QUANTIFICATION OF SUBSIDENCE RATES ASSOCIATED WITH GROUNDWATER FLOW USING SAR INTERFEROMETRY

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ABSTRACT

In this work we present the results of an experiment to detect a subsidence phenomenon by SAR interferometry in the city of Lisbon, Portugal. A time series of ERS and ENVISAT-ASAR images, covering four different time periods, was acquired over the Lisbon city and processed by the Persistent Scatterers (PS) technique. Furthermore, a topographic survey was carried out in the urban area interested by the subsidence phenomenon at different times, 1976, 1996 and 2010. An interpretation of terrain deformations using also measurements of piezometric heads, geotechnical reports of the underground and building constructions is given.

1. INTRODUCTION

Land subsidence is a phenomenon affecting many urban areas that often results in severe and extensive damages to building and infrastructures. Subsidence is the result of natural compaction of sediments induced by various processes including extraction of ground water, oil, natural gas, mining and underground constructions. Examples of subsidence reported world-wide are the city of Mexico [1], Venice [2,3], Paris [4] and Bangkok [5]. In recent years, Synthetic Aperture Radar Interferometry (InSAR) has been applied to monitor ground deformation related with subsidence. The InSAR technique has several important advantages over traditional methods, such as the capability to provide spatial information on deformation patterns. Furthermore, the availability of archived InSAR data acquired since nineties allows to study phenomena occurred in the recent past. In the scope of GMES Terrafirma experiment (www.terrafirma.eu.com) significant ground subsidence was detected north of Lisbon city, figure 1. The phenomenon was not known and generates major concern. The subsidence was interpreted as the result of neotectonic activity deduced from the correlation with deep geological features [6,7] and latter correlated with over-exploration of groundwater [8]. In one of our recent papers, we interpreted this subsidence as the result of anthropogenic activity related with the urbanization and construction of the subway [9].

In this paper we give a further contribution to the interpretation of this subsidence phenomenon, with emphasis on the validation of the deformation rate estimated by InSAR, and the temporal evolution of the deformation and possible cause.

Figure 1. Lisbon metropolitan area.
The study area is marked with a red rectangle.

2. SAR DATA PROCESSING

2.1 SAR data

A set of 94 SAR images, acquired between May 1995 and September 2010 by ERS1, ERS2 and ENVISAT satellites were used in this study. The images were supplied by ESA in the scope of ESA Cat-1 (n. 5763) Project "Landslide risk mapping in the Lisbon area, Portugal, by means of SAR interferometry". During this period, we cover the life time of all these satellites. ERS1 stops working in 1995, ERS2 had a serious problem with the gyroscopes with consequences on the Doppler centroid and stops on 2010 and ENVISAT is no longer acquiring SAR images for Interferometry since end of 2010. Though, in this period, the only limiting factor for interferometric processing is the Doppler centroid frequency of ERS2. In fact, in the beginning of 2001, the last gyroscopes on board of ERS2 stop spinning affecting the estimation of the platform attitude. As a consequence, the consistency of the Doppler centroid frequency was considerably reduced. Though an alternative strategy for attitude control called Zero-Gyro Mode (ZGM) was established. Very large Doppler frequencies results in misalignment in azimuth and loss of interferometric coherence. The azimuth bandwidth available to make an interferogram is determined by the Doppler centroid between the master and the salve images. Increasing the Doppler centroid frequency reduces the frequency overlap

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(between master and slave) reducing the number of useful interferometric pairs. Although there are a large number of archived ERS2 scenes, after this incident many of them are unsuitable for InSAR processing due to this Doppler centroid problem.
The complete set of 94 SAR images used in this study is displayed in figure 2.

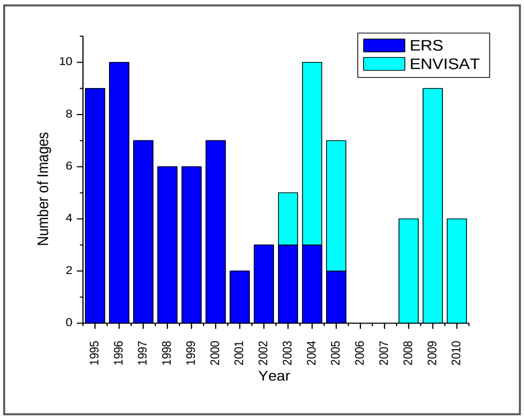

Figure 2. Distribution in time of ERS and ENVISAT images used in this study.

