013).

Figures 4-14 through 4-22 illustrate some of the expensive physical infrastructure problems caused by land subsidence in this area. Loss of flow capacity has occurred on the Outside, Poso, and Main and Delta Mendota Canals (**Figure 4-11)**. The Central California Irrigation District's (CCID) Poso Canal, which runs parallel to the San Joaquin River and is not shown on **Figure 4-11**, has lost 10 percent of its flow capacity. Embankments were raised on CCID's Main Canal near the Russell Avenue bridge and flow capacity has been reduced near Los Banos. Embankments were raised on CCID's Outside Canal in 1971 (unknown costs), and 1994 ($315,000 in 2013 dollars) (Russell Landon, CCID, oral comm. Nov. 20, 2013). A current (2007-2014) subsidence remediation program to raise 25.7 km (16 mi) of embankments, construct two new weirs and 20 service turnouts will cost $5.4 million when completed (Chris White, CCID, oral commun. December 3, 2013). When the Russell Avenue bridge over the Outside Canal was constructed in 1954, the flow capacity of the canal was 17.6 m^3/s (620 ft^3/s). The bridge now restricts canal flow to 9.63 m^3/s (340 ft^3/s) partly because subsidence has changed the structure from a free flowing conduit to a siphon (Landon, 2006). In 1960, 0.61 m (2 ft) high sidewalls were added to the Russell Avenue bridge to prevent water from the canal from flowing across road surfaces. Currently, water seeps through the road bed onto the bridge, and on windy days waves splash over the sidewalls and wet the road surface. Facility inspections were conducted routinely by staff of the CCID by examining the canal and turnouts from a boat which passed easily under the bridge (Chris White, CCID, oral commun. July 10, 2013) — something that is obviously impossible now that the bridge is partly submerged (**Figure 4-21**). The bridge has been judged structurally deficient and is scheduled for replacement by CCID, Caltrans, and the Fresno County Department of Public Works at a cost of $2.5 million.



Figure 4-14. Location map of Central Valley Project, State Water Project and selected private canals.



Figure 4-15. Delta Mendota Canal at Russell Road bridge north from Mendota, CA, looking downstream. Raised wing walls prevent water from overtopping Russell Avenue.



Figure 4-16. Delta Mendota Canal at Athena Road north from Mendota, CA; downstream is to the left. The bridge has experienced a substantial loss of clearance as the land subsided.



Figure 4-17. Raised canal linings and embankments upstream from Russell Avenue remediated the water-ponding effect of land subsidence.



Figure 4-18. Ruptured lining of the Delta Mendota Canal in the subsiding area about 0.6 miles upstream from the Russell Avenue bridge.



Figure 4-19. Desilting the Outside Canal and raising embankments remediated subsidence downstream from Russell Avenue (photograph courtesy of Chris White, Central California Irrigation District).



Figure 4-20. Importing fill material to raise embankments in subsided areas of the Outside Canal (photograph courtesy of Chris White, Central California Irrigation District).



Figure 4-21. Outside Canal at Russell Road, north from Mendota looking generally upstream. The Russell Avenue bridge has been deemed a hazardous structure by the Fresno County Road Department.



Figure 4-22. Well casings protruding from land surface just south from El Nido. Left: casing of an abandoned gas well protrudes more than 46 cm (1.5 ft) higher than when it was painted 2 years earlier. Right: protruding casing of an irrigation well lifts its concrete surface pad and piping off the ground as land settles around it (photographs courtesy of Chris White, Central California Irrigation District).

Prokopovich (1967, 1969, 1973, 1975, and 1986), Prokopovich and Herbert (1968) and Prokopovich and Marriot (1983) summarized the effects of historical subsidence on federal canals and drains on the west side of the San Joaquin Valley. Subsidence impacted about 48 km (30 mi) of the Delta Mendota Canal upstream from its terminous at Mendota Pool (**Figure 4-12 C**) by submerging canal service turnouts, drain inlets, bridges, pipelines, and check structures used to control water surface elevation in the canal, and by over topping the concrete lining of the canal. In the 1960s, the USBR raised bridges, and relocated pipeline crossings. In

1977, the USBR extended the canal berms and concrete lining, modified bridges, and modified Check Structure No. 18 by adding a new deck on top of the existing structure and adding a 1.2 m (4 ft) extension to the three radial flow gates. The cost for these modifications, $7.821 million, was given by Prokopovich and Marriot (1983) as a total unadjusted for inflation. Using 1977 as the base year, the cost of these repairs in 2013 dollars is conservatively estimated as $30.14 million. In 1992, operation of the Delta-Mendota Canal passed to the San Luis Delta-Mendota Water Authority (SLDMWA). In 2004, the SLDMWA installed 3,048 linear m (10,000 ft) of concrete canal-lining extensions in areas of reduced freeboard; costs for this work have not been tabulated. Since then, SLDMWA has identified many areas where canal freeboard has been reduced to less than 0.15 m (0.5 ft). Sneed and others (2013) mapped additional subsidence along the canal during 2003 to 2010.

The San Luis Canal **(Figure 4-14)**, a shared asset of the federal Central Valley Project and the California State Water Project that was completed in 1968, has been affected by subsidence along 136.7 km (85 mi) of its length between the Los Banos and Kettleman City areas. The canal, now considered the middle section of the California Aqueduct, passes through three major subsidence bowls: 1) southwest of Mendota, 2) near the town of Cantua Creek, and 3) near the town of Huron (Ireland and others, 1984). Because subsidence had adversely affected the earlier-built Delta-Mendota Canal, designers incorporated as much as 2.75 m (10 ft) of extra freeboard into the San Luis Canal, adding $4.573 million ($30.67 million 2013 dollars) to construction costs. Additional subsidence required raising of canal linings, bridges, and other canal structures and rehabilitation of roads at costs of $1.575 million, $4.731 million, and $4.5 million, respectively, during 1982, 1983, and 1984 (Prokopovich and Marriot, 1983). Adjusting for inflation, these costs amount to $55.7 million in 2013 dollars. Subsidence due to hydrocompaction caused two sags in the canal, centered at California Aqueduct mile posts 120 and 128 near Cantua Creek (Ireland and others, 1984, p.I40), but no remedial actions have been discussed in the readily available literature. The USGS, in cooperation with DWR, is currently studying subsidence during 2003-2010 along this middle reach of the California Aqueduct (Sneed, U. S. Geological Survey, written commun., November 18, 2013).

Although subsidence caused by structure settlement, groundwater extraction, hydrocompaction, hydrocarbon production, and perhaps other unknown causes has been described for the California Aqueduct in reaches south of San Luis Canal, no remedial activities have been discussed in the readily available literature. DWR is currently compiling historical information on subsidence magnitude, repairs, and operational impacts in order to assess the reliability of water deliveries from the entire California Aqueduct (Sheree Edwards, DWR, oral commun., November 21, 2013). The performance of all engineered structures, (check dams, turnouts, siphons, concrete lining, etc.) will be evaluated. Because the aqueduct cannot be shut down for this evaluation, divers will be employed to examine the concrete lining below the water surface.

Drainage canals, which collect irrigation tail water, run northward on the floor of the San Joaquin Valley in the area served by the San Luis Canal reach of the California Aqueduct. Subsidence has lowered the gradients (slope) of the drains, reducing their flow capacity and making them more difficult to design and build (Viets and others, 1979). Design of the San Luis Drain included 15 cm (0.5 ft) of extra freeboard to account for potential subsidence from aquifer compaction caused by distant irrigation wells. Construction costs were $350,000 in 1968 ($2.35 million in 2013 dollars).

The total cost to the U.S. government to account for or repair subsidence damage from groundwater extraction to major canals and drains built by the federal government on the west side of the San Joaquin Valley was $88.19 million (2013 dollars). These are contract construction costs and do not include costs for design, inspection, or studies. They also do not include the considerable cost of precompacting the San Luis Canal and major lateral canal alignments by diking and flooding to avoid subsidence caused by hydrocompaction of moisture deficient soils in the western San Joaquin Valley. (Hydrocompaction is described in **Appendix A.**)

Costs for repairs to other infrastructure in the San Joaquin Valley, including replacement and repair of wells damaged and destroyed by land subsidence, have not been compiled systematically. Realistically, costs probably cannot be determined because there is no centralized repository of this information. According to Wilson (1968), 275 wells were reported with failed casings due to subsidence-induced compressive rupture in the 1,600 km^2 (618 mi^2) region of maximum subsidence in the valley between 1950 and 1961. Current costs to replace an 18-in diameter agricultural well averages $660-$820 per m ($200-$250 per ft) (Scott Lewis, Luhdorff and Scalmanini Consulting Engineers, oral commun. November 20, 2013). A conservative cost estimate to replace these wells, assuming each well is 500 m (1640 ft) deep, is $90 million dollars (2013 dollars). Viets and others (1979) present the example of a 486 km^2 (120,000 acres, 188 mi^2) farm on the west side of the San Joaquin Valley where 60 wells of an average depth of 610 m (2,000 ft) had failed casings. The current cost to replace the wells on this farm would be $24 million (2013 dollars).

The most comprehensive and systematic estimate of economic costs of land subsidence in the San Joaquin Valley was $180 million by Bertoldi in 1993 dollars (Galloway and Riley, 1999). Bertoldi (Gilbert Bertoldi, U. S. Geological Survey (ret.), oral commun., November 29, 2013) collected billing invoices from land surveyors and other contractors and repair estimates from county agencies for remediating subsidence damage during 1955-1972 in areas of Fresno and Kings Counties that had subsided more than 1.22 m (4 ft) between 1925 and 1972. The invoices and repair estimates showed costs for: periodic surveying and regrading of agricultural fields to enable proper flow of water during flood irrigation, replacing networks of broken 20 to 25.4 cm (8 to 10-in) ceramic pipes that were buried trenches to transport irrigation water to fields, and

broken sanitary sewers in urban areas. (Fresno and Kings County agencies had reported that sanitary sewers had broken for undetermined reasons; Bertoldi determined that broken sewers were in the subsiding areas.) Costs to repair or replace wells damaged by subsidence, the value of structures lost by condemnation, and decreased property values as a result of zoning changes where subsidence increased the extent and depth of flooding were also included in the damage estimates. Conservatively estimating the total cost in 2013 dollars, by assigning a cost of $10 million to each of the 18 years from 1955-1972 and accounting for inflation, results in total economic costs of $1.321 billion during 1955-1972. This estimate does not include the costs to repair damage to canals estimated above or the indirect costs of land subsidence such as flood damage to inundated farm equipment, long-term environmental effects, or any damage that may have occurred in areas where land subsidence from over pumping groundwater was less than 1.22 m (4 ft), or for subsidence damage that occurred prior to 1955 or after 1972.

Water districts, ranchers, and others are dealing with the impacts of recent subsidence on water delivery infrastructure in an information vacuum because there has been no coordinated monitoring of land subsidence. Were it not for fortuitous satellite radar analyses (NASA-JPL, Stanford University, USGS) and recent attention focused by the San Joaquin River Restoration Program planning activities, the breadth and magnitude of recent subsidence in the San Joaquin Valley would be unknown. Much infrastructure in both the northern and southern subsiding areas potentially could be impacted by subsidence. Fortunately, federal, state and local agencies have been alerted to the issues of recent subsidence and can begin to implement appropriate strategies to monitor subsidence and minimize its impacts. For example, geotechnical and design engineers now can adapt plans for design **(Figure 4-13)** of the CHSR to accommodate potential future subsidence.

4.3 Sacramento Valley

The Sacramento Valley forms the northern one-third of the agriculturally rich Central Valley of California. Although it possesses substantial supplies of surface water, land subsidence in the Sacramento Valley has occurred when groundwater-levels declined in response to pumping for irrigation and public water supplies during droughts or in areas undersupplied by surface water. The earliest subsidence investigations in the southwestern Sacramento Valley were done using leveling data collected by the USGS and the NGS during 1935-1964. Land-surface profiles based on these data showed apparent land subsidence of more than 0.61 m (2 ft) along a level line between Zamora and Knights Landing in northern Yolo County; more than 0.3 m (1.0 ft) near Arbuckle in southern Colusa County; and more than 0.46 m (1.5 ft) in central Yolo County between Zamora and Davis (Lofgren and Ireland, 1973). Sixty miles of geodetic re-leveling was done by the NGS during 1987 to determine whether subsidence rates were within the tolerances specified for siting the proposed Super-Conducting Super Collider (SSC) at Davis or Stockton. Lofgren and others (undated report) determined that subsidence rates were similar to rates determined from historical leveling. (Neither location was selected for the SSC.) Elevation losses

since 1949 ranging from 0.73 ft to 3.9 ft at five bench marks in the Sacramento Valley, damage to concrete pads at irrigation wells, and an increased extent of flooding were documented in the southern Sacramento Valley between Knights Landing and Stockton, California (Blodgett et al., 1990). GPS and spirit leveling by Blodgett and others (1990) and Ikehara and others (1994) identified a north-south trending zone of maximum subsidence where elevation loss ranged from 0.4 m (1.3 ft) to 1.6 m (5.4 ft) between Dixon and Zamora. Most geodetic monuments in the southern Sacramento Valley showed a loss of elevation (Ikehara et al., 1994). The area of greatest subsidence is south of the terminus of the Tehama Colusa Canal, where agriculture developed relying solely on groundwater for irrigation (**Figure 4-20**).

A 1,000 ft-deep extensometer (11N01E24Q008M) constructed in the area of maximum subsidence north of Woodland (**Figure 4-23B**) measured an average annual inelastic compaction of about 55 mm/yr (0.18 ft/yr) during 1988-1992 (Ikehara, 1995). The average annual rate of subsidence since 1988 is 15.5 mm/yr (0.051 ft/yr) (Bill Ehorn, DWR, written commun. July 2, 2013); thus, inelastic compaction at the extensometer site continues, but has slowed considerably since 1992. Borehole extensometers at 10 other locations in the Sacramento Valley operated by DWR indicate that substantial subsidence has not occurred in the areas monitored (**See Section 5**).

The magnitude of permanent land subsidence observed throughout the southwestern Sacramento Valley indicates that groundwater levels have dropped below the preconsolidation head, the historically lowest water level, sometimes called the critical head, beyond which inelastic compaction of aquifer-system sediments is triggered. A comparison of video logs, collected with downhill television cameras (**Figure 4-23B**) and groundwater-levels showed that damaged wells had experienced historically low water levels. Intact wells either were not experiencing historically low water levels, or were constructed subsequent to the 1976-1977 drought that had stressed the aquifer system (Borchers et al., 1998). Rapid rates of subsidence during droughts may have contributed to the well damage.

If coupling between a well casing and the adjacent sediments is strong, compacting aquifer systems grip the casing and exert a downward thrust that creates compressional force powerful enough to cause a steel well casing to fail and collapse telescopically. Several photographs from the video scans illustrate casings that failed in this manner (**Figure 4-24**). If sediments are not well-bonded to casings, they will settle around the well and the casing will appear to protrude from the land surface. This phenomenon commonly occurred in the southwestern Sacramento Valley during the 1976-1977 drought; it also occurred in the San Joaquin Valley when groundwater levels dropped below historically low levels there (Poland and Ireland, 1965).

B

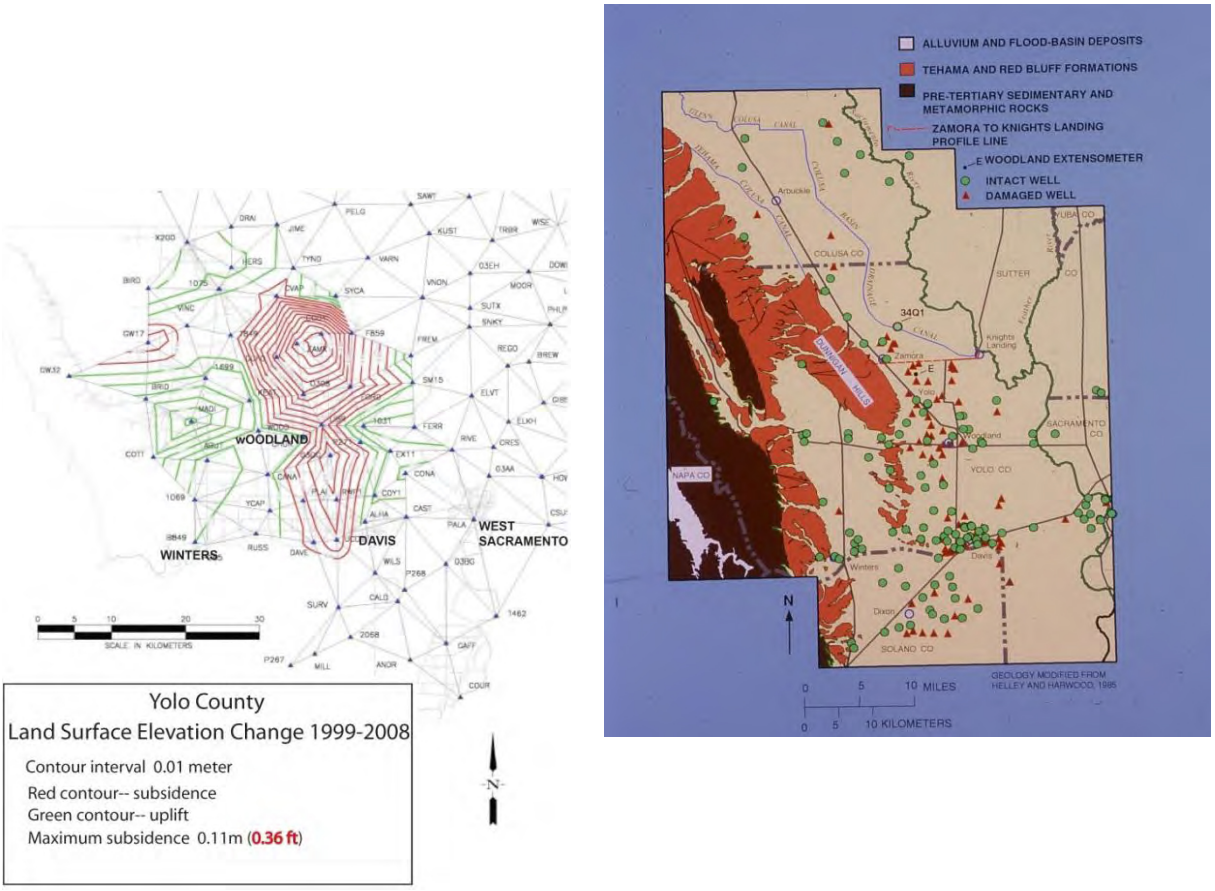


Figure 4-23. A) Elevation change measured by GPS surveys in Yolo County in 1999 and 2008 (Jim Frame, Frame Surveying, written commun. July 2013), and B) location of: intact wells and wells damaged by land subsidence; of the Woodland extensometer (11N01E24Q008M); and selected physical features in the southwestern Sacramento Valley (from Borchers et al., 1998).

A B C

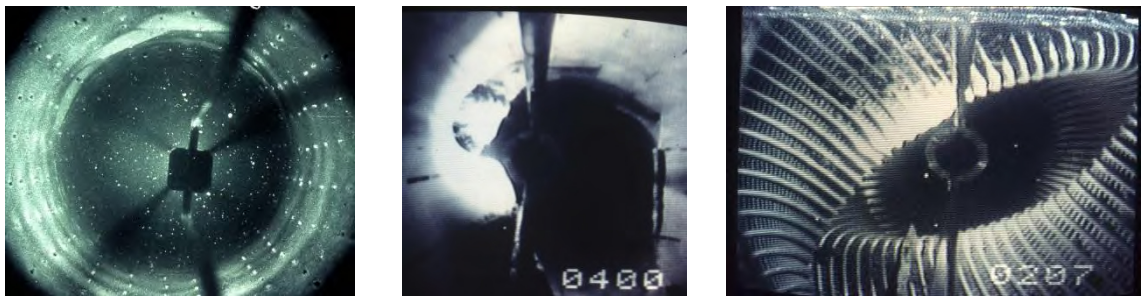


Figure 4-24. Well casings damaged by vertical compression during land subsidence in the Sacramento Valley: A) rippling of perforated steel casing during early stages of compression; B) deformation and ripping of slotted steel casing 400 ft below land surface; and C) crumpled vertical ribbing of the stainless steel well screen 207 ft below land surface produces a radiating effect. Well interiors are illuminated by a light suspended below the camera lens.

Drilling and well-services companies reported that "well casings were snapping like match sticks" throughout the southwestern Sacramento Valley during the 1976-1977 drought, and that they could not keep pace with the demand for replacement wells. Replacement costs for 80 damaged wells that were videotaped (median depth 137 m, 450 ft), using a 2013 cost of $656/m ($200/ft), would be $7.2 million. It is likely that the number of damaged and destroyed wells greatly exceeded the number of videotapes. Therefore, actual replacement costs were likely much larger.

The location of damaged wells indicates a much broader area of subsidence than results of the 1999 and 2008 GPS surveys of the Yolo County network indicate. **Figure 4-23** approximately aligns a map of subsidence calculated from the GPS surveys with a map showing the location of damaged wells. The area of damaged wells extends from central Colusa County through Yolo County, to Dixon in Solano County. GPS surveys show that a more restricted area has subsided. However, the Yolo County GPS network was surveyed later than the period when most wells were damaged (1976-1977). This emphasizes the need for coordination among various agencies in order to understand a regional problem by collecting data regionally. Ideally, GPS surveys in the entire Sacramento Valley, extending through Solano County and including the Sacramento-San Joaquin Delta, would occur in a coordinated campaign that is conducted periodically.

Twelve new monitoring wells were installed at four sites (three nested monitoring wells at each site; the deepest extending to a depth of nearly 2,400 ft) on behalf of Solano County Water Agency (SCWA), as part of its regional Groundwater Monitoring Facilities program (LSCE, 2013). Groundwater level monitoring has been an ongoing effort by SCWA and its cooperating agencies. More recently, SCWA established two new CORS monitoring sites. These two new sites tie into an existing network of land-surface monitoring sites in Yolo and Solano Counties and provide insight into the deformation of the land surface in Solano County. Monitoring land subsidence, coupled with groundwater level measurement, has led to a deeper understanding of the water resource and the general conditions of the aquifer underlying Solano County. Land subsidence is occurring in Solano County, though at relatively low rates, between 1.5 to 3.3 mm/year (0.06 to 0.13 in/year), over the last 8 years. Because the two new sites have only been recording data since June 2012, they have yet to influence understanding of long-term land subsidence. Further evaluation would be needed to determine whether the subsidence is elastic or inelastic, and multi-depth, magnetic marker, or other type of extensometer would be needed to determine which subsurface unit or units are responsible for the compaction.

Subsidence in the southwestern Sacramento Valley is a regional problem that cannot be adequately monitored by local agencies acting independently. Monitoring the magnitude and extent of land subsidence and its cause, and devising workable solutions to limit future occurrences, requires interagency coordination.

Results from groundwater modeling by the USGS suggest that land subsidence may have occurred at several locations in the northern Sacramento Valley (Williamson, et al., 1989; Faunt, et al., 2009); but, published reports of land subsidence investigations in these areas were not located.

4.4 Antelope Valley

Groundwater accounts for as much as 90 percent of the water supply for agricultural and urban uses in the Antelope Valley in the western Mojave Desert east of Los Angeles. In the city of Lancaster where the population quadrupled between 1977 and 2010, extensive pumping contributed to groundwater level declines of as much as 91.4 m (300 ft) since the 1930s. At Edwards Air Force Base (EAFB) groundwater levels declined as much as 45.7 m (150 ft) between 1915 and 1991. A regional relationship between land subsidence and groundwater-level declines in the central Antelope Valley was established on the basis of geodetic and hydrologic monitoring during 1926-1992 (Ikehara and Phillips, 1994). Subsidence of 2 m (more than 6 ft) near Lancaster and more than 1 m (3 ft) at the southern edge of Rogers Lake resulted from groundwater pumping that vastly exceeded recharge to the aquifer system (**Figure 4-25**).

At EAFB, differential subsidence caused sink-like depressions, polygonal cracks, and earth fissures (**Figure 4-26**) on the playa surface of Rogers Lake bed, adversely affecting the runways on the lake bed that were being used for landing aircraft. Numerical modeling at the 840 ft (256 m) deep Holly extensometer site at EAFB indicated that two thick confining units account for most of the compaction measured there (Sneed and Galloway, 2000). Due to the thickness and low permeability of these confining units, only half the ultimate compaction would occur during the 30 years subsequent to the modeling. Residual compaction and land subsidence from slowly draining confining units is a legacy of groundwater mining and must be carefully considered in long-term management of land and water resources at EAFB.

A 600-meter-long (0.37 mi-long), 2.3-meter-deep (7.5 ft-deep) fissure located about 11 km east-northeast of Lancaster was first noticed in 1978 after it flooded (Holzer, 1984). The fissure grew eastward after floods in 1980. Because no recent faulting or seismicity had occurred when the fissure was discovered, and because of its similarity to other human-induced fissures, its formation was attributed to historical water-level declines of 75 m (245 ft) that had occurred prior to its appearance (Holzer, 1984). In addition to earth fissures, other negative consequences of land subsidence in Antelope Valley include altered drainage gradients; increased flooding and erosion; failed well casings; and structural damage to roads, buildings, pipelines, canals, homes, and other structures.

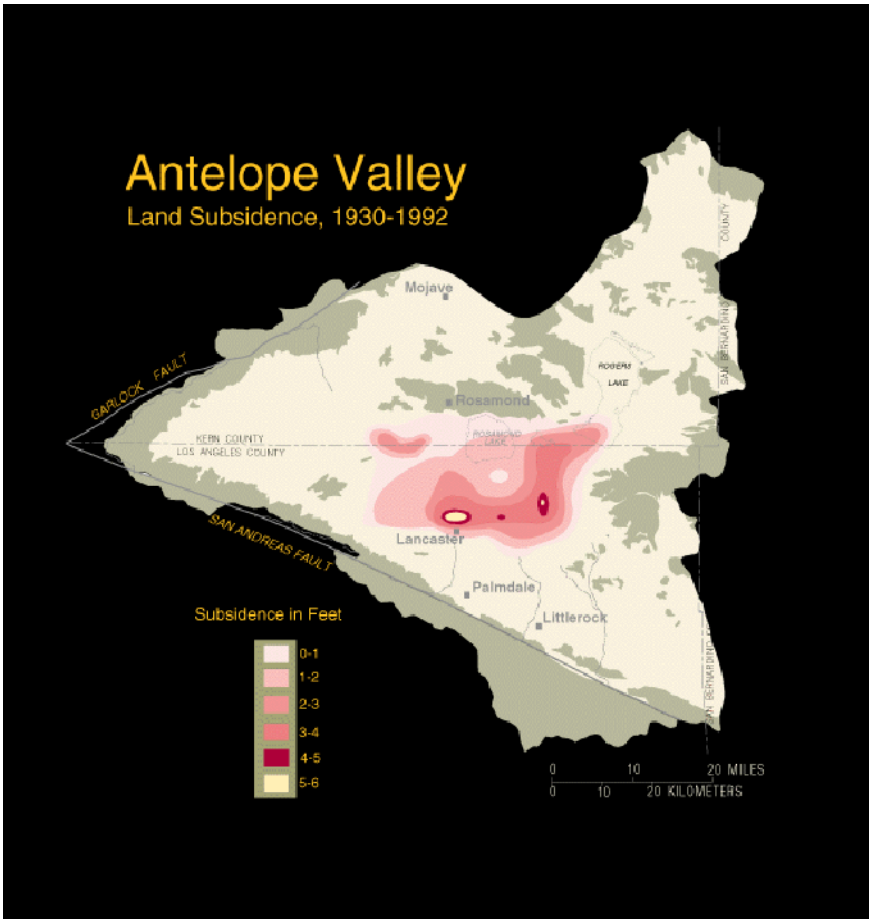


Figure 4-25. Land subsidence in Antelope Valley during 1930-1992 (modified by Galloway et al., 1998 from Ikehara and Phillips, 1994).

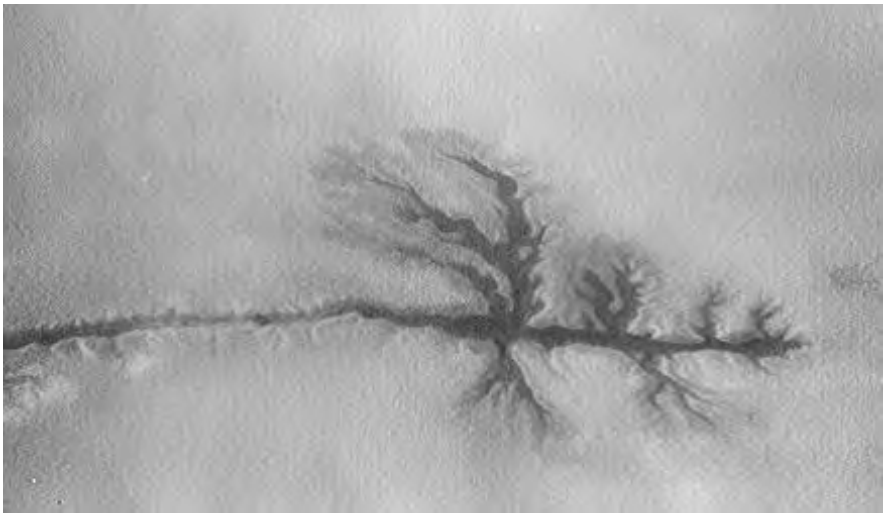
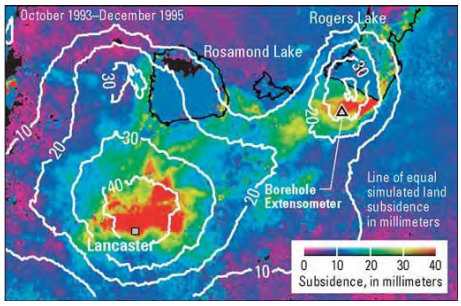


Figure 4-26. Drainage channels (collectively called desert flowers) caused by erosion of playa sediments when floods carry sediment to an earth fissure on Rogers Lake bed at Edwards Air Force Base. Photographed August 1989 (from Blodgett, 1995).

