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Chapter 9

DINSAR MONITORING OF AQUIFER COMPACTION DUE TO WATER WITHDRAWAL: VEGAS BAJA AND MEDIA OF THE SEGURA RIVER (SE, SPAIN) CASE STUDY

R. Tomás[1], J.M. Lopez-Sanchez[2], J. Delgado[3], J.J. Mallorquí[4] and G. Herrera[5]

[1]Departamento de Ingeniería de la Construcción, OO.PP. e Infraestructura Urbana
Escuela Politécnica Superior de Alicante, University of Alicante, Alicante, Spain
roberto.tomas@ua.es
[2]Departamento de Física, Ingeniería de Sistemas y Teoría de la Señal. Escuela Politécnica Superior de Alicante, University of Alicante, Alicante, Spain. juanma.lopez@ua.es
[3]Departamento de Ciencias de la Tierra y del Medioambiente, Facultad de Ciencias, University of Alicante, Alicante, Spain. jose.delgado@ua.es
[4] Remote Sensing Lab (RSLab), Universitat Politècnica de Catalunya, Barcelona, Spain
mallorqui@tsc.upc.edu
[5] Departamento de Investigación y Prospectiva Geocientífica, Instituto Geológico y Minero de España (IGME), Ministerio de Ciencia y Tecnología, Madrid, Spain
E-mail: g.herrera@igme.es

1. INTRODUCTION

It is well known that excessive pumping of groundwater can produce regional-superficial subsidence due to in-depth aquifer compaction. The phenomena can be explained by means of Terzaghi's principle that states that effective stress, σ' (supported by soil grain skeleton) increases when pore pressure, *u* (due to water occupying the soil voids) falls for a constant total stress load, σ. The pore pressure decrease is due to water withdrawal. The phenomena can be expressed mathematically as:

$$\sigma' = \sigma - u \tag{1}$$

Droughts can be classified into several types: meteorological droughts, whose determining factor are the precipitations; agricultural droughts, whose determining factor is the soil moisture; hydrological droughts, whose determining factor is the fluvial contribution; and socio-economic droughts, whose determining factor is the demands supply. Generally, the determining factors for accelerating the processes of subsidence are groundwater withdrawal and hydric deficit over prolonged periods.

Subsidence is a worldwide extended phenomenon affecting wide areas and important cities as Mexico DC (Mexico), Bangkok (Thailand), Po Plain (Italy), Antelope, Santa Clara and San Joaquin Valley (USA), Nobi Plane, Niigata and Suzhou (Japan), Chosui River and Taipei (Taiwan), Shanghai, Tianjin and Beijin (China), among others. 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). In Spain only one case of general subsidence due to water withdrawal has been reported at the Vegas Baja and Media of the Segura River affecting important cities as Murcia (more than 400,000 inhabitants) and Orihuela (with almost 80,000 inhabitants).

The monitoring of this phenomenon is very important to establish the mechanisms, causes and velocities of the subsidence process in order to prevent infrastructures damages, plan the terrain occupation and take a hydrological planning. Subsidence measurement is necessary in order to determinate the extension of the affected area, the deformation or settlement velocities, the phenomenon mechanisms, the critical states of failure, and to evaluate the effectiveness of the adopted correcting countermeasures (Tomás et al., 2005).

Monitoring methods can estimate different deformation magnitudes: absolute or relative displacements, tilts, displacement along an established direction, deformations within depth, etc. The subsidence monitoring methods can be classified into five groups (Tomás et al., 2005): conventional topographic methods, geodesic methods, photogrammetric methods, remote sensing methods and instrumental methods. The selection of one (or more) of these methods depends on several key variables. These are: the cost of use of the technique (usually an important conditioning parameter), the accuracy, the resolution (only for photogrammetric and several remote sensing methods), the kind of data (punctual, linear, spatial, etc.), the frequency (time interval between measures acquisitions), the scene characteristics (rock outcrops, forest, etc.), the environmental conditions (principally the weather), the flexibility of the method (the possibility to select the time and place of the measure acquisition), the accessibility to the available data, the acquisition time (duration of the measurements at each campaign), the geometry, kinematics and nature of the phenomena to be studied, and the measure acquisition automation degree of the monitoring method itself.

Historically, deformation monitoring has been done using topographical and instrumental techniques. However, the development of new remote sensing techniques has allowed studying wide areas affected by these phenomena. Among all them, Differential SAR Interferometry (DInSAR) has the well-known ability to monitor different types of ground deformations (landslides, subsidence, earthquakes, etc.). The principle of the basic technique (interferometry) consists of the combination of two complex images acquired by a SAR sensor on-board a satellite. The resulting phase is called interferometric phase and, in general, provides information about the topography and the terrain displacements occurring between the two image acquisitions. When the topographic term is subtracted, the resulting phase is named differential interferometric phase, which is related to the terrain deformation, but is also contaminated with other contributions. All advanced DInSAR approaches exploit different signal characteristics and the availability of a stack of images (not only two) to estimate the terrain deformation from the other phase terms.

In this work, we have applied the Coherent Pixels Technique (CPT), an advanced DInSAR technique, to study subsidence phenomena due to the excessive pumping of groundwater in the Vegas Media and Baja of the Segura River (SE Spain) from 1993 to 2007. This is a detritic multilayer aquifer composed of silty and clayey layers intercalated with gravels with a total depth up to 200 meters that caused an important subsidence during the 1994-1995 drought period due to a piezometric level decrease up to 8 meters, damaging more than 150 buildings and other structures at the city of Murcia with a total cost over 50 million Euro (Rodríguez and Mulas, 2002; Mulas et al., 2003; Martínez et al., 2004). The settlement map retrieved with CPT shows settlement of up to 8 centimeters at some points of the study area and has been compared with other data provided by ground instruments to analyze the relationship with ground deformation. A good correlation has been observed between these data and the observations from *in situ* piezometric groundwater fluctuations and borehole extensometric settlements.

Damaged buildings, well points, basements and soft soil distributions have been also compared with the DInSAR subsidence values. A weak correspondence among measured subsidence values and damaged building distribution has been noticed because the occurrence of damage also depends on the structural state of the buildings and the characteristics of their foundations. In addition, the pumping wells distribution is not indicative of the distribution of the volume of water withdrawal, which is the real conditioning factor of piezometric level changes. Excessive groundwater pumping originates regional cones of depression that cause land subsidence. 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. Moreover, this technique has also allowed the monitoring of ground subsidence in the Vegas Media and Baja of Segura River for a period (1993-2001) where no instrumental information was available.

2. The Coherent Pixels Technique (CPT): A Method of Advanced Differential SAR Interferometry

This section describes the methodology for measuring ground deformations by processing SAR images. As indicated in the introduction, the general approach is known as differential SAR interferometry (DInSAR), but more advanced techniques are required for providing estimates with the accuracy required in this geological application. Among the available advanced DInSAR algorithms, we have applied the coherent pixels technique (CPT), which has been already detailed in the literature (Mora et al., 2003; Blanco et al., 2006). In this section, the main aspects of this approach are commented. Equations and several implementation details are avoided for not enlarging this section, but they can be consulted in the cited references.

The basic flow diagram of the processing chain, from the images to the deformation estimates, is illustrated in Figure 1. As initial data, we use:

a) A stack of SAR images acquired during the period of study by the same satellite or different satellites working in the same mode. We have used images from SAR sensors on-board ERS-1 and ERS-2 and Envisat satellites, all of them provided by the European Space Agency (ESA).
b) Precise orbits providing the position and velocity of the satellite at the image acquisition time.
c) A digital elevation model (DEM) of the study region.

After selecting a crop of the images, which approximately corresponds to the same area on the ground for all of them, they are coregistered to ensure that the same pixels in all images correspond to the same positions. This coregistration must be performed with sub-pixel accuracy. After that, one can already form the so-called interferograms, which consist in the product (on a pixel basis) of an image times the complex conjugate of another image. The resulting phase is named interferometric phase and contains contributions due to the topography of the scene, the possible deformation of the ground surface between the two acquisitions, the changes in the atmospheric conditions of the scene between the two acquisitions (which cause different delays in the roundtrip propagation of the wave between satellite and ground), and noise terms due to the system.

From the total set of possible interferograms (as many as image pairs), only a reduced set is used in the CPT approach. The selection criterion is based on the following three aspects:

a) The distance or physical separation between orbits (named spatial baseline) should be below certain threshold.
b) The time interval between both acquisition times (named temporal baseline) should not be very long in order to avoid changes in the scene which may hamper the subsequent deformation estimation.
c) The difference in the Doppler centroid frequency (a parameter related to the generation of the image) should be below certain threshold.

