GEO-HAZARD MONITORING IN NORTHERN GREECE USING INSAR TECHNIQUES: THE CASE STUDY OF THESSALONIKI

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ABSTRACT

Temporal monitoring of terrain movements and satellite observations are used here to monitor geophysical Natural Hazards in northern Greece for the period 1992-2010, applying Persistent Scatterer Interferometry and Small Baseline Subset techniques, in an attempt to address their causes: anthropogenic or natural due to geological and geomorphological evolution. Our study highlights new areas that were previously unknown to be at risk and validates the remote sensing estimates using drill data, geomechanics and hydrogeology results. Site-specific results are presented for the broader urban area of Thessaloniki, Thessaloniki plain (Nea Malgara-Kimina, Chalastra) and the broader area of Katerini.

1. INTRODUCTION

Radar Interferometry time-series enables the millimetre scale monitoring of the deformation of an area. Such methods are widely used across the globe and offer valuable insights based on the rich, growing archives of radar data. Most prominent, and used in this work, is the PSI (Persistent Scatterer Interferometry) [1] and SBAS (Small Baseline Subset) [2]. Both of them are time-series methods that detect the temporal evolution of surface deformation using Synthetic Aperture Radar imagery.

Our study depicts new areas of interest, compared to previous work [3, 4, 5, 6] and aims at detecting and distinguishing small - scale movements, tectonic movements and subsidence caused by overexploitation of the aquifers or ground settlement, in Northern Greece. At the same time the results contribute to the seamless monitoring of the region, which acts as a junction of the Balkans, especially important in the new Sentinel era where shorter revisit times provide systematic geodetic measurements over the area.

The city of Thessaloniki (Fig. 1) is the second most populated city in Greece, after Athens, with many important industrial constructions as well as life-lines situated in its proximity, making the hazard evaluation imperative. From a tectonic point of view the city is surrounded by normal and strike-slip faulting, striking roughly E-W and NW-SE. One of these normal faults in the Mygdonian Graben was activated during the June 1978 Mw6.5 earthquake, an event that caused significant damage to the city and loss of life.

Thessaloniki plain surrounded by mountains is an agricultural land in which many geomorphological changes took place over the last thousand years. These changes were induced either from the evolution of natural geography or from man-made interventions. In this area there are the small towns of Nea Malgara-Kimina and Chalastra. In-between those, crosses the Axios river -the most important river in Northern Greece in terms of water and sediment supply.

The third area of our study is Katerini, a greatly agricultural town and a tourist destination due to its proximity to archeological sites. The coastal part near the Gulf of Thermaikos is plain and as we move towards inlands the morphology becomes mountainous.

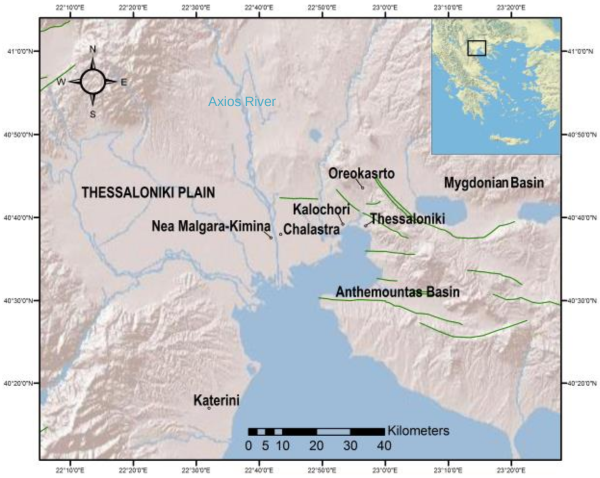

Figure 1. General view of the area of study. Green lines depict active faults. The Inset map showing Greece depicts, with the black rectangle, the area of study.

The strategy of this study is the following:

a) The first step is the identification of the deforming areas using multi-temporal interferometry techniques.

b) For the validation of the remote sensing results, the highlighted deforming areas are compared against other studies or other data sources.

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c) The final step is the interpretation based on a holistic approach.

2. INPUT DATA AND METHODS

Radar data from the European Space Agency (ESA) were processed. The analysis is on 46 Images (level_0) from the ERS 1 and ERS 2 satellites and 37 Images (level_0) from ENVISAT satellite. For the processes an appropriate subset was chosen from these datasets (Tab. 1 & Tab.2). The SRTM DEM was used for the estimation of the contribution of the topography to the interferometric phase (Fig. 2). The orbital data were provided by the Department of Earth Observation and space systems (DEOS) of the Delft University of Technology and ESA, respectively. We use the NOA-faults database of the active faults in the Greek territory [7]. For the interpretation of the deformation mechanisms for selected areas of interest, drill data were used from K.E.D.E (Ministry of Reconstruction of Production, Environment & Energy).

Table 1. Images selected for the SAR analysis and their perpendicular baseline in respect to 3 June 1995 (the selected master for ERS throughout the PS analysis using StAMPS software).