During 1993-1995, InSAR was used to measure about 40 mm (1.57 in) of subsidence at an extensometer site in the Antelope Valley (**Figure 4-27);** the extensometer measured 31 mm (1.22 in) of subsidence. This disparity indicates that 20 percent of the subsidence could have occurred below the maximum depth of the extensometer 256 m (840 ft). InSAR imagery was also used to evaluate a computer model that simulated land subsidence and groundwater flow. These results highlight the potential use of InSAR to better constrain computer models of land subsidence to aid resource planning and management (Galloway et al., 1998; Hoffmann et al., 2003).

A





B

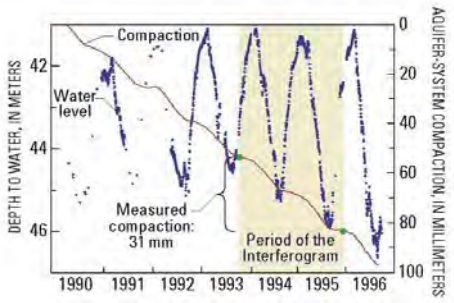


Figure 4-27. A) Subsidence in the Antelope Valley, California during 1993-1994 from computer modeling (white contours) and an InSAR interferogram during the same period. B) Period of the interferogram shown on a plot of water levels and aquifer compaction measured at the Holly extensometer site at Edwards Air Force Base (originally from Galloway et al., 1998; modified from Bawden et al., 2003).

Facing future population growth and limited options for alternative water sources, water managers in Antelope Valley are seeking ways to make the best use of currently available resources. Injection of treated State Water Project water into the aquifer system during the winter (when it is most available) for later use in the summer (the peak demand period) is one potential element of a groundwater management plan. The USGS in cooperation with the Los Angeles County Department of Public Works (LACDPW) and the Antelope Valley–East Kern Water Agency (AVEK) conducted a series of freshwater injection, storage, and recovery tests in the Lancaster area from September 1995 through September 1998 as part of a study to evaluate the feasibility of artificial recharge via injection wells in the Lancaster area. Aquifer compaction and expansion and barometric pressure were measured at a dual extensometer site (shallow and deep extensometers, 735 ft (224 m) and 1,205 ft (367 m) deep, respectively). Water levels were monitored at 13 active and abandoned production wells and 10 nested piezometers. Microgravity was measured at 31 stations. Geodetic data were collected at 124 vertical-control bench marks, one permanent and one temporary continuous Global Positioning System (GPS) stations, and three tiltmeters. Water-chemistry samples were collected from 17 active production wells and the 10 nested piezometers. Flow data were collected using meters mounted on two wells used for water injection. The testing program and subsequent development of a simulation/optimization model helped evaluate the effectiveness of an injection program for halting the decline of

groundwater levels and avoiding future land subsidence while meeting increasing groundwater demand (Phillips et al., 2003).

4. 5 Mojave River Basin and Vicinity

The Mojave River Basin is located in eastern San Bernardino County. California desert basins are areas of current or expected high water demand and are underlain by thick unconsolidated aquifer systems. Because surface water is scarce, groundwater has been the source of water for agricultural, industrial, and municipal uses throughout the Mojave Desert since the early 1900s (Sneed et al., 2001). Unplanned and unmonitored development of groundwater has produced unanticipated land subsidence when aquifer systems transitioned from elastic compression to inelastic compaction. The results included an increase in the extent of inland flooding, damaged engineered infrastructure, and the sudden appearance and erosional enlargement of destructive earth fissures, which have become permanent features of the landscape.

The Fremont Valley, a deep, closed alluvial basin within the Garlock Fault zone at the southern terminous of the Sierra Nevada and just north from Antelope Valley, contains an aquifer system composed of as much as 275 m (900 ft) of sedimentary materials (Holzer, 1984). Prior to 1920, wells in the valley center flowed; by 1977, water levels in the central part of the valley had declined as much as 74 m (243 ft) primarily in response to increased irrigation pumpage (Holzer, 1984). Subsidence caused by groundwater withdrawal was documented by Pampeyan and others (1988). Data were too sparse to map subsidence, but subsidence of 0.48 m (2 ft) was measured between 1962 and 1978 on two leveling lines distant from the pumping centers in the valley. Subsidence near the valley center was likely considerably greater. Koehn Lake, a playa in the northeastern part of the valley, floods during winter rains. Subsidence has tilted the playa surface so that when surface water ponds on the playa, it also floods the area southwest of the playa where subsidence is centralized. Fremont Valley contains numerous faults associated with the Garlock Fault system. These faults act as barriers to groundwater flow, which prevent groundwater on one side of a fault from responding to pumping wells on the other. As a result, sediments compact on one side of the fault only. This differential compaction creates a step in the topography at the outcrop of the fault (the fault scarp) (**Figure 4-28**). If differential subsidence occurs gradually as the water levels decline, movement at the fault is slow and the fault is said to ‘creep’. It can be difficult to distinguish creeping tectonic motion from creeping motion due to differential compaction. Large earth fissures owing to differential compaction between areas where aquifer thickness varies substantially also formed in the Fremont Valley. Because both fault creep and earth fissures were coincident with times of increased pumpage and declining groundwater levels, both effects are believed to be related to groundwater development activities (Holzer, 1984).



Figure 4-28. Earth fissure associated with land subsidence caused by groundwater pumping in Fremont Valley, California, March 1978 (from Holzer and Galloway, 2005).

Sneed and others (2003a) and Stamos and others (2007, an interactive Google map) assessed land subsidence in the Mojave River watershed and the Morongo groundwater basin. Groundwater levels in the Lucerne Valley in the Mojave River watershed east of Victorville, California, have declined as much as 30 m (100 ft) since the 1950s. A GPS survey in 1998 indicated that as much as 0.6 m (2 ft) of land subsidence may have occurred since topographic maps were made in 1969 and 1975 (Sneed et al., 2003). However, because elevations estimated from 3 m (10 ft) contours on the topographic maps contain a ±1.5 m (5 ft) error, the resulting subsidence estimates may not be quantitatively meaningful. InSAR analysis indicated that land surface southeast of the Lucerne Lake playa subsided about 9 cm (0.3 ft) between April 24, 1992 and November 8, 1999, near the areas where the 1998 GPS survey indicated 60 cm (2 ft) ±150 cm (5 ft) subsidence between the early 1970s and 1998 and also near where groundwater levels had declined 30 m (100 ft) by the early 1990s. Interferograms indicate that areas near the west shore of Lucerne Lake playa, where groundwater-level data are sparse, subsided 6 cm (0.2 ft) during the same period. Polygonal cracks are found on the playa, and earth fissures more than 1 m (3 ft) in width and depth trend northeast-southwest across the southern playa (**Figure 4-29**). They likely formed by differential compaction of unconsolidated aquifer sediments southeast from the lake shore, where sediments are believed to be thickest (Sneed et al., 2003).



Figure 4-29. Earth fissure near the southeast edge of Lucerne Lake playa in the Mojave Desert, California. View is to the northeast, with a five-gallon bucket for scale (Sneed et al., 2003a, Fig. 6 B).

InSAR analyses show a large L-shaped pattern of land subsidence near the southeastern tip of the dry El Mirage Lake about 14 km (8.7 mi) northwest of Victorville (Sneed et al., 2003a). Interferograms indicate subsidence of as much as 50 mm (0.16 ft) during April 21, 1995-May 1, 1999. Groundwater-level data are sparse in the area during the period of the interferograms, but groundwater-flow simulations by Stamos and others (2001) indicate that water levels declined as much as 53 m (175 ft) in the regional aquifer south of El Mirage Lake during 1950-1999. Much of the water-level decline in the area may have occurred before the adjudication of the Mojave Basin area (January 1996) that resulted in decreased pumpage. Subsidence measured during 1995-1999 may result partly from residual compaction in response to earlier groundwater-level declines.

InSAR analyses show a persistent pattern of deformation along the northern and eastern shores of the Harper Dry Lake playa near Lockhart, California. Interferograms show that the area subsided as much as 85 mm (0.28 ft) during 1992-1999 (Sneed et al., 2003a). Because groundwater levels declined 27 m (90 ft) to their lowest historical level between the late 1960s and 1999 (Stamos et al., 2001), the subsidence indicated on the interferograms may be a result of inelastic compaction.

InSAR analyses show a persistent pattern of deformation about 10 km (6 mi) east from Newberry Springs California, near Troy Dry Lake (dry). Interferograms show that the area subsided as much as 45 mm (0.15 ft) during 1993-1999. No water-level data are available near Troy Lake, but groundwater levels in wells between Troy Lake and Newberry Springs declined about 3 m (10 ft) during 1993-1999, and Stamos and others (2001) determined that groundwater levels declined as much as 70 m (225 ft) in these areas between the early 1940s and 1999.

Lithologic logs for wells near subsiding areas at Troy Lake indicate that sediments are predominantly clayey. Because clays are highly compressible, and water levels were likely at their historical low levels each summer during 1993-1999, it is likely that the subsidence measured near Troy Lake is a permanent result of inelastic compaction of aquifer sediments.

The USGS, in cooperation with the Fort Irwin National Training Center (NTC) in the Mojave Desert, is investigating the mechanisms driving deformation on the surface of Bicycle Lake Playa. Bicycle Lake Playa contains the runways used to transport troops and supplies to Fort Irwin; its stability is of great concern to the NTC. An earth fissure and sink-like depressions appeared on the playa in 2005 (Densmore, et al., 2010). Giant desiccation cracks have also been observed. Increased groundwater pumping in the 1990s lowered groundwater levels 25 m (82 ft) by 2009 and contributed to 270 mm (10.6 in) of land subsidence during 1993-2006. Future work will determine the driving mechanism for playa surface fissuring—inelastic compaction of aquifer sediments or desiccation-triggered fissuring, or a combination of the two. Preliminary results indicate that the fissure opens at a rate of 1-2 mm/yr (0.04-0.08 in/yr), perhaps responding to groundwater level declines of about 4 m (13 ft) during 2008-2009. Data collected from a horizontal extensometer, surveying, electronic distance measurements, tiltmeters, heat dissipation sensors, and tripod mounted LIDAR scans will be employed to evaluate the cause of the fissures and their relation to desiccation cracks, and perhaps to provide real-time monitoring of fissure hazards (Densmore, et al., 2010).

4.6 Coachella Valley

The Coachella Valley is located in Riverside County and extends 45 miles from the San Bernardino Mountains to the northern shore of the Salton Sea. Groundwater has been a major source of agricultural, municipal, and domestic water supply in the Coachella Valley since the early 1920s. Groundwater levels declined throughout the Coachella Valley from the 1920s until 1949. In 1949, imports of surface water from the Colorado River to the southern Coachella Valley began, resulting in decreased pumping and a recovery of water levels in some areas. Since the 1970s, demand for water in the southern Coachella Valley has exceeded the deliveries of the imported surface water, and water levels have again declined. The declining water levels have the potential to induce or renew land subsidence in the Coachella Valley (Sneed, USGS, oral communication, May 30, 2013).

A large earth fissure was discovered in 1948 about 3 km (2 mi) north of Lake Cahuilla in La Quinta. Because subsidence had not been documented in the southern parts of the Coachella Valley prior to a report by Ikehara and others (1997), it is not known whether this fissure formed in response to differential land subsidence during an early period (early 1920s-late 1940s) of groundwater-level declines. However, fissuring has since recurred in this area (Michelle Sneed, USGS, oral commun. May 30, 2013, citing Clay Stevens, TerraPacific Consultants, Inc., written commun., 2006).

Concerns about land subsidence prompted the Coachella Valley Water District (CVWD) to contact the USGS to cooperatively establish and operate a land subsidence monitoring network. Monitoring results are reported in Ikehara and others (1997), and Sneed and others (2001, 2002, 2007), and via communication with Sneed (Michelle Sneed, U. S. Geological Survey, oral communication, September 2013). InSAR measurements made between June 27, 1995 and September 19, 2010 indicate that land subsidence ranging from about 22 to 60 cm (0.72 to 1.97 feet) occurred near Palm Desert, Indian Wells, and La Quinta (**Figure 4-30**). Average subsidence rates in Palm Desert were relatively stable increasingly only from about 3.9 cm/yr (0.13 ft) during the period 1995-2000 to about 4.5 cm/yr (0.15 ft/yr) during the period 2003-2010. Average subsidence rates for two subsidence maxima in Indian Wells were about 3.4 and 2.6 cm/yr (0.11 and 0.09 ft/yr) for both periods, indicating fairly steady subsidence; average subsidence rates for the third maxima in Indian Wells increased from about 1.4 to 1.9 cm/yr (0.05 to 0.06 ft/yr) between the two periods. Average subsidence rates for five selected locations in the La Quinta subsidence area ranged from about 1.7 to 3.7 cm/yr (0.06 to 0.12 ft/yr) during the period 1995-2000; three of the locations had similar rates during the period 2003–mid-2009 while the other two locations had increased subsidence rates.

Recently, earth fissuring has reoccurred near La Quinta and differential compaction that damaged homes there has resulted in litigation. Differential compaction that damaged homes in the Indian Wells area also has been recently reported. A subsidence profile covering about 27 mi of the Coachella Branch of the All American Canal showed that the canal had subsided as much as 41.2 cm (1.35 ft) in the La Quinta area during June 27, 1995 to September 19, 2010.

The areas that have subsided in the Coachella Valley between 1996 and 2010 are coincident with locations where groundwater levels declined, both during this period and during most of the past century. In the northern and central parts of the study area, where substantial subsidence was measured by 2010, water levels exhibited long-term declines during 1995-2010. The subsidence in these areas is likely to be mostly permanent because water levels have declined to historically low levels.

The CVWD has had initial success in halting declining water levels and subsidence in the La Quinta area, where subsidence rates slowed or land surface slightly rebounded during mid-2009-2010 as water levels rose in response to deliveries of Colorado River water to groundwater recharge facilities. The correspondence between the timing of increased deliveries and significant water-level recoveries suggests that the water applied to the recharge ponds is effectively recharging the aquifer system, although reduced groundwater pumping also can cause water-level recovery. The water-supply portfolio of the Coachella Valley is changing again as Colorado River water allocations are changed, complex water transfers according to the Quantification Settlement Agreement are implemented, and mitigation measures are instituted, including tiered rate structures, aquifer-recharge projects, and conversion from groundwater to

surface water resources for (primarily) golf course irrigation via the Mid-Valley Pipeline Project. The CVWD is encouraging golf courses and other landscape irrigators to employ reclaimed water for irrigation purposes. An effective land subsidence monitoring program helps water managers assess the effects of groundwater recharge, water reuse, and conservation efforts.

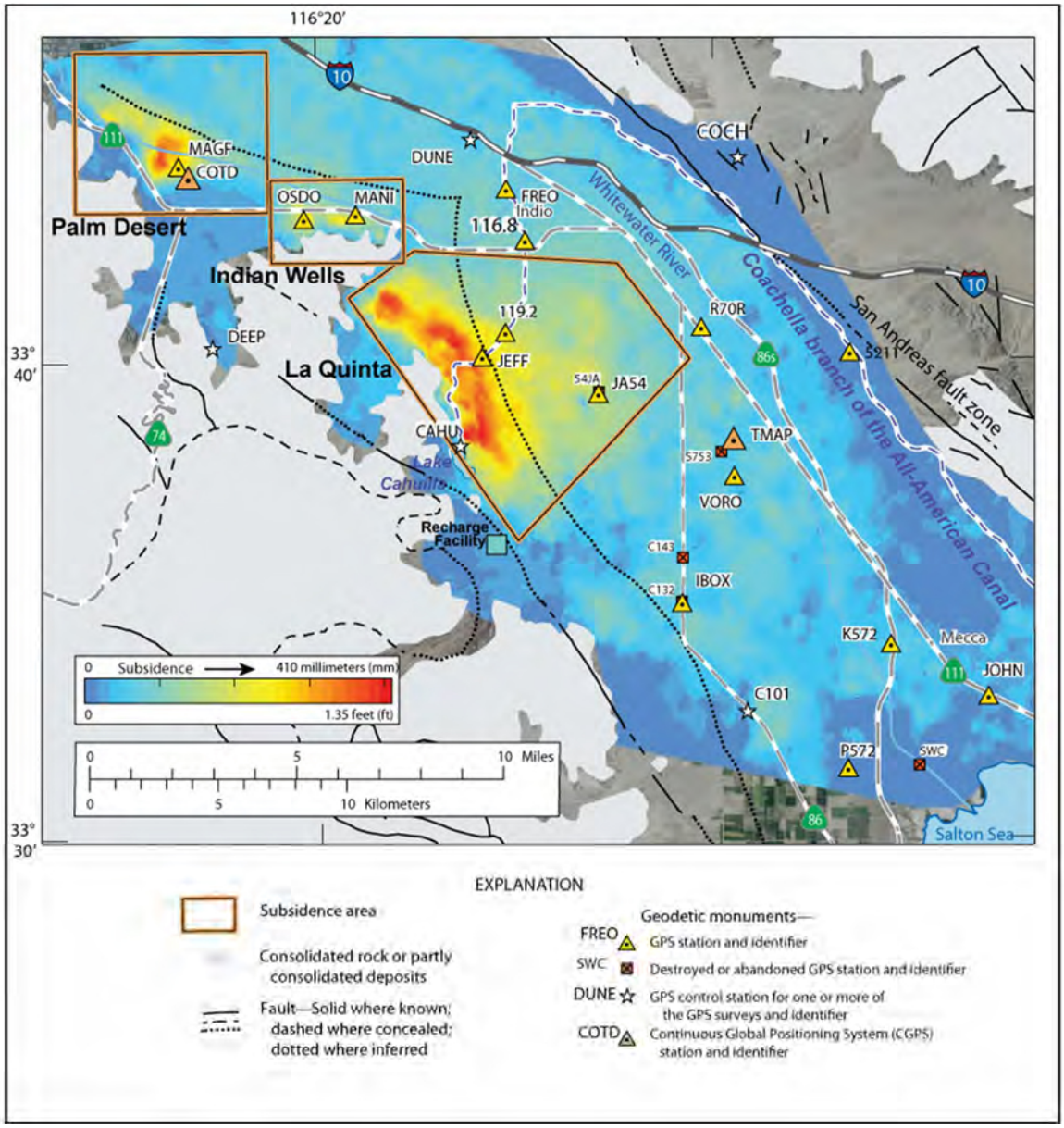


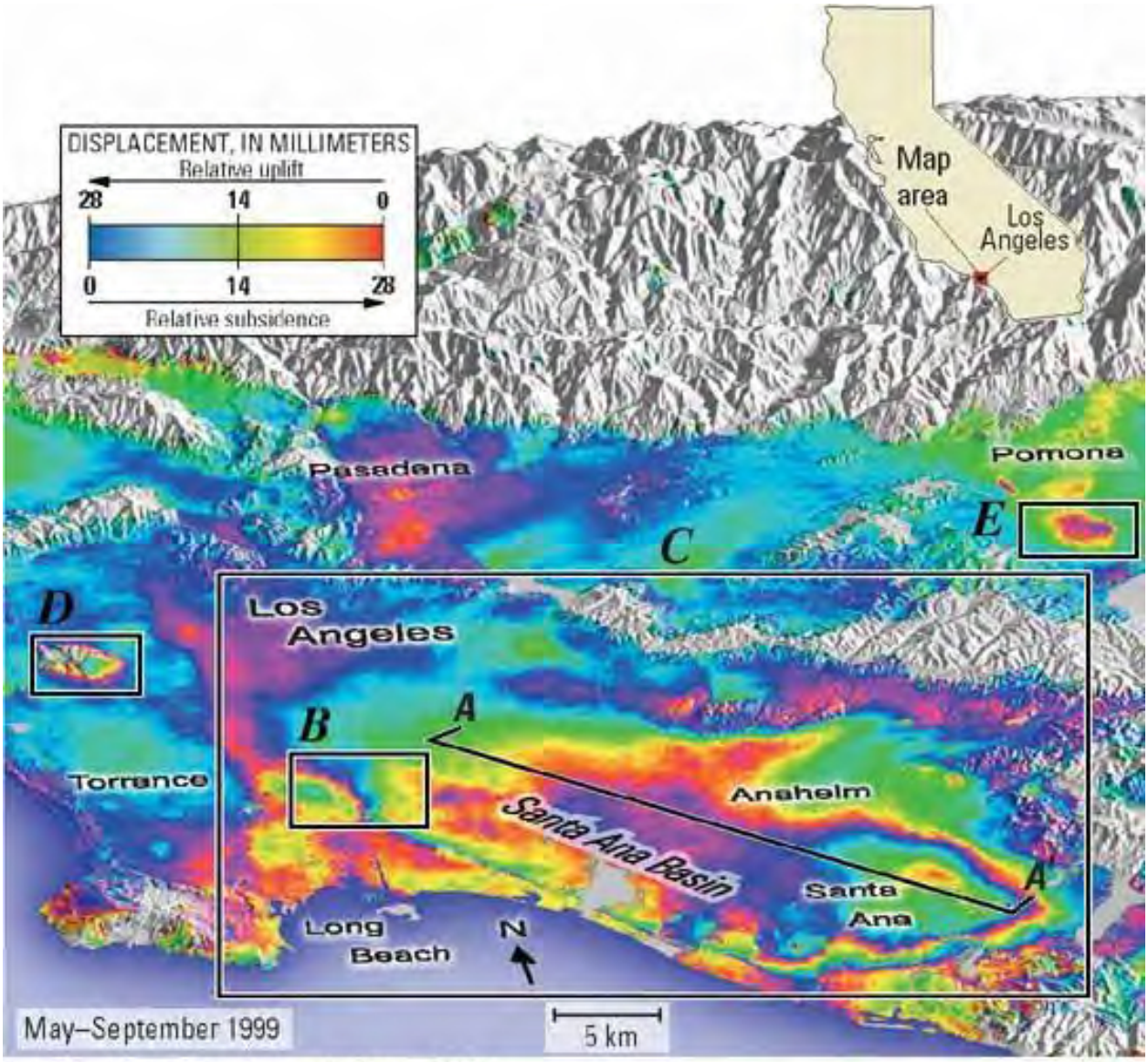
Figure 4-30.Stacked and kriged interferogram in the Coachella Valley, California for June 27, 1995–September 19, 2010 (excludes November 8, 2000–November 30, 2003), showing areas of subsidence, geologic features, and GPS monitoring network components. (interferogram construction is described in Section 5) From north to south the subsiding areas are, Palm Desert, Indian Wells, and La Quinta. Maximum subsidence in the southern Coachella Valley is estimated to be about 600 mm during the period. (Courtesy o the USGS and the CVWD). (Modified from: Michelle Sneed, U. S. Geological Survey, written commun., March 3, 2014).

4.7 Los Angeles

The greater Los Angeles metropolitan area experiences surface deformation due to a variety of natural and human-induced causes. Because tectonic deformation, oil-field operations, and groundwater extraction and injection occur in overlapping proximity, it has proved difficult to determine the cause of observed deformations using standard surveying techniques. Human-induced land deformation also produces horizontal surface motion that obscures, or in some cases mimics, the tectonic signals expected from the blind thrust faults beneath Los Angeles (Bawden et al., 2001). Through the use of continuous GPS, InSAR (both methods described in Section 5), and groundwater-level data, Bawden and others (2001, 2003) were able to measure the separate deformations attributed to tectonic movement on strike-slip faults, tectonic contraction on blind thrust faults, seasonal groundwater pumping, year-round artificial groundwater recharge, and hydrocarbon withdrawal at oil fields (oil-field subsidence processes are described in **Appendix A**). The following information and illustrations are from Bawden and others (2001, 2003).

In metropolitan Los Angeles, interferograms identified widespread seasonal and longer-term surface deformation related to both groundwater and hydrocarbon production. The largest coherent feature in the May–September 1999 interferogram (**Figure 4-31**) is the 40-km long Santa Ana Basin, where groundwater pumping and artificial recharge produced as much as 6 cm (0.2 ft) of seasonal subsidence and 4 cm (0.13 ft) of uplift, respectively, with as much as 2 cm (0.1 ft) of net subsidence in April 1998–May 1999 (**Figure 4-32A**).

Faults and geologic structures can impede the flow of groundwater and can be recognized as linear InSAR features where groundwater levels decline on one side of the fault or rise on the other. The Newport-Inglewood Fault bounds the southwest margin of the Santa Ana Basin (**Figure 4-32B**). InSAR shows that an abrupt boundary to groundwater flow nearly coincides with the fault. The boundary is indicated by a bunching of the color fringes on the northeast side of the fault, showing that the land surface displacements are steepest where the fault barrier prevents groundwater west of the fault from flowing toward subsiding pumping centers farther to the east. Subsidence caused by pumping groundwater northeast of the fault does not affect areas southwest of the fault.



(modified from Bawden and others, 2001)

Figure 4-31. Terrain and InSAR image of Los Angeles and Santa Ana Basin shown as a location map for Figures 4-32 A, B, C, D, and E (from Bawden et al., 2003).

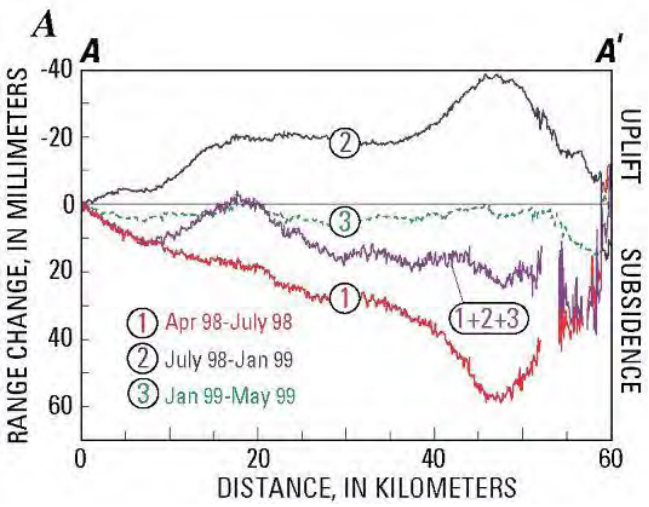


Figure 4-32A. Subsidence and uplift of land surface along profile A-A' in response to seasonal deformation during April 1998-May 1999 (from Bawden et al., 2003).

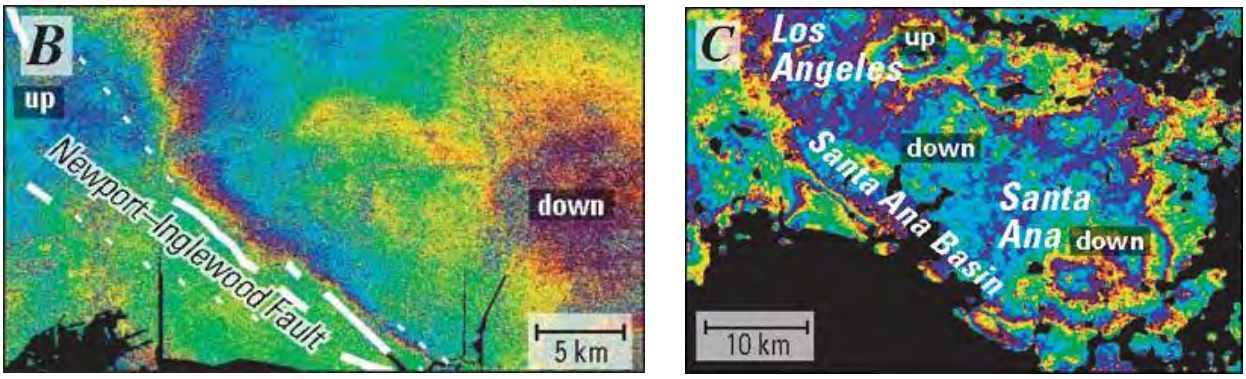


Figure 4-32B-C. B) Interferogram east of Long Beach shows that groundwater flow is impeded by a groundwater barrier nearly coincident with the Newport-Englewood Fault (May-September 1999) (from Bawden et al., 2003). C) Interferogram shows long-term subsidence (October 1993–October 1998) in most of the Santa Anna basin (from Bawden et al., 2003).

Many of the observed deformation features are long-lasting and exhibit substantial subsidence. Declining groundwater levels near Santa Ana caused the land surface there to subside at a long-term rate of about 2 cm per year (0.08 ft/year) (**Figure 4-32A, C**). Using precise leveling, oil production and oilfield water injection volumes, shallow groundwater extraction volumes and groundwater level data, Erickson (1977) concluded that subsidence from oilfield operations at the Beverly Hills Oil Field amounted to no more than a few hundredths of a foot per year (1.5 cm/yr maximum during 1967-1973). Using InSAR, Bawden and others (2003) identified a high resolution bullseye feature (**Figure 4-32D**) typical of interferograms showing deformation from oilfield operations. Subsidence resulted in an oval subsidence bowl. The two studies (Erickson, 1977; Bawden et al., 2003) indicated similar annual rates of subsidence at the oil field but, using InSAR, Bawden and others (2003) rapidly produced a detailed, high resolution map of subsidence over the entire field.

