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ASSESSING GROUND SUBSIDENCE PHENOMENA WITH PERSISTENT SCATTERER INTERFEROMETRY DATA IN WESTERN THESSALY, GREECE

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Abstract

The main objective of the present study was to investigate ground subsidence in the wider area of Farsala, western Thessaly basin, by means of remote sensing techniques and to identify potential geo environmental mechanisms that contribute to the development of the observed surface fractures affecting the site. In this context, a set of Synthetic Aperture Radar (SAR) images, acquired in 1995-2003 by the European Space Agency (ESA) satellites ERS1 and ERS2 and processed with the Persistent Scatterer Interferometry (PSI) technique by the German Space Agency (DLR) during the Terrafirma project, were evaluated in order to investigate spatial and temporal patterns of deformation. Groundwater table levels of three water boreholes within the research area were processed providing the mean piezometric level drawdown and the mean annual drawdown rate. In addition, a quantitative comparison between the deformation subsidence rate and the thickness of the compressible sediments was also performed. The outcomes of the present study indicated a clear relationship in the subsidence deformation rate and the groundwater fluctuation and also a correlation between the depth of the bedrock and the deformation subsidence rate. Overall, the multitemporal SAR interferometry (DInSAR) data are proved as a valuable and suitable technique for increasing knowledge about the extent and the rate of the deformations in the current study area, proved to be affected with an increasing intensity.
Keywords: *Surface deformation, remote sensing techniques, water table fluctuation.*

Περίληψη

Ο κύριος στόχος της παρούσας μελέτης ήταν η διερεύνηση των εδαφικών καθιζήσεων που παρατηρούνται στην ευρύτερη περιοχή της πόλης των Φαρσάλων, με τη βοήθεια τεχνικών τηλεπισκόπησης, καθώς και ο εντοπισμός των δυνητικών γεω-περιβαλλοντικών μηχανισμών που συμβάλλουν στην εκδήλωση των εδαφικών διαρρήξεων που πλήττουν την περιοχή. Σε αυτό το πλαίσιο, αξιοποιήθηκαν δεδομένα συμβολομετρίας σταθερών σκεδαστών, τα οποία προέκυψαν από την επεξεργασία ενός συνόλου εικόνων ραντάρ, που λήφθησαν κατά την περίοδο 1995-2003 από τους δορυφόρους ERS1 και ERS2 του Ευρωπαϊκού Οργανισμού Διαστήματος (ESA). Ακόμα, αξιοποιήθηκαν δεδομένα στάθμης του υδροφόρου ορίζοντα από τρεις γεωτρήσεις, παρέχοντας τιμές για τη μέση πτώση και το μέσο ετήσιο ρυθμός ανάληψης. Επιπλέον, πραγματοποιήθηκε μια ποσοτική σύγκριση μεταξύ του ρυθμού καθίζησης και του πάχους των συμπιεστών ιζημάτων της περιοχής έρευνας. Τα αποτελέσματα έδειξαν μια σαφή συσχέτιση ανάμεσα στην εδαφική καθιζήση και τη διακύμανση του υδροφόρου

ορίζοντα καθώς και τη σαφή επίδραση του βάθους του βραχώδους υποβάθρου στο ρυθμό και την ένταση των παραμορφώσεων. Συμπερασματικά, με τη χρήση δεδομένων συμβολομετρίας σταθερών σκεδαστών αναδεικνύεται η σφοδρότητα με την οποία τα φαινόμενα των εδαφικών υποχωρήσεων πλήττουν την περιοχή μελέτης.
Λέξεις κλειδιά: *Εδαφικές παραμορφώσεις, τεχνικές τηλεπισκόπησης, διακύμανση υδροφόρου ορίζοντα.*

