

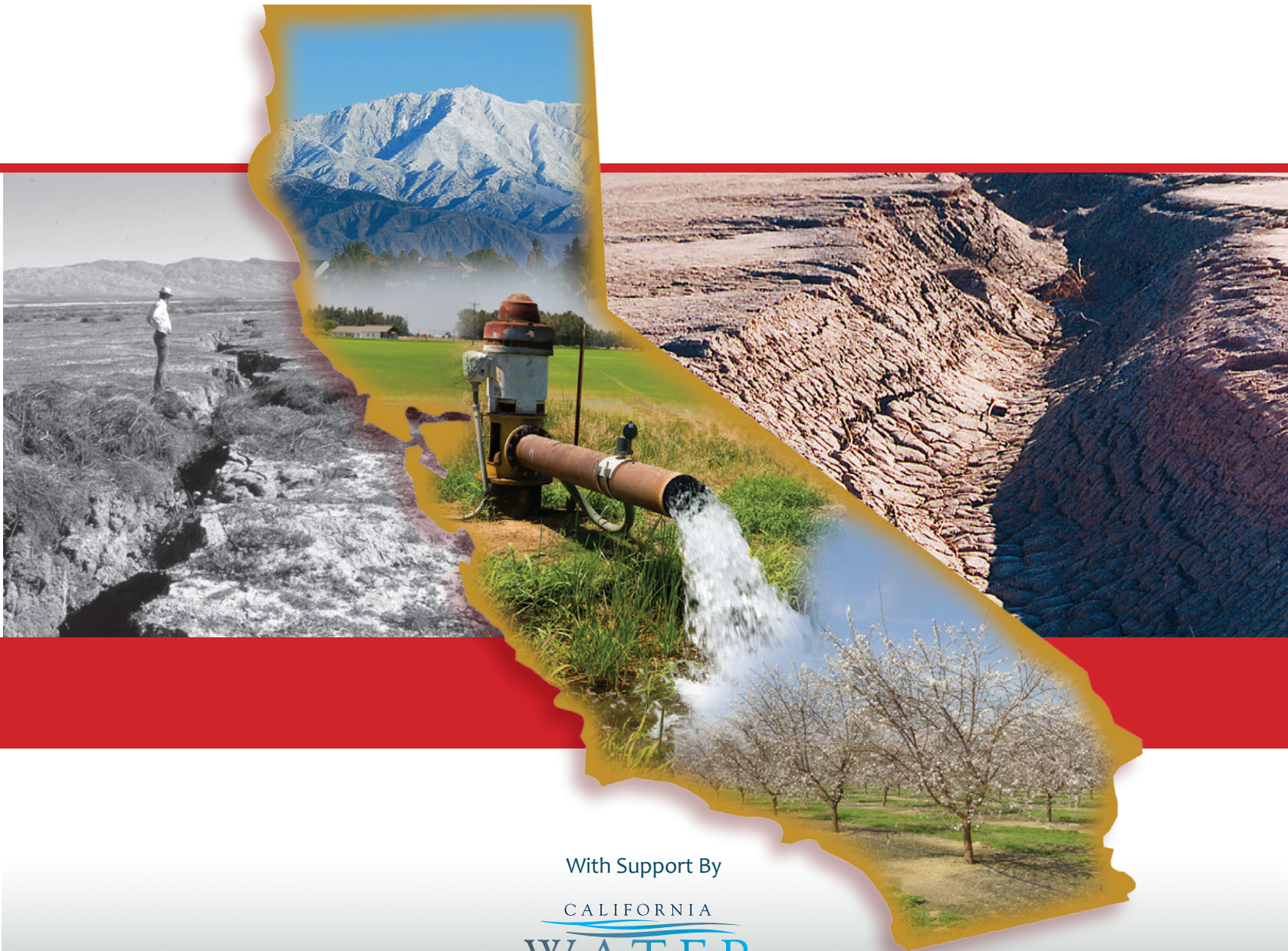
Summary Report / April 2014

Land Subsidence from Groundwater Use in California

Prepared By



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With Support By



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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>.



Land Subsidence from Groundwater Use in California

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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. 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. The purpose of this report is to summarize knowledge about the extent and costs of subsidence so that this information can be part of a larger discussion on sustainable groundwater management in California.

This report confirms that land subsidence in California is not just an 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.¹

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 1955 and 1970, to assist with the construction of the state and federal water projects. Funding for this program ended soon after completion of the state and federal water projects. The lack of comprehensive subsidence monitoring has had costly consequences for the state.

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;

¹ The full report can be found at: Luhdorff & Scalmanini, Consulting Engineers, James Borchers, and Michael Carpenter. 2014. *Report of Findings: Land Subsidence from Groundwater Use in California*.

- 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.

This report summarizes six major areas of subsidence in California. 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.

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 Water District essentially halted inelastic subsidence in the region by implementing a monitoring program, importing surface water, and artificially recharging groundwater. Groundwater pumpers report usage to the District. The District issues permits for wells and collects a groundwater production charge to recover those costs.

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 mi²—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 more than 4 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 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 and costs 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.

This report proposes the following recommendations to help California address the ongoing economic and environmental impacts associated with over extraction of groundwater and the resulting land surface subsidence.

- Monitor Land Surface Elevation Changes and Compaction
- Characterize Aquifer System and Monitor Groundwater Levels
- Collect, Store and Disseminate Subsidence and Groundwater Data
- Prioritize and Evaluate Subsiding Groundwater Basins

INTRODUCTION

As California contends with possibly the worst drought on record, the condition of the state's groundwater basins takes on increased importance. California's groundwater is a vital resource for urban, rural and agricultural water users, and for the health of aquatic ecosystems and biological habitats. Groundwater basins underlie 40 percent of California. In an average year, groundwater provides about 40 percent of the state's water supply; in drought years, it may provide 65 percent or more. In many basins, groundwater is the principal source of supply. Groundwater levels in some areas of California are declining past historical lows. Projected population increases, along with alteration of precipitation patterns due to climate change, will put added stress on groundwater resources in the state.

In an average year, groundwater provides about 40% of the state's water supply; in the current drought, it is expected to be 65% or more.

Historically in California, groundwater has been pumped as needed, often with little regard for the deleterious effects of over pumping. Chronically declining groundwater levels 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 for well deepening or replacement; streamflow depletion; environmental effects; and land subsidence. This report highlights issues and key findings related to land subsidence in California due to groundwater extraction^{2,3}

When groundwater pumping chronically exceeds recharge, a long-term decline of groundwater levels usually results. This can lead to inelastic compaction of the aquifer system, permanent subsidence of the land surface, and even 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
- damage to buildings, roadways, bridges, pipelines, canals, aqueducts, levees, sewerages, and wells; and
- increased sediment erosion or deposition and impairment of leveled agricultural fields

²The full report can be found at: Luhdorff & Scalmanini, Consulting Engineers, James Borchers, and Michael Carpenter. 2014. *Report of Findings: Land Subsidence from Groundwater Use in California*.

³References are contained in the full report.

As described below, significant subsidence has occurred historically in the San Joaquin Valley and elsewhere in California, creating substantial economic costs. Indeed, the cost of remediating subsidence in the San Joaquin Valley alone during 1955-1972 was estimated to be over \$1.3 billion in 2013 dollars not including the significant damage to canals, river levees, and flood channels. This is not merely a historical issue. Recent observations of subsidence in the San Joaquin Valley are unanticipated and alarming, and likely to continue unless changes occur. The purpose of this report is to summarize knowledge about the extent and costs of subsidence so that this information can be part of a larger discussion on sustainable groundwater management in California.

Recent observations of subsidence in the San Joaquin Valley are unanticipated and alarming, and likely to continue unless changes occur.

A review of published literature revealed that there is no single compilation of historical and active occurrences of subsidence in the state. Although this report is not an exhaustive detailing of every occurrence of groundwater extraction-related subsidence in California, it presents key examples of significant historical and active subsidence, including the impacts and costs. A more detailed inventory is presented in the full report (Luhdorff and Scalmanini Consulting Engineers, et al., 2014, [Report of Findings: Land Subsidence from Groundwater Use in California](#))

California lacks a coordinated statewide subsidence monitoring program, uniform monitoring and analysis procedures, and an accessible repository for subsidence-related data, which are essential to the assessment of subsidence. Furthermore, the state lacks funding to support technical synthesis and evaluation of data and remotely sensed imagery. Legislative and policy changes are needed to address this ongoing problem that has immense economic and environmental implications for the state of California.