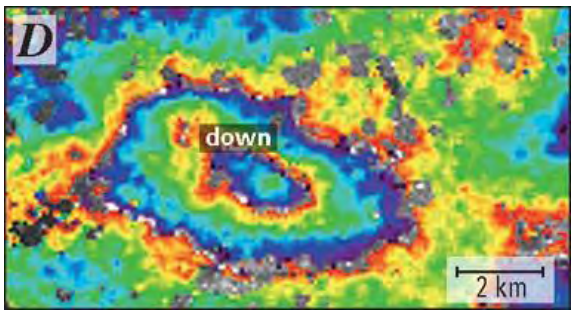


Figure 4-32D. Interferogram showing subsidence at the Beverly Hills Oil Field during October 1993-October 1998 (from Bawden et al., 2003).

4.8 Chino

The Chino Groundwater Basin in the southwestern corner of San Bernardino County includes the cities of Chino, Chino Hills, Pomona, Ontario, and Upland. Water levels declined more than 40 m (131 ft) from the early 1900s through 1978. As much as 1.2 m (3.9 ft) of subsidence occurred during 1986-1993 (Stewart and others, 1998).

Earth fissures developed as early as 1973 and again during 1987-1995 in conjunction with 0.7 m (2.3 ft) of subsidence (Wildermuth Environmental, 2007). The earth fissures developed along a zone of flexuring or differential subsidence associated with an inferred fault-zone groundwater barrier in the deep aquifer (**Figures 4-32E and 4-33**). With a possible depth of deformation of as much as 420 m (1,400 ft), the Chino fissure zone may be more than 200 m (600 ft) wide. It extends almost 3,200 m (2 mi) from the California Institute for Men prison, where it exists as two parallel fissures, to Chino Avenue. In the 1990s, it emptied a liquid manure pond and split a house that was then condemned and demolished at what is now a vacant lot for storage at 5500 Daniels Street.

Limited repeated horizontal-distance surveys and leveling at Daniels Street over monuments spaced 3 m (10 ft) apart indicated a crack zone of more than 30 m (100 ft) with a possible graben (downdropped) block 3 m (10 ft) wide. Buried end-to-end quartz-tube horizontal extensometers that span 51 m (167) ft across the crack zone have exhibited more than 2 mm (0.08 in.) of predominantly elastic opening and closing in response to about 22 m (72 ft) of drawdown and recovery in a nearby observation well. In spite of being elastic, the measured strains are about 40 percent of the lowest value of strain-at-failure as provided by Jachens and Holzer (1982).

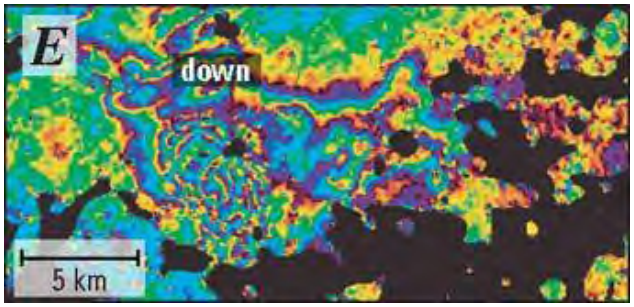


Figure 4-32E. Interferogram showing subsidence near Pomona-Chino during 1993-1995 (from Bawden et al., 2003).

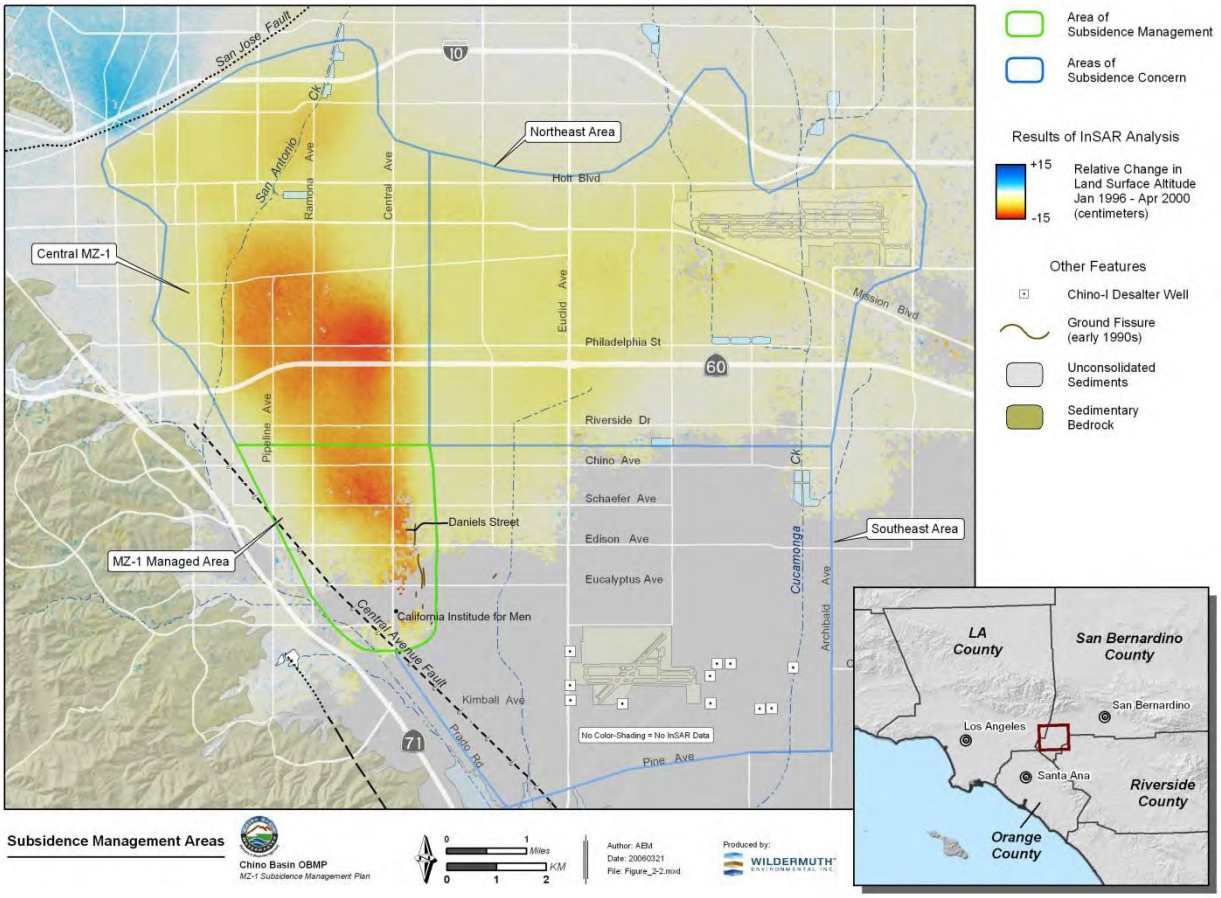


Figure 4-33. Interferogram during January 1996 – April 2000, showing subsidence bounded by faults and earth fissures in Chino (Wildermuth Environmental, 2007). Differential subsidence across the San Jose Fault and Central Avenue Fault is visible.

4.9 Paso Robles Area

As in much of California, the population of San Luis Obispo County has grown substantially. Land has been converted from dry farming and grazing to irrigated agriculture and urban development. Groundwater has been relied upon to make up for shortages of surface water. Valentine and others (2001) used InSAR techniques to determine that three areas northeast of

Paso Robles and one area northeast of Atascadero subsided during March 28-August 15, 1997 (**Figure 4-34**). The maximum downward displacement northeast of Paso Robles during this 6-month period was 2 cm (0.8 in), whereas groundwater levels declined about 18 m (60 ft) during the same period (Valentine et al., 2001). It is likely that concentrated pumping is responsible for localized land subsidence. The small area of deformation in the Atascadero area subsided 2.8 to 5.6 cm (about 1 to 2 in), coincident with seasonal water-level declines of about 16 m (54 ft). Small amounts of subsidence owing to seasonal changes in groundwater levels may be elastic and recoverable. However, during 2013 substantially declining groundwater levels have been reported. Many formerly reliable wells have gone dry. Interferograms spanning 1997-2013 could indicate whether declining groundwater levels have triggered inelastic compaction of aquifer sediments and permanent subsidence in Paso Robles area.

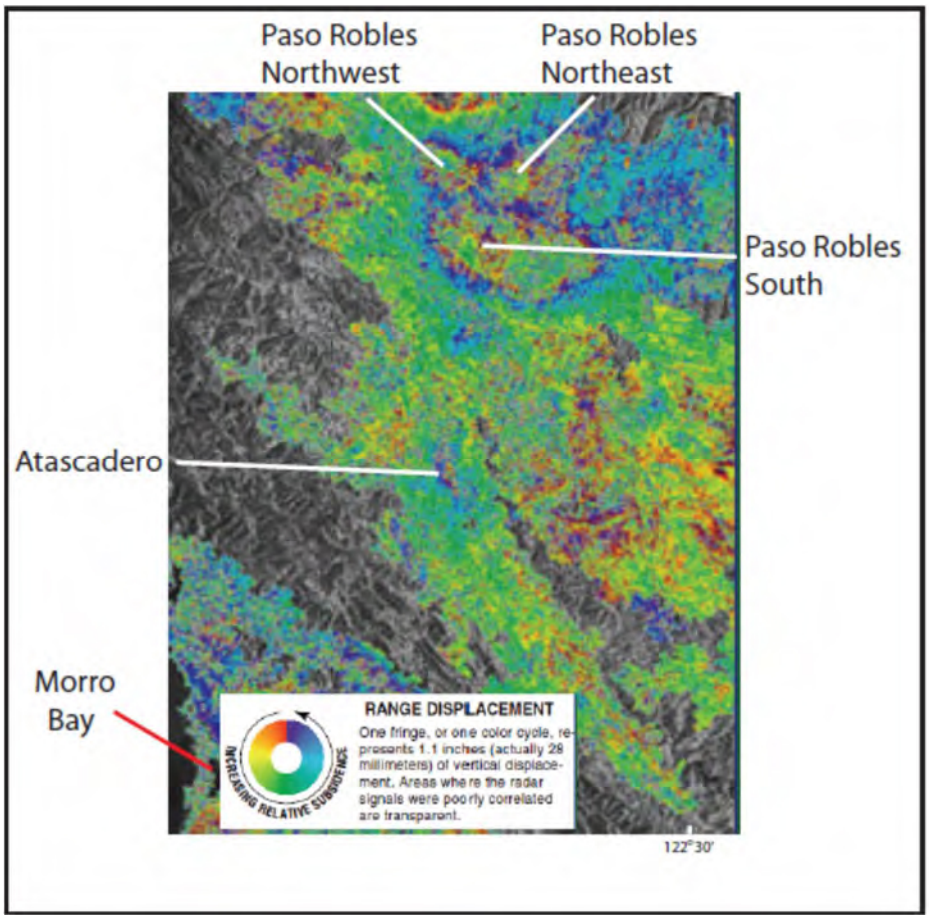


Figure 4-34. Interferogram of the Paso Robles area showing four areas of likely subsidence during March 28-August 15, 1997 (modified from Valentine and others, 2001).

4.10 San Luis Obispo Area

The city of San Luis Obispo, about 20 miles inland from the central California coast at Morro Bay, is dependent on local water sources, including surface reservoirs and groundwater, for municipal water supplies. Water shortages became severe during the 1987-1992 drought.

Mandatory water rationing was enforced in 1989. When one of the two surface-water reservoirs dropped to its minimum pool elevation in 1990, the city increased groundwater extraction dramatically to meet water demands (Ron Munds, City of San Luis Obispo, California, oral commun., November 4, 2013). In 1991, tenants and owners of businesses near two of the city wells began to notice unusual effects on their infrastructure. The Bear Valley Shopping Center, a strip mall on Los Osos Valley Road, experienced differential subsidence; floors were shifted unevenly. The middle of the long, narrow mall subsided less than either end of the building so that the floor had an inverted V-shape in its long dimension. Doors and windows would not close properly, and sidewalks sloped back toward the building so that slot drains had to be cut in order to remove pooling precipitation. A surveyor measured a 12-inch drop in the floor along the 45-foot length of one store. After the floor was leveled, a 1-foot step had to be built to allow safe access to the store. Because the steel frame construction of the building remained structurally sound, repairs could be made without complete reconstruction (John Rosesetti, Los Osos Valley Associates, oral commun., November 4, 2013). The adjacent building housing the Sunset Honda dealership had to be razed and completely rebuilt. Many homes in the nearby development were damaged. Owners of the strip mall successfully sued the city and were awarded $1 million in damages (John Rosesetti, Los Osos Valley Associates, oral commun., November 4, 2013). After that settlement the automobile dealership and many homeowners filed claims with the city. Total cost of the claims were about $2 million (Ron Munds, City of San Luis Obispo, California, written commun., November 5, 2013).

4.11 Cambria

At Cambria, on the central California coast, earth fissures resulting from substantial decline of groundwater levels during the 1976-1977 drought damaged buildings and other infrastructure (Cleveland, 1980). Subsequently, the city of Cambria developed additional sources of water for public supply; since then groundwater levels have not returned to historical low levels and fissuring has not reoccurred (Robert Gressens, Cambria Community Service District, oral commun. Sept. 13, 2013).

4.12 Santa Clara-Calleguas Basin

Subsidence in the Santa Clara-Calleguas basin, in coastal Ventura County, is caused by a combination of tectonic movement, hydrocarbon extraction, and groundwater pumping (Hanson et al., 2003). Some vertical movement – uplift north of the Oxnard Plain subbasin and subsidence in the Oxnard Plain subbasin – has been caused by tectonic deformation and related earthquakes. At the southern edge of the Oxnard Plain (**Figure 4-35**), elevation data from bench marks (BM) on bedrock (for example, BM Z 583) indicate that the 0.1 m (0.17 ft) of subsidence that occurred during 1939-1978 (at a rate of about 0.004 ft/yr) may be related to tectonic activity (Hanson et al., 2003). More than 9.7 million m^3 (7,900 acre-ft) of brines, 7.86 million m^3 (8,000 acre-ft) of oil, and 2.04 million m^3 (1,653 ac-ft) of natural gas were withdrawn from oilfields in

the Oxnard Plain (**Figure 4-35**) between 1943 and 1991 (Hanson et al., 2003, citing Steven Fields, Operations Engineer, California Department of Conservation, Division of Oil and Gas, written commun., 1992). Pressure declines equivalent to more than 335 m (1,100 ft) of groundwater-level decline have occurred in the Oxnard oilfields since the onset of oil and gas production. These declines alone could potentially account for local subsidence of 0.4 to 1 m (1.5 to 3.3 ft). However, the oil and gas fields are located several miles north of the bench marks used to measure subsidence and therefore likely do not affect those bench marks. Water-level declines in this coastal basin have induced land subsidence that was first measured in 1939. Subsidence of 0.8 meters (2.6 ft) between 1939 and 1978 was measured at bench mark E 584, about 7 km (4.3 mi) from the coast in the valley of Calleguas Creek. Numerical flow modeling by Hanson and others (2003) simulated a total of 0.9 m (3 ft) of land subsidence in the southern part of the Oxnard Plain and as much as 1.5 m (5 ft) in the Las Posas Valley subbasin. Model simulations indicate that most of the land subsidence occurred after the drought of the late 1920s and during the agricultural expansion of the 1950s and 1960s. Subsidence occurred primarily in the upper-aquifer system prior to 1959; some subsidence also occurred in the lower-aquifer system during 1959-1993 owing to an increase in pumpage there (Hanson et al., 2003).

Indirect evidence that subsidence is in fact related to groundwater withdrawal includes water-level declines greater than 30 m (100 ft), subsurface collapse of well casings in the South Pleasant Valley subbasin and South Oxnard Plain subarea, repeated re-leveling of irrigated fields for proper drainage, less effective drainage ditches in agricultural areas, and lowering of levees along Calleguas Creek in the South Pleasant Valley subbasin (Hanson et al., 2003). In the Las Posas Valley and South Pleasant Valley subbasins, water-level declines of as much as 30 m (100 ft) in the upper-aquifer system and more than 91 m (300 ft) in the lower-aquifer system have occurred since the early 1900s. Considering the widespread water-level declines, the area of probable subsidence may include the Las Posas Valley subbasin and the remainder of the Pleasant Valley subbasin. Although the amount and areal extent of subsidence in the basin from each contributing source remains unknown, groundwater withdrawal and oil and gas production are probably major causes in the Oxnard Plain subbasin, and tectonic activity is probably a minor cause (Hanson et al., 2003).

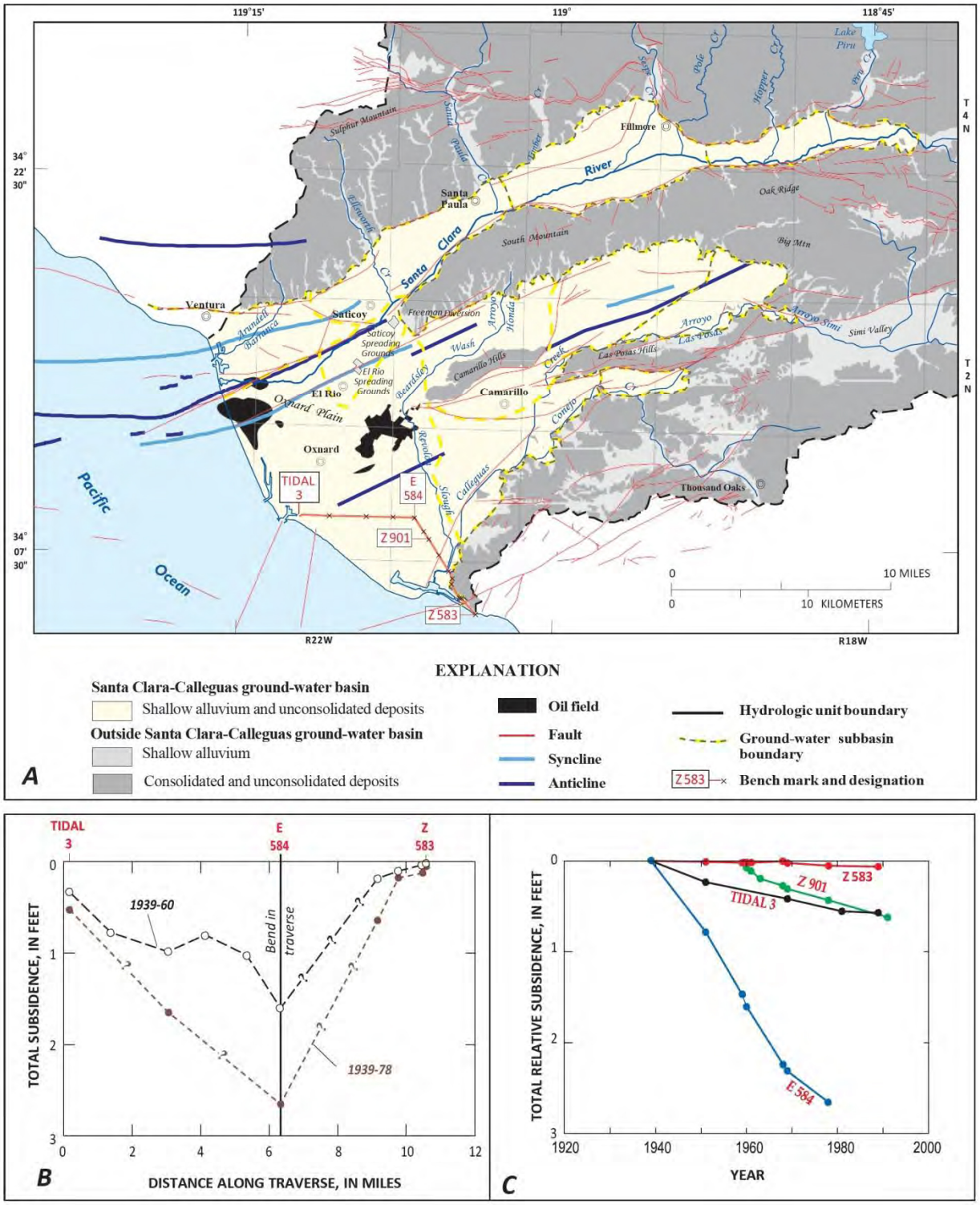


Figure 4-35. Subsidence in the Oxnard Plain and Pleasant Valley, Santa Clara-Calleguas groundwater basin, California. A) geographic features, B) subsidence profile, C) subsidence of bench marks through time (from Hanson et al., 2003, Figure 9).

4.13 Elsinore Trough - Wolf Valley to Murrieta

There are two separate areas of subsidence in the Elsinore trough, a broad structural depression bounded by faults in western Riverside County (Shlemon and others, 1998). Subsidence in these two areas was likely caused by different mechanisms. Fissures appeared in the Wolf Valley area in 1987 and advanced northward seven miles to the Temecula-Murrieta area (Earth Consultants International, 2000). By 1991, damages to surface structures exceeded $50 million (Corwin and others, 1991). Study of the fissures led to discovery of the previously unknown Murrieta Creek and Wolf Valley Faults. The location of the fissures is primarily controlled by these two faults (Shelmon and Hakakian, 1992), but most investigators believe that the fissures formed when increased pumping caused inelastic compaction and subsidence (Shlemon and Davis, 1992). Tensile stresses that concentrated along the trough-bounding faults pulled apart subsurface materials. Evidence for this hypothesis is simply that several new wells began pumping in the days and weeks before subsidence was noted, and that since pumping stopped the fissures have not increased in number or size. Fissures in the other subsiding location in the Elsinore trough, the California Oaks subdivision in Murrieta, were caused by hydrocompaction upon wetting, rather than extraction of groundwater. Hydrocompaction is discussed in **Appendix A**.

4.14 San Jacinto Valley

Land surface deformation in the San Jacinto Valley, in eastern Riverside County, a structural depression within the San Jacinto Fault zone, has components of both tectonic deformation and aquifer compaction. Tectonic subsidence of the structural trough has been occurring at rates of 3 to 5.6 mm/yr (0.1 to 0.2 in/yr) for the past 10,000 to 40,000 years (Morton, 1977). Groundwater levels, which had been 7 m (25 ft) above land surface in the 1930s, declined to more than 61 m (200 ft) below land surface in the 1970s. Proctor (1962) reported 71 cm (2.34 ft) of subsidence between 1939 and 1959 east of the trough-bounding Casa Loma fault, with no subsidence west of the trough. Lofgren (1976) measured compaction of aquifer materials with a 377-m (1,237-ft) deep extensometer during 1970-1974 and concluded that inelastic compaction of aquifer materials in the depth range of the extensometer amounted to about 1 cm /yr (0.04 ft/yr) and that tectonic subsidence amounted to 0.3-0.6 cm/yr (0.1-0. 2 in/yr). That is, most permanent subsidence (70-80 percent) resulted from groundwater withdrawal, with the remainder from tectonic downwarping of the valley. After 1953, linear fissures and sinkhole-like depressions formed along traces of the eastern basin-bounding faults, and arcuate fissuring occurred near the contact of alluvium and basin-bounding hills to the west (Morton, 1977). Holzer (1984) concluded that although the fissures were co-located with basin-bounding faults, they could have been induced by groundwater pumping that concentrated stresses where aquifer deposits thin near bedrock outcrops on the west side of the trough, and at a groundwater-barrier fault on the east side of the trough.

4.15 Yucaipa Valley

The Yucaipa Valley, in southwestern San Bernardino County, is a small, tectonically formed trough mostly filled with silt and clay. The valley has a long history of water development. The first irrigation ditch was constructed in 1819 to support farming and cattle raising. By 1909, about 95 percent of the area's water supply was used for agricultural irrigation. (Yucaipa Valley Water District web page, http://www.yvwd.dst.ca.us/index.aspx?page=133, accessed January 13, 2014). Irrigation wells to support agriculture and post-World War II urbanization contributed to groundwater-level declines of more than 35 m by 1952. In January 1952, a 600-m-long fissure opened about 5 km (3.1 mi) west of the town of Yucaipa (Holzer, 1984, citing Burnham, unpublished report, 1952). Hydrogeologic studies were not performed to determine whether historically low groundwater levels in 1952 triggered the fissure or if tectonics caused or contributed to its formation. Managers at the Yucaipa Valley Water District are not aware of the location of the fissure reported by Burnham (1952, unpublished report) and have not observed other fissures in Yucaipa Valley (Jack Nelson, Yucaipa Valley Water District, oral commun., January 2014).

4.16 Cuyama Valley

Groundwater is the sole source of water supply in Cuyama Valley, a rural agricultural area east of Santa Barbara in the Coast Ranges near the edge of the southern San Joaquin Valley. Groundwater levels there have declined as much as 91 m (300 ft) since the 1940s. The magnitude of land subsidence from this historic groundwater-level decline has not been reported; however, the potential for increased groundwater extraction has raised concerns about land subsidence. Relevant factors include active tectonics and hydrocarbon extraction, as well as groundwater extraction. The USGS assessed the relationship between groundwater-level and land-surface elevation changes during 2008-2012 (Everett et al., 2013). The valley and surrounding mountains are moving 0.7 to 1.3 mm (0.03 to 0.05 in) upward and 25 to 36 mm (1 to 1.4 in) to the northwest each year, consistent with motion on the San Andreas Fault system. Comparison of changes in land-surface elevation determined from continuous GPS stations and Synthetic Aperture Radar (SAR) satellites with groundwater levels measured in observation wells indicated that the aquifer system in the valley experiences seasonal elastic land deformation and expansion that results in small amounts of recoverable subsidence. In parts of the valley where groundwater levels had declined below historically low levels during December 2002-May 22, 2008, InSAR detected longer-term land subsidence of 8 to 12 mm/yr (0.31 to 0.47 in/yr), amounting to 40 to 65 mm (1.6 to 2.6 in) total subsidence during the period. This long-term subsidence results from inelastic compaction of the aquifer system. The InSAR derived trend at one locality, 8 mm/yr (0.31 in/yr), was confirmed by a continuous GPS station located near observation wells where water levels had declined below historic lows. Extraction of hydrocarbons at two oil fields in the valley apparently had little effect on subsidence during 2002-2011. USGS evaluation of the Cuyama Valley aquifer system is ongoing.

5 MEASURING AND MONITORING LAND SUBSIDENCE

5.1 Methods

Alarming rates of subsidence recently have been measured in several areas of California. This information has been reported only after disruptive impacts from subsidence have occurred; this emphasizes the need for increased monitoring. There is no state or federal agency in California that has the responsibility or program in place, specifically to monitor land subsidence. Consequently, there are no statewide monitoring networks for subsidence. Smaller regional, county-wide, or local monitoring networks are sometimes constructed to address a specific subsidence issue. These small networks usually are not designed for long-term monitoring, but rather for a project-specific period of time, usually implemented in reaction to a subsidence crisis that has damaged or impaired the function of essential infrastructure.

There a few exceptions: adjudicated basins sometimes have management objectives that require detailed subsidence monitoring and reporting, as do some agencies that are the primary water purveyor in a region. But, if land subsidence monitoring is defined as the systematic and regular acquisition of information to describe the changing extent and magnitude of the problem, then most of California must be considered unmonitored.

Land subsidence can be measured by determining the change in land surface elevation by several methods; other methods directly measure that part of land subsidence resulting from groundwater extraction.

Borehole extensometers combined with water-levels in observation wells have been providing time series monitoring of subsidence at a few selected points in California since 1958. Repeat leveling of existing monuments along U.S. Coast and Geodetic Survey (now National Geodetic Survey) and USGS level lines since the early 1900s establish the areal distribution of subsidence. Civilian use of the Department of Defense Global Positioning System (GPS) began in the 1980s, and space-borne Interferometric Synthetic Aperture Radar (InSAR) in the 1990s. All these techniques augment each other. Borehole extensometers and GPS stations can provide continuous records to compare with water-level records and determine elastic and inelastic (or permanent) deformation. GPS establishes a context of measurements in a fixed reference frame and allows continuous monitoring of horizontal and vertical deformation at a location. InSAR can provide remotely sensed measures of small magnitude land-surface displacements over large areal extents.

The Gravity Recovery and Climate Experiment (GRACE) measures changes in the position of mass and is being used for measuring very-large-scale water-level changes in unconfined aquifer systems (Famiglietti, et al., 2011). GRACE by itself provides no information on land subsidence, and satellite-based gravity measurements do not appear to have sufficient resolution for the

typical regional and local scales of aquifer systems in California. GRACE operates at relatively low resolution in space and time; it can measure monthly changes in gravity, for regions with a minimum area 150,000 km^2 (more than 93,000 mi^2), with an accuracy of 1.5 cm (0.6 in) of equivalent water height (Bridget Scanlon, University of Texas at Austin, pers. commun. October 31, 2012). Its performance improves with increasing area and time period. Due to spatial resolution limitations, the GRACE method is not discussed further in this report.

Viable methods for measuring and monitoring subsidence are discussed further below.

5.1.1 Measuring Changes in Land Surface Elevation

Surveying and the Global Positioning System

Ground deformations associated with land subsidence are measured in several ways (**Table 5-1**), generally referenced to the position of land surface at geodetic monuments. Geodetic monuments, such as bench marks (which are capped with a brass disk identifying the installing agency and a unique name), are anchored well below land surface to assure that changes in elevation represent deep-seated processes rather than shallow surface processes such as soil shrink and swell or frost heave. Changes in vertical and/or horizontal position of geodetic monuments are referenced to other monuments that are assumed to be stable, or to a global reference frame. In California, where local land surveys using spirit levels indicated historical subsidence activity, accurate quantification of subsidence was sometimes hindered by uncertainty regarding the stability of the bench mark(s) used for control.

