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Research papers

Mapping groundwater level and aquifer storage variations from InSAR measurements in the Madrid aquifer, Central Spain

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ABSTRACT

Groundwater resources are under stress in many regions of the world and the future water supply for many populations, particularly in the driest places on Earth, is threatened. Future climatic conditions and population growth are expected to intensify the problem. Understanding the factors that control groundwater storage variation is crucial to mitigate its adverse consequences. In this work, we apply satellite-based measurements of ground deformation over the Tertiary detritic aquifer of Madrid (TDAM), Central Spain, to infer the spatio-temporal evolution of water levels and estimate groundwater storage variations. Specifically, we use Persistent Scatterer Interferometry (PSI) data during the period 1992–2010 and piezometric time series on 19 well sites covering the period 1997–2010 to build groundwater level maps and quantify groundwater storage variations. Our results reveal that groundwater storage loss occurred in two different periods, 1992–1999 and 2005–2010 and was mainly concentrated in a region of ~200 km^2. The presence of more compressible materials in that region combined with a long continuous water extraction can explain this volumetric deficit. This study illustrates how the combination of PSI and piezometric data can be used to detect small aquifers affected by groundwater storage loss helping to improve their sustainable management.

1. Introduction

Groundwater is a very precious resource that represents almost 99% of all liquid freshwater on Earth and is a fundamental source for industrial, agricultural and domestic water supply in many regions of the world (Alley et al., 2002; Zektser and Everett, 2004). Groundwater represents the main source of water for many populations and its use increases during drought periods. This contributes to generate a great stress on aquifer-systems that can lead to a loss of groundwater storage when equilibrium between withdrawals and recharge is unattainable (Döll et al., 2012; Famiglietti, 2014). A recent study using satellite measurements of Earth's gravity shows that a third of big groundwater basins are in distress threatening regional water security and resilience (Richey et al., 2015a). This problem will be exacerbated by climate change and rapid population growth particularly in densely populated areas in arid and semi-arid environments (Döll, 2009; European Union, 2016; Famiglietti, 2014; Ferrant, 2014; Taylor, 2014; Wada and Bierkens, 2014). Hence monitoring the evolution of piezometric levels and quantifying groundwater storage variations is essential for identifying vulnerable areas experiencing groundwater storage loss and achieving sustainable water management of aquifers, especially in arid areas prone to droughts.

Estimates of piezometric levels are generally based on networks of wells monitoring water level variations (Fasbender et al., 2008; McGuire et al., 2003). Unfortunately, in many regions around the

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world, groundwater levels are poorly monitored due to the high cost of piezometers and, thus, information regarding the spatio-temporal evolution of groundwater resources is extremely limited and shows a wide dispersion (Shah et al., 2000).

Groundwater storage can be estimated by combining measurements of changes in groundwater levels over time and area with estimates of storativity (Davis, 1982; McGuire et al., 2003). These studies are generally based on punctual measurements, leading to a high uncertainty in the estimated groundwater storage (Famiglietti, 2014; Richey et al., 2015b). Recently, studies based on satellite measurements of gravity changes over time have greatly improved the monitoring of groundwater level changes and storage variations (Forootan et al., 2014; Famiglietti, 2011; Feng et al., 2013; Jiao et al., 2015; Richey et al., 2015a; Tangdamrongsub et al., 2016; Voss et al., 2013), helping to identify large areas where groundwater depletion is occurring and quantify the loss of groundwater storage. These studies are very useful to detect large-scale groundwater storage variations, but lack the spatial resolution to characterize and monitor small-scale water loss. Satellite-based methods to measure terrain deformation, specifically Differential Interferometric Synthetic Aperture Radar (DInSAR) and Persistent Scatterer Interferometry (PSI) techniques, have been successfully used to detect and monitor aquifer-related deformation (e.g., Colesanti et al., 2003; Lanari et al., 2004; Schmidt and Burgmann, 2003), estimate aquifer hydraulic properties (e.g., Hoffmann et al., 2001; Tomás et al., 2009; Ezquerro et al., 2014) and model hydraulic head at well locations (e.g., Reeves et al., 2014; Chen et al., 2016). Finally, the potential of InSAR and PSI techniques to predict water level changes at basin scale has been evaluated, with promising results (e.g., Chaussard et al., 2014; Chen et al., 2016; Castellazzi et al., 2016).

