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Evaluation of the potential of InSAR time series to study the spatio-temporal evolution of piezometric levels in the Madrid aquifer

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Abstract. The Tertiary detritic aquifer of Madrid (TDAM), with an average thickness of 1500 m and a heterogeneous, anisotropic structure, supplies water to Madrid, the most populated city of Spain (3.2 million inhabitants in the metropolitan area). Besides its complex structure, a previous work focused in the north-northwest of Madrid city showed that the aquifer behaves quasi elastically trough extraction/recovery cycles and ground uplifting during recovery periods compensates most of the ground subsidence measured during previous extraction periods (Ezquerro et al., 2014). Therefore, the relationship between ground deformation and groundwater level through time can be simulated using simple elastic models. In this work, we model the temporal evolution of the piezometric level in 19 wells of the TDAM in the period 1997–2010. Using InSAR and piezometric time series spanning the studied period, we first estimate the elastic storage coefficient (S_{ke}) for every well. Both, the S_{ke} of each well and the average S_{ke} of all wells, are used to predict hydraulic heads at the different well locations during the study period and compared against the measured hydraulic heads, leading to very similar errors when using the S_{ke} of each well and the average S_{ke} of all wells: 14 and 16 % on average respectively. This result suggests that an average S_{ke} can be used to estimate piezometric level variations in all the points where ground deformation has been measured by InSAR, thus allowing production of piezometric level maps for the different extraction/recovery cycles in the TDAM.

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1 Introduction

Piezometric maps are one of the most useful hydrogeological tools to manage aquifers, providing information about groundwater flow direction, interactions between groundwater and surface water and identifying groundwater recharge zones (e.g. Todd and Larry, 2005). These maps are built using discrete water level measurements in wells that are usually sparsely distributed, leading to accurate point measurements but low spatial resolution contour maps (Fasbender et al., 2008).

Here we assess the potential of InSAR data to build piezometric maps with high spatial resolution of the Tertiary detritic aquifer of Madrid (TDAM). Using InSAR-derived displacements and piezometric time series spanning 1997–2010, we first estimate the elastic storage coefficient (S_{ke}) for 19 well locations and also an average S_{ke} of all wells. We then use these coefficients to model hydraulic heads at the different well locations and compare them with in situ measurements. Finally, the implications of our results for the construction of piezometric maps and limitations of the approach are discussed.

2 Study area

The Madrid Metropolitan area is located above a triangular shape basin, the Madrid Basin, consisting of a tectonic depression filled with continental deposits of Tertiary age. The detritic facies of these deposits, located in the northwestern part of the basin, define the TDAM. This is a single, heterogeneous and anisotropic aquifer with an average thickness of 1500 m and altitudes ranging from 650 to 800 m a.s.l. (Martínez-Alfaro, 1977; Yélamos and Villarroya Gil, 2007).

3 Data used

3.1 InSAR data

We use the InSAR time series processed in Ezquerro et al. (2014), covering the period April 1992 to September 2010. These data were processed with the PSP-IFSAR technique (Costantini et al., 2008) to calculate the radar line-of-sight (LOS) displacement temporal evolution of each Persistent Scatterer (PS). See Ezquerro et al. (2014) for more details about the InSAR processing. Figure 1 shows one of the resulting deformation maps. The main deformation signal corresponds to the Fuencarral and Pozuelo Well Fields (labelled as Well Fields 1 and 2 respectively in Fig. 1), The deformation pattern follows a ∼ N45° E direction. Maximum deformation occurs at the centre of the well fields, reaching 80 mm of cumulated displacement during 1992–2010.

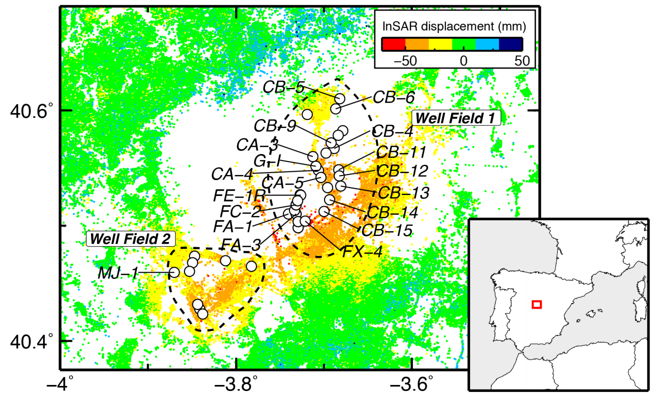

Figure 1. Location map and data distribution over the study region. InSAR deformation corresponding to an extraction episode from January 1999 to April 2000 is shown in the background. Black dashed lines outline the two well fields in the area.

3.2 Piezometric time series

We have used the water level data available for the period 1997–2010 for 19 wells distributed over the two wells fields in the study area (Fig. 1). The average depth of these wells varies between 300 and 700 m below the surface. Since 1997, these well fields have undergone three cycles of water extraction, coinciding with drought periods, with dates: February 1999–March 2000, March 2002–December 2002, April 2005–November 2006 (Fig. 2). After each extraction period there is a recovery phase of different duration. Elevation of water level during these extraction/recovery cycles varies between 390 and 600 m a.s.l.