Dates	**Perp. Baseline(m)**	**Δt (days)**
12-Nov-92	127 m	-933
19-Aug-93	-318 m	-653
28-Oct-93	593 m	-583
03-Jun-95	0 m	0
13-Aug-95	100 m	71
30-Dec-95	445 m	210
31-Dec-95	199 m	211
09-Mar-96	527 m	280
14-Apr-96	201 m	316
18-May-96	157 m	350
19-May-96	82 m	351
01-Sep-96	-67 m	456
06-Oct-96	-506 m	491
15-Dec-96	-369 m	561
04-May-97	-310 m	701
08-Jun-97	-15 m	736
13-Jul-97	-361 m	771
17-Aug-97	-158 m	806
21-Sep-97	-110 m	841
30-Nov-97	129 m	911
04-Jan-98	-261 m	946
19-Apr-98	206 m	1051
28-Jun-98	116 m	1121
02-Aug-98	221 m	1156
06-Sep-98	-831 m	1191
28-Feb-99	47 m	1366
13-Jun-99	48 m	1471
18-Jul-99	340 m	1506
22-Aug-99	-525 m	1541
26-Sep-99	481 m	1576

Table 2. Images selected for the SAR analysis and their perpendicular baseline in respect to 13 November 2005 (the selected master for Envisat data for the PS analysis using StAMPS software).

Dates	**Perp. Baseline(m)**	**Δt (days)**
09-Mar-03	-713	-980
22-Jun-03	-539	-875
11-Jul-04	-541	-490
24-Oct-04	87	-385
06-Feb-05	-783	-280
13-Mar-05	69	-245
17-Apr-05	-160	-210
22-May-05	-435	-175
04-Sep-05	331	-70
13-Nov-05	0	0
26-Feb-06	-627	105
11-Jun-06	-623	210
16-Jul-06	483	245
11-Feb-07	-607	455
05-Aug-07	-467	630
06-Apr-08	-95	875
20-Jul-08	-261	980
02-Nov-08	-310	1085
11-Jan-09	-358	1155
15-Feb-09	-387	1190
26-Apr-09	-464	1260
31-May-09	-280	1295
13-Sep-09	56	1400
22-Nov-09	-101	1470
27-Dec-09	-688	1505
07-Mar-10	-521	1575
11-Apr-10	-178	1610
20-Jun-10	-310	1680
03-Oct-10	-56	1785

For the analysis of the time series of the satellite data we used the commercial software SARscape by Sarmap and the open source codes of StAMPS (Stanford Method for Persistent Scatterers) [8], for raw SAR image focusing ROI_PAC (Repeat Orbit Interferometry Package), by California Institute of Technology and Jet Propulsion Laboratory, and for the interferograms generation DORIS (Delft object-oriented interferometric software developed by the Delft Institute of Earth Observation and Space Systems. For the PSI time series analysis we chose as master the acquisition of June 3rd 1995 (Tab.1) and November 13th 2005 (Tab.2) for ERS and Envisat datasets, respectively. For the processing, using both software, more than 250 interferograms were created. Visual inspection and filtering took place, based on coherence quality and interferogram unwrapping results; those with poor quality were discarded and did not participate to the stacking.

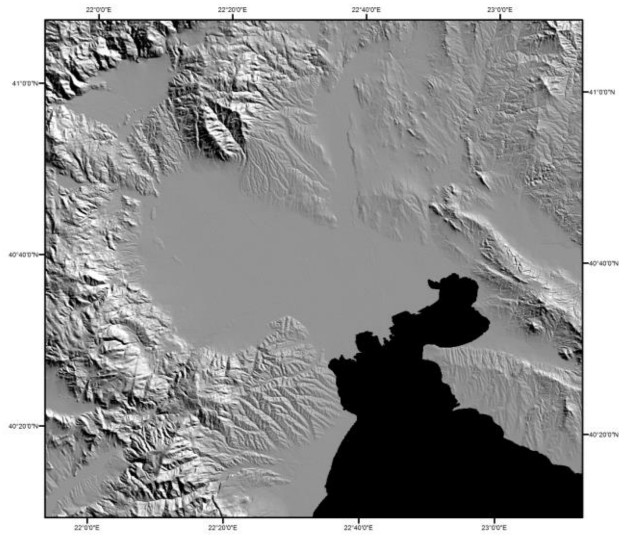

Figure 2. DEM used during the Interferometric processing.

