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Role of agricultural activity on land subsidence in the San Joaquin Valley, California

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ABSTRACT

The center of the San Joaquin Valley is one of the most productive agricultural regions in the US. Farmers rely heavily on surface-water diversions to meet irrigation water demand. However, the 2007–2010 and 2012–2017 droughts have caused strong increases in groundwater pumping causing land subsidence with strong variability in location, magnitude (total subsidence) and rate of subsidence. In this study, we try to understand what caused these variations. We focus our analyses on three areas: (i) the Westland water district where subsidence was very small during the two drought periods, (ii) ‘El Nido’ area where the greatest subsidence rate was monitored from 2008 to 2010, and (iii) the’ Kings-Tulare counties’ area where the subsidence was small during the 2008–2010 and the largest during 2015–2017 droughts. Our main finding is that land subsidence is located in areas where the water demand for agriculture and the density of groundwater wells is the highest, whereas the rate of subsidence is strongly affected the amount of local and imported surface water and by groundwater resources. Based on these simple observations, we propose using continuous satellite-based ground deformation monitoring and geomechanical modeling to (i) localize areas most prone for future subsidence and (ii) to estimate and manage groundwater resources.

Keywords: Agriculture activity, Central valley, Subsidence, InSAR, Water supply, Groundwater wells

1. Introduction

At the center of the San Joaquin Valley (California, Fig. 1a) lies the counties of Tulare, Fresno, Merced, Kings and Madera (Fig. 1b), which are among the most productive agricultural regions in the US. In 2016, Tulare and Fresno ranked second and third in the US in terms of gross agricultural farm gate value with $6.37 and $6.18 billion and the counties of Merced, Kings and Madera combining together had a gross production value of $7.25 billion. Because the valley is semi-arid farmers rely heavily on surface-water diversions to meet irrigation water demand, but the recent droughts have induced substantial increases in groundwater pumping. Unfortunately, this excessive water extraction from the unconsolidated deposits of the San Joaquin Valley causes land subsidence. The relation between changes in pore-fluid pressure (Pf) due to groundwater pumping and subsidence due to elastic or inelastic compaction of the aquifer system is based on the principle of effective stress (σ_e) (Terzaghi, 1925, Eq. (1)), with σ_T the geostatic load (or vertical stress).

$$\sigma_e = \sigma_T - P_f \tag{1}$$

The pore structure of a sedimentary aquifer system is supported by the granular skeleton of the aquifer system and by the groundwater that fills the intergranular pore space (Meinzer, 1928). When groundwater levels are lowered, the pore fluid pressure is decreased, support provided by the water is transferred to the skeleton, and the skeleton compresses. The compaction of the aquifer system is a well-known problem in the valley (Poland et al., 1975; Lofgren and Klausing, 1969; Bertoldi et al., 1991a; Swanson, 1998; Galloway and Riley, 1999; Brandt et al., 2005; Quinn and Faghih, 2008; Faunt, 2009; Sneed et al., 2013). It may permanently decrease its capacity to store water and may have major consequences on the surface and subsurface infrastructure as:

- the loss of conveyance capacity in canals. NASA shows that sections of the Californian aqueduct have sunk so much that the canals have a carrying capacity 20 percent less than its design capacity (California Department of Water Resources, 2017).
- the exhumation and/or damage of pipeline infrastructure.
- damages on road, bridges and railroads.

In 2017, the California Energy Commission funded a study to characterize the impact of California's drought-related subsidence on natural gas infrastructure. The goal of this research is to identify areas with relatively high risk of potential natural gas infrastructure damage and failures due to subsidence and the identification of potential remedial actions. The recent drought has induced substantial increases in groundwater pumping in the Central Valley of California. In turn, excessive water extraction has resulted in unprecedented rates of subsidence, which has affected infrastructure in the Central Valley. On September 24, the CPUC held an En Banc meeting (Pursuant to the Commission's Safety Action Plan) to discuss safety issues for the natural gas system. A representative from PG&E indicated that about 50 miles of their natural gas pipelines have been affected by subsidence. To prevent such things from happening there is a need to better understand the links between water demand, water supply and land subsidence in order to develop methods and tools to predict where subsidence will occur and to provide the appropriate remedial action. In these perspectives, the USGS (United States Geological Survey) developed a hydrologic modeling tool, the Central Valley Hydrologic Model (Faunt, 2009) to accounts for changing water supply and demand across the entire Central Valley and to simulate surface water and groundwater flow across the entire Central Valley. The USGS and NASA/JPL are also monitoring ground surface deformation, which is primordial to understand the processes and the causes. In the Valley, it has been measured by using interferometric synthetic aperture radar (InSAR), continuous GPS (CGPS) measurements, and extensometer (Sneed et al., 2013 for reviews). InSAR is a technique whereby surface change occurring between two radar imaging passes may be measured and mapped to high precision (Madsen and Zebker, 1998; Massonnet, 1997 for reviews). Under favorable conditions, this technique can detect centimeter level ground-surface deformation over hundreds of square kilometers at a spatial resolution of 10 s of m (Bawden et al., 2003). Synthetic Aperture Radar (SAR) imagery is produced by reflecting radar signals off a target area and measuring the two-way travel time back to the satellite. SAR imagery has two components; amplitude and phase. The amplitude is the measure of the radar signal intensity returned to the satellite, and the varying reflective properties delineate features of the landscape such as roads, mountains, structures, and other features. The phase component is proportional to the line-of-sight distance from the ground to the satellite (range) and is the component used to measure land-surface displacement (subsidence and uplift) (Sneed et al., 2013). GPS provides continuous measurements of the threedimensional position of one point and extensometer the one-dimensional change in thickness of a specified depth interval (Poland, 1984). InSAR processing was accomplished with JPL's ISCE (Interferometric Scientific Computing Environment; Rosen et al., 2012; earthdef.caltech. edu) and Giant (Generic InSAR Analysis Toolbox; Agram et al., 2013; winsar.unavco.org). ISCE uses the Small Baseline Subset (SBAS) approach to generating interferograms (Berardino et al., 2002; Sansosti et al., 2010). For our analysis of the Sentinel-1 data, we used a 'skip-2' strategy, i.e. we produced interferograms for a particular acquisition + the next two acquisitions. The two Sentinel-1 satellites are capable of acquiring data every 6 days and this was the case for most of the study period. To reduce noise, we averaged (took radar looks) to create approximately 100 m pixels. Due to the large number of interferograms, we found that temporal decorrelation was less of a problem than anticipated. We set a coherence threshold of about 0.3. As the Valley is flat and we were not interested in the surrounding mountains, we made no corrections for topographically correlated water vapor delays. Also, as we had many pairs with which to work, we made no corrections or filtering for other atmospheric artifacts. Finally, we assumed that the line-of-sight changes measured by Sentinel-1 were due entirely to vertical deformation, and projected them accordingly.

