Hydrological Parameters of the Vega Media of the Segura River Aquifer (SE Spain) Obtained by means of Advanced DInSAR

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***Abstract*—The hydrological quality of an aquifer system is evaluated by means of two parameters: its capabilities to transmit water (transmissivity, T) and to store water (storage coefficient, S). In this work, a method based on temporal data of the surface subsidence is employed to calculate storage coefficients (S) and transmissivities (T) of the Vega Media of the Segura river aquifer-system. Subsidence data are obtained by means of differential SAR interferometry. The retrieved values of S for all available wells vary from 3.2 x 10^{-5} to 1.9 x 10^{-3}m/m. For the only well where water flow is available, a T value of 0.302 m^2/day is estimated. First results show a reasonable agreement between data calculated with this technique and other acquired by means of *in situ* measurements.**

Keywords-component; DInSAR, transmissivity, storage coefficient, subsidence

I. INTRODUCTION

During the last decade, differential SAR interferometry (DInSAR) has been successfully used to monitor terrain deformations produced by several natural and antropic causes: volcanoes, earthquakes, mining, aquifer exploitation, landslides, etc. The use of advanced DInSAR techniques, like Permanent Scatterers [1][2], Small BAselines Subset technique (SBAS) [3][4] or Coherent Pixels Technique (CPT), [5][6], has improved notably the accuracy in the deformation estimation. The use of long time series of satellite SAR images enables the computation of the ground deformation evolution in a grid of points of the Earth surface with millimetric precision.

This work presents a new contribution in the exploitation of deformation measurements obtained by DInSAR consisting in the retrieval from them of hydrogeological parameters. Note that the great potential of DInSAR in hydrology [7][8] has been already exploited in [9] and [10] to estimate hydrological properties of aquifer systems. The capability of an aquifer to transmit and store water is essential to evaluate the formations quality from a hydrological point of view. The parameters used to characterize them are the effective porosity (n) or the storage coefficient (S) and the permeability (k) or the transmissivity (T). These parameters are usually evaluated from *in situ* tests, although they can be also estimated from laboratory tests over selected specimens. A pumping test is the most usual method to evaluate transmissivity and storage coefficient of an aquifer. This test involves monitoring water level changes along time for a known water flow, which can be interpreted by means of classic methods like the ones proposed in [11], [12] and [13].

The paper is organized as follows. Section II describes the formulation and the methodology to obtain the estimates of hydrological parameters of an aquifer system from an interferometric SAR processing. Then, the test site is described in Section III. Experimental results are presented and discussed in Section IV. Finally, conclusions are summarized in Section V.

II. METHODOLOGY

A semi-log graphical technique was proposed in [14] to calculate storage coefficient and vertical transmissivity in an accurate way. This algorithm uses the slope of the semi-log plotted time-compaction data during a wide period to calculate a value of storage coefficient, which has resulted to be more accurate and representative than values derived from traditional approaches. The vertical hydraulic conductivity of the semi-confining layer can be computed from these data too. The storage coefficient for one-dimensional consolidation in elastic range (not exceeding pre-consolidation stresses) can be expressed as

$$S = \frac{\Delta b}{\Delta h}, \tag{1}$$

where Δb (in m) is the vertical compaction, measured by means of DInSAR in our case, for a Δh piezometric level change (in m), which is equivalent to a change in applied effective stress. Note that this expression rejects the elastic expansion of water. Once S has been obtained, one can calculate the transmissivity (in m^2/day) by means of the following equation [14] derived from Cooper and Jacob method [13]

$$T = \frac{2.303SQ}{\Delta b 4\pi} = \frac{SQ}{5.46\Delta b}, \tag{2}$$

where Q is the water flow (m^3/day), S is the storage coefficient (dimensionless, m/m) and Δb (m) is the straight-line that fits the measured compaction occurring over one log cycle of time.

