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Land subsidence in the San Joaquin Valley, California, USA, 2007–2014

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Abstract. Rapid land subsidence was recently measured using multiple methods in two areas of the San Joaquin Valley (SJV): between Merced and Fresno (El Nido), and between Fresno and Bakersfield (Pixley). Recent land-use changes and diminished surface-water availability have led to increased groundwater pumping, groundwater-level declines, and land subsidence. Differential land subsidence has reduced the flow capacity of water-conveyance systems in these areas, exacerbating flood hazards and affecting the delivery of irrigation water.

Vertical land-surface changes during 2007–2014 were determined by using Interferometric Synthetic Aperture Radar (InSAR), Continuous Global Positioning System (CGPS), and extensometer data. Results of the InSAR analysis indicate that about 7600 km^2 subsided 50–540 mm during 2008–2010; CGPS and extensometer data indicate that these rates continued or accelerated through December 2014. The maximum InSAR-measured rate of 270 $mm\,yr^{-1}$ occurred in the El Nido area, and is among the largest rates ever measured in the SJV. In the Pixley area, the maximum InSAR-measured rate during 2008–2010 was 90 $mm\,yr^{-1}$. Groundwater was an important part of the water supply in both areas, and pumping increased when land use changed or when surface water was less available. This increased pumping caused groundwater-level declines to near or below historical lows during the drought periods 2007–2009 and 2012–present.

Long-term groundwater-level and land-subsidence monitoring in the SJV is critical for understanding the interconnection of land use, groundwater levels, and subsidence, and evaluating management strategies that help mitigate subsidence hazards to infrastructure while optimizing water supplies.

1 Introduction and background

The extensive withdrawal of groundwater from the unconsolidated deposits of the San Joaquin Valley (SJV), California has caused widespread land subsidence–locally reaching 9 m by 1981 (Ireland, 1986). Long-term groundwater-level declines can result in a vast one-time release of "water of compaction" from compacting silt and clay layers in the aquifer system, which causes land subsidence (Galloway et al., 1999). Land subsidence in the SJV from groundwater pumping began in the mid-1920s (Poland et al., 1975; Bertoldi et al., 1991; Galloway et al., 1999), and by 1970, about half of the SJV, or about 13 500 km^2, had subsided more than 0.3 m (Poland et al., 1975).

Surface-water imports from the Delta-Mendota Canal (DMC) since the early 1950s and the California Aqueduct since the early 1970s resulted in decreased groundwater pumping in some parts of the valley, which was accompanied by a steady recovery of water levels and a reduced rate of aquifer-system compaction in some areas (Ireland, 1986). During the droughts of 1976–1977 and 1987–1992, diminished availability of surface water prompted increased pumping of groundwater to meet irrigation demands. This increased groundwater pumping resulted in water-level declines and periods of renewed compaction. Following each of these droughts, recovery to pre-drought water levels was rapid and compaction virtually ceased (Swanson, 1998; Galloway et al., 1999). Similarly, during the more recent droughts of 2007–2009, and 2012–present, groundwater pumping has increased in some parts of the valley. Groundwater levels declined during these periods in response to increased pumping, approaching or surpassing historical low levels, which reinitiated compaction.

Groundwater pumping that resulted in renewed aquifer-system compaction and land subsidence caused serious operational, maintenance, and construction-design problems for the California Aqueduct, the DMC, and other water-delivery and flood-control canals in the SJV. Subsidence has reduced the flow capacity and freeboard of several canals that deliver irrigation water to farmers and transport floodwater out of the valley; structural damages have already required millions of dollars' worth of repairs, and more repairs are expected in the future (Bob Martin, San Luis and Delta-Mendota Water Authority, and Chris White, Central California Irrigation District, personal communication, 2010). Even small amounts of subsidence in critical locations, especially where canal gradients are small, can impact canal operations. On the DMC between the canal intakes and San Luis Reservoir, where less than 15 mm of subsidence was measured during 2007–2010 (Sneed et al., 2013), a 5-day window of opportunity to recharge the Reservoir in spring 2014 fell short because of reduced flow capacity (Bob Martin, San Luis and Delta-Mendota Water Authority, personal communication, 2014).