The images cover a long time period of more than 15 years and are unevenly distributed in time. There are long periods without images, 24 consecutive months in 2006 and 2007, and periods with a good temporal resolution (from 1995 to 2000). The aforementioned Doppler centroid problem has a strong impact on the number of usable scenes mainly after 2001, see figure 2. Because of this, ERS scenes were divided into two sets (Table 1) taking into account the temporal resolution and the Doppler centroid problem. The first data set has a good temporal resolution and the Doppler centroid frequency are within 1000 Hz. The other group includes all other ERS scenes after 2000 and is characterize by a high variable Doppler centroid frequency and long periods (a maximum of 7 months) without scenes. From 2001 to 2005 there are 3 images per year. ENVISAT scenes were divided into two data sets due to the lack of images in 2006 and 2007.

Table 1.Processed datasets and main characteristics.

Years	N.images	Satellite	Track	Mode
1995-2000	47	ERS1, ERS2	452	Desc
2000-2005	20	ERS2	452	Desc
2003-2005	14	ENVISAT	223	Desc
2008-2010	18	ENVISAT	125	Asc

2.2 PSI processing

Interferograms were computed using one master scene for each data set. The master scene was chosen minimizing both the temporal and the perpendicular baselines. Table 2 summarizes all baseline values. The perpendicular baselines range from -1002m to 1015m with a mean value of 108m for ERS dataset.

Table 2. Master date, maximum perpendicular and temporal baseline

Years	master date	max $|B_{\perp}|$ (m)	Period (days)
1995-2000	1997/07/25	1015	2096
2000-2005	2000/12/01	1075	2065
2003-2005	2005/04/13	444	980
2008-2010	2009/05/17	421	700

Interferograms were computed using the DORIS software [10], with a 1x5 multi-looking and a spatial resolution of 20x20m. Precise orbits from Delft University and from ESA were used to estimate the orbital parameters. A high precision digital terrain model (DTM) with a resolution of 20x20m was used to remove the topographic phase contribution. The final result was geolocated to the ETRS89/GRS80 map geometry.
A first analysis of the interferograms revealed a low coherence for interferograms with perpendicular baseline greater than 300m and a good coherence on the urban area for temporal baselines larger than 700 days. On urban areas, the limiting factor is clearly the perpendicular baseline. On coherent interferograms, it was identified the presence of significant tropospheric noise and no evidence of large deformation signal. To overcome above limitations, the Persistent Scatterers technique was applied to the interferograms time series [11]. We have selected all pixels with amplitude dispersion less than 0.4 as PS candidates and used STAMPS for further processing [11]. Interferograms characterized by a large perpendicular baseline and a high residual phase standard deviation were removed from the PS analysis. The ground deformation is given by the PS velocity, measured in $mm.yr^{-1}$. The temporal reference is the master date and the spatial reference is a stable point on the ground. The estimated PS velocity is a mean velocity for the period covered by the interferograms. It was assumed a linear deformation model. For all four data sets the stable reference was Campo Grande Church mark used as a reference for the leveling measurements. The temporal reference is different for every data set and depends on the master date. The temporal reference is irrelevant since we are dealing with mean velocities for a period of years. The four deformation maps are displayed in figure 3. The number of PSs is dependent of many factors but in this experiment there is clear correlation with the sensor. The number of PS is much less on ERS scenes than on ASAR ENVISAT scenes. On table 3, the PS results are summarized.

Table 3. Summary of PSI statistics.

Dataset	Sensor	Number PS'	Min vel. [mm/yr]	Max vel. [mm/yr]
1	ERS	35483	-4.8	2.6
2	ERS	14570	-5.0	6.3
3	ENVI	161019	-7.3	7.8
4	ENVI	619677	-12.8	9.9

The number of PS on the first dataset is twenty times less than on the last data set acquired by ASAR aboard ENVISAT. The effect of Doppler centroid problem is reflected on the number of PS' which in the second dataset is even less than that of the first one. In all the four periods the estimated mean velocity is quite stable, ranging from -13 mm/yr to 9.9 mm/yr.