1. Introduction

Ground subsidence is considered among the most frequent geological hazard worldwide that usually occurs as a consequence of a number of phenomena, namely; natural compaction of unconsolidated fine-grained deposits, groundwater over-exploitation, urbanization and load imposition, presence of great thickness of young, peat-rich materials and finally, tectonic activity (Ziaie *et al.*, 2009; Loupasakis and Rozos, 2009). The evolution of such phenomena is related with damages observed in buildings and linear infrastructure over large areas that extent from ten to hundreds km^2. Numerous studies have been contacted during the last decades in Greece concerning areas that experience ground subsidence phenomena especially due to aquifers over-exploitation. The Thessaly Plain is among the well-known areas in Greece presenting ground subsidence related to reservoir compaction with cases observed since the early 90's (Soulios, 1997; Kaplanidis and Fountoulis, 1997; Marinos *et al.*, 1997; Salvi *et al.*, 2004; Ganas *et al.*, 2006; Apostolidis and Georgiou, 2007; Kontogianni *et al.*, 2007; Rozos *et al.*, 2010; Vassilopoulou *et al.*, 2013; Apostolidis and Koukis, 2013; Modis and Sideri, 2015). According to Apostolidis and Georgiou (2007) and later confirmed by Rozos *et al*. (2010), the over-exploitation of the groundwater resources activates the subsidence mechanism and subsequently leads to the evolution of surface deformations and raptures. Despite, the efforts of numerous researchers that have been involved in the investigation of the land subsidence phenomena, a clear understanding of the subsidence mechanism is not always easy to formulate. However, the geoscience community share a common belief; the multi-parametric nature of the subsidence mechanism can only be evaluated by the holistic and in depth study of the geological, hydrogeological, morphological and tectonic settings of the area along with the examination of the human activities and the land use data. In recent years, synthetic aperture radar interferometry (SAR) technology has been enabled in order to enhance the ability of the researchers to resolve the spatial distribution and temporal evolution of displacements. Specifically, Persistent Scatterer Interferometry (PSI) has been developed as an advanced remote sensing technology, with application in areas that are affected by land subsidence (Dixon *et al*., 2006; Herrera *et al*., 2009; Osmanoglu *et al*., 2011; Chaussard *et al*., 2013; Raspini *et al*., 2013, 2014). In this context, the main objective of the present study was to investigate land subsidence in the wider area of Farsala, western Thessaly basin, by means of remote sensing techniques and identify potential geo environmental mechanisms that contribute to the development of the observed phenomena.

2. Study area

2.1. General settings

The Thessaly water district is located in central Greece covering approximate an area of 13.700 km^2. It is a plain region divided into two large basins, the Pinios basin and the Almirou - Piliou basin. Elevations range from sea level at the eastern coastal area to more than 2.800m at the eastern and western mountain areas. The current study focuses on the western part of the plain as illustrated in figure 1.

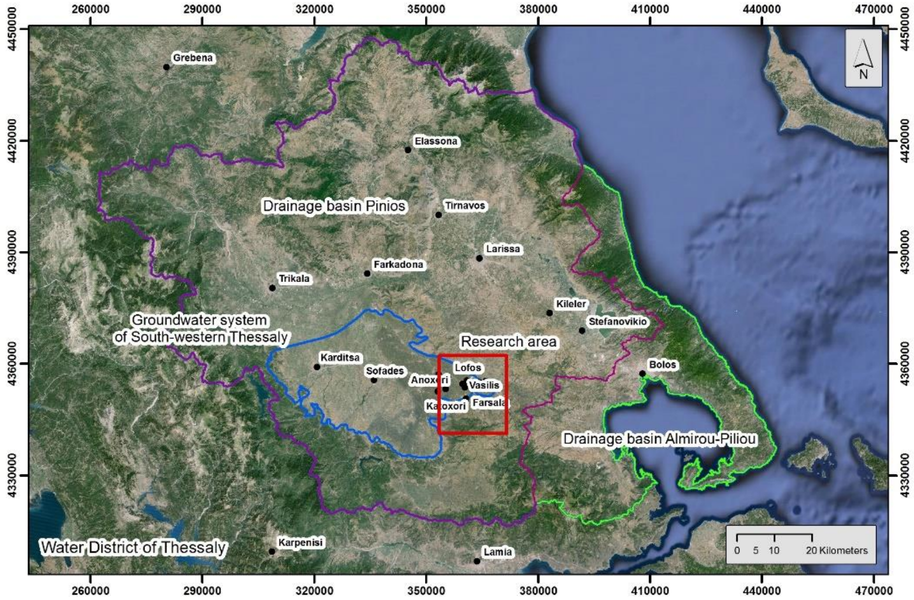

Figure 1 - The study area.