Finally, the permeability (k) of a layer can be calculated from T considering its thickness b:

$$k = \frac{T}{b}. \tag{3}$$

ERS-1 and ERS-2 images from 1993 to the present have been processed with CPT to obtain the evolution of the surface deformation as a function of time, which is the input required for the expressions (1) and (2). As it is known, CPT assumes that the differential interferometric phase ($\Delta\psi_{int}$) can be expressed as:

$$\Delta\psi_{\mathrm{int}} = \Delta\psi_{flat} + \Delta\psi_{topo} + \Delta\psi_{mov} + \Delta\psi_{atmos} + \Delta\psi_{noise} \tag{4}$$

where $\Delta\psi_{flat}$ is the flat earth component related with range distance and can be calculated easily, $\Delta\psi_{topo}$ is the topographic phase component that can be removed using an external digital elevation model (DEM), $\Delta\psi_{atmos}$ is the phase component related with atmospheric artifacts, $\Delta\psi_{noise}$ is the degradation factor of the interferometric phase, and $\Delta\psi_{mov}$ is the phase term due to ground displacements between two SAR images measured along the Line of Sight (LOS). The last term can be divided into two: one due to the linear deformation and another due to the non linear one. The retrieval of the linear term entails the estimation of both the DEM error and the mean velocity of deformation. These are calculated by adjusting a model function to data only over those pixels of the scene that show good interferometric coherence along time. The non-linear term is estimated by applying spatio-temporal filtering techniques to separate the contribution of atmospheric artifacts from the low and high-resolution components of the non-linear deformation. Such separation is possible because of the different behavior of the non-linear movement with respect to the atmospheric artifacts in time and space.

III. GEOLOGICAL AND HYDROLOGICAL SETTING

The Vega Media of the Segura River aquifer is located in the South-East of Spain, in the oriental sector of the Betic Cordillera. It is a broad syncline in which progressively younger sediments have been deposited. The basement of the basin is made up of old (Permian and Triassic) deformed materials corresponding to the Internal Zones of the Betic Cordillera and the basin fill consists of Upper Miocene to Quaternary sedimentary rocks. Piezometric levels in this area fell down between 5 and 8 meters during the 1992-1995 drought period, when an indiscriminate water withdrawal occurred. A ground surface settlement of 1 to 8 cm, which took place during the same period, has been estimated [15]. From a hydrological point of view, two units with aquifer properties have traditionally been identified [15][16]. The first, or surface aquifer, consists of fine sediments, very deformable, with poor hydrological properties. Its vertical and horizontal hydraulic conductivity vary between 2.4 x 10^{-3} and 3.1 x 10^{-4}m/day, and 3.6 x 10^{-3} and 2.6 x 10^{-6}, respectively [16]. The second, or deep aquifer, is located immediately below the recent sediments. It consists of a 10 to 30 m non deformable thick sequence of gravels. The horizontal and vertical hydraulic conductivity of this aquifer vary depending on site, but they are typically between 0.2 and 100m/day, and 0.2 and 50m/day, respectively [15][16].

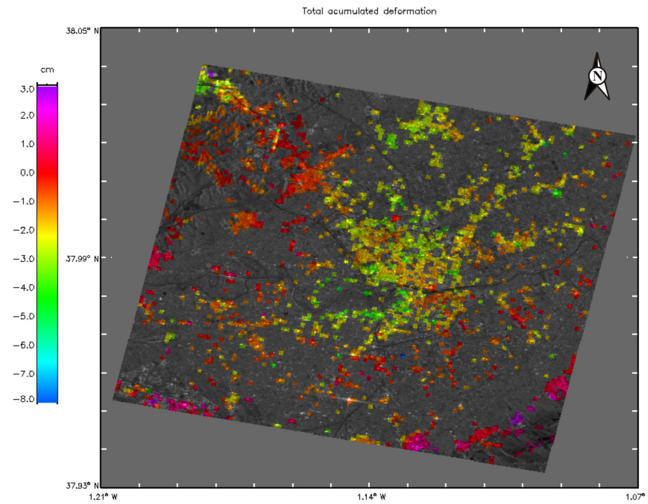

Figure 1. Accummulated deformation map retrieved from DInSAR [17]