The report is organized into the following sections: Section 1 explains subsidence processes related to groundwater extraction. Section 2 offers examples of subsidence as a result of groundwater extraction in California. Section 3 describes methods used to measure the magnitude of land subsidence and ground-surface deformation, and Section 4 presents recommendations related to subsidence monitoring and sustainable groundwater management.

1.0 GROUNDWATER EXTRACTION AND SUBSIDENCE

A balance occurs naturally in an undeveloped aquifer system where recharge and discharge of groundwater are equal. As seen in **Figure 1**, an aquifer system consists of layers of gravel, sand, silt, and clay deposited by streams and rivers or in lakes or wetlands. Coarse-grained materials

such as sand and gravel transmit water readily; fine-grained materials such as clay and silt impede the movement of water. Groundwater pumping changes the water balance of the aquifer system (Galloway et al., 1999), deforms the land surface and may create permanent land subsidence. In particular, when water is drained from clays, permanent subsidence will result because much of the water drained cannot be replaced. This permanent deformation, called inelastic or non-recoverable compaction, is responsible for permanent or non-recoverable land subsidence (Hoffmann et al, 2003) (**Figure 2**). Inelastic compaction occurs when the structure of the clays is compromised during compaction, such that it is unable to expand to its original thickness even when groundwater levels rise to pre-pumping levels.

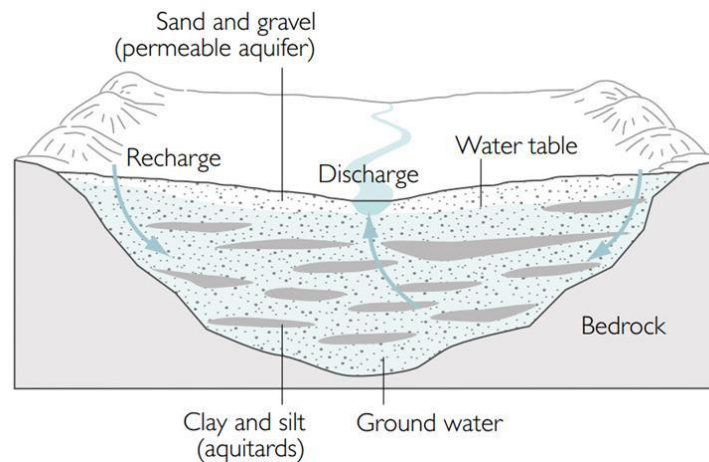


Figure 1. An undeveloped aquifer system in balance (adapted from Galloway et al., 1999)

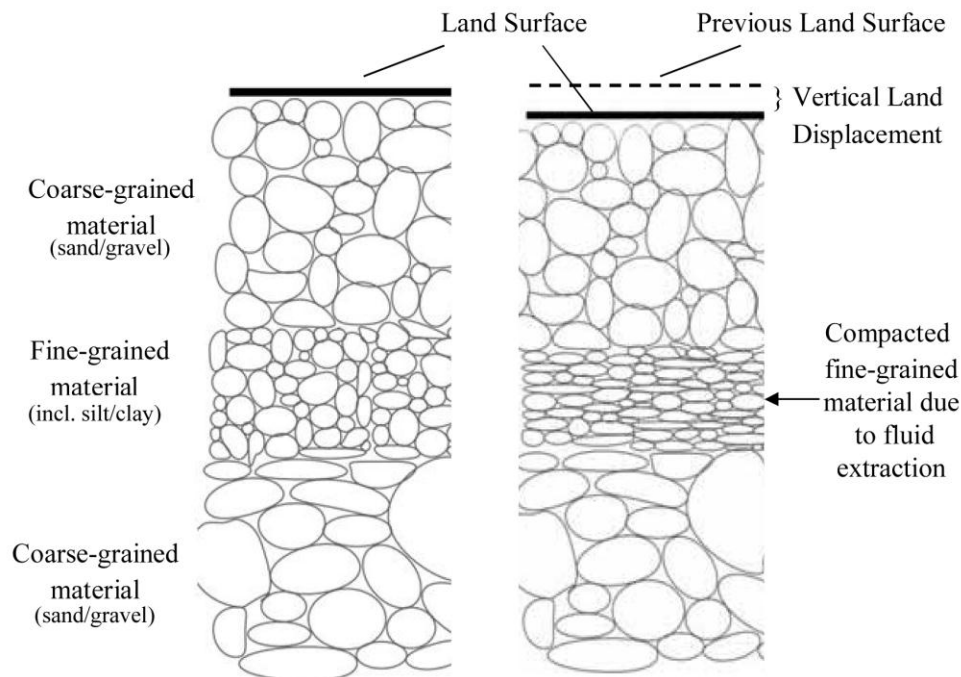


Figure 2. Land subsidence due to compaction of fine-grained material after fluid extraction (adapted from Sneed and Galloway, 2000).

Aquifer-system compaction caused by groundwater pumping and extensive water-level declines is responsible for most subsidence in California and has been observed for decades in the Santa Clara Valley, San Joaquin Valley, Sacramento Valley, Antelope Valley, and elsewhere.

The relative timing of changes in groundwater levels and aquifer-system compaction is complex. Residual compaction may continue long after water levels have stabilized in the aquifers. An example of this residual compaction is at Edwards Air Force Base in Antelope Valley, California, where the ongoing long-term effects of delayed yield from thick, slowly draining, clayey, confining units continues in response to large water-level declines that occurred between 1950 and 1975 (Sneed and Galloway, 2000).

Groundwater pumping is responsible for most subsidence in California.

In over-pumped, confined aquifer systems, water provided during inelastic compaction of clayey layers typically amounts to between 10 and 30 percent of the total volume of water pumped (Riley, 1969). Water of compaction is available

Subsidence may continue long after water levels have stabilized in the aquifers.

only once—usually beginning when the aquifer system experiences historically low water levels. 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 available only 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.

Water managers have to deal with long-term water supply and economic issues created by inelastic compaction of thick confining units. Inelastic compaction permanently reduces the amount of storage space for water in the aquifer system. 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. This occurs for two reasons—because 1) less water is stored in the aquifer system due to irreversible removal of water from now-collapsed clays and fine-grained materials, and 2) compaction during the first pumping cycle inhibits the ability of water to drain from confining units and clayey interbeds by decreasing their permeability⁴. Lowering water levels further, to produce the same volume of water initially retrieved, will induce additional inelastic compaction and land subsidence. 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.

2.0 EXAMPLES OF 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 deform the land surface, moving it up or down in response to expansion or compression of aquifer materials. Substantial and damaging subsidence from

⁴ Permeability is the ease with which water moves through a material. Sand and gravel have high permeability; clay has very low permeability.

groundwater extraction in California is nearly always related to inelastic compaction in an aquifer system, or to differences in the magnitude of compaction over short lateral distances.

In California, subsidence has resulted in expensive remediation to address loss of conveyance capacity in canals, streams and rivers, flood bypass channels, diminished levee effectiveness, and damage to roads, bridges, building foundations, pipelines, and other surface and subsurface infrastructure. Development of earth fissures has damaged surface and subsurface structures and also provided conduits for contamination at the land surface to enter shallow aquifers, degrading groundwater resources.

Subsidence is occurring today at nearly historically high rates (almost 1 ft/yr) in some areas. Even so, the location of all subsiding areas and the magnitude of subsidence throughout the state cannot be determined by reviewing published reports or databases because California does not have a coordinated statewide monitoring and reporting program for land subsidence. Therefore, instead of a comprehensive description of this statewide phenomena, the following sections provide examples pieced together from local or regional studies, some ongoing but mostly historical, that were conducted by state, federal, or local agencies after subsidence was discovered to have reached alarming proportion.