3. RESULTS

In Fig. 3 we present the velocities for the frame of ERS 1 and 2 (1992-2000) from the track 279 with a descending orbit. Previous researchers have studied the broader area of Thessaloniki or parts of it [3, 4, 5, 6]. New areas are now added that are detected to be in a deforming regime. Further investigation is done based on in-situ data in order to distinguish the deformation drivers. The results we are presenting are merged results

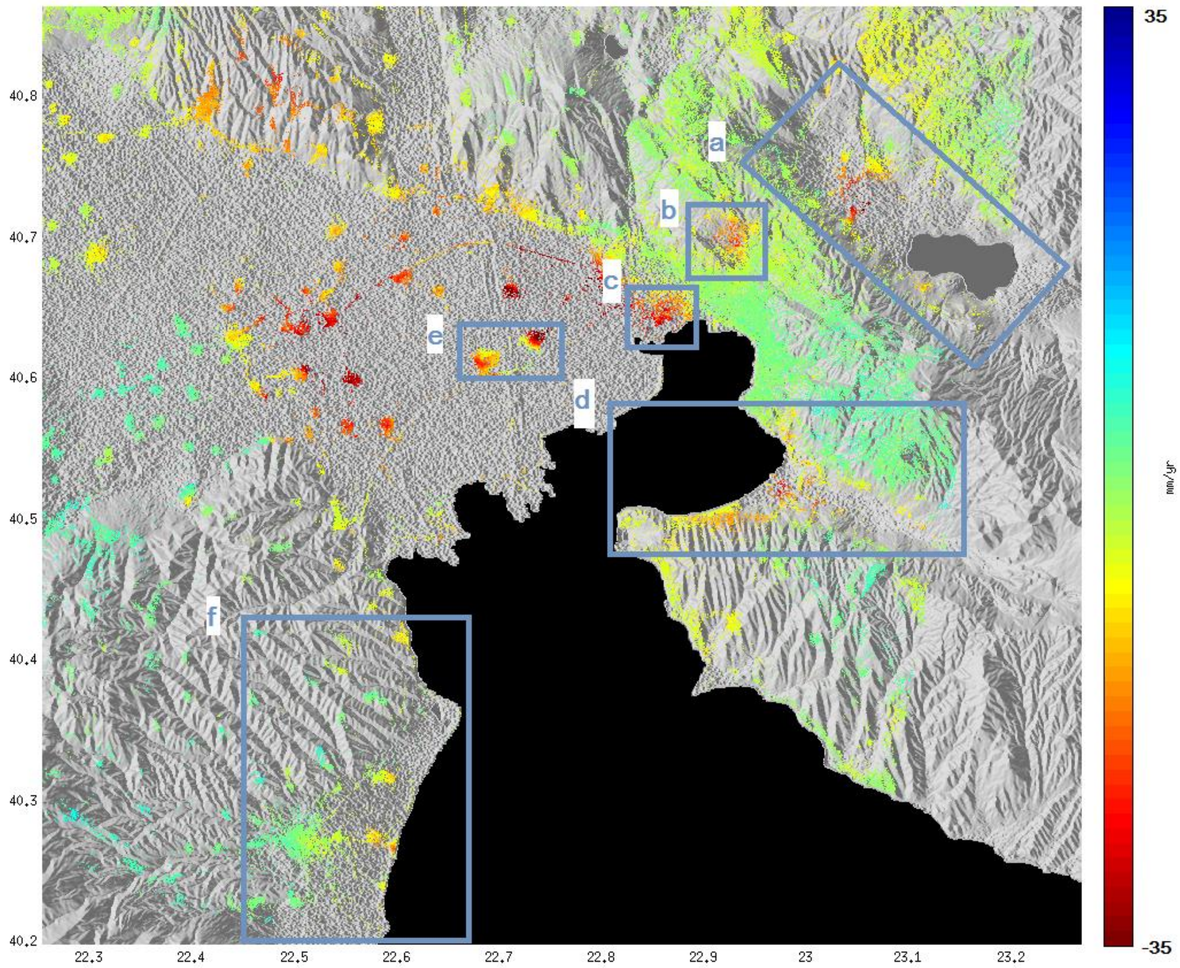

Figure 3. Velocities of deformation detected for the period 1992-2000 derived from a merging of PS and SBAS analysis. Areas with red colours represent vertical displacements. Blue triangles indicate the areas of interest. Mygdonian Graben shown in (a); The area south of Oreokastro shown in (b); Kalochori in (c); (d): Anthemountas Basin; (e): Nea Malgara- Kimina and Chalastra and the broader Katerini area shown in (f).

of the methodologies of PS and SBAS [9]. As expected urban areas offer much more to the final point cloud measurements due to the fact that they have reduced temporal alterations in their landscape.

On the contrary areas with significant alterations show less coherence and as a result no point measurements can be retrieved. An example is the area of Thessaloniki plain (Fig. 1 & Fig. 3) where there are some point measurements mainly at the locations where urban fabric exist but other than these, there are no point measurements. This is better understood if we look at the land use map of the area (Fig. 4).

The existence or rivers makes Thessaloniki plain a fertile land. Most part of it is covered by agricultural land – the area is one of main rice crops in Greece. Each year in the middle of spring the farmlands are filled with water creating extended areas of wetland. Thus, for the processing of the satellite images the land use leads to limited interferometric coherence, and therefore careful interferogram filtering and phase unwrapping of the input stack was crucial for reliable velocity generation.

