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Mapping ground subsidence induced by aquifer overexploitation using advanced Differential SAR Interferometry: Vega Media of the Segura River (SE Spain) case study

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Abstract

Differential SAR Interferometry (DInSAR) is a remote sensing technique with the well-proven ability to monitor ground deformations. In this work we have applied an advanced DInSAR technique – the Coherent Pixels Technique (CPT) – , to study subsidence phenomena due to the excessive pumping of groundwater in the Vega Media of the Segura River (SE Spain) from 1993 to the present. The settlement map retrieved with DInSAR shows settlement of up to 8 cm at some points of the study area and has been compared with other data provided by ground instruments to analyse the relationship with ground deformation. A correlation has been observed between these measurements and the observations from on-site testing of piezometric groundwater fluctuations and borehole extensometric settlement. However, the distribution of damaged buildings, well points and basements does not show a clear relationship with measured subsidence values because the occurrence of damage also depends on the structural state of the buildings and the characteristics of their foundations. In addition, the distribution of pumping wells is not indicative of the distribution of the volume of water withdrawal which is the real conditioning factor of piezometric level changes. It can be concluded that the results obtained provide very useful spatial and temporal data about this phenomenon in an urban area at a low cost. The data can be used for forecasting purposes and helps to define zones with future ground settlement problems if the same conditions are repeated. This technique has also allowed the monitoring of ground subsidence in the Vega Media of Segura River for a period (1993–1995) where no instrument information was available.

Keywords: Differential SAR Interferometry (DInSAR); Subsidence; Piezometric level; Urban areas

1. Introduction

Ground subsidence induced by excessive overexploitation of aquifers is a common problem affecting our society. This phenomenon involves the settlement of the surface of the ground and affects wide areas. Civil structures built on these areas must withstand these vertical (and sometimes horizontal) ground deformations, and widespread damage occurs when differential settlements cannot be accommodated for beneath their foundations. It is estimated that there are over 150 cities in the world with serious problems of subsidence due to excessive groundwater withdrawal (Hu et al., 2004). For instance, well-known examples of subsidence include the

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Po Valley (Italy), Mexico DC, Antelope and San Joaquin Valley (USA), Bangkok (Thailand) and many other areas in the world.

Subsidence has occurred in the metropolitan area of the city of Murcia (SE Spain) as a result of excessive pumping of groundwater during a drought period (1992–95). A lowering of the piezometric level, 8 m approximately, caused a maximum estimated ground settlement of 8 cm (Martínez et al., 2004), and damaged over 150 buildings and other structures. The cost of the damages was assessed by local authorities to be over 50 million Euros (Mulas et al., 2003; Rodríguez Ortiz & Mulas, 2002) and had a significant repercussion in the local society.

Knowledge of the spatial and temporal distribution of the deformations is essential to delineate the most severely damaged areas and to establish counter measures to mitigate (or even eliminate) the causes that have led to this ground subsidence. Moreover, this would allow us to predict future subsidence processes resulting from further overexploitation of aquifers.

During the last decade, Differential Interferometry Synthetic Aperture Radar (DInSAR) has become an important remote sensing tool for estimating temporal and spatial surface motions due to subsidence (Berardino et al., 2002; Colesanti et al., 2001; Ferretti et al., 2000, 2001; Galloway et al., 1998; Mora et al., 2003).

DInSAR has several important advantages over classical methods used to measure subsidence deformation. One of the main advantages of DInSAR is its high spatial coverage in urban areas. If we compare DInSAR with other common techniques, such as Differential Global Positioning System (DGPS) and instrumental methods, the latter can only measure ground deformations at a few discrete points, not over a wide and continuous area. In the case of levelling methods, they can cover a whole territory but the average distance between benchmarks is much higher than DInSAR resolution. In addition, complete levelling surveys cannot be repeated frequently because the cost of carrying out the measurements of a levelling network is very high. With respect to the time repetition, DGPS is not time and cost effective for measurements periods shorter than a year. However, DInSAR could be used to set up a monthly or annual monitoring service at moderate cost.

In this paper, subsidence due to overexploitation in the Vega Media of the Segura River, located in the southeast of Spain, is studied by means of an advanced DInSAR technique called Coherent Pixels Technique (CPT, Mora, 2004; Mora et al., 2003). The data set consists of 28 SAR images acquired from April 1993 to October 2004. Due to the lack of suitable images in 1992, we have been able to measure subsidence only for part of the drought period that took place during 1992–95. The study has two main objectives. Firstly, DInSAR will be used to determine the deformation of the study zone, and the results will be compared with available extensometric measurements and with modelled movement. Secondly, the relationship between piezometric changes and surface deformation will be analysed.

2. Description of the study area

2.1. Location and description of the problem

The study zone consists of a section of the Segura River Valley (SE Spain) (Fig. 1). More specifically, the zone monitored corresponds to the metropolitan area of the city of Murcia. This area has developed by occupying the flood plain of the Segura River, also known as the Vega Media. This area covers a surface of 206 km^2, with approximately 50% being cultivated land (Gumiel et al., 2001).

The sediment accumulated by the Segura River since the Pliocene makes up an aquifer that had been scarcely exploited up to recent times, with the use of running river water being more common. Nevertheless, recent population growth (currently more than 400,000 inhabitants) and changes in agricultural practices, from classical extensive to intensive irrigated land, favoured the exploitation of this aquifer. In this context, several drought periods, especially during years 1992 to 1995, led to an overexploitation of this aquifer.

2.2. Geological and geotechnical setting

The study area is located in the oriental sector of the Betic Cordillera. A compressive stress field has acted since the Upper Miocene in this sector and has led to the development of a basin bounded by two active faults, the Lorca-Alhama, to the north, and the Carrascoy-Bajo Segura, to the south (Montenat et al., 1990). The sedimentary record of the basin has been deformed as it has been deposited, creating 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. These materials also crop out along the edge of the Segura River Valley (Figs. 1 and 2).

The basin fill consists of sedimentary Upper Miocene to Quaternary rocks that can be divided into three units (Figs. 1 and 2). Older materials (Upper Miocene) mainly consist of a thick sequence (more than 600 m) of marls (Cerón & Pulido, 1996; Mulas et al., 2003). Above them, pliocene–quaternary rocks consist of marls and clays interbedded with several levels of conglomerates and sandstones, deposited in a continental environment. These conglomerate levels are of great interest for hydrological purposes. The overall thickness of these materials is about 150 m, although they can reach 200 m in some places (Aragón et al., 2004). At surface level, recent continental (meander, channel, oxbow lakes, flood plain, alluvial fans, etc.) sediments are found. Silts and clays are abundant in the flood plain and oxbow deposits, while sand is common in channel areas and in the alluvial fans formed in the relief features around the valley. The thickness of the recent sediments varies between 3 and 30 m (Rodríguez Jurado et al., 2000). Anthropic deposits can also be found at surface level in certain places.