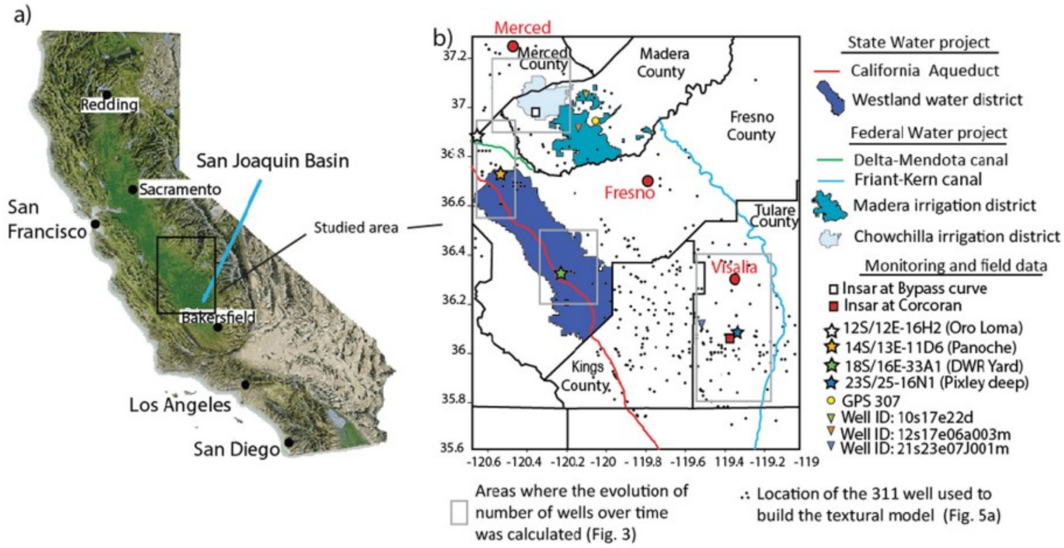

Fig. 1. Location of (a) the studied area in California, (b) the county boundaries, the Westland water district, the Madera and Chowchilla irrigation districts, the aqueducts and the locations of wells (triangles), GPS stations (circle), extensometer (starts) and InSAR data (squares) used in this study.

In this paper, we investigate how the evolutions of the agricultural activity, the climate variability, the water supply, the water level variation and the groundwater wells influence the subsidence in the San Joaquin Valley. These data are investigated at the valley and water district scales. Three smaller areas are studied: the Westland water district (in Fresno County) where land subsidence exceeded 8.5 m before 1970 (Poland, 1984), the Madera and Chowchilla irrigation district (in Madera County) where the highest subsidence rate was identified in 2010 (close to the town of El Nido, Faunt et al., 2015), and the Tulare County where the highest subsidence rate was identified in 2017. Subsidence was monitored by interferometric synthetic aperture radar (InSAR) from 2008 to 2010 (Faunt et al., 2015) and from 2015 to 2017 (this study), continuous global positioning systems (CGPS) since 2000s, and extensometer data since 1960s. Finally, we propose a new method to predict location and magnitude of subsidence during drought and to assess the use of groundwater at the valley scale.