3.1. The city of Thessaloniki and the broader area

Due to the city's long history, underground Thessaloniki there are many remains of the ancient times. Recent buildings and constructions are actually built on a subsurface that from an archaeological point of view is very rich. However, SAR Interferometry time series results indicate that the city and especially its historical centre appear to be in a stable, non-deforming situation. There are places only at some coastal parts (2 jetties) of the city that are exhibiting deformation of ~ -5 to -4mm/yr. This deformation is mainly due to the fact that these areas were man-made constructions for the extension of the coastal front to the inner Gulf of Thessaloniki.

The Mygdonian Graben (Fig. 3, rectangle a) is a tectonic graben and the extensional forces have created NE-SW striking normal faults. Some of them are active since Miocene [10, 11, 12]. The latest major and most known earthquake is the June 1978 Mw6.5 event that caused damages and fatalities. In the Mygdonian Graben the deformation signal is possibly related with the so-called "aseismic slip" or "aseismic creeping". Even though the terms "aseismic slip" and "aseismic creeping" are widely used in geophysics and remote sensing, it could be argued that they are not accurate enough and they appear to have no physical meaning. The distinction between "seismic" and "aseismic" is just a matter of earthquake detection based only on the type and the abilities of the seismological network installed

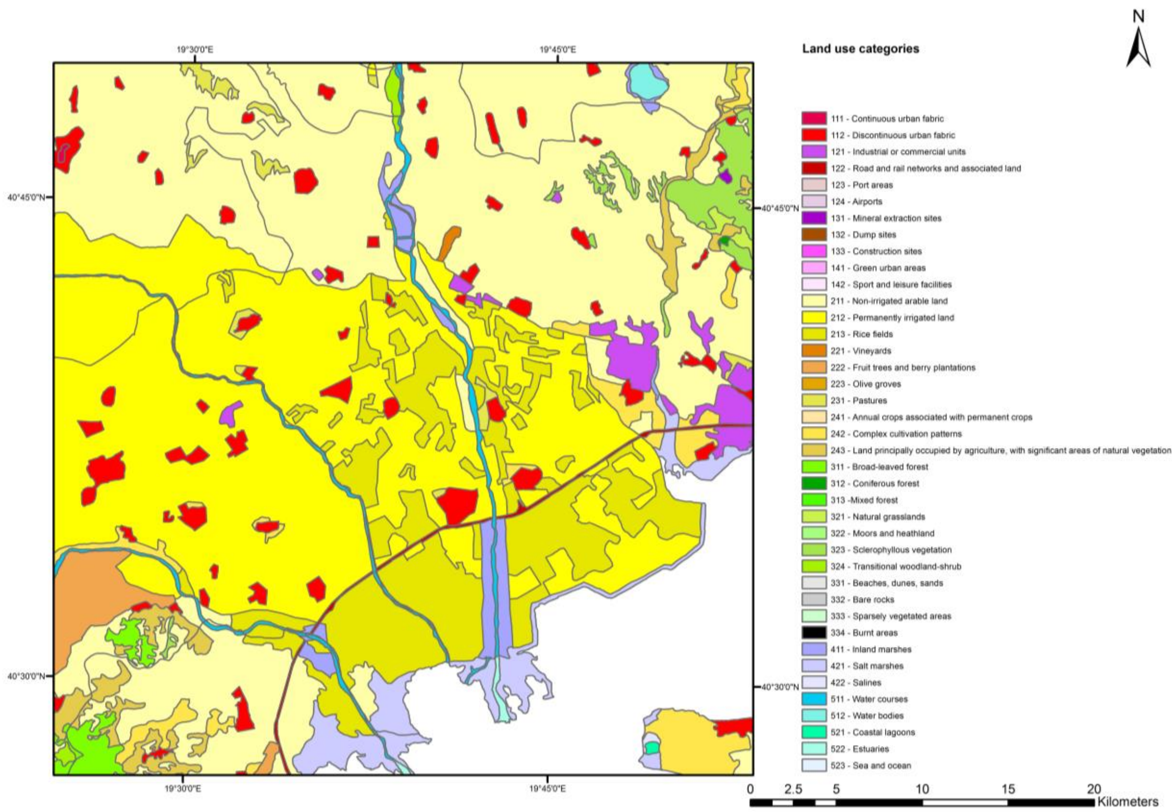

Figure 2. Map of Land Use at the area of Thessaloniki plain. The major part of the plain is related with agricultural activities (rice fields) making the area challenging when it comes to coherence estimation and unwrapping [13].

at each area. In other words anything that tectonically moves (in a non-geological time scale), i.e. anything that slips, would be more proper to be considered as seismic. Another potential factor of deformation in the area is overpumping. A combination of tectonics and overpumping is the most probable cause [4]. We would also add one more possible factor of the deformation that is the geothermal activity that acts in Lagadas. Tertiary grabens, which like the Mygdonian Graben, are common to be related with thermal springs in northern Greece. The geochemistry of the springs indicate a temperature of 40°C [14] in the area that the maximum deformation is detected. The question though is still open and more data sources are needed.