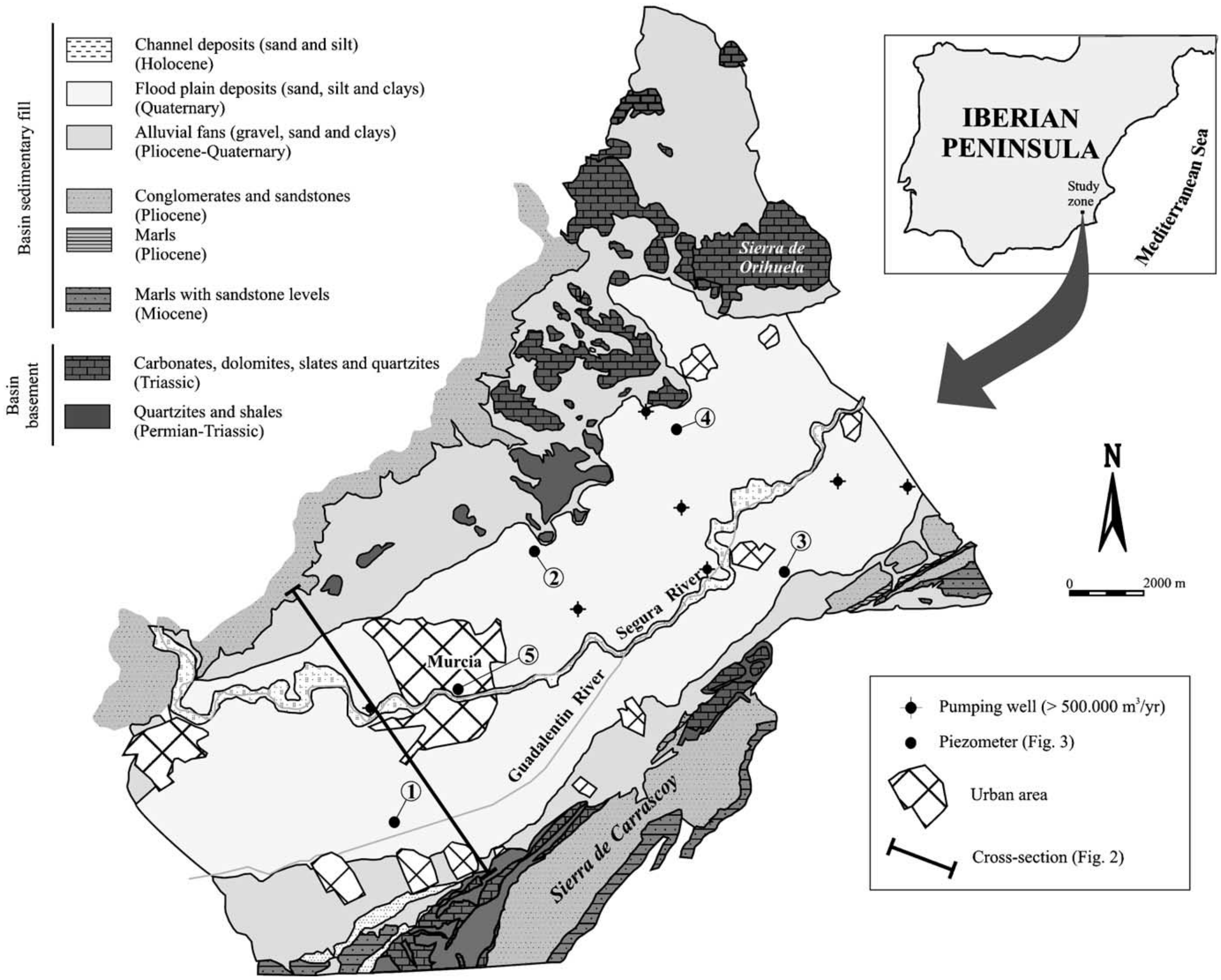

Fig. 1. (a) Situation and (b) geology of the Vega Media of the Segura River (based on Aragón et al., 2004).

From a hydrological point of view, two units with aquifer properties have traditionally been identified (Aragón et al., 2004; Cerón & Pulido, 1996). The first, or surface, aquifer consists of recent sediments. Since fine sediments are very abundant, its hydrological properties are poor (vertical and horizontal hydraulic conductivity varying between 0.03–0.1 m/day and 0.01–5 m/day, respectively) and it is scarcely exploited. The second unit, or deep aquifer, is located immediately below the recent sediments. It consists of a 10 to 30 m thick sequence of conglomerates with a matrix of variable nature (sand, silt and clays) which is part of the Pliocene – Quaternary sedimentary rocks. The horizontal and vertical hydraulic conductivity of this aquifer vary depending on site, but they are typically between 10–100 m/day and 1–50 m/day, respectively (Aragón et al., 2004). This level of conglomerates is found at the top of the Pliocene – Quaternary sedimentary rocks. Other conglomerate levels in this unit are also aquifers that sometimes are exploited. The piezometric level of the deep aquifer is high (Fig. 2), typically situated a few metres below ground level, and completely saturating most of the surface sediments.

The recent sediments, or materials that constitute the surface aquifer, are the most compressible in the zone. They consist of a layer of medium to soft sediments, susceptible to suffering consolidation due to variations (increases) in the effective stresses acting on them. On the contrary, the underlying conglomerates and marls are more rigid and represent the geotechnical substratum of the zone, used as the support level for deep foundations. Because of their rigidity, no significant deformations due to effective stresses increase are expected (Martínez et al., 2004).

3. Previous investigations and available data

During the 1992–95 drought period, excessive pumping of the deep aquifer caused an average decrease of 5 to 8 m in the piezometric level of the deep aquifer (Fig. 3). Associated with this decrease, there was an increase in effective stresses in the subsoil, causing consolidation of the clayey/silty surface sediment layers. At surface level, this consolidation became apparent with large areas of the metropolitan area

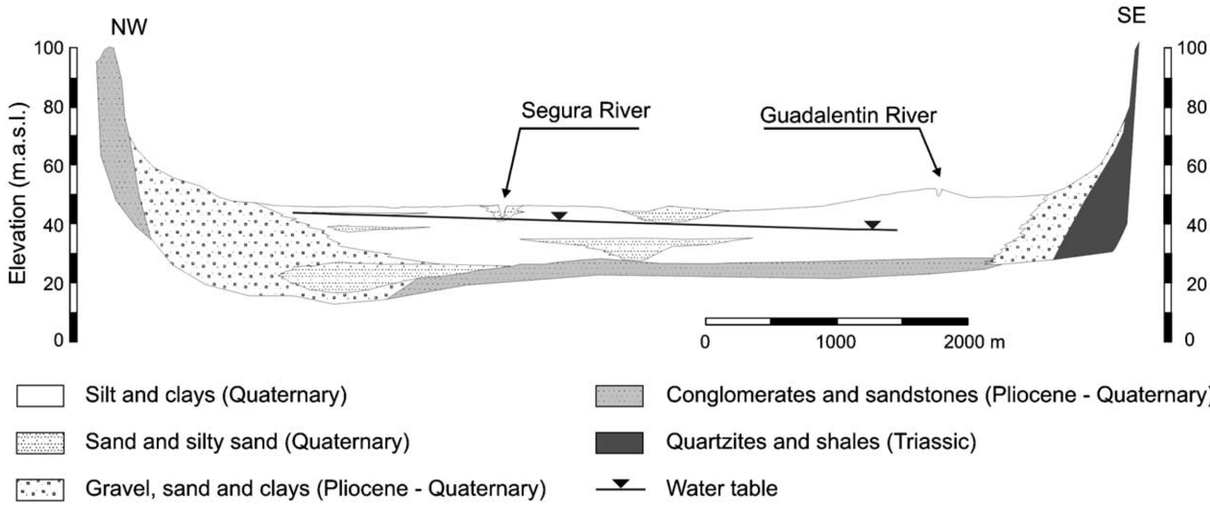

Fig. 2. Schematic geological cross section of the Vega Media of the Segura River (based on Aragón et al., 2004). (See location in Fig. 1).

Murcia suffering land subsidence. More than 300 complaints were received, and more than 150 buildings and other structures (sidewalks, roads, walls, etc.) suffered moderate damage (Fig. 3). This was the first time that land subsidence due to aquifer overexploitation had been noticed in an urban area in Spain on such a scale, so no quantitative data about ground vertical movements is available for this period. Later, the Regional Government requested a field study of ground movement, involving geotechnical surveys, field instrumentation (extensometers) and topographical surveys.

