Monitoring and Analysis of Ground Subsidence due to Water Pumping in the Area of Thessaloniki, Hellas

Ioannis D. DOUKAS, Ioannis M. IFADIS, and Paraskevas SAVVAIDIS, Greece

Key words: ground subsidence, water pumping, geodetic methods, geodetic measurements, high precision leveling

SUMMARY

Water pumping is one among several serious causes capable to cause ground subsidence. The pumping of large volumes of water (e.g. for irrigation and water draining purposes) by using ground drillings is very possible to produce ground subsidence, a phenomenon which usually gets worse as water pumping continues. The consequences of such phenomena may be dangerous, especially when the ground subsidence is not smoothly distributed in the problematic area.

Starting from the decade of 1950, the public service of water supply of the city of Thessaloniki (O.Y.Th.) established water-pumping stations, in the industrial area of the community of Kalohori (15 Km West of the city of Thessaloniki). The number of these pumping stations was 51 from 1950 to 1980. Nowadays, the number of stations operational on a continuous base is 8. Also, there are more than 700 industrial plants, many of them having their private water drillings. The number of these drillings is estimated to be more than 200. Although the amount of water pumped by O.Y.Th. stations is under continuous monitoring, there is only a rough estimation of pumped water regarding the private water pumping stations.

The Kalohori area suffers from ground subsidence that causes several problems to local environment. In order to monitor these phenomena, a leveling network consisted of 37 stations was established within this area in 1992. The region under investigation is approximately 12,000,000 m^2 (3Km X 3.5Km). The control network was measured several times in a period of ten years. At the early epochs, a Zeiss Ni 2 automatic level carrying an optical micrometer was used, while later on, an electronic Leica NA 3000 electronic level was employed in the measurements. The evaluation of the geodetic measurements shows that the greatest subsidence occurred in the SE area of Kalohori, where a subsidence speed of 2.8 - 5 cm/year was detected. Furthermore, a strong correlation between ground subsidence and time seems to exist in this area, a fact that could be directly attributed to the extensive pumping of water by many industries in a relatively small area.

Monitoring and Analysis of Ground Subsidence due to Water Pumping in the Area of Thessaloniki, Hellas

Ioannis D. DOUKAS, Ioannis M. IFADIS, and Paraskevas SAVVAIDIS, Greece

1. INTRODUCTION

The most serious problems related to the excessive ground water pumping (also called aquifer mining or overdraft) are as follows (Dripps, 2002):

- Subsidence
- High pumping costs
- Depletion of surface water
- Degraded water quality.

Ground subsidence can be defined as the vertical downwards-small movements of the ground. Several physical causes (like earthquakes, tectonic movements, underground cavities etc.) and human activities as well, can produce ground subsidence. The most important to refer human activities, obviously as main components of the urban growth and industrialization, are (Poland 1984, Vanicek et al. 1982, Leonard et al. 1983, Ajalloeian et al. 1998):

- The tunnel excavations
- The extraction of minerals from underground mines
- The pumping of oil or gas
- The pumping of underground water.

Factors that are contributing to the evolution of the subsidence process are:

- The existence of geological gaps
- The moisture of the surface ground
- The level of the underground water
- The kind of the existing rock.

It is important to mention here that, even if the responsible for the subsidence factors are in most cases alike, the specific combinations of their physical and non-physical causes compose a set of unique characteristics for each subsidence case. Consequently, as a rule, we need to consider each subsidence case as a special one.

The pumping of large volumes of ground water is very possible to produce ground subsidence that usually continues to evolve with the water pumping. In most of the cases, gentle subsidence bowls develop slowly (even almost imperceptibly) but can extend over large areas. This phenomenon is not reversible and its results may be dangerous, especially when the ground subsidence is not smoothly distributed in the problematic area. There are many large areas on the earth’s surface with such problems. The city of Bologna (Italy) has experienced ground subsidence due to water pumping, in its NW area (Barbarella et al. 1986). The magnitude of this subsidence was approximately 2 m during the last 30 years. The subsidence, in combination with the geological peculiarities of the territory, caused deformation problems to the historic buildings of this city. Large areas in USA (Texas, California, Arizona, Nevada etc.) do show serious problems related with the aquifer overdraft (Blodgett et al. 1990, Carpenter 1993, Epstein 1987, Galloway et al. 1995, Holzer et al. 1979, Jones et al. 1975, Metzger et al. 2001, Sneed et al. 2001, Sneed et al. 2002). In North China (Dripps 2002, Chen et al. 2003), during the last thirty years the water table has fallen from 8 to 50 m. The most common reason for these effects is ground water pumping. In several areas of Mexico, the land subsidence was 7.5 m and the water pumping was the cause during 1930-1960. In Italy, along the Adriatic coast, the ground subsidence has been 1 m since 1950 (Dripps 2002).