Another area that is showing strong signals of vertical displacements is the area to the south of Oreokastro (Fig. 3, b). SAR Interferometry results were cross-checked with more than one software and were identical in terms of spatial correlation. The difference in deformation values was negligible (~2mm). Moreover, as stated in [3], this signal is not an atmospheric artefact because it is present to more than one interferograms. We agree with [3] and [4] that the deformation appears to be related with faulting. But for a systematic proof of tectonic deformation further investigation using seismological data needs to be performed. Moreover, we would not conclude that this is the only source of deformation and that is due to the fact that the value of vertical displacement is too high (~ -18mm/yr). The wider Kalochori region (Fig.3 c), where the industrial activity of the broader area of Thessaloniki, is located below sea level suffering from land subsidence for more than 50 years [15], with several marine invasions reported in the past years (Fig 5).

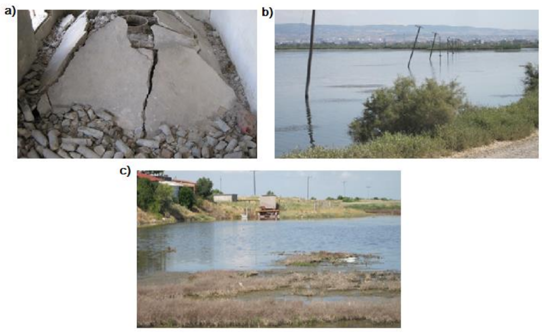

Figure 3. Phenomena caused by subsidence in Kalochori. a) pipe upheaval b) destroyed electricity network c) Inland view of flooded area [6].

The results show strong deformation signals. Previous studies on this area [16, 17, 18] claimed that the area was suffering from absence of a fair withdrawal policy (i.e. intense groundwater withdrawal). In [6] they have made a thorough study in this area for the period using 6-year radar data (1995-2001). Through modelling and remote sensing they have proved that the deformation signal in Kalochori is subsidence due to overpumping of the aquifers.

Another area with strong negative vertical deformation signals is the Anthemountas basin (Fig. 3 rectangle d). The area is related with potentially active and active faults (Fig. 1). Maximum subsidence is located at the areas next to the “Macedonia airport” which is an International airport used by around 4 million travellers every year and is crucial for the economic and human activities in northern Greece.

3.2. Deformation in Nea Malgara-Kimina, Chalastra and Katerini

This study led to the mapping of the spatial deformation characteristics (wherever it was possible) using SAR Interferometry in areas that previously were not investigated. More specifically we investigate the detection of vertical deformation in Thessaloniki plain at the towns of Nea Malgara – Kimina, Chalastra and at the area of Katerini. The towns of Nea Malgara Kimina and Chalastra (Fig. 3 rectangle e) lie to the neighbourhood of Axios River (Fig. 1). Axios’ river routes carve Thessaloniki plain. The river’s routes were changed in 1930’s to a more western location (its present location) because they were going to cause problems to the activities of the port of Thessaloniki. Now the place accommodates irrigation lands (Fig. 4).

It was detected that for the period 1992 - 2000 the area has been deforming vertically with over -32 mm/yr. The villages in the area are founded over resent alluvial deposits, consisting of fine to very fine materials carried by the rivers and spread along the plane during the repeated floods of the past. Currently the unintended flooding of the site has been avoided by the encasement of the lower river route. According to the available geotechnical data [19, 20, 21] (Fig. 6) the alluvial deposits consist of fine sand, clay sand, silty clay and clay alterations with no particular order. By comparing the preconsolidation effective stresses with the effective geostatic stresses it is clear that, as expected, the materials are under-consolidated. This fact, combined with the high compression index and the high void ratio of the clay layers justifies the manifestation of notable vertical displacements due to the natural compaction of the material. One important aspect of this finding is that the reason of these vertical deformation patterns is natural -part of a procedure- and it is not a man-induced hazard.

In the area of Katerini we detected negative vertical movements with values over 13 mm/yr (Fig. 3, rectangle f). Katerini belongs to the Katerini-Kolindros aquifer system. The Quaternary formations located there are macro to micro pore permeable. There are conglomerates, gravels, sand, and clays. In the past, at some locations of the aquifer system, intense atresianism occurred but now this is something that tends to disappear.