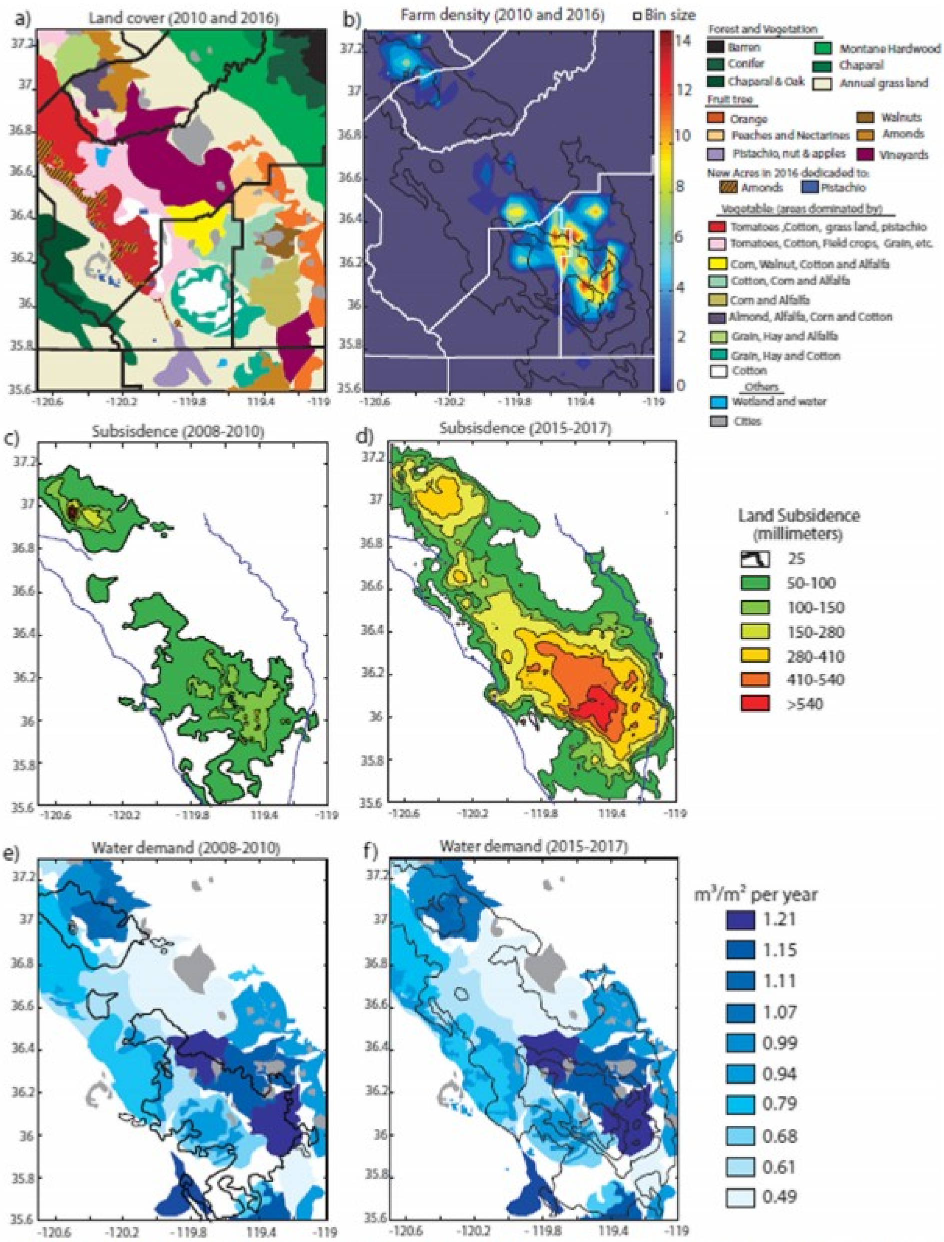

Fig. 2. (a) Land cover in 2010 and 2016 (sources from https://databasin.org/maps/ and https://mangomap.com/land-information/), (b) Farm density in 2010 and 2016, (c) and (d) subsidence monitored by satellite from 2002 to 2010 (Faunt, 2015) and from 2015 to 2017 (this study). (e) and (f) Estimated water demand from 2008 to 2010 and from 2015 to 2017 with subsidence contour lines monitored during the same periods.

2. Agricultural activity and water demand in the central valley

The study area (~28,750 km^2) is a large sediment-filled valley (Farrar and Bertoldi, 1988) bounded by the Sierra Nevada on the northeast and the Coast Ranges on the southwest (Fig. 1a). Between lies a vast agricultural region (~16,600 km^2) with only ~3.2% of its surface covered by urban land. The largest population centers are the cities of Fresno (population ~ 500,000), Visalia (population ~ 125,000) and Merced (population 80,000) (Fig. 1b).

Fig. 2a shows a simplified map of the land cover and agricultural crops distribution in 2010 and 2016 in the valley. On the southwest side of the valley agricultural crops are dominated by tomatoes and cotton in Fresno County, and by cotton, alfalfa and feed grain in Kings County. On the northeast side, agricultural crops are dominated by almonds (in Madera county), vineyards (in Fresno County) and by deciduous fruit and nut orchards (in Tulare county). The remainder is covered by pasture and various field crops. This distribution over the valley has evolved with the market price. Historical acreage trends show a shift toward high-value crops, such as almond and pistachio, away from traditional, lower-value field crops (e.g., cotton, alfalfa, corn, and feed grains, etc.). This evolution is illustrated in Fig. 3 within the Westland water district (Fig. 3a), the Madera and Chowchilla irrigation districts (Fig. 3b), and the Tulare County (Fig. 3c). Livestock farming is also well developed in this area, with ~1.2 million of cattle (beef and dairy cows) in 2016. We counted 806 farms in this area (~1500 animals per farms) mostly located in Tulare and Merced counties (Fig. 2b).

