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A quasi-elastic aquifer deformational behavior: Madrid aquifer case study

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ABSTRACT

The purpose of this paper is to analyze the quasi-elastic deformational behavior that has been induced by groundwater withdrawal of the Tertiary detrital aquifer of Madrid (Spain). The spatial and temporal evolution of ground surface displacement was estimated by processing two datasets of radar satellite images (SAR) using Persistent Scatterer Interferometry (PSI). The first SAR dataset was acquired between April 1992 and November 2000 by ERS-1 and ERS-2 satellites, and the second one by the ENVISAT satellite between August 2002 and September 2010. The spatial distribution of PSI measurements reveals that the magnitude of the displacement increases gradually towards the center of the well field area, where approximately 80 mm of

maximum cumulated displacement is registered. The correlation analysis made between displacement and piezometric time series provides a correlation coefficient greater than 85% for all the wells. The elastic and inelastic components of measured displacements were separated, observing that the elastic component is, on average, more than 4 times the inelastic component for the studied period. Moreover, the hysteresis loops on the stress-strain plots indicate that the response is in the elastic range. These results demonstrate the quasi-elastic behavior of the aquifer. During the aquifer recovery phase ground surface uplift almost recovers from the subsidence experienced during the preceding extraction phase. Taking into account this unique aquifer system, a one dimensional elastic model was calibrated in the period 1997-2000. Subsequently, the model was used to predict the ground surface movements during the period 1992–2010. Modeled displacements were validated with PSI displacement measurements, exhibiting an error of 13% on average, related with the inelastic component of deformation occurring as a long-term trend in low permeability fine-grained units. This result further demonstrates the quasi-elastic deformational behavior of this unique aquifer system.

Keywords: DInSAR, subsidence, uplift, PSI, elastic behavior, monitoring.

1

2 1. INTRODUCTION

3 Subsidence caused by underground water extraction increasingly affects major cities in
4 the world such as Mexico City (Mexico), Bologna (Italy), Houston-Galveston (USA),
5 Tokyo (Japan), Bangkok (Thailand) and Kolkata (India) (Osmanoglu et al., 2008,
6 Strozzi et al., 2003, Gabrysch, 1976, Yamamoto, 1995, Phien-wej et al., 2006,
7 Chatterjee et al., 2006). The relationship between groundwater level changes and
8 aquifer system consolidation can be explained by means of Terzaghi's effective stress
9 principle (Terzaghi, 1925). According to the soil consolidation curve, a reduction of
10 voids occurs in the soil (i.e. consolidation) when piezometric level declines (i.e.

11 effective stresses increase) inducing ground subsidence. Conversely, when
 12 piezometric levels recover (i.e. effective stress decrease), the soil undergoes an
 13 expansion that generates a surface uplift with a magnitude that depends on its
 14 deformational properties. Terzaghi's one-dimensional diffusion equation was extended
 15 by Riley (1969) and Helm (1975, 1976) to explain the aquitard drainage delay when
 16 hydraulic heads are lowered in adjacent aquifers, and the residual compaction of
 17 aquitards long after aquifer hydraulic heads are lowered. Soil deformation phenomena
 18 may produce damages on urban structures and infrastructures, causing important
 19 economic impacts on developed societies (Galloway and Burbey, 2011) and warning
 20 about the importance of monitoring those areas.

21 In this framework, effective and efficient subsidence monitoring is a key issue to
 22 improve prevention and mitigation within urban management strategies. Classical
 23 ground subsidence monitoring techniques are leveling topographic networks,
 24 permanent GPS measurements and extensometers (Galloway and Burbey, 2011;
 25 Tomás et al., 2014). The first two techniques measure total surface displacement, while
 26 the extensometric boreholes measure deformation of underground soil layers.
 27 However, these techniques are only able to monitor a limited amount of points due to
 28 their cost. In order to monitor large urban areas Differential Synthetic Aperture Radar
 29 Interferometry (DInSAR) and advanced DInSAR (A-DInSAR) techniques have proven
 30 to be cost effective. A-DInSAR or Persistent Scatterer Interferometry (PSI) techniques
 31 belongs to a family of algorithms based on the simultaneous processing of multiple
 32 interferograms derived from a large set of Synthetic Aperture Radar (SAR) images
 33 (Ferretti et al., 2000; Berardino et al., 2002; Mora et al., 2003; Arnaud et al., 2003;
 34 Werner et al., 2003; Hooper et al., 2004); Costantini et al., 2008). PSI techniques are
 35 able to provide dense surficial displacement measurements over large areas (Tomás et
 36 al. 2014).

37 The purpose of this paper is to analyze the quasi-elastic deformational behavior that
38 has been induced by groundwater withdrawal of the Tertiary detritic aquifer of Madrid
39 (TDAM), which is a strategic resource for the most populated city of the country. The
40 paper is organized as follows. Section 2 introduces the TDAM. Then details about the
41 radar satellite images, the PSI processing and the estimated displacement
42 measurements are described. The discussion is focused firstly on the spatial and
43 temporal analysis of measured displacements with respect to well locations and the
44 piezometric time series. Then a one dimensional numerical elastic model is proposed
45 and validated with PSI measurements.