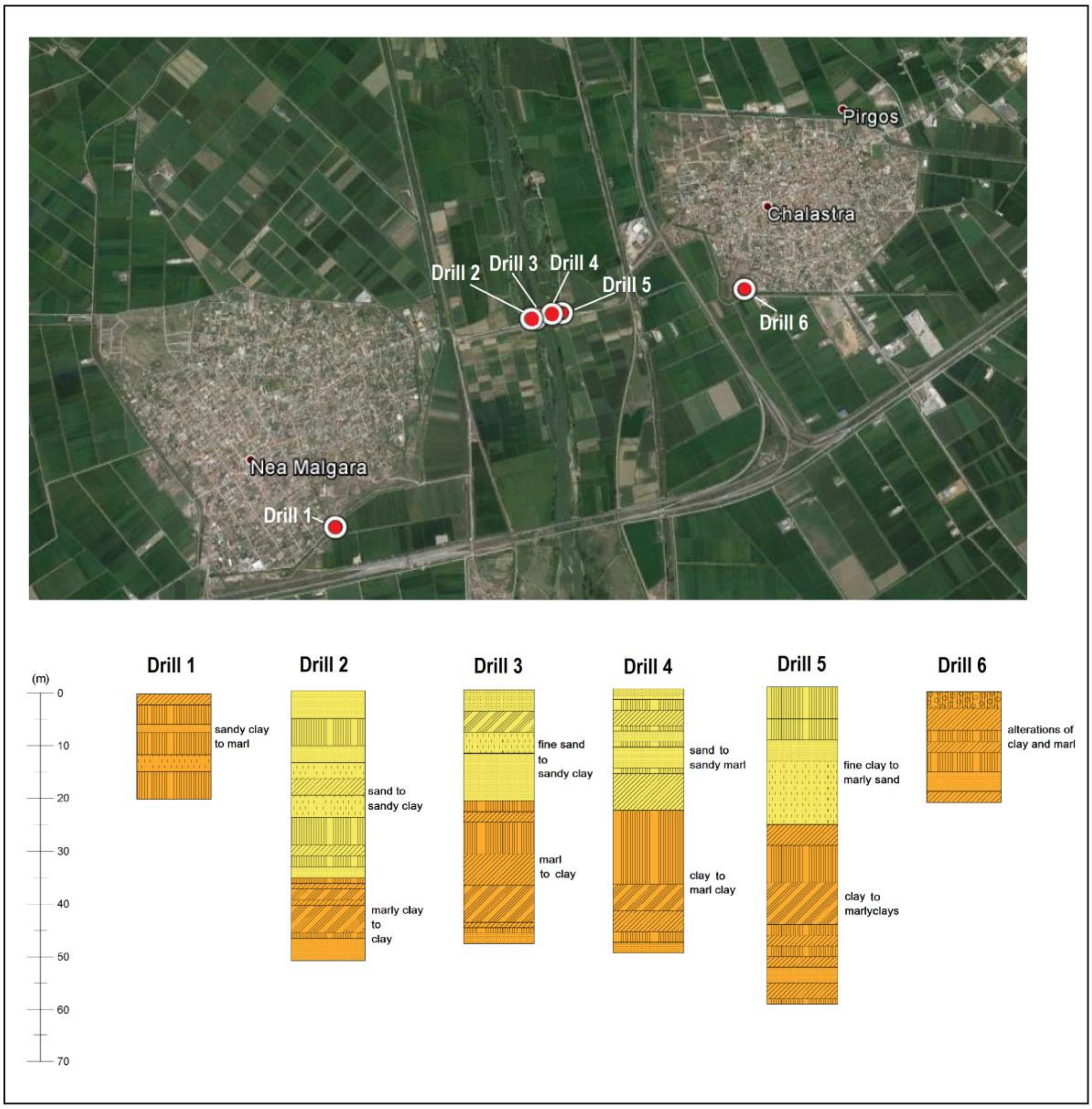

Figure 4. Drills from the area of Nea Malgara, Kimina and Chalastra. In past times the area was filled with loose material (like marls and clays) and now there is natural consolidation causing the settlement of the area.

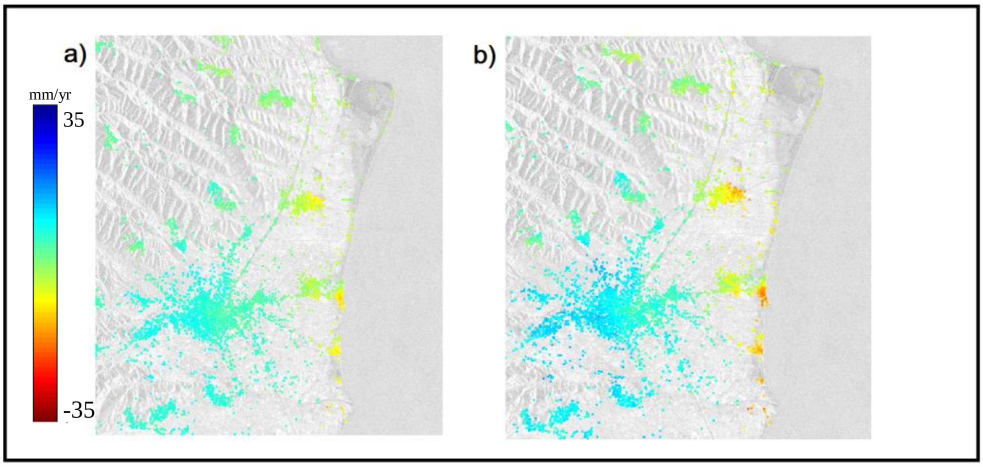

Figure 5. Velocities (1992-2000) of the broader area of Katerini (rectangle f, from Fig.3) a) SBAS method b) PS method.