According to the Köppen climate classification system (Aguado and Burt, 2012), the wider area of research is characterized as Mediterranean type (Csa) with heavy winters and cool summers. During the winter, the temperature reaches low levels, rainfall and snowfall is abundant with a notable prolonged snow cover. The cloud coverage is high, while frost occurs from October to May. Summer is cool, with several local rainstorms. The rainy season is from October to May accounting to almost 90% of the total amount of annual rainfall which approximately reaches 31.7 to 87.7 mm/month. December appears the rainiest month (87.7mm) followed by November (86.2mm), while the driest month appears to be August (10.4mm) followed by July (14.1mm). The annual average mean temperature is 15.13^{0}C with the highest and lowest average temperature being 20.94^{0}C and 9.39^{0}C respectively (Fig. 2). The climate data were obtained from the University of East Anglia Climate Research Unit (CRU) and referred to a period over 107 years between 1901 and 2008 (Jones and Harris, 2008).

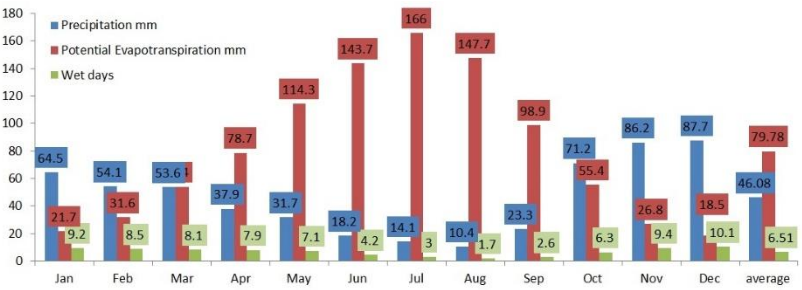

Figure 2 - Climate data of the wider area.

According to the data derived from the meteorological stations of Skopia, Loutropigi and Karditsa, the mean annual rainfall showed significant fluctuations during the last twenty years. A significant drop at the mean annual values have been observed during the year 2000 (Loutropigi 630mm, Karditsa 400mm, Skopia 380mm) while 1994 appears as the year with the highest rainfall values (Loutropigi 1380mm, Karditsa 820mm, Skopia 790mm).

2.2. Geological and tectonic settings

Concerning the geotectonic evolution of Thessaly, the eastern part of Thessaly belongs mainly to the Pelagonian zone of the Internal Hellenides, while western Thessaly belongs mainly to the Pindos zone. According to Robertson *et al.* (1991), the Pelagonian zone is considered as a micro-continent that rifted from Apulia during the Permo-Triassic period, and formed two oceanic basins, Pindos Ocean in the west and Axios-Vardar Ocean in the east. Caputo and Pavlides (1993), reported that the physiography of Thessaly plain is the result of the older orogenic tectonism (Oligo - Miocene) and post - orogenic collapse (Pliocene - Lower Pleistocene). Furthermore, the last tectonic phase (Middle Pleistocene to present) that also affected the Thessaly area generated a new system of relatively small basins with a general E-W trend. This graben system has been superimposed onto the inherited NW-SE trending, causing the complex block pattern observed today (Caputo, 1995). The wider area of research is characterized by a great variety of geological formations. Specifically, the western Thessaly basin compromises of Mesozoic Alpine formations that belong to the Pelagonian, Sub-Pelagonian, Ultra-Pindic and Pindos geotectonic zone and post - Alpine deposits that are located in the lowland of the basin (Apostolidis and Koukis, 2013). The Mesozoic Alpine formations constitute the bedrock of the Quaternary deposits that appear in the wider area of Farsala. These formations consist of Schist-chert formation, Ophiolites, Limestones and Flysch sediments, while the post-Alpine deposits include Neogene, Pleistocene and Holocene deposits (Mariolakos *et al.*, 2001; Rozos and Tzitziras, 2002). The geological formations appear as follows (Fig. 3): a) quaternary deposits (cl-sl, gr-sd, sd-gr, sc-cs), b) neogene sediments (Ne), c) limestones (Le), d) shale and chert formations (sh) and e) basic and ultrabasic igneous rocks (o) (Apostolidis, 2014).