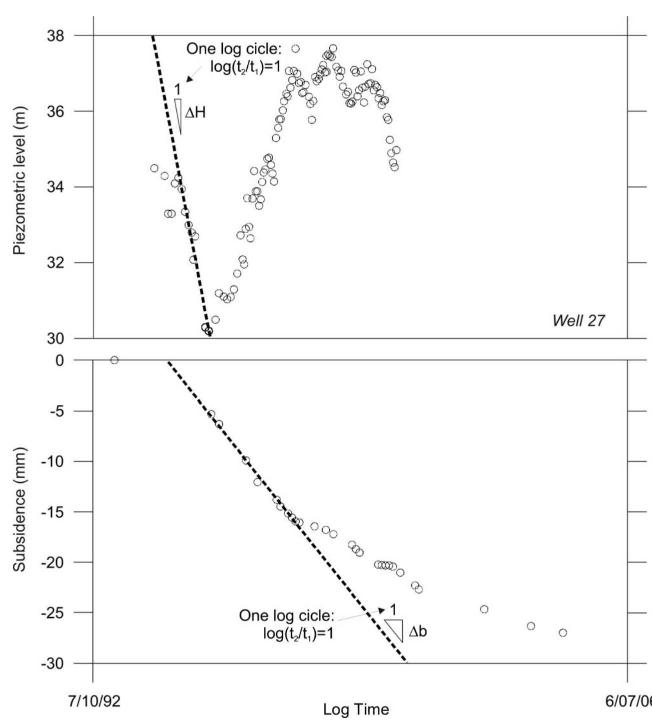

Figure 2. Piezometric level and subsidence evolution at well 27 used for the calculus of storage coefficient.

IV. RESULTS

A. *Storage coefficient*

The methodology previously described has been used to calculate storage coefficients, transmissivities and permeabilities of the Vega Media of the Segura River aquifer-system. For this purpose, we have used DInSAR subsidence maps [17] (Figs. 1 and 2) and *in situ* data (piezometric level evolution, average pumped water flow, and lithological local section). The computations have been made for those pixels and well-points where DInSAR ground subsidence and water head data were available for the 1994-1996 withdrawal period. The first step in the procedure is to fit a least-square logarithmic function to the values of piezometric level and vertical component of subsidence data versus time for the considered period (Fig. 2). The slope of both functions corresponds to the change in piezometric level and subsidence, respectively, for one log cycle of time (Fig. 2). The second step consists in applying equation (1) to calculate the storage coefficient (S). The obtained value of S is then used to calculate the transmissivity (T) by means of expression (2), together with the corresponding values of water flow for the considered pixel/well-point. Finally, the permeability (k) can be computed by means of equation (3) taking into account the aquitard thickness in the considered pixel/well-point.

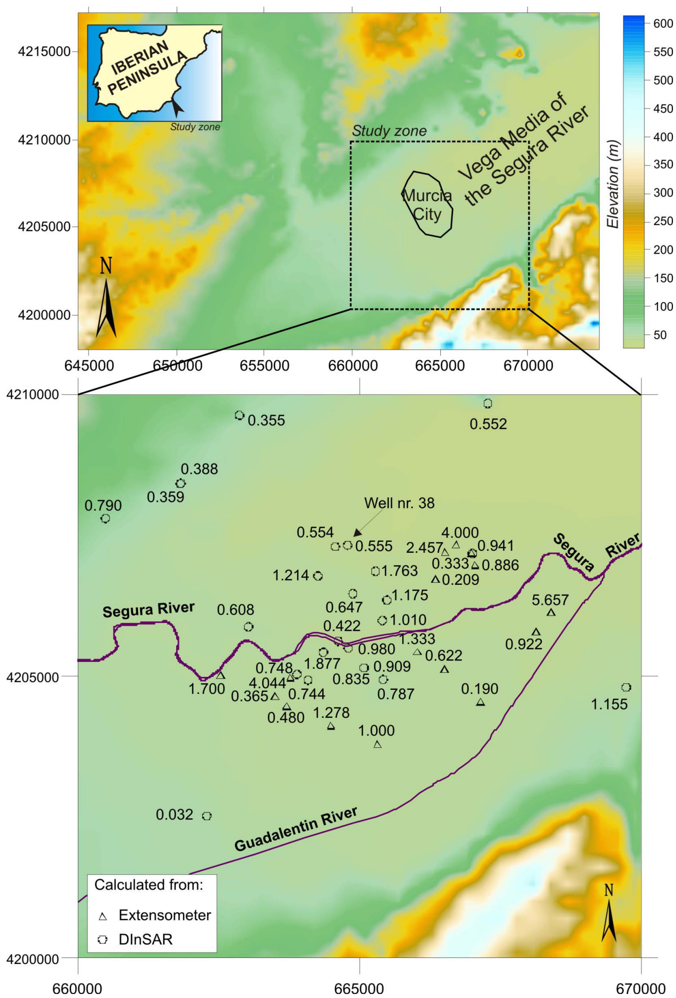

Figure 3. Storage coefficients (x 1000) obtained combining DInSAR and piezometric level data.

