33 Predictability of Hydraulic Head Changes and Characterization of Aquifer System Properties from InSAR-Derived Ground Deformation

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Introduction

Groundwater management relies mostly on ground-based observations, which are expensive and spatially limited. Here, we demonstrate the benefits of space-derived ground deformation measurements for characterization of aquifer properties and groundwater levels. We use Interferometric Synthetic Aperture Radar (InSAR) time-series analysis of ERS, Envisat, and ALOS data to resolve 1992–2011 vertical ground deformation in the Santa Clara Valley, California. T-mode Principal Component Analysis successfully isolates temporally variable deformation patterns embedded in the multi-decadal time series. The data reveal uplift at 4 mm/yr between 1992–2000 and >1 mm/yr in 2000–2011, illustrating the end of the poroelastic rebound following recovery of hydraulic heads after the 1960s low stand. Seasonal elastic deformation with amplitude of 3 cm is observed over the confined aquifer sharply partitioned by the Silver Creek Fault (SCF). Integration of this deformation with hydraulic head data enables characterization of basin-wide aquifer system storativity. Additionally, we show that after a period of calibration, InSAR can be used to accurately characterize water level changes without well measurements.

Approach

We use over 100 SAR acquisitions from the ERS, Envisat, and ALOS satellites to produce ~300 interferograms covering 1992–2011. We then invert a network of small-to-moderate spatial and temporal baselines interferograms, following the Small Baseline (SBAS) technique (Berardino, 2002), to retrieve time-dependent ground displacement. We focus here on the vertical deformation that we isolate by combining ascending and descending viewing geometries (Wright et al., 2004).

To separate transient patterns embedded in long-term trends without involving a priori models we use T-mode Principal Component Analysis (TPCA), a mathematical transformation of a set of inter-correlated variables into a new set of uncorrelated variables. The Principal Components (PCs) are a transformation of the time-dependent data into a set of representative spatial patterns of deformation, shown by the scores maps, which highlight a signal coherent in space but variable in time (Figure 2.33.1c). The variable gains through time are shown by the eigenvectors (Figure 2.33.1b).

Results

The change of slope of the Scree plot (Figure 2.33.1a) indicates that only the first three PCs need to be kept to represent over 90% of the data variance. The first PC corresponds to the longer-term deformation. Positive scores (red on Figure 2.33.1c) are observed in the Evergreen and Santa Clara basins. The eigenvector time series (Figure 2.33.1b, top) shows an increase (corresponding to uplift in positive-score areas) between 1992–2000 and remains nearly constant during 2000–2011. This pre-2000 uplift at 4 mm/yr can be either correlated with hydraulic head changes (short-period elastic aquifer deformation), or can be associated to delayed poroelastic rebound of aquitards due to their low hydraulic conductivity resulting in a lag of hydraulic heads compared to aquifers (Terzaghi, 1925). In the Santa Clara Valley, after the intense groundwater extraction of 1920–1965, artesian levels were reached in the early 1990 (Galloway et al., 1999), which suggest that the post-1992 deformation is due to delayed aquitards poroelastic rebound.

The second and third PCs correspond to seasonal deformation as shown by their eigenvector time-series (Figure 2.33.1b bottom). PC2 consists of spatially extensive deformation encompassing most of the confined aquifer west of the SCF with an average peak-to-peak amplitude of ~2.5 cm (Figure 2.33.1c score map PC2). Peaks in PC2 occur immediately after rainfall, also confirmed by cross-correlation analysis, which suggests elastic deformation of a highly permeable aquifer system. PC3 is limited to a ~3 km wide region west of the SCF and has an average peak-to-peak amplitude of ~0.5 cm (Figure 2.33.1c score map PC3). Peaks in PC3 occur with a time lag of ~105 days, suggesting that it corresponds to a later phase of deformation, possibly due to delayed aquitards deformation.

Using hydraulic head data from the Santa Clara Valley Water District at 50 wells we normalize the seasonal ground deformation (PC2+PC3) by the head changes to constrain the storativity, S (Burbey, 2001). The storativity represents the volume of water taken into or released from storage per unit decline in hydraulic head, per unit area, and helps define sustainable pumping rates. S is roughly constant across most of the aquifer at ~2x10⁻³ (blue on Figure 2.33.2a), in agreement with values derived from traditional techniques (Poland and Ireland, 1988). Higher storativity near the shoreline, over the Holocene Bay mud (red on Figure 2.33.2b, constrained by one well) and around the SCF (constrained by three wells) are highlighted by this basin-wide study, with values representative of clays.

Finally, we evaluate how well seasonal water level changes can be predicted from the observed deformation and calculated storativity. We estimate the storativity using 1995–2001 deformation and water data, the first time period with good InSAR temporal sampling, and examine how well we can predict 2006–2011 hydraulic head changes from InSAR data of that period (second period with good temporal sampling). The mean prediction accuracy for each 2006–2011 season, defined as 100–(100*(observations-predictions)/observations) (Wu et al., 1995) is of 70% for the entire basin (Figure 2.33.2b). The best accuracy is achieved in the confined aquifer west of the SCF, where the deformation and head changes are the largest.

Conclusion

We characterize the 1992–2011 hydrologically induced
ground deformation in the Santa Clara Valley, California, using InSAR time-series analysis. Poroelastic rebound of the aquifer system following recovery of hydraulic heads after the 1960s low stand occurs mostly prior to 2000, leading to uplift one order of magnitude smaller than its preceding subsidence.

Using TPCA we isolate temporally variable deformation embedded in the multi-decadal time-series without a priori constraints, which show the potential of TPCA for improving characterization of complex deformation. In the Santa Clara Valley two patterns of seasonal deformation exist, both sharply partitioned by the SCF, illustrating that the fault is a barrier to across fluid flow. Combining this seasonal deformation with hydraulic head data, enables characterizing of basin-wide aquifer system properties.

Finally, we show that InSAR-derived ground deformation can be used to evaluate basin-wide water level changes without well measurements with an accuracy of ~70%, which demonstrates its benefits for groundwater management.

Acknowledgements

We thank NASA for support through grant NNX12AQ32G and we thank the Santa Clara Valley Water District for their close collaboration and for sharing the hydraulic head data.

References