46

47

48 2. THE STUDY AREA

49 The Madrid Metropolitan area is underlain by a large Tertiary detritic aquifer (TDAM),
 50 which has formed in a large tectonic depression (6,000 km²) that was filled with
 51 continental deposits of Tertiary age. The boundaries of the basin (Fig. 1) are the
 52 Guadarrama Range and Somosierra ranges to the north-northwest, and the Toledo
 53 Mountains to the south. The rivers Manzanares and Henares drain this part of the
 54 basin, contributing to the Jarama River, which is tributary of Tajo River. Altitudes of the
 55 Madrid Aquifer range from 650–800 m a.s.l and the altitudes of the surrounding
 56 mountains range from 1,000–2,400 m a.s.l. According to the National Meteorological
 57 Agency (AEMET), average rainfall is between 620 mm/yr, and up to 2,000 mm/yr in the
 58 mountains. Part of it is as snow lasting several months in the north-northwest ranges.
 59 The period of July–August is dry (Hernandez-Garcia and Llamas 1995).

60 Paleozoic schists and granites from the central mountain range bound the basin from
 61 the southwest to north, and account for the impervious basement of the aquifer.
 62 Erosional deposits of Tertiary age fill the tectonic depression, changing from northwest
 63 to southwest from detritic to evaporitic facies. These deposits result from a classic
 64 superimposed alluvial fan configuration. Low permeability sediments near the Central
 65 Range are heterogeneous in size, ranging from silts and clays to boulders. This is
 66 followed by a more permeable band made of arkosic sand lenses embedded in a clay
 67 and clay-sand matrix that constitute the main body of the TDAM (Fig. 2). These
 68 deposits gradually evolve into very low permeability evaporitic deposits towards the
 69 southeast (Martínez-Santos et al, 2010). According to Martínez-Bastida et al. (2009)
 70 and IGME (1981, 1985), TDAM is a heterogeneous and anisotropic aquifer with an
 71 average thickness of 1500 meters and variable transmissivity ($1 - 852 \text{ m}^2 \text{ day}^{-1}$) (IGME
 72 1985). Fig. 2 shows the lithological columns of wells included along the AB cross
 73 section shown in Fig. 1. There is a clear increase of low permeability deposits towards
 74 the Pozuelo de Alarcon well field, since it is located further away from the mountain

75 range to the southwest, being closer to the very low permeability facies. The same
 76 transitional facies is observed in depth according to Vicente and Muñoz-Martín (2012).
 77 The contact between Intermediate Miocene sands and Lower Miocene clays or sandy
 78 clays is placed about 300 meters deep for the study area. This has been observed in
 79 most of the available boreholes, where less permeable detritic materials (clay and clay-
 80 sand matrix) are thicker with depth (Fig. 2).

81 *(Figure 1)*

82 The strongest increase in population growth for Madrid City (1900%) occurred between
 83 the 1940s and the 1970s due to rural-urban migration. From the 1970s to 1990s the
 84 population of Madrid City decreased in order to a migration from City center to
 85 metropolitan area and commuter towns. Since then metropolitan area of Madrid has
 86 experienced a steady growth and reached 3.2 million inhabitants in 2011. An
 87 additional 10% growth is expected in the next decade. Natural water supply of the city
 88 is provided by reservoirs located in the north mountain ranges (Comunidad de Madrid).
 89 The combination of drought periods and the rapid population growth (Martínez-Santos
 90 et al., 2010) has made it necessary to also exploit groundwater. Since 1970, a network
 91 of 70 wells provides water during droughts with a capacity between 60 and 80
 92 hm³/year. TDAM has estimated renewable resources capacity of 120-150 hm³/year.
 93 This aquifer is additionally exploited by industries, agricultural activities and water
 94 supply of minor municipalities, accounting for 54 hm³/year (López-Camacho et al.,
 95 2006).

96 In this study we focus on Fuencarral and Pozuelo de Alarcón well fields located in the
 97 north-northwest of Madrid City (Fig. 1) that covers an area of 500 km². The former is
 98 composed by 32 wells and 26 piezometers with an average depth between 300 and
 99 700 meters below the surface. The latter, is formed by numerous minor wells less than

200 m deep, which are usually exploited by private individuals. Therefore piezometric data is not available for these wells.

Since 1990, these well fields have undergone five cycles of extraction/recovery (Tab. 1) coinciding with drought periods. Year 2005 was extremely dry with 400 mm of rain (AEMET, 2006) and provides important information during second data set. The relationship between drought and extraction periods underpins the increasing importance of aquifer management in the framework of climate change effects in major Mediterranean cities and metropolitan areas, such as Madrid.

(Table 1)

(Figure 2)

3. PSI PROCESSING AND RESULTS

3.1 SAR dataset and PSP-IFSAR processing

Persistent Scatterer Interferometry (PSI) techniques are based on the identification and exploitation on SAR images of individual radar reflectors, or persistent scatterers (PS), which are smaller than the resolution pixel cell and remain coherent over long time intervals in order to develop displacement time series (Ferretti et al., 2001). The resolution that is achieved by the identification of these PS targets effectively results in the creation of a dense data set consisting of ground “benchmarks” (Bell et al., 2008). The identification of stable scatterers is carried out by analyzing the time series of the radar amplitude values, and by looking for persistent, bright radar reflectors, most commonly fixed dihedral structures, such as buildings or other similar objects. The main advantages of PSI techniques are: the exploitability of most of the available SAR images since good phase coherence is obtained regardless of geometrical baseline (perpendicular separation of the satellite positions); the atmospheric phase contributions removal from the deformation phase signal through the use of an atmospheric phase screen (APS) analysis, which is determined for each radar

126 acquisition and subtracted from the total phase residuals derived from the
 127 interferometry process; the generation of long deformation time series through the
 128 exploitation of more than 20 radar scenes.