The published data available consists of the results of numerical modelling of ground consolidation due to lowering of the piezometric level (Fig. 4) and experimental ground deformation measured with extensometers (Table 1 and Fig. 5) for a short period (Feb/2001–Dec/2003). Meteorological data (accumulated rain) and time evolution of the piezometric level of the deep aquifer (from 1972 up to present) are also available (Fig. 3).

De Justo and Vázquez (1999) and Vázquez and De Justo (2002) studied the consolidation process by means of one-dimensional consolidation models. Advanced numerical modelling of soil consolidation was carried out by Rodríguez Ortiz and Mulas (2002) and Martínez et al. (2004), using a geotechnical model of the Vega Media which took into account vertical and horizontal changes in soil stratigraphy and its mechanical properties. This model was created from several dozen geotechnical boreholes and undisturbed soil samples that were tested. The results of this model show that, for a 10 m lowering in the piezometric level, ground settlement typically varies between 2 and 4 cm in the downtown city of Murcia, while it is greater than 6 cm in surrounding areas (Fig. 4). There is not a good correlation between the results of this model and the distribution of damage (Rodríguez Ortiz & Mulas, 2002).

In 2001, 22 extensometers were installed in four areas of maximum theoretical settlement (south and southeast of the city). The results are shown in Table 1 (Peral et al., 2004). In the aforementioned period, the piezometric level shows a downward trend, superimposed on typical annual cyclical changes, although absolute variations vary depending on the area. Whatever the case, a small subsidence (between 4 and 14 mm) was detected, in agreement with such changes in piezometric level.

4. Advanced DInSAR applied to the Murcia subsidence study

The data processing required to obtain ground displacements from SAR imagery is summarized in this section. A detailed description of the whole algorithm can be consulted in Mora et al. (2003) and Mora (2004), but this summary is included here for the sake of completeness.

4.1. General methodology

The differential interferometric phase ($\Delta\psi_{\text{int}}$) obtained by combining two complex SAR images can be expressed as the sum of several terms (Hanssen, 2001; Mora, 2004):

$$\Delta\psi_{\text{int}} = \Delta\psi_{\text{flat}} + \Delta\psi_{\text{topo}} + \Delta\psi_{\text{mov}} + \Delta\psi_{\text{atmos}} + \Delta\psi_{\text{noise}} \quad (1)$$

where $\Delta\psi_{\text{flat}}$ is the flat-earth component related to range distance differences in absence of topography, $\Delta\psi_{\text{topo}}$ is the topographic phase, $\Delta\psi_{\text{mov}}$ is the phase contribution due to ground displacement occurring between the two SAR image acquisitions, measured along the line of sight (LOS), $\Delta\psi_{\text{atmos}}$ is the phase component due to atmospheric disturbances or artefacts, and, finally, $\Delta\psi_{\text{noise}}$ includes the remaining noise sources. The first two terms in Eq. (1) can be expressed analytically. More specifically, $\Delta\psi_{\text{flat}}$ is assumed to be known, and $\Delta\psi_{\text{topo}}$ can be extracted from an external DEM.

In this study, we have made use of the Coherent Pixels Technique (CPT) algorithm (Mora, 2004), which assumes that the phase component linked to deformation ($\Delta\psi_{\text{mov}}$)

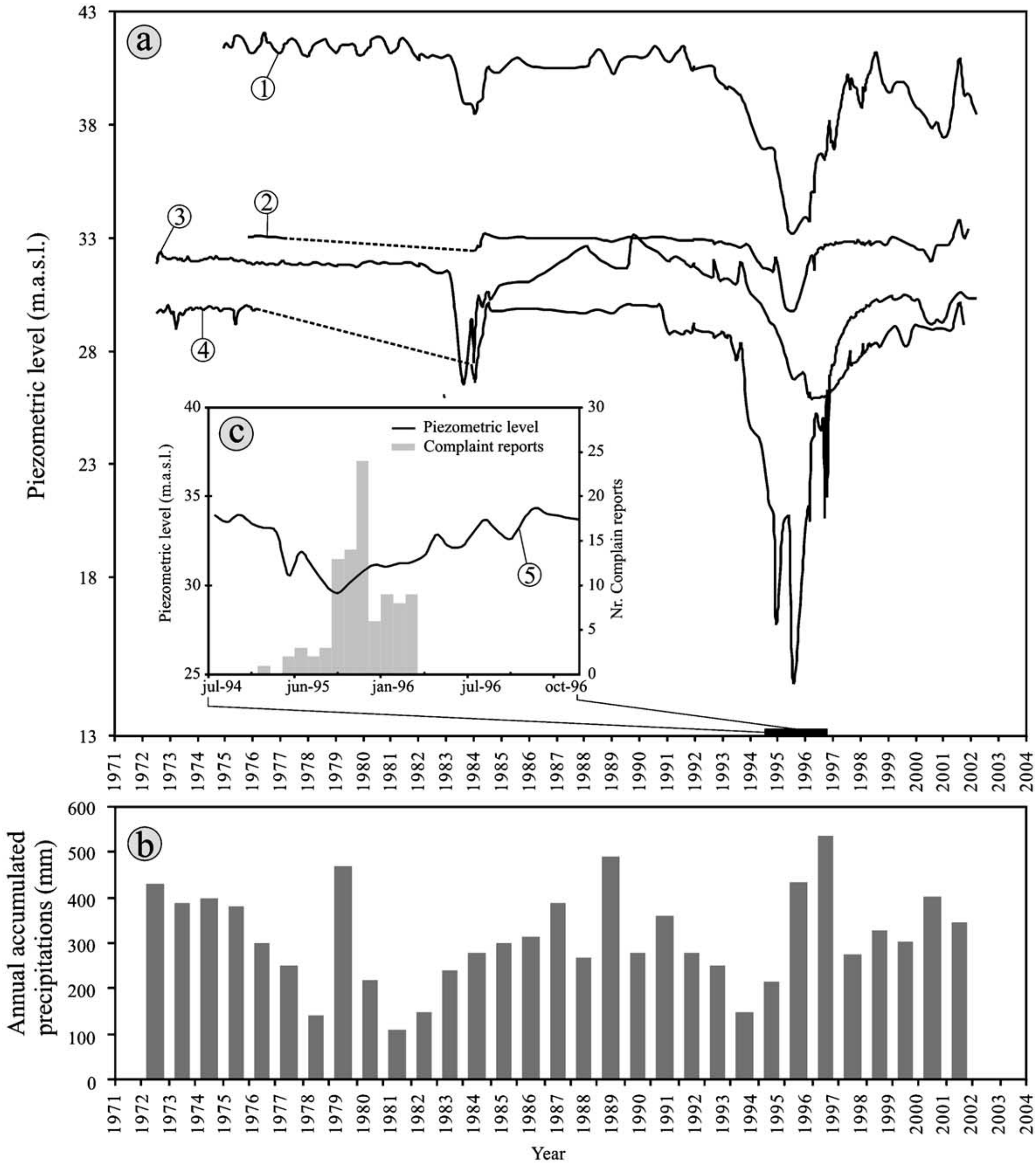

Fig. 3. (a) Evolution of piezometric level and (b) accumulated precipitations in the Vega Media of the Segura River. Piezometer locations are shown in Fig. 1. (c) Comparison between the number of complaint reports and the evolution of the piezometric level in the city of Murcia during the 1994–97 period (data from Mulas et al., 2003 and Aragón et al., 2004).

can be broken down, as shown in Eq. (2), into two new phase terms, one due to linear deformation ($\Delta\psi_{\text{linear}}$) and another due to non linear deformation ($\Delta\psi_{\text{non-linear}}$).

$$\begin{aligned}\Delta\psi_{\text{mov}} &= \Delta\psi_{\text{linear}} + \Delta\psi_{\text{non-linear}} \\ &= \frac{4\pi}{\lambda}\cdot\Delta v\cdot T + \frac{4\pi}{\lambda}\cdot\Delta\rho_{\text{non-linear}}\end{aligned} \tag{2}$$

where λ is the radar wavelength, Δv is the velocity increment between pixels, T is the temporal separation between both SAR acquisitions, and $\Delta\rho_{\text{non-linear}}$ is the non-linear term of the surface deformation.