The objective of this paper is to describe the location, extent, and magnitude of land subsidence in the SJV during 2007–2014, which includes both drought and non-drought periods (http://www.ncdc.noaa.gov/cag/, assessed 18 April 2015). The SJV is a broad alluviated structural trough constituting the southern two-thirds of the Central Valley of California, that is a substantial source of the nut, fruit, and vegetable supply for the United States (Faunt, 2009).

2 Land subsidence and groundwater levels

Interferometric Synthetic Aperture Radar (InSAR), continuous Global Positioning System (CGPS), and extensometer data were used to determine the location, extent, and magnitude of aquifer-system compaction and resultant land subsidence. Analysis of interferograms generated from synthetic aperture radar images from the European Space Agency's ENVISAT satellite and the Japan Aerospace Exploration Agency's ALOS satellite acquired between 2008 and 2010 indicated 50–540 mm of subsidence in two large agriculturally-dominated areas in the SJV. One area is centered near the town of El Nido (2100 km^2) and the other near the town of Pixley (5500 km^2; Fig. 1). The period 2008–2010 is shown in Fig. 1 because interferograms covering the entire study area were generated for this period only. Because suitable InSAR data were not available for 2010–2014, CGPS data collected during 2007–2014 were used to generate land subsidence time series, which confirmed the InSAR-derived rates and generally indicated that these rates continued or accelerated through 2014 (Fig. 2). Extensometer data collected at four sites during 2012–2014 (data were not available for 2007–2011) were used to generate aquifer-system compaction time series at locations along the major canals, and generally indicated higher compaction rates during the growing season of 2014, the third consecutive year of drought, than for the previous two growing seasons (Fig. 3). To help explain the variability in location and magnitude of land subsidence, computed subsidence and compaction were compared with water-level measurements retrieved from US Geological Survey and California Department of Water Resources databases (Figs. 2 and 3).

3 El Nido

The largest subsidence magnitude in the SJV during 2007–2014 was measured near El Nido. The interferograms are the only measurements that captured the maximum magnitudes because the CGPS stations and extensometers are located on the periphery of the most rapidly subsiding area (Fig. 1); however, InSAR data were only available for 2008–2010. The interferograms indicated a local maximum of about 540 mm during January 2008–January 2010, or 270 $mm\,yr^{-1}$, which is among the highest rates ever measured in the SJV. The maximum subsidence measured at nearby CGPS station P303 was about 50 mm during that same time period, indicating a large subsidence gradient between the two locations (Fig. 1). Assuming the same rate of subsidence occurred during 2007–2014 as occurred during 2008–2010 at the local subsidence maximum near El Nido, about 2 m of subsidence may have occurred during 2007–2014.

Data from the three CGPS stations and two extensometers near the periphery of the El Nido subsidence area show seasonally variable subsidence and compaction rates (including uplift as elastic rebound during the fall and winter), but different characters over longer periods of time. Vertical displacement at P307 and P303 indicated subsidence at fairly consistent rates during and between drought periods (Fig. 2a). These fairly consistent subsidence rates indicate that these areas continued to pump groundwater despite climatic variations (possibly due to lack of surface water availability); residual compaction also may be a factor. Vertical displacement at P304, however, indicated that most subsidence occurred during drought periods and very little occurred between drought periods (Fig. 2a). This suggests that this area received other sources of water, most likely surface water, when it was available between drought periods, and also that residual compaction was not very important in this area. Data from the extensometers 12S/12E-16H2 and 14S/13E-11D6 were available only during the recent drought period, so comparison to a non-drought period was not possible. CGPS and extensometer data indicated subsidence and compaction rate increases during 2014, the third year of drought (Figs. 2a and 3a). In parts of the El Nido subsidence area, where the planting of permanent crops (vineyards and