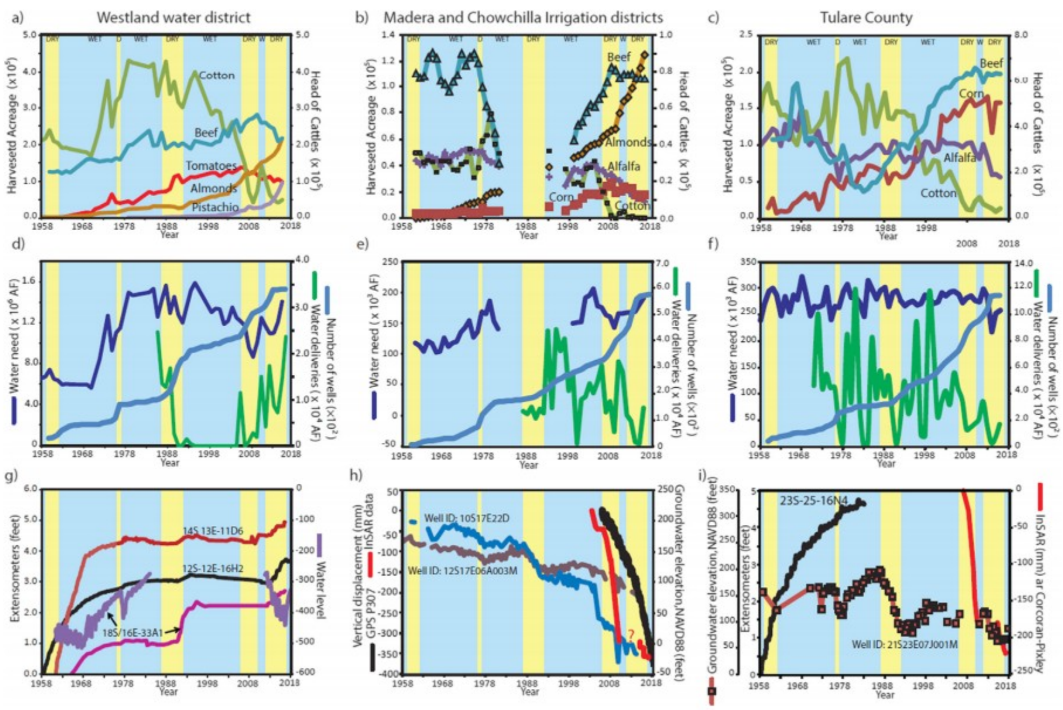

Fig. 3. Evolution of (a–c) the agricultural activity (based on the annual crop report from the Agricultural Commissioner in the Fresno, Madera and Tulare counties), (d–f) estimated water demand, water deliveries and number of groundwater wells (calculated in small grey rectangles shown in Fig. 1b), (g–i) water level (in wells present in Department of Water Resources CASGEM database) and surface deformations monitored (from USGS data: https://ca.water.usgs.gov/land_subsidence/california-subsidence-measuring.html) in the Westland water district area, The Madera and Chowchilla Irrigation districts area and in the Tulare County area, respectively.

Based on the land cover maps, the farm distribution and the wateruse coefficients per year for the different crops and per head (Table 1) we draw two maps showing the water demand for the agriculture activities for 2010 (Fig. 2c) and 2016 (Fig. 2d). Areas of high water demand (~1.2 m^3/m^2 per year) appear in Madera County and in KingsTulare counties where the highest subsidence rates were identified in 2010 and 2017, respectively. We also estimate the evolution of the water demand since 1958 based on the evolution of the agricultural activity. In the Westland water district (Fig. 3d), the import of irrigation water in the early 1970s caused a strong development of the agriculture, a strong increase in water demand, but a decrease in groundwater pumping. This demand stayed high until the 1990s, when after the evolution of the economic market caused a drop in the cotton production and a corresponding drop in water demand. Only in 2009, a sharp increase in production of pistachio nuts and almonds caused an increase in water demand towards historical levels. In the Madera and Chowchilla irrigation district (Fig. 3e), the water demand has kept increasing since 1958, whereas it has stayed constant in the Tulare County (Fig. 3f).

3. Water supplies in the central valley

Water supplies in the Central Valley rely on a combination of local and imported surface water and groundwater pumping.

Surface water is managed by the California State Water Project (SWP), the Central Valley Project (CVP) and local agencies which deliver water through canals, streams and pipelines. The SWP is under the supervision of the California Department of Water Resources. Water is collected from rivers in Northern California, most of it travels along the Californian Aqueduct (Fig. 1b) and since the early 1970s water is delivered in Southern California to the SWP Water Supply Contractors who distribute it to farms, homes, and industry. In our study area the water supply contractors are the Kings and Tulare Lake Basin Water Storage District (Tulare counties) (Fig. 1b). Water supply depends on rainfall, snowpack, runoff and water in storage facilities, as well as operational constraints for fish and wildlife protection, water quality, and environmental and legal restrictions. As a result, surface water delivered to the Tulare County strongly varies from one year to another, between wet and dry periods, and has also been reduced since the 1990’s even during wet periods (Fig. 3f).