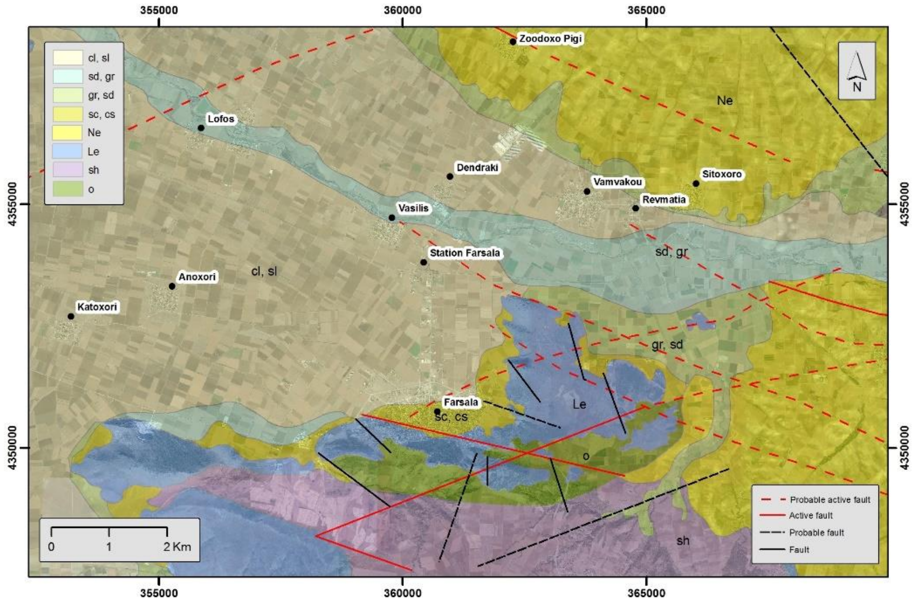

Figure 3 - Geological settings of the wider research area (Apostolidis, 2014).

2.3. Hydrogeological settings

Thessaly consists of two main hydrogeological basins, east and west that are divided by a range of hills. In western Thessaly where our research focuses, based on the hydrolithological properties of the Quaternary and Pliocene deposits and their bedrock tectonic features, four sub-basins, have been identified, namely (Kallergis, 1971; Kallergis, 1973; Manakos, 2010; Apostolidis, 2014): (a) Kalambaka sub-basin, (b) Trikala sub-basin, (c) Karditsa - Sofades sub-basin and (d) Zaimi - Sofiadas - Farsala sub-basin. The most productive aquifers of the study area are developed in the Zaimi - Sofiadas - Farsala sub-basin. Generally, the aquifer systems develop mainly in Quaternary deposits and secondly in the karstic systems extending at the perimeter of the plain area. However, additional aquifers of local importance are developed in the metamorphic formations, with numerous springs covering the local water demand. The dynamic of the groundwater systems varies and depends mainly on the surface runoff and secondly, on the grain size characteristics for the alluvial systems, on the degree of karstification for the karstic systems, and on the tectonic fragmentation and the thickness of the weathering mantle for the groundwater system developed in the metamorphic formations.

Regarding the narrow study area the main aquifer is located in the Quaternary deposits, constituting a system of unconfined shallow aquifers that extend through the upper layers and successive confined artesian aquifers developing in the deeper permeable layers (Apostolidis and Koukis, 2013). These systems are recharged mainly from the infiltration of the surface water but also through the lateral infiltration of the karstic aquifers that are developed in the carbonate formations that outcrop in the margins of the plain basin (Rozos *et al.*, 2010).

3. Materials and Methods

3.1. The followed methodology

During the present study three main investigation processes were conducted: a) defining the geological, hydrogeological and tectonic settings of the wider research area, b) analysing the PSI data and c) evaluating the groundwater table level from existing boreholes. Based on the outcomes of each analysis, the main goals were to examine any potential correlation between PSI measurements and groundwater table levels and also to compare the PS velocities with the thickness of the compressible Quaternary deposits.

Concerning the PSI data, they come from a descending data set provided by the German Space Agency (DLR), acquired in 1995-2003 by the European Space Agency (ESA) satellites ERS1 and ERS2. This set of data were processed within the framework of the Terrafirma project, that was supported by the Global Monitoring for Environment and Security (GMES) Service element Program, promoted and financed by the European Space Agency (ESA). Within the ESA Terrafirma project a Wide Area Product (WAP) has been developed by DLR (Adam *et al*., 2011). It involved processing nine satellite image frames in order to produce a PSI ground motion map covering a 65000 km^2 wide area of Greece. For the interpretation of the final product it should be noted that, the negative sign indicates a movement away from the sensor that measures the displacement, while positive values represent a movement towards the sensor. Concerning the colour scale, green indicates points that are characterized as stable, while the gradation from yellow, orange to dark red represents movement away from the sensor (subsidence), and the gradation from light blue to dark blue represents movements toward the sensor (uplift).

