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Evidence and implications of extensive groundwater overdraft-induced land subsidence in Greece

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Abstract: Groundwater resources have been over-utilized in Greece with water table drops of tens of meters becoming common the last thirty years and tens of thousands of wells developed without reference to the EU Water Framework Directive. This has led to extensive land subsidence with rates ranging from 1 to over 4 inches per year and becoming apparent throughout the country. The principal subsidence mechanism appears to be that of consolidation with aquifer re-organization and drainage and compaction of aquitards. Drainage of the extensive wetlands in Greece undertaken from the 1920s to 1960s, for control of malaria and flooding, and to increase the cultivated lands has also led to oxidation of the rich peat soils and to land subsidence of meters. In addition to subsidence occurrences on mainland Greece, recent DInSAR results for the island of Crete indicated that the productive Messara Plain is subsiding at a rate of at least 2 cm/yr as a result of the 40-meter groundwater drop over the last 20 years. Groundwater resources' depletion and widespread land subsidence pose serious infrastructure threats for the country. In order to mitigate the situation extensive water diversion and aquifer replenishment projects, in conjunction with water savings and crop selection measures need to be implemented.

Key words: Land subsidence, Groundwater, Overdraft, Interferograms

1. INTRODUCTION

Land subsidence resulting from groundwater over-exploitation due to increased water demand from the agricultural sector has become noticeable in many parts of the world. Land subsidence mechanisms, depending on an area's geologic character, include consolidation, that is compaction of confined aquifers and aquitard drainage; gradual settling or abrupt sinking of the Earth's surface due to collapse of karstic formations and infilling of the developed cavities by overlying layers; and organic soil subsidence due to land drainage and the ensuing oxidation of peat (Galloway et al., 1998).

Land subsidence incidents in the United States are extensively documented in several states with more prominent those in California, Florida, Texas, and Arizona (Galloway et al., 1999). Several studies have also been conducted in Italy (Gambolati et al., 1999) and Spain, which have recently used differential interferometry SAR techniques to identify affected areas and rates of subsidence (Tomas et al., 2005).

Direct and indirect costs of land subsidence are hard to estimate, but can run into hundreds of millions. The Santa Clara, California subsidence direct cost was estimated to be about 131 million 1979 dollars (the majority of which included levee construction). In addition extensive water diversion projects, involving 10 reservoirs, 393 acres of percolation ponds and 159 miles of conduits and pipelines were required for the aquifer recharge program (Galloway et al. 1999). The Sacramento-San Joaquin delta, California oxidation-of-the peat induced subsidence, as a result of the 1930s wetland drainage and reclamation projects required 1,100 miles of levees, whose repairs and maintenance averaged about \$20 million per year in the 1980s (Rojstaczer et al., 1991; Deverel and Rojstaczer, 1996). The cost of damages to 150 buildings and other structures resulting from the 1990s subsidence in the city of Murcia, Spain was estimated to exceed \$60 million (Tomas et al., 2005).

The principal aim of this work is to present a critical analysis of the land subsidence incidents in Greece, including some recent results through differential SAR interferometry that indicated significant ground deformation in Crete, Greece. The second objective of the article is to draw attention to a little recognized fact by public officials of that country that over-exploitation of the aquifers, with tens of thousands of pumping wells producing water table drops of tens of meters, apart from the well-known salt-water intrusion problems has the potential to create significant damages to the country's infrastructure.