129 In this study two different satellite data sets obtained from the European Space Agency
 130 (ESA) were processed using the PSP-IFSAR technique. The first set contains 50 ERS
 131 satellite SLC SAR images in a descending track mode between April 1992 and
 132 November 2000. The second set contains 31 ENVISAT satellite SLC SAR images in an
 133 ascending track mode taken between August 2003 and September 2010. Selected
 134 master images for image coregistration are the 7th of January 1998 for the ERS
 135 dataset and the 5th of June 2007 for the ENVISAT dataset.

136 Both datasets were processed with the PSP-IFSAR technique (Costantini et al., 2008)
 137 to calculate the radar line-of-sight (LOS) displacement temporal evolution of each PS
 138 and to estimate the average velocity from both temporal datasets. Interferograms were
 139 generated from pairs of SAR images with a perpendicular spatial baseline smaller than
 140 1198 m, a temporal baseline shorter than 2089 days and a relative Doppler centroid
 141 difference below 321 Hz, for both analyzed periods. The digital elevation model (DEM)
 142 of the Shuttle Radar Topography Mission (SRTM) has been used to remove
 143 topographic effects. The point target (PS) selection for the estimation of displacements
 144 was based on a combination of several quality parameters including low amplitude
 145 standard deviation and high model coherence.

146 **3.2 PSP-IFSAR results**

147 The PSP-IFSAR technique yielded 1,300,000 PS on a 100 km by 100 km area. The
 148 reference points used for each period are located in a stable area 25 km northwest
 149 from Madrid City. The main deformation signal detected in the study area corresponds
 150 to the Fuencarral and Pozuelo Well Fields, located on the north-northwestern part of
 151 TDAM. For this reason, a 40 km by 40 km subset area containing 250,000 PS centered

over these areas was selected to study the displacements estimates in greater detail (Fig. 1).

During the period 1992 – 2000, the whole study area shows an average cumulated displacement of -34.9 ± 22.0 mm, with values ranging from 44.1 to -144.8 mm (Fig. 4a). Within this period subsidence rate accelerations coincide with aquifer extraction periods, showing uplift during aquifer recovery (Table 1). The spatial analysis of the retrieved displacements indicates three zones with different deformational behavior. The Fuencarral extraction well field (zone 1 in Fig. 4), which is the target of this work, presents a subsidence/uplift behavior that correlates well with aquifer extraction/recovery periods (Fig. 6). The second zone corresponds to central-southern Madrid City, which shows an overall stable behavior, with an average deformation of -7.5 ± 13.2 mm (zone 2 in Figs. 4 and 6). Finally to the southwest, Pozuelo de Alarcón well field (zone 3 in Figs. 4 and 6) shows a continuous subsidence behavior similar to other described case studies such as Murcia City (Tomás et al., 2005; 2009; Herrera et al., 2009). In this zone, during the 1992-2000 period, accelerated subsidence during aquifer extraction is followed by a slower subsidence or a slight uplift during aquifer recovery (Fig. 5). This elasto-plastic behavior can be explained by the greater presence of clays observed in this part of the aquifer (Fig. 2) and by the higher concentration of private wells exploited by local entities and individuals for water supply. Unfortunately, no piezometric data are available to confirm this hypothesis.

The period 2003-2010 is characterized by a general uplift (2.8 ± 11.1 mm, see Table 1). This period includes the longest aquifer extraction episode that lasted from April 2005 to November 2006, and resulted in the greatest cumulative subsidence in the area (17.7 ± 16.7 mm on average, see Table 1) equivalent to 12.3 mm/year subsidence during 20 months (extraction 5 Fig. 6). It also includes the longest recovery period that lasted from December 2006 to December 2011 and resulted in the greatest cumulative uplift in the area (10.9 ± 17.2 mm on average, see Table 1) that represents 3.1

179 mm/year uplift during 60 months. Similarly to the previous time span, there are also
 180 three zones that exhibit different deformational behavior. Central-southern Madrid City
 181 (zone 2 in Fig. 4) remains stable (-5.5 ± 9.2 mm). Measured displacements around the
 182 Fuencarral extraction well field (zone 1 in Fig. 4) showed the same fast response to
 183 aquifer extraction/recovery periods (Fig. 5) exhibited in the period 1992-2000. Finally,
 184 Pozuelo de Alarcón well field (zone 3 in Fig. 4) showed a slightly different deformation
 185 pattern compared to the previous period. The magnitude of measured subsidence is
 186 smaller and there is a slight uplift that could not be appreciated previously (Fig. 5). This
 187 positive displacement (13.8 mm on average) is 4.6 times smaller than that registered in
 188 Fuencarral extraction well field (63.4 mm on average). Assuming that the piezometric
 189 evolution of both well fields is similar, it seems that the greater content of clays and
 190 sand-clays in Pozuelo de Alarcon field (Fig. 2) is responsible for either a slower elastic
 191 aquifer recovery after its exploitation, or to an elasto-plastic deformation of those clayey
 192 layers. However this hypothesis cannot be evaluated in more detail because of the lack
 193 of piezometric data in Pozuelo de Alarcon field and of geotechnical laboratory tests.