2. SOME HISTORICAL DATA

The community of Kalohori and its rural territory belongs to the county of Thessaloniki and is located in the west side of the city of Thessaloniki (Figure 1). A big part of the rural territory of Kalohori has already been transformed into a very dynamic industrial area. During the first years of the fifties, the public service of water supply of Thessaloniki (from now on O.Y.Th.) established a number of water pumping stations (W.P.S.) in the rural area of Kalohori. The number of these stations from 1950 to 1980 was 51. Nowadays, the number of stations operate on a regular basis is 8. On the other hand, there are more than 700 industries in Kalohori industrial area, where many of them have their private water pumping stations. The number of these stations is estimated to be around 300. Although O.Y.Th. keeps records of the pumped water volumes for all its W.P.S. on a systematic basis, there are no data at all regarding the private water pumping stations.

The average height above sea level of the northern part of the rural territory in the area under study is approx. + 2.5 to + 3.0m. The south area (which expands to the sea) should have an average height approx. zero (0 m), some parts already being below the mean sea level. The area faced several problems in the past, mainly due to inundation (especially during the years 1968, 1974, 1976, 1979, and 1999).

Figure 1: The geographic position of Kalohori area in relation to the city of Thessaloniki.

In order to minimize these problems, an embankment between land and sea was built (1968), while several improvements in the construction were made until 2000. Due the subsidence of the whole above mentioned area, O.Y.Th. today pumps approx. 5,000 m^3 of water per day, when a roughly estimation of the industrial water pumping varies between 10,000 to 36,000 m^3 per day.

3. FIELD STRATEGY AND WORK

The territory under research covers approximately 12,000,000 sq.m. of land (an area of 3 Km X 3.5 Km). Monitoring of subsidence is being done with the help of a high precision leveling control network, which was established with 37 stations (named R1, R2, R3, ..., R37) in cooperation with O.Y.Th. Nine (9) leveling campaigns were carried out. The basic rules for the location of the network stations were the good space distribution in order to cover all the area and the establishment of at least one network station as near as possible to each of O.Y.Th.'s W.P.S.

The first six (P1, P2, …, P6) leveling campaigns were carried out by using a Zeiss Ni 2 level (carrying an optical micrometer) and were scheduled to fall between or after the epochs of rain or dryness, respectively. The main scope of this schedule was to offer the possibilities of correlation analysis between subsidence and epoch of the year. Each of the next three (P7, P8, P9) campaigns were scheduled to end with the beginning of the autumn (for years 1996, 1997 and 1998) and carried out by using a Leica NA 3000 electronic level. In Table 1, the dates for each leveling campaign are illustrated.

Table 1: Dates of each period of measurements

Period	Date
P1	October, 1992
P2	March, 1993
P3	July, 1993
P4	March, 1994
P5	October, 1994
P6	August, 1995
P7	August, 1996
P8	August, 1997
P9	August, 1998

4. DATA ANALYSIS AND EVALUATION OF THE RESULTS

The network was least squares adjusted for every period of measurement (Van Mierlo 1975, Savvaidis 1992). The mean square error, of every height and of every height difference as well, was never greater than ±0.49cm. Although the control network established at the beginning of the project consisted of 37 stations, a few of them are not included in the final analysis, because it was impossible to be measured in every period of measurements due to field problems. The layout of the stations is illustrated in Figure 2 where the relation between station subsidence and water pumping can be also seen. At the end of the measurements of period P4, all network stations seemed to suffer a rather systematic subsidence. After the completion of period P5, O.Y.Th. decided to stop the water pumping from some of its W.P.S. due to the detected subsidence. The result of this action is obvious in Figure 2, where we have a group of network stations that do show a significant decrease in their subsidence rate. On the other hand, most of the network stations which are close to private pumping stations belong to another group as they do continue to increase their subsidence.

By choosing two representative network stations of the above mentioned groups we can see that station R28 shows an increasing subsidence with a correlation coefficient >0.90 all during the research time (Figure 3). Station R28 is located near private water pumping stations. On the other hand, concerning station R37, it seems that, when the nearby W.P.S. of O.Y.Th stopped water pumping, the subsidence changed its direction and after period P7 showed a stabilizing behavior (Figure 4).

A study and comparison of observed elevations among different epochs and especially between periods P1 and P9 (Figure 5), shows that in approximately six (6) years in the North-West (NW) area, where most of O.Y.Th.'s out-of-operation pumping stations are located, the subsidence has become negligible. The most significant subsidence characteristics belong to the South-East (SE) area where most of the water pumping stations are private (consequently out of effective public control). In Figures 6 and 7, these subsidence formations are illustrated in different ways and come to a final global picture of the subsidence problems in Kalohori

area. In any case, the same subsidence behavior exists in every comparison of every two periods of measurements.
The comparison between the first and the last periods (i.e. P1 and P2) just shows almost the same characteristics of subsidence formations, as if were comparing p.e. P3 and P1, or P4 and P1 etc. The only difference has to do with the absolute subsidence values as they are greater at specific locations as time passes.

