THE ISES PROJECT SUBSIDENCE MONITORING OF THE CATCHMENT BASIN SOUTH OF THE VENICE LAGOON (ITALY)

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Abstract

The catchment located south of the Venice Lagoon experienced during the last century a general land settlement owing to groundwater pumping, oxidation of organically rich soils enhanced by agricultural activities, and natural sediment compaction. High land subsidence rates (2-4 cm/year) have been estimated in the area comprised between the lagoon edge and the Adige River and located between two leveling lines of the Italian national network (IGM lines n° 7 and n° 19). Only a partial knowledge on the behavior of land elevation is available in this region. To overcome this lack of information, a new fine leveling and GPS network has been established in the area within the *ISES* Project funded by National/Local water and administrative Authorities. The first field measurement carried out in 1999 have produced as a major result an accurate knowledge of the geoid height in this part of the Po River plain and has pointed out the stability of the area located along the lagoon boundaries during the six-year period from 1993 to now.

Keywords: Leveling, GPS, southern Venetian catchment, land subsidence.

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1. INTRODUCTION

The regulation of groundwater exploitations from the Venetian multiaquifer system started in 1970 induced a very fast recovery of the piezometric levels along with a remarkable slowing down of the ensuing subsidence definitely ascertained in 1973 (Carbognin *et al*., 1976). A high precision leveling survey carried out in 1993 confirmed the arrest of the anthropogenic subsidence in Venice and its surroundings, and concurred to evaluate the natural subsidence rates for the Venetian region (Carbognin *et al*., 1995a; 1995b). Results of the 1993 survey have also shown that land subsidence is still in progress with a 1-2 mm/year rate in the southern and northern lagoonal areas and in the nearby mainland. The littoral and lagoon extremities are subject to the consolidation process of the recent river delta progradations caused by the fluvial sedimentary loads and to the residual compaction of the highly compressible marine-lagoonal Holocene clayey and silty layers.

The mainland and the lagoon margins, that before this century were wetlands (salt and fresh water marshes and swamps), are now reclaimed areas intensively used for agricultural activities and characterized by highly organic soils. Subsidence of coastal lowlands with these environmental features is mainly caused by the loss of organic matter due to peat oxidation (Rojstaczer and Deverel, 1995; Deverel and Rojstaczer, 1996).

Land subsidence has increased the vulnerability and the geological hazard of these areas, a large portion of which lies below the mean sea level, and are crossed by watercourses whose water level is above the surrounding ground surface. River flooding, riverbank stability, and intrusion of seawater in the aquifer system are the main hydrogeological problems. In particular, the loss in elevation has increased the requirement of pumping to maintain the subsiding lands free of inundation with a consequent increase of the saltwater intrusion in the coastal aquifer and river systems. Moreover, land settlement has contributed to deteriorating of the littoral sectors with a general coastline regression and an increment of the sea bottom slope close to the shoreline (Carbognin *et al*., 1995a).

ISES, *i.e.*, Saltwater Intrusion and Land Subsidence, is a project started in 1999 to accurately quantify and control saltwater intrusion and land settlement in the basin south of the Venice Lagoon (Figure 1). The project is supported by the Public Agencies that manage this part of the Veneto Region. ISES has instituted in 1999 a new fine leveling and GPS network connected to the more stable Euganean Hills to measure the vertical movement of this area. The network configuration, with the superimposition of a traditional leveling and a GPS network (with one GPS benchmark every 5 leveling benchmarks), has been planned so that in the future every Local Agency will be able to independently control its territory within an homogenous framework.