Table 1
Water-use coefficients per year for the different crops (*Johnson and Cody, 2015) and per head (**Lovelace, 2009).

crop group*	Average Acre-feet (AF) Applied per Acre per year	m^3/year
Alfalfa	5	6167.4
Almonds Pistachio	3.5	4317.2
Corn	2.8	3453.7
Cotton	3.1	3823.8
Grain	1.4	1726.9
Vine	1.9	2343.6
Deciduous	3.3	4070.5
other Field	2.6	3207.1
	Gallons per animal per day	m^3 per animal/ year
Cattle**	65	89.8

The Central Valley Project (CVP) is a federal water management under the supervision of the United States Bureau of Reclamation (USBR). The project started in the late 1930s and was completed in the early 1970s. In recent years, a combination of drought and regulatory decisions have forced USBR to turn off much of the water supply for the west side of the San Joaquin Valley in order to protect the fragile ecosystem in the Sacramento-San Joaquin Delta and keep alive the fish populations of Central Valley rivers. Water can be interchanged between SWP and CVP canals as needed to meet peak requirements. In our study area, the CVP provides water to several local agencies (e.g. the Westland water district, the Madera and Chowchilla Irrigation districts) through the Delta-Mendota and Friant-Kern canals (Fig. 1b). Data are only available since 1985, but it can be seen that water was delivered to the Westland water district only during droughts (Fig. 3d), and inversely to the Madera and Chowchilla Irrigation districts mostly during wet periods and less during droughts (Fig. 3e).

The valley also relies heavily on groundwater pumping. The aquifer system is made of confining units and unconfined, semi-confined, and confined aquifers (Page, 1986; Farrar and Bertoldi, 1988; Williamson et al., 1989). The majority of natural recharge from infiltration of streamflow occurs on the east side of the valley along the mountains (Faunt, 2009; Bertoldi et al., 1991b; Planert and Williams, 1995). In 2009 it was estimated that 30% of the annual water demand for agricultural lands and cities is provided by groundwater pumping during wet years and up to 70% during extremely dry years (Faunt, 2009). This amount is difficult to estimate because private groundwater pumping for irrigation is not reported. In 2018, there were 81,531 groundwater wells in the valley (Fig. 4a). Only 63,775 have a known completion depth (Fig. 4b), but it can be seen on Fig. 4 that the shallowest wells are located along the Sierra Nevada foothills (53,432 wells are less than 150 m deep, Fig. 4d) where the sedimentary cover is the thinnest, and the deepest wells along the Coast Ranges (2015 wells are deeper than 305 m, Fig. 4f) where the sedimentary cover is the thickest. In the center of the valley, groundwater is pumped from 6882 wells with a completion depth between 150 and 305 m (Fig. 4e). Fig. 3d, e and f, show the evolution of the number of wells present in four areas since 1958 (two in Fresno County and one in Madera and Tulare Counties, see gray rectangles on Fig. 1b). This number slowly evolves during the wet periods and sharply increases during droughts especially when the surface water deliveries dropped.

4. Subsidence in the Central Valley

Subsidence has been a major concern in the Central Valley since the 1950s for the reasons described previously. It was documented in many reports and scientific papers generated by the USGS and the California Department of Water Resources (DWR) (Sneed et al., 2013 for an exhaustive reference list). It is actually monitored by USGS by means of extensometers, GPS and InSAR.

