

A new project to monitor land subsidence in the northern Venice coastland (Italy)

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Abstract The paper deals with the implementation of a levelling and Global Positioning System (GPS) network to control land subsidence in the coastal area north of the Venice Lagoon. About 480 km of levelling lines with 527 benchmarks, 45 of which suited for Differential GPS measurements, were established in 2004. A complete survey of the net was carried out in 2004 soon after its establishment. The 2004 records have been compared with previous scattered data obtained by the use of levelling surveys, DGPS and SAR interferometry. The results show a trend in land settlement that increases from the lagoon margin to the north and jeopardize the Venice coastland. Groundwater withdrawals for domestic, agricultural, and health spas uses, peat oxidation of reclaimed marshlands for farming, natural consolidation of the Holocene deposits, and tectonics of the pre-Quaternary basement are the causes of land subsidence in the study area. Since most of the area lies below the mean sea level and on account of the expected sea level rise due to global change, a detailed monitoring of land displacements in the near future will be of paramount importance to plan necessary works for coastland protection.

Keywords Land subsidence monitoring · Levelling · GPS · Data integration · Venice coastal area (Italy)

Introduction

Many maps showing the extent and the occurrence of land subsidence in Venice and the surrounding lagoon over the last 50 years were drawn using the surveys on a levelling network formed by a few lines around the lagoon margins and along the littoral strips and of a fine grid covering the historical center (Fig. 1). This network was established to control the sinking of the Venice area that had accelerated since the early 1950s due to the large groundwater withdrawal related to the post-war industrial boom on the mainland and tourist development on the shoreline. The maximum subsidence rate in Venice reached 5 mm/year during the 1960s and then significantly decreased after 1970 because of the reduction of water withdrawals (Carbognin et al. 1977).

The map of subsidence rates observed from 1973 to 1993 (Fig. 2a) confirmed the effectiveness of the groundwater regulation with the stability or at least a significant reduction of the subsidence velocity in the Marghera industrial zone, in Venice, and at the Lido littoral (Carbognin et al. 1995a, b; Carbognin and Tosi 1995, 2002; Teatini et al. 1995).

On the contrary, a significant land settlement was observed around the southern and the northern lagoon extremities, the two portions of the Venice coastland characterized by the lowest land elevation, usually below the mean sea level (down to -4 m) and where subsidence was never accurately monitored. The historical levelling network was extended in the southern Venice watershed in 2000 within the ISES Project (the

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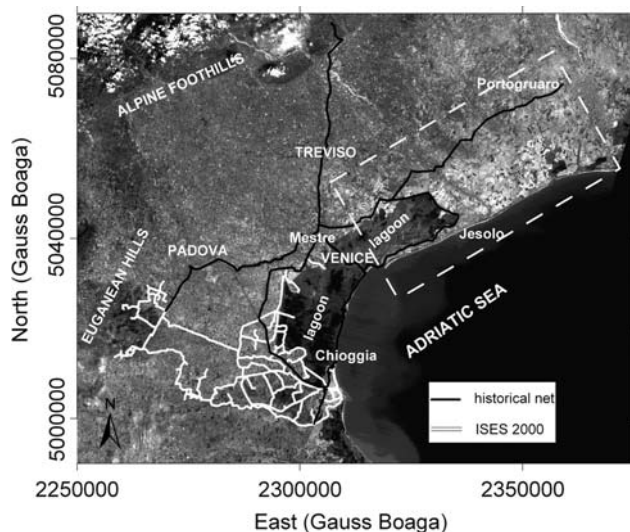


Fig. 1 Map of the levelling network in the Venice area before 2004. The historical lines used in the last century are colored in *black* and the network established in 2000 by the ISES Project in *white*. The *dashed box* on the north-east represents the IRMA study area

Italian acronym for Salt Water Intrusion and Land Subsidence) (Fig. 1). The new monitoring network with a total length of about 520 km was composed of about 600 benchmarks, 119 of which were used both for levelling and for DGPS surveys (Tosi et al. 2000, 2002; Carbognin and Tosi 2003; Carbognin et al. 2004). Analysis of the displacements recorded between 1993 and 2000 confirmed the subsidence trends previously detected over the 1973–1993 period (Fig. 2b).