Summaries of such subsidence in the Santa Clara Valley, San Joaquin Valley, Sacramento Valley, Antelope Valley, Coachella Valley, and Mojave River Basin and vicinity follow. More information on each of these and other areas, as identified in **Figure 3**, is included in the full report (Luhdorff and Scalmanini Consulting Engineers, et al., 2014, [Report of Findings: Land Subsidence from Groundwater Use in California](#)).



X:\2013 Job Files\13-007\GIS\map files\2014\02\Figure 4-1 Location of known subsidence_v6.mxd

Figure 3. Areas of subsidence caused by groundwater extraction in California. (Historic subsidence occurred before 1993.)

2.1 Santa Clara Valley

The northern Santa Clara Valley, an alluvial lowland at the south 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 substantial inelastic subsidence caused by massive withdrawals of groundwater that supplied water first for agricultural development and later primarily for domestic and industrial uses.

Agriculture in this region developed rapidly in the early 1900s; two thirds of the valley was irrigated by 1920. Subsidence was first

Between 1910 and 1995, downtown San Jose subsided by 14 feet.

noted in 1933, when bench marks installed in 1912 were found to have subsided more than 3 feet (Fowler, 1981)⁵. Between 1910 and 1995, subsidence was greatest (14 feet) in downtown San Jose, and about 100 mi² of land had subsided by more than one foot. As a result, the Santa Clara Valley Water District (SCVWD) now manages the aquifer system within tight water-level and subsidence tolerances designed to prevent the reoccurrence of land subsidence.

Aquifer compaction that occurred in the Santa Clara Valley was inelastic, and land subsidence is permanent. The importation of surface water, construction of artificial groundwater recharge facilities, comprehensive subsidence monitoring networks, and efficient and coordinated management of groundwater and surface-water supplies by a single water purveyor (the SCVWD), allowed groundwater levels to return nearly to predevelopment levels in the Santa Clara Valley and essentially stopped inelastic subsidence by 1969-1970.

The estimated cost of subsidence remediation in the Santa Clara Valley translates to more than \$756 million in 2013 dollars.

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 19 mi² of the Santa Clara Valley would be under water. The growing threat of flooding likely spurred initial recognition of the subsidence issues.

⁵Units are provided in metric and English in the full report; for simplicity the Summary Report includes only English units.

Roll (1967), Viets and others (1979), and Fowler (1981) estimated the direct costs of subsidence remediation activities in the Santa Clara Valley, including repairing water wells damaged or destroyed during 1960-1965, building and operation of sanitary and storm sewers and pumping stations where waste fluids no longer flowed easily by gravity, building bayfront dikes and stream channel levees to prevent flooding, and raising bridges and roads. Translated to 2013 dollars, these costs totaled \$756 million. Additional costs included replacing destroyed wells or repairing wells at times other than 1960-1965, raising 50 miles of levees protecting 30 mi² of privately owned salt evaporation ponds, de-silting stream channels in flood-prone areas, repairing flood damaged roads, moving flooded railroad tracks, or property values lost by flood zone designation or levee-obstructed views.

Although subsidence has been halted in the Santa Clara Valley, considerable effort and expense are expended annually to deal with its legacy. Strict subsidence monitoring programs assure that these continuing investments are not wasted.

2.2 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.

Land subsidence from groundwater extraction in the San Joaquin Valley has been called the greatest human alteration of the Earth's surface.

Agriculture in the San Joaquin Valley developed a reliance on the aquifer system because the region is semi-arid; streamflow into the east side of the valley varies substantially from year to year and is mostly not available on the west side. More than half of the thickness of the aquifer system in the valley 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.

Subsidence related to groundwater withdrawal in the valley began in the mid-1920s and increased as agricultural development intensified after World War II. Subsidence rates eventually exceeded 1 ft/yr in some places. Eventually groundwater levels in the deep aquifer system on the west side of the valley declined by more than 400 feet. By 1970, subsidence of more than 1 foot had affected 5,200 mi²—more than half of the valley—and subsidence southwest of Mendota exceeded 28 feet (Poland et al., 1975) (**Figure 4**).

Despite early recognition of the relation between groundwater-level decline and subsidence near Delano (Ingerson, 1940), subsidence from groundwater overdraft was not investigated regionally until the early 1950s, when government agencies became concerned about a 30 percent reduction

Figure 4. Joseph Poland standing near a pole depicting more than 29 feet of land subsidence between 1925 and 1977 in the San Joaquin Valley southwest of Mendota (Ireland and others, 1984).



in the design capacity of the San Joaquin River, about the effect of subsidence on the Delta-Mendota Canal which was under construction, and on the California Aqueduct which was 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.

By 1970, subsidence of more than 1 foot had affected 5,200 mi²—more than half of the valley—and subsidence southwest of Mendota had exceeded 28 feet.

In 1954, a Federal-State interagency committee and the United States Geological Survey (USGS) “Mechanics of Aquifers Project” 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, and developed new monitoring methods and techniques for analysis of field data that allowed accurate computer models of aquifer system compaction to be built. This 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. Imported surface water decreased reliance on the aquifer system. Groundwater levels recovered more than 200 feet in some areas. Subsidence slowed and eventually stopped, reoccurring during subsequent droughts and regulatory reductions in surface water diversions.

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. The California Department of Water Resources (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 analysis of this information has not been coordinated.

2.2.1 Historical Subsidence in the San Joaquin Valley

Specific instances and costs of historical subsidence in the San Joaquin Valley include the following:

- Delta-Mendota Canal—Repairs to submerged canal service turnouts, drain inlets, bridges, pipelines, check structures, embankments and concrete linings. Subsidence has impacted about 30 miles of the Delta-Mendota Canal upstream from its terminus at Mendota Pool by submerging canal service turnouts, drain inlets, bridges, pipelines, and check structures used to control water surface elevation in the canal, and by overtopping the concrete lining of the canal, reducing embankment freeboard, and flow capacity (**Figure 5C**). The United States Bureau of Reclamation (USBR) raised embankments and bridges, and relocated pipeline crossings, and they and the San Luis Delta Mendota Water Authority made other repairs and modifications. Using 1977 as the base year for these repairs, the cost of USBR repairs in 2013 dollars is conservatively estimated as \$30 million. (Prokopovich (1969, 1973, and 1986), Prokopovich and Herbert (1968) and Prokopovich and Marriot (1983))
- Outside Canal—Costs to raise embankments, bridges, turnouts, and weirs. Expensive physical infrastructure problems have been caused by land subsidence in the Mendota area. The flow capacity of the Central California Irrigation District's Outside Canal has been reduced 45 percent at the partly submerged Russell Avenue bridge (**Figure 6**). Embankments were raised on the Outside Canal in 1971 and 1994, and improvements are still continuing. Total costs for subsidence remediation on the Outside Canal are expected to exceed more than \$8.2 million.
- Friant-Kern Canal—Repairs to canal berms, pumping plants, bridges, concrete linings, canal turnouts, drains, and inlets. About 30 miles of the Friant-Kern Canal were impacted by subsidence in the Tulare-Wasco area. Between the date construction was completed in 1951, and January 1975, parts of the affected reach of the canal subsided 5.5 feet, interfering with operational activities (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 16.67 mile reach of the canal was rehabilitated. Canal berm materials were excavated and re-compacted, concrete linings

were extended upward, bridges were raised, 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).

- San Luis Canal—Raising of canal linings, bridges, and other canal structures, as well as the rehabilitation of roads. The San Luis Canal, a jointly used feature of the federal Central Valley Project and the California State Water Project that was completed in 1968, has been affected by subsidence along 85 miles 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 due to groundwater extraction had adversely affected the earlier-built Delta-Mendota Canal, designers incorporated as much as 10 feet of extra freeboard into the San Luis Canal, adding \$30.7 million (2013 dollars) to construction costs. Additional subsidence required additional raising of canal linings, bridges, and other canal structures and rehabilitation of roads at costs of \$1.6 million, \$4.7 million, and \$4.5 million, respectively, during 1982, 1983, and 1984 (Prokopovich and Marriot, 1983). Adjusting for inflation, these costs amounted to \$55.7 million in 2013 dollars. Total construction costs to account for subsidence were \$86.4 million.