Fig. 7 presents SAR Interferometry results as derived from the application of a) SBAS and b) PS for the city of Katerini. Piezometric results of the broader area of Katerini-Kolindros aquifer system (Fig. 8) show that

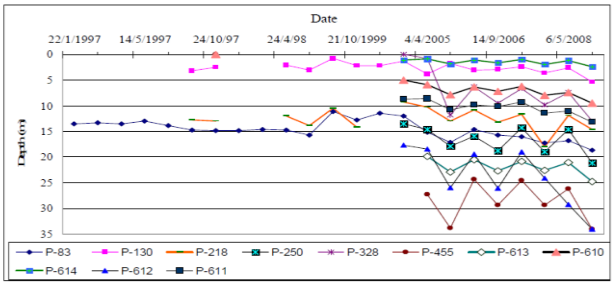

Figure 6. Piezometric surface of the area [22].

there was a lowering of the piezometric surface. The gradual decline of the underground water level was due to pumping. At the area in-between Katerini and the coast, the direction of groundwater flow is W→E. During 1996 to 2006 at the plain area of Katerini, the piezometric lowering was 0.20 m/yr [22]. Our results (1992-2000) detected this change and that is why we claim that the area is under subsidence due to the lowering of the underground water level. Thus in the case of Katerini the detected hazard is man-made.

4. CONCLUSIONS & DISCUSSION

The deformation during 1992 to 2010 is investigated in Northern Greece. The detected areas under hazard are the Mygdonian Graben, the area south of Oreokastro in the city of Thessaloniki, Kalochori and Anthemountas basin to the west and east of Thessaloniki, respectively. Moreover, we investigate the drivers of deformation for areas not previously studied. Next to the banks of Axios the towns Kimina, Nea Malgara and Chalastra are showing strong deformation signals. Based on drill data we conclude the reason of this deformation is settlement from natural consolidation, due to the fact that at this location there used to be the paleo-delta of Axios River. Another area showing negative vertical velocities is Katerini, an area previously unknown to be deforming. The deformation is due to the pumping of the permanent groundwater reserves. The deformation of Nea Malgara, Kimina and Chalastra is a natural procedure and no governmental actions needs to be taken whereas at the case of the plain and coastal areas of the vicinity of Katerini, the detected deformation was caused by man intervention. We also present (Fig. 9) PS time series results using ENVISAT data for 2002-2010 from our on-going research. The deforming trend is mostly the same with the exception of Kalochori and the area south of Oreokastro. On-going works includes the validation of these results together with their interpretation.

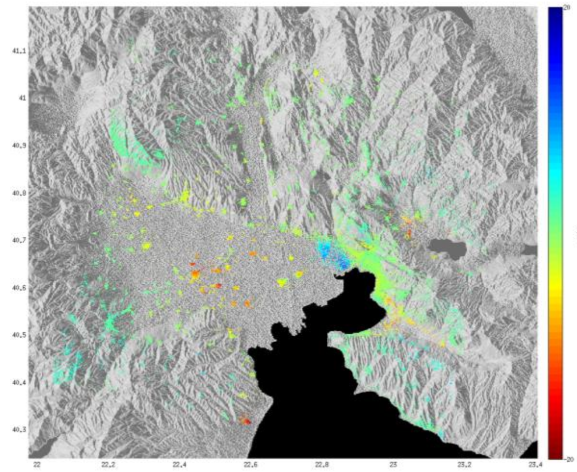

Figure 7. PS results from Envisat data (2002-2010).

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5. REFERENCES

1. Ferretti, A., Prati, C. & Rocca, F. (2000). Nonlinear subsidence rate estimation using permanent scatterers in differential SAR interferometry, *IEEE Trans. Geosci. Remote Sens.*, 38, 2202 – 2212.
2. Berardino, P., Fornaro, G., Lanari, R. & Sansosti, E. (2002). A new algorithm for surface deformation monitoring based on small baseline differential SAR interferograms, *IEEE Transactions on Geoscience and Remote Sens*., 40, 2375-2383.
3. Mouratidis, A. & Constantini, F. (2012). PS and SBAS Interferometry over the broader area of Thessaloniki, Greece, using the 20-year archive of ERS and ENVISAT data, *Proc. 'Fringe 2011 Workshop*', Frascati, Italy, (ESA SP-697).