After selecting which pairs will be processed, the interferograms are computed. Then, by using the orbital information and the available DEM, the phase term due to the topography is predicted and cancelled out for each interferogram. The resulting phase is named differential interferometric phase, and may maintain residuals of the topographic term due to errors in the DEM.

The quality of the interferograms (i.e. the fidelity of their phase) can be measured by computing the so-called coherence, which is a maximum likelihood estimator of the phase quality based on an average of pixels surrounding the pixel of interest. Coherences close to one indicate a high quality of the phase, whereas close to zero correspond to low quality phases. The coherence computation implies a spatial averaging of the interferograms, also known as multi-looking.

In the CPT technique, the coherence of the differential interferograms at each position is used as the initial indicator of the quality of the future estimation procedure at that position. For this purpose, only those pixels whose coherence is above a certain threshold for a percentage of interferometric pairs are selected for the subsequent application of the CPT. As a result, this algorithm will compute (and provide) the deformation of the ground surface at a number of positions on the scene, but not over the whole scene. This selection approach is the origin of the name of this algorithm, since it will work, from this stage, only on the most coherent pixels.

After the selection of pixels from the set of differential interferograms, the ground deformation estimation starts. The algorithm is divided in two sequential stages. In the first stage, in order to avoid the influence of several disturbing contributions to the phase (atmospheric artifacts among others), it is assumed that the deformation exhibits a linear behavior, that is, the surface of each pixel moves (up or down) at a constant velocity during the whole study period. In addition, since the same DEM is used to compensate the topography in all differential interferograms, the error of the DEM at each pixel is also constant with time. With these assumptions in mind, this stage of the CPT estimates the velocity and DEM error for each pixel by fitting this model to the data, being the data the differential interferometric phases. To ease the model fitting procedure, this strategy is applied to pairs of neighboring pixels, so we compute an increment of the velocity and DEM error for each pair. Neighboring pixels are always closer than a maximum distance (1 km, in general) which is decided by taking into account the correlation length of the spatial distribution of atmospheric characteristics. After that, the solution is integrated for obtaining the final values of the velocity and DEM error at each pixel.

After the estimation of the deformation velocity and DEM error, the second stage of the CPT addresses the computation of non-linear deformation patterns for the selected pixels. However, in this stage the estimation is not based on a model fitting, but on the filtering of the phase according to the spatial and temporal characteristics of the different contributions still present in the data. Since the atmospheric contribution does not change much over the scene (it is low pass in space) but is completely uncorrelated from one date to another (it is as white noise in time), the phase is low-pass filtered in space and the resulting phase is filtered in time (or frequency) to neglect most of the contribution from the atmosphere. The cut frequency also defines the maximum frequency of the non-linear movement to be estimated. Of course, this approach is not able to separate completely both contributions (movement and atmosphere), but it is enough for most scenes. The spatially high-pass terms of the phase (resulting from subtracting the low-pass terms from the total phase) are usually filtered in time to reduce noise in the final deformation estimation.

In conclusion, the CPT provides a linear deformation term (at constant velocity) plus a non-linear term. The addition of both contributions result in a realistic deformation evolution for all the coherent pixels, which is able to follow most of the deformations treated in different scenarios. If a priori information is available, about the spatial and temporal characteristics of the targeted deformation, it can be used for choosing the processing parameters which best fit the problem at hand. Figure 1 constitutes a flow chart of the above described CPT DInSAR processing.

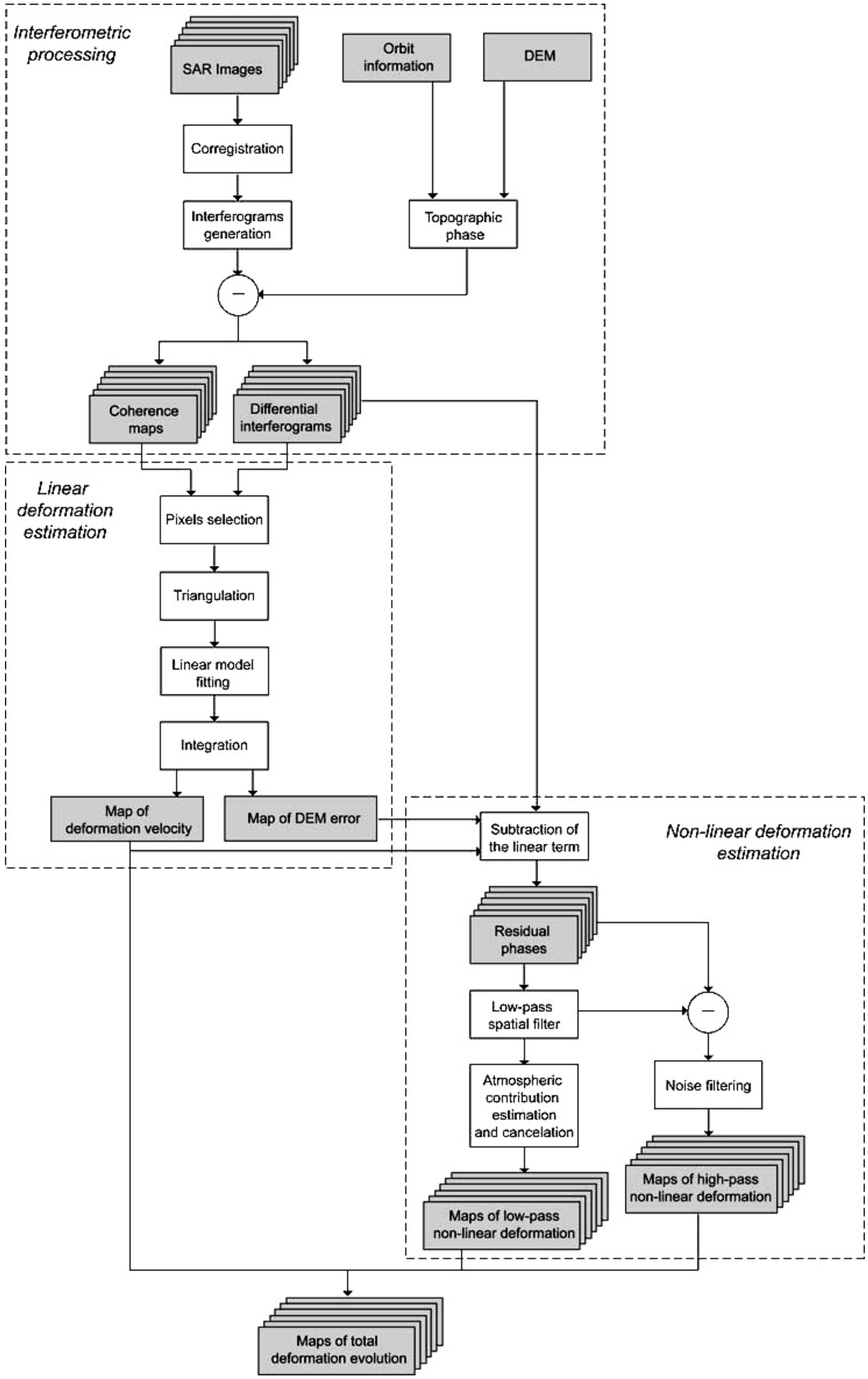

Figure 1. Flowchart of the Coherent Pixel Technique (CPT) processing.

3. FRAMEWORK OF THE VEGA BAJA AND MEDIA OF THE SEGURA RIVER

3.1. General Features

This study is focused on the Vega Baja and Media of the Segura River aquifer located at SE of the Iberian Peninsula (Figure 2a). This aquifer system occupies a surface of approximately 425 Km^2 belonging to the Alicante and Murcia provinces. The geographical border between the two provinces coincides approximately with the limit that separates the regions called as the aquifer: Vega Baja and Vega Media of the Segura River Basin.

The study zone belongs to the so-called "Bajo Segura basin" (Montenat, 1973). This basin comprises the current valley of the Segura river as well as the reliefs located towards the south of the valley (Figure 2b). This is mainly an agricultural area where traditional irrigation systems are used. However, agriculture activities have been progressively substituted by industrial and urban land uses.