The total cost to the government to account for or repair subsidence damage to major public canals and drains in the San Joaquin Valley was \$133.86 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.

In addition to these costs to the government, additional costs such as well replacement were borne by farmers and irrigation districts. According to Wilson

The [direct] cost of subsidence in the San Joaquin Valley during 1955-1972 was estimated to be more than \$1.3 billion in 2013 dollars.

(1968), 275 wells were reported with failed casings due to subsidence-induced damage in the 618 mi² region of maximum subsidence in the valley during 1950-1961. Current costs to replace an 18-in diameter agricultural well average \$200-\$250 per foot (Scott Lewis, Luhdorff and Scalmanini Consulting Engineers, oral comm. November 20, 2013). A conservative cost estimate to replace these wells, assuming each well is about 1,600 feet deep, is \$90 million dollars (2013 dollars).

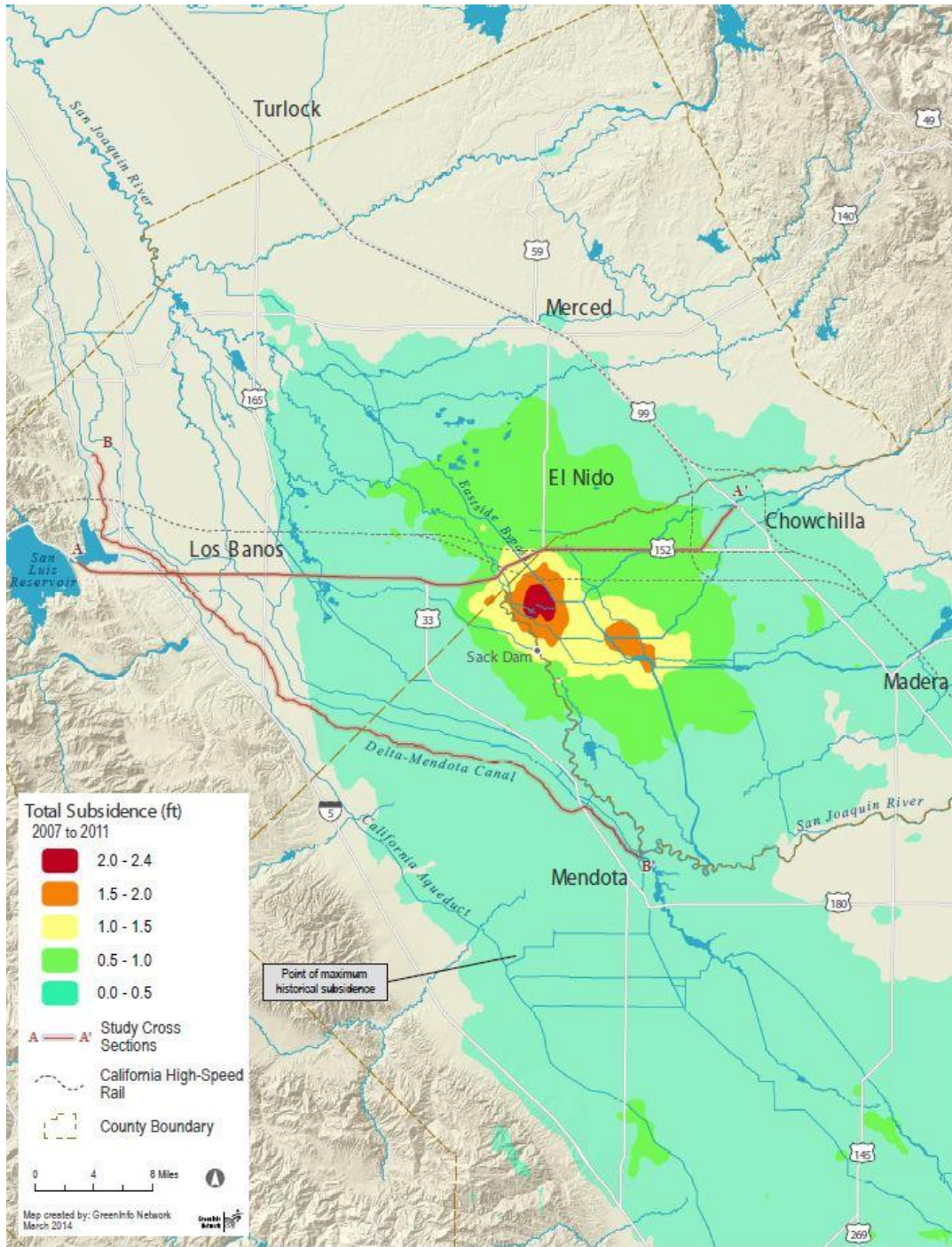


Figure 5. A) Recent subsidence in the central San Joaquin Valley near El Nido between January 2007 and March 2011. Cross sections A-A' and B-B' are shown in Figures 5B and 5C, respectively. (InSAR derived subsidence data were provided as preliminary unpublished data courtesy of NASA-JPL).

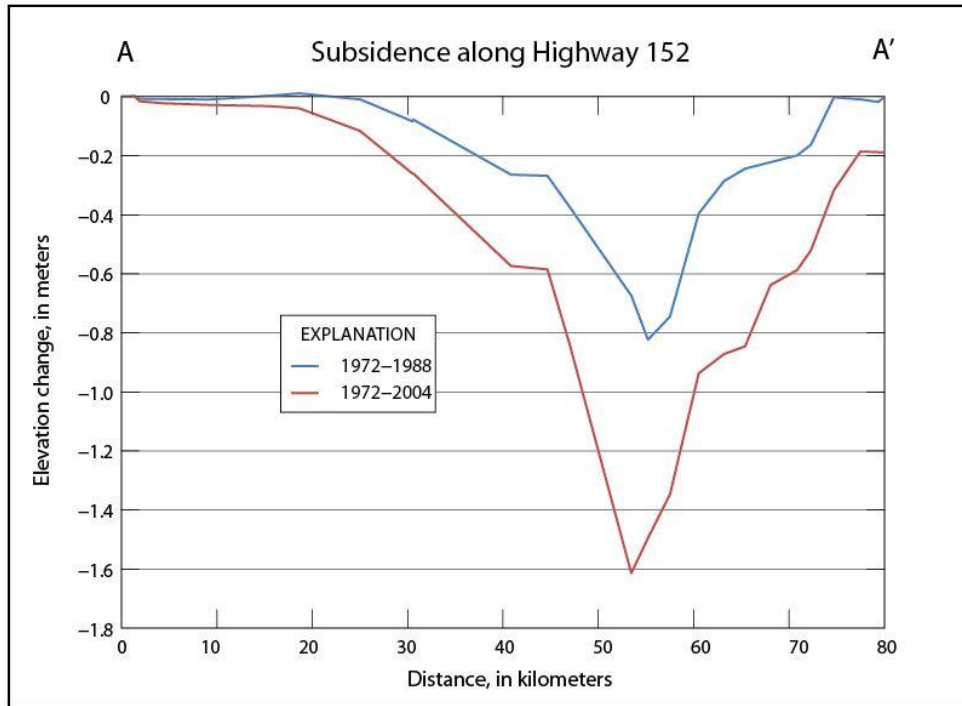


Figure 5. B) Elevation changes between 1972 and 2004 computed from repeat geodetic surveys along Highway 152. (Modified from Sneed et al., 2013, Fig. 17).