2. MAN-INDUCED LAND SUBSIDENCE IN GREECE

2.1 Northern and Central Greece

In northern Greece the Kalochori (Figures 1 and 2), a western suburb of the city of Thessaloniki, has subsided at a rate of up to 13 cm/year until the early 2000, the rate being reduced to about 5 cm/year recently (Mouratidis et al., 2009). The total subsidence based on historical leveling and recent GPS data is about 3.5m, and land up to 2km inland has been submerged under the sea (Stiros, 2001; Psimoulis et al., 2007). The area constitutes a tectonic graben with Quaternary and Neogene deposits of depth up to 700m, and is located on the 2,500 year old deltaic sediments of four main rivers. The hydrostratigraphy of the area consists of the following: from the surface to a maximum depth of 15m there exists a layer of yellow-brown fine- to medium-grained sand and silty sand, defining a shallow unconfined aquifer; subsequently, and to a maximum depth of 35m a layer of black-grey silty sand and organic material acts as an aquitard between the unconfined and the deeper confined aquifers. The confined aquifers consist of alternating layers of brown medium to coarse-grained sands and black-grey silty sands and clays, with the layers' thickness varying from 5m to 50m. Since 1955 the confined aquifers were used for groundwater extraction (a total of about 500 deep drill-wells extending to depths of 200m) for industrial purposes and the needs of the Thessaloniki metropolitan area, at a rate of 1600-1900 m³/hr during the period of 1958-1963. Thus, the piezometric surface that in the 1950s was above ground surface fell, due to deep drilling, by 37m in 1981, and partially recovered (varying between 20m to 30m) by 2000 because of the cessation of the non-industrial wells (Loupasakis and Rozos, 2009).



Figure 1. Left: Submerged electricity poles at the Kalochori area, Greece (Mouratidis et al., 2009). Right: Land subsidence in Thessaly, Greece (newspaper "Ethnos, January 31, 2012).

Land subsidence became noticeable in the 1960s with marine invasion and flooding first appearing in 1964. The fact that the uniform subsidence that has occurred is localized to the Kalochori-Sindos area excludes regional scale tectonic effects as the cause of the phenomenon. Subsidence is considered to have been caused mainly by consolidation, i.e. compaction of the

confined aquifers and drainage of the highly compressible black silty clays, and secondarily by the oxidation of the near surface peat soils and the shifting of the deltaic mud that resulted from the deep layers' consolidation (Loupasakis and Rozos, 2009). Pumping was drastically reduced in the 1980s, but despite the partial recovery of the piezometric surface no significant land rebounding has been reported.

Drainage of the extensive wetlands of Greece was undertaken from about the 1920s to 1960 for control of malaria and flooding, and to increase the cultivated land in order to accommodate the influx of one and a half million Greeks from Asia Minor in 1923 (Sivignon, 2007). Natural wetlands, where the water table is slightly under, or at the ground surface are net carbon sinks because the rate of organic accumulation at the anaerobic bottoms dominates organic decomposition. The creation of aerobic conditions upon drainage of a wetland or a permanent drop of the water table turns a wetland into a carbon source by accelerating microbial decomposition and loss of soil carbon as gaseous CO₂ (Deverel and Rojstaczer, 1996). Land subsidence due to peat oxidation and self-ignition in drained wetlands has occurred in Philippi (Figure 2) at the prefecture of eastern Macedonia; at the Chimaditis Lake (Figure 2) at the prefecture of western Macedonia; and at Lake Kopais (Figure 2) at the prefecture of Boeotia, south-central Greece.

The Philippi mire, the thickest peat deposit in the world (thickness 190m, surface area 55km², reserves 4,300 million m³), was drained for agricultural purposes between 1931 and 1949 (cultivated now with tobacco and corn), subsiding to a maximum of 3.5m by 1960, and to 6m by early 2000 (Kalaitzidis, 2007). The 1930s drainage of the 25 km² mire (one million m³ reserves) north of the Chimaditis Lake, West Macedonia resulted in the loss by oxidation of a 3.5m thick peat. In addition, the lake is found 1.5km away from the Amynteon open lignite pit, where extensive pumping takes place for protection of the mine. Preliminary studies indicate that dewatering of the mine has not affected, until recently, the lake (Koumantakis and Dimitrakopoulos, 1999), although ruptures have rendered most of the houses in nearby villages uninhabitable (Soulios et al., 2011). Drainage of the shallow, seasonal marshy Lake Kopais, which commenced in the mid 19th century led to self-ignition of the exposed bottom peat and to a 4m subsidence rendering the original drainage network and main tunnel inoperative. The lake was fully drained by 1931 after the elevations of the drainage works were adjusted (Papadopoulou-Wrinioti, 1990).