194 Only one permanent GPS station is available in the north edge of Fuencarral well field.
 195 According to Valdes et al. (2012) GPS continuous data gathered since the beginning of
 196 2009 exhibits a subsidence/uplift trend that could be related with aquifer
 197 extraction/recovery phases. Even though the common temporal period is too short (5
 198 months) to perform a validation both time series have been compared. The purpose of
 199 this comparison is to demonstrate that within the period March to September 2010,
 200 both techniques measure the same trend of the ground surface, i.e. uplift, characteristic
 201 of the fifth recovery cycle of the TDAM (recovery 5 in Fig. 6). In order to do so, radar
 202 ground targets (PSs) located 50 m around the GPS station have been selected and
 203 averaged. Mean line of sight (LOS) displacement time series have been projected in
 204 the vertical direction so they are comparable with GPS vertical measurements. A good
 205 agreement can be observed between the PSI and GPS measurements (Fig. 3), since

206 they both measure the same uplift trend, identifying similar acceleration and
207 deceleration events.

208 (Figure 3)

209 (Figure 4)

210 (Figure 5)

211

212 **4. Analysis of aquifer system exploitation cycles**

213 **4.1. Regional analysis**

214 The influence area of the aquifer system exploitation has been assessed by the
215 relationship between the differential displacements measured for every extraction-
216 recovery phase with respect to the distance to the wells (Fig. 6a). For this purpose in
217 every extraction/recovery cycle, we have computed the average differential
218 displacement measured in those PSs included within different buffer areas defined by a
219 distance from the wells varying from 500 to 10,000 m. As it is shown in Fig. 6b, ground
220 displacement was rather homogeneous and intense from 500 to 4,000 m, reaching a
221 nearly stable behavior from 7,000 m to 10,000 m. Therefore, the greatest influence
222 area of the aquifer exploitation is limited to the 4,000 m radius circle around the wells
223 and to a lower extent, within 7,000 m.

224 (Figure 6)

225 The overall balance of the differential displacement measured for every
226 extraction/recovery cycle within the 4,000 m radius influence area reveals a regional
227 subsidence of 31.8 mm (Table 2) and 22.9 mm excluding cycles 3 and 4, which were
228 not fully covered by SAR images. This balance was reduced to a 22.7 and 16.2 mm
229 subsidence, respectively, measured within 500 m distance from the wells (Table 2).
230 These results evidenced that aquifer exploitation in the period 1992 – 2010, produced a

regional 20-30 mm subsidence that was smaller (10-20 mm) nearby the wells, where a greater uplift was measured during the recovery phases.

(Table 2)

The relationship between differential ground surface displacement and the duration of the extraction-recovery phases for every cycle has been also analyzed. For this purpose the uplift - subsidence ratio (SR) and the cycle temporal ratio (TR) were calculated (Table 2). The SR represents the ratio between ground surface uplift (δ_{uplift}) measured during the recovery phase with respect to the subsidence (δ_{subs}) measured in the extraction phase (i.e. $\delta_{\text{uplift}}/\delta_{\text{subs}}$) expressed in percentage. The TR corresponds to the relationship between the duration of the recovery (t_{recov}) over the duration of the extraction (t_{extract}) also expressed in percentage (i.e. $t_{\text{recov}}/t_{\text{extract}}$). According to current management practices, TR should be between 2 and 4 for a good aquifer recovery.

For the first cycle, ground surface subsidence associated with the extraction phase decelerated during the recovery phase, when no net uplift was measured (SR=0%, TR=0.9). In the cycle 2 recovery phase, there was a clear uplift that compensates both the subsidence produced during the extraction phase of cycle 2 and part of the first one (SR=126% and TR=3.7). The third and fourth cycles cannot be analyzed because the satellite data for these periods were incomplete. Cycle number 5 includes the longest extraction that produced the greatest subsidence in whole period 1992-2010, followed by a long recovery phase responsible for an uplift that compensated 75% of the previous subsidence (SR=75%, TR=3). This analysis suggests that for this aquifer system, the greater the cycle temporal ratio the greater the uplift-subsidence ratio.

4.2. Temporal analysis and modeling

Displacement time series obtained from the analysis of ERS SAR images (1992-2000) and ENVISAT SAR images (2003-2010) were compared with water level data available for the period 1997-2010 for 17 wells (Fig. 9). For this purpose the average

257 displacement time series of all the PS located closer than 500 m around each well
 258 have been calculated. A high correlation coefficient (r) is observed between
 259 displacement time series and water level variation ranging from 0.64 to 0.92, with an
 260 average value of 0.85 ± 0.07 . A quasi-elastic deformational behavior of the aquifer
 261 system can be assumed taking into account the great linear correlation obtained
 262 between piezometric level changes and aquifer system displacements. As a first
 263 approximation, the inelastic component of deformation occurring as a long-term trend
 264 in low permeability fine-grained units is removed from the stress-strain data (Fig. 7)
 265 following Sneed and Galloway (2000). Moreover the elastic/inelastic deformation ratio
 266 ($R_{ed/id}$) was calculated (Tab. 3). The inelastic component was calculated as the slope of
 267 the line fitted by a minimum square regression multiplied by the monitoring time span.
 268 The elastic component represents the difference between the maximum and minimum
 269 deformation measured during the monitoring period (i.e. the maximum amplitude of the
 270 displacements measured during the different extraction-recovery phases for the
 271 monitored period). Values higher than 1 indicates a dominant elastic behavior and
 272 positive values a predominantly inelastic behavior. In the case of the TDAM, this ratio
 273 range from 1,66 to 10,36. Thus the elastic component is on average 4,34 times the
 274 inelastic component of TDAM deformation.