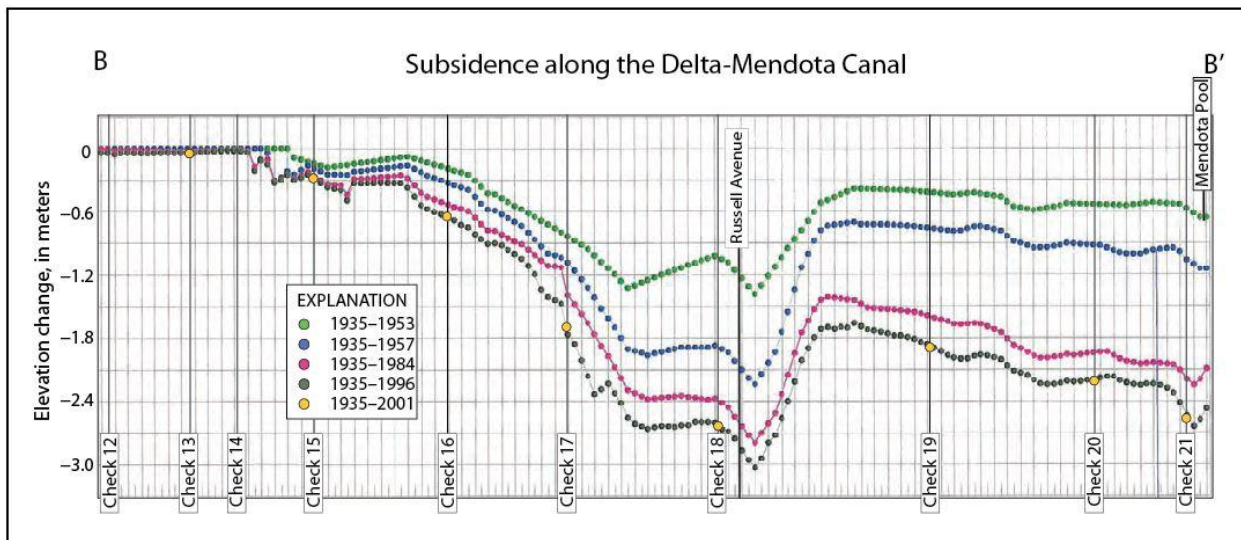


Figure 5. C) Elevation changes between 1935 and 2001 along the Delta-Mendota Canal (modified from Sneed et al., 2013, Fig. 17).



Figure 6. The partly submerged Russell Avenue bridge over the Outside Canal north of Mendota, California. Before subsidence, canal inspections by Central California Irrigation District staff were conducted from a boat passing under the bridge.

When costs of lost property value due to condemnation, re-grading irrigated land, and replacement of irrigation pipelines and wells in subsiding areas are considered, the economic cost of subsidence in the San Joaquin Valley was estimated to be \$1.3 billion in 2013 dollars during 1955-1972 (Gilbert Bertoldi, USGS (ret.), written commun., November 29, 2013). No estimates of the indirect costs of land subsidence, such as flooding and long-term environmental effects, have been made. Costs to repair canals also are not included in Bertoldi's estimates.

2.2.2 Current Subsidence in the San Joaquin Valley

The current drought and changes to cropping patterns from row crops and rangeland to tree and other permanent crops have again forced reliance on aquifer systems in the San Joaquin Valley for agricultural irrigation

Recent InSAR analyses show two large areas in the San Joaquin Valley currently subsiding substantially.

supplies. Recent Interferometric Synthetic Aperture Radar (InSAR) analyses show that two large areas (**Figure 7**) in the San Joaquin Valley are currently subsiding substantially (Thomas Farr,

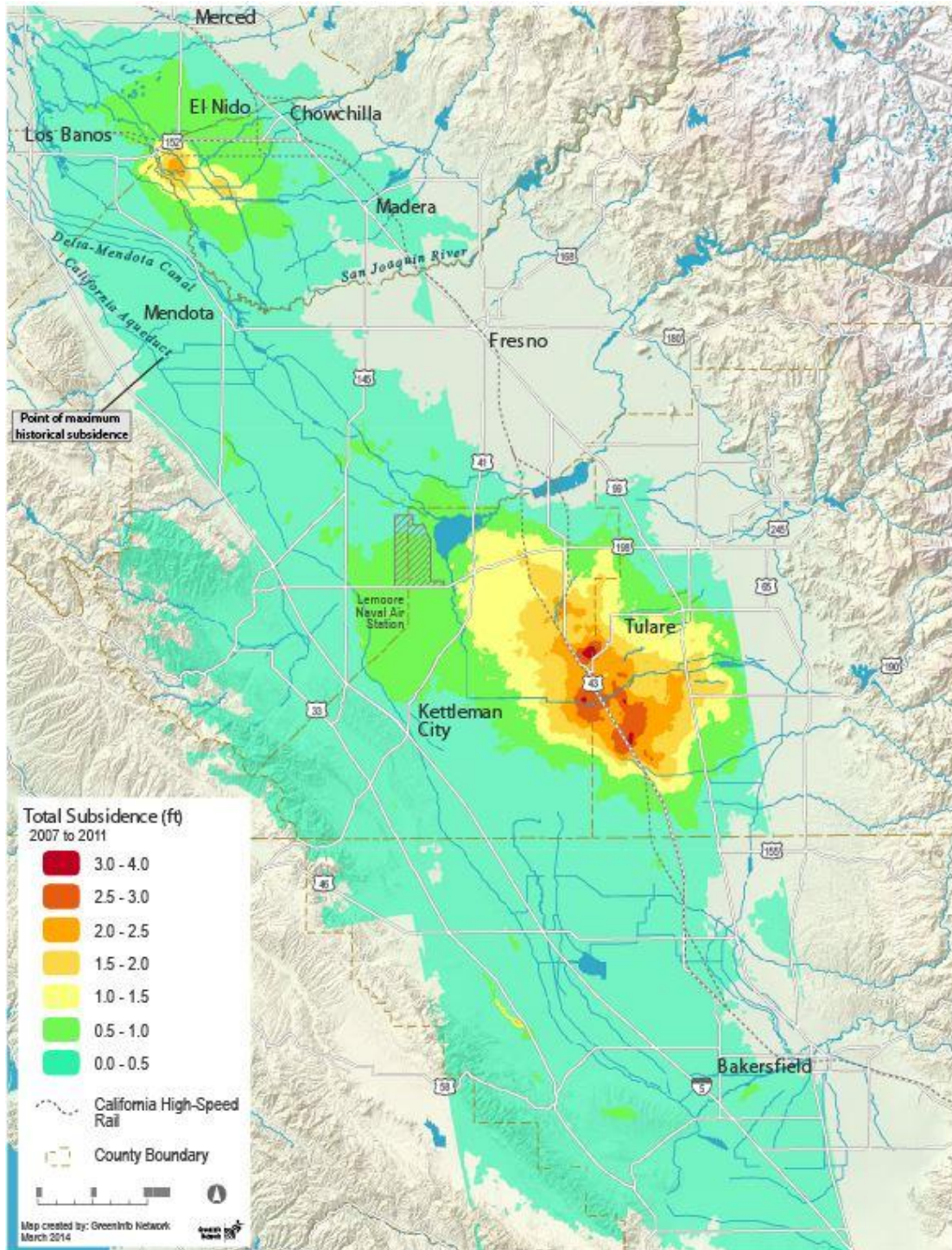


Figure 7. Recent subsidence in the central and southern San Joaquin Valley. Subsidence in the southern subsidence bowl is during 2007-2010, and in the northern subsidence bowl during 2007-2011. Recently subsiding areas are distant from the point of maximum historical subsidence during 1926-1970. (InSAR derived subsidence data were provided as preliminary unpublished data courtesy of NASA-JPL).

NASA-JPL, written communication, September, 2013; Jessica Reeves, Stanford University, written commun., July 9, 2013; Sneed et al, 2013). These areas are a 1,200 mi² subsidence bowl near El Nido (south of Merced, and west of Madera) and a larger bowl, about 2,700 mi², west of Tulare and east of Kettleman City (**Figure 7**). Currently subsiding areas shown on **Figure 7** are shifted substantially from the locales of major subsidence during 1926-1970. Studies and planning efforts associated with the San Joaquin River Restoration Program have made much more information available in the northern subsidence bowl than in the southern bowl to describe specific instances of infrastructure problems related to current subsidence in the San Joaquin Valley. These include:

The northern subsidence bowl: El Nido (**Figures 5, 7**). Subsidence rates in the El Nido area are currently about 20 times the rate of average historical subsidence in this area. The U. S. Army Corps of Engineers (USACE) predicts that 17 feet of subsidence will occur in the northern subsidence bowl during 2000-2060.