Beginning in 2001, a research project known as the VENEZIA Project (Strozzi et al. 2003c) was carried out with the goal of planning a subsidence monitoring service in the Venice region for the regional administrations and water authorities. Differential SAR Interferometry (InSAR) and Interferometric Point Target Analysis (IPTA) were integrated with levelling and GPS measurements. The SAR-based measurements

pointed out that the built-up centers located in the coastal plain between the north lagoon margin and the Tagliamento River experienced a settlement rate up to 5 mm/year over the period 1992–2000 (Fig. 3) (Strozzi et al. 2003a, b, c, 2005).

The combination of the ISES and VENEZIA project measurements revealed the necessity to extend the subsidence network to the northern Venice watershed, an area not adequately covered by a geodetic monitoring net (Carbognin et al. 2005a).

This paper describes the characteristics of the subsidence monitoring network established in this portion of the Venice coastland in 2004 within the IRMA Project (i.e. the Italian acronym of Integration of the ISES subsidence Monitoring Network). We also provide the last updates concerning the vertical ground-movement in this area characterized by the presence of a significant historical heritage (e.g., Concordia Saggittaria), resort villages known all over Europe (e.g., Jesolo, Lido), well-preserved natural environments (e.g., the northern Venice Lagoon), and an intensely cultivated farmland (Provincia di Venezia 1983; Consorzio di bonifica Pianura Veneta tra Livenza e Tagliamento and Provincia di Venezia 2001).

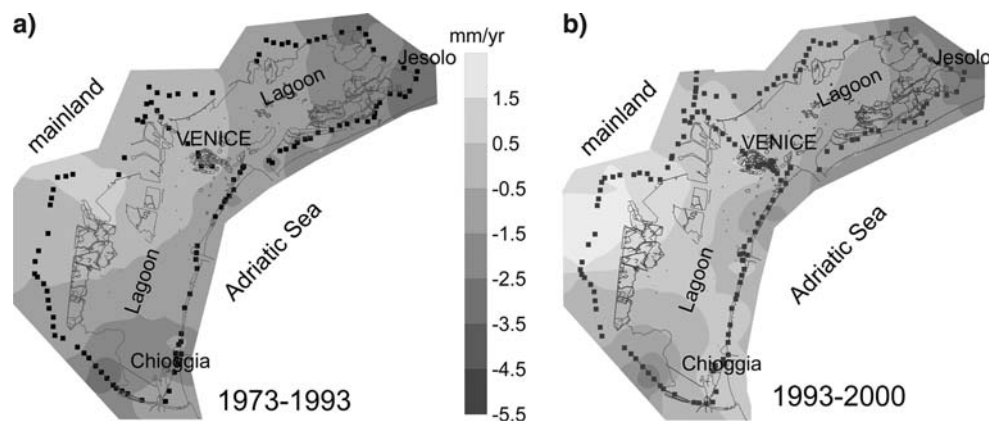
The IRMA subsidence monitoring network

The IRMA subsidence monitoring network extends the ISES net to the northern extremity of the Venice coastal area. The network is composed of levelling and GPS benchmarks and its geometry was planned on the basis of the SAR results provided by the VENEZIA Project (Strozzi et al. 2003c, 2005; Teatini et al. 2005).