Storage coefficients calculated by means of expression (1) using DInSAR subsidence data vary from 3.2 x 10^{-5} to 1.9 x 10^{-3} m/m depending on their location in the study area (Fig. 3). The average value is 8.1x10^{-4}. These values are generally largest for locations in the central part of the study area, close to the river, and smallest for sites in the northwest and southwest part of the valley, close to peripheral relieves that delimit the valley (Fig. 3). The cause can be found on the larger thickness of the aquitard of the semiconfining system composed by deformable soil that exists in the central part of the valley than in the boundary areas.

In addition, storage coefficient values obtained applying this methodology have been compared with storage coefficient values calculated, also using expression (1), but from *in situ* subsidence data measured by means of extensometer during a different time period (February 2001 and December 2003) [18], and piezometric level changes for the same period (Fig. 3). The new storage coefficients range from 1.4 x 10^{-4} to 5.7 x 10^{-3} m/m, with an average value of 1.59 x 10^{-3} m/m (Fig. 3). It is important to note that these storage coefficients have been calculated considering only the first and the last value of subsidence measured by means of extensometers, and the average piezometric level fall for the same period in the area where the well is located. Consequently, these values are expected to be less representative than the ones obtained using a real time series of subsidence data.

The only available value of storage coefficient of the aquifer system obtained by means of an *in situ* pumping test is 1.6 x 10^{-3} m/m. This value is typical of semi-confining aquifer-systems, where S varies from 10^{-5} to 10^{-3} m/m.

B. *Permeability coefficient*

Unfortunately, the pumping rate (Q) is only available for one well (nr. 38, Fig. 2). Consequently, vertical transmissivity and permeability properties of the aquitard only have been calculated for this point of the aquifer. The lithology of this well, from top to bottom, is composed of 16 meters of clays and silts, and 12 meters of gravels over silts. The storage coefficient retrieved by equation (1) in this well is 5.6 x 10^{-4} m/m. Here we suppose that all measured deformation is due to the water pumped at well nr. 38 and is not influenced by the pumping of others wells. The average pumping rate in this well during the 1994-1996 period was 139.9 m^3/day. Finally, the transmissivity of the aquifer calculated by means of expression (2) is 0.02 m^2/day, and the permeability, considering an aquitard thickness of 16 meters that is supposed as the only deformable layer [18], is 1.2 x 10^{-3} m/day. The values of vertical permeability obtained by means of *in situ* and laboratory tests vary among 2.4 x 10^{-3} and 3.1 x 10^{-4} m/day [15]. Therefore, the retrieved estimate falls within the expected range.

V. CONCLUSIONS

An approach to estimate storage coefficient of the aquifer of the Vega Media of the Segura River has been presented and tested. Subsidence data obtained by means of a DInSAR advanced technique called Coherent Pixel Technique (CPT) has been combined with ground-based observations of piezometric levels evolution and pumping rates for the considered period. The retrieved storage coefficient values have been compared with others obtained from available extensometers and with the only value obtained by means of *in situ* pumping test. Although unfortunately there are only a few available *in situ* data, an acceptable coincidence has been noticed. In addition, transmissivity and permeability have been calculated for one well, where water pumping rate were available, showing a good correspondence.

This methodology will be very useful for future aquifer-subsidence modeling, because it provides a more accurate and "real" value of aquifer system properties.

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References

[1] A. Ferretti, C. Prati and F. Rocca, "Nonlinear subsidence rate estimation using permanent scatterers in differential SAR interferometry", IEEE Trans. Geosci. Remote Sensing, vol. 38, pp. 2202–2212, September 2000.

[2] A. Ferretti, C. Prati, and F. Rocca, "Permanent scatterers in SAR interferometry", IEEE Trans. Geosci. Remote Sensing, vol. 39, pp. 8–20. January 2001.