The CPT application is divided into two main steps, corresponding to the extraction of both linear and non-linear components. Firstly, the retrieval of the linear term includes the estimation of both the mean velocity deformation and the DEM error. These are calculated by adjusting a model function applied only over those pixels of the scene that show good interferometric coherence over time. The non-linear term is then estimated by applying spatio-temporal filtering to extract the contribution of atmospheric artefacts and the low and high-resolution components of the non-linear deformation. Atmospheric isolation is possible because of the different behaviour of

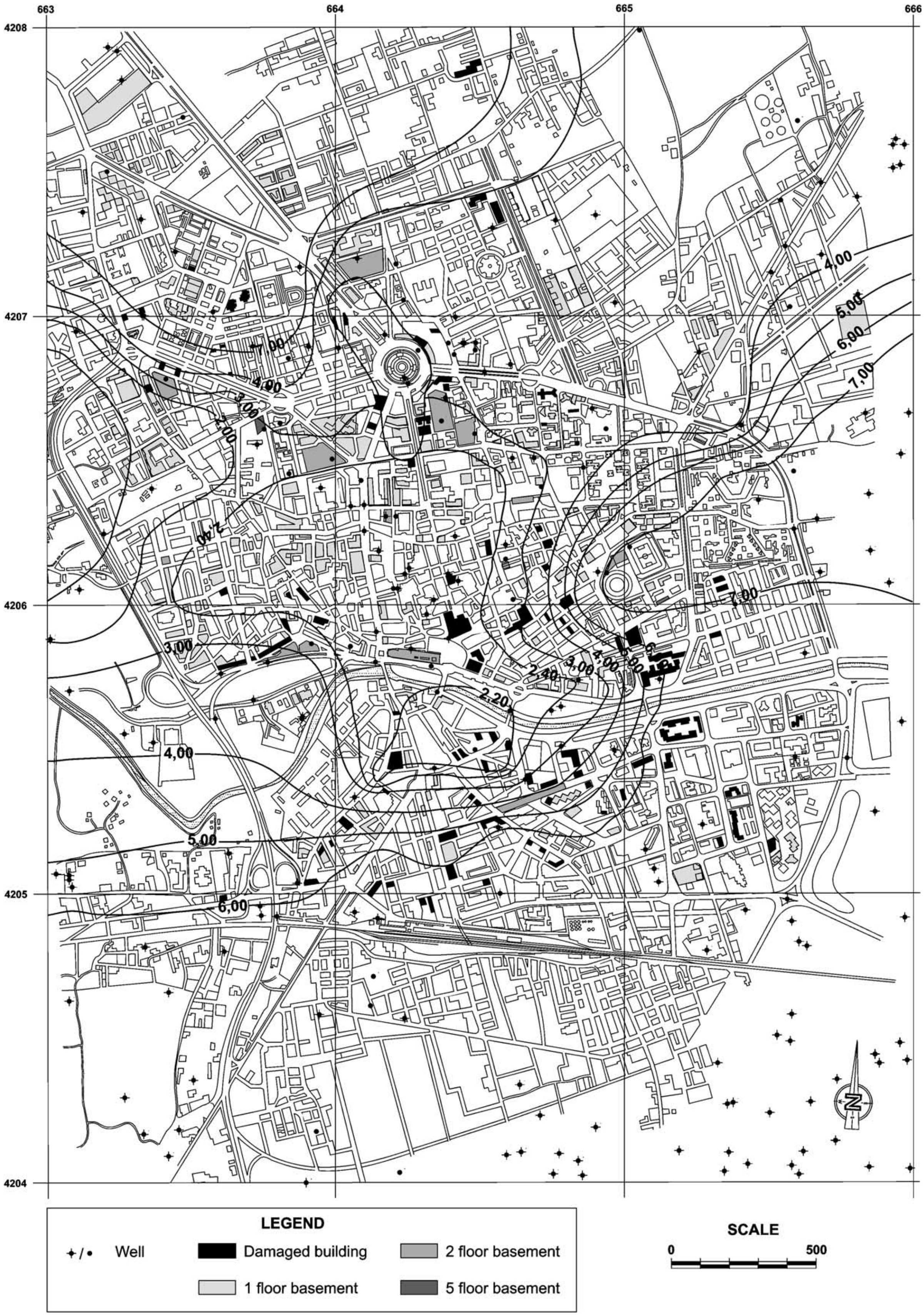

Fig. 4. Inventory map of damaged buildings, wells and basements showing subsidence values in the city of Murcia estimated using numerical models for the 1993–1998 period (based on Mulas et al., 2003 and Vázquez & De Justo, 2002). Settlement values are in cm.

atmospheric artefacts in time and space with respect to non-linear movement.

The retrieval of the deformation maps from SAR imagery is a complex task involving several steps: image focusing from the raw data, image co-registration and filtering for the generation of the interferograms, proper calculation of satellite orbits and the DInSAR processing itself previously described. The complexity of the different steps involved in the whole chain and the different processing conditions (number of images available, baseline distribution, Doppler differences, etc.) make it almost impossible to find a close expression for evaluating the error budget of this technology. From the results obtained using this technique with different datasets (Lanari et al., 2004; Mallorquí et al., 2003; Mora et al., 2003), comparing them with available ground-truth, and looking at the oscillations in the deformation pattern for stable zones, it can be assumed that the error in estimating accumulated non-linear deformation is around ± 0.5 cm in the worst case. In contrast, the linear estimate is more robust, as it comes from a model adjustment to all available data, and can achieve a millimetric precision. In all cases, the larger the number of images, the more precise the results are for both linear and non-linear estimates. However, the error may have a strong dependence on the conditions of the acquired images, and the most perturbing elements are the atmospheric artefacts, which can be coupled with the non-linear deformation.

4.2. Data set and processing details

A set of 28 SLC SAR images acquired by the European Space Agency remote sensing satellites ERS-1 and ERS-2 between April 1993 and October 2004 has been used in this study. An area of about 10×10 km was selected from the images, corresponding to the urban area of Murcia.