5. CONCLUSIONS

The phenomena of the ground subsidence detected in the Kalohori territory (starting from early 1950), are components of a complicated mechanism that needs a systematic and multi-specialist research based on a long time schedule of observations. By taking into account all the possible causes (Metzger et al. 2001), the most significant seem to be the geological structure and the water pumping, as well. In such complex subsidence mechanisms, the classic geodetic methods like leveling are only one component of the available methodology (Ge Li et al. 2001, Amelung et al. 1999, Booker et al. 1985, Fruneau et al. 2000, Najjar et al. 1993, Ng et al. 1995, Sneed et al. 2001, Sneed et al. 2002).

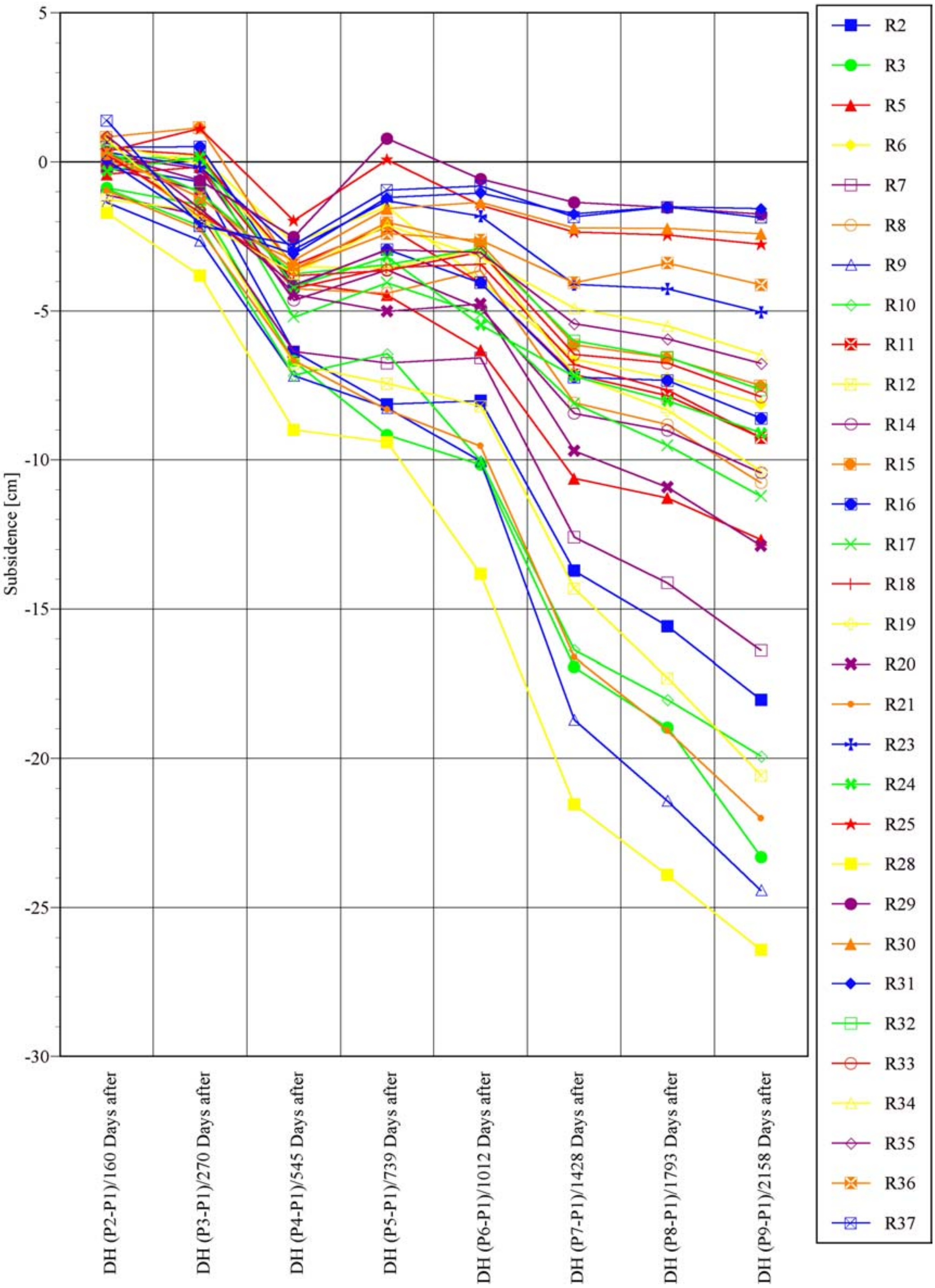

Fig. 2: Subsidence of the control network points with the time.

