1D compaction modelling for subsidence prediction in California's San Joaquin Valley

M. M. Lees[1], R. Knight[1], W. Neely[1], M. Malenda[1]

1 Stanford University, Department of Geophysics.
Contact: mlees@stanford.edu

Abstract

We used 1D compaction models, which simulate the time-dependent drainage of subsurface clays, to aid with subsidence management in California's San Joaquin Valley. We applied models at two locations, calibrated over the period 1950s- present, and then made subsidence predictions through 2080. We found that our modelling was a significant improvement over existing approaches which either do not consider any physical-based modelling or consider simplified, elastic models with no time-dependent clay drainage. While remaining simplifications in our modelling approach limit the accuracy of subsidence predictions, 1D compaction modelling represents a promising direction to reliably simulate subsidence for groundwater management with the potential for further important scientific contributions to be made to meet management needs.

Introduction and background

Subsidence in California's San Joaquin Valley (SJV) has long been amongst the most dramatic in the World and in 2020 continued to occur at rates exceeding 20 cm/yr (Figure 1a). In 2014, California passed the Sustainable Groundwater Management Act, which requires groundwater managers to make plans to avoid 'undesirable results' of groundwater extraction, including excessive subsidence (Dickinson, 2014). A number of the first round of the so-called Groundwater Sustainability Plans (GSPs) were rejected as inadequate, with the lack of rigorous modeling of subsidence one reason for rejection. At present, GSPs either do not use physical subsidence models at all and assume that stabilization of heads will lead to cessation of subsidence, or they use elastic modeling, which assumes all subsidence occurs instantaneously with a head drop.

Here, we summarize a recent project where we worked in the Kaweah subbasin and applied 1D compaction modelling to simulate subsidence for their revised GSP. 1D compaction modelling solves for the time-dependent drainage of clays in response to head drops in sands, based on the aquitard drainage model, but has seen limited use in the SJV (Helm, 1975). We took the study of Lees et al. (2022), which developed and calibrated a 1D compaction model of historic subsidence at the South Hanford site in the basin, and extended it in two ways. First, we applied the workflow to a second location (the Tulare Irrigation District or TID site); and secondly, we extended the modelling to include future projections. The locations of both sites are displayed in Figure 1a.

Methods

The conceptual model we used at both sites is shown in Figure 1b. We separated the subsurface into an unconfined and a confined aquifer separated by the Corcoran Clay, where each aquifer consists of an interconnected coarse-matrix with clay interbeds. The variable d_i represents the depth of the lower aquifer below the deepest well. The number and thickness of the interbeds were determined using electrical-resistivity logs and lithology data. We used head measurements to determine the effective stress in the coarse-grained matrices, and used this effective stress as the temporally-varying boundary condition to solve for the evolution of effective stress in clays (Equation 1, Lees et al., 2022). It is this step capturing the time-dependent drainage of clays which is omitted in elastic models. We then converted the effective stress changes into compaction (Equation 3, Lees et al., 2022); this step is the same as in elastic models. We solved for compaction many times using different parameter values until we obtained a good match between simulated deformation and observed subsidence. The methodology is described in detail for the South Hanford site in Lees et al. (2022).

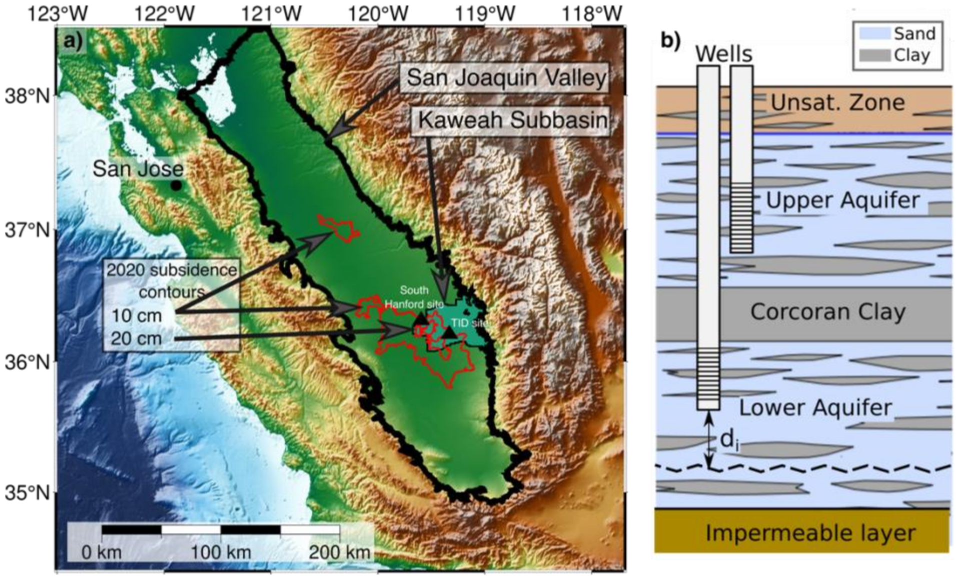

Figure 1 a) Map showing the Kaweah subbasin in relation to the San Joaquin Valley and 2020 subsidence, with 10 and 20 cm contours labelled. Subsidence contours come from TRE Altamira InSAR data, available at https://data.cnra.ca.gov/dataset/tre-altamira-insar-subsidence. The TID site and South Hanford site locations are shown by black triangles. b) the conceptual model we used for subsidence modelling.