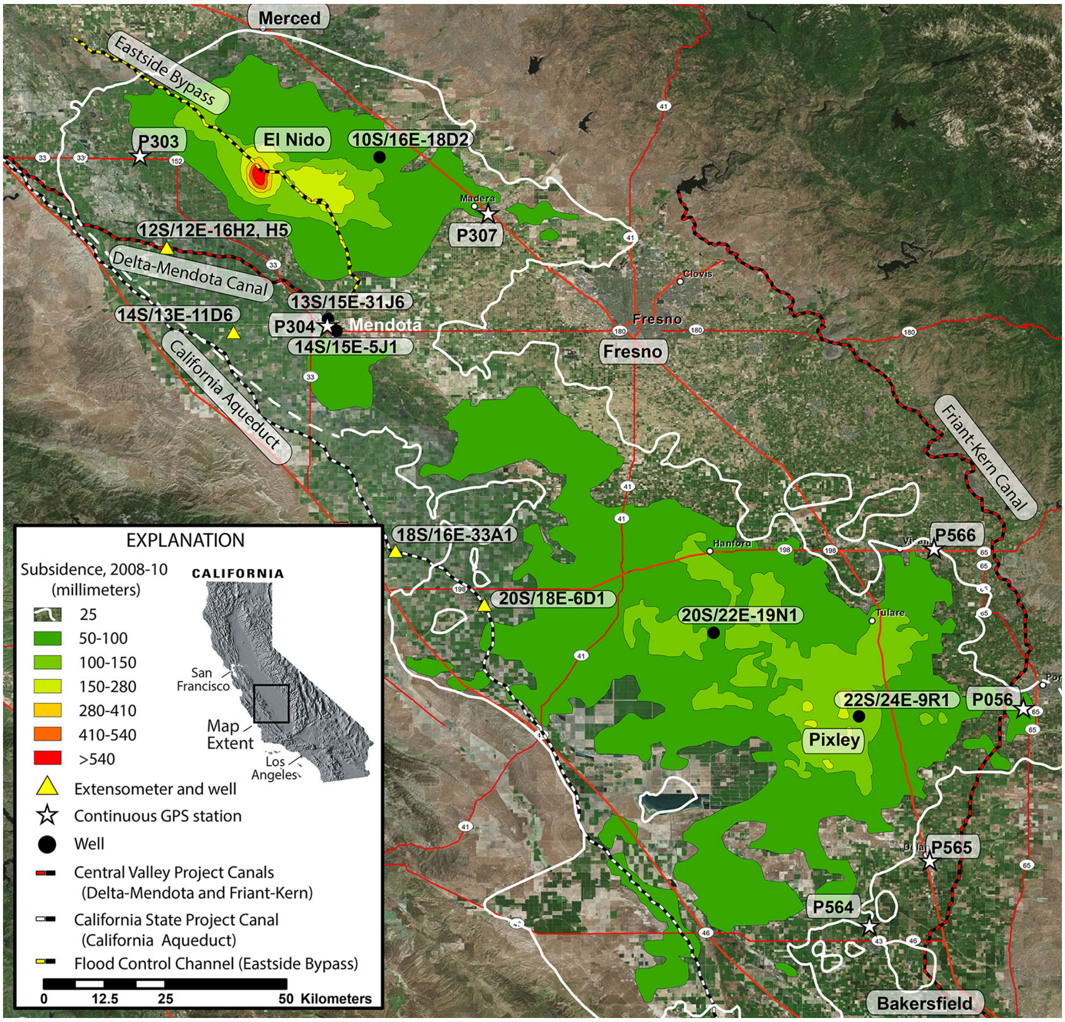

Figure 1. Map showing regions of subsidence derived from interferograms for 2008–2010, and locations of major canals, extensometers, Continuous GPS stations, and wells.

orchards) has increased, groundwater was either the primary source of water or groundwater pumping increased when surface-water availability was reduced, and groundwater levels declined to near or below historical lows during 2007–2010 and 2012–2014 (Figs. 2a and 3a). The correlation between high rates of compaction or land subsidence and water levels near or below historical lows indicates that the preconsolidation stress likely was exceeded; if so, the subsidence likely is mostly permanent.

4 Pixley

The Pixley subsidence area is larger than the El Nido subsidence area, but subsided at a lower rate during 2007–2014. Similar to the El Nido area, the interferograms provided the only measurements that captured the maximum magnitudes because the CGPS stations and extensometers are located on the periphery of the most rapidly subsiding area (Fig. 1); however, InSAR data were only available for 2007–2010. The interferograms indicated a maximum subsidence of about 180 mm during January 2008–January 2010, whereas the maximum measured subsidence at nearby CGPS station P056 (40 km distant) was about 65 mm during that same time period (Figs. 1 and 2b). If the same rate of subsidence occurred during 2007–2014 as occurred during 2008–2010 at the local maximum near Pixley, then about 0.7 m of subsidence may have occurred during 2007–2014. Data from the four CGPS stations and two extensometers near the periphery of the Pixley subsidence area show seasonally variable subsidence and compaction rates (including uplift as elastic rebound during the fall and winter), but different characters over longer periods of time. Vertical displacement at P564 and P565 indicated that most subsidence occurred during drought periods and very little occurred between drought periods (Fig. 2b). This suggests that this area received other sources of water, most likely surface water, when it was avail-