The levelling network

Geodetic levelling is the traditional method for the determination of ground elevation changes and despite

Fig. 2 Displacement rates observed over the 1973–1993 (a) and 1993–2000 (b) periods



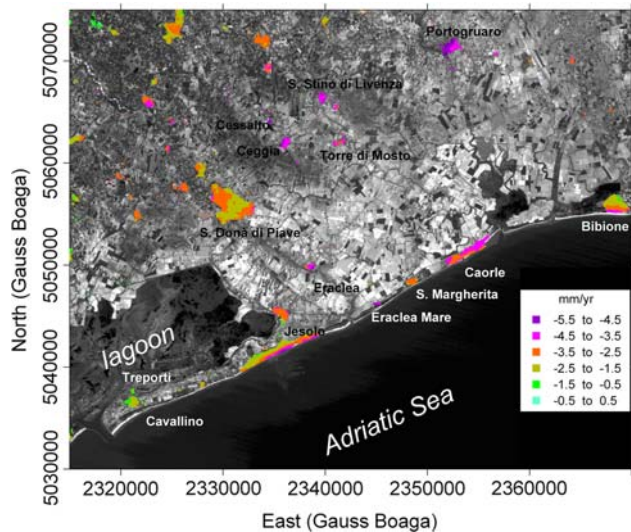


Fig. 3 Ground vertical movements detected by SAR Interferometry (*InSAR*) on the built-up areas of the IRMA Project over the period 1992–2000. The grayscale zone corresponds to coherence lack in the InSAR analysis (modified after Strozzi et al. 2003b)

its simplicity can be very accurate. The technique, developed in the nineteenth century and still much used at present, allows the surveyors to carry out an elevation from a known reference point to other geodetic markers by the use of a precisely levelled telescope and a pair of graduated vertical rods. For each survey the elevation difference e_d between two benchmarks is recorded twice by accumulating the elevation differences between a series of temporary turning points. Typically, benchmarks are spaced 1 km apart and turning points are 20–100 m apart. Once a network of benchmarks has been established and surveyed by precise levelling, a further survey at some later date shows whether vertical movements have occurred and quantifies their magnitude. Digital levels and invar rods help to guarantee the selected accuracy, eliminating human errors and increasing the measurement speed.

With a total number of 527 benchmarks and an overall length of about 480 km, the IRMA levelling network is composed of 23 lines forming 40 closed polygons (Fig. 4). The lines are located along roads and watercourse embankments, with a first-order benchmark always placed in the nodal positions, i.e., where two or more lines meet.

The IRMA and ISES networks share the levelling lines around the lagoon margin. Moreover, all the available benchmarks scattered in the study area, established by local reclamation authorities/municipalities over the past decades, and the historical levelling lines of the Istituto Geografico Militare

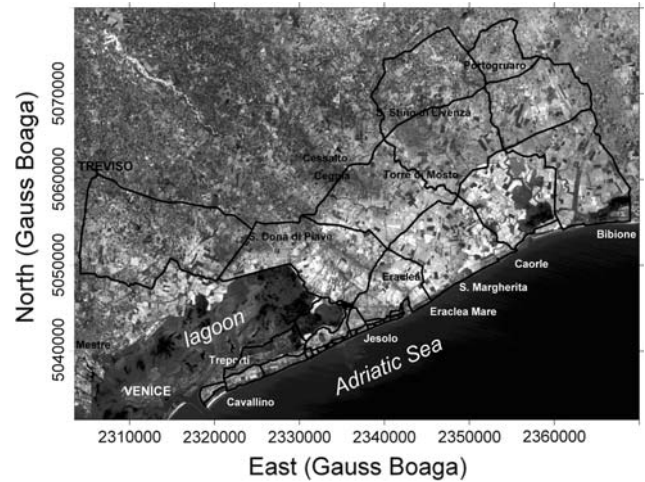


Fig. 4 Map of the IRMA levelling network

Italiano (IGM) connecting Venice to Trieste, were integrated in the IRMA network.

The first survey of the IRMA network was carried out in 2004 in accordance with the guidelines for a “high” (second order) and “very high” (first order) accuracy measurement, depending on the importance of the line and the environmental condition. The discrepancy between e_d measured in the forward and backward directions (relative to the direction of the traverse) must not exceed $1.5\sqrt{D}$ (expressed in millimeters) and $2.5\sqrt{D}$ (expressed in millimeters) for a “very high” or “high” accuracy survey, respectively, where D is the length of the benchmark line in kilometres. Figure 5 shows the recorded e_d versus D for the 2004 IRMA survey compared with the threshold values of the tolerance. Only two values do not respect the prescribed tolerance. They correspond to the measurements carried out by a directional theodolite (trigonometric levelling) to connect the benchmark couples at the opposite sides of river mouths.