For the United States, the National Geodetic Survey, or NGS (formerly U.S. Coast and Geodetic Survey), is the most complete source for digital National Spatial Reference System (NSRS) data. The NGS is responsible for defining, managing, and providing public access to the NSRS, which provides a consistent national coordinate system for mapping latitude, longitude, and elevation with high accuracy. Unfortunately, past records of vertical land elevation are difficult to compile and utilize; the NGS emphasizes the most recent x, y, and z value for a bench mark as the most valuable. The 'superseded', or historic, vertical elevation values sometimes are embedded in an ASCII file called a Datasheet, one per monument, whereby one can extract some previous elevation values for each monument[3]. Usually, only the most recent historical elevation is shown on the Datasheet, although in subsidence-prone regions, there may be dozens of superseded elevations.

[3] There also is an issue with the vertical datum for all sites. Newer values are referenced to a different vertical datum than historical values, and an adjustment is needed to convert all values to the same datum.

Table 5-1. Methods of measuring land subsidence

Method	Displacement Direction	Resolution[1]	Spatial Density[2]	Spatial Scale
		(millimeters)	(measurements per survey)	(elements)
Spirit level	vertical	0.1-1	10-100	line-network
Electronic Distance Measuring (EDM) Device	horizontal	1	10-100	line-network
Borehole extensometer[3]	vertical	0.01-0.1	1-3	point
Horizontal Extensometer				
Tape	horizontal	0.3	1-10	line-array
Invar Wire	horizontal	0.0001	1	line
Quartz tube	horizontal	0.00001	1	line
GPS	vertical horizontal	20 5	10-100	network
Satellite SAR Interferometry				
InSAR	range (satellite to ground)	5-20	100,000-10,000,000	map pixel[4]
PS InSAR	range (satellite to ground)	1-5	variable[5]	map pixel[4]
LIDAR				
Tripod	vertical horizontal	10 10	1,000,000-100,000,000	3-D point cloud
Airborne	vertical horizontal	300 360	variable	Map pixel[6]

Note: data modified from Galloway and others, 2008
[1]Measurement resolution attainable under optimum conditions. Values are given in metric units to conform with standard geodetic guidelines. (One inch is equal to 25.4 millimeters and 1 foot is equal to 304.8 millimeters.)
[2]Number of measurements generally necessary to define the distribution and magnitude of land subsidence at the scale of the survey."
[3]Counter-weighted pipe extensometer (Riley, 1969)
[4]Typically 40 to 80 meters square on the ground.
[5] Depends on the presence and number of permanent scatterers
[6]Typically 0.25 to 2 meters square on the ground

Figure 5-1 shows the location of 55,000 NGS bench marks where land surface elevation is referenced to the North American Vertical Datum of 1988 (NAVD88); measurements are categorized by their relative vertical accuracy. The relative vertical accuracy (of the difference in elevation between any two bench marks) typically ranges from 3 to 8 mm multiplied by the square root of the distance (in km) between stations of the leveling line or section. These marks provide vertical control for elevation surveys for any purpose, including subsidence monitoring. Most of the vertical control (71percent) has been measured more than once, although not to the same vertical datum. For some bench marks (16percent), 50 or more years has passed between

the first and last measurements performed by NGS. This historic record of time-series elevation data would be of great value for a statewide assessment of subsidence, but unfortunately the data are not readily available and would require quite a bit of effort to be made suitable for use[4].

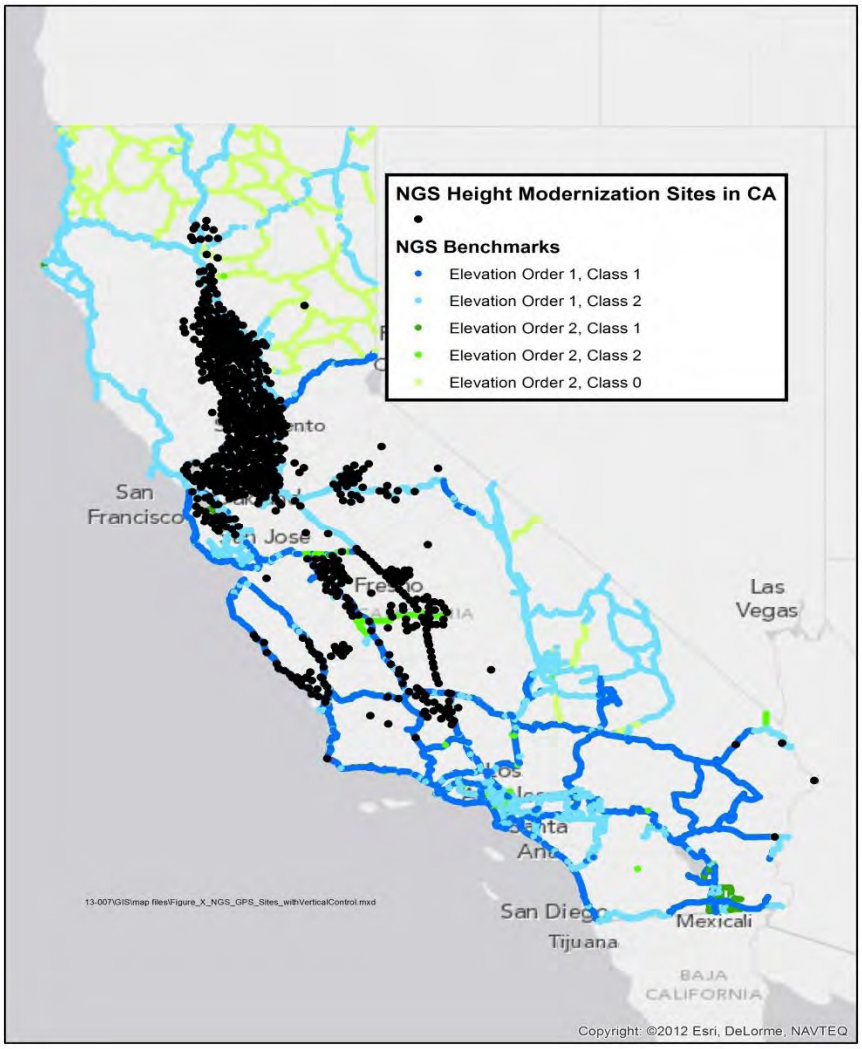


Figure 5-1. NGS Sites with vertical control.

[4] There are several storage boxes of paper records that include additional coordinates and elevation data for historical bench marks. Because there is no current NGS geodetic advisor in the state, the boxes likely will be removed from California and warehoused in the Washington, D. C. area. The historic data sheets will never be made available as a digital database, but if they were scanned and stored electronically this valuable data would be available for statewide assessments of historic land subsidence referenced to NGVD29.

Historically, spirit-level surveys were used to measure changes in land-surface elevation of bench marks. If land surveys collected both horizontal and vertical information, a theodolite or, since the 1980s, a device such as a total station, which includes an electronic distance measurement distance measuring (EDM) device, was employed.[5] In 1995, the Navstar GPS, based on 24 earth-orbiting satellites, became fully operational, providing continuously available access to at least 6 satellites visible to users in North America. The Navstar system allows 3-dimensional positions to be determined for geodetic monuments with an accuracy of 20 mm (0.0656 ft) vertically and 5 mm (0.0164 ft) horizontally, when geodetic procedures are employed and under ideal conditions. GPS measurements are expressed relative to a reference ellipsoid. A reference ellipsoid is a mathematically-defined surface that approximates the geoid, an idealized model of the Earth. Because of their relative simplicity, reference ellipsoids are the preferred surface on which geodetic-network computations are performed and point coordinates such as latitude, longitude, and elevation are defined. The reference ellipsoid is frequently updated as improved information becomes available. GPS measurements can be made with portable GPS receivers on a campaign basis or can incorporate data from more permanent installations at Continuous GPS sites (CGPS). The height modernization program of the NGS defines geodetic procedures and standards in order to provide the highest possible accuracy for elevations determined via GPS surveys (referenced to NAVD88). Elevations determined by GPS surveys that meet these standards are available in the NGS database as 'Height-mod' sites (**Figure 5-1**).

There are more than 800 CGPS sites in California. These are autonomous sites that receive data from GPS and sometimes other navigation satellite systems, and record their location (including vertical position) every 1, 5, 15, or 30 seconds. They are installed, owned, and operated by public agencies, consortiums, and private entities. Several of these entities archive geodetic information from their own sites and from sites operated by other entities and make the data available via the internet. These include: 1) Plate Boundary Observatory (PBO), which is a component of the University Navstar Consortium (UNAVCO) and funded by the National Science Foundation, 2) NASA/JPL, 3) UC Berkeley's Bay Area Regional Deformation (BARD) network, 4) Scripps Orbit and Permanent Array Center (SOPAC), 5) U. S. Geological Survey, 6) California Spatial Reference Center (CSRC), 7) NGS, 8) U. S. Coast Guard, 9) California Department of Transportation, and 10) various commercially owned CGPS sites that distribute data to their subscribers. CGPS sites are used as components of land deformation monitoring networks that primarily measure the horizontal movement of tectonic plates; very few were installed with the intent to monitor land subsidence.

Although they own and operate only one CGPS site in California, the NGS archives and provides on their website x, y, and z coordinates as well as time series data for approximately 284 CGPS

[5] Generally, surveys using the total station do not meet the high standards of vertical accuracy required for inclusion in the NGS database. Electronic Distance Measuring devices are most often used to determine changes in horizontal distance such as occurs across an earth fissure in a subsiding area.

sites in California (**Figure 5-2**) that were constructed and are operated by other agencies or consortiums of other agencies. These sites form the Continuously Operating Reference Station (CORS) network of the NGS. The CORS network data provide much-needed insight into the daily, seasonal, and climatic variations of land surface elevation and horizontal location, referenced to the NAD83 ellipsoid. The availability of high frequency position information (sampled at 1-second intervals, **Figure 5-2**) improves the accuracy of GPS data collected from moving planes and other aerial platforms (Snay and Soler, 2008) and shortens the time necessary for collection of data by portable GPS receivers. CORS time-series elevation data can be paired with groundwater-level measurements to define relationships between groundwater stresses and land-surface elevation changes.

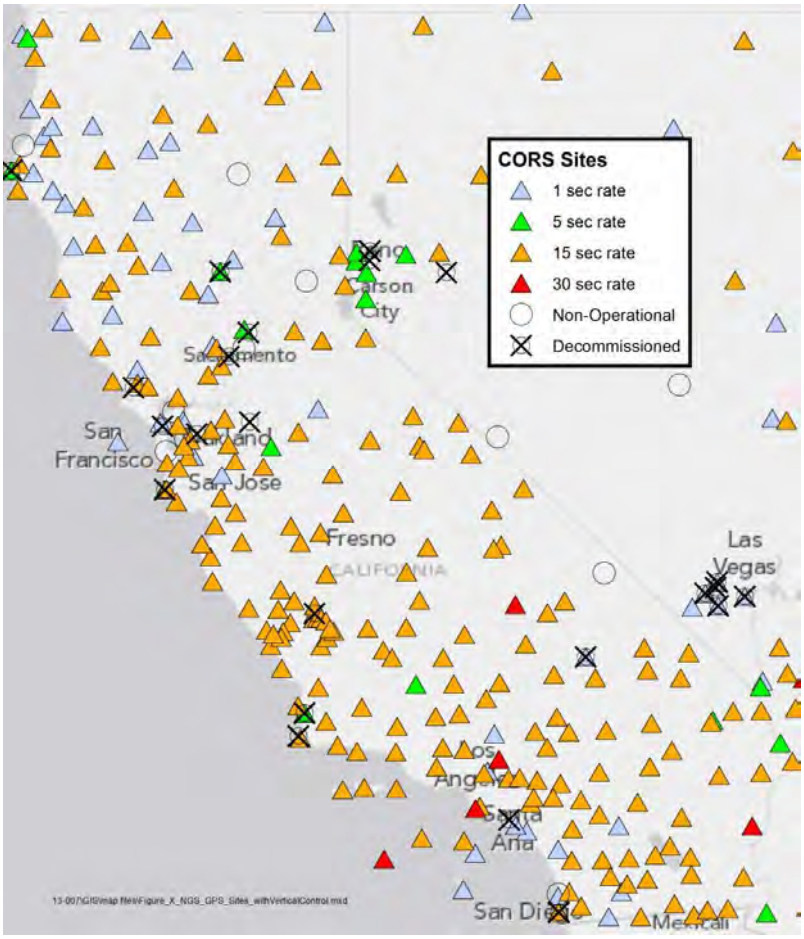


Figure 5-2. Continuously Operating Reference Station (CORS) Network (retrieved from NGS September 16, 2013).

Time-series data retrieved from other providers such as PBO or SOPAC can be used for the same purpose as CORS data, although mixing data from different providers can be problematic; NGS and SOPAC use a different reference frame than does PBO.

Satellite Synthetic Aperture Radar Interferometry

Interferometric Synthetic Aperture Radar (InSAR) is an invaluable satellite-based remote-sensing technique that uses radar signals to measure land-surface deformation at an unprecedented level of spatial detail and high degree of measurement resolution (**Table 5-1**). InSAR can provide detailed subsidence mapping over larger areas than can be measured by any other technique. Measurements can be done entirely retroactively, by acquiring historic (1992 to present) repeat satellite Synthetic Aperture Radar (SAR) data sets for the area of interest, and then processing the SAR data using interferometric techniques to determine changes in elevation over large areas with a precision of a few millimeters. Much of the Earth was repeatedly surveyed by the SAR satellites for establishing digital elevation models and to detect deformation associated with earthquakes, volcanoes, and glaciers. Those data sets provide the early basis for InSAR. Unfortunately, constructing long-term time series with SAR data can be difficult because of the short life spans of the satellites (i.e., they are generally decommissioned after about 5 years of service). The U.S. does not have a civilian SAR satellite, so presently data must be acquired from international sources (e.g., Canada, Germany, Italy, Japan, and Europe).

Under ideal conditions, InSAR can detect surface deformation of less than a centimeter over hundreds of square kilometers, at a spatial resolution of 90 m (295 ft) or better (Sneed et al., 2013). Radar signals generated from a satellite are bounced off stable and unstable radar reflectors on the Earth's surface. Stable reflectors are, roads, buildings, other engineered structures, mountains, and undisturbed ground and rocks. The travel time of the radar signal from the satellite to the ground and back to the satellite is proportional to the distance between the satellite and the ground.

Over a period of time changes in the position of radar reflectors on the Earth's surface can be measured by subtracting, or "interfering", two radar scans (scenes) of the same area that are made at different times. A difference in the calculated distance of a pixel indicates that the Earth's surface there has moved closer to the satellite (usually uplift) or away from the satellite (usually subsidence) during the time between acquisition of the two scenes. Processing of SAR data in this manner data results in map images called interferograms that show the magnitude of measured displacements by variation in the color of pixels overlain on a map of the scanned area. Typically this conventional processing technique is unsuccessful in areas where the surface has been disturbed or tilled, contains rapidly growing or harvested vegetation, or experiences dramatic changes in surface moisture. Manufactured devices designed to reflect Radar signals are sometimes installed in areas that otherwise would be poor candidates for InSAR analysis.

In agricultural areas or other areas where vegetation or ground disturbances affect ground reflectors between SAR acquisitions, Persistent Scatterer InSAR (PS InSAR) processing techniques have been used to measure subsidence and uplift. PS InSAR processing is similar to

the conventional technique but requires that 20 or more SAR images be processed simultaneously to identify pixels that have consistent strength (amplitude) of the radar pulse reflected from the surface (Ferretti et al., 2000, 2001; Warner et al., 2003). Such persistent reflections are returned from roads, power-transmission towers, levees, canals, buildings and other engineered structures that are often found within the otherwise disturbed surface of agricultural areas. Interferometric calculations are done only for stable pixels (pixels containing these persistent reflectors (scatterers) rather than every pixel in each SAR image pair. Again, colors representing the magnitude of displacement are assigned to each pixel that contains persistent scatters and overlain on a map. The size of each colored pixel is gradually increased until uncolored gaps in the map (as long as the gaps are not too large) disappear. The result is very similar to interferograms created using conventional InSAR techniques.
The quality of SAR data and the usefulness of interferograms can be affected by atmospheric conditions (fog and clouds), land-use, satellite orbit geometry, ground cover, and topographic relief. Methods have been developed to identify and discard, or correct for SAR images with these issues. InSAR techniques have proved invaluable for remotely assessing large areas with a high degree of measurement resolution.

LiDAR

LiDAR is a remote sensing technology that measures distance by illuminating a target with a laser and analyzing the reflected light. LiDAR has been used extensively both in tripod-mounted ground scanning and in airborne mapping surveys. LiDAR collects measurements independent of weather conditions or time of day, but is limited to line-of-sight measurements unless a target is scanned from different vantage points. Tripod mounted LiDAR provides distance from the instrument to millions of points on the land surface with a resolution of at least 1 cm (0.4 in). It has been used to measure displacement of land surface by faulting, landslides, and other geologic processes, and to estimate the volume of rock falling from cliffs by using scans before and after the event. Airborne LiDAR has been invaluable in geologic mapping and understanding geomorphic processes that shape the land surface. There are many potential sources of error in elevations acquired by airborne LiDAR: LiDAR equipment, interpolation, horizontal displacement, flight height, terrain slope, and ground cover all influence LiDAR-determined elevations (Hodgson and Bresnahan, 2004). Airborne LiDAR measurements have a lower vertical resolution compared to other methods of measuring the elevation of land surface.

Measuring Aquifer Compaction

Borehole extensometers measure the continuous change in vertical distance between the land surface and a subsurface reference point in a borehole (Riley, 1986). Several different kinds of borehole extensometers have been used to measure aquifer-system compaction, including pipe,

cable (steel), rod, and magnetic/radioactive marker. Fiber-optic components for borehole extensometers have been proposed. Only pipe and steel-cable extensometers are discussed in this section. The pipe and steel cable extensometers are most common and have been used extensively in California. Generally, pipe extensometers are built with a small diameter pipe inside a larger diameter well casing (**Figure 5-3A**). The pipe inside the well casing extends from land surface to a concrete pad that is usually emplaced at the base of compressible aquifer-system sediments. A table at the land surface holds instruments that monitor change in distance between the top of the pipe and the table (**Figure 5-3B**). Often pipe extensometers include a pipe, to reduce frictional coupling of the extensometer pipe to the extensometer casing. Cable extensometers typically consist of a cable anchored at the bottom of the borehole and counter weighted at the surface. The cable travels across a pulley that is connected to instruments that measure the distance that the cable travels. Both pipe and cable extensometers provide continuous measurements of the shortening and lengthening of the distance between land surface and the base of the monitored aquifer. Aquifer-system compaction measured using extensometers can be used to determine whether groundwater extraction from a particular part of the aquifer system may be contributing to land subsidence. These measurements can be compared to measurements of total land subsidence at the site (e.g., as determined from surveying, co-located continuous GPS sites, or InSAR) to determine whether processes other than aquifer-system compaction are also contributing to land subsidence. Extensometers are necessary to distinguish subsidence caused by groundwater extraction from deeper-acting processes such as hydrocarbon extraction and tectonics.

Aquifer systems often contain several major aquifers and confining units. Because it often is desirable to monitor compaction in more than one depth interval extensometers monitoring different depths are sometimes constructed at the same site. Multi-stage extensometers (and magnetic marker extensometers) at the same location have been used to monitor compaction simultaneously in different depth intervals. This is the only way to measure compaction occurring in different parts of the aquifer system, that is, in different depth intervals.. Pipe extensometers have been constructed that are sensitive enough to record the minute elastic compression and expansion that accompany even very small changes in water levels in unconsolidated alluvial aquifer systems, as well as the relatively large deformations typical of the inelastic and irreversible compaction of aquitards (Galloway et al., 1999).

When combined with water-level data, the deformation history provided by an extensometer can be used to constrain the average compressibility and vertical hydraulic conductivity of confining units; these are characteristics that must be determined to estimate eventual subsidence magnitude under various pumping scenarios and to optimally manage the storage capacity of an aquifer system.

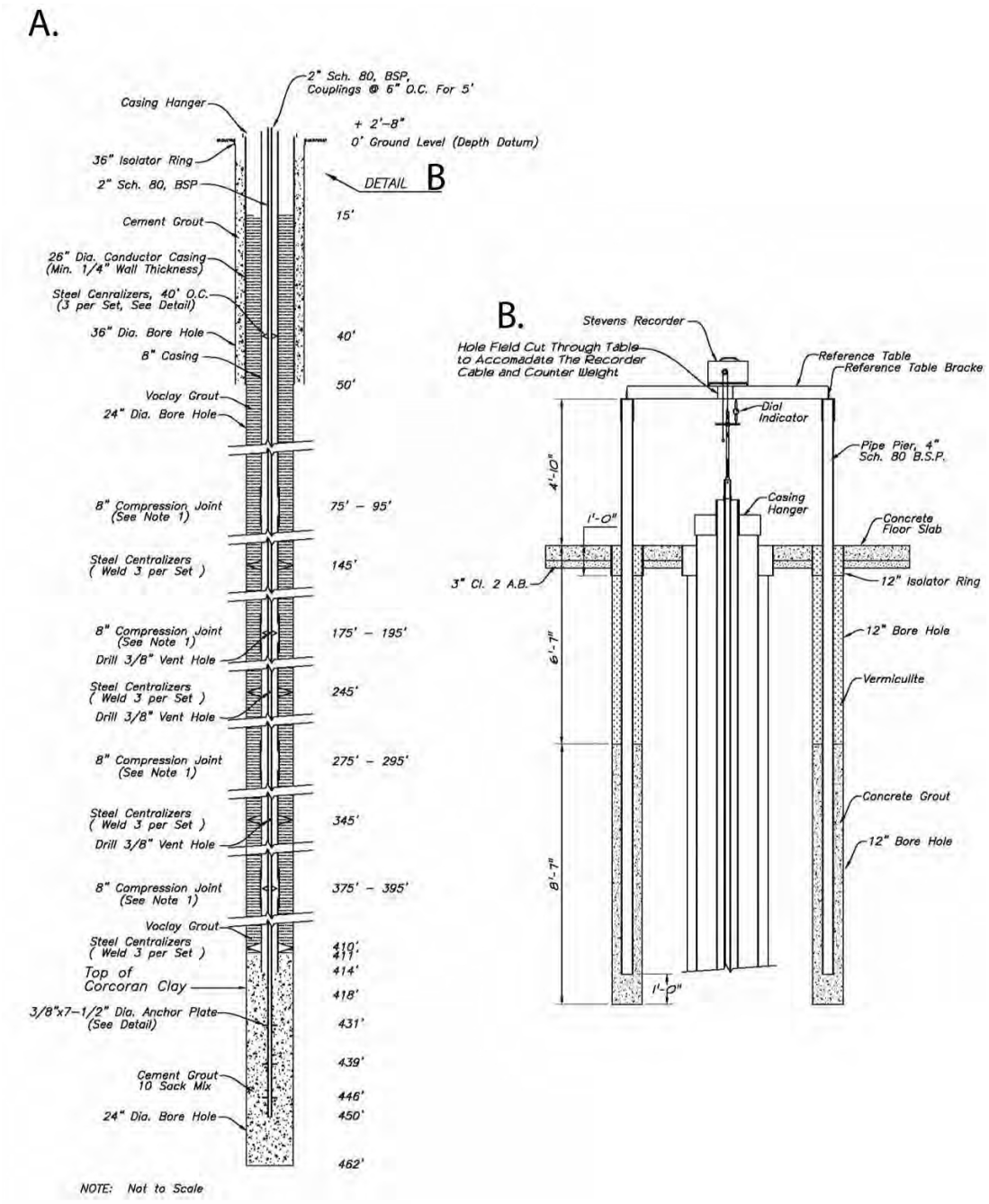


Figure 5-3. Fordel extensometer, Mendota. A) The 2″ pipe inside slip-jointed well casing is anchored in a concrete plug completed in the Corcoran Clay that underlies the aquifer sediments. B) A dial indicator monitors the change in distance between the top of the 2″ pipe and the reference table (land surface). This records the amount of compaction in the aquifer sediments (from LSCE, May 1999).

5.2 Earth Fissures – Methods for Measuring and Monitoring

Monitoring of earth fissures requires measuring complex horizontal and vertical pattern of deformation over relatively small horizontal distances. Monuments for repeated horizontal-

distance surveys and leveling must be closely spaced. In the absence of continuous data, surveys should be done twice a year, including at the end of the groundwater pumping season and at the end of the groundwater-level recovery period. Continuous measurements are invaluable to understanding the relationship between fissure deformation and pumping.

Earth fissures behave like extensional tears in an elastic body. When fissures open astensile cracks, nearby surficial material compresses horizontally, and that compression decreases farther from the fissure. The vertical component of deformation associated with horizontal opening exhibits uplift near the crack and subsidence farther from the crack. A dip-slip (vertical movement) fault exhibits uplift near the crack and subsidence farther from the crack on the up-thrown side, and subsidence near the crack and uplift farther from the crack on the downthrown side. Wherever both horizontal and vertical deformations near earth fissures have been measured, vertical movement has been as large as or larger than horizontal movement, although the vertical movement is seldom visually apparent. What might seem a 'counterintuitive' pattern of deformation could result from: (1) the crack having a limited depth, (2) measurements that started after the material had already stretched, or simply (3) the effects of the elastic properties of earth materials. The measurable zone of deformation of a fissure is about twice the depth. However, surface deformation should be measured over a minimum of four times depth to enable removal of background regional deformation.

Normal strain is a change in distance divided by the distance over which the change is measured. It has no units or dimensions and can be thought of as a ratio. Assuming elastic material, Jachens and Holzer's (1982) suggested range of horizontal tensile strain-at-failure is 0.02-0.1percent. Measurements of deformation always begin after subsidence has already occurred, so tensile failure is likely to occur when measured strain is toward the lower end of this range. The earlier in the process that precise measurement commences, the better the ability to predict and deal with negative consequences associated with fissuring.

5.2.1 Precise Leveling and Horizontal Distance Surveys

The horizontal strains to be measured across a fissure zone range from 10^{-6} to 10^{-3}. As monument spacing decreases, the resolution and precision of the measuring instrument must be finer to determine the same strain. Precision of both leveling and EDM (horizontal distance surveys) should be about 0.1 mm (0.0039 in) or better. It is desirable to obtain one order of magnitude better resolution than the required precision.

Wherever possible, survey lines should be established perpendicular to a fissure with permanent monuments such as 10 cm (4 in) diameter pipes, set 3 m (10 ft) deep, with 12 m (40 ft) or finer spacing within about 60 m (200 ft) of an existing or developing fissure zone. Ideally, regular surficial monuments would extend from a fissure with 24 m (80 ft) spacing for about 150 m (500

ft) and 48 m (160 ft) spacing for about 300 m (1000 ft). Significant movement on a survey line would be cause to establish a parallel line in the probable area of new fissuring off the end of the existing fissure.

Survey lines should be established with several repeated sets of measurements to determine measurement errors, then measured quarterly for one year and twice a year in ensuing years. These survey lines should be tied into broader survey networks and GPS networks using surrounding CORS and HARNs (High Accuracy Reference Network[6]) monuments.

5.2.2 3-D Deformation and Continuous Measurements of Fissure Movement

Three-dimensional movement of the land surface is the surface expression of what is occurring at depth. In addition to measuring vertical compression and expansion with borehole extensometers and lateral surface deformation as discussed above, describing differential horizontal movement at depth is a key to understanding and accurately modeling three-dimensional deformation and movement of the skeletal frame of an aquifer system (Verruijt, 1969). Lateral movement at depth is currently the least known (least measured) subsurface phenomenon. Variation with depth in the lateral deflection of borehole inclinometer casing in response to wells extracting groundwater from an aquifer system would provide insights to 3-dimensional deformation and perhaps fissure initiation processes (Burbey, 1996; Burbey, 2001).

Coordinated use of precise surface and subsurface instruments can provide substantial understanding of fissuring processes. Integration of highly precise leveling and horizontal-distance surveys with continuous measurements of horizontal strain using horizontal quartz tube extensometry, and of vertical movement and tilt using biaxial tilt meters, can provide independent corroboration for measurements at the limit of their resolution. The combination of horizontal strain, liquid level, and tilt information complement each other to give an estimate of the depth of deformation. Integration of these techniques with GPS, CGPS, and subsurface deformation information collected from inclinometer logging of boreholes installed in fissure-prone areas will provide 3-D deformation information helpful for understanding fissuring processes.

Long-term monitoring of fissures as hydrologic conditions change will allow scientists to identify the likely modes of fissure formation about which there is considerable uncertainty in

[6] A High Accuracy Reference Network (HARN) and a High Precision Geodetic Network (HPGN) were two designations used for a statewide geodetic network upgrade. The generic acronym HARN is now used for both HARN and HPGN and was adopted to remove the confusion arising from the use of two acronyms. A HARN is a statewide or regional upgrade in accuracy of NAD 83 coordinates using Global Positioning System (GPS) observations. HARNs were observed to support the use of GPS by Federal, state, and local surveyors, geodesists, and many other applications (http://www.ngs.noaa.gov/faq.shtml, accessed November 26, 2013).

the scientific community currently. This would address an intriguing set of unanswered questions about fissures:

(1) Do fissures initiate at depth and propagate to the surface (or the reverse), or does initiation and fissure growth vary with site conditions?
(2) How and why do fissures close over time?
(3) Is there a sustainable rate of water-level decline and subsidence that can be maintained without causing fissures?
(4) Will renewed drawdown cause renewed fissuring, and where will this occur with respect to older fissures?