The situation of groundwater reserves in Spain, which is the most arid country in Europe, is largely unknown because the number of private extraction wells remains uncertain, and thus the pumped volumes are not known (Hernández-Mora et al., 2007; Llamas and Garrido, 2007; WWF/Adena, 2006). The Tertiary detritic aquifer of Madrid (TDAM), in central Spain (Fig. 1) is of strategic importance because it provides water to Madrid, the most populated city of Spain (3.2 million inhabitants in the metropolitan area), during drought periods. Numerical models for the entire aquifer suggest that piezometric levels tend to decline due to groundwater extraction, even when simulated scenarios include recovery periods (Iglesias-Martín, 2005; Martínez-Santos et al., 2010). These regional studies could be uncertain since they are based on discrete water level measurements obtained in wells and piezometers. In this study, we reduce this hydrogeological uncertainty taking advantage of the spatial coverage of PSI data to map in detail the evolution of groundwater level and groundwater storage in two extractions areas of the TDAM along several extraction/recovery periods.

This paper is organized as follows. In Section 2, we give an overview of the Tertiary detritic aquifer of Madrid, including its main characteristics and deformation behaviour according to previous studies. In Sections 3 and 4, we summarize the PSI and piezometric data and we describe the methodological approach. In Section 5, we show the main results regarding the stress-strain analyses at 19 wells, the predicted groundwater levels and the groundwater storage variations. Finally, the potential factors controlling the observed groundwater loss and the implications of our results for the management of water extractions during future droughts in the TDAM are discussed.

2. The Tertiary detritic aquifer of Madrid

The TDAM is located in the northwest part of the Madrid basin (Fig. 1a), a tectonically controlled, triangular shape basin of

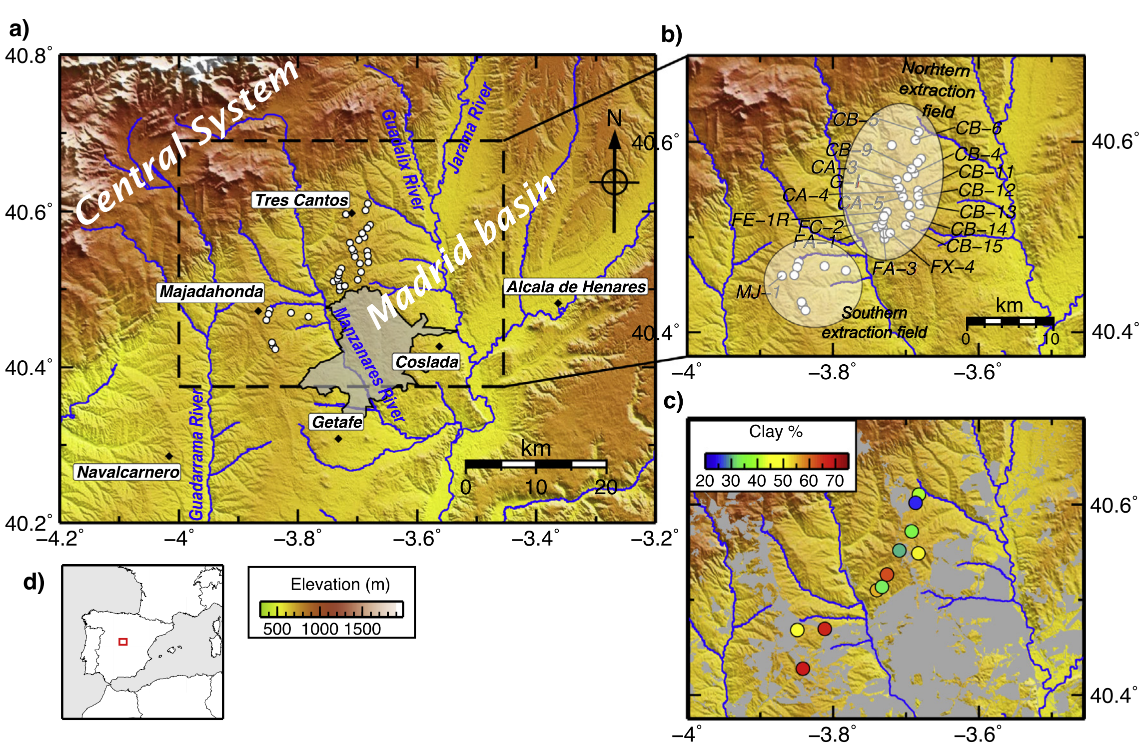

Fig. 1. Location map. (a) White dots show wells location (see zoom in b). Blue lines indicate main rivers in the area. The semi-transparent grey polygon in the centre shows the location of the Madrid urban area. The black-dashed rectangle outlines the region shown in b. SRTM-90 Digital Elevation Model was used to generate the background topography. (b) White dots indicate the well sites. Names for the 19 well sites used in this study are indicated. The semi-transparent ellipses indicate the location of the two extraction areas. (c) Urban areas are depicted in grey (http://www.eea.europa.eu/data-and-maps/data/urban-atlas). The percentage of clays at 11 well locations is shown as coloured circles (9 of them were compiled by Ezquerro et al. 2014 and the other 2 were compiled in this study). (d) Location of the study region in central Spain. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)