Exploring drivers of spatio-temporal variation of subsidence in the San Joaquin Valley, California, USA

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Abstract

The San Joaquin Valley, California, USA, has experienced massive amounts of land subsidence dating from the 1920s to present day (2022). The regions experiencing the most subsidence have shifted from the mid-1900s to present day, but the drivers for this shifting spatio-temporal pattern have not been explored. In this study, we model deformation in two areas: the Los Banos/Kettleman City region, which experienced up to 8.9 m of subsidence from 1926 to 1972, and the Tulare/Pixley region, which has been experiencing over 20 cm/yr of subsidence in some regions since 2007. We implement a novel technique to reduce noise in estimates of change in groundwater level, or head, aggregated over large regions and long (80 year) time periods by solving systems of linear equations composed of measured head change over multiple overlapping periods. We find that the distinct stress histories of the two regions drives their response to historic and current declines in head. The Los Banos/Kettleman City aquifer has only recently experienced heads at or below historically low heads that were experienced in the 1960s, while the Tulare/Pixley aquifer has been at historically low heads since the mid-2000s. We find that although the Los Banos/Kettleman City region has experienced relatively low subsidence rates over the past two decades, it is likely to begin experiencing dramatic subsidence now that heads are once again at historically low levels.

Introduction

The San Joaquin Valley comprises the southern portion of the Central Valley, California, which is home to 6.5 million people, a $50 billion agricultural industry (California Department of Food and Agriculture, 2021). The Los Banos/Kettleman City region (region a in Figure 1) has experienced up to 8.9 m of historical subsidence due to groundwater extraction, with a regionally averaged subsidence rate from 1926 to 1969 of 7.9 cm/yr (Poland, 1975), but has experienced little long-term subsidence in the recent droughts of the 2000s (Chaussard and Farr, 2019). In contrast, the Tulare/Pixley region (region b in Figure 1) experienced much lower historical subsidence, with a regionally averaged subsidence rate of 4.7 cm/year from 1926 to 1970, but subsidence has increased substantially with greater than 20 cm/year of sustained subsidence from 2007 to present that has been characterized as primarily inelastic (Smith et al., 2017; Chaussard and Farr, 2019; Lees et al., 2022). One challenge in evaluating mechanisms driving these changes is that the key temporal input, groundwater levels, have been sparsely monitored with a changing network of wells. In this paper, we present a new approach to model subsidence in both regions with sparsely sampled head measurements. We show that the lower subsidence rates experienced in the Los Banos/Kettleman City region in the 2000s is driven primarily by the high pre-consolidation stress in the region, but that recent droughts threaten to make this region once again a subsidence hot-spot.

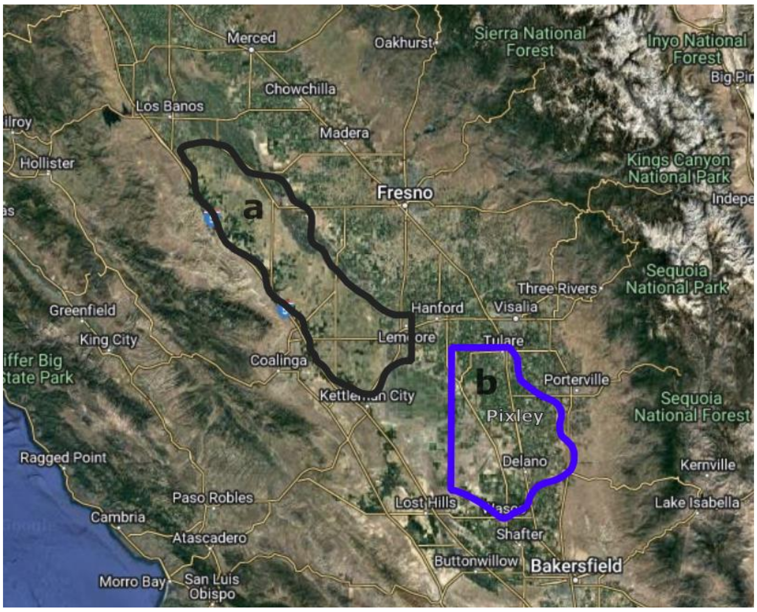

*Figure 1 Regions of subsidence modeled in this study. Region **a** has a high historic subsidence and is near Los Banos and Kettleman City, and region **b** has high recent subsidence and is near Tulare and Pixley.*

Methods

In order to understand the mechanisms driving spatiotemporal changes in deformation in the San Joaquin Valley, a model was developed that simulates deformation as a function of head changes within the aquifer. The method to determine head change within the aquifer is described in Section 2.1. The head in the aquifer is then used to simulate the distribution of head within fine-grained units, which is then used to estimate deformation. This process is described in Section 2.2. The model was calibrated using deformation estimates from both InSAR (Tre Altamira, 2022) and historical leveling surveys (Poland, 1975). This is done over two distinct regions: the area with highest historical subsidence, denoted as the Los Banos/Kettleman City area (Figure 1, region a) and the area with highest recent subsidence, denoted as the Tulare/Pixley area (Figure 1, region b). The time period of the model is from 1940 to 2022

Estimating changes in head

Typically, regional changes in head are best estimated by measuring head changes at an individual well and averaging these head changes over multiple wells (i.e. Butler et al., 2016). This approach reduces error that can occur by comparing heads over time at different wells, which are likely tapping different portions of the aquifer system, and are subject to errors due to the natural spatial variability in head. However, this method is challenging to implement in the San Joaquin Valley over long time periods because the wells that have been monitored over the past 80 years have changed significantly.