Subsidence rates in the central San Joaquin (El Nido) area are currently about 20 times the rate of historical subsidence in this area.

- Sack Dam—Design and construction challenges. Surveys by DWR contractors found 0.6 feet of subsidence near the Sack Dam during 2008-2010. InSAR analysis by NASA-JPL during 2007-2011 determined that more than 1 foot of subsidence had occurred near the Sack Dam. Surveying by the USBR associated with redesign of the Sack Dam as part of the San Joaquin River Restoration Program determined that subsidence near the dam continued at a rate of about 0.5 ft/yr during 2011-2013. These discoveries halted planned construction and design efforts for the \$25 million project, as agencies considered how to adapt to the lowered land surface and prepare for likely continued subsidence.
- San Joaquin River—Reduction in flow capacity. Results of InSAR analysis and surveying showed at least 1.8 feet of subsidence near the San Joaquin River between 2008 and 2010. Subsidence causes flow channels to sag, erosion at the upstream end of the sag and sediment deposition in the sagged area. Subsidence likely has reduced the flow capacity of the San Joaquin River west of El Nido to less than half its design capacity of 1,500 ft³/s (Reggie Hill, Lower San Joaquin Levee District (LSJLD), oral commun., December 11, 2013).
- Eastside Bypass—Reduction in levee freeboard, reduction in flow capacity, increased extent of flooding. InSAR analysis and surveying show 1.8 feet of subsidence near the Eastside Bypass during 2008-2010. In 2008 the flow capacity of one reach of the bypass was 5,000 ft³/s lower than the designed capacity, 17,500 ft³/s. Modeling studies by DWR

predict that subsidence continuing at current rates will reduce levee freeboard by an additional 1.5 feet between 2011 and 2016 reducing the flow capacity of this reach to 10,000 ft³/s. The USACE predicts that a flood breaching the west levee, which had subsided more than the east levee, would inundate at least 32 mi² and possibly as much as 170 mi² west from the bypass.

- Highway 152—Surveying by California Department of Transportation (Caltrans) indicates that Highway 152 has subsided about 5.3 feet during 1972-2004 (**Figure 5B**). The highway likely continues to subside along with all other surface infrastructure in this subsidence bowl.
- California High Speed Rail (CHSR)—Initial alignment of the Merced to San Jose section of the planned CHSR indicates that the currently planned alternative routes pass through parts of the northern subsidence bowl and that the southernmost route of the rail line traverses the northern edge of the area of maximum subsidence and greatest rate of subsidence south from Highway 152 (**Figure 5A, 7**).

The southern subsidence bowl: Tulare-Kettleman City (**Figure 7**). Maximum subsidence during 2007-2011 was 3.9 feet. The rate of subsidence in this area is similar to and in some places greater than that of the northern subsidence bowl and extends much more broadly throughout the San Joaquin Valley. The maximum rate of subsidence here is about twice the maximum rate that occurred historically in the area. Current known effects include:

- Highway 198—Caltrans surveying along Highway 198 (**Figure 8**) shows that the road subsided 9.37 feet during 1900s-2004. The highway passes through the northern edge of the subsidence bowl and so the survey data do not fully capture the maximum subsidence in this region. Subsidence studies at the Lemoore Naval Air Station (Corbett and others, 2011) indicate that total subsidence there between 1925 and 2010 exceeded 10 feet—considerably more than the Caltrans survey showed during the 1960s-2004 (3.5-4.0 feet).
- Canals—flow capacity has been reduced in many canals in the area and canal check structures in sagging canals have been rendered marginally useful.
- California High Speed Rail—the proposed alignment of the main north to south line of the CHSR runs directly through the subsidence bowl.

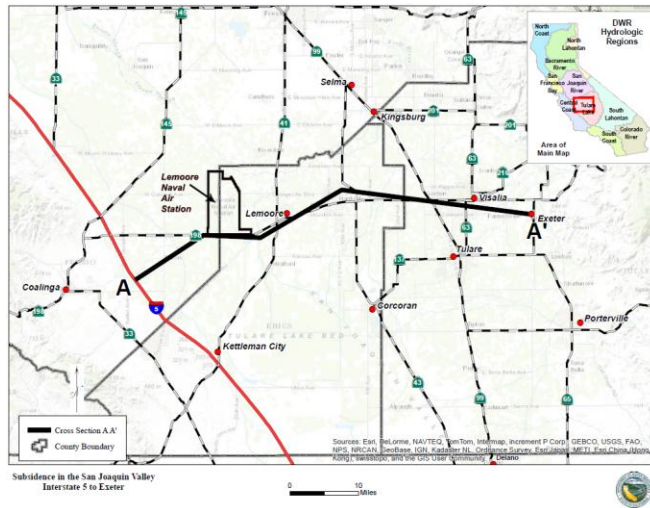


Figure 8. A) Location of Caltrans surveying profile along Highway 198 in the southern San Joaquin Valley, and Lemoore Naval Air Station. (Courtesy of California Department of Water Resources.)

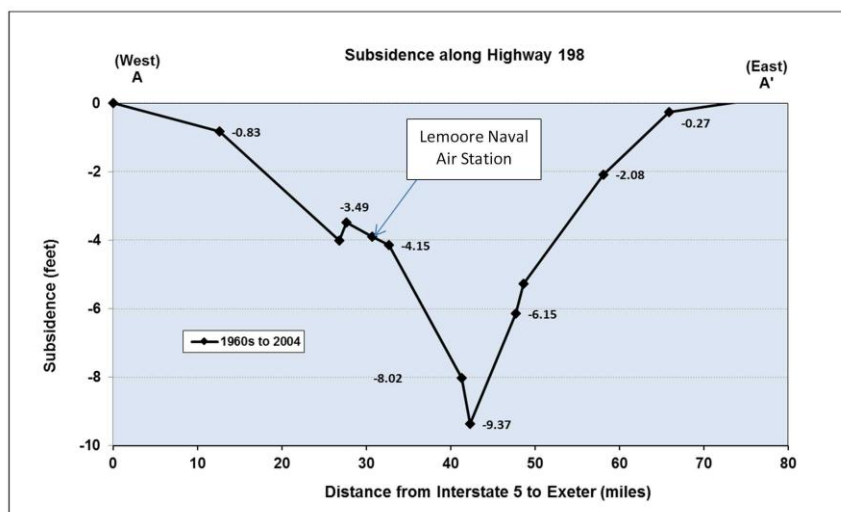


Figure 8. B) Elevation changes between the 1960s and 2004 computed from repeat geodetic surveys along Highway 198. (Courtesy of California Department of Water Resources.)

Water districts, ranchers, and others are dealing with subsidence impacts 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 subsidence in the area would be unknown. Much infrastructure in both the northern and southern subsidence bowls 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 of the CHSR to accommodate potential future subsidence.

2.3 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 National Geodetic Survey (NGS) between 1935 and 1964. Land-surface profiles based on these data showed apparent land subsidence of more than 2 feet along a level line between Zamora and Knights Landing in northern Yolo County; more than 1.0 foot near Arbuckle in southern Colusa County; and more than 1.5 feet in central Yolo County between Zamora and Davis (Lofgren and Ireland, 1973). The area of greatest subsidence is south of the terminus of the Tehama Colusa Canal, where agriculture developed relying solely on groundwater for irrigation.

The magnitude of permanent land subsidence observed throughout the southwestern Sacramento Valley indicates that groundwater levels have dropped below the water level at which inelastic compaction of aquifer sediments is triggered. An early evaluation of video logs from 317 water wells and water-level data 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). 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.

Damaged wells are located in central Colusa County, through Yolo County, to Dixon in Solano County. However, the Yolo County Global Positioning System (GPS) network was surveyed later than the period when most wells were damaged (1976-1977) and does not extend into the adjacent counties, so it cannot identify the extent of subsidence regionally. 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.