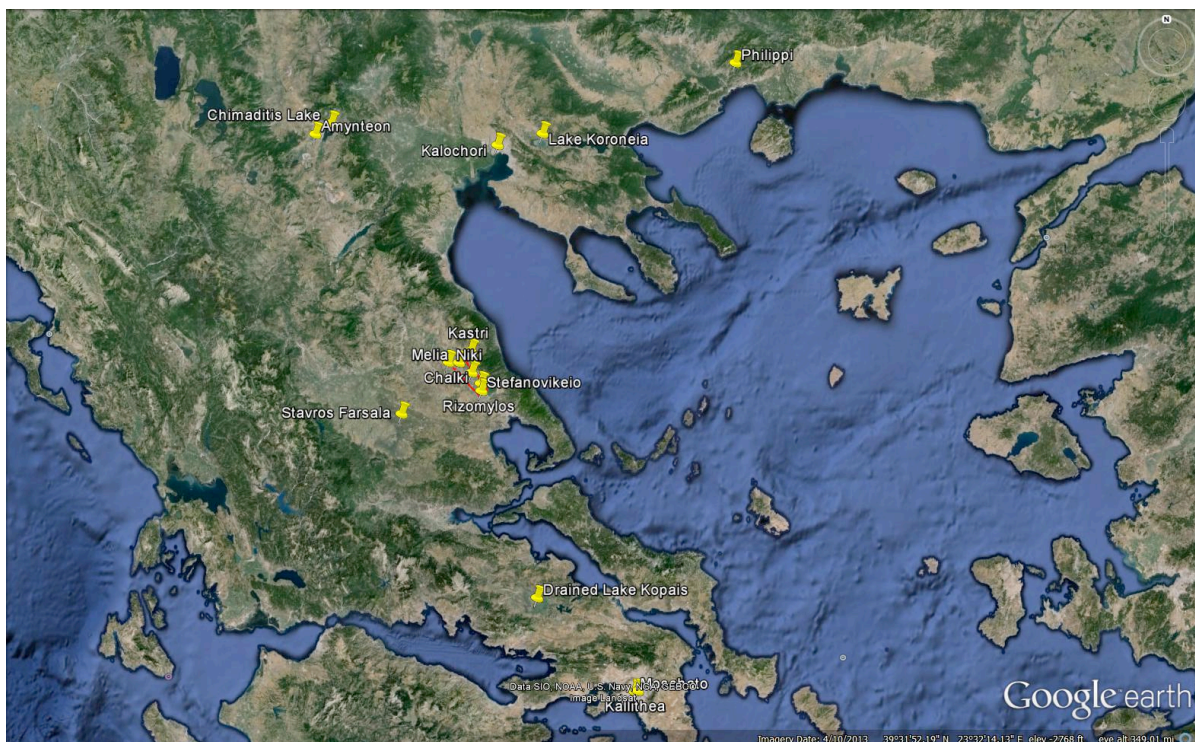


Figure 2. Reported water-overdraft-and-drainage induced subsidence locations, mainland Greece (Google Earth image).

Conditions of consolidation exist also in Lake Koroneia (Figure 2), which is found 12 km north-northeast of Thessaloniki. From close to the surface to a depth of about 50 m a shallow phreatic aquifer exists, followed by very low permeability black clay layers extending from a depth of 50 m to 80 m, indicating the existence of lake deposits. Shallow aquifers are exploited for irrigation purposes by at least 2,000 wells. Deep confined aquifers are found below the clay zone to a depth of 450m, and are also exploited by approximately 500 wells. Although past studies had assumed no connection between shallow and deep aquifers (with clay layers considered as impermeable layers separating deep confined and shallow unconfined aquifers) borehole drillings in the late 1990s revealed the existence of red discontinuous clays indicating a hydraulic connection between deep and shallow aquifers. The total mean aquifer drawdown rate in the lake's sub-basin during 1971-1996 was 0.2m/yr, doubling (0.5m/yr) during a 5-year period (1997-2001) as a result of the intensification of pumping (Mylopoulos et al., 2007). The existence of the 30 m thick clay layer and the intense exploitation of the groundwater resources, which has practically eliminated the lake, are preconditions for disruption of the water pressure balance between the aquifer and the clay formations, and for drainage of the clay. Since no subsidence incidents have been reported up to now the clay may still be at a pre-consolidation stage, in which case the situation may be reversible with the planned lake-aquifer replenishment projects.