275 For this reason we assume that aquifer system pore pressure (or hydraulic head)
 276 quickly equilibrates with piezometric level changes of the most permeable layers,
 277 proposing a one-dimensional elastic model to simulate ground subsidence due to water
 278 level changes. Note that this assumption implies no consolidation when the piezometric
 279 level is stable. Also the delay between hydraulic head changes and aquifer system
 280 deformation would not be significant, as can be seen in Figs. 8 and 9.

281 *(Figure 7)*

282 Consequently, the vertical displacements (δ) only depend on the magnitude of the
283 hydraulic head change (Δh) and the deformational properties of the aquifer system.
284 Hence, modifying the equation proposed by Hoffman (2003, eq. 2.15):

$$285 \quad \delta = \Delta h \times S_{sk} \times D = \Delta h \times S_k \quad (1)$$

286 where S_{sk} is the the skeletal specific storage, D is the aquifer system thickness, and S_k
287 is the skeletal storage coefficient (dimensionless) of the aquifer system. S_{sk} and S_k are
288 related with the widely used storage coefficient, S , by means of:

$$289 \quad S = S_s \times D = (S_{sk} + S_{sw}) \times D \quad (2)$$

290 where S_{sw} is the water specific storage, and S_s is the specific storage defined as the
291 volume of water expelled per unit area from a layer of thickness D due to a unit decline
292 in the hydraulic head (Todd, 1980). Note that in an aquifer system, water is derived
293 from two processes (e.g. Sneed and Galloway, 2000): a) void changes, which causes
294 the compaction or expansion of the aquifer system caused by the effective stress
295 changes, and; b) from the expansion or compression of the water owing to a change in
296 pore pressure. The first process, which for unconsolidated aquifer systems is the
297 dominant process, is controlled by the skeletal specific storage, and strongly depends
298 of the grain-size of the aquifer system. For aquitards S_{sk} from equation (1) represents
299 the deformability of the aquitards and varies with the stress state (Sneed and Galloway,
300 2000). When the stress induced by the hydraulic head variation exceeds the maximum
301 preexisting stress, i.e. preconsolidation stress, deformations are very high and mainly
302 irrecoverable due to soil rearrangement and compaction. However, if induced stress
303 does not exceed the preconsolidation stress the deformations are much smaller and
304 mostly elastic. This different soil behavior can be introduced to eq. (1) by assigning two
305 different skeletal specific storages, elastic (S_{ske}) and anelastic (S_{skv}), according to the
306 state of stress with respect to the preconsolidation stress. However, typically for
307 coarse-grained deposits within aquifers inelastic deformation is negligible and S_{ske} is

used regardless of the preconsolidation stress (Sneed and Galloway, 2000). In this case study, as previously mentioned, the aquifer system exhibits a clear elastic behavior, the piezometric seasonal changes present similar amplitudes, and the soil is mainly composed of coarse material (sands). Consequently, eq. (1) is rewritten as:

$$\delta = \Delta h \times S_{ske} \times D = \Delta h \times S_{ke} \quad (3)$$

Where 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 (the elastic branch in this case). Note that this methodology for computing storage coefficients has been widely used by other authors using InSAR derived and borehole extensometers derived displacements (Hanson, 1989; Sneed and Galloway, 2000; Hoffman, 2003; Hoffmann et al., 2003; Burbey, 2003; Tomás et al., 2006; Galloway and Hoffmann, 2007; Zhang et al., 2007a,b; Tomás et al., 2010).

In this work, the elastic storage coefficients S_{ke} of aquifer has been computed for the period 1997-2000 using piezometric series for the 17 available wells where DInSAR retrieved deformations are also known (Fig. 8). These data allowed plotting the stress-strain curves that represent the relationship between piezometric level changes and aquifer system deformations, from which elastic storage coefficients were determined following the expression:

$$S_{ke} = \frac{\Delta D}{\Delta h} \quad (4)$$

Where ΔD is the displacement caused by a Δh piezometric level decrease. S_{ke} was calculated during the third extraction of each well as shown in Fig. 8.

Additionally, the aquifer storage coefficient (S), commonly used in the groundwater flow equation, was calculated as:

$$S = S_w + S_{ke} = S_{sw} \times b + S_{ke} \quad (5)$$

Where S_{sw} is:

$$S_{sw} = (n \times \gamma) / E_w \quad (6)$$

where n is the porosity of the aquifer (varying from 1 to 20% according to Rodriguez, 2000), γ is the unit weight of water ($9.81 \times 10^3 \text{ N/m}^3$), E_w is the bulk modulus of elasticity of water ($2.15 \times 10^9 \text{ Pa}$) and b the thickness of the aquifer layers. S was computed only in those wells where lithological data were available (Tab. 3).

(Figure 8)

The hysteresis loops on the stress-strain plot (Figure 8) indicate that the response is in the elastic range. The loops correspond to the aquifer extraction and recovery periods. As it can be seen, data dispersion is low, indicating that there is a good temporal correlation and a small irrecoverable compaction (Zhang et al., 2013). This fact indicates that the aquifer system exhibits a quasi-elastic behavior. The computation of S_{ke} has been performed considering the extraction phase of the first cycle (Fig. 8). The computed elastic storage coefficients (S_{ke}) for the available wells of the TDAM vary from 1.12×10^{-4} to 4.68×10^{-4} , with an average value of $2.99 \times 10^{-4} \pm 9.30 \times 10^{-5}$ (Tab. 3). Taking into account the sandy composition of TDAM, the S_{ke} has been considered to predict subsidence from the rest of the piezometric level time series (1997-2010). In the Following, DInSAR data are used to validate the robustness of the model.