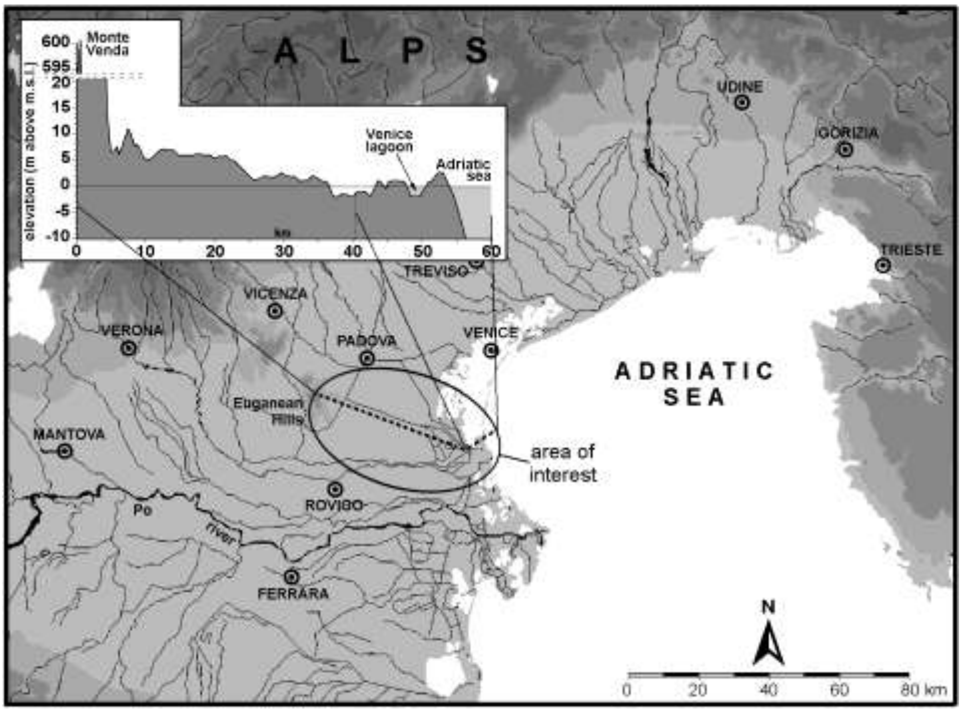

Figure 1. Location of the area of interest in the Eastern Po plain with a vertical cross section showing the elevation above the mean sea level.

After a short overview on the historical subsidence measurements performed in the study area, the present work describes the main characteristics of the new ISES controlling network and gives some preliminary results obtained at the end of the first field measurements.

2. OVERVIEW ON LAND SETTLEMENT MEASUREMENTS IN THE STUDY AREA

Ground vertical movements in the central-southern part of the Veneto Region have been measured with sufficient accuracy and reliability since the end of the previous century with different National and Local Agencies involved in the monitoring effort. However, leveling surveys have been carried out only along the east and west boundaries of the study area (*i.e.*, along the coast and the lagoon edges, and in the Euganean area and along the National Route 16 "Adriatica" connecting Padova and Rovigo, respectively), usually assuming as reference stable position a benchmark located in Treviso some 20 km north of Venice (Figure 1).

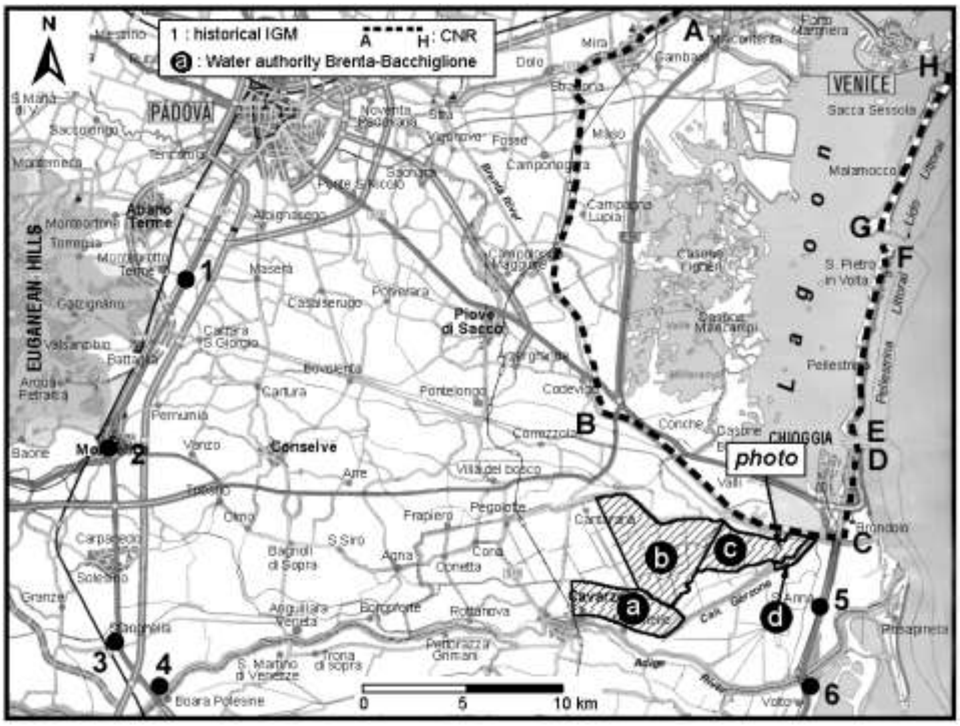

Figure 2: Locations in the study area where land subsidence measurements have been carried out in the past.