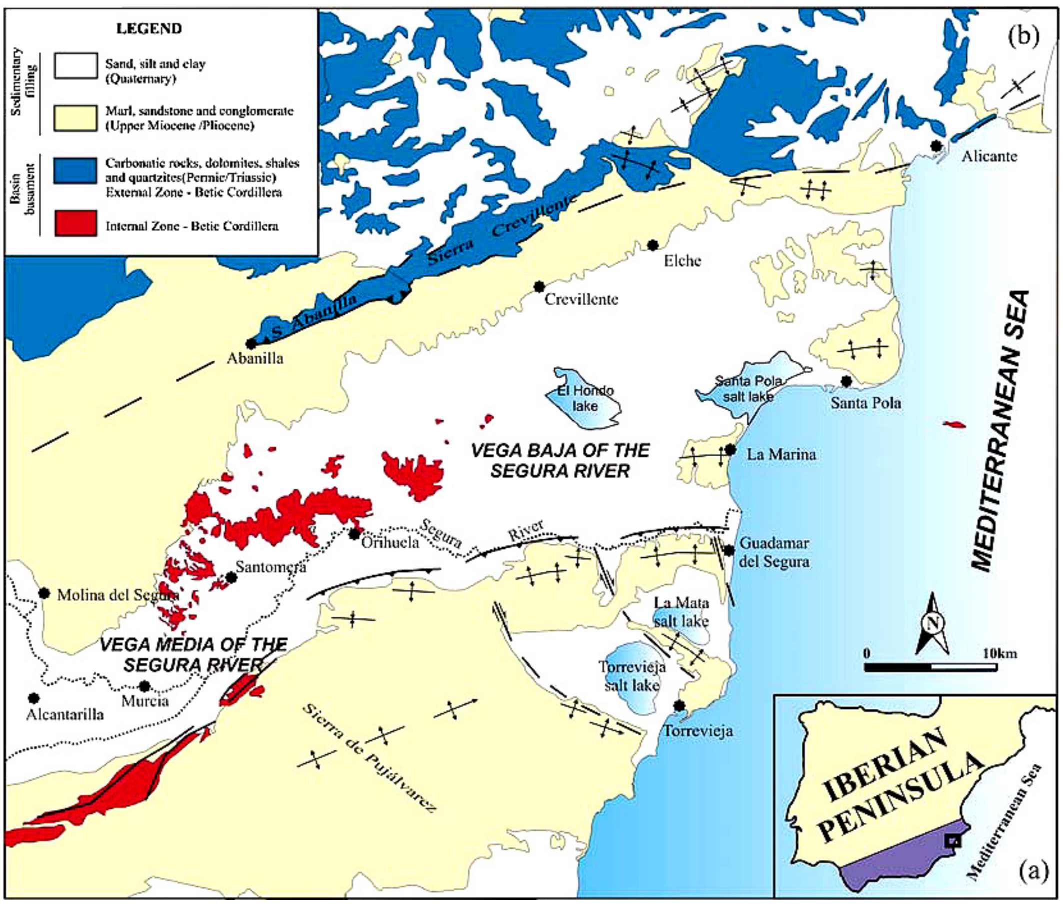

Figure 2. Geological setting of the Vega Baja and Media of the Segura River (after Tomás et al., 2007).

3.2. Climate

This area suffers a dry subtropical Mediterranean climate with semiarid features. The precipitations are low, temporally and spatially irregular and random, with drought periods up to five months and a low number of rainy days. The rainiest seasons correspond to autumn and spring, with less rain during winter and a minimum in summer. The accumulated precipitations are lower than 320 mm per year.

Historically, twelve drought periods are known on the meridional area of Alicante province (Labclima, 2007): 1841-1842, 1875-1879, 1909-1914, 1920-1921, 1935-1937, 1940-1941, 1944-1945, 1953-1954, 1973-1974, 1980-1985, 1990-1995, 1999-2000 and 2005-2007.

3.3. Geological Setting

3.3.1. Basin Substratum

Basin basement is constituted by old rocks corresponding to the Internal Zones (Permian and Triassic in age) and to the External Zones (Mesozoic in age) of the Betic Cordillera. These materials outcrop mainly to the north and southern borders of the Segura river valley (Crevillente and Carrascoy ranges), although they are also found at Orihuela and Callosa mountains, just in the middle of the flood plain of the river (Figure 2b).

3.3.2. Sedimentary Filling

The sedimentary record of the basin comprises materials with ages ranging from Late Miocene up to present day. The oldest ones, Upper Miocene, are mainly made up of marls, with sandstones at their base. They constitute a thick sedimentary sequence, more than 600 m in the western part of the valley (Cerón and Pulido, 1996; Mulas et al., 2003) and even thicker towards the east. Pliocene-Pleistocene materials show a characteristic regressive sequence, comprising marine marls at the base that evolve towards shallow marine (sandstones) and continental sediments (conglomerates interbedded with marls). Continental sedimentation evolved from west towards the eastern parts of the basin. The thickness of these materials also show the same trend, being about 150 m in the western part of the basin (Aragón et al., 2006) and increasing towards the coast (Gauyau, 1977). Finally, on the top of these units, recent (Holocene) sediments are present in the Segura river valley. They correspond to unconsolidated sediments deposited in alluvial, fluvial, lagoon and coastal environments (Rodríguez-Jurado et al., 2000; Delgado et al., 2002; Mulas et al., 2003). The thickness of this unit increases from valley borders towards the valley centre as well as from west towards east. Usually, in Murcia city maximum thickness of this unit is about 20-30 m (Figure 3), while it increases to about 30-40 m in Orihuela and over 60 m at the mouth of the Segura River (Delgado et al., 2000; Rodríguez Jurado et al., 2000).

3.3.3. Hydrogeology

The aquifer system of the Vega Media and Baja of the Segura River belongs to the so-called "Number 47 aquifer - Segura-Guadalentín". It comprises a thick sequence of alluvial filling constituted by alternating layers of permeable, semipermeable and impermeable materials (IGME-DPA, 1996).

Two principal units are differentiated (IGME-DPA, 1996), the first is constituted by a phreatic superficial aquifer and the second one, located under the previously described unit, is constituted by a group of confined aquifer levels capable of working as a whole aquifer or as a multilayer aquifer depending of the considered area and with a piezometric level higher than the superficial one. The superficial aquifer comprises the first 5 to 30 meters (depending on the site and measured from ground surface) of recent sediments (clay, silt and sands) with poor hydrological parameters. The deep aquifer system, located under the previously described aquifer, is composed of a sequence of gravels and sands alternating with marls, clay and silts (Pleistocene to Pliocene materials). On the upper part of this aquifer, in contact with the superficial aquifer, there is a gravel layer with good hydrological and geotechnical parameters that has been intensively exploited since 90 decade as an important water resource.

The subsidence model suggest that when water is pumped out from the upper gravels of the deep aquifer system, a gradient is created that implies a water flow from upper aquifer to gravels (Mulas et al., 2003). Consequently, pore pressure on the superficial aquifer falls and the soil suffers a consolidation.

4. SUBSIDENCE OF THE VEGA BAJA AND MEDIA OF THE SEGURA RIVER: CAUSES AND CONSEQUENCES

The dramatical drought that suffered the Vegas Baja and Media of the Segura River Basin during 1992-1995 forced to the local and national authorities to look for water resources for population consumption by means of emergency “drought wells” that pumped water from subsoil aquifers. Figure 4 shows the temporal evolution of water availability in the Vegas Baja and Media of the Segura River Basin. As it can be observed, during 1983-1984, an important drought caused a great hydric deficit that affected this area, but the overexploitation of the aquifer was not important. During the 1992-1995 period, an important draught affected the Vega of the Segura River Basin causing an important hydric deficit that extended until 1998. During this period, the complementary resource demand increased notably (Figure 4) and, as a consequence, groundwater overexploitation grew up. This overexploitation of the aquifer caused intense piezometric level falls (Figure 5) that produced the consolidation of the more deformable, fine, soil layers.