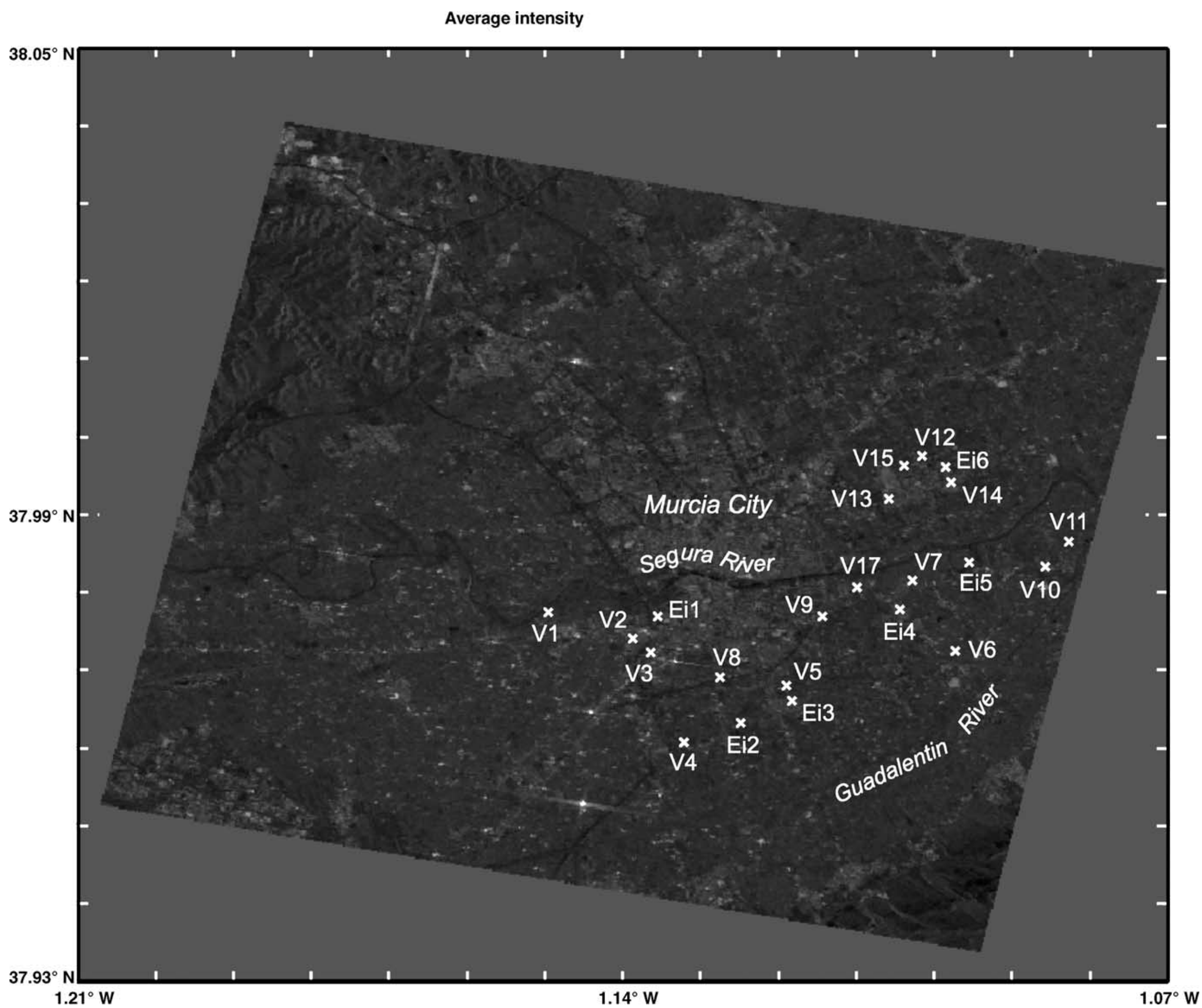

Fig. 5. Average intensity map of the study zone showing the location of extensometers.

Table 1
Comparison between extensometric (Peral et al., 2004) and DInSAR measurements with indication of piezometric level variation (W: wire extensometer; I: Incremental extensometer; NCP: Non Coherent Pixel; N/A: not available data)

Area	Borehole	Type	Deformation (mm)				Water level decrease (m)
			Instrumental		DInSAR (2)	Difference (1)−(2)	
			Measured	Projected along LOS (1)			
Carmen	V1	W	− 17.0	− 15.6	NCP	–	− 8 to − 10
	V2	W	− 3.6	− 3.3	NCP	–	
	V3	W	− 4.8	− 4.4	− 6.8	2.4	
	Ei1	I	− 1.9	− 1.7	NCP	–	
Patiño	V4	W	N/A	N/A	–	–	− 8 to − 9
	V5	W	N/A	N/A	–	–	
	V8	W	− 11.5	− 10.6	NCP	–	
	Ei2	I	+ 2.5	+ 2.3	NCP	–	
	Ei3	I	− 8.3	− 7.6	− 5.2	− 2.4	
Los Dolores	V6	W	− 19.8	− 18.2	NCP	–	− 3.5
	V7	W	N/A	N/A	–	–	
	V9	W	N/A	N/A	–	–	
	V10	W	− 3.1	− 2.9	NCP	–	
	V11	W	− 8.6	− 7.9	NCP	–	
	V17	W	− 14.0	− 12.9	NCP	–	
	Ei4	I	− 0.7	− 0.7	− 1.2	0.5	
	Ei5	I	N/A	N/A	–	–	
Puente Tocinos	V12	W	− 6.0	− 5.5	− 3.4	− 2.1	− 1 to 4.5
	V13	W	− 18.2	− 16.8	− 4.8	− 12.0	
	V14	W	− 4.5	− 4.1	− 3.2	− 0.9	
	V15	W	− 2.8	− 2.6	NCP	–	
	Ei6	I	− 1.5	− 1.4	− 1.3	− 0.1	

The locations of the extensometers are shown in Fig. 5.

All possible interferograms formed by pairs of images were generated. Due to the multi-look factor of 25×5 pixels (azimuth $\times$ range), the final resolution has been degraded to 100×100 m. From the whole set of interferograms, only those with a normal baseline smaller than 50 m and a relative Doppler centroid difference below 0.15 were chosen for the algorithm.

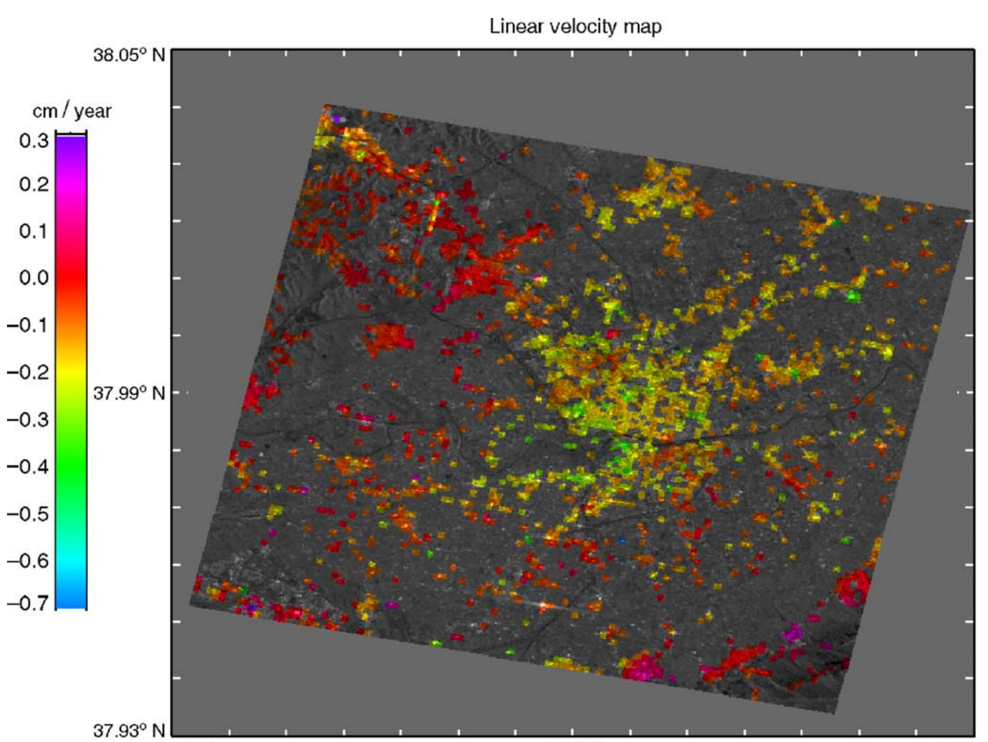

Fig. 6. Linear velocity deformation map of the study zone, superimposed on the intensity map.

The external DEM used to cancel the topographic component of the interferometric phase was the free distribution DEM from NASA's SRTM mission. This is an approximately 90×90 m (3 s arc) global DEM with a standard deviation in height of 10 m. With this DEM, all the selected differential interferograms and their associated coherence maps are computed. Fig. 5 shows the average intensity map.