To expand the modelling to the TID site, we gathered model inputs in a similar fashion to the South Hanford site. We took head records from seven wells to reconstruct a record of head in the coarse-matrices and we used a resistivity log and a lithology log to estimate the number and thickness of clay interbeds. Compaction models were assessed and calibrated using InSAR measurements from 2015-21 and a levelling survey from 1962-1970. To project future subsidence at both sites, we continued our models to 2080 using the projected upper and lower aquifer head pathways contained within the GSP.

Results

The simulated subsidence for both sites, as well as the historic and projected head, are shown in Figure 2. While a perfect fit was obtained with calibration data for the South Hanford site, as described in Lees et al. (2022), there was a small residual misfit at the TID site. At the South Hanford site, we projected approximately 7.8 m of subsidence between 2020-2040, and an additional 7.2 m from 2040-2080. At the TID site, we projected approximately 3.7 m of subsidence between 2020-2040, and an additional 2.9 m from 2040-2080.

Discussion

Our modeling represents a significant improvement over previous approaches used in GSPs. We include residual compaction, which is an important component as evidenced by the high rates of subsidence we simulate during 2040-80. Our simulations are based on the aquitard drainage model, which is long-established and gives physical basis to our simulations. Finally, our models are data-driven, which gives them a good physical grounding.

One downside is the limited spatial sampling: only two locations within an entire subbasin. The number of locations was low because the modelling required a large effort per site. This effort included both the collection of high-quality input data and the computational burden of the modelling itself[1]. Spatial sampling could be improved by embedding 1D compaction models into regional groundwater models, yet this would lead to lower reliability, as the compaction would be driven by modelled rather than measured head, and it would exacerbate the computational intensity. In our case, higher spatial sampling was required for the purposes of the GSP, and Montgomery & Associates took our two models and used a scheme to interpolate the results, although the accuracy of this approach was not tested (Montgomery & Associates, 2022).

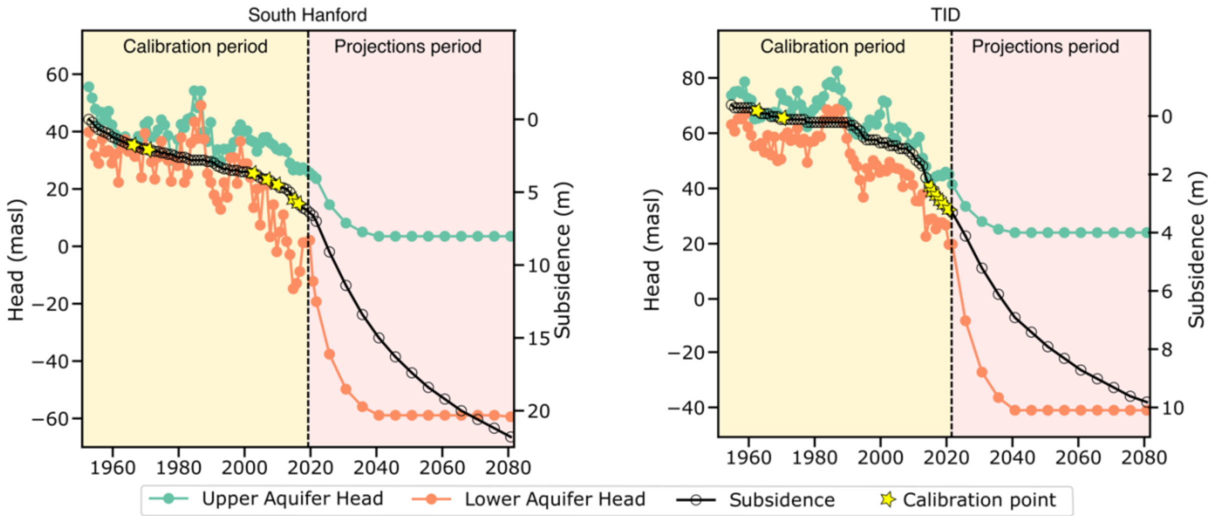

Figure 2 The input head and simulated subsidence for the two sites. The calibration period is where we used measurements of input head, tweaking input parameters until the simulated subsidence matched observations at calibration points. The projections period is where head was based on GSP-predictions and subsidence was simulated using calibration period parameters.

There remain aspects of the modeling which reduce our confidence in the predictions made. Foremost is the assumption of constant parameters. In the 1970s, Helm suggested that it is unlikely that S_{skv} will be constant with time as it is a function of stress (Helm, 1975, 1976). Nonetheless, he also found that a relatively good result could be obtained using a constant value. Helm's finding was relevant to a 20-year period, and it is unclear whether constant parameters remain a good approximation when considering the ~100+ years of subsidence required today. This may be a reason we could not perfectly fit the calibration data at the TID site. If, as is likely, S_{skv} decreases significantly between 1952 and 2080, our simulations will over-estimate subsidence.

[1] It took tens-to-hundreds of hours to run 100,000s of models at a site. This large number of models was needed to explore the parameter space for inputs such as K_v, S_{skv}, d_i and others in order to match the observed subsidence. Each model, containing up to 10 layers of different thickness clays, took 1-2 minutes.

Additionally, concerns include the lack of in-situ measurements of model inputs such as S_{skv} and K_v, which leads to a reliance on sweeping over large regions of parameter space to calibrate parameters. Finally, pumping now extends deeper than it did in the 1970s, and the lower aquifer is commonly >100 m thick. This begs the question of whether it might be necessary to divide the lower aquifer into multiple layers, each with a different head in the interconnected matrix, which could alter the results of projections.

Conclusions

1D compaction modelling for sustainable groundwater management in the SJV is a powerful tool likely to gain increasing attention in coming years. Despite its proven potential, there are important avenues of investigation and advancement for the scientific community to make in order to fully meet the management need.

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