The central plain of Greece at Thessaly consumes 25.10% of the irrigated water in Greece. Although the mean annual precipitation (which ranges from an annual of 400mm on the plain to 1850mm on the western mountain ranges) shows a clear declining trend over the last 40 years water demand has dramatically increased since the 1980s (Kokkinos and Mylopoulos, 2007). This has resulted from the five-fold expansion of the farm land during 1962 to 2004, and the intensive cultivation of crops that are dominated by cotton, wheat, alfalfa and corn. The over-exploitation of water resources has led to a negative water budget in the two main basins, the Pinios River basin to the west, and the Karla Lake basin to the east, as well as in the four smaller coastal basins. Groundwater contributes about 70% of the irrigation water needs, with more than 5,000 new wells having been drilled only in 1984-85, leading in some locations, to a 50m water table drop, and to severe salt water intrusion problems (Kontogianni et al., 2007; Loukas and Mylopoulos, 2010).

The geologic environment of Thessaly is characterized by Mesozoic Alpine formations in the margins of the region, with post alpine deposits on the plain. The plain is a relic of a Pliocene lake, which was partly drained by the opening of the Pinios valley during the Lower Quaternary. The hydrogeology of Thessaly, in general, is characterized by sand and gravel horizons Pleistocene in age, with brown and grey clayey silt to silty clay intercalations. These alternations of permeable coarse-grained deposits (aquifers) with impermeable to low permeability strata (aquitards) create shallow unconfined aquifers and a number of successive semi-confined to confined aquifers, sometimes artesian. Hydraulic communication between the two basins is provided primarily by the Pinios River and fractured carbonate aquifers. Basement rocks at the Eastern basin area (a Quaternary tectonic depression) are found at a depth of 50-700 m and below 80m at the Western basin (Ntakoulas et al., 2004; Kontogianni et al., 2007; Rozos et al., 2010).

Anthropogenic-induced land subsidence in Thessaly was first observed in the late 1980s with surface soil ruptures and since then with damages to buildings, roads, and public infrastructure projects in several towns (Figure 2: Chalki, Melia, Stefanovikeio, Rizomylos, Niki, Kastri, Stavros) (Ntakoulas et al., 2004; Kontogianni et al., 2007; Sideri et al., 2012). In the drained Karla Lake area the subsidence has been exacerbated by the 1962 lake's drainage (drained area 180km², approximately) and elimination of its contribution to the aquifer's natural replenishment (Gerakis, 1992). Despite the existence of two faults in the vicinity of the drained Karla Lake the magnitude of subsidence at surrounding locations cannot be explained by deep tectonic effects and fault creep, which appear to have a small effect (<1mm/yr), and subsidence appears to have resulted, primarily, from consolidation and karstic dissolution following ground water over-exploitation (Kontogianni et al., 2007). Persistent Scattering Interferometry and DInSAR studies of the period 1992-2006 and 1992-2010, respectively, indicate a maximum subsidence rate of 25mm/yr north and east of the city of Larissa, with the remaining plain subsiding at 5-10 mm/yr, and insignificant deformation changes

close to the mountains. The maximum total subsidence at some locations has reached 2.7 m (Parcharidis et al., 2011; Vassilopoulou et al., 2013).

2.2 Southern Greece and Crete

In the broader Piraeus-Athens area subsidence has been observed since the early 1960s predominantly at the coastal suburbs of Faliro, Moschato, and Kallithea (Figure 2) (Georgopoulos and Teleioni, 2010), along the loose alluvial deposits of Ilissos and Kifisos Rivers with maximum total subsidence of about 12 cm. The geology of these suburbs at depths of about 10m is characterized by clay layers with width between 2 to 5m, and to a depth of 30m by silt, sand and clayey sands. At locations where subsidence has been observed the water table was measured during 1996-97 to lie 10 m below the elevation of the sea. Parcharidis et al. (2006) based on 264 differential interferograms, and excluding co-seismic deformation from the 1999 Athens earthquake, reported for the period 1992-2002 a total subsidence of 12mm in the southern and about 40mm in the northern suburbs of Athens, respectively. Subsidence exists also for parts of the city center, but was associated with recent underground construction activities for the Athens subway system. In general, land subsidence in Athens is attributed to mining activities, major underground construction projects, large magnitude earthquakes, river modifications, and groundwater over-exploitation. Drilling-well distribution exhibits good correlation with the deformation patterns in the southern and the northern suburbs. Thus, land subsidence in these areas, is thought to result from groundwater withdrawal, with aquifer compaction and clay compressibility constituting the dominant subsidence mechanism (Parcharidis et al., 2006).