The first step of linear component retrieval is the selection of the pixels with coherence higher than 0.3 in more than 75% of the previously selected interferograms. The pixels above this threshold, and with a minimum value of 0.1, are triangulated by a Delaunay algorithm, but only relating those pixels whose distance is lower than 1500 m, assuming that atmospheric influence is the same for pixels below that distance. All the details concerning this processing can be consulted in Mora (2004). Fig. 6 shows the linear velocity map obtained for the whole period 1993–2004.

This method provides all deformation components, so a complete evolution of the deformation can be estimated for every coherent pixel.

5. Results and discussion

This section aims to present and analyse the results obtained with this technique. The values obtained have been compared with piezometric changes, with available extensometric deformation measures from 2001, with the distribution of water extraction points and damaged buildings, and with an appropriate model, as explained in the following sections.

5.1. Spatial and temporal evolution of settlement

Fig. 7 shows the evolution of the accumulated settlements measured by DInSAR from April 1993 to October 2004, with a temporal step of one year approximately. From 1993–1995, deformations were almost inexistent, showing a very slight subsiding area in the southwest of the city of Murcia. Note that there are no images for 1994 due to the operating mode of the ERS-1 satellite.

From 1995–97, the southwest area and a new subsiding area located in the northeast of the city were gradually affected by average settlements that exceeded 20 mm, with typical settlement velocities of about 5–10 mm/year. This was the most dramatic period.

From 1998 to 2004, vertical deformations mainly affected the central part of the valley, corresponding to the zone occupied by recent, unconsolidated sediments of the Segura River. In this period, measured descending deformations are less than 10 mm, with general velocity patterns of 2 mm/year. On the contrary, two areas of the study zone remain with almost no deformation until 2004. They are located towards the northwest and the southeast of the city of Murcia. Both areas are broadly located on quaternary alluvial fan (coarse, low deformable, sediments) or older materials.

Note that total accumulated deformations were lower than 10 cm in the whole 1993–2004 period.

5.2. Comparison with the piezometric level

In general, annual accumulated precipitations are closely related with the piezometric level because rain infiltration and irrigation overflow are the most important sources for recharging the aquifer (Fig. 3). The historical piezometric level evolution shows a stable situation over time, with only small annual oscillations which never exceed 2–4 m (Figs. 3 and 8). During the prolonged periods with low precipitations, water extractions in authorized drought-wells and illegal wells from deep aquifer increase notably, while infiltrations decrease. The consequence is a fall in the piezometric whose effects have been observed during the major droughts of 1980–83 and 1992–95 (Fig. 3). The drought in the 80's led to piezometric falls of over 5 m during 1983 in the Segura Valley. However, there is no information (complaints) concerning ground subsidence during this period. The 1992–95 drought caused a generalized lowering of 8 m (Vázquez & De Justo, 2002), with maximum values exceeding 15 m.

The temporal evolution of DInSAR measured ground deformations shows a good correlation with piezometric level changes of the deep aquifer. Analysis of these results has allowed the identification of three main patterns of ground surface behaviour for the study zone during this period. Fig. 8 shows the relationship between DInSAR measured surface deformation and the piezometric level for five representative sites (Fig. 8). Sites A and D are located in the city of Murcia, on recent, deformable sediments (20 m layer of recent clays situated over conglomerates). Site B is located near the Carrascoy mountain, over alluvial fan sediments (mostly gravels and sand with layers of sandy silts). Site E is situated on old (Pleistocene) silty clays and clayey silts lying over tertiary shales and, finally, site C is located in the very south of the study zone, on clays interbedded with levels of sand and gravel.

Ground deformation was fast in sites A and D during the piezometric level lowering occurring between 1993 and 1995, and did not stop until the piezometric level of the aquifer completely recovered its previous level in 1997. This can be interpreted as deformation occurring while ground conditions remain altered. Later, the piezometric level remains almost constant, presenting only small seasonal fluctuations of a few metres, and showing a general downwards trend. The consequent deformations show only slow velocities for this period. These behaviours have been observed in the city of Murcia, and are more representative in the southern zone of the city.

Sites B and E show different behaviour to the previous ones. They are located on older and less compressive materials. Although variations in piezometric level are

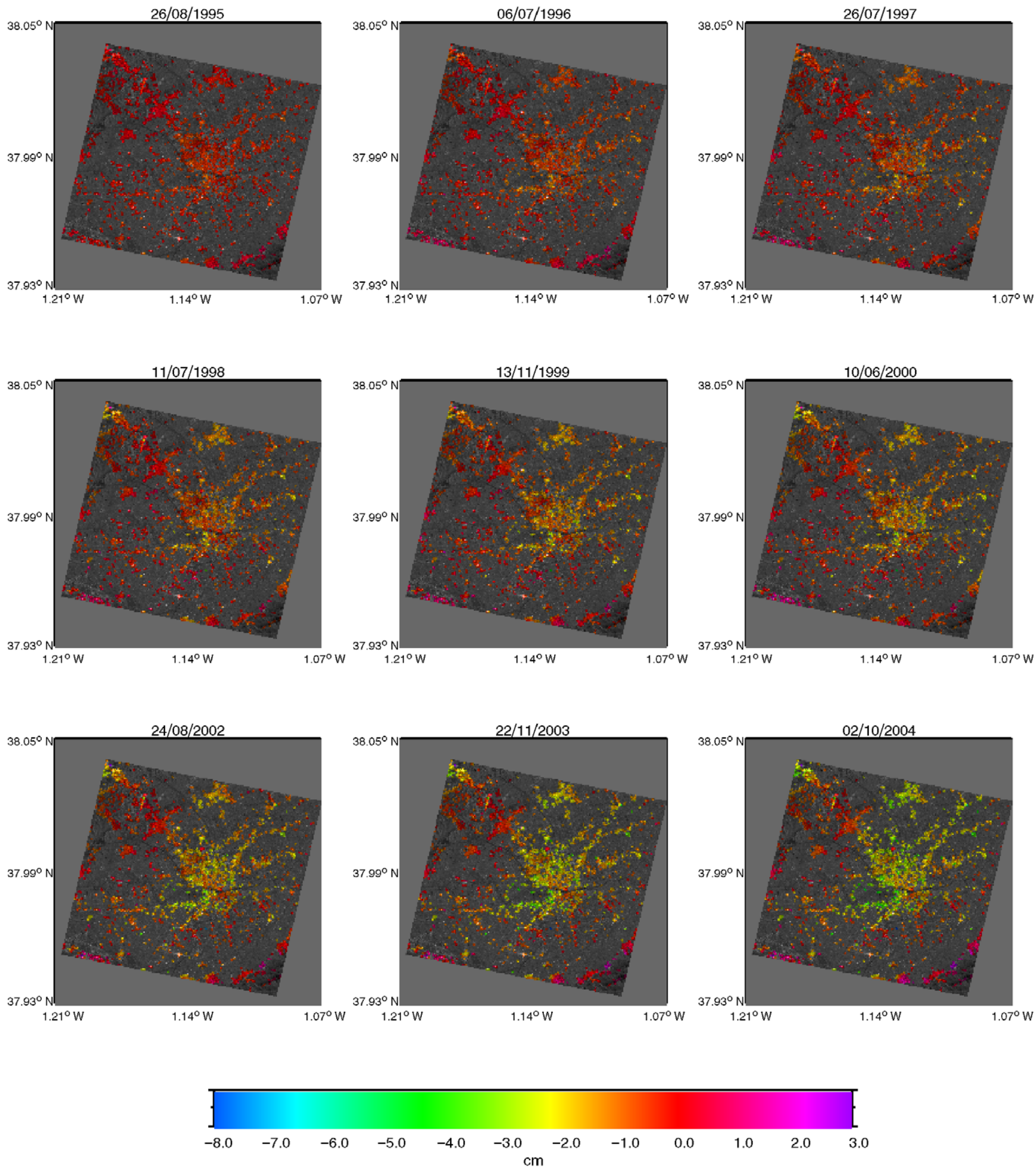

Fig. 7. Evolution of accumulated deformation in the study area. Results from April 14, 1993.

similar to that observed in the centre of the valley, here settlements reach only a few millimetres. They are greater at point E point than at point B because the thickness of the compressive materials is higher (Fig. 8). It can be observed that only five metres of compressive materials are affected by piezometric level changes at site B, thus explaining the low deformation for the corresponding pixel measured with DInSAR. The results of these sites can be considered as representative of the behaviour of areas located on non-deformable materials, corresponding to lithologies of the substratum basin, alluvial fans located near high relief features, and old basin filling materials.