The overall region is basically stable with a mean velocity smaller than 1-2 mm/yr in amplitude. However, in the first dataset, corresponding to the period 1995-2000, a localized subsidence, with a mean velocity up to -5 mm/yr, was observed in the centre of the map (see figure 3a). This subsidence was already detected within TERRAFIRMA project and afterwards analysed and validated by [8] and [9]. The event detected in the first period is not observed in the subsequent periods. On the most recent period there is no evidence of any deformation in this area.

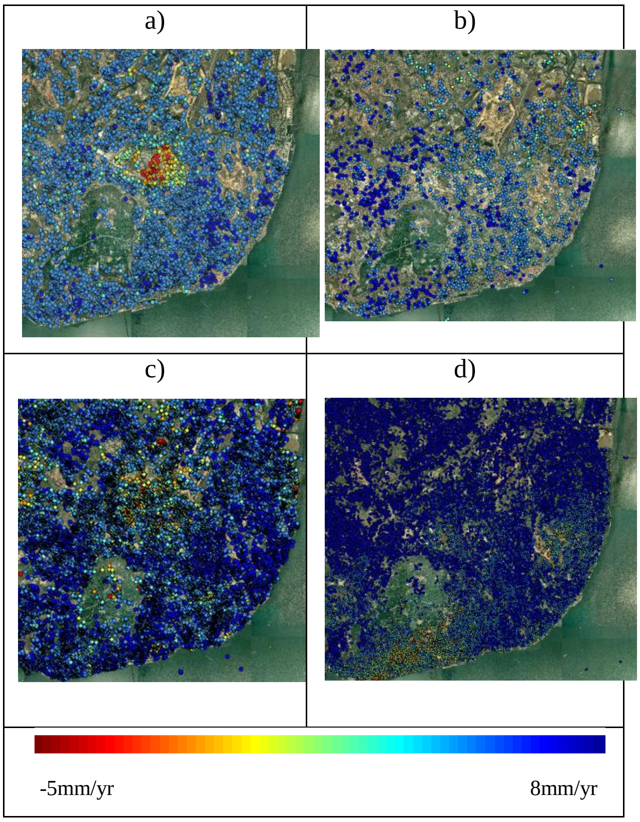

Figure 3. Mean velocity of the ground deformation estimated by the interferometric processing of SAR data. a) ERS 1995-2000; b) ERS 2000-2005; c) ENVISAT 2003-2005; ENVISAT 2008-2010. Velocities are given in mm/y

2.3 Mitigation of tropospheric phase delay artefacts

Some of the interferograms of the last period, acquired by ASAR instrument, presented pronounced tropospheric phase delay artefacts. In order to minimize these effects on interferograms we computed the atmospheric delay using the Weather Research and Forecasting (WRF) model and a ray-tracing procedure [12]. Delays were interpolated over the geolocated InSAR grid. The synthetic interferogram corresponding to the atmospheric phase delay was then obtained as the difference between the atmospheric phase delays computed at the acquisition times of the master and slave SAR images.

Results of the InSAR processing, before and after mitigation of tropospheric phenomena are shown in figure 4. The estimated deformation pattern is very similar and the mean velocity bounds are in agreement within a few millimetres. The most significant difference is the number of PS'. In fact, the atmospheric effects mitigation on every interferograms reduces the phase variability in time. The number of PS' increased more than 15%. In areas with a dense distribution of PS', the atmospheric mitigation strategy did not show great improvement. But in areas with less dense PS', the increase in its number has a benefit effect on the unwrapping result and better solutions are produced.

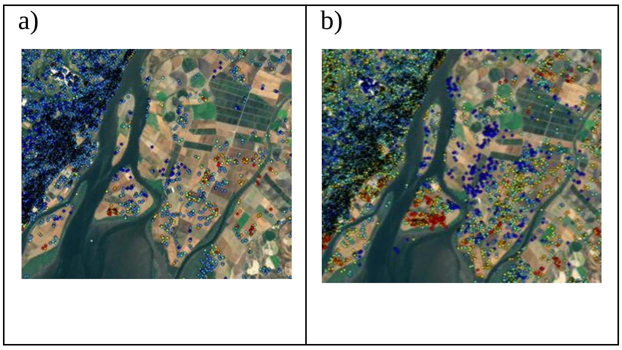

Figure 4. a) Standard PS solution b) PS solution using the WRF model.