For each closed polygon, it must be verified that the absolute value of the closure error be less than the recommended tolerance $2.5\sqrt{D}$ (expressed in millimeters) with D the actual length of the levelling loop in km. For open levelling lines, the error per kilometer u :

$$u = \frac{1}{2} \sqrt{\sum_{i=1}^n \left(\frac{e_{d,i}^2}{D_i/n} \right)} \quad (1)$$

must be less than 1.5 mm. In Eq. 1 n is the number of sections forming the line, $e_{d,i}$ and D_i the forward–backward elevation difference (in mm) and the length (in km) of the i -th section, respectively.

Finally the recorded values have been adjusted to balance the heights for the whole net. The benchmark

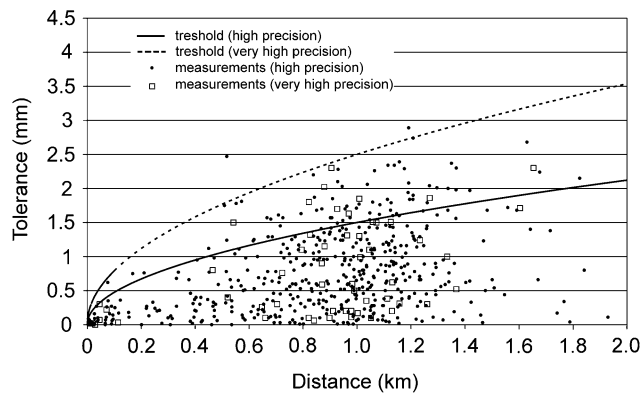


Fig. 5 Levelling survey carried out in 2004. Absolute values of the recorded discrepancies between the height difference of all the benchmark pairs of the IRMA network measured in the forward and backward direction, compared to the threshold tolerance. The dataset is divided between the “high” and “very high” accuracy measurements

NOD_63 located in the stable area at Treviso (Fig. 4), 13.1970 m high with respect to the mean sea level (Italian Datum), is used as reference.

Global Positioning System network

The GPS network is formed by 45 benchmarks established on nodal levelling benchmarks, with a ratio of about 1/10 between the GPS and geometric measurement points. Eight GPS benchmarks are shared between the ISES and IRMA nets (Fig. 6).

The GPS measurements were performed in 2004 following the Federal Geodetic Control Committee (FGCC) guidelines that prescribe for the high-accuracy GPS network the triple occupation of 80% of the monitoring benchmarks. The survey was carried out in differential static mode (DGPS) using as reference point the PA_11_G benchmark of the ISES GPS net located at Mogliano (Fig. 6), the stability of which was confirmed by regional levelling surveys carried out over the last 20 years. This benchmark was preferred to NOD_63 because of its central position within the ISES-IRMA GPS network.

The survey was carried out connecting the benchmarks by a number of intersecting and redundant baselines and considering as points of strategic relevance few nodal benchmarks with an optimal visibility. These benchmarks were used as reference points for local sub-networks, each of them characterized by short baselines 3–5 km long, and connected by longer baselines (10–15 km) measured by dual frequency receivers with prolonged observing sessions of 10–12 h. Good accuracy was achieved with excellent repeatability using precise ephemeris.