InSAR data processing techniques implement a method called Small Baseline Subset (SBAS, Berardino et al., 2002) that creates a system of equations from multiple overlapping interferograms containing information of change in surface elevation over different combinations of single measurements. This approach reduces noise by using redundant measurements. In this study, we implement a similar approach, using measurements of change in head for every 1, 2, 5, 10, 15 and 20 years at each well where data over these time spans is available. Each of these periods with head-change data is treated like an interferogram. These datasets are averaged over all wells containing the time spans, producing a system of equations that is used to solve for the average annual change in head, X:

$$TX = Y, \quad (1)$$

where T is an m x n matrix representing time in years between each estimate of head change, with m rows for each period of change in head measurements and n columns for each year of the period of record containing a value of 0 or 1. X is an m x 1 matrix with m rows representing the change in head for each year, and Y is an m x 1 matrix with m rows representing the average change in head over each period of change in head measurements. The change in head during each year, X, is solved for by inverting the matrix in Equation 1. A visual representation of T, X and Y is given for the Tulare/Pixley region in Figure 2a, b and c respectively. Figure 2d shows the head relative to 1940 given by integrating X over time.

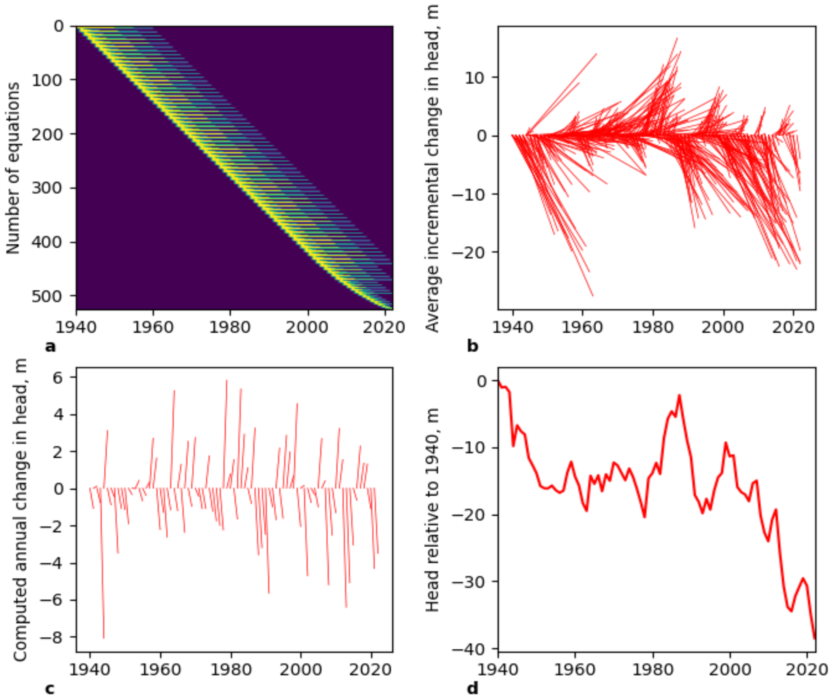

Figure 2 Example of our approach for estimating head in the Tulare/Pixley region. ***a)*** *A visual representation of the matrix T from Equation 1. Yellow pixels represent a value of 1, and the blue pixels represent a value of 0.* ***b)*** *Average head changes measured at wells in the valley in increments of 1, 2, 5, 10, 15 and 20 years. This is a visual representation of matrix Y from Equation 1.* ***c)*** *Average yearly change in head, solved for by invertong Equation 1. This is a visual representation of matrix X.* ***d)*** *Integrated change in head to produce head relative to 1940 levels.*

Modeling deformation as a function of changes in head

Deformation in compressible fine-grained units is modeled as a function of change in head using the following equation:

$$d = \Delta h S_{sk} b_0, \qquad (2)$$

where d is the deformation, Δh is the change in head, S_{sk} is the skeletal specific storage, and b_0 is the original thickness of the compacting layer. There are two possible values for S_{sk}, one that represents elastic deformation (S_{ske}), which occurs when the head is above the previously lowest experienced head (preconsolidation head), and one that represents inelastic deformation (S_{skv}) when the head is below the preconsolidation head. S_{skv} is roughly 100 times larger than S_{ske} (i.e. Sneed, 2001).