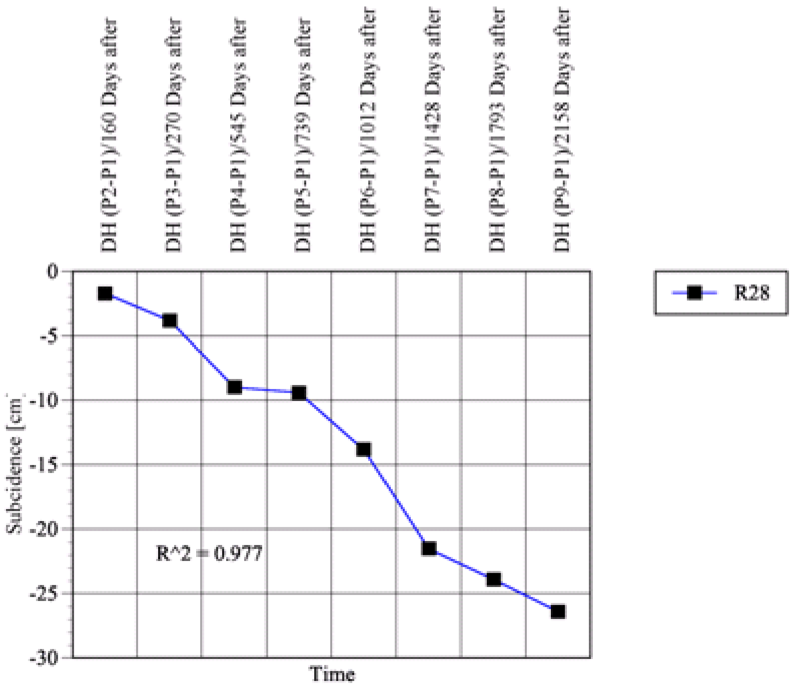

Figure 3: The subsidence of control network point R28

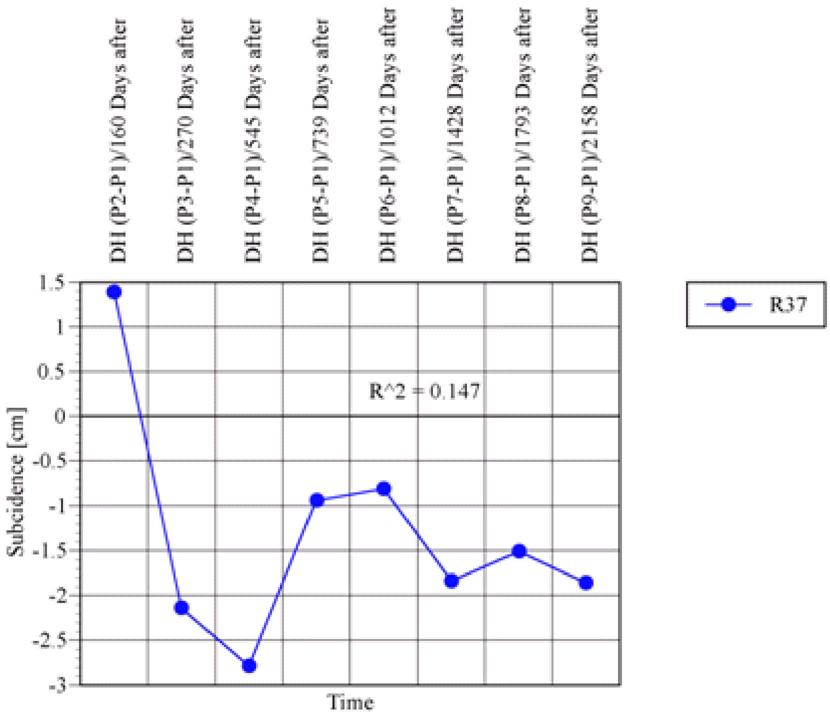

Figure 4: The subsidence of control network point R37

The evaluation of the geodetic measurements (carried out between 1992 and 1998) shows that the greatest subsidence has occurred at the South-West area, where subsidence from 16.8 cm to 26.4 cm was detected, equivalent to a subsidence speed of roughly 2.8 - 5 cm/year. Furthermore, in this area there is a strong correlation between subsidence and time, a fact that shows a direct connection with the presence of many industries (concentrated in a relative small area) and the (out of public control) water volumes they pump. On the contrary, the subsidence phenomena are smoother (subsidence varies from 1 cm to 7 cm, i.e. a speed of roughly 0.2-1.2 cm/year) beyond the west side of the town of Kalohori where most of the O.Y.Th. pumping stations exist. In this area, except for the O.Y.Th.'s pumping stations, there are also neighbouring private water pumping stations with unknown volume of water pumping. Starting from 1994, due the reduction of water pumping from O.Y.Th., the specific territory shows a considerable stability.