4 Models

4.1 Estimates of elastic storage coefficients

The elastic storage coefficient (S_{ke}) can be computed by means of the graphical methodology proposed by Riley (1969), which consists of the determination of the slope of the stress–strain curve branch. Using this method, we determined the S_{ke} at well locations comparing water levels and InSAR-derived ground displacements (Fig. 2). The resulting elastic storage coefficient estimates ranged from 2.61×10^{-4} at well CB-5 in the northern part of Well Field 1 to 7.09×10^{-4} at well CB-15 in the southern part of Well Field 1, with an average S_{ke} of 4.48×10^{-4}.

4.2 Models of hydraulic head

The S_{ke} values estimated in the previous section were used to predict hydraulic head at specific well locations during the period 1997–2010. Figure 3 shows the comparison of estimated and measured hydraulic heads at two well locations. The error between observations and each of these models ranges between 10 and 28 % among the 19 wells. We also

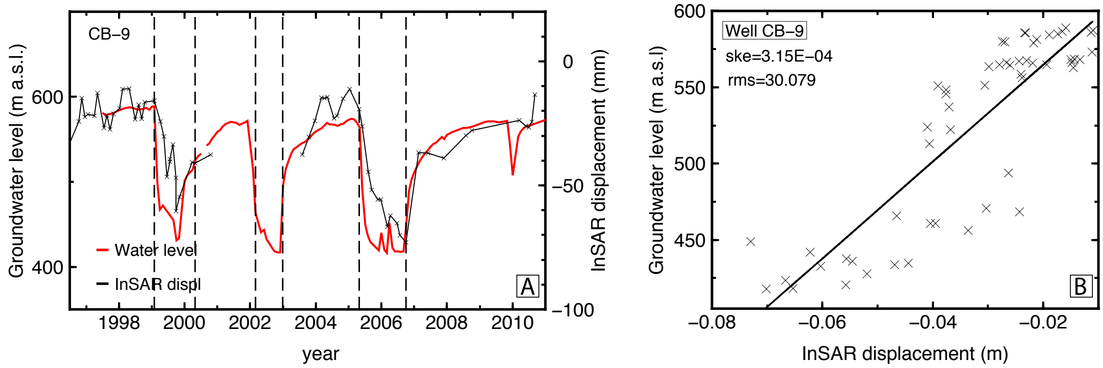

Figure 2. Estimation of skeletal elastic storage coefficient from stress displacement analysis for well CB-9 (see location in Fig. 1). On the left, InSAR displacement and piezometric time series On the right, stress-strain diagram. Vertical dashed lines represent dates limiting water extraction cycles.

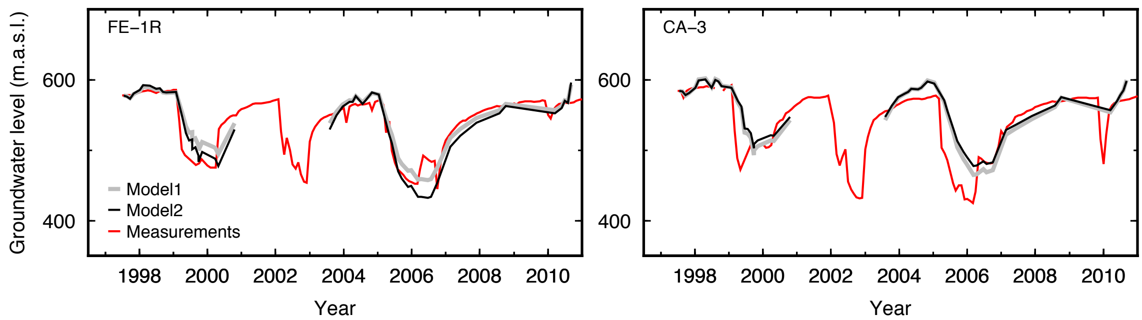

Figure 3. Estimated and measured hydraulic head at two well locations (FE-1R and CA-3). Red line represents measured hydraulic head, gray line represents estimated hydraulic head using the elastic storage coefficient S_{ke} of each well and black line represents estimated hydraulic head using the average elastic storage coefficient S_{ke} computed from all 19 wells labelled in Fig. 1.

tested a model of hydraulic heads using the average S_{ke} for all wells, which resulted in Model 2 in Fig. 3. The error using this model ranges between 10 and 24 % among the 19 wells. Therefore, both Models 1 and 2 produce very similar errors (14 and 16 % on average among the 19 wells, respectively)

5 Conclusions

Our results indicate that an average S_{ke} can be used to estimate piezometric level variations in the 19 wells analysed here. The next step would be to use the complete InSAR dataset to extend this analysis to the complete region covered by InSAR measurements (an area of 40 km × 40 km around the two Well Fields producing the observed deformation), thus allowing to produce piezometric level maps for the different extraction/recovery cycles in the TDAM. These maps will help identify and monitor vulnerable areas of the TDAM and should help mitigate future geological and geotechnical risks induced by the ongoing ground deformation.

This approach however has some limitations: (i) there is a densely vegetated area with no deformation data in the middle of our deformation region (Fig. 1). The use of geostatistical techniques would allow interpolating deformation in these regions; (ii) a piezometric initial map is necessary to add/subtract the water level differences obtained in the models. The uncertainties of this map would be incorporated to the InSAR-derived piezometric maps. All these limitations should be taken into account and appropriately assessed when producing the final piezometric maps, clearly indicating the associated error and reliability of each region.

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