5.3 Numerical Modeling

The earliest numerical model to successfully simulate time-dependent aquitard compaction, expansion, and residual subsidence was COMPAC (Helm, 1972, 1975, 1976). It was part of Riley's (1969) and Poland's (Poland, et al, 1975, Ireland, et al, 1984, Poland and Ireland, 1988) pioneering effort to develop a field-laboratory method of site-specific parameter evaluation. Precise vertical displacement and field-scale stress data (namely borehole extensometer and water-level measurements) allowed parameter values that control future land subsidence at any site of interest to be determined directly and effectively at the field scale. These field-laboratory parameter values, calibrated from a few years' data, allowed accurate predictions of land subsidence using COMPAC at the same site over a period of decades (Helm, 1977, 1978).

The COMPAC model treats compaction of a specified cell within an aquitard to be recoverable (elastic) when the effective stress within this cell is calculated to be less than the cell-specific preconsolidation stress and to be nonrecoverable (inelastic and permanent) when this calculated transient effective stress becomes greater than the continuously updated cell-specific preconsolidation stress. To be consistent with actual field data, Helm's effort restricted COMPAC to modeling only the vertical component of deformation at any specified site.

In contrast, more recent efforts in modeling land subsidence approximate an average amount of subsidence that is occurring over larger areas at the regional scale. Leake and Prudic (1991) wrote a one-dimensional model, the Interbed Storage Package (IBS1) that became the standard for modeling subsidence in groundwater basins. Leake (1990) improved the capabilities of subsidence modeling using MODFLOW by creating IBS2 which allowed the evaluation of delayed drainage from aquitards. Leake (1991) further refined MODFLOW with IBS3 in which total load (from, for example, a changing water table elevation) can be treated as a variable and storage parameters are stress dependent.

The USGS Subsidence and Aquifer System Compaction Package (SUB) (Hoffman et al., 2003) updates the functionality of ISB1 and ISB2 for use with newer versions of MODFLOW. SUB,

like COMPAC, simulates the drainage, changes in groundwater storage, and compaction of aquifers, interbeds, and confining units while accounting for delayed drainage from aquitards. An additional modeling package called SUB-WT (Leake and Galloway, 2007), updates the IBS3 package for use with newer versions of MODFLOW. It is specifically tailored for water-table aquifers, simulating, like COMPAC (Helm, 1984a) the effects of subsidence and compaction in shallow, unconfined flow systems, and similar to COMPAC, simulates stress dependent changes in storage properties.

The USGS MODFLOW subsidence packages are one-dimensional models of vertical deformation of the aquifer system skeleton. They have proven useful for regional simulations of groundwater flow, aquifer system compaction, and land subsidence. They do not simulate horizontal components of displacement and therefore are not applicable for describing deformation where horizontal motions are significant—at local scales, for example near pumping wells (Galloway and Burbey, 2011). They also cannot simultaneously simulate aquifer systems that exhibit both time-dependent drainage and compaction of thick aquitards, and stress-dependent skeletal specific storage; and they do not simulate changing hydraulic conductivity as aquitards compact.

Poroelsticity theory describes the more fully coupled processes of groundwater flow and 3-D deformation of aquifer systems. Hseih (1995, 1996) developed a model on based poroelasticity theory originally developed by Biot (1941) to analyze deformation and deformation induced changes in hydraulic head in a confined aquifer system near a pumping well. Zhang (2009) has developed an even newer subsidence code that is truly three-dimensional as a module within MODFLOW. Its overall modeling strategy is described in detail by Helm (2013). It makes use of MODFLOW's own solution schemes, which makes it orders of magnitude faster than Burbey's (1994) earlier truly three-dimensional subsidence code, which was also written as a module within MODFLOW. Li and Ding (2013) have added to Zhang's code a capability to simulate compaction-related changes in specific storage (actually, the changes in compressibility due to ongoing changes in the grain-to-grain structure of the skeletal frame of the aquifer system). In other words, Li and Ding have added SUB's nonlinear capabilities, only they have done so within a three-dimensional model.

The paucity of three-component deformation data at depth and at the land surface has been one factor limiting the use of poroelastic models. Other limitations are the intensive computational requirements, and the scarcity of data describing aquifer system physical and hydraulic properties sufficient to constrain the models (Galloway and Burbey, 2011).

To date, only COMPAC (Helm, 1976) has successfully simulated compaction-related reduction in hydraulic conductivity (permeability). Substantial reduction in the hydraulic conductivity of compacting aquitards in the San Joaquin Valley during 1920s-1970s is believed to be one factor

(along with reductions in skeletal specific storage) contributing to subsequent rapid water-level declines during the droughts of 1976-1977 and 1987-1992, after water levels had recovered substantially in the early to mid-1970s.

5.4 Networks Monitoring Land Subsidence Caused by Groundwater Extraction

The following descriptions are a brief overview of various California programs that included one or more components of subsidence monitoring described above. These programs and networks are described in published reports or in written communications received from various government agencies and consulting firms. Other entities in the state also monitor land subsidence using one or more subsidence measurement techniques, including water districts, large farms and probably other local agencies. Their information is not readily available.

Federal and State Cooperative land subsidence studies in the San Joaquin Valley, 1954-1980 – A state and federal interagency cooperative investigation of land subsidence was initiated in the San Joaquin Valley in 1954, in response to concerns that the subsidence that had decreased the nominal flow capacity of the San Joaquin River by 30 percent by 1953 would also affect the Delta-Mendota Canal, being constructed by the U. S. Bureau of Reclamation, and the California Aqueduct, then being planned by the California Department of Water Resources. The program relied primarily on topographic maps and spirit-level surveys by the NGS to measure the magnitude of land subsidence and determine the correlation between declining groundwater levels and subsidence. Eventually, a substantial network of 35 extensometers and paired water-level observation wells was established in the valley (**Figure 5-4)**. These extensometers operated mostly during the 1950s and 1960s; most have not been actively monitored since the early 1980s. In 2009, only 4 extensometers were still being monitored, and all of these were completed above the top of the Corcoran Clay. Consequently, aquifer-system compaction within and deeper than the Corcoran Clay, such as that occurring currently in the El Nido area near Highway 152, is not being measured.

The USGS has acquired the original field data sheets for historically operated extensometers in the San Joaquin Valley (Michelle Sneed, written commun., September, 2013). The compaction data on the field sheets has been extracted and entered into spreadsheets for the complete period of record for all sites. A list of sites for which historical data is available through the USGS is shown in **Table 5-2**.

No extensometers currently monitor the very broad subsidence feature in the southern San Joaquin Valley, east from the Tulare Lake bed. Current subsidence in this area was identified by InSAR techniques at NASA/JPL. Subsidence measured by InSAR in this area is preliminary and presented at the courtesy of NASA/JPL for general information purposes, rather than quantitative conclusions (**Figure 4-8**).

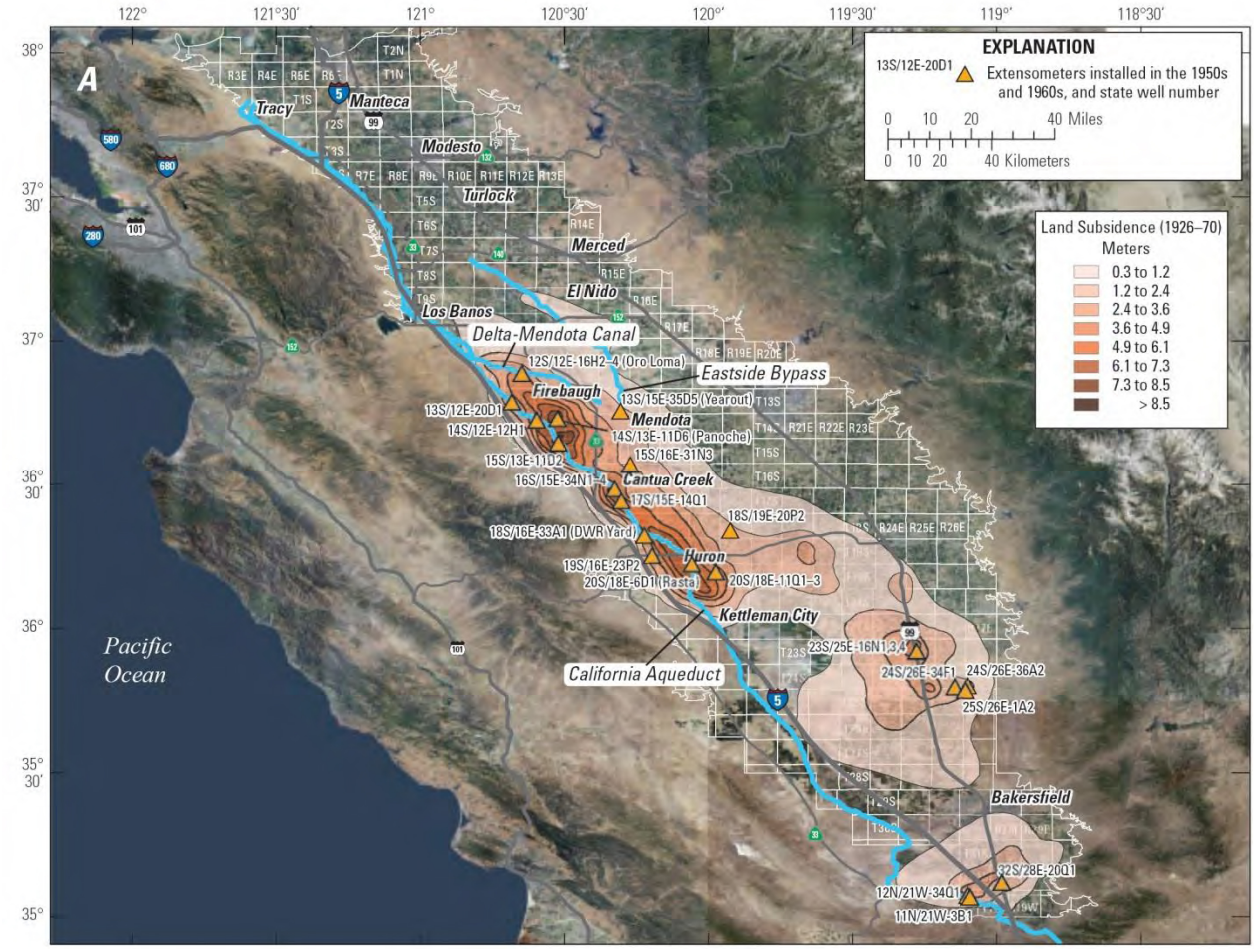


Figure 5-4. Extensometers installed in the 1950s and 1960s, San Joaquin Valley.

Table 5-2. Central Valley historical extensometer data newly available through the USGS

State Well No.	USGS	DWR	SLDMWA	LSCE
11N/1E-24Q8	1988-1992[1,2]			
12S/12E-16H2[3]	1958-1983, 2010-2012	1985-2000	2009-2010	
12S/12E-16H3	1958-1982, 2010-2011	1997-2000	2009-2010	
13S/15E-31J[4]				1999-2012
13S/15E-35D5	1966-1983			
14S/12E-12H1	1964-1983	1983-1998		
14S/13E-11D6[3]	1961-1983, 2010-2012	1983-2009		
15S/13E-11D2	1964-1983	1983-1988		
15S/16E-31N3	1967-1983			
16S/15E-34N1				
17S/15E-14Q1	1969-1982[5]	1983-1998		
18S/16E-33A1[3]	1965-1982[5], 2012	1983-1998		
20S/18E-06D1[3]	2012			
22S/27E-30D2	1970-1983			
23S/25E-16N1	1958-1983			
23S/25E-16N4	1959-1983			
24S/26E-34F1	1957-1983			
24S/26E-36A2	1959-1983			
26S/23E-16H2	1978-1983			
26S/23E-16H3	1978-1983			
32S/28E-20Q1	1963-1978[6]			

Note: All data, unless specified otherwise, represents relative cumulative compaction based on field measurements from US Geological Survey (USGS), California Department of Water Resources (DWR), San Luis and Delta-Mendota Water Authority (SLDMWA), and/or Luhdorff and Scalmanini Consulting Engineers (LSCE)

1 USGS data from National Water Information System (NWIS), daily values do not represent field measurements.

2 DWR has operated the Zamora extensometer, 11N01E24Q008M, since 1992 and stores compaction data from 1988-present.

3 Four extensometers (6D1, 33A1, 11D6, 12S/12E-16H2) were refurbished and have compaction and water levels measured hourly since early 2012.

4 The extensometer at this location is referred to as the “Fordel extensometer”. Daily water levels are measured in the nearby USGS monitoring well 31J3.

5 USGS data from cumulative annual compaction values from Table 1 of USGS Water Resources Investigation Report 85-4196.

6 USGS data, digitized from Figure 64 of USGS Professional paper 437-I, daily values do not represent field measurements.

Mendota Pool Group Pumping and Monitoring Program – The Mendota Pool Group pumps groundwater as part of a water transfer exchange project with the San Joaquin River Exchange Contractors Water Authority, Paramount Land Company, and Paramount Pomegranate Orchards. Part of this agreement involves a pumping and monitoring program. Compaction and land subsidence are monitored along with pumpage, groundwater levels, groundwater quality, surface-water flow, surface-water quality, and sediment quality, and annual reports are created. Continuous compaction data are collected from two extensometers in the Mendota area (Fordel Extensometer and the Yearout Ranch Extensometer). The Fordel Extensometer was installed by the Mendota Pool Group in 1999 and has been recording since; the Yearout Ranch Extensometer was installed by DWR in 1965 and DWR recorded data from 1966 to 1982. This instrument was reinitiated in 1999 by Central California Irrigation District and has been recording since then. In addition to these extensometers, which only measure compaction above the Corcoran Clay, a nearby CORS site in the Mendota area is used to determine total compaction. The CORS site (P304) has been recording land elevation since 2004.

North Solano Groundwater Monitoring Program – The Solano County Water Agency has successfully implemented a groundwater-monitoring program, including multiple-completion monitoring wells, and installed two new CGPS sites that are part of a groundwater monitoring and subsidence network in northern Solano County. This network complements other groundwater monitoring wells in the area. The two CGPS sites (DIXN and VCVL) have been recording data since June 2012.

Yolo County GPS and Extensometer Subsidence Network – Yolo County has developed a network of geodetic control that they have surveyed in 1999, 2002, and 2005 to determine the extent of land subsidence. Results of their surveys show greatest subsidence along the corridor north from Davis, through Woodland, north to Zamora and through the northeast corner of Yolo County.

Sacramento/San Joaquin Delta Subsidence Project – DWR organized three series of GPS measurements (1997, 2002, and 2011) on a network of between 100 and 130 passive stations to assess the occurrence and distribution of land subsidence in the Delta. Several Delta stations were measured during the GPS surveys of the Sacramento Valley in 2008 (described below).

2004 Glenn County GPS Subsidence Project – In 2004, Glenn County undertook a survey of 58 stations to establish a baseline against which future subsidence can be measured.

DWR CVFED Project – GPS surveying was done in 2010 by contractors to DWR's Central Valley Floodplain Evaluation and Delineation (CVFED) Program in order to rectify vertical control for LiDAR surveys in the San Joaquin River Restoration Program area downstream from Mendota. This survey identified discrepancies with historic elevations at survey monuments.

Observations at geodetic control stations followed NGS procedures for the highest level of vertical accuracy. However, within a couple of years, the control points had subsided; the magnitude was found to be consistent with data from InSAR analyses by the USGS (Sneed et al., 2013). The USBR and DWR now monitor a large area adjacent to the San Joaquin River and flood bypass channels on an annual or semi-annual basis as needed for implementation of the San Joaquin River Restoration Program.

Sacramento Valley Subsidence Project – DWR's Sacramento Valley subsidence-monitoring network includes 11 extensometers and a GPS network. The 11 extensometers (**Table 5-3**), built to monitor compaction of the aquifer system, straddle the center of the valley from Sutter and Yolo Counties to the south to Butte County in the north. In 2008, DWR and USBR established a comprehensive Sacramento Valley GPS subsidence network that would serve as a framework for monitoring land subsidence and for extending high-accuracy geodetic control to facilities operated by the USBR (including portions of Shasta and Folsom Lakes). This project included all GPS stations from the Glenn and Yolo County projects described above and ultimately consisted of 335 stations (Frame and D'Onofrio, 2008). As of 2014, the network has not been resurveyed.

Table 5-3 Sacramento Valley extensometers currently operated by the California Department of Water Resources

State Well No.	Latitude	Longitude	Depth (ft)	County	Type	Recording Resolution (ft)	Start of Record	Total Displac-ement (ft)	Avg Annual Subsid-ence (ft)
19N01E35B002M	39.46344	-21.82776	1026	Butte	Cable	0.005	7/7/2005	0.010	0.001
20N01E18L001M	39.57706	-121.9082	1060	Butte	Cable	0.005	3/3/2005	0.000	0.000
18N01E35L001M	39.36744	-21.82787	1006	Butte	Cable	0.005	7/8/2005	0.005	0.0007
16N02W05B001M	39.27527	-122.10568	813	Colusa	Cable	0.005	2/3/2005	-0.020	-0.003
17N02W09H002M	39.34169	-122.08377	863	Colusa	Cable	0.005	8/10/2005	0.005	0.0007
19N02W08Q001M	39.5157	-122.11224	1000	Glenn	Cable	0.005	12/1/2005	0.000	0.000
21N02W33M001M	39.62991	-122.10067	1020	Glenn	Cable	0.005	3/2/2005	-0.050	-0.007
22N02W15C002M	39.76341	-122.07714	880	Glenn	Cable	0.005	3/1/2005	0.050	0.007
11N04E04N005M	38.823863	-21.543073	780	Sutter	Pipe	0.001	4/13/1994	-0.029	-0.001
11N01E24Q008M	38.779855	-21.812422	1002	Yolo	Pipe	0.001	6/17/1988	-1.381	-0.055
09N03E08C004M	38.64643	-21.667379	716	Yolo	Pipe	0.001	1/24/1992	-0.297	-0.014

Caltrans Highways 152 and 198, San Joaquin Valley – Caltrans surveyed bench marks along highways 152 and 198 in order to expand the North American Vertical Datum of 1988 (NAVD88) network to the east side of the San Joaquin Valley from its alignment on the west side near the California Aqueduct and Interstate Route 5. Surveys in 1972, 1988, and 2004 revealed about 1.6 m (5.25 ft) of subsidence during 1972-2004 along Highway 152; surveys in the 1960s and 2004 show that as much as 2.86 m (9.37 ft) occurred along Highway 198.

Delta Mendota Canal Subsidence Project – The USGS (Sneed et al., 2013) used InSAR techniques to determine that the El Nido region, north of Madera near the San Joaquin River Restoration Project area, had subsided 53 cm (21 inches) between January 2008 and January 2010. Data from historical leveling and GPS surveys, continuous GPS sites, water-level observation wells, and compaction recorders were used to assess land subsidence in the vicinity of the Delta-Mendota Canal. As a part of this work by the USGS, USBR, and San Luis Delta-Mendota Water Authority, five multi-piezometer well sites were constructed and instrumented to collect continuous water-level data above and below the Corcoran Clay. Four extensometer sites were instrumented to collect continuous water levels.

Antelope Valley Groundwater Basin, 2003 – Increasing demands on groundwater and a potential for further land subsidence throughout Antelope Valley prompted a regional groundwater and land-subsidence investigation by the USGS. A large-scale network of bench marks was established to calculate historical subsidence and enable precise measurements of future subsidence (Ikehara and Phillips, 1994) (**Figure 5-5**). The network was designed and GPS-surveyed for a valley-wide subsidence-monitoring program. Geodetic surveying of 85 stations using GPS tied newer parts of the network to the previously established subsidence-monitoring network at Edwards Air Force Base (EAFB). Eventually the network also incorporated two extensometer sites, the Holly site at EAFB, 256 m (840 ft) deep, and a dual shallow and deep extensometer 224 m (735 ft) and 367 m (1,205 ft) deep at Lancaster; elevations from differential leveling spanning more than 60 years; and InSAR.

Coachella Valley – Concerns about land subsidence resulting from declining groundwater levels prompted a series of USGS investigations to detect and quantify subsidence using GPS surveying and InSAR tools. Subsidence monitoring began in the southern Coachella Valley with the establishment of 17 geodetic monuments during GPS surveying in 1996 (Ikehara et al., 1997). The network was modified in 1998 by replacing two monuments that had been destroyed. The network was modified again by replacing an unstable monument and adding four new monuments prior to the 2000 GPS survey (Sneed et al., 2001, 2002). A GPS survey was conducted in 2005 (Sneed et al., 2013) and the network was again expanded before the 2010 GPS survey. Data showing groundwater level changes between the early and mid-1990s to 2010 were compared to GPS measurements and InSAR-generated maps of land-surface displacement to determine whether vertical changes in land surface elevation were related to changes in groundwater levels (Sneed, USGS, oral communication, October 18, 2013). The land subsidence monitoring program in the Coachella Valley is expected to continue to provide information useful to optimize groundwater management in the valley.

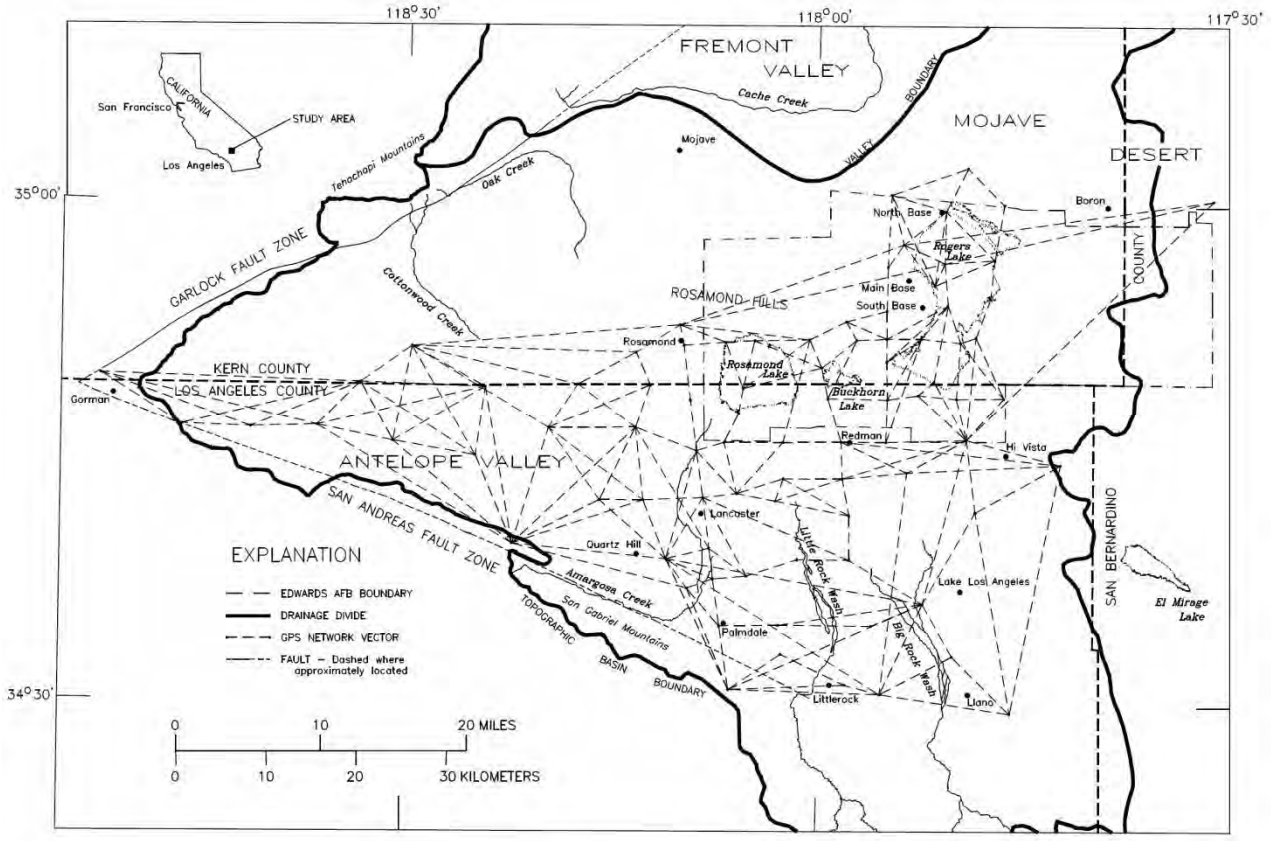


Figure 5-5. Antelope Valley and Edwards Air Force Base Global Positioning System Networks.

Santa Clara Valley – The Santa Clara Valley Water District conducts annual monitoring of bench marks and continuous monitoring of extensometers to determine whether land subsidence is occurring or threatening to exceed established subsidence thresholds. Monitoring of land subsidence is performed by annual spirit leveling of three established routes and continuous measurement of vertical ground movement at two extensometers. The District has established an acceptable subsidence rate of no more than 0.01 feet per year, which has been endorsed by the Water Retailer Groundwater Subcommittee. Monitoring data indicate that this target has generally been met. In 1991, the District evaluated the remaining land subsidence potential in order establish water-level thresholds to avoid additional permanent subsidence due to groundwater overdraft. Ten index wells throughout the Santa Clara Subbasin were selected as control points for subsidence calibration and prediction and the tolerable rate of 0.01 feet per year of inelastic subsidence was applied to determine threshold groundwater levels for these wells. These subsidence thresholds are the groundwater levels that must be maintained to ensure a low risk of land subsidence. The USGS installed the extensometers in Santa Clara County in 1960 as part of an early study of aquifer compaction. The extensometers measure vertical ground motion relative to a central, isolated pipe that is set beneath the water-bearing units. The USGS terminated field monitoring in January 1983, at which time monitoring was transferred to the District. Two 1,000 foot deep extensometer sites are currently monitored, one in Sunnyvale near

Moffett Field ("Sunny") and the other near downtown San Jose ("Martha"). Hanson and others (2004) reconceptualized the aquifer system and built a numerical groundwater-flow model, incorporating a subsidence package, for use as a management tool by the Santa Clara Valley Water District.

Mojave Desert Basins – A GPS survey of a geodetic network was used to determine the location, extent, and magnitude of vertical land-surface changes in Lucerne Valley in the Morongo groundwater basin. The GPS survey was conducted in 1998 to estimate historical elevation changes by comparing GPS-derived elevations with historical elevations (which were available for some of the monuments in the network as early as 1944) and to establish baseline values that can be used for comparisons with future GPS surveys. Results were compared to SAR interferograms and historical groundwater-level trends in nearby wells. SAR interferograms and historical groundwater-level data were used similarly for subsidence reconnaissance near Newberry Springs, the Lockhart-Harper Lake area, and near El Mirage Lake. Concerns about the stability of runways on Bicycle Playa that are used to transport troops and supply the Fort Irwin National Training Center prompted an investigation to determine mechanisms causing fissuring, giant desiccation cracks and deformation of the playa surface. The USGS monitors fissuring using repeated geodetic leveling, Electronic Distance Measurement (EDM) surveys, ground-based LIDAR, tiltmeters on each side of the fissure, and horizontal tape extensometer (tapex) measurements. Desiccation mechanisms are studied with heat-dissipation sensors paired with controlled bench-scale desiccation experiments. Water-level measurements are collected at monitoring wells.

Chino Basin – The Chino Basin is a large alluvial groundwater basin that has experienced declines in groundwater levels during the past century, in some places more than 61 m (200 ft). The decline in groundwater levels has resulted in inelastic compaction and land subsidence, including ground fissuring in a portion of the basin. The Chino Basin Watermaster manages the basin to minimize land subsidence and ground fissuring. Monitoring includes a network of over 200 ground-level surveying bench marks, remote-sensing analyses to monitor ground surface deformation (InSAR), one horizontal and six vertical borehole extensometers **(Table 5-4)**, and groundwater level measurements (Wildermuth Environmental, 2013) (**Figure 5-6**).

Extensometers paired with water-level monitoring wells record data every 15 minutes. Results of the ongoing monitoring are included in annual State of the Basin reports. SAR data is collected every few months. The period of InSAR analysis is 1993 to present, with some gaps due to unavailability of satellite data. Leveling surveys have been performed every one to three years since 1987, and are used with the InSAR data and extensometer data to determine the state of land subsidence.

Table 5-4 Extensometers currently monitored by the Chino California Water Master.

Name	Latitude	Longitude	Depth Monitored (ft)	Type	Start of Record
Ayala Park Shallow	33.993718	-117.687000	30-550 ft	Pipe	2003
Ayala Park Deep	33.993718	-117.687000	30-1400 ft	Pipe	2003
PC 4	33.995118	-117.686343	50-727 ft	Cable	2008
PC 2	33.995118	-117.686343	50-1120 ft	Cable	2008
CCX-1	33.967195	-117.647403	0-140 ft	Cable	July 2012
CCX-2	33.967195	-117.647403	0-610 ft	Cable	July 2012

Continuous measurements of fissure deformation are being made in Chino by Wildermuth Environmental under the auspices of the Chino Basin Watermaster. Measurements of horizontal strain, tilt, liquid-level, temperatures, air pressure, and humidity are recorded.

East Bay Municipal Utility District – The USGS and EBMUD cooperatively constructed and, since 2008, have operated a dual-stage extensometer (**Table 5-5**) paired with six water-level monitoring wells at the Bayside Artificial Storage and Recovery (ASR) facility in San Lorenzo, California. The extensometer is designed to measure aquifer system compaction and expansion during extraction and injection of water at ASR wells.

Table 5-5. Construction details and period of record for extensometers currently monitored by the East Bay Municipal Utility District at the Bayside Artificial Storage and Recovery Facility in San Lorenzo.