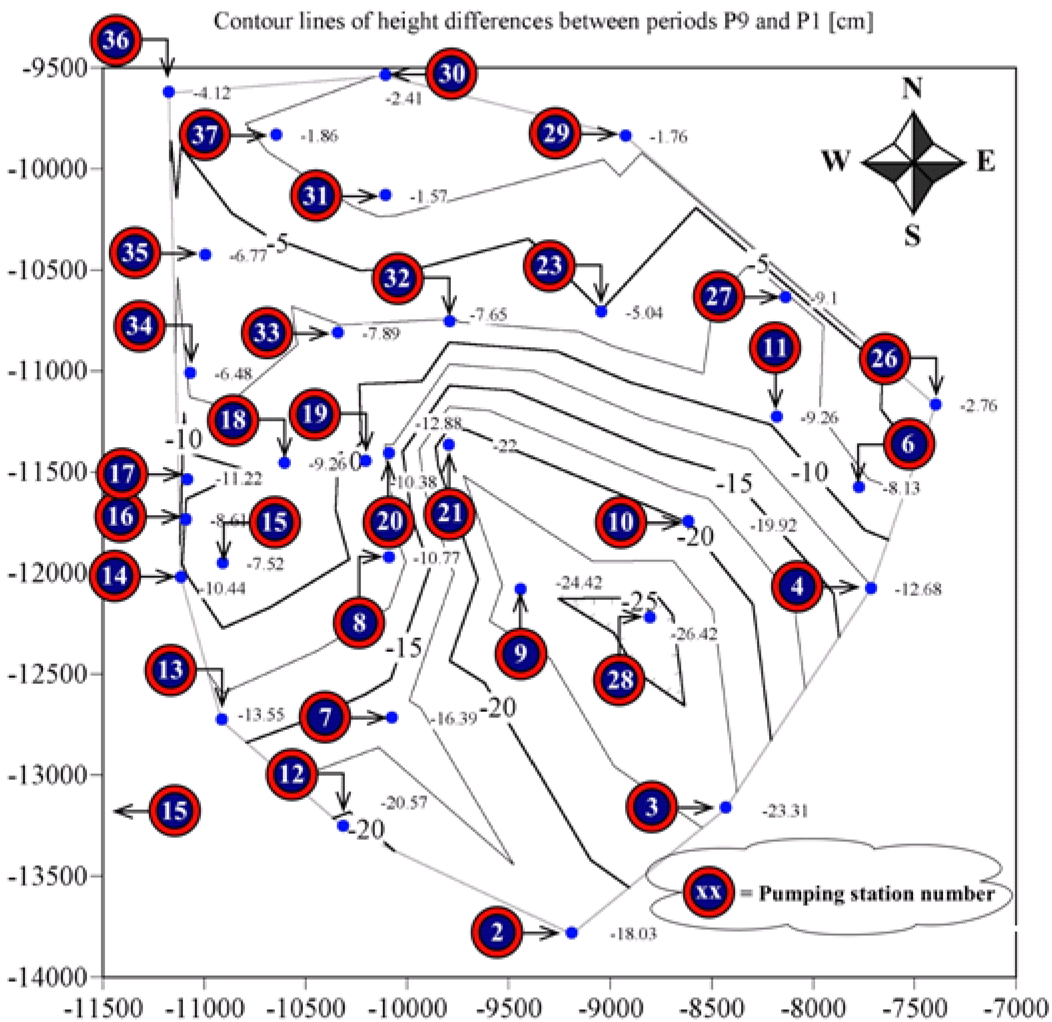

Figure 5: The stations of the control network and the subsidence contour lines (Between periods P9 and P1)