The first IGM (Military Geographic Institute) leveling was made in 1884/87-1897 in a number of reference points of the national topographic network, and other surveys followed in 1942/47-1951 and every 5-10 years during the last half century (Salvioni, 1957; Bondesan *et al.*, 1997). Unfortunately, most of the 1884/87-1897 network benchmarks were missing and only six reference points, shown in Figure 2, were leveled in the following surveys. Their subsidence rates are presented in Table 1. Higher rates occurred from 1970 to 1986 at point 1 due to thermal water exploitation from the Euganean basin (Gottardi *et al.*, 1995), and from 1950 to 1970 at positions 6 and 5 (to a lesser extent) for their closeness to the Po River delta where a huge amount of gas-bearing water was pumped during that period (Caputo *et al.*, 1970).

Periodic leveling measurements were carried out during the last 30 years in the Venice Lagoon and its hinterland by the CNR (National Research Council) (Carbognin *et al.*, 1976; 1994). The available information is summarized in Figure 3. Figure 3a shows the changes in land-surface elevation along the leveling line A-C of Figure 2 (from Mestre surrounding the lagoon towards the South) assuming the IGM 1951 as reference survey. The first leveling for the entire littoral strip was carried out in 1968 (Figure 3b), and only for the Lido littoral a previous measurement (in 1961) is available. Inspection of Figure 3 reveals the higher subsidence rate during the period 1960-1970 due to groundwater withdrawal at Porto Marghera for industrial use, at Lido for tourism needs, and in the Chioggia-Brondolo area for the superimposition of several causes such as a higher natural compaction rate, sediment loss due to oxidation and water pumping for drinking and agricultural purposes. The subsidence peak pointed out by all the measurements between points B and C (Figure 3a) is anomalous and its causes are currently under investigation.

Besides the National Agencies, also the Local Water Management Authorities ("Consorzi di bonifica") have established during the last century few leveling networks to control major hydraulic structures such as watercourse embankments and pumping stations. Leveling surveys were carried out in 1916, 1929, 1935, 1941, and 1965 in the area comprised between the lagoon and the Adige River (Consorzio di Bonifica Adige-Bacchiglione, 1996), but their results are difficult to use and compare because different and unstable reference benchmarks were adopted. Nevertheless, since the area has experienced a high rate of land subsidence mainly related to peat oxidation, as it is supported by the evidences of the disastrously lowering of the territory (Figure 4), these data are useful for a qualitative analysis. This is done by comparing the local leveling output with the ground elevation of the 1983 Regional Topographic Map (scale 1:10000) obtained by aerial photogrammetry. The average subsidence rate obtained for the 4 sub-basins shown in Figure 2 is given in Table 2. Due to the inaccuracy introduced in the elevation assessment, the error associated to the Table 2 values can be estimated in ±1 cm/year.

Table 1. Subsidence rate (cm/year) at the IGM benchmarks of Figure 2.

	Point			
Period	1	2	3	4
1884-1947	0.5	0.3	0.4	0.4
1947-1970	0.7	0.0	0.2	1.0
1970-1986	1.6	0.1	0.0	0.1

	Point	
Period	5	6
1897-1951	0.5	0.7
1951-1956	1.1	9.3
1956-1958	1.7	16.3
1958-1970	1.3	3.7
1970-1977	0.7	0.6
1977-1988	0.4	0.5