Groundwater table level was evaluated by processing measurements from three nearby boreholes (SR4, Pz6 and LB119) referring to the years 1995 to 2003, providing data for the mean piezometric level drawdown and mean annual drawdown rate concerning the research area. The water table level data were obtained from the department of Hydrology of the Thessaly Prefecture. Finally, 81 boreholes obtained from the Ministry of Agriculture with data concerning the depth of the bedrock for the Thessaly basin was also analysed (SOGREAH, 1974). The processing of the spatial data was conducted with the use of SURFER 11 and ArcMap 10.1.

4. Results

The wider area of Farsala is mainly founded on Quaternary deposits and only a small part at the south of the town is founded on the Alpine bedrock formations. These Quaternary deposits consist of talus cones and scree with cobbles and rubbles of carbonate, sandstone and chert composition (Apostolidis, 2014). As reported earlier, the main objective of the current research was the correlation of the PSI data with the groundwater level fluctuation. Concerning the PSI analysis, about 5848 PSs were identified in the data set acquired at the descending orbit of ERS1/2 from 19/6/1995 to 18/10/2003. The Line of Sight (LOS) displacement rates vary from +14.861 to -20.339 mm/year and are relative to a reference point, located at 4398839.50, 659935.19 (Coordinate system WGS 1984, UTM Zone 34N), assumed motionless. The analysis of the velocity of the PSI data showed that with a threshold of ±1.50 mm/yr, the stable PSs are 94.19% of the total. About 5.06% of the PSs shows a downwards velocity greater than -1.50 mm/yr, indicating subsiding movement. Subsiding movements can be clearly identified in the wider area of Farsala. Specifically, the northern parts of the town shows significant movements, while the highest LOS velocities have been observed in the Dendraki and Vasilis village, north of Farsala (Fig. 4a). Figure 4b illustrates locations of surface ruptures identified through field investigations and previous studies within Farsala town (Apostolidis and Georgiou, 2007; Rozos *et al*., 2010).

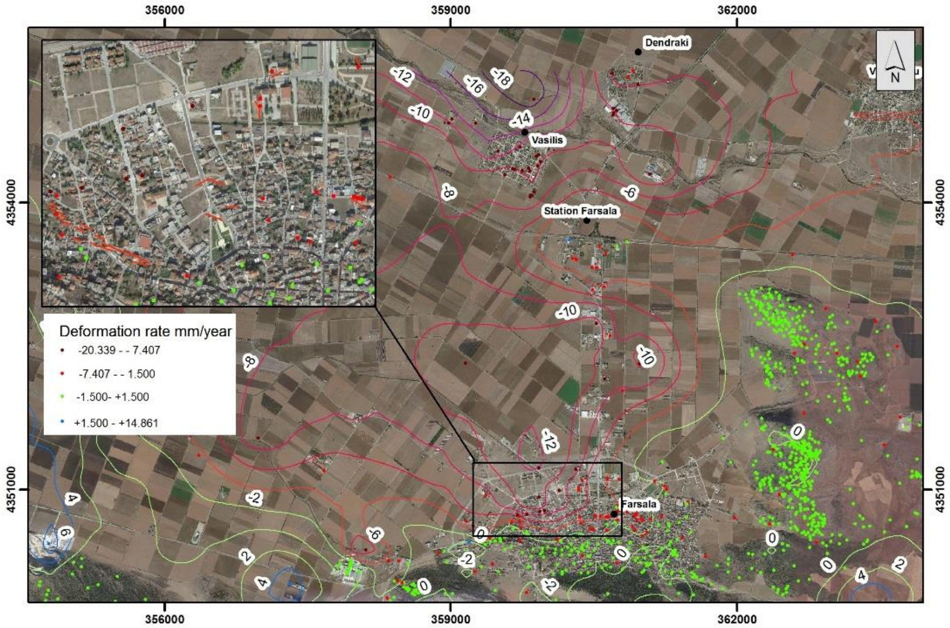

Figure 4 - Contours of PSI deformation rate measurements.