Recently (Mertikas et al., 2010), Differential Synthetic Aperture Radar Interferometry (DInSAR) stacking techniques (Hanssen, 2001; Strozzi et al., 2001) were used to analyze images of ground deformation at the Messara valley of Crete, Greece. Images were obtained from the European Remote Sensing (ERS) C-Band Synthetic Aperture Radar (SAR) satellites 1 & 2, as well as from Japan's Advanced Land Observing Satellite (ALOS) Phased Array L-Band Synthetic Aperture Radar (PALSAR), and covered the period of 1992 to 2000, and 2007 to 2009, respectively.

The valley of Messara is surrounded by mountains and covers an area of more than 300 km² in the central-southern area of the island of Crete, Greece. The valley is a graben formation, oriented in an E-W axis and bounded by normal faults. It is covered by Miocene to Quaternary sediments that consist mainly of alluvial clays, silts, sands and gravels with thickness from a few metres to 100 m or more. The northern slopes are mainly silty-marly Neogene formations while the southern slopes are mainly schists and limestone Mesozoic formations. The two basin catchments are drained by two rivers, one with an eastward, and another with a westward direction. The upper alluvial aquifer, which covers the largest part of the central plain, is excessively exploited by drilling, which has led to a 45 m water table drop.

These authors concluded that although stacking ERS SAR C-band images could not reveal the ground deformation at the Messara valley, the ALOS PALSAR L-band succeeded in penetrating the valley's vegetation canopy to indicate a land subsidence of at least 2cm/yr for the period 2007-2009 (Figure 3). Given that the total seismic slip in the region during this period amounted to 0.06mm, Mertikas et al. (2010) suggested that the excess land subsidence had resulted from groundwater over-exploitation.

3. IMPLICATIONS OF LAND SUBSIDENCE FOR GREECE

Groundwater exploitation beyond any sustainable limit of natural groundwater replenishment has become common in most areas in Greece. Large geographical areas, such as Thessaly, exhibit in some cases over 60m water table drops (Ntakoulas et al., 2004), whereas in Lake Koroneia, Macedonia, thousands of legal and illegal boreholes have disrupted the hydraulic connection between lake and shallow aquifer, resulting, practically, in the elimination of the lake. The lake is

part of the NATURA 2000 network of sites and illegal borehole water-withdrawal together with unregulated discharges of urban and industrial waste has led the European Commission to refer Greece to the European Court of Justice for failure to protect Koroneia (Case reference: IP/11/89 January 27, 2011). The existence of thick discontinuous clay layers there favor the mechanism of consolidation in terms of land subsidence, which if activated the planned lake-aquifer replenishment projects will not be capable to reverse.