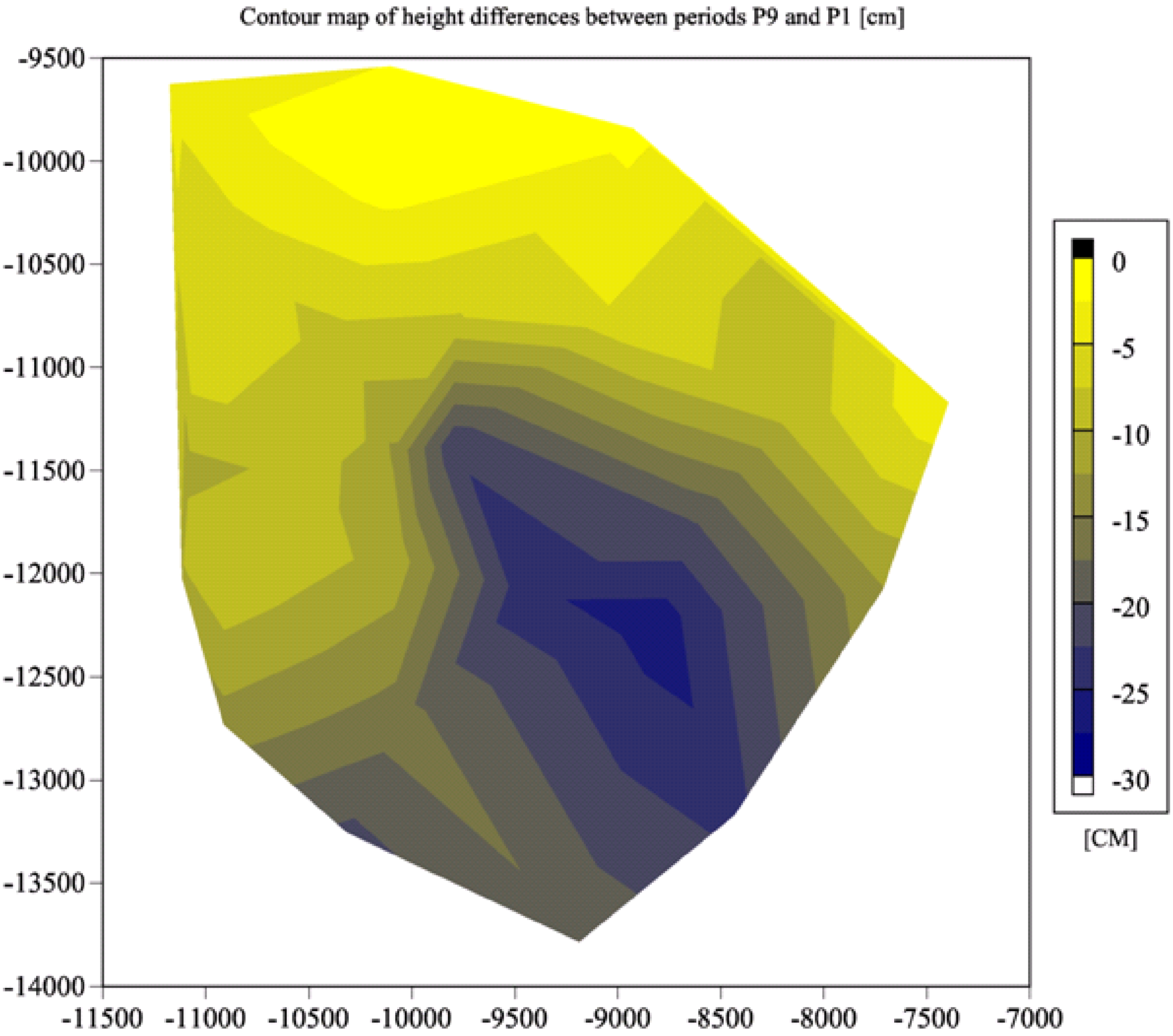

Figure 6: The subsidence between periods P9 and P1 (Contour map)

So far, the subsidence phenomena have a smooth distribution in the land area under investigation, with no differential settlements. But the West-South part shows intense subsidence formations and, if we take also into account that it contains a coastal zone along the embankment, there is a serious danger of inundation. Furthermore, the excessive water pumping could result into the reverse of the natural gradient. Such a hazard will cause the intrusion of sea water into the aquifer.

The leveling campaigns need to be continued for several years (at the autumn's beginning of every year), in relation with the establishment of a public control method to monitor the private water pumping. Additionally, more advanced techniques like GPS and GIS (Bitelli et al. 2000, Blodgett et al. 1990, Ge Li et al. 2001, Laboratory of Geodesy 1996) is planned to be applied, combined with the leveling campaigns, in order to expand the horizons of this research.