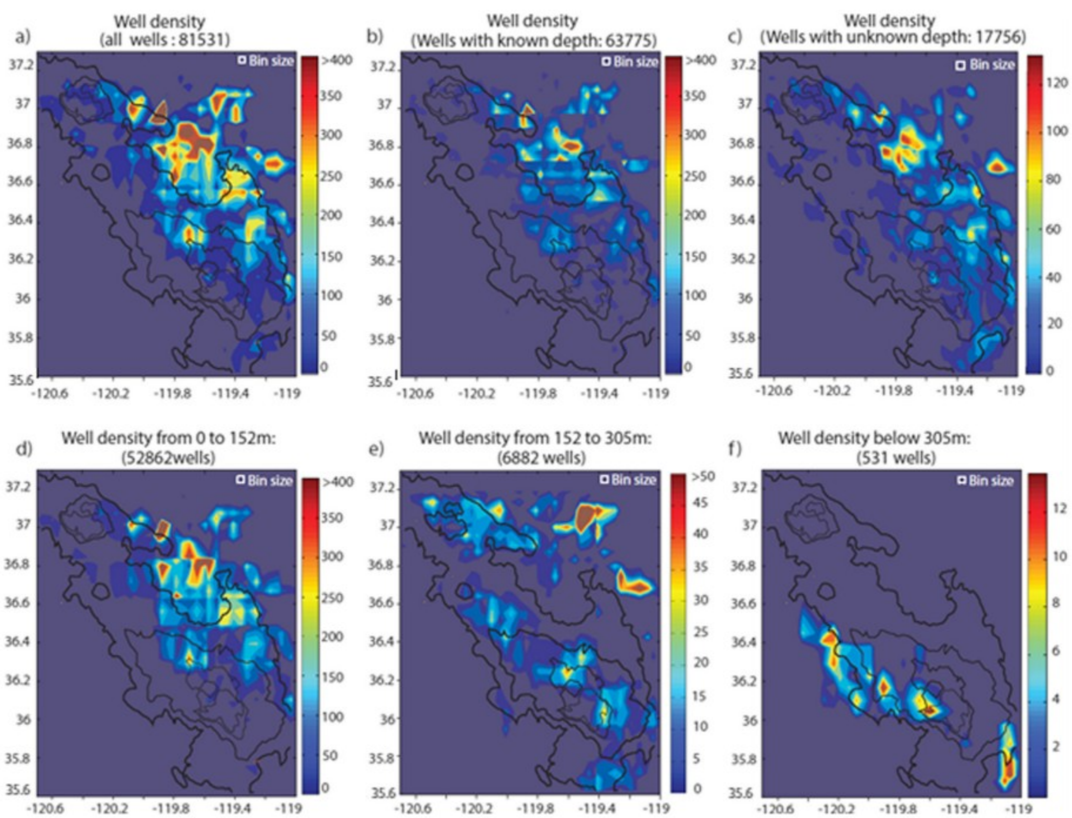

Fig. 4. Maps showing: (a) the well density in the valley, (b and c) the well density in the valley with a known and unknown completion depth, and the density of wells having a completion (d) above 152 m depth (e) between 152 and 305 m depth and (f) below −305 m (data from CASGEM), with subsidence contour line monitored from 2015 to 2017.

- In the Westland water district (Fresno County), from the 1950s the excessive water pumping resulted in significant land subsidence of up to 8.5 m (Poland, 1984), but in the early 1970s, the import of irrigation water caused a decrease in groundwater pumping, a decrease in subsidence rate and partial water-level recovery. In the Westland water district, during the drought from 1986 to 1992, water deliveries were sufficient to maintain the agricultural production and prevent subsidence only during the first two years. In 1990 water deliveries stopped and numerous wells were drilled for groundwater pumping which restarted aquifer compaction. Later in the 1990s, the drop in water demand associated with the drop in cotton production, stopped the aquifer compaction and allowed the water-level to recover. Only recently and during the 2012–2017 droughts, the sharp increase in production of pistachios and almonds caused a renewed increase in water demand towards historical level. Water supply delivery and groundwater pumping increased during the drought and compaction restarted (Fig. 3g).

• In the Madera and Chowchilla irrigation districts (El Nido area), since 1958 water demand has kept increasing and the water table has decreased, and since 1998 the surface water deliveries have dropped. The consequence is that in 2010, the highest subsidence rate (~270 mm/year) was monitored in this area (Fig. 2e, Faunt et al. 2015). Unfortunately, subsidence was not monitored in this area before, but it can be assumed that subsidence also occurred before 2008 (Farr et al., 2017 progress report).

• In Tulare County, since 1958 the water demand is stable. The import of irrigation water in the 1970s has stopped aquifer compaction and allowed the water-level to recover. But after the 1986–1992 droughts, the water level dropped to a historically low level and never fully recovered (Fig. 3i). The consequence is that during the 2012–1017 droughts, the water table reached a new historically low level, and the highest subsidence rate was monitored in this area (Fig. 2f).

InSAR data were obtained from 2008 to 2010 (Faunt et al., 2015) with the European Space Agency’s (ESA) ENVISAT satellite and the Japan Aerospace Exploration Agency’s ALOS satellite, and from 2015 to 2017 (this study) with the ESA’s Sentinel-1 satellites. These data show that almost all the valley sunk at a very slow rate (~12.5 mm/year) during these two periods, but with strong variability in location, magnitude and rate of subsidence.

• From 2008 to 2010, the highest subsidence rate (~270 mm/year) was monitored near the town of El Nido in Madera County. Farther south, in Kings-Tulare counties, a larger subsidence bowl (5500 km^2) developed with a smaller subsidence rate (between ~25 and ~75 mm/year) (Faunt et al., 2015).

• From 2015 to 2017, the subsidence rates doubled or tripled almost everywhere (only the rate of subsidence near the town of El Nido decreased from ~270 to ~220 mm/year), the highest subsidence rate was observed in Kings-Tulare counties area (~33 mm/year), and a third subsidence bowl appeared in Fresno County (with a maximum subsidence rate of ~22 mm/year).