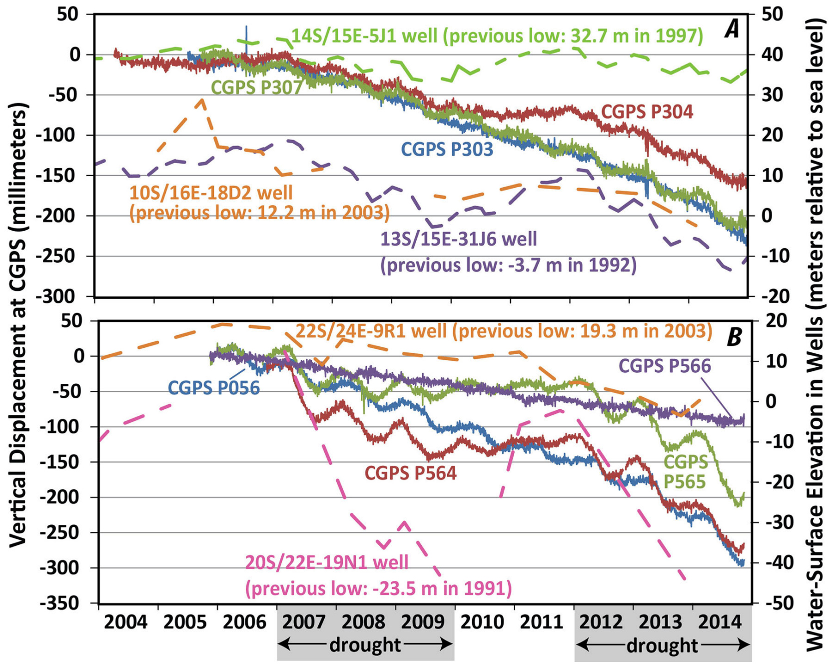

Figure 2. Graphs showing vertical displacement at selected CGPS stations and water-surface elevation in selected wells for 2004–2014 near **(a)**. the El Nido subsidence area and **(b)**. the Pixley subsidence area. (See Fig. 1 for CGPS and well locations.)

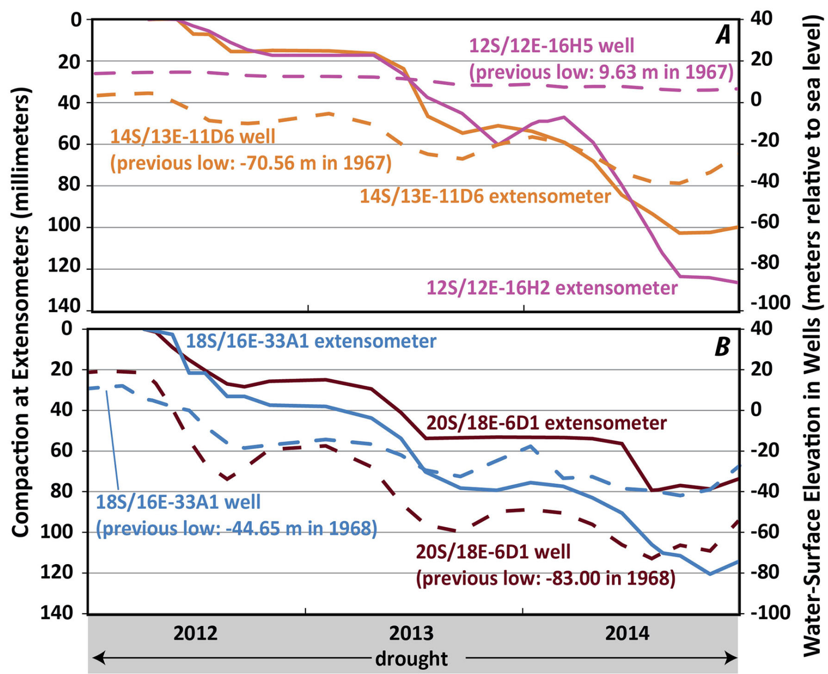

Figure 3. Graphs showing compaction and water-surface elevation at selected extensometers and associated wells for 2012–2014 near **(a)**. the El Nido subsidence area and **(b)**. the Pixley subsidence area. (See Fig. 1 for extensometer and well locations.)