(Table 3)

Fig. 9 shows modeled and DInSAR based displacement time series for six wells, whereas the statistics of the comparison between the model and DInSAR values is summarized in Table 4. The average absolute difference between DInSAR and modeling time series is of $8.2 \pm 2.8 \text{ mm}$, being defined as a quality indicator of the fit

355 between both time series. This error has been compared with the maximum measured
 356 DINSAR displacement for every well (Table 4). Consequently, an average relative error
 357 of $13 \pm 3\%$ has been obtained for all the wells considering the period from 1997 to
 358 2010. Excluding the calibration period (1997-2000) this relative error increases slightly
 359 to $16 \pm 4\%$. However, this error is clearly observed in the 2005-2007 extraction cycle,
 360 where the model underestimates ground settlements measured with DInSAR. This
 361 mismatch between both time series can be related to the duration of this extraction
 362 cycle (20 months), which is 1.5 times the extraction cycle from the period 1999-2000
 363 (13 months). A longer duration of the extraction cycle permits the aquitards composed
 364 by less permeable materials (clays and clay-sands) gradually to reduce water pore
 365 pressure, increasing effective stress and producing a greater consolidation of these
 366 materials than in shorter extraction cycles. However, even though the extraction cycle
 367 duration was 53% longer, there is only a $13 \pm 3\%$ error in the model–DInSAR time
 368 series comparison. This fact is specially noted in FA-1, FC-2 and FE-1 wells, where the
 369 clay & clay-sand percentage is 25% greater than in the rest. For instance in the wells
 370 depicted in Fig. 9 this content varies from 25% in the North East of the study area (CB-
 371 6) to the 68% in the South West (PM-7).

372 (Table 4)

373 (Figure 9)

374 5. Discussion and Conclusions

375 Most of the available literature case studies describe plastic or elasto-plastic aquifer
 376 deformation. These aquifers are usually overexploited and exhibit a continuous
 377 piezometric decline together with seasonal variations that are responsible for
 378 continuous plastic deformation and cyclic elastic deformations. Galloway and Hoffmann
 379 (2007) reviewed the deformational behavior of several aquifer systems in United
 380 States. In Antelope Valley (California) 10 m seasonal ground water level changes

381 triggered a ± 5 mm elastic deformation and a plastic deformation that reached 60 mm
 382 after 4 years. In other works, intermittent extractions triggered a deceleration of ground
 383 surface response. Liu et al. (2004b) described cumulated subsidence of 1.8 m related
 384 to a 30 m decrease of groundwater level during 20 years in a multilayer aquifer system
 385 in Taiwan. During this time span subsidence deceleration could be explained by a
 386 smaller groundwater level decline. Liu et al. (2004a) observed that although the
 387 piezometric level of the Choshui River alluvial fan aquifer system increased, ground
 388 uplift was not observed. Zhang et al. (2013) described subsidence phenomenon in the
 389 multilayer confined aquifer of Beijing city plain. In this case Long term deformation (80
 390 cm in the past 40 years) was related to a historical groundwater level drawdown of 20
 391 m. This elasto-plastic deformation occurred mainly below 60 m deep, whereas in the
 392 surficial aquitard and aquifer layers a ± 2 mm elastic deformation was triggered
 393 instantaneously by 10 meters of groundwater level variation.

394 In our particular case study, TDAM exhibits a quasi-elastic aquifer deformational
 395 behavior induced by groundwater withdrawal affecting the Tertiary detritic aquifer of
 396 Madrid (Spain). The spatial and temporal evolution of ground surface displacement
 397 was estimated processing two datasets of radar satellite images (SAR) using
 398 Persistent Scatterer Interferometry (PSI) from April 1992 to October 2000 and from
 399 August 2003 to September 2010. Note that although the PSI techniques assumed a
 400 linear model of deformation during the processing, many examples exist of detection of
 401 non-linear component inside the PS time series, confirming the power of PSI to monitor
 402 ground deformation (Ferretti et al. 2000, Cigna et al. 2011, Tofani et al. 2013). Cyclic
 403 and quasi-elastic ± 80 mm deformation triggered by 120 to 200 m cyclic water level
 404 changes was higher near well fields and decreases with the distance. Differently from
 405 previous case studies, groundwater drawdown was caused by long extraction cycles
 406 (10-20 months) produced during drought periods. High correlation coefficient between
 407 piezometric level changes and surficial displacement demonstrate a high permeability

408 of the aquifer that favors fast pore water pressure dissipation. Furthermore, a quasi-
 409 elastic behavior was observed in Fuencarral well field area where the sandy
 410 component of the aquifer is dominant. In this area, when groundwater level drops the
 411 aquifer is continuously deformed, being recovered when the groundwater level
 412 rebounds. In Pozuelo de Alarcon well field, an elasto-plastic deformation was
 413 appreciated probably due to the higher clay percentage of the different layers from the
 414 aquifer system observed in this part of the basin.

415 Different aquifer subsidence models have been implemented by Gambolati (1975),
 416 Gambolati et al. (2001), Xue et al. (2008), Wu et al. (2009), Herrera et al. (2009),
 417 Tomás et al. (2009), Luo and Zeng (2011) and Raspini et al. (2014) among others. The
 418 selection of the most convenient model for predicting subsidence depends on several
 419 complex factors and on the local geological conditions, which can vary from place to
 420 place (Hu et al., 2002). However, under certain conditions, simpler models have
 421 demonstrated to be useful for this task. In this case study, due to the lack of soil
 422 parameters, we implemented a one-dimensional elastic model following the work
 423 published by Tomas et al. (2009). In our model cyclic hydraulic changes were
 424 instantaneous across the whole aquifer system due to its dominant sandy nature, being
 425 deformations (subsidence and uplift) directly related to these changes. Therefore on
 426 the basis of the elastic storage coefficient (S_{ke}) of the aquifer system we assumed a
 427 linear elastic behavior. The comparison of computed displacements with respect to
 428 DInSAR displacement measurements revealed a good agreement, being 8.2 ± 2.8 mm
 429 and 13%, respectively, the average and the percentage error of the proposed model.