Settlements measured at site C exhibit a new overall behaviour, which is observed in the southwest area of the study zone. In this case, ground deformation mimics piezometric level changes. Once the piezometric level started to recover, the surface rose too. It might be explained by the presence of expansive materials in the more superficial layers, which expand when the moisture content increases. The existence of swelling in this part of the basin is documented (Cartomur, 2004), and some recommendations are provided by regional authorities about requirements of geotechnical studies made for civil engineering purposes in this zone (COPOT, 2001).

Other isolated points of the study area show irregular behaviour not apparently related to piezometric level changes.

5.3. Comparison with available extensometric measures

Borehole extensometric data provide only a few measurement points situated in the South and East perimetre areas of the city. These data show deformation varying between −0.73 and −19.8 mm, with only one uplift value of + 2.5 mm, and an average value of −8 mm (Table 1). Only seven points with extensometric measurements have been considered in this paper for comparison purposes, because the remaining ones did not correspond to coherent pixels.

An acceptable relationship between both sets of data can be observed by comparing these borehole extensometric deformation data values, obtained between February 2001 and December 2003 and projected over the Line of Sight

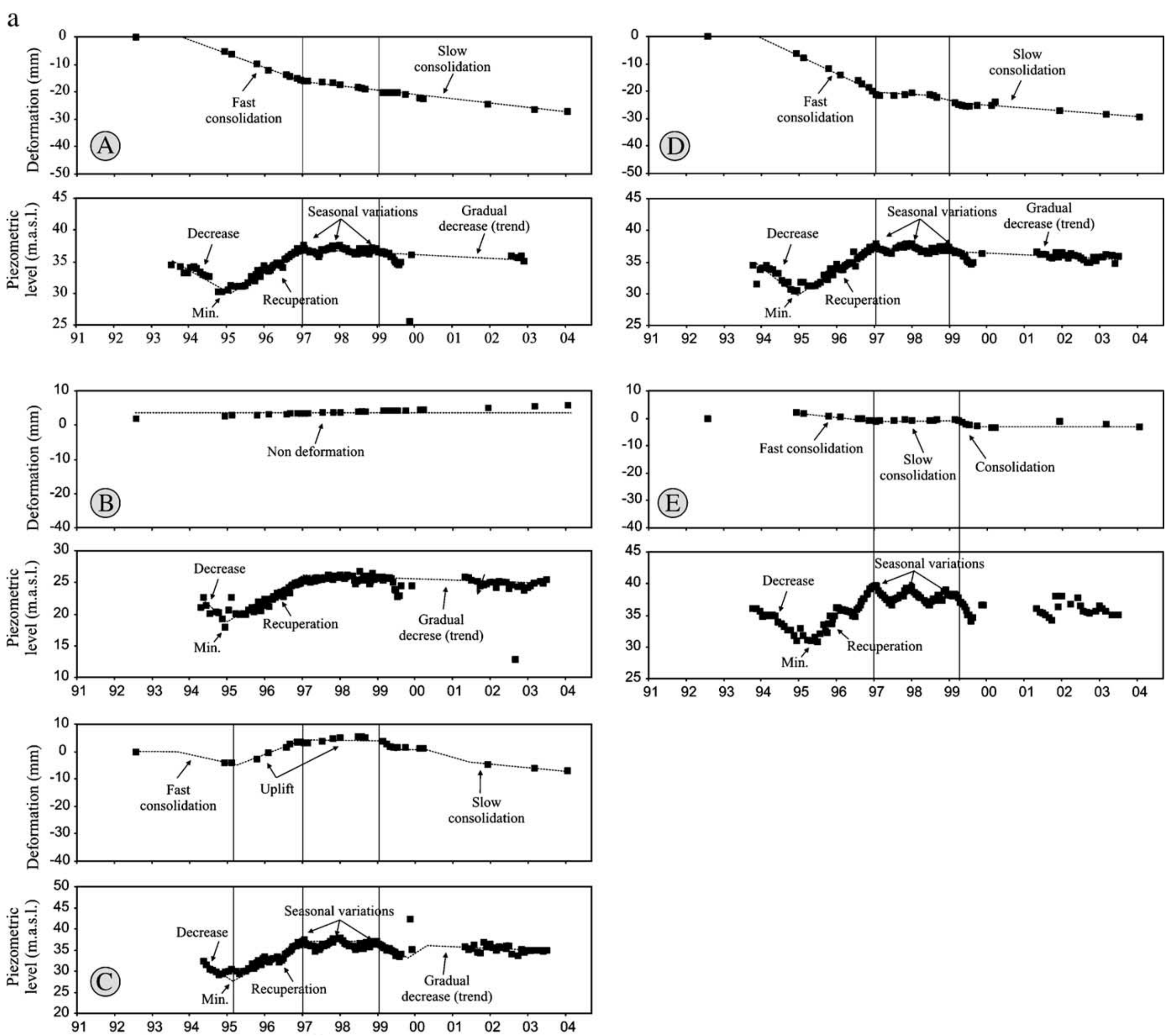

Fig. 8. a. Comparison between the evolution of the piezometric level and settlement measured by DInSAR during the period 1993–2004. Note the absence of deformation measurements in 2001. See location of piezometers and lithological composition of the subsoil in Fig. 8b. Fig. 8b. Location and lithological description of piezometric boreholes.