Well No.	Latitude*	Longitude*	Monitored Depth Interval Meter (ft)	Start of Record	Type	Total Measured Compaction ft
003S003W14K015	37°40'04.4"	122°09'20.4"	0-182 (598)	7/10/2010	Pipe	No permanent compaction
003S003W14K016	37°40'04.8"	122°09'20.2"	0-299 (980)	7/10/2010	Pipe	No permanent compaction

*NAD83

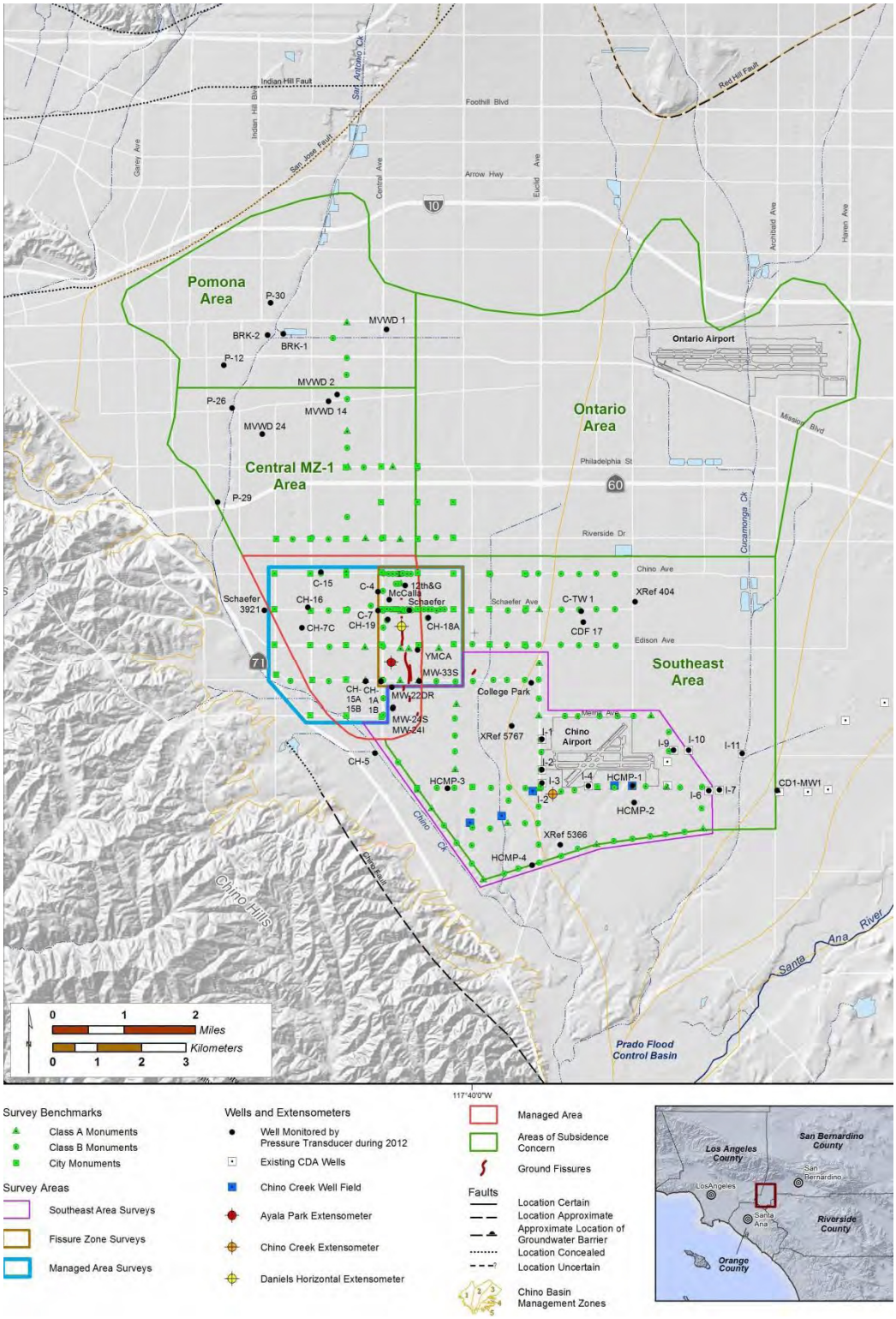


Figure 5-6. Land subsidence monitoring network in the Chino Basin (from Wildermuth Environmental Inc., 2012).

Semitropic Water Storage District, Kern County – Semitropic WSD installed a 277–m (910 ft) deep extensometer (**Table 5-6**) about 16 miles west of Delano in April 2006. The SWSD monitors aquifer compaction and measures water levels in a multi-completion monitoring well nearby.

Table 5-6. Construction details and period of record for the extensometer currently monitored by the Semitropic Water Storage District near Kern Wildlife Area, Delano.

Well No.	Latitude	Longitude	Monitored Depth Interval m (ft)	Start of Record	Type	Total Measured Compaction (ft)
25S22E35B001M	35°43'07"	119°33'58.2"	0-277 (910)	4/1/2006	Cable	No permanent compaction

Cuyama Valley -- As part of groundwater investigations conducted in cooperation with the Water Agency Division of the Santa Barbara County Department of Public Works, the USGS is collecting and analyzing data from the GPS and SAR satellites and 68 wells in the valley. These data are used to estimate the magnitude and extent of land subsidence related to groundwater withdrawal. Data from five GPS stations and 133 unique interferograms (conventional and PS InSAR) spanning December 5, 2002 to May 22, 2008 have been examined to date. No compatible SAR data were available after June 2008.

6 SUMMARY

California's groundwater is a vital resource for municipal, rural residential, agricultural, and commercial water users, and for the health of ecosystems and biological habitats. In an average year, groundwater supplies about 40 percent of the state's overall water demands. During droughts when surface supplies are limited, groundwater offers a critical buffer, providing a higher percent of the state's water supply. In 2014, it is anticipated statewide groundwater use will be closer to 65 percent because of the critical nature of this year's drought. Increasing population and changing cropping and land-use patterns in agricultural areas— replacement of annual row crops orchards or conversion of range land to crops— place more demands on California's aquifer systems.

Historically in California, groundwater has been pumped as needed with little regard for the deleterious effects of over pumping. Chronic groundwater mining, when pumping exceeds recharge, results in a long-term decline of groundwater levels, eventual inelastic compaction of the aquifer system, permanent subsidence of the land surface, and in some cases earth fissures. Some of the more costly consequences of subsidence include coastal flooding, increased extent and depth of inland flooding, reduced freeboard and carrying capacity of canals, aqueducts, rivers and flood bypass channels, and damage to engineered structures such as buildings, roadways, bridges, pipelines, canals, aqueducts, levees, sewerages, and wells.

The northern Santa Clara Valley, an alluvial lowland at the south end of the San Francisco Bay, was the first area in California where land subsidence due to groundwater overdraft was recognized, monitored, and stopped. Subsidence probably began by the 1920s but was first recognized during surveys in 1933. Massive withdrawals of groundwater, initially to support agricultural development and later for domestic and industrial uses, eventually resulted in subsidence over much of the area. Subsidence reached a maximum of 4.2 m (14 ft) in downtown San Jose. Direct costs of land subsidence, including damaged and destroyed wells, construction of levees around the southern San Francisco Bay and the bayward ends of stream channels, raising grades of roads and bridges, enlarging sewers, construction and operation of pumping facilities to remove sewage effluent and storm drainage, are estimated at $756 million (2013 dollars). This estimate does not include costs to raise railroad grades, repair damage to flooded roads, construct 80 km (50 mi) of levees to protect salt evaporation ponds that fringe the bay, construct and operate facilities for importation of surface water or artificial recharge of the aquifer system, or to conduct subsidence studies and monitoring programs. It also does not include costs for levees constructed since 1973, the decreased value of property with obstructed views, and limited access to the bay and streams as a result of levee construction.

Subsidence in the Santa Clara Valley was halted by 1969 due to the well-coordinated and effective conjunctive use of surface and groundwater that was implemented and is managed by the Santa Clara Valley Water District. Components of the conjunctive use program include

importation of surface water, construction of reservoirs to store local runoff, operation of infiltration ponds for aquifer recharge, implementation of conservation programs, and strict adherence to low tolerance for inelastic compaction of the aquifer system (not more than 3 mm/yr (0.01 ft/yr) on average). Conformance with the requirements for minimal inelastic compaction and subsidence is assessed by a comprehensive monitoring program that continually evaluates data collected from survey lines, groundwater-level index wells, extensometers, and data on both groundwater extraction and groundwater infiltration at surface recharge facilities. The successful arrest of subsidence has been facilitated by the fact that responsibility for water supplies, facility operations, and monitoring of subsidence and related water resources information is centralized at a single agency, the Santa Clara Valley Water District. Impetus for stringent management of subsidence was provided by the obvious effects of coastal flooding.

Despite information available describing land subsidence due to groundwater overdraft in the northern Santa Clara Valley (Poland and Tolman, 1940) and recognition of the relation between water-level decline and subsidence near Delano in the Tulare-Wasco area of the San Joaquin Valley by I. H. Althouse (Ingerson, 1940), subsidence from groundwater overdraft was not investigated regionally in the Central Valley until the early 1950s. This is when government agencies became concerned about reductions in the flow capacity of the San Joaquin River and effects of subsidence on the Delta-Mendota Canal, then under construction. Part of the reason for the delayed reaction to subsidence is that it typically occurred uniformly and over such a broad area that few residents or agencies realized that it had happened. As late as the mid-1950s, subsidence in the Arvin-Maricopa area of the valley was ascribed to tectonically uplifted survey control points in the Tehachapi Mountains south of the valley (Whitten, 1955) rather than to the actual causative agent, decline of groundwater levels (Lofgren, 1975).

Cooperative studies by DWR and the USGS beginning in 1954 identified three large areas of subsidence from groundwater overdraft, the Los Banos-Kettleman City area on the west side of the mid-valley, the Wasco-Tulare area of the southern valley east of the Tulare Lake bed, and the Arvin-Maricopa area in the extreme southern end of the valley. Eventually, groundwater levels in the deep aquifer system on the west side of the valley declined by more than more than 122 m (400 ft). By 1970, more than 13,400 km^2 (5,200 mi^2) had subsided more than 0.3 m (1 ft) and the maximum subsidence, near Mendota, was more than 8.5 m (28 ft). Damage to water infrastructure was widespread, but the costs of historical subsidence are not easily determined. Repairs and design changes to the federal canals (Delta-Mendota Canal, Friant-Kern Canal, and the San Luis Drain) totaled more than $103 million. Costs to remediate subsidence on Central California Irrigation District's Outside Canal will total more than $8.2 million after the scheduled Russell Avenue bridge replacement is complete. Steel casings of thousands of wells were probably destroyed by vertical compression as the land subsided, but there was no centralized collection of this information. Current costs to replace the 275 wells that were reported to have failed casings during 1950-1961 would be $90 million. Surface water imports

from federal and state projects allowed groundwater levels to recover by more than 61 m (200 ft) in some areas on the west side of the valley by 1974.

Although increasing water levels slowed subsidence by the early 1970s, some subsidence continued due to delayed drainage of water from compacting clayey aquitards. The rapid decline of groundwater levels during subsequent droughts (1976-1977, 1987-2003) and regulatory reductions in surface water diversions (2007-2010), in response to relatively small amounts of renewed pumping (compared to that of the 1960s), resulted from a loss of storage space in the aquifer system—mostly from inelastic compaction of aquitards and decrease in the hydraulic conductivity (permeability) of compacted aquitards. Observations showed that drought-period water levels were considerably higher than those during the 1960s, yet still triggered renewed land subsidence. This illustrates the complex effects of unequal distribution of preconsolidation stress both within aquitards and between the aquitards and more permeable units of the aquifer system.

Comprehensive leveling surveys of the San Joaquin Valley ended in 1970 and, over time, funding for coordinated subsidence investigations ended, and field installations such as borehole extensometers and water-level monitoring wells fell into disrepair. DWR continued to collect compaction data from a few extensometers and from deep monitoring wells where available, and state, federal, and local water agencies continued to run surveys on canal alignments intermittently, but storage and analysis of this information were not centralized.

Although anecdotal information from water districts and occasional surveys indicated that continued subsidence was affecting canals and roads, the magnitude, rate, and extent of subsidence revealed from interferometric analysis (InSAR) of data from space-based, SAR satellites during 2003-2011 was startling (Sneed, et al., 2013; Thomas Farr, NASA-JPL, written commun., September, 2013; Jessica Reeves, Stanford University, written commun., July 9, 2013). Two large areas in the San Joaquin Valley are currently subsiding at rates similar to the highest rates observed historically. Subsidence in the northernmost area, encompassing more than 3,100 km^2 (1,200 mi^2) south of Merced has been occurring in parts of the area at rates of up to 43 cm/yr (11 in/yr)— similar to the maximum rates that occurred in the 1950s and 1960s. Alternative alignments for the Merced to San Jose section of the California high-speed rail line pass through this area (CHSRA, May 2013). Geodetic surveys confirm the InSAR rates and magnitude in the area of the San Joaquin River Restoration Program (SJRRP). There, the flow capacity and levee freeboard of the San Joaquin River, the Eastside Bypass flood channel, and major irrigation canals have been substantially reduced. The capacity of the Eastside Bypass to carry flood flows from the San Joaquin Joaquin River will be reduced by more than 40 percent by 2016 if subsidence continues at current rates. The Sack Dam, which diverts water from the San Joaquin River to the Arroyo Canal, subsided 0.18 m (0.6 ft) during 2008-2010 and 0.5 ft/yr during 2011-2013, halting redesign efforts intended as a part of the SJRRP as water agencies

consider how to adapt to the lowered land surface. It is likely that if interest had not been focused on the San Joaquin River in this reach by SJRRP much less would be known about subsidence there.

Current subsidence in the southernmost area, between Tulare and Kettleman City, occurs at rates similar or greater than in the northern area, and this area is more than twice as large as the subsiding area to the north. Maximum subsidence here was 1.2 m (3.9 ft) during 2007-2011. The effects of subsidence on water (and other) infrastructure in this region are probably large, but have only been anecdotally reported, except for a single Caltrans survey line on Highway 198 that shows more than 2.7 m (9 ft) of subsidence between the 1940s and 2004, and subsidence estimated by Corbett (2011) at Lemoore Naval Air Station. Because the alignment of the California high-speed rail line also passes through this subsiding area, studies focused by CHSRA are expected to provide additional information.

Land subsidence has been tremendously expensive; partial costs of subsidence to private and local infrastructure in the San Joaquin Valley during 1955-1972 were estimated at $1.321 billion (Gilbert Bertoldi, U. S. Geological Survey (ret.), oral commun., November 29, 2013) and $88.9 million to federal and state canals since they were constructed. Even so, there is currently no centralized, land-subsidence monitoring program in the valley. Funding for monitoring programs usually has not been available except for local surveying, or for the duration of specific and loca1 design, construction, or research projects.

Land subsidence from overdraft of groundwater in the Sacramento Valley produced a trough of subsidence from just north of the Colusa-Yolo County line southward through Woodland and Davis to the Dixon area of Solano County. The greatest subsidence, 1.65 m (5.4 feet) (Ikehara, 1994), occurs south of the terminous of the Tehama-Colusa Canal, where agriculture developed relying solely on groundwater for irrigation. Steel casings of many wells in the subsiding area have failed. The current cost to replace 80 wells that were scanned with a downwell television camera to confirm subsidence damage would be $7.2 million. In 2008, DWR and USBR established a comprehensive Sacramento Valley GPS subsidence network, consisting of 335 geodetic monuments that would serve as a framework for monitoring land subsidence. As of 2013, the network has not been fully reoccupied, although Glenn and Yolo Counties have resurveyed monuments within their borders.

Extensive pumping in Antelope Valley in the western Mojave Desert since the 1930s contributed to groundwater-level declines of as much as 91 m (300 ft) near Lancaster, California and 45.7 m (150 ft) at Edwards Air Force Base (EAFB). Subsidence of 2 m (more than 6 ft) near Lancaster and more than 1 m (almost 4 ft) at the south edge of Rogers Lake resulted from groundwater pumping that vastly exceeded recharge to the aquifer system. A 600-m-long (0.37 mi-long) fissure located about 11 km (6.8 mi) east-northeast of Lancaster formed in 1978 as a result of

water-level declines of 75 m (245 ft) that occurred prior to its appearance. Differential subsidence caused sink-like depressions and earth fissures on the playa surface of Rogers Lake bed, adversely affecting the runways on the lake bed that are used for landing aircraft. A network of 85 bench marks was designed and GPS-surveyed in Antelope Valley to establish a valley-wide subsidence-monitoring program. Eventually, the subsidence monitoring network expanded to include bench marks at EAFB, InSAR, and extensometers at EAFB and Lancaster. Numerical modeling at the Holly extensometer site at EAFB indicated that two thick confining units account for most of the compaction measured there, and that only half of the ultimate compaction was likely to occur during the 30 years subsequent to the modeling (Galloway and Sneed, 2000). Intensive monitoring of water-levels, aquifer compaction, elevations at 113 bench marks and two GPS stations, surface tilt, well pumpage and injection rates, and subsequent optimization modeling allowed tools to be developed for artificial storage and recovery (ASR) programs to stop land subsidence and store surface water in the aquifer for later use.

Groundwater overdraft has also caused subsidence and fissuring in other Mojave Desert basins (Holzer, 1984; Sneed, et al., 2003a; Stamos et al., 2007). In Fremont Valley, water levels in formerly artesian wells declined as much as 74 m (243 ft). Subsidence has tilted the surface of the Koehn Lake playa so that winter rains now flood subsided areas. Differential subsidence has occurred across faults that act as barriers to groundwater flow, creating stepped topography. Large fissures, one of which damaged a house in Rancho Seco, likely formed as a result of differential compaction in areas where aquifer-system thickness varies substantially. There is no active subsidence monitoring in the Fremont Valley. In Lucerne Valley, InSAR and GPS surveys indicate that as much as 6 m (2 ft) of land subsidence may have occurred since 1969 in areas where groundwater levels have declined as much as 30 m (100 ft) since the 1950s. Earth fissures on Lucerne Lake playa likely formed by differential compaction of unconsolidated aquifer sediments southeast of the lake shore, where sediments are believed thickest. InSAR-measured subsidence of 5 cm (0.16 ft) during April 21, 1995-May 1, 1999 at El Mirage (dry) Lake was likely due, in part, to residual inelastic compaction from water-level declines of as much as 53 m (175 ft) during 1950-1999. Subsidence of as much as 8.5 cm (0.28 ft) at Harper Dry Lake playa during 1992-1999 is likely a permanent result of inelastic compaction caused when groundwater levels declined 27 m (90 ft) between the late 1960s and 1999. Subsidence of as much as 45 mm (0.15 ft) indicated by InSAR during 1993-1999 near Troy Dry Lake is likely a permanent result of inelastic compaction of the predominantly clayey aquifer sediments in the area. At Fort Irwin National Training Center, increased groundwater pumping in the 1990s lowered groundwater levels 25 m (82 ft) by 2009 and contributed to 27 cm (10.6 in) of land subsidence during 1993-2006. Concerns about stability of runways on Bicycle Playa that are used to transport troops and supplies prompted an investigation to determine mechanisms causing fissuring, giant desiccation cracks and sink-like depressions. The USGS currently monitors surface deformation there.

The results of USGS GPS surveys beginning in 1996 and InSAR analysis beginning in 2001 indicate that substantial subsidence has occurred in the southern Coachella Valley. Groundwater overdraft has resulted in subsidence of as much as 60 cm (1.97 ft) between June 27, 1995 and September 19, 2010 in the La Quinta and Palm Desert areas. Average subsidence rates were relatively stable, increasing from about 3.9 cm/yr (0.13 ft/yr) during 1995-2000 to about 4.5 cm/yr (0.15 ft/yr) during 2003-2010 in Palm Desert. Subsidence rates in Indian Wells were fairly constant and as high 3.4 cm/yr (0.11 ft/yr) during the same period. Average subsidence rates in the La Quinta area were as high as 3.7 cm/yr (0.12 ft/yr) during 1995-2000, held constant or increased during 2003-2009, and decreased or reversed during 2009-2010 as water levels rose in response to deliveries of Colorado River water to groundwater recharge facilities. An earth fissure was discovered in the 1948 in the La Quinta area (Sneed, USGS, oral commun., May 30, 2013), and fissuring recently reoccurred there. The Coachella branch of the All American Canal subsided as much as 41 cm (1.35 ft) in the La Quinta area during June 27, 1995 to September 19, 2010.

Groundwater level declines of more than 40 m (131 ft) during 1978-early 1990s caused as much as 1.2 m (almost 4 ft) of land subsidence during 1986-1993 in the Chino Groundwater Basin. Earth fissures developed in 1973 and again during 1987-1995. The fissure zone extends almost 3,200 m (2 mi) and may be more than 200 m (656 ft) wide and 420 m (1400 ft) deep. In the 1990s, it drained a manure pond and split a house that was condemned and razed. The fissure likely formed in response to flexure or differential compaction across a fault barrier in the deep aquifer. The Chino Groundwater Basin is intensely monitored. Monitoring includes a network of over 200 ground-level surveying bench marks, InSAR analyses, one horizontal and 6 vertical borehole extensometers, and about 50 groundwater-level monitoring wells. Differential subsidence also occurs across the Pomo fault in Pomona, California area. Monitoring likely will continue indefinitely to provide the Chino Basin water master with the data needed to manage the basin while minimizing land subsidence and ground fissuring.

Small amounts of land subsidence were noted in InSAR analysis (March 28-August 15, 1997) in three places in the Paso Robles area. Subsidence ranging from about 1.4 cm (0.6 in) to 5.4 cm (2 in) occurred in areas where groundwater levels declined seasonally. Some of this subsidence then was likely elastic. Recently, though, substantially declining groundwater levels have been reported that may trigger inelastic compaction and permanent subsidence. Land subsidence is not currently being monitored.

There is no land subsidence monitoring program in the San Luis Obispo area, either, despite significant damage from land subsidence. In 1991, during the fourth year of a drought, the City of San Luis Obispo decided to increase groundwater extraction to meet demand that could no longer be supplied by their dwindling surface reservoirs. The resulting differential land subsidence damaged a strip shopping mall, a car dealership, and homes in a nearby development.

Eventually, the City paid about $2 million to claimants. This is the only example of a damage suit for subsidence caused by groundwater extraction decided in favor of the plaintiffs. Water-supply wells in the affected area have been abandoned and groundwater levels are monitored by the City staff.

Earth fissures that formed in Cambria in response to lowered groundwater levels during the 1976-1977 drought damaged buildings and other infrastructure. The City of Cambria developed additional sources of water, and fissures have not reoccurred. The area has no land subsidence monitoring.

Active tectonic uplift and subsidence due to hydrocarbon extraction complicates assessment of aquifer compaction in the Santa Clara-Calleguas Basin. However, a bench mark distant from known tectonic influences and oil fields subsided as much as 0.8 m (2.6 ft) between 1939 and 1978. Water-level declines greater than 30 m (100 ft), subsurface collapse of well casings in the South Pleasant Valley subbasin and South Oxnard Plain subarea, the necessity of repeated leveling of irrigated fields for proper drainage, degraded drainage ditches in agricultural areas, and lowering of levees along the Calleguas Creek all indicate that subsidence has occurred. Numerical modeling of the aquifer system indicates that subsidence of 0.9-1.5 m (3-5 ft) occurred during agricultural expansion in the 1950s and 1960s (Hanson et al., 2003). Monitoring of land subsidence is not described in published reports.

Earth fissures formed in Wolf Valley in 1987 and moved northward seven miles through the Elsinore Trough, a fault-bounded structural basin, to the Temecula-Murrieta area. By 1991, fissures had caused damage to surface structures that exceeded $50 million. The location of the fissures is primarily controlled by two faults, but most investigators concur that that fissures formed when increased pumping caused inelastic compaction and differential subsidence across the faults. Many lawsuits and consulting reports describe this event. Since pumping stopped, fissures have not increased in number or in size. Current subsidence monitoring is not described in the available literature.

Subsidence in the San Jacinto Valley has components of both tectonics and aquifer compaction. Groundwater levels declined more than 68.6 m (225 ft) during the 1970s, and fissures and sinkholes formed after 1953, coincident with faults on the east and basin-bounding hills to the west. Differential subsidence of 71 cm (2.34 ft) measured across the basin-bounding fault likely resulted from differential compaction of the aquifer system. Aquifer compaction measurements collected at an extensometer during 1970-1974 indicated that 70-80 percent of permanent subsidence measured in the valley resulted from aquifer compaction; the remainder was attributed to tectonics. The current status of subsidence is unknown.

The Yucaipa Valley has a long history of water development. By 1909, about 95 percent of the area's water supply was used for agricultural irrigation. Irrigation wells to support agriculture and post-World War II urbanization contributed to groundwater-level declines of more than 35 m by 1952. In January 1952, a 600-m-long (1970 ft-long) fissure opened about 5 km (3.1 mi) west of the town of Yucaipa. Hydrogeologic studies were not performed to determine whether historically low groundwater levels in 1952 triggered the fissure. Subsidence currently is not monitored in the Valley.

Tectonic deformation and hydrocarbon production also complicate assessment of subsidence due to aquifer compaction in the Cuyama Valley, where groundwater is the sole source of supply for a large agricultural industry. The subsidence due to groundwater level decline of as much as 100 m (300 ft) since the 1940s is unknown. Continuous GPS measurements indicate that the valley moves tectonically 0.7 to 1.3 mm (0.03 to 0.05 in) upward and 25 to 36 mm (1 to 1.4 in) to the northwest each year. In parts of the valley where groundwater levels declined below historically low levels during December 2002-May 2008, InSAR detected longer-term subsidence of about 8 to 12 mm/yr (0.31 to 0.47 in/yr), which amounts to 40 to 65 mm (1.6 to 2.6 in) of total subsidence during the period of observation. This long-term subsidence results from inelastic compaction of the aquifer system. Extraction of hydrocarbons at two oil fields in the valley and nearby oil wells apparently had little effect on subsidence during 2002-2011. USGS monitoring and evaluation of the Cuyama Valley aquifer system continues.

6. 1 Conclusions

Subsidence is a significant problem in California that has gone largely unrecognized by the general public. Recently, the work by Sneed et al. (2013) has raised awareness of ongoing land subsidence within the geotechnical community. But much more remains to be done to educate the general public on the significance and implications of land subsidence. Land subsidence resulting from inelastic compaction of aquifer systems has generally gone unnoticed until substantial infrastructure disruption occurs. Cost estimates for infrastructure repair have been very high; the future costs of infrastructure malfunction, disrepair, and destruction are unknown.

Data collection related to subsidence, and the interpretation of such information, is fragmented. It is critical to develop coordinated data colllection, storage, and analysis standards for subsidence-related information. No state or federal governmental agency in California has the responsibility or a program in place, specifically to monitor land subsidence. Consequently, there are no state-wide monitoring networks. Smaller local monitoring networks are sometimes constructed to address a specific subsidence issue. These small networks usually are not geared for long-term monitoring, but rather operate for a project-specific period of time. There a few exceptions. Adjudicated basins sometimes have management objectives that require detailed subsidence monitoring and reporting, as do some agencies that are the primary purveyor of water

in a region. In response to SB 1938 for subsidence monitoring as part of Groundwater Management Plans, some such plans now include local monitoring for subsidence.

7 RECOMMENDATIONS

There is a strong need for regional-to-statewide coordination of ongoing data collection and monitoring, including groundwater level data. And whereas solutions to subsidence issues may be developed (sub)regionally, consistent procedures for collection and storage of water-resources data pertinent to subsidence need to be centrally coordinated by a single agency. Although the costs of subsidence in the San Joaquin Valley were estimated as more than $1.321 billion in 2013 dollars, there is currently no centralized, land-subsidence monitoring program in the valley. Funding for monitoring programs usually has not been available except for the duration of a specific loca1 design, construction, or research project.

The lack of a multi-agency coordinated data repository, which is essential to the evaluation of subsidence, and the lack of funding to support technical synthesis and evaluation of land-based and remotely sensed data, point to a real need to address an ongoing problem that has immense implications for the State of California. This section presents recommendations for the monitoring and research needed to address historical and recent subsidence issues, better understand areas susceptible to future subsidence, and minimize future subsidence-related damages.

7. 1 Data Collection, Storage, and Dissemination

Currently, collection, storage, dissemination, and reporting of the data required to monitor and evaluate land subsidence is dispersed among many federal, state, and local agencies. Centralized data maintenance responsibility could assure consistent procedures for the collection, storage, and availability of pertinent water-resources data. Alternatively, regional coordination of these responsibilities and an ongoing repository for the storage and disbursement of these data would facilitate their efficient use by government agencies, water purveyors and their consultants, and the public.

The Arizona Department of Water Resources (ADWR) has developed a land subsidence monitoring program (Conway, 2013) that could provide a model for implementing a statewide subsidence-monitoring program in California. ADWR has developed an extensive library of over 1,200 SAR scenes used to develop InSAR data, covering an area greater than 150,000 square miles at a cost of more than $750,000, mostly paid for by grants and cooperating agencies. ADWR has compiled a statewide dataset for the active land subsidence areas identified with InSAR in Arizona. Using these data, ADWR has identified more than 25 land subsidence features in Arizona, collectively covering more than 1,100 square miles. ADWR provides land subsidence maps on their website. As of May 2013, 163 land subsidence maps are available for download and are used on a daily basis by the geotechnical community. GPS surveying supports the InSAR program. ADWR uses InSAR data for monitoring land subsidence and seasonal land deformation; assessing natural and artificial recharge events; geological mapping and

investigations; locating earth fissures; identifying areas where conditions may exist for future earth fissure formation; and dam mitigation and land subsidence modeling.