430 These results evidence the quasi-elastic aquifer deformational behavior induced by
 431 groundwater withdrawal of the Tertiary detritic aquifer of Madrid (Spain). Groundwater
 432 management exploitation practice seems adequate since the piezometric level
 433 recovers well after every extraction period. Moreover, detected displacements reveal a
 434 moderate subsidence phenomenon affecting a wide area of 500 km^2 on the north-west

435 of Madrid metropolitan area, where no major damages have been acknowledge on
 436 urban structures and infrastructures. In the near future, the integration of both the PSI
 437 monitoring techniques and aquifer numerical models will permit to predict subsidence
 438 in further drought periods, which are expected to increase in the context of climate
 439 change evolution and population growth. They could be also a tool to evaluate the
 440 effectiveness of mitigation measurements eventually adopted in subsidence-affected
 441 areas.

442

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Figure 1. a) Geological map and b) cross sections of the study area.

Figure 2. Illustration of the lithological logs of the wells from the study area. Upper line corresponds to ground surface and medium and lower lines indicate the position of the piezometric level maximum and minimum depths, respectively, across the cross section. Low permeability lithologies (fine clayed sands and clays) are represented in black while high permeability lithologies (medium-coarse sands) are represented in white. Wells location is shown in Figure 1. Grey marks left side of the logs shows the position of the productive areas of each well.

Figure 3. DInSAR – GPS comparison around Tres Cantos GPS Station (3CAN). Note that both series have different origin.

Figure 4. a) Cumulated displacements from April 19th 1992 b) Cumulated deformation from August 5th 2003. Blue labels in temporal axes represent extraction periods. Yellow marks in the same axes represent the dates of the plotted images.

Figure 5. Well field (zone 1) and Pozuelo de Alarcón area (zone 3) average displacements. Zone 3 shows a continuous subsidence during first set and a lower amplitude movement during the second. Zone 1 fits better with the aquifer extractions and recoveries.

Figure 6. a) Differential displacement for every extraction - recovery phase. b) Differential displacement for every extraction-recovery phase with respect to the well field distance. Extraction–Recovery cycle duration is shown in table 1.

Figure 7. Total displacements divided into elastic and inelastic components of deformation (FE-1).

Figure 8. a) Surface movements and underground water position for well FE-1, Green line shows the model calibration area. b) Strain-stress curve for well FE-1. S_{ke} is the elastic storage coefficient.

Figure 9. Piezometric level, DInSAR and modeled displacements time series for six wells from the study area including FE-1. See wells location in figure 1.

Figure 1

Figure 2

Figure 3

Figure 4

Figure 5

Figure 6

Figure 7

Figure 8

Figure 9

Table 1. Dates and duration of each extraction – recovery cycle

Cycle	Phase	Start date	End date	Duration (months)	Piezometric displacement		Average velocity (mm/year)	Average displacement (mm)
					Max (m)	Mean (m)		
Cycle 1	Extraction 1	Mar. 1992	Sep. 1993	19	n/a	n/a	-8,07	-10,2
	Recovery 1	Oct. 1993	Feb. 1995	17			-2,11	-2,8
Cycle 2	Extraction 2	Mar. 1995	Dec. 1995	10	n/a	n/a	-14,7	-11,2
	Recovery 2	Jan. 1996	Jan. 1999	36			2,28	8,8
Cycle 3	Extraction 3	Feb. 1999	Mar. 2000	13	-197.2	-131.9	-15,07	-15,9
	Recovery 3	Apr. 2000	Feb. 2002	22			n/a	n/a
Cycle 4	Extraction 4	Mar. 2002	Dec. 2002	10	-197.2	-128.7	n/a	n/a
	Recovery 4	Jan. 2003	Mar. 2005	27			6,68	9,6
Cycle 5	Extraction 5	Apr. 2005	Nov. 2006	20	-173.7	-136.3	-12,28	-17,7
	Recovery 5	Dec. 2006	Dec. 2011	60			3,07	10,9

Table 2. Average differential displacement (mm) around the well field for every cycle and phase at different distances. SR: uplift-subsidence ratio (%); TR: cycle temporal ratio (adimensional)

Cycle	Phase	Distance from the well field (m)		
		7000	4000	500
Cycle 1	Extraction (mm)	-13.0	-17.3	-21.8
	Recovery (mm)	-2.9	-1.8	-1.0
	SR (%)	0.0	0.0	0.0
	TR	0.9	0.9	0.9
Cycle 2	Extraction (mm)	-13.0	-15.0	-13.8
	Recovery (mm)	12.8	18.9	25.0
	SR (%)	98.5	126.0	181.2
	TR	3.7	3.7	3.7
Cycle 3	Extraction (mm)	-20.6	-26.8	-35.1
	Recovery (mm)	-1.8	1.6	10.1
	SR (%)	0.0	6.0	28.8
	TR	1.7	1.7	1.7
Cycle 4	Recovery (mm)	12.6	16.3	18.5
	TR	2.7	2.7	2.7
Cycle 5	Extraction (mm)	-22.7	-30.8	-45.1
	Recovery (mm)	15.1	23.1	40.5
	SR (%)	66.5	75.0	89.8
	TR	3.0	3.0	3.0

Table 3. Clay percentage, Elastic storage coefficient (S_{ke}), S_w , Storage Coefficient (S) and elastic deformation/inelastic deformation ratio ($R_{ed/id}$) and for every well. The location of the different wells is shown in figure 1.

