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Technical Note

Multiband PSInSAR and long-period monitoring of land subsidence in a strategic detrital aquifer (Vega de Granada, SE Spain): An approach to support management decisions

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ABSTRACT

This work integrates detailed geological and hydrogeological information with PSI data to obtain a better understanding of subsidence processes detected in the detrital aquifer of the Vega de Granada (SE Spain) during the past 13 years. Ground motion was monitored by exploiting SAR images from the ENVISAT (2003–2009), Cosmo-SkyMed (2011–2014) and Sentinel-1A (2015–2016) satellites. PSInSAR results show an inelastic deformation in the aquifer and small land surface displacements (up to −55 mm). The most widespread land subsidence is detected during the ENVISAT period (2003–2009), which coincided with a long, dry period in the region. The highest displacement rates recorded during this period (up to 10 mm/yr) were detected in the central part of the aquifer, where many villages are located. For this period, there is a good correlation between groundwater level depletion and the augmentation of the average subsidence velocity and slight hydraulic head changes (<2 m) have a rapid ground motion response. The Cosmo-SkyMed period (2011–2014) coincided with a rainy period, and the land subsidence is only concentrated in some points. Rates of average subsidence up to 11.5 mm/yr are obtained for this period and are anthropogenic in origin, being related to earthmoving works. During the Sentinel-1A monitoring period (2015–2016) most of the region showed no deformation, except for some points of unknown origin in the NE sector. A general conclusion is that there is a clear lithological control in the spatial distribution of ground subsidence; all the subsiding areas detected are located where a higher clay content was identified. Although the SE sector of the aquifer had more intense groundwater exploitation, no land subsidence processes were detected, as coarse-grained sediments predominate in the substratum. This research will contribute to the drawing-up of a management plan for the sustainable use of this strategic aquifer, taking into account critical levels of groundwater depletion to avoid land subsidence in the areas identified as vulnerable. The European Space Agency satellite Sentinel-1A could be an effective decision-making tool in the near future.

1. Introduction

In many agricultural regions worldwide, prolonged groundwater exploitation has caused land subsidence related to falling groundwater levels. During recent decades, numerous cases of land subsidence related to intensive agricultural practices have been reported in many developed aquifer systems (Motagh et al., 2008; Amelung et al., 1999; Calderhead et al., 2011; Galloway and Burbey, 2011; Papadaki, 2014; Zhu et al., 2015; Farr and Liu, 2015; Faunt et al., 2016). In Spain, the most arid country in Europe,

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groundwater irrigates around one million hectares (Hernßndez-Mora et al., 2015), most of which are concentrated in some intensively exploited aquifers in the Mediterranean basin, and particularly on the SE fringe of the Iberian Peninsula. Similarly, literature also reports many cases of land subsidence related to groundwater withdrawal in susceptible aquifer systems located in SE Spain; they are usually unconsolidated alluvial or basin-fill aquifers (Herrera et al., 2009; Herrera et al., 2010; Pulido-Bosch et al., 2012; Rigo et al., 2013; Boni et al., 2015; Notti et al., 2016; Béjar et al., 2016). This kind of unconsolidated aquifer system usually has great heterogeneity in the distribution of facies and a significant proportion of compressible fine-grained materials. When subjected to water head declines that exceed critical levels, much of the compaction is related to an inelastic deformation and, consequently, the subsidence is permanent (Galloway et al., 2016).

DInSAR and more specifically, Persistent Scatterer Interferometry (PSI) approaches allow monitoring ground subsidence over large areas and for a long period of time. These techniques have been successfully applied in numerous regions affected by land subsidence where intense exploitation of aquifers occurs (Bell et al., 2008; Herrera et al., 2009; Herrera et al., 2010; González and Fernández, 2011; Ezquerro et al., 2014; Tomás et al., 2014; Farr and Liu, 2015; Tessitore et al., 2016; Boni et al., 2016; Chen et al., 2016).

The present work focuses on the Vega de Granada aquifer, located in the postorogenic intermontane Basin of Granada (SE Spain) (Fig. 1). The Vega de Granada aquifer (with an extension of 200 km^2) is one of the largest groundwater reservoirs in Andalusia and is considered of strategic importance for the economy of this semi-arid region. Ground subsidence had already been detected using DInSAR based techniques in the Vega de Granada. Fernandez et al. (2009) exploited ERS images covering a period of 7 years (from June 1993 to December 2000), and obtained deformation rates of up to 8 mm/yr in the village of Santa Fe, located in the central part of the aquifer (Fig. 1). They concluded that "*the only process which could be related to the subsidence is an intensive aquifer exploitation due to crop irrigation and urban water supply*", but the origin was not investigated in depth. Sousa et al. (2008), Sousa et al. (2010) and Notti et al., (2016) analysed ground subsidence processes related to the exploitation of a small-scale detrital aquifer on the southeastern edge of the Granada Basin, in the municipality of Otura (Fig. 1). Notti et al. (2016) integrated detailed geological and hydrogeological data with differential SAR interferometry monitoring from ENVISAT (2003–2009) and Cosmo-SkyMed (2011–2014) images. They concluded that a clear lithological control exists in the spatial distribution of the ground subsidence; the sector with highest rates of subsidence (up to 15 mm/yr) does not correspond to the area with the most intense groundwater exploitation but to the area with the greatest presence of clays.