5. Geomechanical simulations

In this section we try to understand the cause(s) of the variability in location, magnitude and rate of subsidence monitored from 2008 to 2010 and from 2015 to 2017. The main difference between these two periods is that 2015–2017 was the last two years of a severe drought that started in 2011, whereas the period from 2008 to 2010 covers the last years of a drought that started in 2007 and a wet year (2009–2010). So, it can be assumed that these strong variations in location, magnitude and rate of subsidence are the result of a change in the water supplies during these two periods, with less local and imported surface water and more groundwater pumping for crop irrigation during droughts. This simple assumption is also strongly supported by the fact that the highest subsidence rate observed during the severe drought (2015–2017) are located where the crops with the highest water demand are (Fig. 2), and the shape of the subsidence bowl coincides with the zone of high well density with a completion depth below 150 m and located in agricultural areas (Fig. 2). Indeed, no subsidence was monitored in urban areas despite the huge number of wells in these areas (~50,000 in and around the city of Fresno). To explain this discrepancy, it can be assumed that (1) these wells are private wells which are either not used anymore or uses for gardening which require little amount of groundwater, or (2) these wells are older and the accessible clay layers have already been subject to pressure reductions and inelastic permanent volume change and hence undergo mostly elastic changes.

Faunt et al. (2015) also suggested that these differences in rate of subsidence could be partly caused by variation in mechanical properties of the saturated geologic materials constituting the aquifer. They suggested that the aquifer in the non-glaciated fluvial fan (in El Nido area) are fine grained and more compressible than the aquifer in glaciated fluvial fans, that coarse grained (in Tulare and Kings County area). It should also be noted that the third subsidence bowl, which appeared in Fresno County between 2015 and 2017, is located within a wetland (Fig. 2a). Thus, it could be possible that the 2012–2017 droughts caused dewatering of this area inducing the subsidence.

To test and verify these different assumptions we developed a 3D textural model (Fig. 5a) to simulate groundwater pumping inducing subsidence with the geomechanical numerical simulator TOUGH-FLAC (Rutqvist, 2011). The texture of the subsurface layers was inferred from 322 drillers' logs of wells and boreholes ranging in depth from 0 m to 700 m below land surface using the 'DOGGR' and 'CASGEM' databases (well locations are represented by the black dots on Fig. 1b). Based on these logs a percentage of coarse-grained material was defined over 30 m intervals and textural groups were created (Table 2). These goups were used to build a 3D numerical model (35 × 35 ×

19 cells) which extends to a depth of 680 m and laterally ~158 km in the eastern and 195 km in the northern direction. Then, by considering the wells with a completion depth below 150 m, we defined 152 clusters of wells called here ‘pumping zones’ (Fig. 5b). A ‘pumping zone’ was created if at least 5 wells had the same completion depth (± 30 m) in an area of ~23 km^2 (thus, the same area can have several ‘pumping zones’ located at different depths). For each ‘pumping zone’ a production rate is defined based on (i) the water demand in the agricultural area, (ii) the total number of wells present in the agricultural area and (iii) the number of wells composing the ‘pumping zone’ (for simplicity we consider that the water demand and the number of wells in 2008–2010 and in 2015–2017 are the same). For example, in Madera county the agricultural area of ~98 km^2 dominated by alfalfa, corn, cotton and almonds (Fig. 2a) and by livestock (35 farms, Fig. 2b) has an estimated water demand ~9.8 × 107 m^3 of water per year. We defined 7 ‘pumping zones’ representing 69 groundwater wells: 6 ‘pumping zones’ (representing 62 wells) located between 150 and 180 m below the surface (in detail, they are made of 3, 2 and 1 ‘pumping zones’ representing 6, 7 and 14 groundwater wells) and 1 ‘pumping zone’ located between 275 and 305 m below the surface (representing 7 groundwater wells). By considering that all the water demand in this area is fully supplied by these 69 wells, we estimated a pumping rate of 0.98, 1.14 and 2.28 m^3/s for the ‘pumping zones’ representing 6, 7 and 14 groundwater wells. In addition to these 152 clusters of wells, we also defined 40 ‘pumping zones’ to consider the wells with an unknown completion depth. In their case, an average depth was attributed to them. This average depth was calculated based on the wells with a known completion depth present in the vicinity. Hydraulic and mechanical properties used in the simulation are listed in Table 2.

Fig. 5c presents the calculated vertical ground surface deformation after two years. Despite the coarse grid we still roughly reproduce the shape, magnitude and location of the small subsidence bowls in Madera County and the larger one in Kings-Tulare counties monitored from 2015 to 2017. This shows again the good correlation between water demand, well locations and subsidence rate. Moreover, despite the use of homogeneous mechanical properties for the saturated geologic materials constituting the aquifer we were able to simulate the formation of two different subsidence bowls but with magnitude similar to those observed in El Nido area and in Kings-Tulare counties area in 2015–2017.