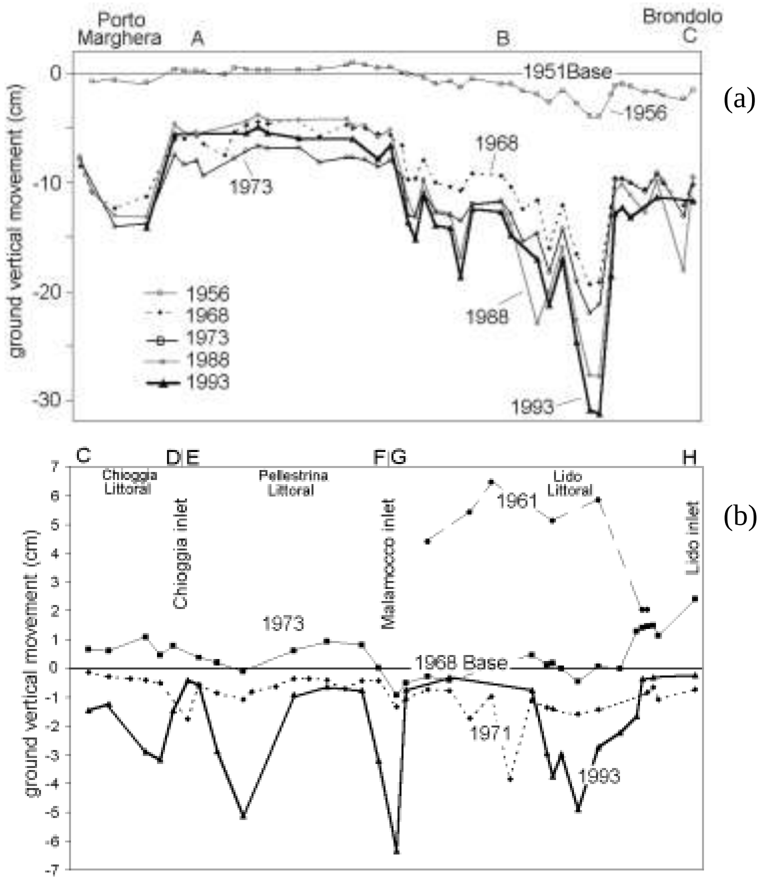

Figure 3. Ground vertical movement obtained from IGM/CNR leveling surveys (a) along the south-western boundary of the Venice Lagoon (dashed line A-C, Figure 2) and (b) along the Chioggia, Pellestrina, and Lido littorals (dashed line C-H, Figure 2).

Table 2. Average land subsidence rate in the 4 sub-basins shown in Figure 2 estimated from the Regional Topographic Map and the leveling surveys carried out by the Local Water Management Authorities (after Consorzio di Bonifica Adige-Bacchiglione (1996)).

Zone	Leveling survey (year)	Land subsidence rate (cm/year) up to 1983
a	1935	1.9
b	1965	2.7
c	1929	2.6
d	1941	3.5

Figure 4. An old bridge constructed in the Twenties whose foundation protrudes about 150 cm owing to land subsidence caused by peat oxidation and groundwater exploitation. In the background, the newer bridge today in use reveals a subsidence of about 50 cm during the last 30 years. The location of the photo is given in Figure 2.

3. ISES LEVELING NETWORK

The ISES Project has established during the 1999 a new refined leveling network in the eastern part of the Po Plain comprised between the Venice Lagoon and the Adige River with the purpose of efficiently controlling the vertical movements of this area where, aforementioned, precise leveling measurements have been carried out in the past only along its boundaries (Figure 2).

The area covered by the network (Figure 5) extends between the alignment Lova - Piove di Sacco - Pontelongo in the north-west direction and the conclusive part of the Adige River southward, and is bounded eastward by the Adriatic coastline from the Adige mouth to Chioggia and the Venice Lagoon. This low-lying area is connected to the southeastern part of the Euganean Hills through the lines that from Pontelongo and Borgoforte reach Battaglia Terme. This latter is linked to Monte Venda and to the thermal resort area of Galzignano, Abano, and Montegrotto where stable reference marks on rock of the Veneto Region are located. Moreover, new benchmarks have been instituted in the lagoonal areas of Valle di Millecampi, Conche, Valli, and along the CNR monitoring lines of Pellestrina and Lido littorals. The existing benchmarks of IGM, CNR, Veneto Region and Consorzio di Bonifica Adige Bacchiglione have been included in the network.