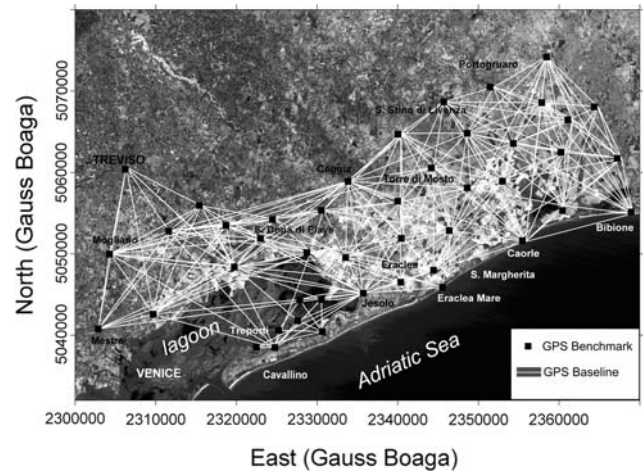


Fig. 6 Map of the IRMA DGPS network with the indication of a portion of the baselines measured in the 2004 survey

Four to seven single and/or dual frequency GPS receivers equipped with geodetic antennas were simultaneously used, recording with at 15-s intervals. The post-processing phase showed that the best data quality was obtained by L1 frequency (157,542 MHz) because L2 (122,760 MHz) was occasionally affected by cycle slips. Only data acquired with an optimal satellite configuration regarding the pseudo random noise (PRN), position dilution of precision (PDOP) and geometric dilution of precision (GDOP) parameters were processed. Each recording session spanned more than 3 h and was prolonged if GDOP became larger than 8 and when the satellite number simultaneously available was less than 6. The large amount of records available from the various baseline combinations allowed for the elimination of anomalous data, thus increasing the quality of the overall survey.

After the baseline processing by the software SKI Pro v.3.0 (Leica AG), the control of loop misclosures L_m was performed using the least-squares adjustment through the software Columbus v.3.5 (Best Fit Computing). The resulting L_m were generally smaller than 1 ppm. Finally, the WGS84 coordinates have been converted to the Gauss-Boaga local reference system using the 7-parameter Helmert transformation linearized into the Molodensky equations calculated for the Venice Lagoon by Magistrato alle Acque di Venezia (2003).

Data analysis

Records before IRMA

Monitoring of ground vertical movements in the area north-east of Venice was performed over the last

century only along three levelling lines (Fig. 7). Major surveys were conducted by IGM in 1952, 1980, and 1989, by CNR (National Research Council) in 1973 and 1993, and by ISES in 2000 and 2003.

The general stability of the inland area between Treviso and Mogliano has been verified by the levellings performed by CNR and ISES over the 1973–2000 period (Fig. 8).

Figure 9 shows the displacement records along the IGM line from Portegrandi to Fossalta di Portogruaro over the 1952–1980 and 1980–1989 periods. The movement analysis points out two different trends. During the older period (1952–1980) a quite homogeneous subsidence rate of about 1 mm/year was recorded with the exception of a 4 mm/year peak around S. Stino di Livenza. In the following decade (1980–1989) a similar velocity continued in the sector between Portegrandi and S. Stino di Livenza, while an uplift up to 4 mm/year was measured from Levada to Fossalta di Portogruaro. Information presently available does not allow for a rigorous explanation of this significant change even though it is well known that the area is characterized by the presence of tectonic faults (Carbognin et al. 2005b; Teatini et al. 2005). Moreover, an earthquake of 8.2 magnitude on the Richter scale occurred in 1976 in the nearby Friuli Region.

Concerning the levelling line bordering the lagoon margin, past displacement trends are given in Fig. 10. The two zones of Caposile and Jesolo were characterized by a significant land subsidence (about 4 mm/year) over the 1973–1993 period whereas a subsidence of about 2 mm/year was recorded along the Jesolo-Lido sector. A similar picture occurred from 1993 to 2000 with the exception of Jesolo and the surrounding area where subsidence increased up to 5 mm/year.