Recommendations for data collection are listed topically below.

7.1.1 Monitoring Land Surface Elevation Changes and Compaction

Remote Surveillance and Analysis

InSAR

InSAR provides the most cost efficient method to generate high-resolution land-surface deformation information over large areas with high spatial detail. Different InSAR products would provide the information and imagery to communicate to the general public the occurrence of subsidence.

- The United States does not have an operating radar satellite that can provide data for InSAR analysis. Encourage the federal government to launch new SAR satellites or participate in a consortium to do the same. (NASA and the Indian Space agency are cooperating to construct and launch a SAR satellite this decade.)
- Acquire all available SAR data covering unconsolidated aquifer systems in the State of California.
- Systematically prepare conventional InSAR interferograms (C-band and L-band as needed) for reconnaissance assessment of land subsidence in alluvial basins.
- Identify areas of decorrelation on interferograms that also are areas likely to subside.
- Install radar reflectors in key positions in areas that appear consistently decorrelated.
- Prepare Persistent Scatterer (PS) InSAR interferograms in areas where SAR data are adequate and conventional InSAR or ancillary data to indicate potential aquifer compaction.
- Immediately process PS InSAR for all major canal systems in agricultural areas or areas of known over pumping of groundwater.
- Make time series of the interferograms available for web-based access by the public (see http://ca.water.usgs.gov/mojave/gmaps/mojave.cgi).

Continuous GPS

Many CGPS sites are used as components of land deformation monitoring networks that were designed to quantify the horizontal movement of tectonic plates. Because very few CGPS sites were installed with the intent to monitor land subsidence, most are not optimally located for subsidence monitoring purposes. More CGPS sites and data evaluation in conjunction with InSAR analysis will greatly enhance the interpretation of land subsidence.

- Examine CGPS data statewide for deformation/motion signals and likely deformation sources.

- Evaluate CGPS locations with respect to unconsolidated aquifer systems.
- Correlate CGPS motions from suitable locations with InSAR results.
- Install new CGPS stations, including locations relevant to areas of actual or potential aquifer system compaction. Co-locate new CGPS installations with extensometers.

Ground Surveillance and Analysis

Surveying

- Collect and archive (digitize) historical leveling surveying information.
- Make historical leveling data available for web-based access by the public.
- Conduct GPS surveys where InSAR or infrastructure effects indicate that subsidence is occurring or where groundwater use is increasing.
- Correlate surveys with InSAR and CGPS data.
- Correlate surveys with groundwater-level data (including temporal data that indicate highest and lowest groundwater levels historically).
- Improve geodetic networks by upgrading and protecting geodetic monuments.
- Investigate conjunctive application of innovative techniques of surface (and subsurface) monitoring to elucidate the processes responsible for fissuring and aid development of predictive capabilities.

Borehole Extensometry

- Evaluate the distribution of extensometers in groundwater basins and subbasins; determine which basins/subbasins are covered and which are not.
- Compile and assess compaction data for the period of extensometer records.
- Refurbish abandoned extensometers in priority areas.
- In unmonitored areas identify aquifer system intervals likely to compact if stressed by groundwater pumping.
- Design and install new extensometers to monitor likely compacting intervals in areas where InSAR, CGPS, surveying, or infrastructure effects indicate that subsidence is occurring, or where groundwater use is increasing.
- Collocate extensometers and multi-level (multi-depth) piezometers so that water-level change (stress) can be analyzed jointly with compaction (stress) in compacting intervals of aquifer systems.

7.1.2 Characterize Aquifer System and Monitor Groundwater Levels

Because groundwater level declines can trigger land subsidence, it is important to monitor, compile, and interpret groundwater levels throughout the state. Because aquitard compaction supplies much of the water produced from confined aquifers, monitoring changing hydraulic head in thick aquitards would advance the understanding of delayed yield from these layers and their compaction when hydraulic heads vary in adjacent aquifers. In order to make groundwater level monitoring measurements meaningful, and to use these measurements to understand the response of the aquifer system to natural factors (e.g., precipitation and

droughts), imposed factors (e.g., pumping and artificial recharge) and the potential for land subsidence, requires that the construction of monitored wells be understood in the context of the aquifer system. Subsurface lithology used to characterize the aquifer system can be obtained from a variety of sources; the most prevalent form of this information is well completion reports submitted by drilling contractors. Although these reports vary greatly in the quality of information recorded, they capture subsurface information that is critical to understanding the relationships between measured groundwater levels and the subsurface location and thickness of clayey layers susceptible to compaction.

- Centralize the collection and storage of groundwater-level data collected by all federal, state, and local entities.
- Provide web access to these data as charts, text files, spreadsheets, and database files.
- Provide timely updates to web-based data files upon collection of new groundwater-level data.
- Correlate wells in the groundwater-level data base with the representation of their construction relative to the aquifer system so the measured data can be used to assess the representation of hydraulic head.
- In cases where construction information for groundwater-level monitoring wells is unavailable, establish a program to collect this information by borehole investigations such as down-well TV camera scans, depth measurement, and interviewing owners and drilling companies.
- Assess the distribution of groundwater-level monitoring wells areally and vertically within the aquifer system to identify locations where additional monitoring wells are needed to track changes in hydraulic head. Find or construct suitable wells in these areas.
- Investigate and experiment with innovative techniques to measure changing hydraulic head in aquitards at collocated extensometers.
- Establish standards for drillers to report well locations as GPS-determined latitude and longitude or other horizontal coordinate system. Continue traditional reporting by sketch or other maps.
- Create a data base of unconsolidated deposits/basin-texture information based on a consistent coding of lithology or sediment type reported on DWR well completion reports, which would aid in locating fine-grained materials which are susceptible to subsidence.

7.2 Prioritizing and Evaluating Subsiding Groundwater Basins

If the above data were in centrally available databases and archives, groundwater basins statewide could be more easily and consistently prioritized for subsidence-relevant planning. In priority basins, a step-wise planning assessment might proceed as follows:

- After evaluating historical groundwater-level monitoring information, establish augmented groundwater-level monitoring networks to fully characterize the variation in hydraulic head throughout the aquifer system.

- After characterizing land surface deformation in priority basins with InSAR techniques, and follow-up geodetic surveys in subsiding areas, establish a program of regular InSAR monitoring. Data needed for InSAR analysis are not always available or of sufficient reliability for this, therefore, ground-based surveying is needed to verify and augment InSAR analysis.
- Establish a network of CGPS stations in subsiding areas to provide time-series data at critical points.
- Establish borehole extensometers and associated multi-level monitoring well arrays to measure compaction and hydraulic head in various depth intervals of the aquifer system at selected points. This enables determination of aquifer mechanical and hydraulic properties and identification of critical groundwater levels that trigger permanent land subsidence; this information is needed to inform design of subsidence mitigation efforts.
- Test innovative new techniques to improve the accuracy and lower the cost of extensometers, incorporating magnetic markers, fiber optics and other new materials.
- In seriously affected areas, assess alternative sources of water and evaluate the potential for artificial recharge.
- Establish measurable basin management objectives (BMOs) that identify goals for groundwater levels, land-surface elevations, and rates of change of each to avoid amounts or rates of inelastic compaction judged to be inappropriate for efficient operation of local infrastructure. These BMOs could be implemented through pumping strategies, artificial recharge, conservation strategies, and other sustainable groundwater management alternatives.
- Develop numerical models that can be applied basin-wide (regionally) and account for delayed drainage of aquitards, stress-dependent parameters hydraulic conductivity and skeletal specific storage.
- Continue to develop data needed to improve numerical models of three-dimensional deformation of aquifer systems and fissuring.

7.2.1 Reporting

Groundwater management plans and water-supply investigations in alluvial basins should include historical information on land subsidence, spatial and temporal variation of groundwater levels, and estimate critical water-levels that will trigger permanent land subsidence. The evaluation of critical water levels should consider relations between, confining unit thickness and hydraulic conductivity and open intervals in wells, to assess the likelihood that groundwater levels declining in the future, but not exceeding historically low levels, might trigger subsidence. Land subsidence should be regularly assessed for each groundwater basin and/or subbasin (especially priority basins) and reported to establish and record current conditions and future trends.

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APPENDIX A

Subsidence Processes in California

SUBSIDENCE PROCESSES IN CALIFORNIA

In California, land subsidence occurs as a result of collapse of underground cavities, tectonic activity, natural consolidation of sediment, oxidation of organic deposits, hydrocompaction of moisture-deficient soil and sediments, development of geothermal energy, extraction of hydrocarbons from the subsurface, and extraction of groundwater. Physical processes causing land subsidence resulting from groundwater extraction, and locations of areas subsiding as a result of groundwater extraction, are described in the main body of this report.

A 1 Collapse of Underground Cavities

Collapse of underground cavities (solution and piping cavities, mines and other engineered openings), can be catastrophic but is rare in California and unusual in areas where groundwater is pumped from unconsolidated sedimentary aquifers. Collapse of shallow underground mines has occasionally disrupted the land surface (**Figure A-1**), and collapse of voids created by piping of sediment, due to leaking storm sewers or water pipes for example, has created shallow collapse features in urbanized areas. Because the geographic extent of soluble limestone or marble is rather limited in California, sinkholes formed by cavern collapse are rare. However, the School of Earth Sciences building at U.C. Santa Cruz suffered some damage when a sinkhole partly collapsed beneath it, and similar but smaller-scale collapse has affected roads on the campus. Caverns occur in marble of the Sierra Nevada foothills, butinfrastructure damage from sinkholes formed over collapsing caves has not been reported there. Collapse is a threat in areas underlain by lava tubes, in littoral caves and soil pipes along the seacoast, and in mud caves similar to those at Anza-Borrego State Park.



Figure A-1. Collapse into the Old Brunswick Mine, Grass Valley, California (photo courtesy of California Department of Conservation).

A 2 Tectonic Activity

California is earthquake country. California is earthquake country. Ground shaking during earthquakes can induce liquefaction in subsurface sand layers. Liquefaction induces bearing capacity failure that damages overlying structures. Post liquefaction consolidation of the sand layers can result in wide-spread lowing of land surface due to both the loss of pore space in the sand layers and 'soil loss' from sand that escapes to land surface at 'sand boils'. Earthquakes and the faults on which they occur are caused by the movement of tectonic plates. North of Cape Mendocino, oceanic crust subducts beneath the North American continental plate. South from Cape Mendocino, the Pacific Plate rubs past the North American Plate along the San Andreas Fault (**Figure A-2**). Motion of the tectonic plates creates other faults and can substantially elevate or depress land surface inland from the coast. Huge tectonically subsided basins have filled with thousands of feet of sediment eroded from adjacent mountains. Sediments filling these basins contain oil, gas, and groundwater (**Figure A-3**).

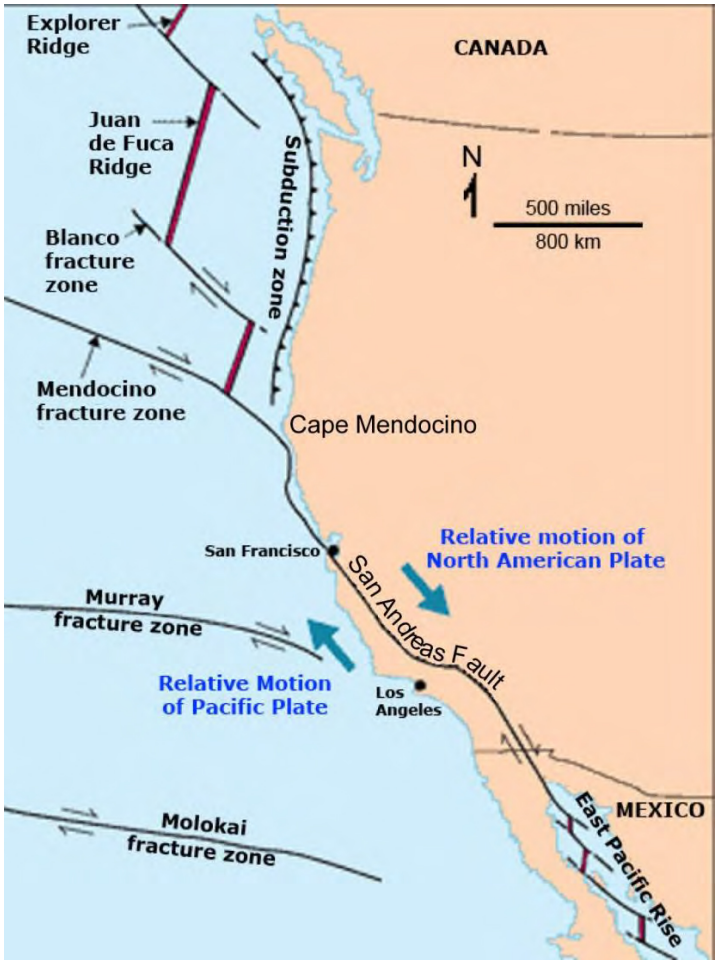


Figure A-2. Plate tectonics of western North America (Source: Geology.campus.ad.csulb.edu /people/bperry /Geol303photos/ContinentalBorderland/PlateTectonicsWestNAmericaUSGS.jpg).

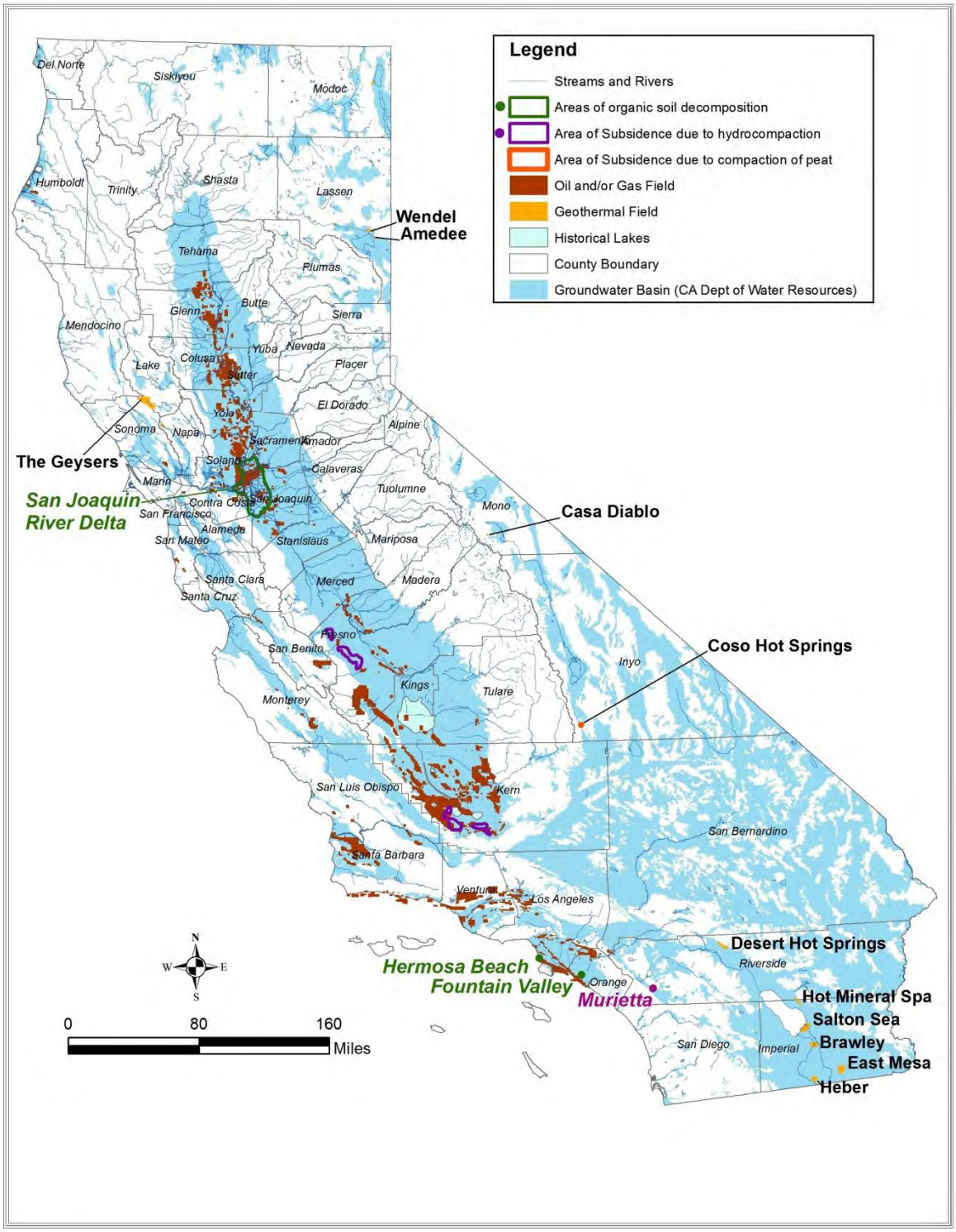


Figure A-3. Alluvial aquifers, major areas of subsidence due to water level decline, oil and gas fields, locations of geothermal development, areas of hydrocompaction in the San Joaquin Valley, and the towns of Murietta, Hermosa Beach, and Fountain Valley in Orange County, California.

Vertical movement in response to tectonic forces can be slow and continuous or episodic on geologic time scales. For example, Bowersox (2004) calculated that, during the last 5.5 million years, the rate of tectonic subsidence in the northwestern San Joaquin Valley has varied considerably in response to changing tectonic forces, from about 10 cm (4 in) per thousand years to more than 140 cm (55 in) per thousand years. Tectonic downwarping of the southern San Joaquin Valley averaged about 0.3 m (1 ft) per thousand years during the last 600,000 years, while the rate of sediment deposition in the trough of the valley varied from 0.46 to 1.2 m (1.5 to 4 ft) per thousand years (Lofgren, 1975). At shorter time scales, tectonic uplift of survey control points in the mountains flanking the San Joaquin Valley likely was responsible for about 0.3 m (1 ft) of apparent subsidence at stable bench marks in the southern San Joaquin Valley between 1930 and the mid-1960s (Lofgren, 1975) and for the nearly uniform 0.15 m (0.5 ft) apparent subsidence indicated by surveying a 7.2 km (4.5 mi) transect through the town of Lost Hills, in the southern San Joaquin Valley, during 1953-1966 (Ireland et al., 1980). The rate of apparent subsidence that is caused by tectonic uplift of reference bench marks assumed to be stable is variable depending on location but averages about 20 times the rate of tectonic downwarping of the valley floor (Lofgren, 1975).

Because tectonic forces influence all of California, it is important to consider their effect on land surface elevation in both subsiding areas and areas used for reference elevations when evaluating subsidence resulting from groundwater extraction.

A 3 Natural Consolidation of Sediment

Sediments buried deeply in basins compress, expel water, and consolidate, thinning in the vertical dimension and causing overlying materials and the land surface to move downward. This can be thought of as 'natural' subsidence from sediment consolidation occurring slowly over long periods of time. Rates of natural sediment consolidation are generally low compared to other local and regional processes that contribute to total subsidence in an area. Brooks and others (2012) noted small amounts of subsidence that likely were caused by natural consolidation of sediment beneath the inland Delta of the Sacramento-San Joaquin Rivers, but this subsidence is insubstantial compared to that caused by oxidation of peaty soils in the Delta.

A 4 Oxidation of Organic Deposits (Peaty Soils)

Draining water from peat deposits in marshes allows oxygen to reach richly organic soil layers, promoting the growth of aerobic bacteria, which increase the rate of decomposition of organic material by as much as 100 times relative to the anaerobic rates of decomposition that occur under natural, undrained conditions. Inasmuch as organic carbon is aerobically converted to carbon dioxide, peaty soil disappears and the land surface lowers (Broadbent, 1960).

Land subsidence resulting from oxidation of organic soils is a serious issue in California. Large areas of the inland Delta of the Sacramento-San Joaquin Rivers in California have lowered by more than 4.6 m (15 ft), and as much as 6.4 m (21 ft) on some islands in the central Delta (**Figure A-4**) in response to peat oxidation on Delta islands and tracts after these areas were leveed and shallow groundwater was drained for agricultural development (Deverel et al., 1998). Subsidence of Delta islands adds stress to island levees (**Figure A-5**), which, should they fail, imperils water supplies for millions of Southern Californians and Central Valley farms that rely on the levees to shunt water through the Delta to intake pumps for the California Aqueduct and Delta Mendota Canal (DMC). If Delta levees failed catastrophically, for example during a coincident earthquake and storm or high tide, or in response to rising sea levels resulting from global warming, salty water from downstream bays would flood into the Delta, denying fresh water to California Aqueduct and DMC intakes (Mount and Twiss, 2004). Repairs that might take years would require over pumping of groundwater in the San Joaquin Valley and elsewhere to satisfy water demand south of the Delta. Ironically then, shallow subsidence in the Delta would be indirectly responsible for a huge increase in land subsidence south of the Delta as aquifer sediments compact in response to groundwater levels lowered by over pumping. (Galloway et al., 1999)



Figure A-4. Shaded contours of subsidence in the Sacramento-San Joaquin Delta and the Delta pumping plant (from Ingebritsen et al., 2000).



Figure A-5. Wind-whipped waves spilling over the levees on the north side of Jersey Island in the Sacramento-San Joaquin Delta December 3, 1983 (photo by Kenneth L. Kjeldsen).

Oxidation of peaty deposits in drained marshlands has also resulted in land subsidence elsewhere in California. Fairchild and Weibe (1977) describe subsidence due to decomposition of peat that filled old stream channels and land-surface depressions from about 1.6 km (1 mi) inland from the coast at Hermosa Beach discontinuously westward at least as far south as Fountain Valley in Orange County (**Figure A-3**). There, fresh-water marshes supplied by upwelling groundwater produced peat deposits as much as 7.6 m (25 ft) thick. Upwelling groundwater discharged from what became locally know as "peat springs." Subsurface tile drains installed during the late 1800s and early 1900s, and later water-supply development, lowered groundwater levels by more than 13.7 m (45 ft), drying up the springs and causing as much as 6 m (20 ft) of land subsidence locally by 1976. Localized subsidence possibly due to peat decomposition has also been reported in scattered areas inland from the coast between Sunset and Newport Beaches in Orange County, California (U. S. Army Corps of Engineers, 1988, citing Leighton-Yeh and Associates, 1974).

A 5 Hydrocompaction

Hydrocompaction is compaction caused by wetting of near-surface, moisture-deficient sediments. It occurs in alluvial-fan deposits that lie above the highest prehistoric water table in areas where sparse rainfall and ephemeral runoff do not penetrate the soil below the root zone. These sediments are deposited as muddy debris flows in areas of very low average rainfall and infrequent, flashy, sediment-laden runoff from small, relatively steep upland watersheds that are underlain by easily erodible shale and mudstone. The resulting deposits typically contain a substantial amount of montmorillonite clay that, when dry, acts as a cementing agent providing substantial dry strength to the deposits and preserving a highly porous structure of vesicles

(bubble cavities) and desiccation cracks. Where the water table is deep, in the western and southern San Joaquin Valley, these sun-baked deposits retain their high dry strength, even as they are subjected to the increasing load of more than 30 m (100 ft) of accumulating overburden. When water is first applied in quantities sufficient to penetrate below the root zone, cementing clays are drastically weakened by wetting, and the weight of the overburden crushes out the excess porosity (Galloway et al., 1999). The deposits may lose as much as ten percent of their thickness depending on their depth and the overburden load. If the deposits are thoroughly wetted, compaction is rapid, proceeding with the downward movement of infiltrating water.

In the 1940s and 1950s, farmers irrigating virgin soils in the western San Joaquin Valley (**Figure A-3**) found that hydrocompaction caused an irregular, hummocky settling of their fields and localized settlements of as much as 3 m (10 ft) where water ponded or flowed in canals. Hydrocompaction disrupted the distribution of irrigation water and damaged pipelines, power lines, roadways, airfields, and buildings. Recognition of its obvious impact on the design and construction of the proposed California Aqueduct played a major role in the initiation in 1956 of intensive studies to identify, characterize, and quantify the subsidence processes at work beneath the surface of the San Joaquin Valley (**Figures A-6, A-7, and A-8**) (Lofgren, 1960; Bull, 1964, 1973, 1998; Lucas and James, 1977; James et al., 1997; Bean, 1998; Galloway et al., 1999)



Figure A-6. Concentric tension fissures and differential subsidence resulting from hydrocompaction at a 6-ft diameter corrugated infiltration test pit on the proposed alignment of the California Aqueduct, December 12, 1960.



Figure A-7. Flooding basin in Kern County, California, used to "presubside" sediments subject to hydrocompaction along the proposed route of the California Aqueduct. Note the step-wise, differential subsidence between tension-fissured scarps on the basin dikes. To prevent deleterious effects of hydrocompaction, large sections of the alignment of the Aqueduct were precompacted in this manner prior to construction (photograph by Joseph F. Poland, October 13, 1965).



Figure A-8. Hydrocompaction damage to a canal test section in the west–central San Joaquin Valley. The earthfill embankment cracked and settled, the concrete lining and earthfill embankment separated, and the 4-in thick concrete lining cracked and buckled after the test section was flooded. (Photograph from Prokopovich, 1983). Precompacting the alignment of the California Aqueduct by flooding helped to prevent similar damage.

Differential subsidence and earth fissuring in response to irrigation at California Oaks, a new development in Murrieta (**Figure A-3**), in urbanizing Riverside County also was due to hydrocompaction of moisture-deficient soils. Groundwater levels rising in response to golf course and landscape irrigation triggered hydrocompaction of Holocene alluvium that had been left in place during grading. Residences and infrastructure that were in various stages of construction sustained damage from earth fissures that disrupted the land surface. Subsequent litigation and damage claims led Riverside County to establish the California Oaks Subsidence Reporting Zone that required geotechnical studies and removal of sediments susceptible to hydrocompaction before construction (Shlemon, 1995; Shelmon et al., 1998; Kupferman, 1998).

A 6 Geothermal Energy Development

Development of geothermal resources to produce electric power causes subsidence by two primary mechanisms. Firstly, removing hot water and steam from subsurface formations reduces the pressure in fractures, pore space, and other voids in the hot bedrock. The pressure drop causes a loss of void space as mineral grains and fractures squeeze more tightly together to support the weight of overlying material. Secondly, removing hot fluids and steam or injecting cold fluids to create steam for power production causes a thermal contraction of the hot bedrock that is expressed as subsidence at the land surface. Some geothermal development occurs in areas underlain by unconsolidated aquifers (**Figure A-3**). Geothermal energy producers operate subsidence monitoring networks in the Imperial Valley.

A 7 Extraction of Hydrocarbons from the Subsurface

Gas and oil wells produce hydrocarbons and saline formation water from sedimentary rocks and deposits deep in the subsurface (**Figure A-3**). Because aquifers that provide groundwater for water supply purposes and environmental needs often overlie hydrocarbon reservoirs, distinguishing subsidence resulting from hydrocarbon extraction from that resulting from pumping groundwater can be difficult.

Similar to removing groundwater from an aquifer, removing hydrocarbons and associated formation water reduces the fluid pressure, causing mineral grains to squeeze more tightly together. The resulting compaction allows overlying deposits and the land surface to subside, often forming a bowl-shaped depression in the land surface. Land subsidence occurs directly above and in some cases beyond the lateral boundaries of many oil and gas fields (Yerkes and Castle, 1969). Subsidence is greatest where hydrocarbon reservoir deposits are thick, relatively shallow, and poorly consolidated (Martin and Serdengecti, 1984). However, if deposits overlying oil and gas reservoirs are consolidated rocks, they may resist settling and partly bridge compacting hydrocarbon-bearing deposits, in which case subsidence at the land surface may be less than the change in thickness of the oil and gas reservoir (Nagel, 2001). Subsidence at two

gas fields, River Island and Rio Vista, is indicated on **Table A-1** (at end of Appendix), but Yerkes and Castle (1970) do not identify the specific source of the measurements. Gas fields, located north of Fresno, (**Figure A-3)** mostly produce gas from consolidated sandstone. Production of gas reportedly has not caused significant land subsidence issues at most locations; the single reported incident of subsidence, when a plow struck a buried gas well casing, was reportedly due to subsidence caused by oxidation of peaty soils on a Delta island rather than gas withdrawal (B. G. Tackett, California Division of Oil Gas and Geothermal Resources, oral commun., September 17, 2013).

Fluid pressure decline within a producing hydrocarbon reservoir can be substantial—increasing the force on mineral grain contacts (the effective stress) by thousands of pounds per square inch (psi) in some cases. Laboratory tests on sandy hydrocarbon reservoir rocks have shown that increasing the effective stress between 1,000 and 20,000 psi, which includes the range of effective stress increases in many oil fields, fractures and crushes sand grains. Crushing and subsequent rearrangement of broken grains leads to a dense packing of compacted mineral fragments. Depressured reservoir sands can be as compressible as or more compressible than clays (Roberts, 1969). Allen and Mayuga (1969) showed that about two thirds of the compaction in the Wilmington oil field in Long Beach occurred in sands and only about one third occurred in clayey shale layers.

Some of the most productive oil and gas fields in California produce hydrocarbons from clayey diatomaceous deposits (diatomites) that have 50-70 percent porosity, that is, more than half of volume of the deposit is void space filled with oil, gas, or water. Diatoms are microscopic algae, single-celled or colonial, and encased by silica frustules—fragile hollow shells that accumulate in thick sedimentary layers in marine and some fresh-water environments. When oil production reduces reservoir pressure, effective stress increases and hydrocarbon-bearing diatomites compact substantially because of their high porosity and because delicate diatom frustules are crushed (Stosur and David, 1976; Bruno and Boverg, 1992; De Rouffignac and Bondor, 1995). Laboratory testing indicates diatomites compact inelastically at nearly all stress levels; compaction is permanent regardless of future reductions in effective stress (Bruno and Boverg, 1992).