The piezometric level history of the Vega Media (curves 1 to 6 in Figure 5) and Baja (curves 7 to 9 in Figure 5) of the Segura River aquifer shows a constant value until the 80’s, when a long draught period affected this area causing a fall up to 5 meters. The piezometric level corresponding to the period before this draught exhibited a long term constant value of the piezometric level with seasonal changes lower than 3-4 meters. The piezometric level of the aquifer grew up after the drought and remained invariable until 1993, when another long drought stage started. During this time, emergency wells were built and pumpage intensity was increased drastically, as previously commented. The piezometric level on the gravel layer

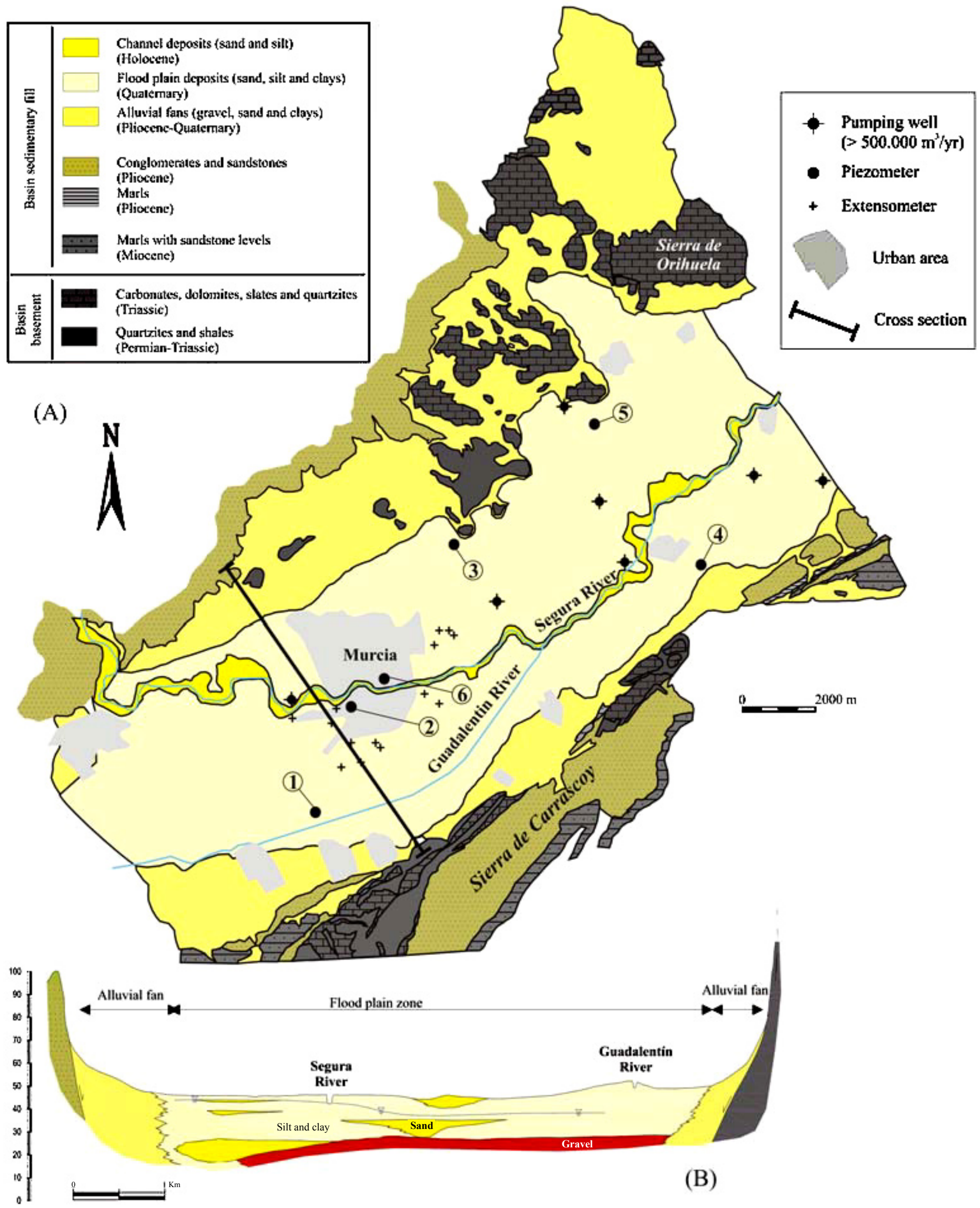

Figure 3. A) Detailed geological map of the Vega Media of the Segura River with location of extensometers, piezometers and important pumping wells. B) Cross section of the Vega Media of the Segura River (based on Aragón et al., 2004 and Aragón et al., 2006).

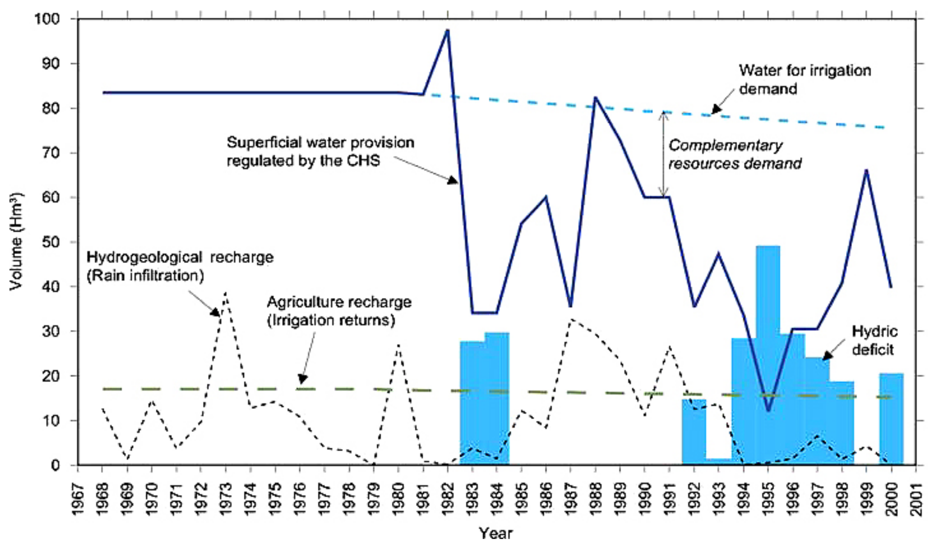

Figure 4. Water availability on the Vega Media of the Segura River for 1968-2000 period (data from Aragón *et al.*, 2006). CHS: Segura Basin Hydrographic Regulation Authority.

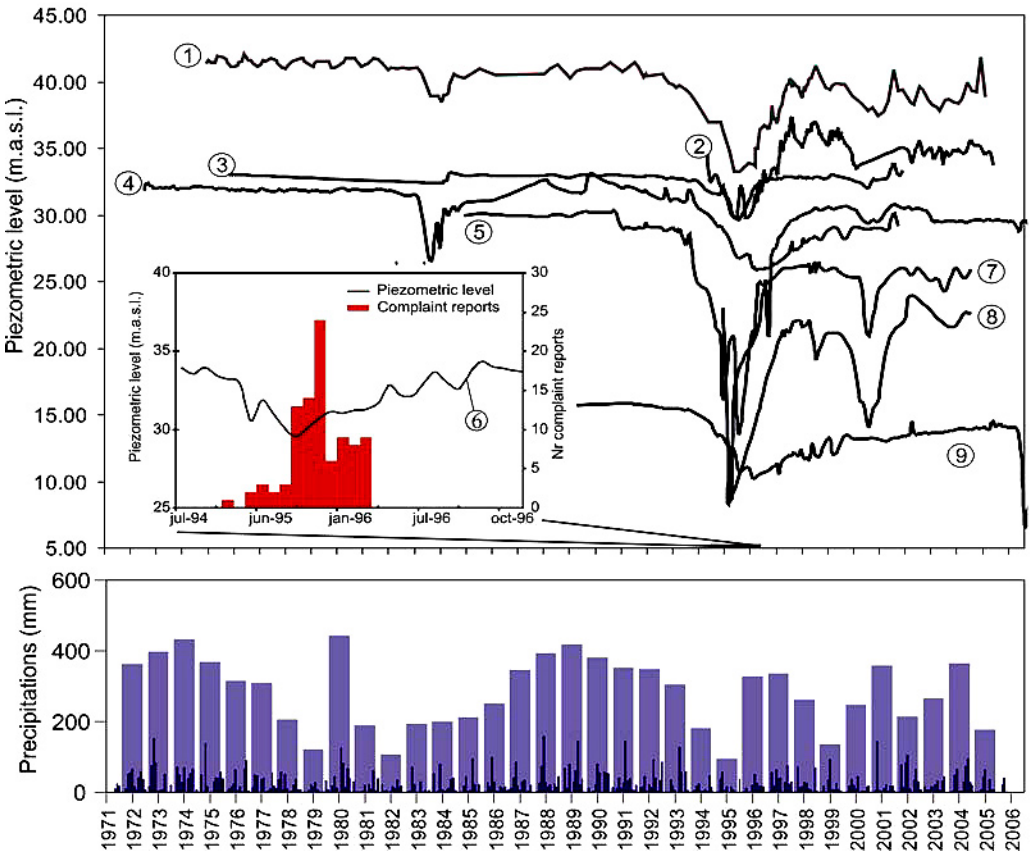

Figure 5. Variation of piezometric levels at several locations of the Vegas Media and Baja of the Segura River and relationship with complaint reports in Murcia city and annual precipitations. See location of piezometers 1 to 6 at Figure 3. Piezometers 7 to 9 are located near Orihuela city.