3. TOPOGRAPHIC SURVEY

The interferometric result was validated with levelling measurements. For that, a topographic survey was carried out in 2010, in the urban area interested by the subsidence phenomenon, and compared with previous levelling measurements made at different times, 1976 and 1996. On Lisbon area there is a dense 2nd order leveling network maintained by the CML (Camara Municipal Lisboa, Lisbon City Hall). The leveling network is regularly surveyed and locally densified in response to urban changes and growth. Besides this permanent effort, every 20-25 years all the marks are re-surveyed and a new list of heights is published. In the last half of the last century two complete leveling surveys were made in 1976 and 1996. All these marks were again surveyed in May 2010. A total of 46 measurements were made using the 25 marks. The heights were determined by weighted least squares adjustment of the height differences between every two marks. The standard deviation of the measurements was assumed to be $2.5\sqrt{L}$ in which L is the distance in kilometer between the two marks. The estimated *a posteriori* variance of unit weight was 1.67 and was accepted by chi squared test for a significant level of 95%. Relative height changes are referred to the Campo Grande Church referred in figure 5 as the “reference”.

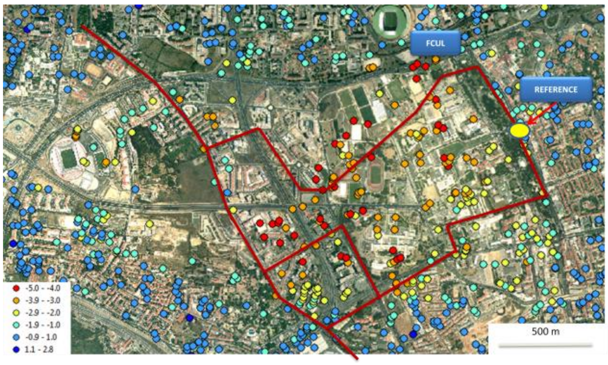

Figure 5. Leveling survey on May, 2010. The main circuit is depicted in red. The dots are the persistent scatterers for the period 1995-2000.

The height differences between 2010 and the two other surveys (1996 and 1976) are presented in figure 6. Assuming that the errors of each two campaigns are not correlated, the relative uncertainty in the height change is $\sigma_\Delta^2 = \sigma_a^2 + \sigma_b^2$ where σ_a^2 and σ_b^2 are the random errors in millimeters determined for the two surveys. Assuming a relative uncertainty of 5 mm for 1976 and 1996 surveys, the relative uncertainty for the height differences is between 5 mm and 7 mm.

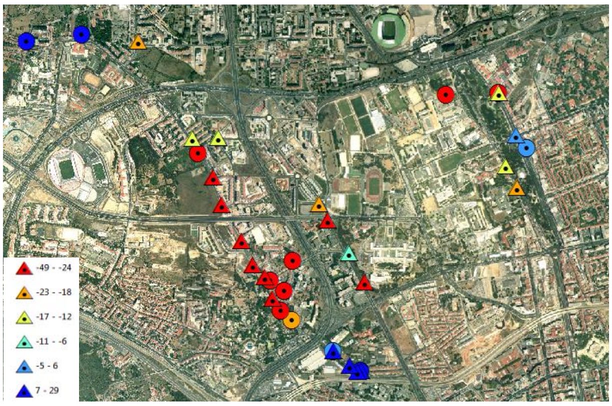

Figure 6. Result of the comparison between 2010 survey and 1976 (circles) and 1996 (triangles) surveys. Vertical displacement is shown in millimeters.

The topographic survey shown a depression along the Larajeiras road (alignment of 6 orange triangles) with a median subsidence of -40 mm. It has also shown the stability of the north and south area delimiting the subsidence by two main roads.

4. RESULTS AND DISCUSSION

In this section we present and analyze the results of the comparison between InSAR and levelling, piezometric level measurements and anthropogenic activity.

4.1 InSAR time series

The time evolution of the deformation was analysed in the period 1995-2010 using the InSAR results. To be comparable, the estimated PS velocities are referred to a common ground point (Campo Grande Church) in all datasets. Also the colour scale is the same. The time series of InSAR velocities is displayed in figure 7. The first period is characterized by a high velocity gradient with a rate of -4 mm/yr. On the forthcoming periods there are no evidence of any deformation. Though, there are in 2000/2005 some instable areas. We may conclude that the deformation was a sporadic event, rather a long term deformation process. It was signalized in 1995 and reduces considerably until 2000.