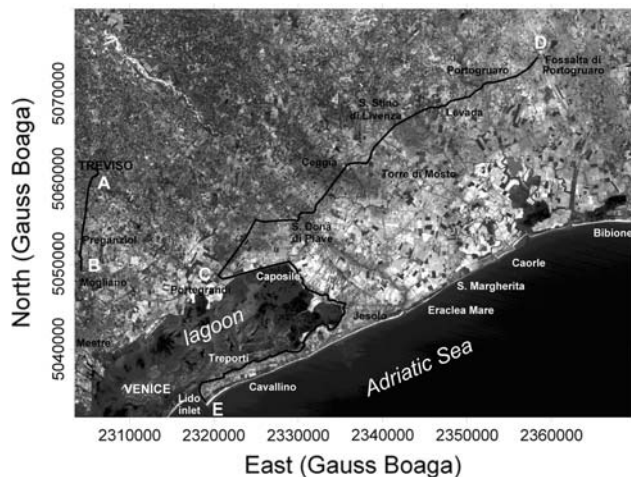


Fig. 7 Map of the levelling lines where measurements are available before 2004

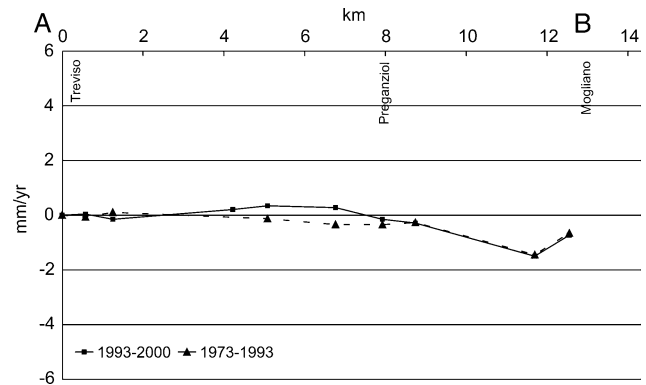


Fig. 8 Vertical displacements between 1973 and 1993, and since 1993 to 2000 along the section Treviso-Mogliano (see A–B position in Fig. 7)

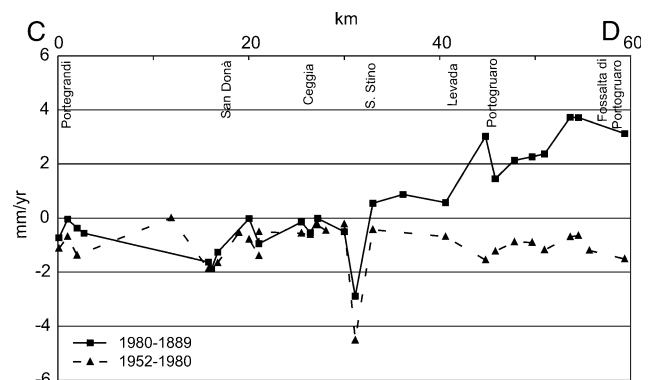


Fig. 9 Vertical displacements from Portegrandi to Fossalta di Portogruaro (see C–D position in Fig. 7) for the 1952–1980 and 1980–1989 periods

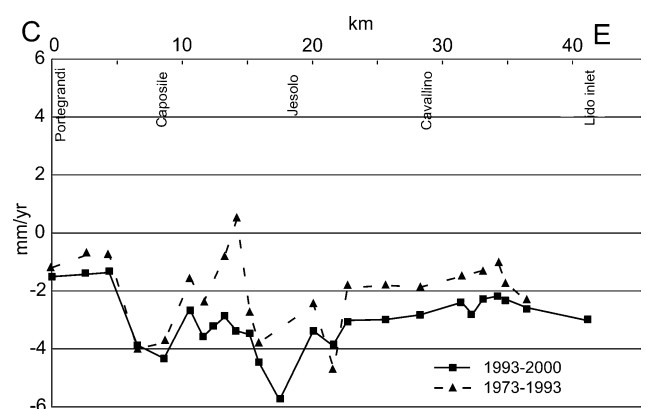


Fig. 10 Vertical displacements measured in the 1973–1993 and 1993–2000 periods along the section from Portegrandi to Lido inlet (see C–E position in Fig. 7) around the margin of the northern Venice Lagoon