able between drought periods, and also that residual compaction was not very important in this area. Vertical displacement at P056 and P566 indicated subsidence at fairly consistent rates during and between drought periods (Fig. 2b). These fairly consistent subsidence rates indicate that these areas continued to use groundwater despite climatic variations (possibly due to limited surface water availability); residual compaction also may be a factor. Data from extensometers

18S/16E-33A1 and 20S/18E-6D1 were available only during the recent drought period, so comparison to a non-drought period was not possible. CGPS and extensometer data indicated subsidence and compaction rate increases during 2014, the third year of drought (Figs. 2b and 3b). In the Pixley area, groundwater pumping continued or increased when surface-water availability was reduced, and groundwater levels declined to near or below historical lows during 2007–2010 and 2012–2014 (Figs. 2b and 3b). The correlation between high rates of compaction or land subsidence and water levels near or below historical lows indicates that the preconsolidation stress likely was exceeded; if so, the subsidence likely is mostly permanent.

5 Summary and conclusions

Groundwater and surface water are generally used conjunctively in the SJV (Faunt, 2009). During recent drought periods (2007–2009 and 2012–present), groundwater pumping increased in areas where surface-water deliveries were curtailed; in response, groundwater levels declined. However, in areas where surface-water deliveries were normally an absent or minor component of the water supply, pumping was fairly steady during drought and non-drought periods; accordingly, groundwater levels declined at fairly consistent rates regardless of climatic conditions. Groundwater levels in both water-supply-source scenarios declined to levels approaching or surpassing historical low levels, which caused aquifer-system compaction and land subsidence that likely is mostly permanent.

Land use in some parts of the SJV has trended toward the planting of permanent crops (vineyards and orchards) at the expense of non-permanent land uses such as rangeland or row crops. This may have the effect of "demand hardening", which refers to the need for stable water supplies to irrigate crops that cannot be fallowed. As land use and surface-water availability continue to vary in the SJV, long-term groundwater-level and land-subsidence monitoring is critical because continued groundwater use in excess of recharge, which the historical record indicates is likely, would result in additional water-level declines and associated subsidence. Such long-term data can be used to better understand the interconnection of land use, groundwater levels, and subsidence, and to enable the evaluation of management strategies to mitigate subsidence hazards to infrastructure while optimizing water supplies. This knowledge will be critical for successful implementation of California's recent legislation aimed toward sustainable groundwater use without damage from land subsidence.

References

Bertoldi, G. L., Johnston, R. H., and Evenson, K. D.: Ground water in the Central Valley, California–A summary report, US Geological Survey Professional Paper 1401-A, 1991.

Faunt, C. C. (Ed.): Groundwater availability of the central valley aquifer, California, US Geological Survey Professional Paper, 1766, 2009.

Galloway, D. L., Jones, D. R., and Ingebritsen, S. E.: Land subsidence in the United States, US Geological Survey Circular 1182, 1999.

Ireland, R. L.: Land subsidence in the San Joaquin Valley, California, as of 1983, US Geological Survey Water-Resources Investigations Report 85–4196, 1986.

Poland, J. F., Lofgren, B. E., Ireland, R. L., and Pugh, A. G.: Land subsidence in the San Joaquin Valley, California, as of 1972, US Geological Survey Professional Paper 437-H, 1975.

Sneed, M., Brandt, J., and Solt, M.: Land subsidence along the Delta-Mendota Canal in the northern part of the San Joaquin Valley, California, 2003–2010, US Geological Survey Scientific Investigations Report 2013–5142, 2013.

Swanson, A. A.: Land subsidence in the San Joaquin Valley, updated to 1995, in: Borchers, J.W., ed., Land subsidence case studies and current research, Proceedings of the Joseph F. Poland Symposium on Land Subsidence, Sacramento, Calif., 4–5 October 1995, Association of Engineering Geologists, Special Publication no. 8, 75–79, 1998.