(located on top of the deep aquifer) descended up to 10 meters at some points of the aquifer, causing a consolidation of the superficial aquifer that reached values up to 10 cm, damaging more than a hundred buildings in Murcia city (Figure 5). This was the first documented case of subsidence due to water withdrawal in Spain.

The causes of the damages were mainly caused by (Vázquez and Justo, 2002; Mulas *et al*., 2003): differential settlements on superficial foundations, negative skin friction on pile foundations, corruption of wood piles foundations, and other damages caused on sidewalks, walls, roads and other infrastructures of the city (Figures 6 and 7).

Figure 6. Examples of building and infrastructures pathologies caused by subsidence occurred during 1993-1995 drought period (Murcia).

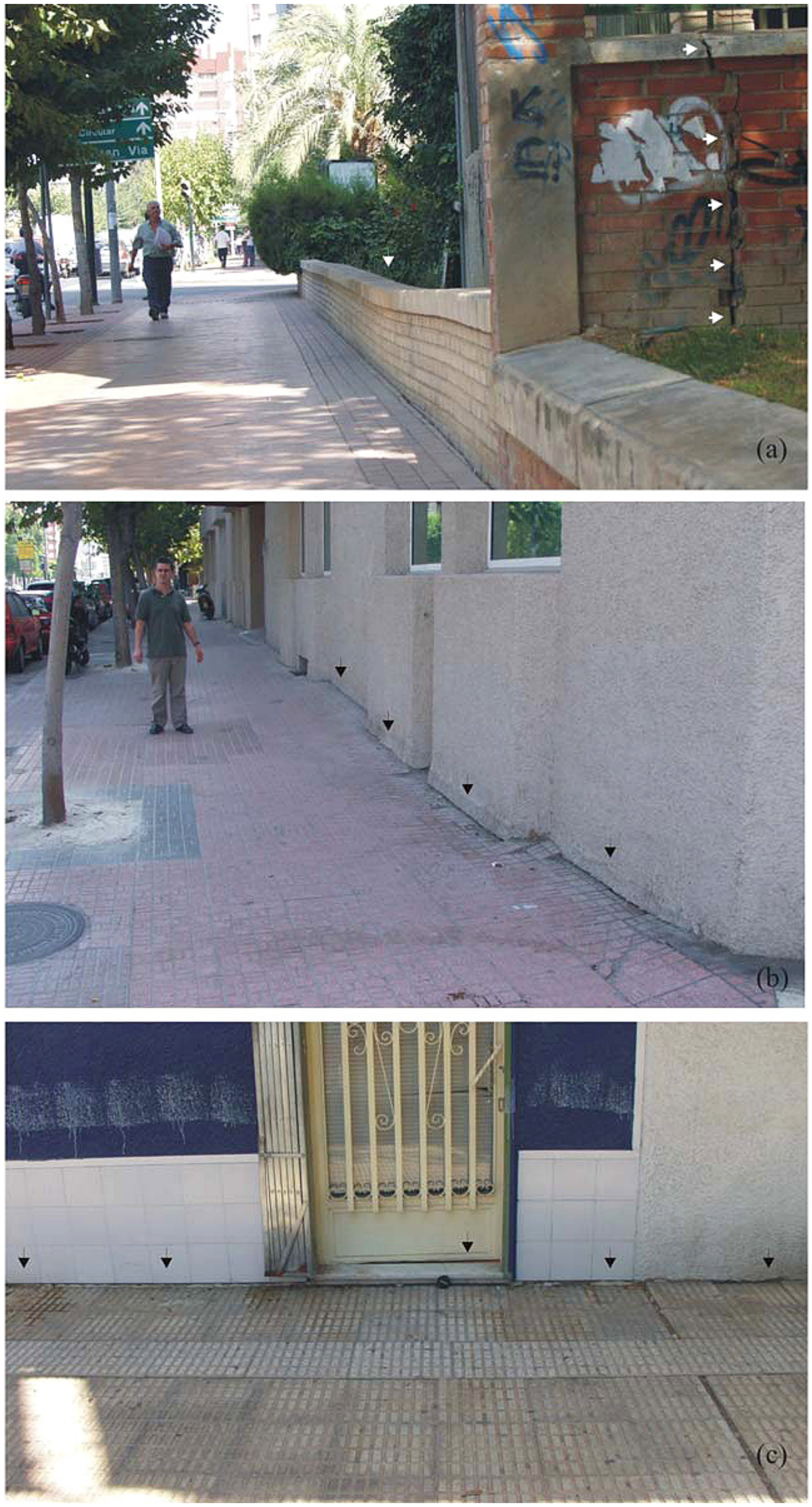

Figure 7. Examples of infrastructures pathologies caused by subsidence occurred during 1993-1995 drought period (Murcia).

5. Monitoring Subsidence by Means of an Advanced DInSAR Technique in the Vega Baja and Media of the Segura River Basin

5.1. Results

Subsidence occurred by surprise and, consequently, no instrumental measures of the phenomena were taken until damages had developed. Since that moment (year 2001) local authorities set up an extensometric control network consisting of 22 borehole extensometers, 16 of them rod extensometers and the remaining of incremental type extensometers, located within the metropolitan area of Murcia (Figure 3). The rod extensometers monitor the ground movement occurring between ground surface and a depth varying between 10 to 15 m, with three depth measurement intervals, while incremental extensometers monitor between 0 and 15 to 22 meters depth and provide measurements every meter of depth (Peral et al., 2004). Complementarily, 650 topographical benchmarks were installed in order to complement the subsidence measurement campaign (Peral et al., 2004).

CPT has allowed us to measure, by means of a postprocessing of the ERS-1, ERS-2 and ENVISAT available images, the subsidence from 1993 to present, providing a subsidence map even for a non instrumented period.

A total number of 6 ERS-1, 55 ERS-2 and 17 ENVISAT images have been used for the generation of 185 interferograms. The coherence criterion used for the pixel selection has been divided into several levels with 0.55, 0.50 and 0.40 at 40% of the interferograms and with a minimum value of 0.01. The minimum coherence value to adjust the model with the data has been established at 0.35. Finally, the maximum distance considered to establish a relationship among coherent pixels has been fixed in 1 km.

The processing of the whole study area has been divided into three rectangular areas in order to optimize the hardware resources and to focus the results on the interest zone. The three processing crops are the city of Murcia and its metropolitan area (SW of the Vega Media of the Segura River), the NE area of the Vega Media of the Segura River, and the Vega Baja of the Segura River. For the visualization of subsidence of the whole area, the different processing zones have been superimposed (Figure 8).

For the whole study area, four main zones of subsidence are recognized (Figure 8):

1) Zone A. Murcia city. The urban and the metropolitan area of Murcia suffered settlements higher than 10 cm that locally can reach values near 15 cm. This area is highly populated (more than 400.000 inhabitants), and the subsidence occurred during the 90's caused an important social alarm.
2) Zone B. Beniel zone. This area is located at the border of the Vega Media, near the Vega Baja. Several villages and towns are located in this area. The maximum values of subsidence obtained by means of DInSAR are up to 10 cm.
3) Zone C. Orihuela city. Curiously, this area suffered and suffers currently the most important settlements of the study region, but not important damages are reported. During the 90's, several newspapers published news related with damages that affected a commercial street of the city and buildings located along it. Deformation

measures and control of subsidence have not been taken yet. The subsidence values measured for the study period reach 12 cm.

4) Zone D. Dolores zone. This subsiding area is located at the NE of the Vega Baja. On this area the settlements range between 2 and 10 cm.

Stable areas are mainly located on relieves that border the valley, constituted by Tertiary and Permotriassic materials.