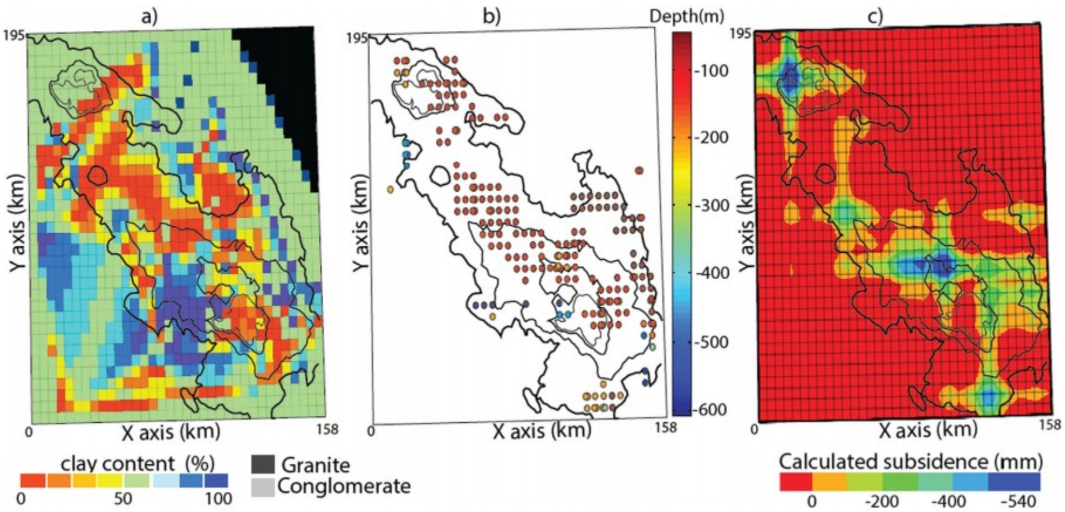

Fig. 5. (a) map view of the textural model around 300 m depth, (b) locations of the 'pumping zones' and (c) calculated vertical displacement after two years of simulation. The black lines are the subsidence contour line monitored from 2015 to 2017 (Fig. 2d).

6. Discussion

In this study we focused our analyses on three areas in the central San Joaquin Valley having different groundwater resources, water demand and water supply before 2008, and which responded differently during the 2008–2010 and 2015–2017 droughts:

- The Westland water district characterized by a historically low water demand (since 1980), an initial important groundwater resource, an increase in water supply during the drought, and a low subsidence rate from 2008 to 2017.
- El Nido area characterized by a continuous increase in water demand since 1958, a continuous decrease in groundwater resource since 1998, a progressive drop in surface water deliveries and the highest subsidence rate during the 2008–2010 drought.
- The Kings-Tulare Counties area characterized by a stable water demand, a progressive drop in surface water deliveries since 2000, a low groundwater level, which was recovering before the 2008–2010 drought, a small subsidence rate during the 2008–2010 drought and the highest subsidence rate during the 2015–2017 drought.

Our numerical simulation, in which we simulated 2 years of groundwater pumping based on the distribution of agricultural activity and groundwater wells and by considering homogeneous groundwater resources, homogeneous mechanical properties and no surface water supply, was capable to roughly reproduce the shape and magnitude of the land subsidence in the valley monitored from 2015 to 2017. Because the agricultural activity in 2008–2010 and 2015–2017 was roughly the same, this indicates that the variability in location, magnitude and rate of subsidence monitored from 2008 to 2010 was caused by a difference in local and imported surface water and/or in groundwater resources.

This can have important implications for (i) prediction of location and magnitude of future subsidence and (ii) estimation of groundwater resources at the scale of the Valley. Indeed, at the beginning of each year the same approach can be applied to calculate what would be the subsidence in the Valley if all the water demand for agricultural activities were provided by groundwater pumping. This will allow identifying areas where subsidence could be substantial in the case of a drought. Then, the comparison between the calculated 'future subsidence map' with InSAR data regularly acquired during the year would allow for an estimate of how much water is provided by groundwater supply or local and imported surface water.

Table 2
Textural groups formed based on drillers' logs and their associated hydraulic and mechanical properties used in the simulation.

group	Mud log description	~clay %	Young modulus (Pa)	Poisson's ratio	Permeability (m^2)	Porosity (%)
1	sand	0–20	1.00E+06	0.25	5.00E−10	30
2	sand with streak of clay	20–30	1.00E+06	0.25	1.00E−10	28
3	sandy clay with streak of sand	30–40	1.00E+06	0.25	5.00E−11	25
4	sand and clay	40–50	1.00E+06	0.25	1.00E−11	23
5	clay and sand	50–60	1.00E+06	0.25	5.00E−12	22
6	sandy clay with streak of clay	60–70	1.00E+06	0.25	3.00E−12	21
7	clay with streak of sand	70–80	1.00E+06	0.25	1.00E−12	18
8	clay	80–100	1.00E+06	0.25	8.00E−13	15
9	conglomerate		1.00E+08	0.25	1.00E−13	20
10	granite		1.00E+09	0.25	1.00E−14	10

7. Conclusion

A large amount of land subsidence in the central San Joaquin Valley is caused by groundwater pumping, and the amount of water pumping from the ground is correlated with:

- The number of active groundwater wells, which vary according to the climate and the surface water delivery.
- The water demand, which vary according to the agricultural activity and therefore according to the market price.
- The local surface water, which depends on the climate
- The surface water delivery, which depends on the climate, environmental factors and system constraints.
- And of course, the water availability in the aquifer.

All these factors and their interactions make it difficult to predict the location, magnitude and rate of future subsidence. However, we show that the location is strongly influenced by the agricultural activity and the well locations, whereas the magnitude and rate will depend on the amount of local and imported surface water for irrigation, which affect the pumping rate. By using continuous InSAR monitoring and geomechanical modeling it is possible to improve our ability to predict subsidence and monitor groundwater resource across the valley.

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