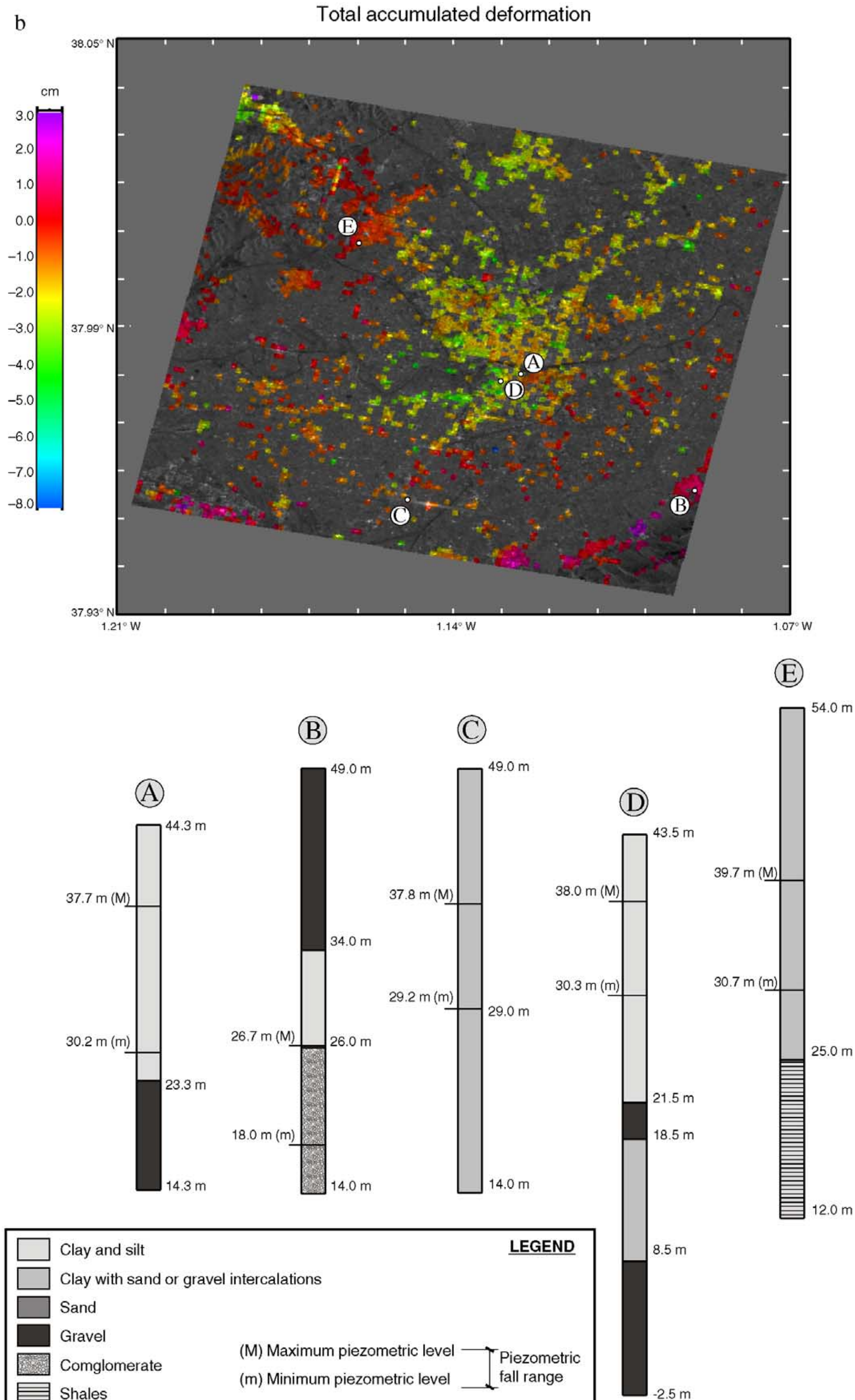

Fig. 8 (*continued*).

(LOS), with DInSAR settlements (which are measured along LOS) between December 2000 and November 2003, (Table 1). The absolute differences are smaller than 2.4 mm, except for the V13 wire extensometer which differs from its DInSAR value by 12 mm.

On the other hand, the differences observed can be partially explained by different thickness of the deformable soil columns monitored by each technique. Extensometers measure only the deformation (subsidence or uplift) occurring along the soil column traversed by the device (between 0 and 10 or 22 m below land surface), not detecting any compaction or expansion of the sediments occurring at greater depths. The DInSAR technique, however, measures surface deformation — this being the whole soil column deformation.

Another important source of discrepancy between both methods can be explained by the size of the pixel. The DInSAR deformation used corresponds to the dominant elements (with more reflectivity) located inside the 100×100 m pixel. So, when deformation is not uniform inside the pixel, point extensometric data is different to that measured with DInSAR techniques for the whole pixel.

Extensometers offer an instrumental on-site technique that can be used in both urban and rural environments. They only need a borehole to be installed. However, the CPT technique provides better results in urban areas where coherence remains constant over time. As a result, the joint use of extensometers (or other on-site techniques such as topography, GPS, etc.) which provide good results with quality and precision in rural environments, and DInSAR techniques, whose results are optimum for urban areas, allows us to monitor the deformations produced in the study area while complementing each other.

5.4. Comparison with modelled deformations and damage distribution during the 1992–95 drought period

As previously stated (Fig. 4), Rodríguez Ortiz and Mulas (2002) and Martínez et al. (2004) carried out numerical modelling of ground consolidation for a 10 m lowering of the water table in this zone (slightly greater than that observed during the 1992–95 drought period). Their results show that maximum settlements should be expected towards the south/southeast and northwest of the city, with maximum computed settlements of over 6 cm. We have compared these results with DInSAR-measured settlements for the 1993–1997 period (Fig. 7, upper right corner), which corresponds to an interval during which ground was being deformed as a consequence of the water table lowering produced during the 1992–1995 drought period. This is the effect of the above-mentioned delay between the periods of variation in water table position and the periods of ground deformation.

When comparing these two figures, we can see that a certain correlation exists in the south and east areas of the city, where DInSAR deformation is about 2–3 cm (depending on the site), although these value are approximately half the numerical (theoretical) deformation. These differences can be explained by the simplifications made during numerical computing and because the numerical model was based on a piezometric level lowering higher than that occurring in reality. On the contrary, towards the NW of the city, the DInSAR measured deformation is negligible, which greatly contrasts with the 7 cm predicted by the numerical models.

Fig. 4 also shows the distribution of damaged buildings in Murcia (presumably caused by the piezometric level lowering during the 1993–95 drought period) and the location of pumping wells and basements. Most of the damaged buildings are situated on the subsiding areas. However, there is no direct relationship between higher subsidence values and the severity (even frequency) of damage, because it depends on the construction quality of the buildings, the kind of foundation used, and the unique features of the terrain beneath the foundations. It means that many structures sited in areas highly affected by ground settlement did not show any damage whereas others in areas with smaller ground settlement suffered severe damage. The distribution of damage in Murcia City thus seems to be erratic. According to Rodríguez Ortiz and Mulas (2002), only 35% of the complaints (damage) could be clearly related to ground subsidence. Finally, there is no clear direct relationship between water extraction points (wells and basements) and ground subsidence. Fig. 4 shows the high number of water extraction points located in the city, but no correspondence with DInSAR measured deformations. This fact can be explained because ground subsidence only occurs when the volume of withdrawals is high enough to depress the piezometric level, which does not always occur, and the magnitude of settlement reflects the magnitude of the piezometric level lowering, which varies according to the volume pumped out.

6. Conclusions

CPT (an advanced DInSAR technique) has been used to present an analysis of ground subsidence due to overexploitation of an aquifer during the 1993–95 years (and subsequent periods) in the metropolitan area of Murcia (SE Spain). This technique has shown itself to be very useful for this purpose, with high quality results for a wide area at low cost.

The principal advantage of applying this technique to the Vega Media of the Segura River is that the spatial distribution and real magnitude of the consolidation process can be studied for a period with no instrumental data. This is because subsidence was not detected until the first damaged appear in some of the city's buildings in 1996, with some delay with respect to falls in piezometric level, meaning there was no instrumental record of subsidence until 2001. DInSAR, by means of the post-processing of available SAR images, has delivered ground surface subsidence values from 1993 to 2004, providing improved knowledge of the subsoil consolidation process mechanisms, as well as settlement distribution and velocities. These results are a great advantage because they provide better knowledge of the behaviour of the medium, with implications on the calibration of models.

Subsidence has been widespread in the study zone during the period 1993 – 2004, with settlements ranging from 2 to 8 cm. Only the borders of the valley, constituted by old materials (tertiary and basin basement) did not suffer any deformation. In this context, the relationship between the distribution of recent, more deformable, sediments and areas of greater deformation has been shown. These results are in close agreement with those from extensometers, and they have the advantage of covering a continuous wide area instead of the point-based extensometer data.

The comparison of these results with available data in this zone for the period in question has allowed us to establish that the ground surface deforms not only during piezometric level depression, but also during humid periods until the piezometric level reaches its previous position. As a consequence, a delay in the end of settlement is observed. This fact is of prime importance when dealing with this geotechnical hazard, because this means that it will continue in time, even if the trigger mechanism (excessive pumping) suddenly ceases.

In the future, the joint use of on-site techniques (e.g. topography, extensometers, GPS, etc.) in rural areas (non-coherent) and DInSAR in urban areas (highly coherent), will allow us to monitor possible deformations produced in the whole Vega Baja of the Segura River by complementing each other.

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