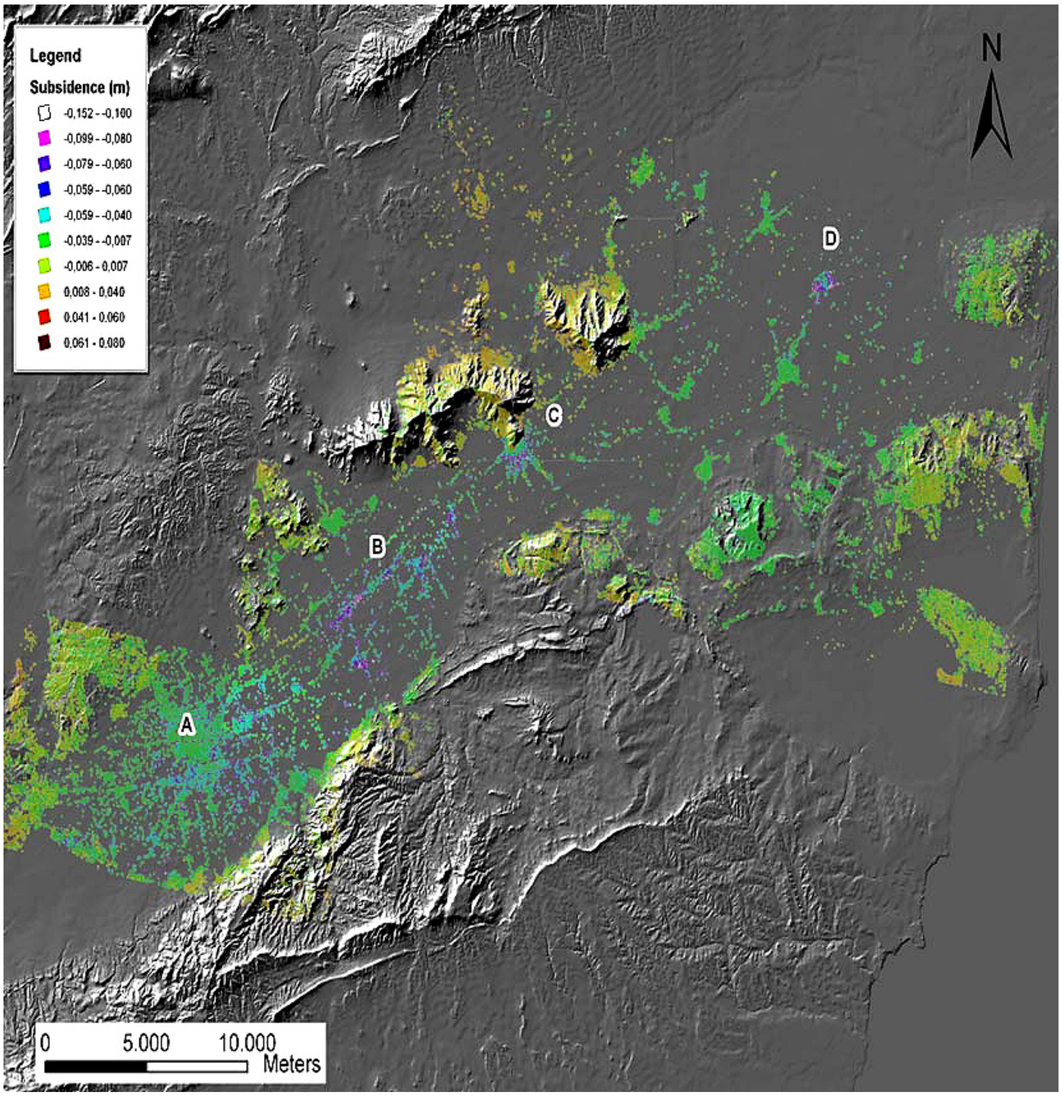

Figure 8. DInSAR Subsidence of the Vega Baja and Media of the Segura River Basin (1993-2007 period).

Figure 9 shows the total subsidence occurred from 14/04/1993 to 31/03/2007 at Orihuela and Murcia cities. Pumping wells, the damaged buildings and soft-soils (unconsolidated and deformable) thickness are shown on this figure too.

In both cases, subsidence mainly occurs over the unconsolidated sediments, being null over Tertiary and Permo-Triassic materials (consolidated and cemented rocks).

In the case of Orihuela city, the above commented fact is clearly noticeable. Some of the buildings of the city are founded over Triassic, non deformable limestones. The rest of the city is settled over the Quaternary, highly deformable sediments whose thickness increase proportionally to the distance to the relief of the Sierra of Orihuela. Ground subsidence of the city follows a pattern similar to that of the deformable thickness, increasing from the relief towards the centre of the valley. It is important to note that subsidence is very intense near the river channel, perhaps due to the presence of sandy layers, with higher permeability, which allow a fast drainage of water table towards deep aquifers when piezometric levels fall down during draught periods. This makes effective stresses increase very fast in these sediments, which consolidate under them. Although it is well known that sandy sediments are less deformable than fine soils, consolidation process is much slower in these last. So when piezometric levels recover, fine sediments usually have not deformed completely while sandy soils have done it.

In the case of Murcia city maximum settlement values are concentrated at the NE and SW area of the Segura River, with values up to 8 cm. Locally, extreme values up to 10 cm have been measured in the metropolitan area around the city. The major part of the city is affected by settlements ranging from 1 to 6 cm.

A relationship between pumping well distribution and subsidence can not be clearly established in the two studied cities. The reason is that there exists a great heterogeneity among the pumping wells location, water volume pumped, time of pumping, and depth of pumping. Nevertheless the joint effect of the water withdrawal causes important regional piezometric level decreases that are the principal cause of subsidence.

In both cities, the damaged buildings are located over areas with settlements varying approximately from 2 to 10 cm. However, a lot of buildings located over areas with high values of subsidence did not suffer any damage. The causes are that the site effect of subsidence depends on the type of foundation, the quality of the materials, the construction technique, the existing lithology and their properties, etc.

Figure 10 shows the spatial and temporal evolution of subsidence in Orihuela city. In 1993-95, the first noticeable deformations are detected. Then, there is a uniform settlement over the whole flood plain until 1999. Since 2001, several bowls with stronger subsidence appear close to the river, and they generalize to the whole urban center until 2007.

The spatial evolution of subsidence in Murcia city is illustrated in Figure 11. It is observed that at the beginning of the monitored period, the entire city shares a settlement of the same magnitude. However, in the last dates, deformation is more pronounced on the East and South parts of the city.

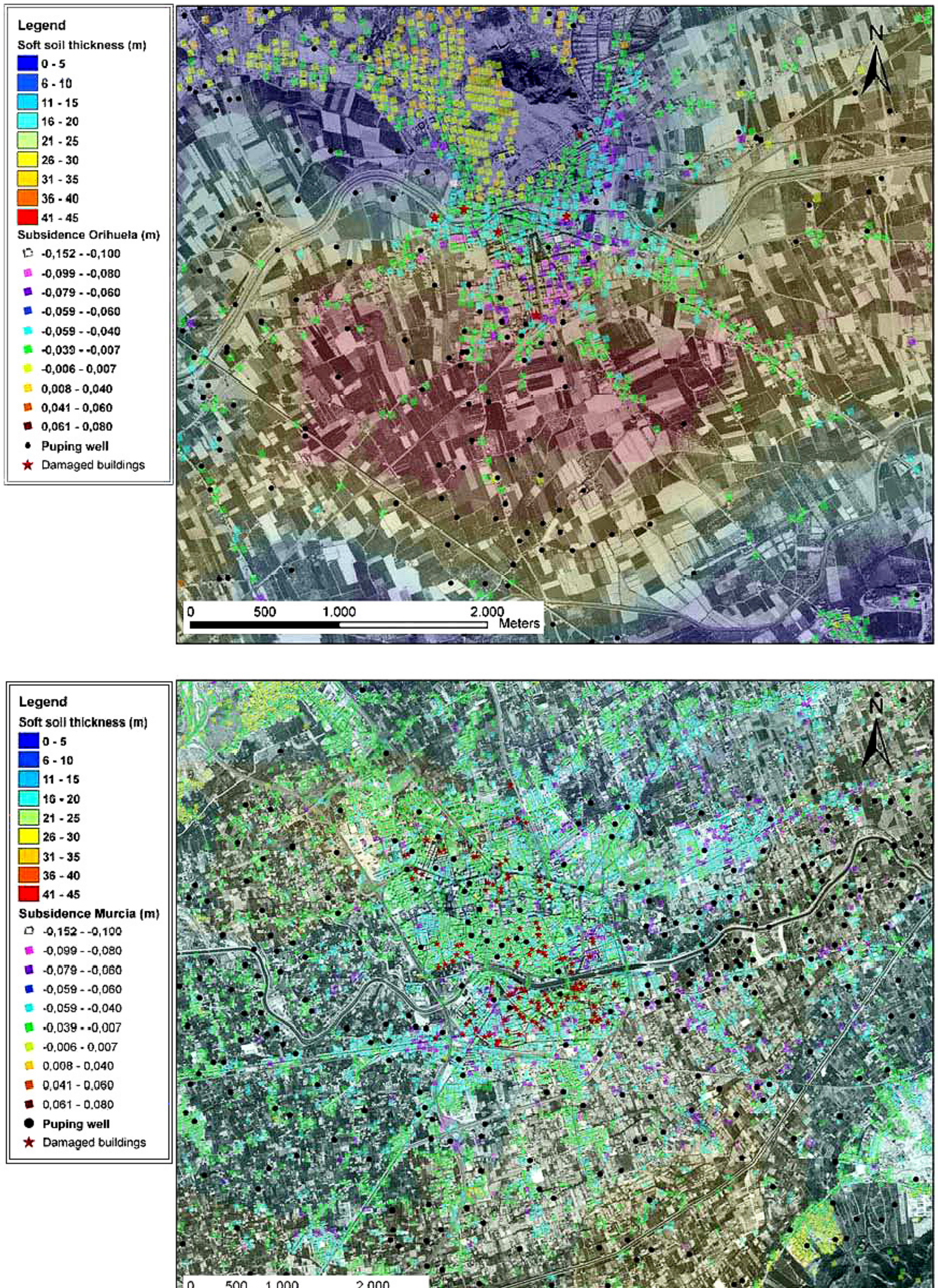

Figure 9. Damaged buildings, deformable soil thickness, well distribution and subsidence from 14/04/1993 to 31/03/2007 in Orihuela (Vega Baja) and Murcia (Vega Media) cities.