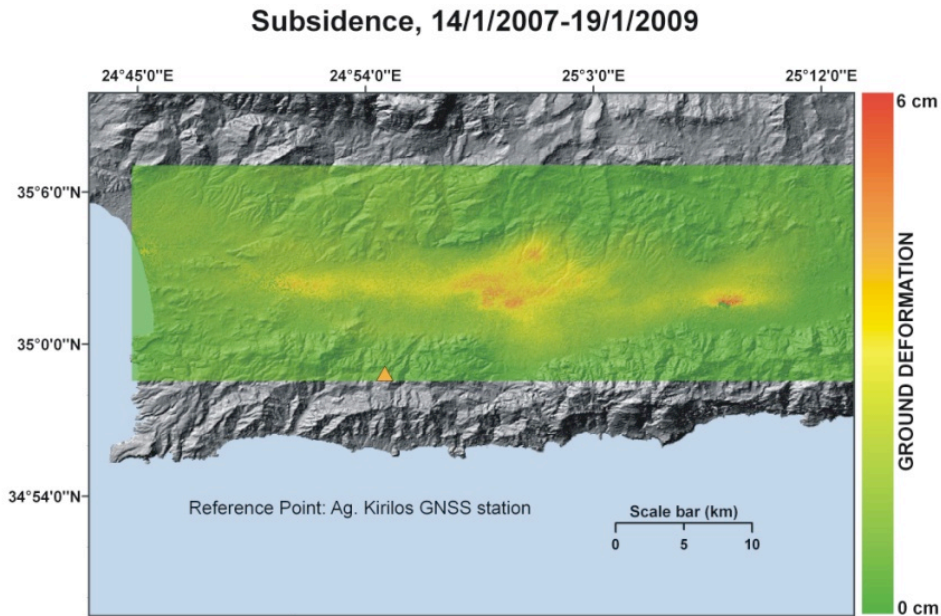


Figure 3. Interferogram for the two year time span 14/1/2007 – 19/1/2009.

In Thessaly, where the water table is estimated to drop by 5 m every year, at several coastal locations, along the Velika-Agiocampos coastal line and at Almyros (Figure 4), where fractured carbonate formations are encountered, severe salt water intrusion problems have appeared. Similar problems exist in coastal locations in Athens where the water table was found in 1996-97 to lie 10 m below the elevation of the sea. Similarly, salt water intrusion problems were detected at the northwestern part of the Messara plain, the Tymbaki basin, by transient electromagnetic, vertical electrical soundings, and radio-magnetotellurics surveys (Pipatpan and Blindow, 2005).



Figure 4. Thessaly and locations of salt-water intrusion (Google Earth image).

The economic consequences of land subsidence in Greece with prominent the Thessaly plain are manifold. Ground failures have caused differential settlement and destruction of homes, public projects, and roads in several communities in Thessaly in the past, and more recently in 2012, leading local authorities to request emergency funds of 1.5 million Euros to address damages (Figure 1 right). Ntakoulas et al. (2004) had recommended cessation of new drilling permits for the affected areas of Thessaly, control and reduction of existing pumping wells, aquifer replenishment projects, and changes in cultivation practices with water savings and the introduction of less water demanding crops. In addition, compaction of earth that resulted from subsidence has made land less productive for agricultural purposes, with further deterioration occurring by evaporation and salt deposition into the soil due to the high summer temperatures in the region.

Furthermore, subsided lands are more prone to flooding, hence requiring flood protection measures. Land subsidence can eliminate these areas as potential urban or agricultural expansion areas due to their increased risk. For example, in Florida, USA home insurance premiums are much higher than in other states due to the high occurrence of sinkholes.

In conclusion, the continuous operation of tens of thousands of pumping wells in productive valleys in Greece, with effectively no restrictions to the amounts of water withdrawn, are expected to increase land subsidence incidents. Given that in most locations the dominant land subsidence mechanism appears to be that of clay consolidation it is doubtful, if the situation remains unchecked, whether large water diversion and aquifer replenishment projects will be effective in alleviating the situation.

4. CONCLUSIONS

Excessive groundwater withdrawals appear to be common practice in most fertile regions of Greece. The north part of the country has seen sea inundation of coastal deltaic areas due to aquifer and clay layers' compaction, as well as lowering of the land surface due to drainage of wetlands' areas and subsequent oxidation of peat. The central part of Greece is where intense agricultural activities concentrate with water-demanding crops based on cotton, wheat, alfalfa and corn. This region is where the maximum subsidence rates of 25mm/yr appear in the country, and where recent effects of land subsidence with road, public infrastructure, and buildings damages have recently appeared. In the Athens broader area, relatively low subsidence had concentrated in the past on coastal suburbs built along alluvial deposits, with recent studies indicating subsidence in the northern suburbs as well. Finally, DInSAR studies showed that the Messara Plain on the island of Crete is currently deforming, primarily along its central east-west axis, at a rate of 2cm/yr.

The main subsidence mechanism for most locations in Greece appears to be that of consolidation, that is aquifer re-organization and aquitard compaction. Drainage of the extensive wetlands of Greece undertaken from the 1920s to 1960s for control of malaria and flooding, and to increase the cultivated lands has also led to oxidation of the rich peat soils and to land drops of meters. Groundwater resources' depletion and widespread land subsidence pose serious infrastructure threats for the country.

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