Compaction of hydrocarbon reservoir sediments provides substantial energy that forces hydrocarbons toward producing wells, increasing production and ultimate recovery of petroleum from an oil field (Nagel, 2001). Unfortunately, substantial thinning of a compacting hydrocarbon reservoir often produces consequent and sometimes rapid subsidence of the land surface.

At some oil and gas fields in California subsidence to date has been minimal (**Table A-1**). At other fields, production of hydrocarbons from oil and gas wells has resulted in substantial land subsidence and lateral movement of earth materials toward the center of a bowl-shaped

depression in the land surface, creating 1) vertical downward compressional forces and in some cases tensional forces, 2) lateral tensional forces and subsequent earth fissures near the edges of a subsidence bowl, 3) lateral compressional forces near the bowl interior, 4) lateral subsurface shearing forces in weak clayey layers and at contacts between sediments of different lithology, 5) small earthquakes, 6) new faults, and 7) movement on existing faults (Frame, 1952; Yerkes and Castle, 1969; Allen and Mayuga, 1969; Bruno and Boverg, 1992; Hilbert et al., 1998). Oil and gas field operation has resulted in damage to near surface infrastructure—bridge and building foundations, dams, roads, railroads, and pipelines—and has increased flooding, inundating coastal areas. Oil and gas extraction has also damaged or destroyed subsurface infrastructure by vertically compressing, and in some cases stretching and laterally shearing, steel casing in hydrocarbon producing wells hundreds to thousands of meters below land surface (Bruno and Boverg, 1992; Bondor and De Rouffignac, 1995; Hilbert et al., 1998; Nagel, 2001).

Most oil produced in California is from fields in four structural basins: the Los Angeles, Ventura, Santa Maria, and San Joaquin basins. Deformations at 27 California oil and gas fields are listed in **Table A-1**. The most thoroughly documented deformations are described for illustrative purposes below – at a coastal and an upland field in the Los Angeles basin and at two fields in the San Joaquin Valley (**Figure A-9**).

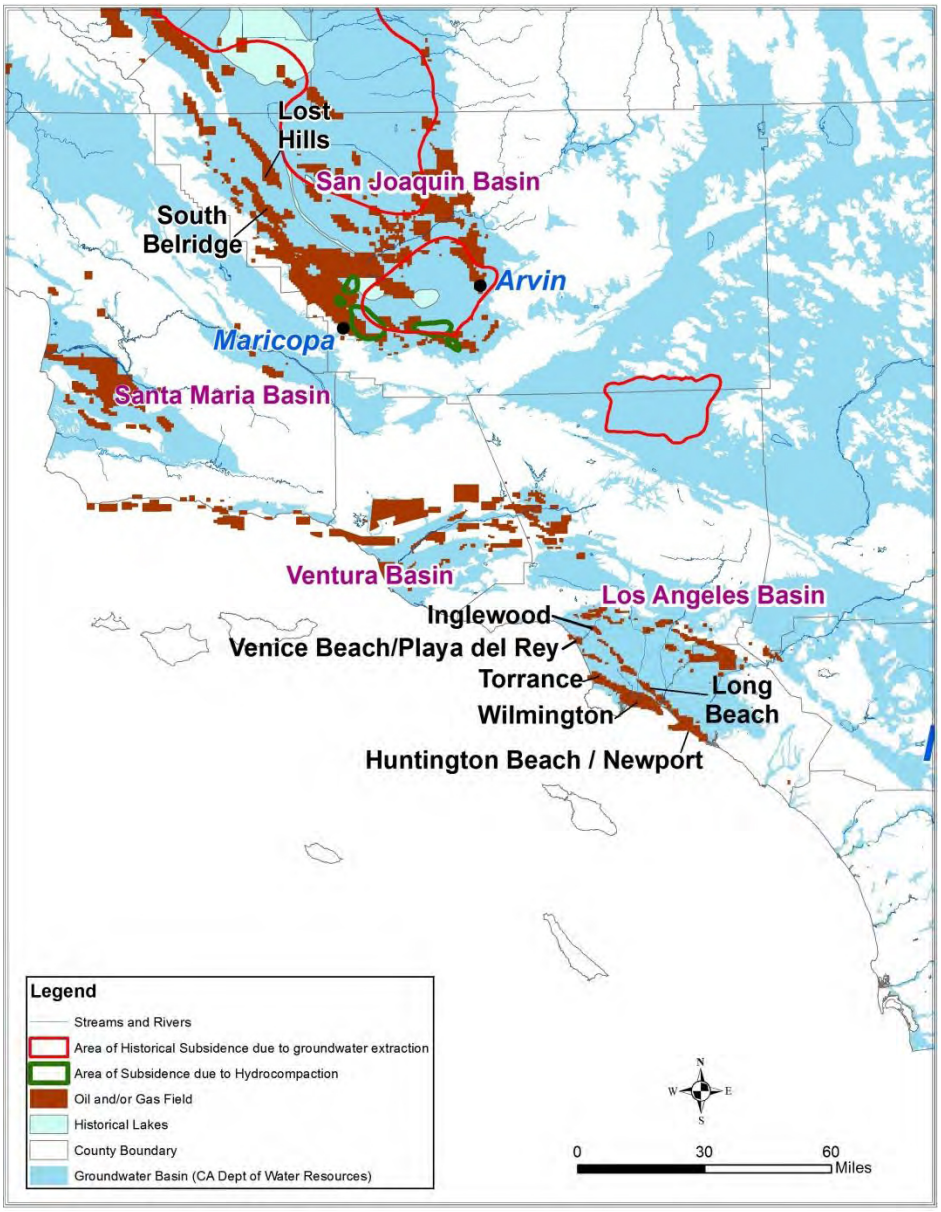


Figure A-9. Map of oil and gas fields in the Los Angeles basin and southern San Joaquin Valley.

A 7.1 Los Angeles Basin

Wilmington Oil Field, Long Beach, California

The Wilmington field is the fourth largest oil field in the United States and the second largest in California, having produced 2.7 billion barrels (429 million m^3) of oil since it was discovered in 1932 (California Department of Conservation, 2010). More than 100 reports, articles, and legal briefs have described the geology, oil-production history, the nearly 10 m (33 ft) of subsidence

(**Figure A-10**) (Hilbert et al., 1998) and subsequent litigation that occurred since oil production began in 1936. Oil and gas are produced from seven sand or silty sand zones between 762-1,829 m (2,500 and 6,000 ft) below land surface in the Long Beach Harbor area (Poland and Davis, 1969). Subsidence noted in the early 1940s was first thought to have resulted from dewatering of a shallow aquifer to allow a 65-ft-deep excavation for construction of a dry dock at the Long Beach Naval Shipyard located on Terminal Island adjacent to the City of Long Beach. It was assumed that subsidence would stop when construction activities ceased (Mayuga and Allen, 1969). However, by January 1945 pressure in the upper four oil-producing zones had dropped by 1100 psi (Gilluly and Grant, 1949; Harris and Harlow, 1947) and leveling by the U.S. Coast and Geodetic Survey in July 1945 indicated subsidence of 1.3 m(4.2 ft) on Terminal Island. Leveling surveys conducted every three months in a network of 300 bench marks installed by the Long Beach Harbor Department tracked subsidence, which reached a maximum rate of 0.7 m/yr (2.37 ft/yr) in 1951, the same year that oil withdrawal from the Wilmington Field reached its maximum rate of 140,000 barrels per day (Poland and Davis, 1969). In the late 1950s effective stress in oil-producing sands 610-1,220 m (2,000 - 4,000 ft) deep had increased to 1,500-3,000 psi, fracturing and compacting sand grains there. Quantitative measurements of subsidence, oil production volume, and producing zone pressure established a causative relation between subsidence and oil production (Poland and Davis, 1969; Miller and Summerton, 1955).

By 1968, a subsidence bowl 8.8 m (29 ft) deep had formed over the Wilmington Oil Field (Mayuga and Allen, 1969). Sea water backed up through the storm drain system and, at high tide, flooded streets in the 8 km^2 (5 my^2) of the industrial area around the harbor that had sunk below sea level. Damage to infrastructure was extensive. Building foundations, bridges, roads, railroads, and pipelines were damaged or destroyed. Horizontal shearing forces that developed in deep, weak shale layers in the subsidence bowl triggered three earthquakes that damaged 515 oil wells at a cost of $21,250,000 (Frame, 1952, 1952 dollars assumed, $186 million 2013 dollars). Huge dikes and retaining walls were built to protect industrial property and oil wells. Bulkheads (flood walls) were constructed on harbor docks to keep out the sea. Eventually, large parts of the harbor industrial area were raised with fill materials, requiring replacement of pipelines and raising of oil well casings, roads, buildings and other infrastructure. The cost of remedial activities had exceeded $100,000,000 by 1962 (Poland, 1962, 1962 dollars assumed, $880 million 2013 dollars). These remedial activities did nothing to reduce subsidence or eliminate its cause.

The Anti-Subsidence Act of 1958 consolidated 117 oil producers in the Wilmington Oil Field to a single entity and compelled it to undertake repressurization of the field (Kopper and Finlayson, 1981). A pilot repressurization program injecting shallow, salty, groundwater into oil-producing zones to halt subsidence began in 1953 (Poland and Davis, 1969). By 1969, subsidence was halted over much of the oil field and some areas had rebounded about 0.3 m (1 ft).

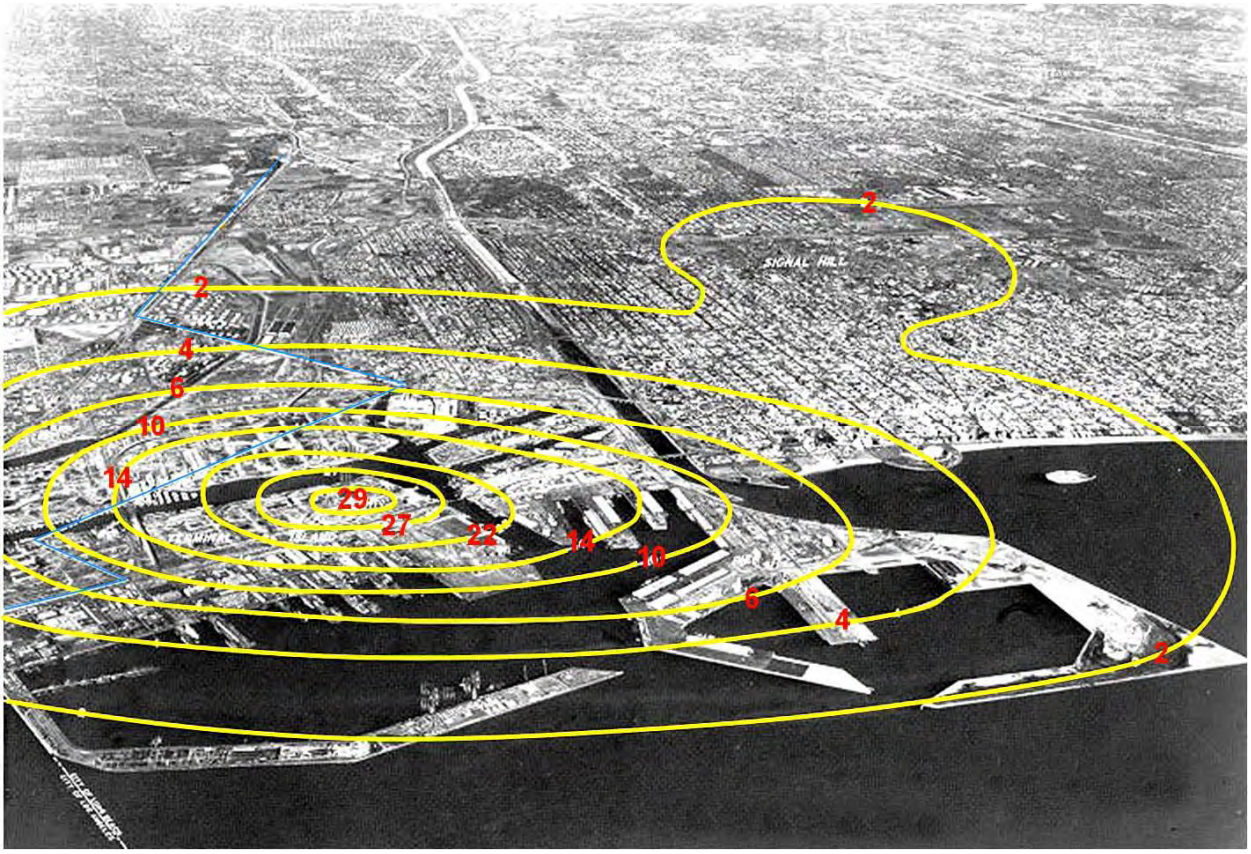


Figure A-10. Subsidence over the Wilmington Oil Field, Long Beach, California during 1928-1974, in feet (photo courtesy of John Jepson, Long Beach Gas and Oil, City of Long Beach, California).

The City of Long Beach implemented a surveillance program to monitor land subsidence over the Wilmington oil field. They measure the elevation of 900 bench marks in the affected areas on a quarterly basis and periodically conduct subsurface pressure surveys in selected oil wells. Tide gages have been installed as a means of detecting subsidence, and several strategically located wells are surveyed throughout their depth annually to detect changes in the length of casing sections which would indicate the depth and amount of subsurface compaction (Mayuga and Allen, 1969).

Currently, the operator of the southern part of the Wilmington Oil Field (the part closest to the coast) is required to maintain water injection equivalent to 105 percent of oil produced from the field in order to prevent subsidence (Nagel, 2001). Between 1993 and 1996, subsidence of 0.7 m (2.4 ft) in the western parts of the Wilmington Oil Field was reportedly caused by steam flooding—a recovery technique that improves extraction of heavy oil (E & B Natural Resources, 2012, citing Mike Henry, personal communication, undated). In 1999, steam flooding was curtailed, and land surface elevation stabilized by 2006. The repressurization program enacted to prevent subsidence also enhanced the recovery of oil from the Wilmington Field.

Deformation of the land surface (subsidence or rebound) in response to oil and gas field operations has been noted or suggested in other coastal southern California oil and gas fields-Torrance (U.S. Army Corps of Engineers, 1990), Huntington Beach, Long Beach (Gilluly and Grant, 1949), and Venice Beach-Playa del Rey (Grant, 1944) (**Table A-1**). Subsidence in coastal areas is sometimes more obvious than subsidence elsewhere because inundation and flooding are immediately noticeable.

Inglewood Oil Field

Baldwin Hills, California

On the afternoon of December 14, 1963, issues of ground deformation above oil and gas fields came sharply into focus for residents downslope from the Baldwin Hills Reservoir, Los Angeles. Three hours after seepage was noticed at its east abutment, the reservoir dam breached, emptying 250 million gallons of water downhill into the adjacent neighborhood. The flood killed five people and destroyed 277 homes, resulting in $12 million ($69 million in 2013 dollars) in property damage (Hamilton and Meehan, 1971). The cause of the disaster was controversial and variously attributed to tectonic movements, movement on existing faults induced by the weight of water filling the reservoir, redistribution of weight during cut-and-fill construction activities, improper compaction of the emplaced clay layer lining the reservoir, inappropriately permeable reservoir-lining materials, land subsidence from extraction of oil, movement on existing faults or on new fissures lubricated by water injected to enhance recovery of oil, or a combination of these causes.

The Baldwin Hills Reservoir was constructed above the Inglewood oil field (**Figure A-9**) during 1947-1951 on an active fault subsidiary to the Inglewood fault. During construction, 7.9 m (26 ft) of previous vertical offset were noted on this 'reservoir fault' (Hamilton and Meehan, 1971). Between 1910 and 1964, an elliptical depression developed over the oil field with more than 3 m (10 ft) of subsidence at its center, 1,500 feet west of the reservoir, and about 0.6 m (2 ft) of subsidence at the reservoir (Hamilton and Meehan, 1971, citing unpublished data from Leps and Walley, 1971). Although DWR (1964) attributed the dam failure to an “unfortunate combination of physical factors,” a State Engineering Board of Inquiry (Jansen et al., 1967) concluded that ground ruptures that triggered the failure likely were related to land subsidence. Hamilton and Meehan (1971) concluded that the “earth-crack ground rupturing of the Baldwin Hills” that triggered reservoir failure was genetically related to high-pressure injection of fluid for disposal of salty oil field waters and enhanced recovery of oil into the previously faulted and subsidence-stressed subsurface. After exhaustive study of earth movements at Baldwin Hills, Castle and Yerkes (1976) concluded that differential subsidence and associated horizontal movements were due to exploitation of the Baldwin Hills oil field; other failure mechanisms were judged implausible.

Controversy about continued oil and gas development and the causes of recent (2012) ground deformation above the Inglewood oil field south of the reservoir site continues today, 50 years after failure of the Baldwin Hills Reservoir. A 2011 settlement agreement between litigating parties defined the conditions under which the field may continue to be developed (http://www.inglewoodoilfield.com/res/docs/SettlementAgreementDatedJuly152011.pdf).

Subsidence and other ground deformation above oil and gas fields in the Los Angeles basin generally is of smaller magnitude then at the Wilmington and Baldwin Hills fields. Ground deformation at areas more remote than the Los Angeles basin often are not as well documented as deformation at the Wilmington and Baldwin Hills oil fields, where the effects on urban infrastructure were widely noted.

A 7.2 San Joaquin Valley

The southern San Joaquin Valley is a major oil-producing region (north from Fresno, California hydrocarbon fields produce mostly gas) (**Figure A-9**). In 1858, asphalt deposits that were noticed on the land surface near the future Sunset oil field hinted at the availability of hydrocarbon deposits in the subsurface of the southwestern valley. By 1993, Kern County alone had 16 oil fields that each had produced more than 100 million barrels of oil (http://www.sjvgeology.org/history/sjv_chronology.html). Oil fields are still being discovered; in 2009, Occidental Petroleum Corporation discovered a major new field, estimated to hold about 150 million barrels of oil, between the Elk Hills and Railroad Gap fields.

Oil fields lie beneath the rolling foothills of the Sierra Nevada on the east side of the valley, beneath the low domed ridges on west side of the valley, and beneath farms and ranches on the flat valley floor. Subsidence due to oil production in the San Joaquin Valley is rarely mentioned in the hydrologic literature, although subsidence there occasionally has been described in petroleum industry literature, mostly because damage to oil wells and pipelines has focused attention on monitoring activities designed to help oil producers avoid damage to infrastructure.

South Belridge

Discovered in 1911, the fourth largest oil field in California had 6,125 active wells and had produced more than 1.56 billion barrels (248 million m^3) of oil by 2009 (California Department of Conservation, 2010) from sands and highly compressible diatomaceous sediments (Bondor and De Rouffignac, 1995). Ground deformation at the field accelerated during the mid-1980s due to aggressive production practices that contributed to about 6.1 m (20 ft) of subsidence (about 0.46 m/yr (1.5 ft/yr), Bondor and De Rouffignac, 1995) at the center of the large subsidence bowl over the field. During four years in the mid-1980s, 15 to 20 percent of the oil wells were destroyed per year (Nagel, 2001) by compressive and shearing forces that developed in the subsurface in response to compaction of oil-bearing sediments. Large surface fissures formed in

response to tensional forces that developed near the edges of the subsidence bowl (Bondor and De Rouffignac, 1995). Subsidence rates decreased in 1987 when water-injection operations, designed to increase oil recovery, slowed the rate of pressure declines in oil producing sediments. However, subsidence was not completely halted. During spring 1995, Fielding and others (1998) measured subsidence of about 1 mm/ day, equivalent to an annual rate of more than 1 ft/yr. Substantial subsidence has also occurred over the contiguous North Belridge field (**Figure A-9; Table A-1**).

Lost Hills

Land subsidence has been costly for oil companies operating in the Lost Hills field (**Figure A-9**), where oil and gas has been produced from five geologic units from 91 m (300 ft) to more than 1,829 m (6,000 ft) below land surface in an elongated anticline. This arched dome of otherwise horizontally layered bedrock runs parallel to and about a mile west of the California Aqueduct. Discovered in 1910 by ranchers drilling for water for their livestock, the field had 2,819 producing oil wells as of 2009. Land subsidence was on the order of tenths of inches per year until 1980. Rapid field development in the mid-1980s through 1992 increased the rate of subsidence to about 0.3 m (1 ft/yr). Geophysical logging indicated that the oil-producing diatomite interval compacted about 0.6 m (2 ft) from 1990 to 1991 (Bruno and Boverg, 1992). Fielding and others (1998) measured subsidence occurring at an annual rate of more than 0.4 m (1.3 ft/yr) during May 26, 1995 to January 26, 1996 (**Table A-1**). Subsidence has destroyed substantial numbers of oil wells and shallow pipelines in the large subsidence bowl over the field.

Enhanced recovery operations employing injected water (water flooding), steam injection, and in-situ combustion (fire flooding) may have contributed to localized subsidence at the field. During steam stimulation on April 23, 1976, an oil well, pump and concrete pad disappeared into a crater 4.6 m (15 ft) deep and 9.1 m (30 ft) wide. The concrete pad and pump were recovered after excavating 13.7 m (45 ft) below land surface but no trace of the 7-in casing, 5 1/2-in casing liner, or well-head piping were found, even though the excavation was deepened to 24.4 m (80 ft). Similarly, in 1978, a well undergoing steam stimulation collapsed into a crater 6.1 m (20 ft) deep. The pump was recovered from a depth of 7.6 m (25 ft), but excavation to 15.2 m (50 ft) failed to find the casing and well-head piping (Land, 1984). Despite damage to infrastructure costing an average of one million dollars annually, the value of oil produced at the field, one million dollars per day, justifies the considerable maintenance expense (Blom et al., 2006).

Other Areas in the San Joaquin Valley

Most readily available subsidence information at oil and gas fields is from fields west and upslope from flat-lying agricultural areas in the southern San Joaquin Valley. Investigations of subsidence at oil and gas fields are primarily conducted within field boundaries by oil companies

or their contractors focused on optimizing operations to minimize subsidence damage to oil and gas wells and pipelines. A study by the NASA Jet Propulsion Laboratory (JPL) used topographic data acquired from the 2000 Shuttle Radar Topography Mission (SRTM) and a digital elevation model published by the USGS in 1989 to produce an animation describing subsidence near the Lost Hills and Belridge fields (Crippen, 2012). The animation indicates that the oil fields subsided about 3 m (9.8 ft) during 1982-1990 and that flat-lying agricultural areas adjacent to the oil fields (including the California Aqueduct) also subsided. The JPL topographic comparison was not designed to evaluate subsidence that might have been caused by groundwater extraction in flat-lying agricultural areas. Ireland and others (1984) concluded that subsidence of the California Aqueduct east of the Lost Hills field was at least partly due to compaction of shallow oil zones at the Lost Hills field. However, subsidence extends more than 9.3 km (15 mi) south of the oil field, and the subsidence rate increases in dry periods and decreases in wet periods, indicating a relation that might be correlated with groundwater pumping (Swanson, 1998). Groundwater levels are not monitored in the area, and no extensometers are located there; both types of data would be needed to determine the cause of subsidence exterior to the oil field.

Lofgren (1975) evaluated land subsidence caused by groundwater extraction in areas underlain by oil and gas fields in the Arvin-Maricopa area of the southern San Joaquin Valley. Comparing the elevation changes at surveying monuments (bench marks) directly overlying the oil and gas fields to elevation changes noted in adjacent agricultural areas, he suggested that only the component of subsidence in the oil fields that exceeded subsidence in adjacent agricultural areas was caused by oil and gas extraction. He concluded that subsidence in oil fields was of little concern compared to subsidence related to groundwater extraction, although he admitted that only a small part of the oil production and, therefore, the consequent subsidence from oil production occurred during the period of available leveling measurements. Subsidence caused by groundwater extraction has reportedly damaged the steel casings of oil and gas wells located near the San Joaquin River west of Fresno, California (Glenn Muggelberg, California Division of Oil, Gas, and Geothermal Resources, Oral Communication, September 17, 2013). Measuring compaction in appropriate subsurface intervals is the only way to discriminate which compacting process has contributed to subsidence measured at the land surface.

Table A-1 Subsidence Over Selected California Oil and Gas Fields.

Field	Discovery Year	Maximum Producing Area (km^2)	Maximum Producing Area (mi^2)	Median Depth of Production (m)	Median Depth of Production (ft)	Measured Subsidence					Surface Faults[b]
						Maximum[a] (m)	Maximum[a] (ft)	Area of Subsidence (km^2)	Area of Subsidence (mi^2)	Period of Measurement	
Buena vista	1910	48	18.5	1130	3707	0.27	0.89			1957-1964	Lr
						2.3	7.55			1942(?)-1964	
Dominguez	1923	7	2.7	1430	4692	>0.07	>0.23			1945-1960	
Edison	1928	6	2.3	1100	3609	>0.09	0.30			1926-1965	
Fruitvale	1928	14	5.4	1370	4495	>0.04	>0.14			1953-1965	
Greely	1936	9	3.5	3235	10614	>0.01	>0.03			1953-1965	
Huntington Beach	1920	16	6.2	930	3051	1.22	4.00	37	14.3	1933-1965	
Inglewood	1924	5	1.9	900	2953	1.73	5.68	11	4.2	1911-1963	Hn
						3.04[1]	10[1]			1910-1964	
Kern Front	1912	19	7.3	745	2444	>0.34	>1.11			1903-1968	Hn
Long Beach	1921	7	2.7	1690	5545	>0.61	>2	31	12.0	1925-1967	
McKittrick	1898	6	2.3	360	1181	(?)					Hr
Midway-Sunset											
Central Area	1901	65	25.1	555	1821	>0.49	>1.6			1935-1965	
Globe Anticline	1912	15	5.8	1020	3346	>0.43	>1.41			1935-1965	
Sunset Area	1894	20	7.7	590	1936	>0.18	>0.59			1935-1965	
Paloma	1939	23	8.9	3800	12467	>0.07	>0.22			1957-1965	
Playa del Rey	1929	2	0.8	1520	4987	>0.29	>0.95			1925-1937	
Rio Vista (gas)	1936	98	37.8	1300	4265	>0.3	>0.98			1939-1964	
River Island (gas)	1950	18	6.9	1250	4101	>0.23	>0.75			1935-1964	
San Emidio Nose	1958	4	1.5	3900	12795	>0.06	>0.19			1935-1965	
Santa Fe Springs	1919	6	2.3	1300	4265	0.66	2.17	16	6.2	1927-1963	
Tejon, North	1957	10	3.9	2800	9186	>0.09	>0.29			1935-1965	
Torrance	1922	27	10.4	1230	4035	>0.1	0.32			1953-1960	
							2.1[12]			1945-1988	
Unnamed (Orange Co.)	1909	5	1.9	1480	4856	>0.05	>0.16			1959-1964	Hr
Wilmington	1932	29	11.2	1000	3281	>9	>29.00	>75	>29.0	1928-1966	
						>10[9]	>33[9]			1932-1998	
						>.7[10]	2.4[10]			1993 - 1996	
						.14[5]	0.46[5]			10/1993-10/1998	
Cimerick											
Belridge[4]	1911					>2.7	>9			during the mid 1980s	
North						>0.2[2]	>0.66[2]			5/26/21995 - 1/26/1996	
						>0.035[2]	>0.12[2]			4/21/1995 - 5/26/1995	
South						>0.2[2]	>0.66[2]			5/26/21995 - 1/26/1996	
						>0.035[2]	>0.12[2]			4/21/1995 - 5/26/1995	
						6.1[6]	20[6]			1911(implied) -1994	
Elk Hills											

Table A-1 (Continued) Subsidence Over Selected California Oil and Gas Fields.

Field	Discovery Year	Maximum Producing Area (km^2)	Maximum Producing Area (mi^2)	Median Depth of Production (m)	Median Depth of Production (ft)	Measured Subsidence					Surface Faults[b]
						Maximum[a] (m)	Maximum[a] (ft)	Area of Subsidence (km^2)	Area of Subsidence (mi^2)	Period of Measurement	
Lost Hills[2]	1910					>0.2	>0.65			5/26/21995 - 1/26/1996	
						>3.4[3]	>13[3]			1950-1991	
						3[14]	9.8[14]				
						>2[8]	>6.5[8]			1989-2001	
						0.15[13]	0.49[13]			11/5/1995 - 2/17/1996	
Beverly Hills[7]	1964	3.4	1.3	1615	5300	>0.01	>0.06			3/1967 - 3/1971	
						>0.01	>0.04			10/1972 - 10/1973	
						>0.05[5]	>0.18[5]			10/1993-10/1998	
Huntington Beach						>1.5[11]	5[11]			1920-1972	

note: Data from Yerkes and Castle, 1976 unless otherwise noted.

[a]significant digits depend on the value reported and on method of measurement

[b]Hn- high angle normal, Ln- low angle normal, Hr- high angle reverse

[1]in Hamilton and Meechan, 1971 citing unpublished data from Leps and Walley, undated

[2] Fielding and others, 1998

[3]inferred from estimated rates in Bruno and Boverg, 1992

[4]Bruno and Boverg, 1992

[5]Bawden, 2003

[6]Bondor and De Rouffignac, 1995

[7]Erickson, 1977

[8]Blom and others, 2006

[9]Hilbert and others, 1998

[10]E&B Natural Resources, 2012, citing written communication from Mike Henry, 2012

[11]estimated by Morton and others, 1976

[12]U. S. Corps of Engineers, 1990

[13]Xu and others, 2001

[14]Crippen, 2012