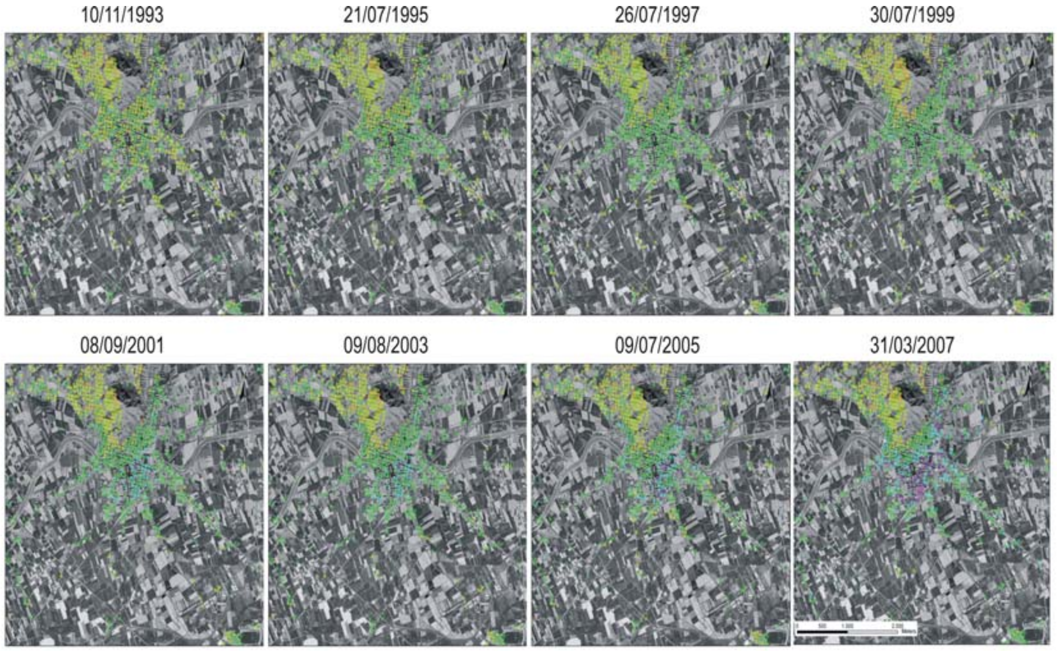

Figure 10. Spatial evolution of subsidence in Orihuela city (1993-2007 period). Origin of measures is established in 14/04/1993. Color scale is the same than the one used at Figure 9.

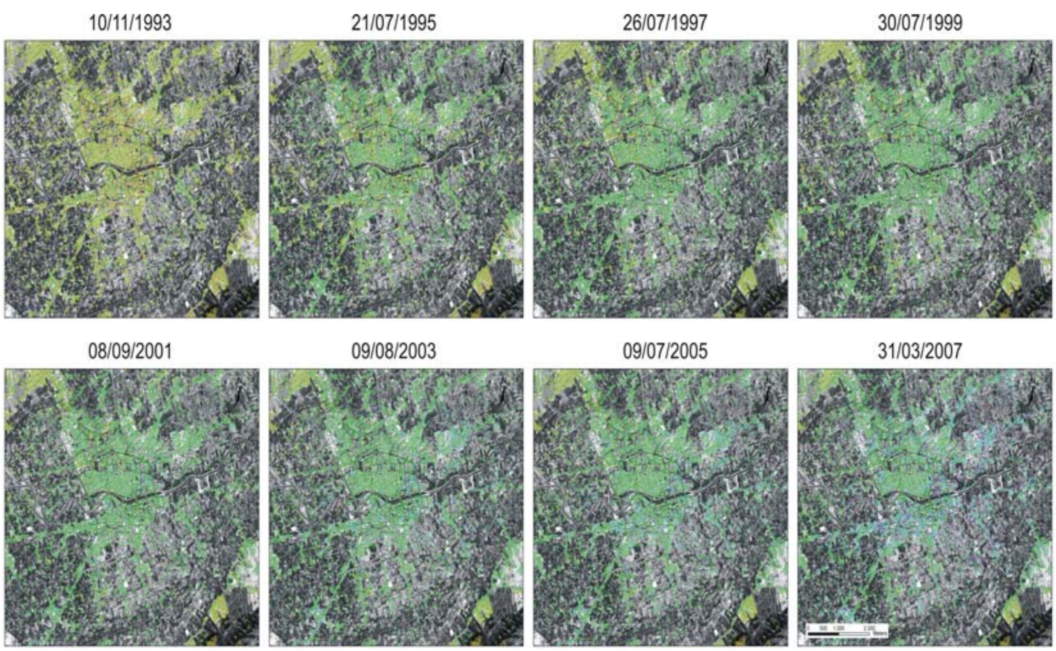

Figure 11. Spatial evolution of subsidence in Murcia city (1993-2007 period). Origin of measures is established in 14/04/1993. Color scale is the same than the one used at Figure 9.

5.2. Comparison of Deformations with Piezometric Level Evolution

Figures 12 and 13 show the evolution of the deformations at several points of Orihuela and Murcia cities, respectively.

All piezometers located near Orihuela city show that levels started to fall in 1994, reaching a minimum drop of 15 m in 1996 (Figure 12). After this period, the water level grew up, getting a maximum value near 1998. Then piezometric level fell in a gradual manner, with a minimum level during 2001. Note that water level was higher than the one reached during the previous draught period (i.e., less rigorous draught period). The level re-established in 2002-03, decreasing again from 2006 to present.

The piezometric level of Murcia City follows a similar variation pattern than the Orihuela's one but with a lower magnitude of the water level changes (Figure 13) that reach 6-8 m in the city.

Two types of behavior have been distinguished during this period in the two studied cities: The first corresponds to those points where deformation is null along time (yellow curves). As previously stated, this area is located over stable lithologies, not affected by subsidence, which correspond to old cemented materials (Triassic and Tertiary). The low milimetric variations correspond to noise in the processing.

The second recognized behavior corresponds to points with elasto-plastic behavior. At these points deformations may be unrecoverable (plastic) or partially recoverable (elastic). The first type of deformation occurs when soils start to withstand the greater vertical effective stresses in its history. In this case, if effective stresses are reduced, soil recovers only a small amount of its initial volume. If effective stress increment does not exceed the maximum one previously supported by the soil, deformation is small and (theoretically) completely recoverable. Taking this into account, if piezometric level fall-down increases effective stresses in such amount that they are the greatest ever supported by the soil, plastic deformation occurs (ground subsidence). This maximum value of effective stress supported by the soil is also known as preconsolidation stress of soil. When piezometric level is reestablished, only a small amount of deformation is recovered (uplift). If after this stage of level growth, a new fall-down of piezometric level occurs, but it is of lower amplitude than previous period (i.e., effective stress does not exceed the preconsolidation stress of soil), ground subsidence is small and can be recovered completely if piezometric level rises again. When effective stress exceeds preconsolidation stress of soil, ground deformation is high and only a small part can be recovered when piezometric level rises.

Depending on the soil state (overconsolidated or normally consolidated) elastic or inelastic deformations are predominant, conditioning the behavior of the soil under piezometric level changes. Red, blue and brown curves on Figures 12 and 13 present this kind of behavior.