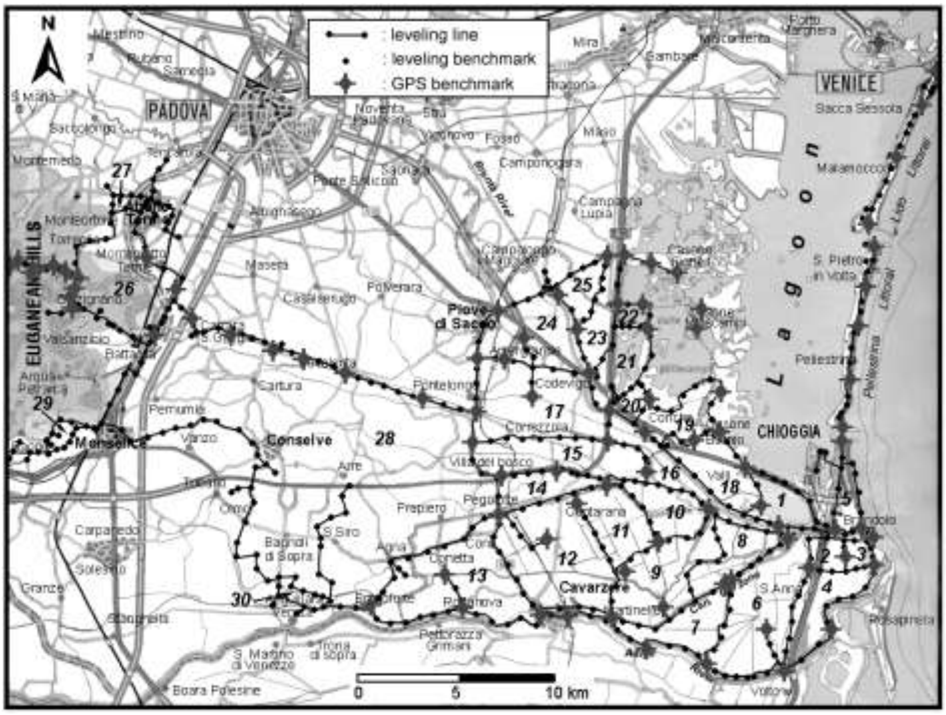

Figure 5. The ISES leveling network and GPS benchmarks.

Table 3. Length of the polygons of the ISES leveling networks. Polygon numeration is given in Figure 5.

Polygon	Length (km)	Polygon	Length (km)
1	19.523	16	29.527
2	9.941	17	24.762
3	10.023	18	17.104
4	23.031	19	18.750
5	12.078	20	10.146
6	33.412	21	17.367
7	30.321	22	7.190
8	22.035	23	18.837
9	25.650	24	19.044
10	20.057	25	13.634
11	16.323	26	27.144
12	24.588	27	7.806
13	34.122	28	80.602
14	16.533	29	8.594
15	27.677	30	9.305

3.1. Geometric leveling network

A total amount of 568 benchmarks, 346 of new installation, have been connected by a leveling network about 522 km long. The network is composed of 42 lines forming 30 closed polygons (Figure 5 and Table 3), with the distance between benchmarks along the different routes averaging 900 m.

The lines have been located along the road and watercourse networks, with a benchmark always placed in the nodal positions, *i.e.*, where two lines or more concur, and in the center of polygons ("*centrimaglia*").

The first leveling of the entire network has been carried out in 1999 in accordance with the guidelines issued by IGM relating to measurement methods and tolerance for high accuracy leveling survey.

3.2. Global Positioning System network

The GPS network is composed of 93 benchmarks with an optimal ratio of 1/5 between the GPS and geometric measurement points. All the nodal and the "*centrimaglia*" benchmarks have been used as GPS stations, and a number of benchmarks have been located on the stable Euganean Hills to be used in the future as reference positions for different and hence more checkable and reliable survey schemes.

GPS measurements has been performed in 1999 following the FGCC (Federal Geodetic Control Committee) guidelines that prescribe for the AA (high precision) GPS network the triple occupation of 80% of the network benchmarks. The DGPS (Differential GPS) technique has been implemented using as reference point the IGM'95 benchmark of Arzergrande (Figure 5) which is located in a quite central position of the study area, and whose WGS-84 coordinates and height are available. The survey has been carried out connecting the benchmarks by a number of intersecting and redundant baselines (Figure 6) and considering as points of strategic relevance few nodal or "*centrimaglia*" benchmarks with an optimal visibility. These benchmarks have been used as reference points for local sub-networks, each of them characterized by short baselines of similar length, and connected by longer baselines measured by dual frequency receivers with prolonged observing sessions. During the survey of the Lido and Pellestrina littorals, the ISES benchmarks have also been connected to the permanent GPS station of the Italian Space Agency located in Venice. The target accuracy of one part per million has been reached with excellent repeatibility using both broadcast and precise ephemeris.

4. PRELIMINARY RESULTS

Since the ISES leveling and GPS networks have been established in 1999 and only the first reference measurement has been carried out, only preliminary results are currently available.