[3] P. Berardino, G. Fornaro, R. Lanari and E. Sansosti, "A New Algorithm for Surface Defiormation Monitoring Based on Small Baseline Differential Intereferograms", IEEE Trans, on Geosacience and Remote Sensing, vol. 40, pp. 2375-2383, November 2002.

[4] F. Masu, M. Manzo, R. Lanari, "A quantitative assesment of the SBAS algorithm performance for surface defoormation retrieval from DInSAR data", Remote Sensing of Environment, in press.

[5] O. Mora, J.J. Mallorquí and A. Broquetas, "Linear and nonlinear terrain deformation maps from a reduced set of interferometric SAR images". IEEE Trans. Geosci. Remote Sensing, vol. 41, pp. 2243-2253, October 2003

[6] O. Mora, "Advanced differential SAR techniques for detection of terrain and building displacements", Ph. D. Thesis, Polytechnic University of Catalonia, 182 pp., 2004.

[7] L.C. Smith, "Emerging applications of interferometric syntetic apertura radar (InSAR) in geomorphology and hidrology", Ann. Am. Geographers, vol. 92, pp. 385-398, September 2002.

[8] J. Hoffmann, "The future of satelite remote sensing in hydrogeology", Hydrogeol. J., vol. 13, pp. 247-250, February 2005.

[9] J. Hoffmann, D.L. Galloway, H.A. Zebker and F. Amelung, "Seasonal subsidenceand rebound in Las Vegas Valley, Nevada, observed by syntethic aperture radar interferometry, Water Resources Res., vol. 37, pp. 1551-1566, June 2001.

[10] J. Hoffmann, D.L. Galloway and H.A. Zebker, "Inverse modelling of interbed storage parameters using land subsidence observations, Antellope Valley, California". Water Resources Res., vol. 39, pp. 1031, February 2003.

[11] C.V. Theis, "The relation between the lowering of the piezometric surface and the rate and duration of discharge of a well using ground-water storage", Transactions of the American Geophysical Union, vol. 16, pp. 519–524, 1935.

[12] C.E. Jacob, "On the flow of water in elastic artesian aquifers", Transactions of the American Geophysical Union, vol. 21, pp. 574–586, 1940.

[13] H.H. Cooper, C.E. and Jacob, "A generalized graphical method for evaluation formation constants and summarizing well-field history", Transactions of the American Geophysical Union, vol. 27, pp. 526–534, 1946.

[14] T.J. Burbey, "Use of time-subsidence data during pumping to characterize specific storage and hydraulic conductivity of semiconfining units", Journal of Hydrology, vol. 281, pp. 3-22, September 2003.

[15] M. Martínez, J. Mulas, G. Herrera and R. Aragón, "Efectos de una subsidencia moderada por extracción de agua subterránea en Murcia, España". Proc. XXXIII Congress of IAH-ALHSUD, Zacatecas, Mexico. Conference on Groundwater Flow Understanding from local to regional scales, pp. 249-252, October 2004.

[16] R. Aragón, J.L. García-Aróstegui, J. Lambán, J. Hornero and A.I. Fernández-Grillo, "Impacto de la explotación intensiva de aguas subterráneas en la ciudad de Murcia (España). Análisis hidrogeológico". Proc. XXXIII Congress of IAH-ALHSUD, Zacatecas, Mexico. Conference on Groundwater Flow Understanding from local to regional scales, pp. 2622-2624, October 2004.

[17] R. Tomás, Y. Márquez, J.M. Lopez-Sanchez, J. Delgado, P. Blanco, J.J. Mallorquí, M. Martínez, G. Herrera and J. Mulas, "Mapping ground subsidence induced by aquifer overexploitation using advanced Differential SAR Interferometry: Vega Media of the Segura River (SE Spain) case study", Remote Sensing of Environment, vol. 98, pp. 269-283, October 2005.

[18] F. Peral, A. Rodríguez and J. Mulas, "Control of subsidence with borehole extensometers and surveying measurements in Murcia (Spain)", Proceedings ISC-2 on Geotechnical and Geophysical Site Characterization, Rotterdam, Holland, pp. 1171-1176, September 2004.