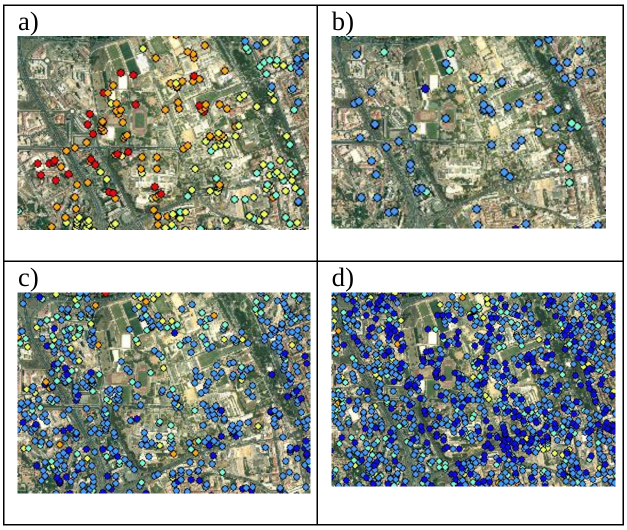

Figure 7. Time series of deformation. A) ERS 1995-2000; b) ERS 2000-2005; c) ENVISAT 2003-2005; ENVISAT 2008-10.

4.2 Comparison with leveling

InSAR velocities are not directly comparable with levelling results. InSAR velocities were determined averaging the displacement with time. Leveling results are the direct measure of the displacement between two dates. To be comparable, the radar line-of-sight (LOS) velocities were projected into the normal and converted to displacement (multiplying by 6 years). Figure 8 shows the vertical displacement at the levelling marks and at the PSs. The vertical displacement between 2010 and 1976 is higher than between 2010 and 1996. InSAR displacements are very similar to the height differences between 1996 and 2010, differing few millimetres. This result confirms the previous conclusion that the deformation is not significant after 2001. The subsidence area is bounded on the north and south by two main roads. The levelling measurements have confirmed the stability of this area since 1976. We conclude that the spatial deformation pattern detected by InSAR is confirmed by levelling measurements.

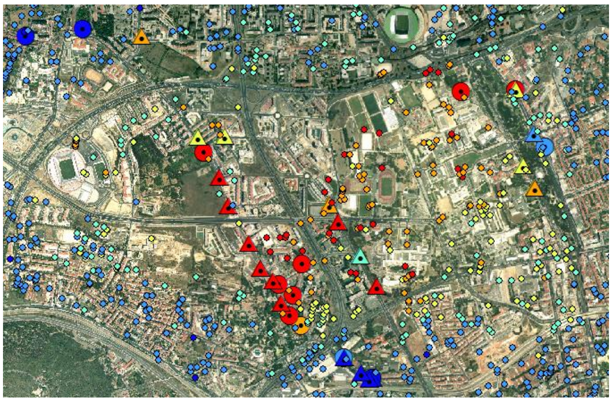

Figure 8. Mean velocity of the ground deformation measured by InSAR (dots) traditional topographic surveys (triangles and circles). The colour scale is the same of figure 5 and 6.

4.3 Anthropogenic intervention

In the late 80's was initiated the construction of two subway lines (represent in red in figure 9) and finalized in 1988. The construction of these lines changed the farmland landscape into a new urban area. In fact at the end of the 80's most of this area were small farms and small pottery factories. There were abundant clay and water. In the beginning of the 90's new urbanized areas were built and on the 1997 a large road were finalized, crossing the area from west to the east. Using ortophotomaps from 1995 and from 2000 was possible to identify and map all anthropogenic interventions. They are marked on figure 9.

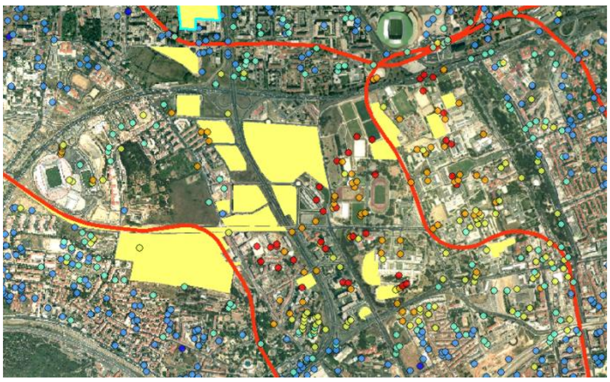

Figure 9. Anthropogenic activity. Subway lines in red and built areas between 1995 and 2000 in yellow.