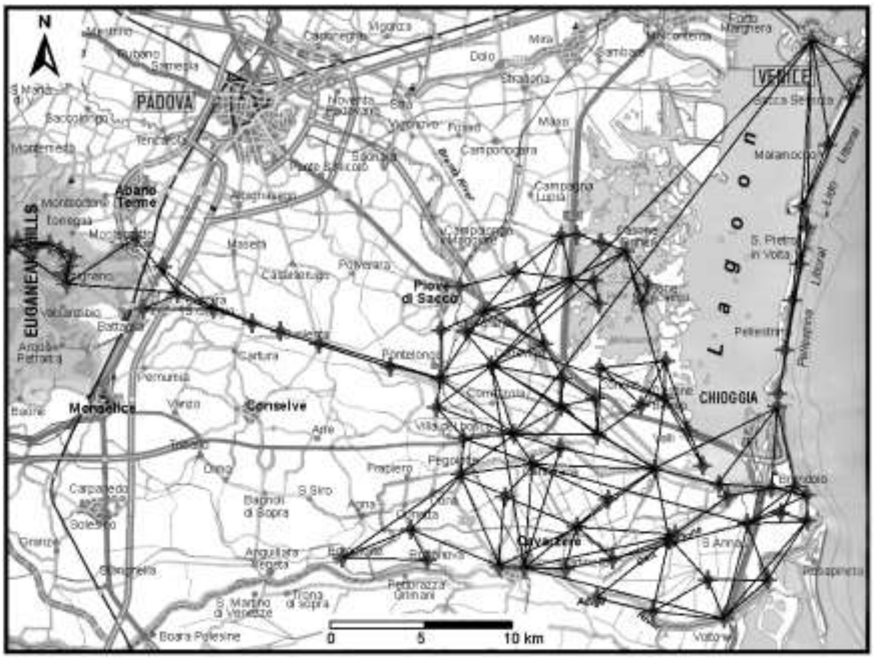

Figure 6. Sketch of the baselines measured during the 1999 GPS survey of the ISES network.

4.1. Geoid height in the ISES area

A result that the first leveling and GPS surveys have made available is a more accurate geoid undulation (or height) N in the ISES area than that given in the literature (Caporali *et al.*, 1989; Barzaghi *et al.*, 1996; Barbarella *et al.*, 1998). The difference between the WGS-84 ellipsoid altitude measured by GPS and the topographical altitude (with respect to the elevation reference of the IGM network, *i.e.*, the mean sea level at the Genoa tidal gauge in 1942) provided by leveling has been computed for all the 93 GPS benchmarks of the ISES network.

For the central part of the study area, where the zone benchmark distribution is homogenous, a local model of the geoid undulation has been computed interpolating the scattered data by the quadratic function:

$$N(x,y) = 39.9315 - 0.0305302\cdot x + 0.101398\cdot y - 0.00029785\cdot xy + \\ + 0.000403801\cdot x^2 - 0.00045003\cdot y^2$$

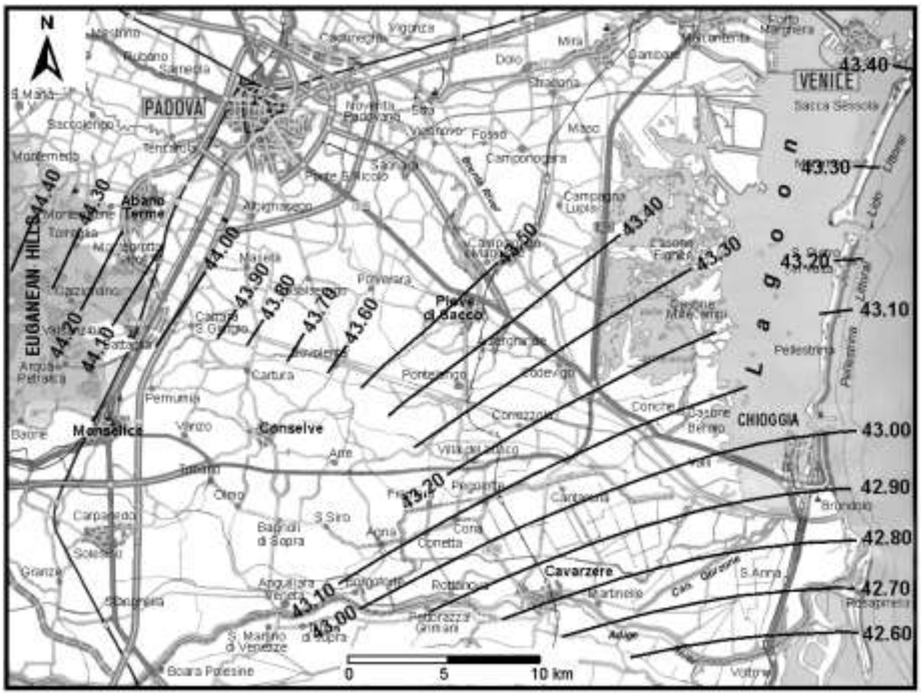

Figure 7. Geoid undulation (m) in the area covered by the ISES Project.