4. Raucoules, D., Parcharidis, I., Feurer, D., Novalli, F., Ferretti, A., Carnec, C., Lagios, E., Sakkas, V., Le Mouelic, S., Cooksley, G., & Hosford, S. (2008). Ground deformation detection of the greater area of Thessaloniki (Northern Greece) using radar interferometry techniques, *Nat. Hazards Earth Syst. Sci*., 8, 779-788, doi:10.5194/nhess-8-779-2008.
5. Raspini, F., Loupasakis, C., Rozos, D., & Moretti, S. (2013). Advanced interpretation of land subsidence by validating multi-interferometric SAR data: the case study of Anthemountas basin (Northern Greece), *Natural Hazards and Earth System Sciences* 13, 2425–2440.
6. Raspini, F., Loupasakis, C., Rozos, D,Adam, N., Moretti, S. (2014). Ground subsidence phenomena in the Delta municipality region (Northern Greece): Geotechnical modeling and validation with Persistent Scatterer Interferometry, *International Journal of Applied Earth Observation and Geoinformation* 28 78–89.
7. Ganas, A , Oikonomou A. & Tsimi C. (2013) NOAFAULTS: A digital database for active faults in Greece, *Bulletin of the Geological Society of Greece*, vol. XLVII 2013 Proceedings of the 13 th International Congress, Chania.
8. Hooper, A. (2006). Persistent Scatterer Radar Interferometry for Crustal Deformation Studies and Modeling of Volcanic Deformation, *Phd thesis*, Stanford University.
9. Hooper, A. (2008*).* A multi-temporal InSAR method incorporating both persistent scatterer and small baseline approaches, *Geophysical Research Letters* vol. 35, L16302, doi:10.1029/2008GL034654.
10. Tranos, M., Papadimitriou, E., & Kilias, A. (2003). Thessaloniki-Gerakarou Fault Zone (TGFZ): the western extension of the 1978 Thessaloniki earthquake fault (Northern Greece) and seismic hazard assessment, *J. Struct.Geol*.,25,2109-2123.
11. Tranos, M., Kilias, A. & Mountrakis, M. (1999). Geometry and kinematics of the Tertiary post-metamorphic Circum Rhodope Belt Thrust System (CRBTS), Northern Greece, *Bull. Geol. Soc. Greece*, 33, 5-16.
12.Pavlides, S. & Kilias, A. (1987). Neotectonic and active faults along the Serbomacedonian zone (SE Chalkidiki, Northern Greece), *Ann. Tectonicae*, 1, 9-104.
13.Corine (coordination of information on the environment)LandCover: *http://www.eea.europa.eu/publications/COR0-landcover* [Accessed:22/3/2015]
14.Chiotis, E., Fytikas, M. & Taktikos, S. (1990). Overview of the geothermal activities in Greece during 1985-1989, *Geothermal Resources Council Transactions*, Vol. 14(1), pp. 79-85.
15.Psimoulis, P., Ghilardi,. M., Fouache, E. & Stiros, S.(2007). Subsidence and evolution of the Thessaloniki plain, Greece, based on historical leveling and GPS data. *Engineering Geology* 90, doi:10.1016/j.enggeo.2006.12.001
16.Loupasakis, C., & Rozos, D., (2009). Land subsidence induced by water pumping in Kalo-chori village (North Greece) – simulation of the phenomenon by means of the finite element method. *Quarterly Journal of Engineering Geology and Hydrogeology* 42 (3), 369–382.
17.Hatzinakos, I., Rozos, D., & Apostolidis, E., (1990). Engineering geological mapping andrelated geotechnical problems in the wider industrial area of Thessaloniki, Greece, *Price, D. (Ed.), Proceedings of Sixth International IAEG Congress*, Balkema, Amsterdam, Netherlands, pp. 127–134.
18.Andronopoulos, V., Rozos, D., & Hatzinakos, I., (1991). Subsidence phenomena in the industrial area of Thessaloniki Greece, *Johnson, A. (Ed.), Land Subsidence*, vol. 200, IAHS Publishers, pp. 59–69.
19. Sellountos,I., (1974). Drills of overpass next to the train station of Alexandria, *Technical report, K.E.D.E*, Ministry of Reconstruction of Production, Environment & Energy.
20.Galanidis, I., & Chaskos, K. (1991). Bridge construction at the Axios river at the 52th provincial road Sindos-Chalastra-Malgara. *Technical report*, K.E.D.E, Ministry of Reconstruction of Production, Environment & Energy.
21.Chaskos, K. (1991). Drainage of wastewater and stormwater N.Malgara-Chalastra and Anatoliko. *Technical report*, K.E.D.E, Ministry of Reconstruction of Production, Environment & Energy
22.Veranis, N., Christidis, C., & Chrysafi, A. (2014). The granular aquifer system of Katerini-Kolindros, region of central Macedonia, Northern Greece, *10th International Hydrogeological Congress of Greece*,Thessaloniki.