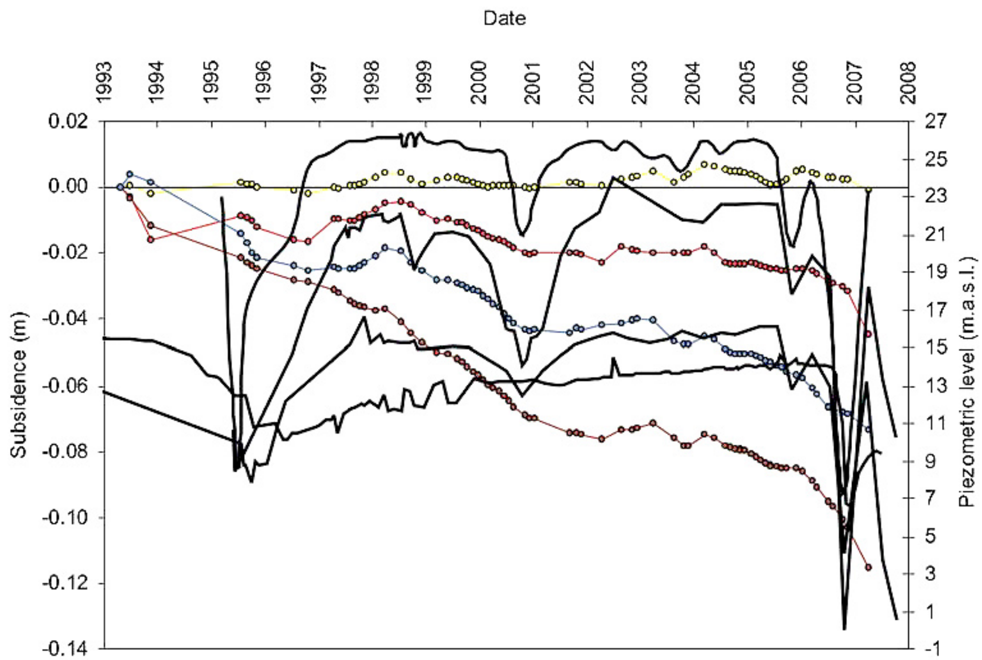

Figure 12. Comparison between DinSAR deformations (points) and piezometric level (continuous lines) evolution for several points located at Orihuela city.

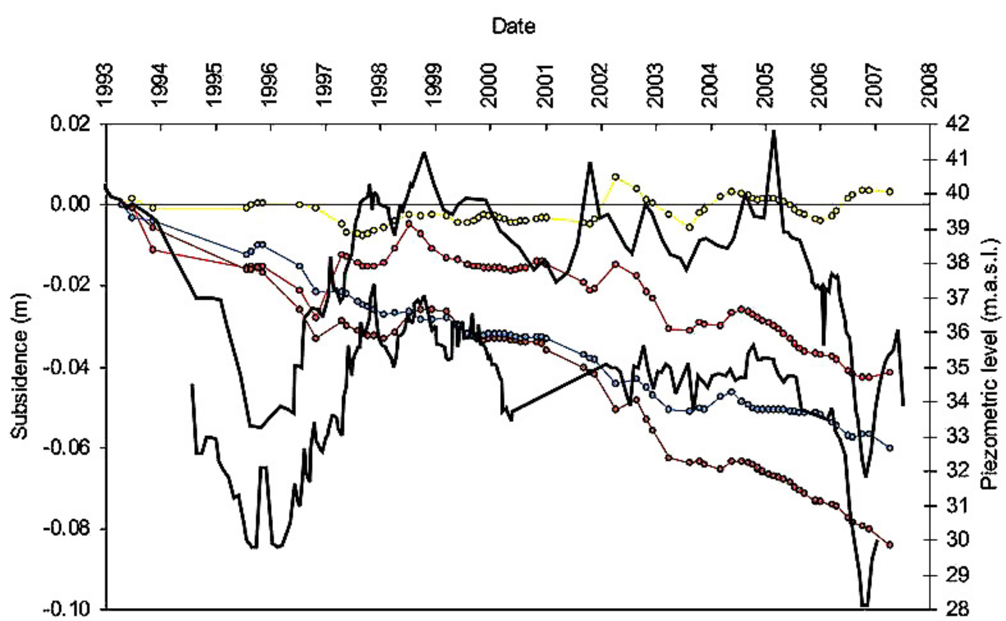

Figure 13. Comparison between DInSAR deformations (points) and piezometric level (continuous line) evolution for several points located at Murcia city.

5.3. Comparison of Deformations with Extensometric Measures

A comparison between DInSAR deformation estimates and extensometric deformations projected along the Line of Sight (LOS) has been made for the 19 extensometers located at the metropolitan area of Murcia (Figure 14). Unfortunately, the whole temporal evolution of these extensometers is not available. Moreover, leveling measures are not available too. Only the extensometer measures from February 2001 to December 2003 period are available from Peral et al. (2004). These data have been compared with DInSAR measured deformations for a similar period (from 6/1/2001 to 22/11/2003) yielding an absolute average difference of 5.7±3.7 mm and maximum differences varying among -5.8 and +12.7 mm when we only consider the coherent pixels located over the extensometers. When there are not coherent pixels on the extensometer location and we consider for the statistic computations the nearest pixel, the average absolute difference is 6.2±3.3 mm. These values agree with those obtained by other authors (Herrera et al., 2007; Casu et al., 2006; Colesanti et al., 2003). It is noticeable that, generally, DInSAR provides absolute values of deformation higher than the ones obtained by means of instrumental techniques.

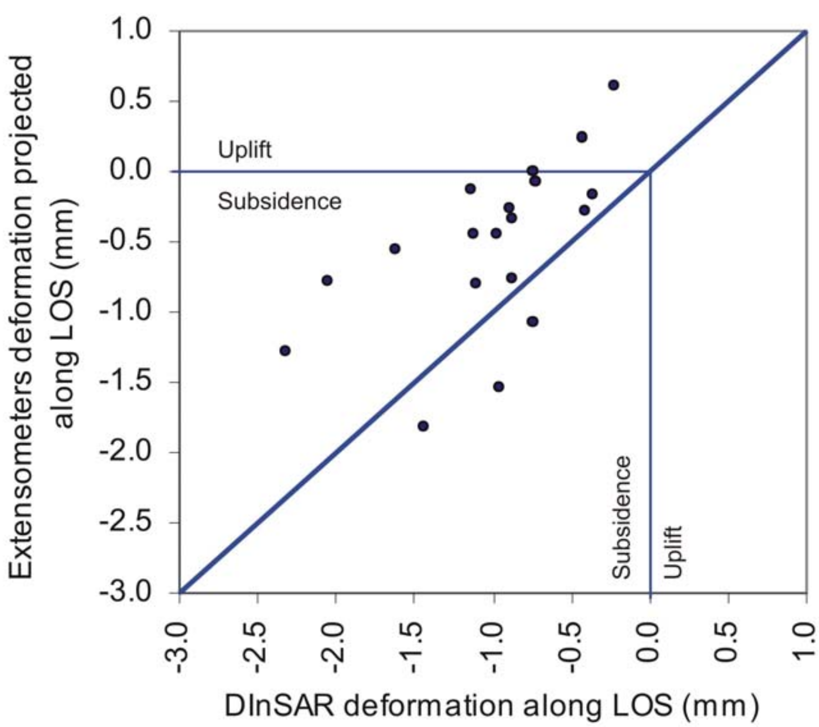

Figure 14. Comparison between DInSAR and instrumental deformations of the extensometers located in Murcia City.

6. CONCLUSION

CPT (an advanced DInSAR technique) has been used to perform an analysis of ground subsidence due to overexploitation of an aquifer during the 1993-95 drought period and subsequent periods in the Vegas Baja and Media of the Segura River Basin (SE Spain). This technique has shown to be very useful for this purpose, with high quality results for a wide area at low cost.

The use of this technique has allowed us to know the spatial distribution and real magnitude of the consolidation process for a period with no instrumental data for the whole Vegas Baja and Media of the Segura River Basin. This is because subsidence was not detected until 1996, when the first damages appeared in some of the Murcia city's buildings, with some delay with respect to piezometric level falls, 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 2007, providing improved knowledge of the subsoil consolidation process mechanisms, as well as settlement distribution and velocities. These results constitute a great advantage, because they provide better knowledge of the behavior of the medium, with implications on the potential calibration of geotechnicals models.

Subsidence has been widespread in the study zone during the period 1993 – 2007, with settlements ranging from 2 to 15 cm. Only the borders of the valley, constituted by old, cemented 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 degree of coincidence between DInSAR and extensometric measures is high, with an average absolute difference of 5.7±3.7 mm for those extensometers located over coherent pixels.

The comparison of these results with available data in this zone for the analysed period 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.

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