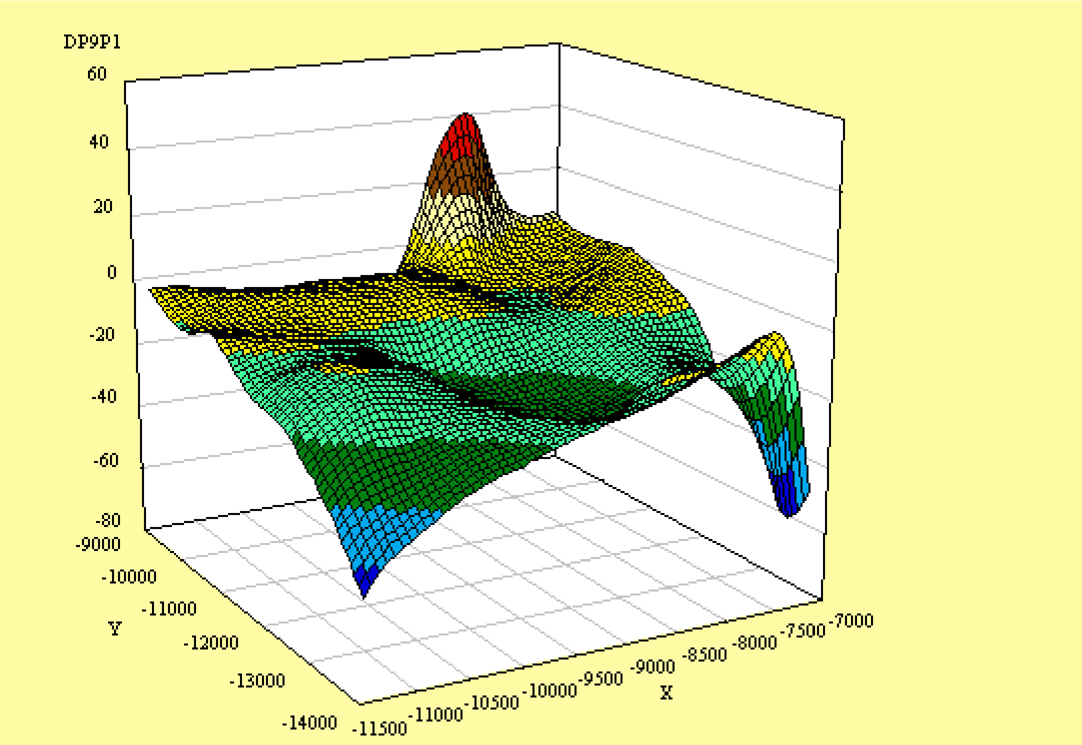

Figure 7: The subsidence between periods P9 and P1 (3D Contour map)

REFERENCES

Ajalloeian, R., Bahadoran, B. (1998). Ground subsidence due to percolating and pumping water (case studies in Iran). *The 19th Asian Conference on Remote Sensing*, November 16-20, 1998, Manila.

Amelung, F., Galloway, L. D., Bell W. J., Zebker A. H., and Laczniak J. R. (1999). Sensing the ups and downs of Las Vegas: InSAR reveals structural control of land subsidence and aquifer-system deformation. *Geology*, Volume 27, No. 6, p. 483-486.

Augarth, W. (1986). The determination of recent crustal movements in Western Europe. Recent state, problems and future activities. *Conference: Height determination and recent vertical crustal movements in Western Europe*, p. 475-485, Hannover.

Barbarella, M., Gubellini, A., Russo, P., and Vettore, A. (1986). Time series analysis by collocation on the vertical movements of the Asinelli Tower in Bologna. *Conference: Height determination and recent vertical crustal movements in Western Europe*, p. 687-702, Hannover.

Bitelli, G., Bonsignore, F., and Unguendoli, M. (2000). Leveling and GPS networks to monitor ground subsidence in the Southern Po Valley. *Journal of Geodynamics*, Volume 30, No. 3, p. 355-369, Elsevier Science Ltd.

Blodgett, J.C., Ikehara, M. E., and Williams, G.E. (1990). Monitoring land subsidence in Sacramento Valley, California, using GPS. *Journal of Surveying Engineering*, Volume 116, No. 2, p. 112-130.

Booker, J.R., Small, J.C., and Carter, J.P. (1985). Prediction of subsidence caused by pumping of groundwater. *21st Congress of the International Association of Hydraulic Engineering and Research*, p. 130-134, Melbourne.

Carpenter, M.C. (1993). Earth-fissure movements associated with fluctuations in ground-water levels near the Picacho Mountains, south-central Arizona, 1980-84. *Professional Paper 497-H*, US Geological Survey, p. 116.

Chen, C., Pei, S., and Jiao, J. (2003). Land subsidence caused by groundwater exploitation in Suzhou, China. *Hydrogeology Journal*, Volume 11, No. 2, p. 275-287, New York, Springer-Verlag.

Dripps, W. (2002). Global Water Issues, *Class Notes 9/24/02*, Department of Earth and Geographic Sciences, University of Massachusetts, Boston.

Epstein, V.J. (1987). Hydrologic and geologic factors affecting land subsidence near Eloy, Arizona. *Water-Resources Investigations Report 87-4143*, US Geological Survey, p. 28.

Fruneau, B., Sarti, F. (2000). Detection of ground subsidence in the city of Paris using radar interferometry: isolation of deformation from atmospheric artifacts using correlation. *Geophysical Research Letters*, Volume 27, No. 24, p. 3981-3984.

Galloway L., D., Phillips, S. P., and Ikehara, M. E. (1995). Land subsidence and its relation to past and future water supplies in Antelope Valley, California. Land subsidence: Case histories and current research. *Proceedings of the Dr. Joseph F. Poland Symposium*, California, Special Publication No. 8, Star Publishing Company, Belmont CA.

Ge Li., Chang, Hs., Janssen, V., and Rizos, C. (2001). Integration of GPS, radar interferometry and GIS for ground deformation monitoring. Satellite Navigation And Positioning Group, p. 8, School of Surveying and Spatial Information Systems, The University of New South Wales

Holzer, T.L., Davis, S.N., and Lofgen, B.E. (1979): Faulting caused by groundwater extraction in south-central Arizona. *Journal of Geophysical Research*, Volume 84, No. B2, p. 603-612.

Jones L., Larson, J. (1975). Economic effects of land subsidence due to excessive groundwater withdrawal in the Texas gulf coast area. *Technical Report No. 67*, Texas Water Resources Institute, Texas ARM University.