2.4 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

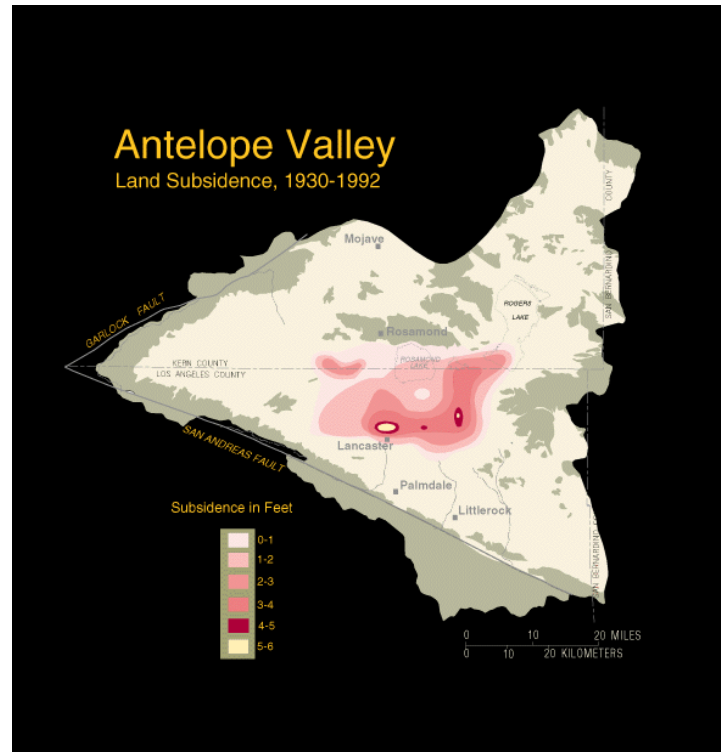
At Edwards Air Force Base, subsidence caused sink-like depressions and earth fissures on the surface of Rogers Lake bed, adversely affecting the runways on the lake bed that are used for landing aircraft.

1977 and 2010, extensive pumping contributed to groundwater level declines of as much as 300 feet since the 1930s. 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 6.6 feet at Lancaster and more than 3 feet at the south edge of Rogers Lake resulted from groundwater pumping that vastly exceeded recharge to the aquifer system (**Figure 9**). A 1,969 feet long by 7.5 feet deep fissure located about 6.8 miles east-northeast from Lancaster was attributed to historical water-level declines of 245 feet that had occurred prior to its appearance in 1978. At Edwards Air Force Base (EAFB) groundwater levels declined 150 feet between 1915 and 1991.

At EAFB, subsidence caused sink-like depressions, polygonal cracks, and large earth fissures on the playa surface of Rogers Lake bed, adversely affecting the runways on the lake bed that are used for landing aircraft. Numerical modeling also indicated that due to the thickness and low permeability of clayey confining units, only half the ultimate compaction would occur during the 30 years subsequent to the modeling. Residual inelastic compaction measured during winter periods in the 1990s is partly caused by the ongoing long-term effects of delayed yield from thick, slowly draining confining units still responding to large water-level declines between 1950 and 1975. Residual compaction and land subsidence from slowly draining confining units and clayey interbeds is a legacy of groundwater mining and must be carefully considered in long-term management of land and water resources at EAFB and elsewhere in the Antelope Valley.

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. 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, with local agencies, studied the feasibility of direct well injection through existing production wells and developed a simulation/optimization model

Figure 9. Land subsidence in Antelope Valley between 1930 and 1992 (modified by Galloway et al., 1998 from Ikehara and Phillips, 1994).



to help evaluate the effectiveness of an injection program for halting the decline of groundwater levels and avoiding future land subsidence while meeting increasing groundwater demand.

2.5 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 1948, a large earth fissure formed in the La Quinta area. 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 renewed land subsidence in the Coachella Valley (Sneed, USGS, oral communication, May 30, 2013).

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. InSAR measurements made between June 27, 1995 and September 19, 2010 indicate that land subsidence ranging from 0.72 to 1.97 feet occurred near Palm Desert, Indian Wells, and La Quinta (**Figure 10**). Average subsidence rates in Palm Desert were relatively stable, increasing

from 0.13 ft/yr during 1995-2000 to about 0.15 ft/yr during 2003-2010. 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 miles of the Coachella Branch of the All American Canal showed that the canal had subsided as much as 1.35 feet 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 one area of the valley. In the southwestern part of the valley, 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 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 and conservation efforts.

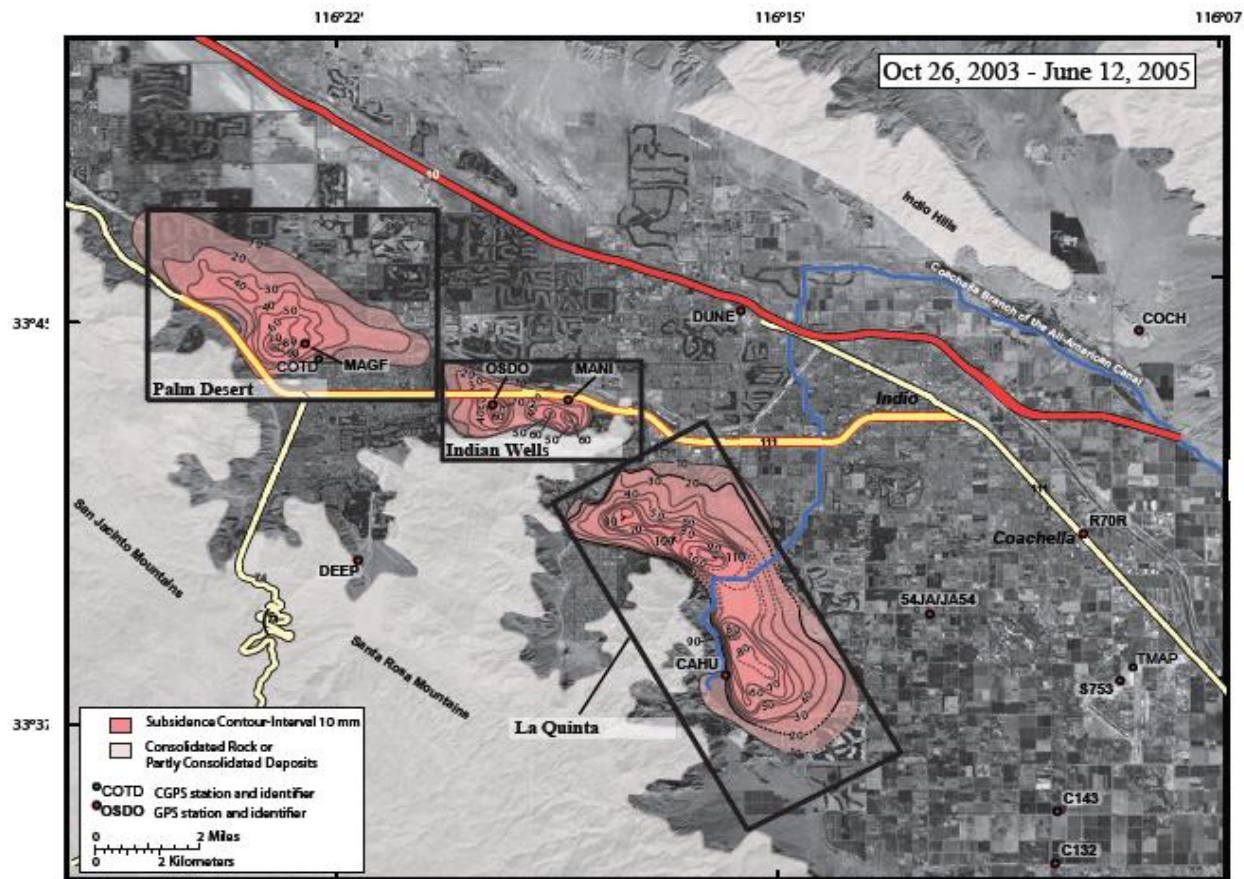


Figure 10. Areas of subsidence between 2003 and 2005 in the western Coachella Valley as shown by subsidence contours interpreted from InSAR (modified from Sneed and Brandt, 2013, Fig. 8).

2.6 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

Unplanned and unmonitored development of groundwater in desert basins areas has produced land subsidence.