where [N]=m, and x and y are the east and north Gauss-Boaga (East fuse, [x,y]=km) coordinates of the generic point, decreased by the constants X=2250 km and Y=4950 km, respectively. The high accuracy of this model is confirmed by the low residuals in the measured positions, always less than 2 cm in modulus. A contour line map of the above model is given in Figure 7, where the geoid height directly obtained by the measurements along the littoral strips and the line connecting the lagoon mainland to the Euganean Hills is also shown.

4.2. Actual land subsidence of the Venice Lagoon boundary

The ISES network has been connected within a project funded by the Venice Water Authority, Consorzio Venezia Nuova, to the IGM/CNR leveling lines surrounding the lagoon and reaching a stable area at the Alpine foothills north of Treviso.

Comparative plots of the leveling profiles of the lagoon boundary from Porto Marghera to Brondolo and of the littoral strips are given in Figure 8. Except for a sector between positions B and C (Figure 2), the vertical movement rate of the lagoon boundary is less than 0.3 cm/year (Figure 8a) and the overall line (A-C) shows a surprisingly similar behavior with the 1951-1956 profile given in Figure 3a. Inspection of Figure 8b reveals more stability of the littoral strips than in the past (Carbognin *et al*., 1995a), with altimetrical movement lower than 1 cm. In particular, the Chioggia littoral seems stable, while the Pellestrina littoral shows positive and negative movements in the lagoonal and sea side, respectively. These oscillations could be related to the huge restoration works carried out both along the sea shore and, to a lesser measure, the lagoon shore during the last 10 years. The movement of the central zone of the Lido littoral confirms the settlement trend pointed out in 1993 (Figure 3b).

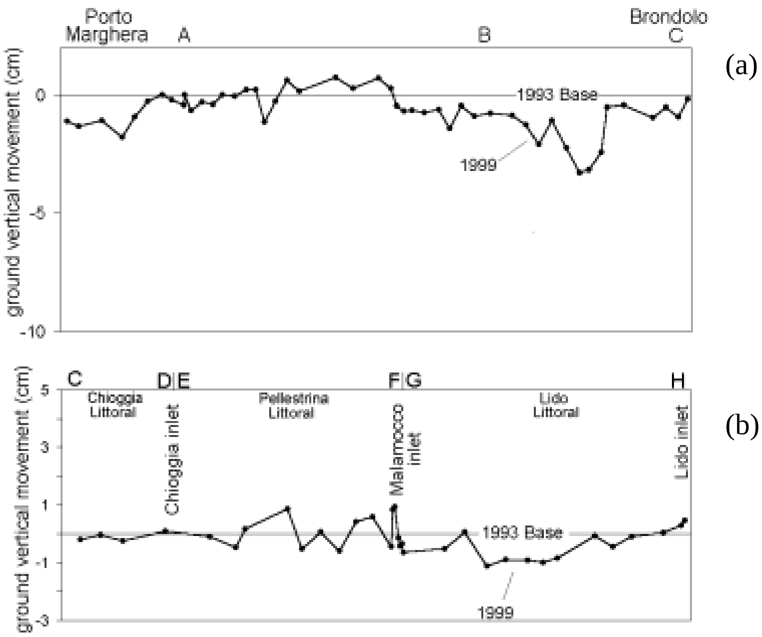

Figure 8. Ground vertical movement between 1993 and 1999 (a) along the south-western boundary of the Venice Lagoon (dashed line A-C, Figure 2) and (b) along the Chioggia, Pellestrina, and Lido littorals (dashed line C-H, Figure 2).

5. CONCLUDING REMARKS

From the knowledge about land settlement in the overall region of Venice and its hinterland, it clearly emerged that the southern and northern lagoon extremities are the more precarious areas. In particular, the most serious condition presently exists in the catchment between the lagoon and the Adige River where the loss in ground elevation has increased the hydrogeological hazard (saltwater intrusion, river bank stability, river overflow). This zone is generally below mean sea level and problems related to agricultural activities and ensuing socio-economic damages have become more and more serious.