Concerning the third processing objective, the piezometric level monitoring data of three nearby water wells, SR4, Pz6 and LB119 were plotted in relation to the time (Fig. 5). According to the measurements conducted between 1995 and 2003, it appears that there is a temporal trend in the levelling of the water table; a sufficient drawdown of the ground water level takes place, reaching up to values of 37m. It seems that even if a significant recharge of aquifers takes place every year during the wet season (October to May), the overall tendency is a constant drawdown. The mean piezometric level drawdown for the period of measurements was approximately 17.0m and the mean annual drawdown rate during the same period of time was estimated to be 2.0m/year.

Figure 6 provides the results of a series of two water level measurements (wet and dry season) that have been performed during the years 1995-2003 corresponding to the highest (May) and lowest (September) ground water level period respectively. It’s clear that for LB119 and SR4 from the year 2000 a drop in both seasons can be observed. The same trend is observed in the year 2003 for Pz6.

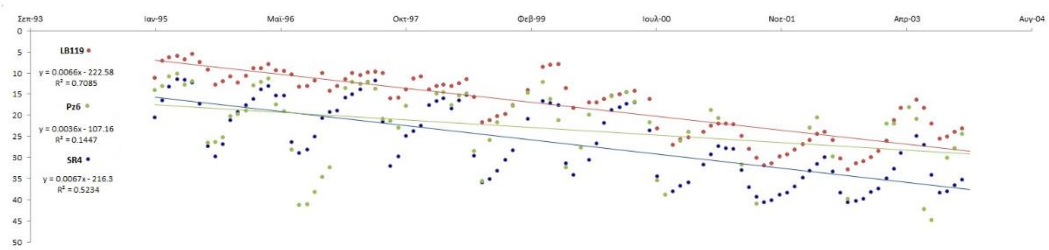

Figure 5 - Piezometric level variation (1995-2003) for water wells SR4, Pz6 and LB119.

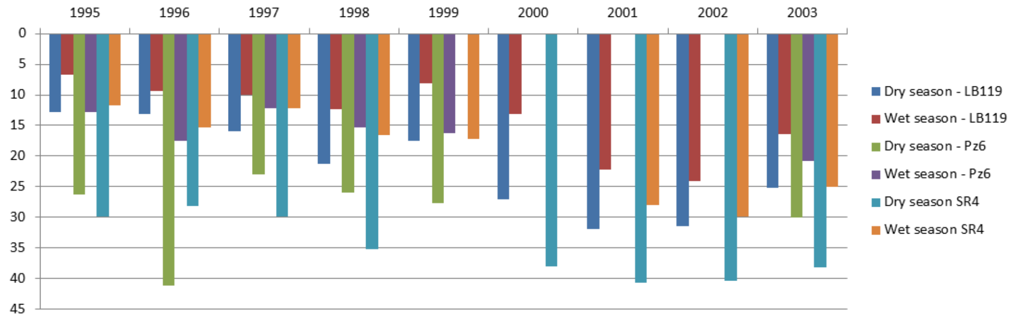

Figure 6 - Piezometric level variation between dry and wet season for water wells SR4, Pz6 and LB119.

The compaction of an aquifer system depends not only on the piezometric level variations, but also on the geometrical and geotechnical characteristics of the aquifer deposits, namely the thickness and its compressibility. In this context, a quantitative comparison between the deformation subsidence rate and the thickness of the compressible sediments has been performed. Figure 7 provides the generated contours concerning the depth of the bedrock.