Laboratory of Geodesy (1996). Monitoring of ground subsidence in the area of Kalohori by using a high precision leveling control network. *Technical Report No. 2853*, Research Committee, Aristotle University of Thessaloniki, p. 157.

Leonhard, Th., Niemeier, W., and Pelzer, H. (1983). Determination of vertical crustal movements from different regional levelings. *Workshop on Precise Leveling*, Hannover, p. 451-466.

Metzger, F. L., Ikehara, M. E., and Howle, F. J. (2001). Vertical-deformation, water-level, microgravity, geodetic, water-chemistry, and flow-rate data collected during injection, storage, and recovery tests at Lancaster, Antelope Valley, California, September 1995 through September 1998. U.S. Geological Survey, *Open-File Report 01-414*, p. 159.

Najjar, Y., Zaman, M. (1993). Surface subsidence prediction by nonlinear finite-element analysis. *Journal of geotechnical engineering-ASCE*, Volume 119, No. 11, p. 1790-1804.

Ng, C., Mei, C. (1995). Ground subsidence of finite-amplitude due to pumping and surface

loading. Water Resources Research, Volume 31, No. 8, p. 1953-1968.
Ngecu, W. M., Nyambok, I. O. (2000). Ground subsidence and its socio-economic implications on the population: a case study of the Nakuru area in Central Rift Valley, Kenya. *Environmental Geology*, Volume 39, No. 6, p. 567-574.
Poland, Joseph F. (1984). Guidebook to studies of land subsidence due to ground-water withdrawal. *International Hydrological Programme Working Group 8.4*, Unesco, Studies and Reports in Hydrology No. 40, p. 305, Paris.
Savvaidis, P. (1992). Program NetS for the adjustment of geodetic control networks, *Scientific Papers of the School of Technology*, Aristotle University of Thessaloniki, Thessaloniki, Greece.
Sneed, M., Ikehara, M. E., Galloway L. D., and Amelung, F. (2001). Detection and Measurement of Land Subsidence Using Global Positioning System and Interferometric Synthetic Aperture Radar, Coachella Valley, California, 1996-98. *Water Resources Investigation Report 01-4193*, U.S. Geological Survey, p. 31.
Sneed, M., Stork, S.V., and Galloway L. D. (2002). Detection and Measurement of Land Subsidence Using Global Positioning System and Interferometric Synthetic Aperture Radar, Coachella Valley, California, 1998-2000. *Water Resources Investigation Report* 02-4239, U.S. Geological Survey, p. 31.
Vanicek, P., Krakiwsky, E.J. (1982). *Geodesy, the concepts*. North Holland.
Van Mierlo, J. (1975): Statistical analysis of geodetic networks designed for the detection of crustal movements. Book: *Progress in Geodynamics*, p. 52-61, North Holland Publ. Co.
Watt, I. (1981). Absolute datum selection and the representation and interpretation of subsidence in dolomitic mining areas, heaving clays and major structures sited in soil foundations. *2nd International Symposium of Deformation Measurements by Geodetic Methods*, Bonn, Germany, p. 589-603.

BIOGRAPHICAL NOTES

Ioannis D. Doukas
Assistant Professor in the Laboratory of Geodesy at the Department of Civil Engineering of the Aristotle University of Thessaloniki. Main interests: Geographic Information Systems, deformation of buildings and technical works, neural networks, system dynamics, data mining, image processing, 3D modeling-rendering, video processing-post production, electronic document processing systems.

Ioannis M. Ifadis
Associate Professor in the Laboratory of Geodesy at the Department of Civil Engineering of the Aristotle University of Thessaloniki. Main interests: Influence of the atmosphere on geodetic measurements, Global Positioning System, Geographic Information Systems, deformation of buildings and technical works.

Paraskevas Savvaidis
Professor and Director of the Laboratory of Geodesy at the Department of Civil Engineering of the Aristotle University of Thessaloniki. Main interests: Engineering surveying, GPS applications, Geographic Information Systems, deformation of buildings and technical works, software development for surveying applications.

CONTACTS

Ass. Professor Ioannis D. Doukas
Aristotle University of Thessaloniki
Univ.Box 465
GR-54124 Thessaloniki
GREECE
Tel. + 30 2310 995725
Fax + 30 2310 996159
jdoukas@civil.auth.gr

Asc. Professor Ioannis M. Ifadis
Aristotle University of Thessaloniki
Univ.Box 465,
GR-54124 Thessaloniki
GREECE
Tel. +30 2310 995745
Fax + 30 2310 996159
ifadis@civil.auth.gr

Professor Paraskevas Savvaidis
Aristotle University of Thessaloniki
Univ.Box 465,
54124 Thessaloniki
GR-GREECE
Tel. + 30 2310 995724
Fax +3 0 2310 996159
psav@civil.auth.gr
http://gserver.civil.auth.gr