Since head measurements are made primarily in coarse-grained units and are not representative of head within fine-grained units, the following equation is used to estimate the vertical and temporal distribution of head within fine-grained units:

$$\frac{\partial}{\partial z}\left(K_v \frac{\partial h}{\partial z}\right) = S_s \frac{\partial h}{\partial t}, \qquad (3)$$

Where z is the vertical position along the fine-grained layer, K_v is the vertical hydraulic conductivity, h is head, S_s is the specific storage (approximated here as the skeletal specific storage), and t is time. These equations are used together to model deformation as a function of change in head. The parameters K_v, S_{skv}, S_{ske}, b_0, as well as a seasonal head fluctuation added to the annual head time series, are estimated in a grid search with roughly 30,000 simulations. This is done in the two areas shown in Figure 1, referred to as Los Banos/Kettleman City (a) and Tulare/Pixley (b). The reader is referred to Smith and Li (2019) for more details on the modeling approach.

Results and discussion

Figure 3 shows the results of our deformation model. The Los Banos/Kettleman City aquifer is shown in Figure 3a and b, and the Tulare/Pixley region is shown in Figure 3c and d. It is clearly visible in Figure 3 that the Tulare/Pixley region has been experiencing historically low groundwater levels since the early 2000s, resulting in accelerated inelastic deformation relative to historic levels. The Los Banos/Kettleman City aquifer, by contrast, is near its historically lowest groundwater level but has not exceeded it in recent years. These variations in preconsolidation head explain most of the variation in subsidence in these areas. However, continued pumping in the Los Banos/Kettleman City region could result in significant drawdown below the preconsolidation head, causing significant subsidence in that region to resume. In both regions, there is strong evidence for delayed subsidence, supporting previous work by Lees et al. (2022).

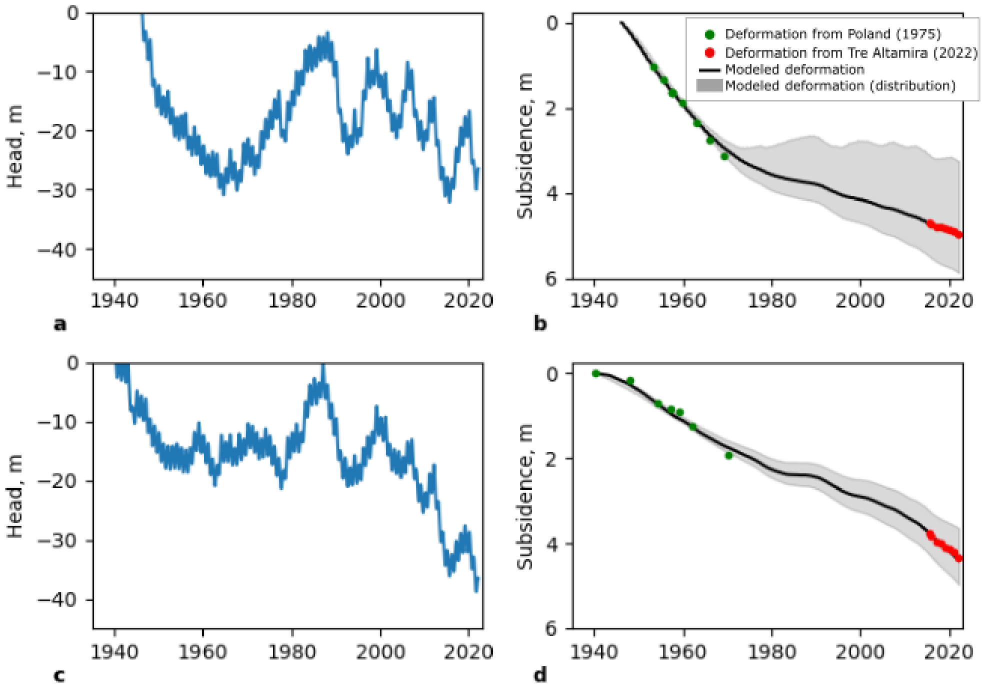

Figure 3 ***a)*** *and* ***b)*** *head and deformation, respectively, relative to 1940 in the Los Banos/Kettleman City region;* ***c)*** *and* ***d)*** *head and deformation, respectively, relative to 1940 in the Tulare/Pixley region.*

Conclusion

In this study, a new approach is presented that makes use of sparsely sampled well data to produce a long-term time series of changes in groundwater levels. This dataset is then used to model deformation in two key regions of the San Joaquin Valley: the Los Banos/Kettleman City region, which experienced massive historic subsidence, and the Tulare/Pixley region, which is currently experiencing over 20 cm/year of subsidence. Our models indicate that the primary driver for the spatiotemporal change in deformation patterns is the preconsolidation head, which was much lower in the Los Banos/Kettleman City region. However, recent droughts have caused stress levels in this region to approach the preconsolidation stress, risking renewed subsidence in that region to accompany ongoing subsidence in the Tulare/Pixley region.

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