The new urban built-up areas are responsible for local subsidence due to the load increase on the ground surface. Besides, and most importantly, the construction of caves, two or three levels underground, have waterproofed the first 6 to 10 meters of soil. The waterproofing of the ground has reduced considerably the water infiltration with implications to the aquifer recharging.

4.4 The piezometric level

In this area there are some artesian wells, deep boreholes and subsurface boreholes that permitted the identification of the lithology and multi-aquifer down to -200 meters (see figure 9).

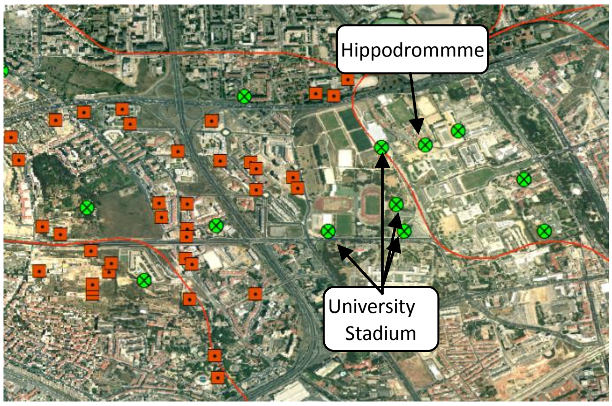

Figure 10. Subsurface boreholes (squares) and deep boreholes (triangles) used in this study.

New urbanizations and buildings have to include a geotechnical study in the construction project. Usually, the geotechnical studies are down to only few meters, enough for the construction of one or two caves. We have assessed to the database of most of the constructions made between 1990 and 2000 on this area. The piezometric level is one of the registered parameters and we have analysed its evolution along time. We have plotted the piezometric level in function of the time of the geotechnical study date (Figure 11). Analysing this figure we verify that the piezometric level is going down with time. We have plotted in this figure the table level determined in 1973 for the construction of the subway.

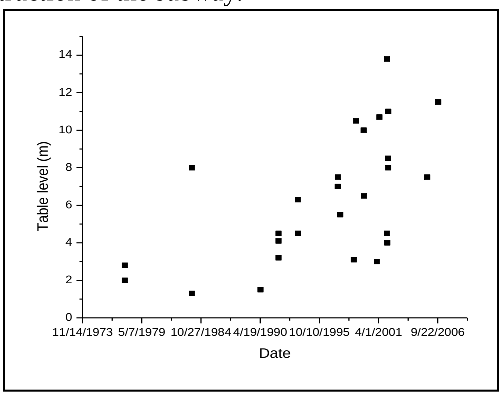

Figure 11. Evolution of the piezometric level with time.

The piezometric level is stable between 1973 and 1990 and goes down after. The subway was built in 1986-88. We see also the increase in construction after this date and the associated fall of the table level. For neighbour buildings, built in different times, we have detected a fall in the table level around 5 meters. We have also analysed deep boreholes on this area. The aquifer is about 80 meters depth. For hippodrome borehole was possible to reconstruct the evolution of the water pump depth. This is not the piezometric level but gives an indication of the variation of this level with time.

5. CONCLUSIONS

As a first result, the levelling measurements confirmed both the location of its rate as estimated by InSAR analysis. The PSI ground velocity reach a maximum value of -4.7mm/yr. As far as the temporal evolution of the phenomenon is concerned, we found that the ground deformation occurred mainly in the period 1995-2000 since there are no evidences of deformation in the subsequent SAR datasets. Also the levelling results show a deformation process initiated before 1996. The time occurrence of this phenomenon seems to confirm that it could be due to anthropogenic activity related to the construction of the subway whose operations were carried between 1984-88 and the urbanization of this area between 1990-2000. The consequence, was the ground waterproofing, caused by urbanization, which reduced the aquifer recharging. This affected the groundwater circulation and gave rise to a aquifer compaction

6. ACKNOWLEDGEMENTS

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