Well ID	Clay Percentage %	S_{ke}	S_w (Porosity 1-20%)	S	$R_{ed/id}$
CA-3	n/a	$2,59 \times 10^{-4}$	n/a	n/a	4,82
CA-4	n/a	$2,53 \times 10^{-4}$	n/a	n/a	3,63
CA-5	n/a	$2,87 \times 10^{-4}$	n/a	n/a	4,70
CB-4	n/a	$2,20 \times 10^{-4}$	n/a	n/a	4,39
CB-5	40	$1,70 \times 10^{-4}$	$8,46 \times 10^{-6}$ - $1,69 \times 10^{-4}$	$1,78 \times 10^{-4}$ - $3,39 \times 10^{-4}$	1,91
CB-6	25	$1,12 \times 10^{-4}$	$8,97 \times 10^{-6}$ - $1,79 \times 10^{-4}$	$1,21 \times 10^{-4}$ - $2,91 \times 10^{-4}$	3,02
CB-9	34	$1,82 \times 10^{-4}$	$8,46 \times 10^{-6}$ - $1,69 \times 10^{-4}$	$1,90 \times 10^{-4}$ - $3,51 \times 10^{-4}$	7,76
CB-11	51	$2,60 \times 10^{-4}$	$5,43 \times 10^{-6}$ - $1,09 \times 10^{-4}$	$2,65 \times 10^{-4}$ - $3,69 \times 10^{-4}$	4,84
CB-12	n/a	$4,07 \times 10^{-4}$	n/a	n/a	4,91
CB-13	n/a	$3,89 \times 10^{-4}$	n/a	n/a	10,36
CB-14	n/a	$3,31 \times 10^{-4}$	n/a	n/a	2,86
CB-15	n/a	$4,68 \times 10^{-4}$	n/a	n/a	1,66
FA-1	55	$2,96 \times 10^{-4}$	$5,66 \times 10^{-6}$ - $1,13 \times 10^{-4}$	$3,02 \times 10^{-4}$ - $4,09 \times 10^{-4}$	3,94
FA-3	n/a	$3,57 \times 10^{-4}$	n/a	n/a	5,46
FC-2	n/a	$3,63 \times 10^{-4}$	n/a	n/a	3,80
FX-4	n/a	$4,14 \times 10^{-4}$	n/a	n/a	3,01
G-1	30	$2,44 \times 10^{-4}$	$7,68 \times 10^{-6}$ - $1,54 \times 10^{-4}$	$2,52 \times 10^{-4}$ - $3,98 \times 10^{-4}$	3,37
FE-1	62	$3,77 \times 10^{-4}$	$4,83 \times 10^{-6}$ - $9,66 \times 10^{-5}$	$3,82 \times 10^{-4}$ - $4,74 \times 10^{-4}$	3,61

Well field media	42	$2,99 \times 10^{-4}$	$7,07 \times 10^{-6}$ - $1,41 \times 10^{-4}$	$2,41 \times 10^{-4}$ - $3,76 \times 10^{-4}$	4,34
Well field standard deviation	14	$9,30 \times 10^{-5}$	$1,71 \times 10^{-6}$ - $3,42 \times 10^{-5}$	$8,67 \times 10^{-5}$ - $5,81 \times 10^{-5}$	2,05

Table 4. Average model error and percentage error for each period. See wells location in figure 1.

	Average difference between model and InSAR time series					
	Complete Period		Period 1 (1997-2000)		Period 2 (2003-2010)	
	Average error (mm)	Percentage error %	Average error (mm)	Percentage error %	Average error (mm)	Percentage error %
CA-3	6,7	14	6,0	15	7,3	13
CA-4	7,0	12	4,9	12	8,6	16
CA-5	5,7	10	4,7	11	6,5	12
CB-4	7,7	12	5,9	12	9,1	15
CB-5	7,1	13	5,4	14	8,3	19
CB-6	7,6	17	6,1	16	8,8	19
CB-9	7,4	12	6,4	13	8,1	13
CB-11	6,1	13	5,6	14	6,6	14
CB-12	6,5	12	5,7	12	7,2	15
CB-13	6,5	12	6,2	11	6,8	14
CB-14	7,6	13	6,2	13	8,6	17
CB-15	12,2	17	9,0	17	14,7	26
FA-1	10,8	15	7,7	16	13,2	18
FA-3	8,9	11	8,0	16	9,4	12
FC-2	17,4	24	14,1	27	19,9	27
FX-4	9,4	12	9,0	15	9,8	14
G-1	6,5	12	5,1	12	7,5	14
FE-1	6,8	9	4,5	9	8,5	12
Well field mean	8,2	13	6,7	14	9,4	16
Well field standard deviation	2,8	3	2,3	4	3,4	4

- 669 • We study surface subsidence in a well field area related with underground water level.
670 • We monitor surface subsidence with DInSAR methods.
671 • Water extraction and recovery related with subsidence and uplift detected.
672 • An elastic model for surface behavior has been performed.
673 • A quasi-perfect elastic terrain behavior is presented.

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