In 1999, the three-year, ISES Project was started with the aim of improving the monitoring of land subsidence and saltwater intrusion in this part of the Po plain by the institution of *ad hoc* networks. To address the demand of the Local Authorities a new refined leveling and GPS network has been established and connected to the more stable area of the Euganean Hills. The network is 568 km long and is composed of 522 benchmarks, 93 of which are used for GPS measurement.

The first geodetic survey carried out in the second half of 1999 constitutes the reference base for the feature leveling and GPS measures in the overall area. Comparison with the 1993 survey along the leveling IGM/CNR routes already existing around the Venice Lagoon has provide a first partial estimate of the present land subsidence rate. Moreover, as preliminary result, a very accurate reconstruction of the geoid undulation has been performed using GPS and leveling output.

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REFERENCES

Barbarella, M., Bianco, A., Carella, P., & Fiani, M. (1998) Ondulazione sperimentale e prevista lungo la costa della Penisola Italiana. *Rivista del Dipartimento del Territorio*, **1**, 25-42.

Barzaghi, R., Brovelli, M. A., Sona, G., Manzino, A., Sanso' F., & Sguerso, D. (1996) The new Italian Quasi-Geoid: ITALGEO95. *Bollettino di Geodesia e Scienze Affini*, n.1/96.

Bondesan, M., Gatti, M., & Russo, P. (1997) Movimenti verticali del suolo nella Pianura Padana orientale desumibili dai dati I.G.M. fino a tutto il 1990. *Bollettino di Geodesia e Scienze Affini*, **LVI**(2), 141-172.

Caporali, A., Dallaporta, G., Marzari, F., Rusconi, A., Curiotto, S., Facchinelli, F., & Zambon, G. (1989) Rete geodetica GPS in territorio veneziano. In: *3° Conv. Nazionale AIT*.

Caputo, M., Pieri, L., & Unguendoli, M. (1970) Geometric investigation of the subsidence in the Po delta. *Bollettino di Geofisica Teor. e Appl.*, **XIII**(47), 187-207.

Carbognin, L., Gatto, P., Mozzi, G., Gambolati, G., & Ricceri, G. (1976) New trend in the subsidence of Venice. In: *Land Subsidence – Proc. II Int. Symp. on Land Subsidence,* IAHS Publ. No. 121, 65-81.

Carbognin, L., Marabini, F., Taroni, G., Teatini, P., & Tosi, L. (1994) *Altimetria recente del comprensorio lagunare Veneziano. Un'analisi critica*. Technical Report n. 193, 32pp., CNR-ISDGM, Venezia.

Carbognin, L., Marabini, F., & Tosi, L. (1995a) Land subsidence and degradation of the Venice littoral zone, Italy. In: *Land Subsidence - Proc. V Int. Symp. on Land Subsidence* (ed. by: F. B. J. Barends *et al*.,) , IAHS Publ. No. 234, 391-402.

Carbognin, L., Tosi, L., & Teatini, P. (1995b). Analysis of actual land subsidence in Venice and its hinterland (Italy). In: *Land Subsidence - Proc. V Int. Symp. on Land Subsidence* (ed. by: F. B. J. Barends *et al*.,) , A. A. Balkema, Rotterdam, 129-137.

Consorzio di Bonifica Adige-Bacchiglione (1996) *Studio del fenomeno della subsidenza nei bacini Orientale, Zennare, Punta Gorzone e Foresto Centrale, ricadenti nel comprensorio consorziale*. Relazione Tecnica, 37pp.

Deverel, S. J., & Rojstaczer, S. (1996) Subsidence of agricultural lands in the Sacramento – San Joaquin Delta, California: Role of aqueous and gaseous carbon fluxes. *Water Resour. Res.*, **32**(8), 2359-2367.

Gottardi, G., Previatello, P., & Simonini, P. (1995) An extensive investigation of land subsidence in the Euganean geothermal basin, Italy. In: *Land Subsidence - Proc. V Int. Symp. on Land Subsidence* (ed. by: F. B. J. Barends *et al*.,) , IAHS Publ. No. 234, 21-30.

Rojstaczer, S., & Deverel, S. J. (1995) Land subsidence in drained histosols and highly organic mineral soils of California. *Soil Science Society of America Journal*, **59**, 1162-1167.

Salvioni, G.(1957) I movimenti del suolo nell'Italia centro-settentrionale. Dati preliminari dedotti dalla comparazione di livellazioni. *Bollettino di Geodesia e Scienze Affini*, **XVI**(3), 325-366.