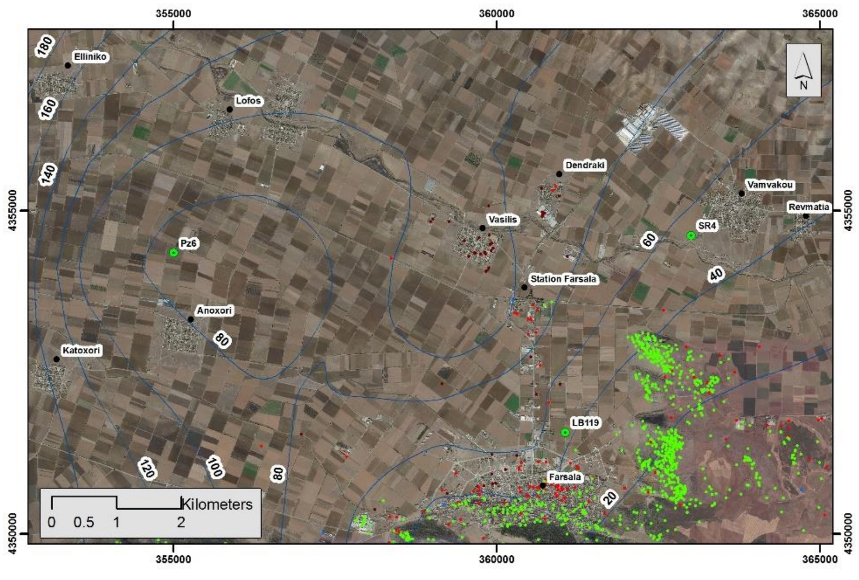

Figure 7 - Contours of bedrock depth.

From the analysis it was concluded that almost 65% of the PSs with deformation rate greater than -3.00mm/yr appear to be located in areas where the thickness of the loose deposits was less than 50m, while almost 64% of the PSs with deformation rate less than -3.00mm appear to be located in areas where the thickness of the loose deposits was greater than 50m.

5. Discussion and Conclusion

According to Manakos (2010), the inrational management of water resources in the plains of western and eastern Thessaly from 1974 up to date, has resulted in the systematic groundwater table drop and also the degradation of the quality of the majority of the aquifer systems. The irrigated crops, especially those of cotton, have increased in the last 30 years in relation to the available for irrigation water, while cultivation has been extended in areas where limited water resources are available. Moreover, as reported in the present study the amount of precipitation during the time of measurements (1995-2003) was low in relation to the water demands, resulting in even further overexploitation of the aquifers.

Manakos (2010) also reported the presence of local water depression cones distributed almost throughout the wider area of research for the year 2007, located mainly in areas that are far away from the regional infiltration and recharge zones of aquifers. As suggested by the author, this element was a sign of over-exploitation in those areas. Following the above conclusion, Modis and Sideri (2015) have examined and analysed PSI data and water table levels in order to estimate the spatiotemporal correlation and cross-correlation of those variables in the research area. They have estimated that these variables are spatiotemporally correlated, enabling the use of the uniformly sampled water level as an auxiliary variable for the estimation of surface deformations.

In the present study, a clear trend has been observed between the thickness of the loose Quaternary deposits and the deformation rate. Specifically, areas with thickness of loose Quaternary deposits greater than 51m are more likely to have deformation rate less than -3.00mm/yr. The outcome is in agreement with the theory suggesting that an excessive lowering of the ground water level leads to the radical change of the geostatic loads triggering or accelerating the consolidation of compressible ground layers. Concerning evidence of ground disruption, beside the available PSI data, surface ruptures and earth fissures where also reported. The spatial distribution of the observed surface ruptures extent mainly in areas where the analyses of PSI data also indicated strong deformation rate. In each case, the severity of the damages recorded on buildings and linear infrastructure was in accordance with the deformation rate.

From the conducted analysis of the groundwater table from existing nearby water boreholes it was estimated that the mean piezometric level drawdown for the period of measurements was approximately 17.0m. The mean annual drawdown rate during the same period of time was estimated to be approximately 2.0m/year.

The outcomes of the Persistent Scatterer Interferometry analysis provided important information about the extent and timing of surface deformation. It is most certain that the continuing irrational management of water resources would further influence the dropdown of the groundwater table that as a result will trigger subsidence phenomena and expand the affected areas. The followed analysis along with the detection of areas with reported ground disruptions it also detected areas that exhibit deformation without any reported damages. This early detection of surface deformations allows taking measures before the outbreak of severe subsidence phenomena and therefore allows for timely protection of the affected areas.

6. Acknowledgments

The Terrafirma Extension project has funded the SAR imagery processing as well as the geological interpretation presented in this paper. The project is one of the many services supported by the Global Monitoring for Environment and Security (GMES) Service Element Program, promoted and financed by ESA. The project is aimed at providing civil protection agencies, local authorities and disaster management organisms with support in the process of risk assessment and mitigation by using the Persistent Scatterer Interferometry. The authors gratefully acknowledge the German Space Agency (DLR) for having processed the SAR data.

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