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 deformation 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 at the southern terminus of the Sierra Nevada and just north from Antelope Valley, contains an aquifer system composed of as much as 900 feet of sedimentary materials (Holzer, 1984). Prior to 1920, wells in the valley center flowed⁶; by 1977, water levels in the central part of the valley had declined as much as 243 feet, primarily in response to increased irrigation pumpage (Holzer, 1984). Subsidence caused by groundwater withdrawal was documented by Pampeyan and others (1988). Subsidence has tilted the Koehn Lake playa surface so that when surface water ponds on the playa during storms, it also floods the area southwest of the playa where subsidence is centralized. Large earth fissures (**Figure 11**) also formed in the Fremont Valley (Holzer and Galloway, 2005).

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 82 feet by 2009 and contributed to 0.9 feet of land subsidence during 1993-2006.

Concerns related to the potential for new or renewed land subsidence and fissuring prompted the Mojave Water Agency (MWA) to contact the USGS to assess land subsidence. The USGS established a geodetic network of monuments to monitor land subsidence in the Lucerne Valley using GPS and prepared spatially detailed maps using InSAR to determine changes in vertical land-surface elevation for the parts of the Mojave River and Morongo groundwater basin that are managed by MWA.

Groundwater levels in the Lucerne Valley, in the Mojave River watershed east of Victorville, California, have declined as much as 100 feet since the 1950s. A GPS survey in 1998 indicated that as much as 2 feet of land subsidence may have occurred since topographic maps were made in 1969 and 1975 (Sneed et al., 2003). InSAR analysis indicated that the land surface southeast of the Lucerne Lake playa subsided about 0.3 feet between April 24, 1992 and November 8, 1999 near where groundwater levels had declined 100 feet by the early 1990s. Earth fissures more than 3 feet in width and depth trend northeast-southwest across the southern playa (**Figure 12**) (Sneed et al., 2003a).

In 2002, an agreement settled the longstanding issues associated with adjudication of water in the Mojave River Basin area, establishing thresholds for pumping that helped to reduce groundwater overdraft. To mitigate subsidence and other effects of overdraft in the Mojave River Basin, the MWA is using imported California State Water Project (SWP) water for artificial recharge by

⁶ The term ‘flowing well’ indicates that the water levels in the well are above the ground surface.

surface spreading. Adjudication, court ordered specification of rights of groundwater withdrawal, is perhaps the last option available to ensure sustainability of water supplies when other options have not been successful.

Figure 11. Earth fissure associated with land subsidence caused by groundwater pumping in Fremont Valley, California, March 1978 (from Holzer and Galloway, 2005).



Figure 12. 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)



3.0 MEASURING AND MONITORING LAND SUBSIDENCE

Alarming rates of subsidence recently have been measured in several areas of California. This information has been reported only after the impacts from subsidence have occurred—

There is no state or federal agency in California that has the specific responsibility to monitor land subsidence.

emphasizing the need for increased monitoring. There is no state or federal agency in California that has the responsibility, or a 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 geared for long-term monitoring, but rather operate for a project-specific period of time, usually implemented in reaction to a subsidence crisis that has damaged essential infrastructure.

There are 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. 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.

Viable methods for measuring and monitoring subsidence are briefly discussed below; additional information is included in the full report (Luhdorff and Scalmanini Consulting Engineers, et al., 2014, [Report of Findings: Land Subsidence from Groundwater Use in California](#)).

3.1 Surveying and the Global Positioning System

Historically, spirit-level surveys⁷ were used to measure changes in land-surface elevation of bench marks. 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. 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).

There are more than 800 CGPS sites in California. These sites are unmanned and receive data from GPS and sometimes other navigation satellite systems. 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 the data

⁷ Spirit-level surveys involve measuring the vertical difference between more than two locations, usually compared to each other and to a known elevation at a benchmark.

are available via the Internet. CGPS sites are used as components of land deformation monitoring networks that primarily show the horizontal movement of tectonic plates. Because very few CGPS were installed with the intent to monitor land subsidence, few are optimally located for that purpose.

Although they own and operate only one CGPS site in California, the NGS archives and provides on their website for x, y, and z coordinates as well as time-series data for approximately 284 CGPS sites in California (**Figure 13**) that were constructed and are operated by other agencies or consortia. These sites form the Continuously Operating Reference Station (CORS) network of the NGS. The CORS network data add much-needed insight into the daily, seasonal, and climatic variations of land surface elevations, which can be related to groundwater levels and extraction.

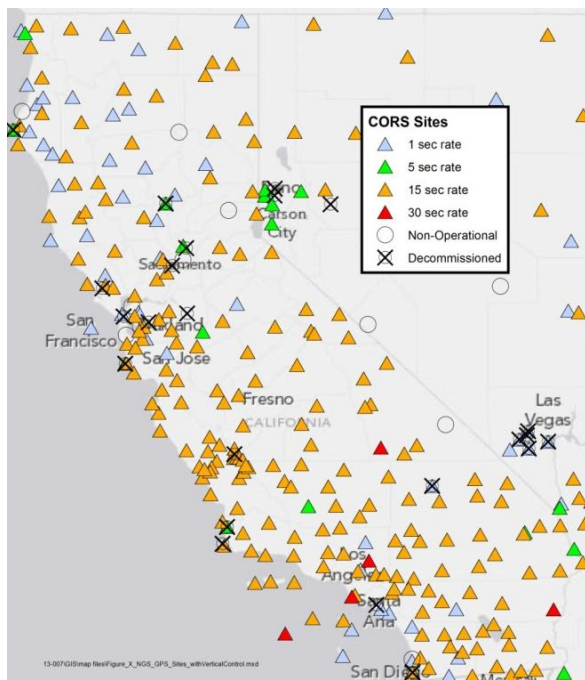


Figure 13. Continuously Operating Reference Station (CORS) Network, retrieved from NGS September 16, 2013.

3.2 Satellite Synthetic Aperture Radar Interferometry (InSAR)

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

InSAR provides more detailed subsidence information over larger areas than can be measured by any other known technique.

measurement resolution. InSAR can provide more 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, analyzing long-term 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 United States does not have a civilian SAR satellite, so presently data must be purchased from international sources (e.g., Canada, Germany, Italy, Japan, and Europe).

Under ideal conditions InSAR can detect surface deformation of less than half an inch over hundreds of square miles, at a spatial resolution of 295 feet or better (Sneed et al., 2013). Radar signals generated from a satellite are bounced off stable radar reflectors on the Earth's surface, such as 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. Subtracting, or interfering, the data collected by a satellite passing over the Earth at different times provides the information needed to prepare interferograms and interpret subsidence magnitude.

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 provided invaluable tools for remotely assessing large areas with a high degree of measurement resolution, especially in California. InSAR techniques must be integrated with ground-based geodetic surveying for ground-truthing and to provide continuity of subsidence monitoring during periods when conditions are unsuitable for InSAR or when satellites are inoperable.

3.3 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 it 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 0.39 inches. Airborne LiDAR has been of invaluable assistance 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 the land surface.

3.4 Borehole Extensometers

Borehole extensometers measure the continuous change in vertical distance between the land surface and a subsurface reference point, usually the bottom of a well (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. Pipe and steel-cable extensometers are most common and have been used extensively in California. 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, such as hydrocarbon extraction, are also contributing to land subsidence. Extensometers must be paired with several, short-screened, water-level monitoring wells, called piezometers, to detect the onset of inelastic compaction for management purposes and to calculate important mechanical and hydraulic properties of the aquifer system.

4.0 RECOMMENDATIONS

The following summary recommendations are provided to help California address the ongoing economic and environmental impacts associated with over extraction of groundwater and resulting land subsidence. A complete set of recommendations is contained in the full report (Luhdorff and Scalmanini Consulting Engineers, et al., 2014, [Report of Findings: Land Subsidence from Groundwater Use in California](#)). 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. An economic analysis should be done to determine the most cost-effective set of actions to limit and address future subsidence.

4.1 Monitor Land Surface Elevation Changes and Compaction

Remote Surveillance and Analysis: InSAR and Continuous GPS

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 facilitates 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 GPS 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 the remote techniques described above. 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.

4.2 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 stresses (e.g., precipitation and droughts), imposed stresses (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.

4.3 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.

4.4 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.