In the present study, multiband PSInSAR measurements have been used to obtain a detailed spatial and temporal distribution of the ground surface deformation affecting the aquifer of the Vega de Granada, covering a large temporal span of 13 years (from 2003 to 2016). Synthetic Aperture Radar (SAR) images from the ENVISAT (2003–2009, C band), Cosmo-SkyMed (2011–2014, X band) and Sentinel-1A (May 2015–April 2016, C band) satellites have been exploited. Additionally, a thorough analysis of the geology and hydrogeology of the region has been carried out, and also a lithological description of the aquifer system based on the interpretation of borehole data. The integration of all these ground data with the results obtained from PSInSAR monitoring aims to give a reliable view of the processes involved in the land subsidence as well as to analyse the deformational behaviour induced by groundwater exploitation which could contribute to a future management plan for the aquifer. The European Space Agency (ESA) satellite, Sentinel-1, represents a significant improvement for land subsidence monitoring due to the shorter revisit time (6 days in the near future), which provides good coherence compared to other SAR sensors (Barra et al., 2016). In this sense, Sentinel-1 could be a very effective decision-making tool for the aquifer in coming years.

2. The study area

2.1. Geographical setting and climate

The Vega the Granada is located on the western flank of the Sierra Nevada and is very close to the metropolitan area of the city of Granada (Fig. 1). It is an almost flat region with an extension of 200 km^2, with a maximum length of 20 km and an average width of 10 km, the average altitude being 630 m a.s.l. The River Genil flows through the centre of the basin, from SE to NW, and is joined by smaller tributaries (Darro, Beiro, Dílar etc.). Traditionally, the Vega de Granada has been one of the most important agricultural regions in SE Spain with very fertile soils and both, surficial and groundwater resources. Numerous dams regulate the rivers of Granada; the Cubillas and Colomera reservoirs (Fig. 1) meet part of the demand for irrigation water from the fields of the Vega de Granada (Chacon et al., 2012). Additionally, its proximity to the city of Granada has determined important urban growth during recent decades (since the 80's) and the population has increased exponentially in most of the villages located there: Armilla, Churriana, Santa Fe, Chauchina, Atarfe, Maracena, and Vegas del Genil (Fig. 1) etc., which exerts substantial pressure on the aquifer (Chica-Olmo et al., 2014).

The climate in the region is dry-Mediterranean. The average annual precipitation is 450 mm and the average temperature lies around 15 °C. The warm season lasts from June to September with an average daily temperature above 30 °C and with very scarce precipitation. Rainfall is mainly concentrated during the autumn and winter months and rainfall data series reflect highly variable alternating periods of rain and drought (AEMET, State Meteorological Agency of Spain). Prolonged droughts have occurred in the region during recent decades. During the period spanning 1992–1995, a devastating drought (the most severe of the 20th century) took place and numerous wells had to be drilled in the eastern fringe of the aquifer to solve urban supply problems. Similar conditions (although not so prolonged) occurred again in 2004–2005, and new wells were drilled to supply the municipalities of Santa Fe, Vegas del Genil and Armilla. However, the period spanning from 2009 to 2013 was extremely rainy in the region, with accumulated rainfall at almost twice the average value (Mateos et al., 2016).

The aquifer of the Vega de Granada is a water reservoir of strategic importance with a very irregular exploitation pattern in time: (1) during summer, the water demand rises to very high values compared to the rest of the year; (2) during periods of drought, the aquifer plays a vital role in supplying water.

2.2. Geology

The Vega de Granada is located in the central sector of the Betic Cordillera and within the Granada Basin domain. The term "Granada Basin" is given to an outcrop of Neogene to Quaternary sediments lying over the NE-SW trending contact between the External and Internal zones of the Betic Cordillera. The sedimentary sequence is over 2 km thick in some areas, containing lower Miocene to Holocene sediments. The Tortonian marine sediments identified in the Basin indicate that the Alborán Sea covered this depression during the late Miocene (Galindo et al., 1999; Rodrí