A further analysis can be carried out on the GPS benchmarks of the ISES network located along the north lagoon margin. Figure 11 shows the displacement rate computed from the DGPS measurements performed in 2000 and 2003. The general trend derived from these data is in agreement with the levelling (Fig. 9) and InSAR (Fig. 4) measurements, showing a near stability of the mainland facing the central lagoon area and a significant land subsidence along the northern lagoon margin. A detailed comparison between DGPS and levelling outputs shows that the former tends to overestimate the actual displacement values. The standard deviation for the displacements obtained by the 2000–2003 DGPS measurements, computed as

$$\sigma_{\text{subs}} = \frac{(\sigma_{q,2000}^2 + \sigma_{q,2003}^2)^{0.5}}{3.5}, \quad (2)$$

where $\sigma_{q,2000}$ and $\sigma_{q,2003}$ are the standard deviation of the 2000 and 2003 heights, respectively, and 3.5 is the time interval (year) between the two surveys, is quite high and ranges from 2 to 6 mm/year. This is probably

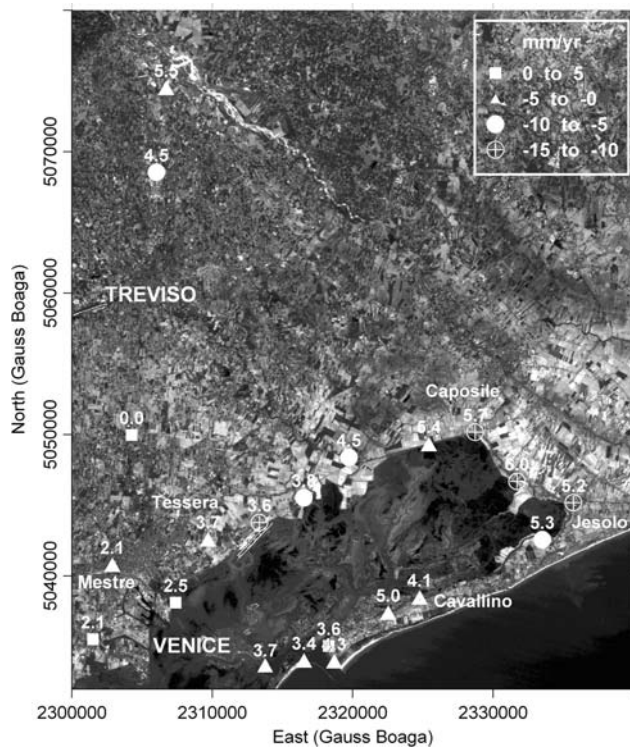


Fig. 11 Subsidence rates measured by DGPS between 2000 and 2003 on the ISES benchmarks located in the southern sector of the IRMA study area. The value above each symbol is representative of the standard deviation (mm/year) associated with the measurement

due to the peripheral position of these benchmarks with respect to the overall ISES net.

IRMA records

The first measurement of the IRMA net, carried out soon after its establishment in 2004, will be used as reference for the future surveys. In any event, it is already possible to calculate the displacement rate for IRMA benchmarks shared with the “historical” lines, i.e. from Treviso to Mogliano, from Portegrandi to Fossalta di Portogruaro, and from Portegrandi to Cavallino through Jesolo (Fig. 7).

The comparison between the ISES survey carried out in 2000 and the IRMA levelling along the Treviso–Mogliano line is shown in Fig. 12. The result confirms the general stability of this part of the Venice plain. In particular, the small differences measured around Mogliano allowed the use of a benchmark located in this town as the reference point for the DGPS records.

Along the Portegrandi–Fossalta di Portogruaro direction, the IGM survey performed in 1989 are the more recent data available before IRMA. The land subsidence rates along this section are shown in Fig. 13. The most recent data shows a quite different behavior with respect to past trends. In particular, a significant loss in land elevation occurs from the lagoon edge northward, with maximum rates of about 5–6 mm/year. This trend is confirmed by the InSAR analysis, which provided an accurate information over the 1992–2000 period of the displacements experienced by all the urban centers with an area greater than about 1 km² (Fig. 4).

Concerning the levelling lines bordering the lagoon margin, the 2000–2004 trend shows a general decrease of the subsidence velocity, although a critical settlement still occurs in Jesolo and Caposile (Fig. 14).

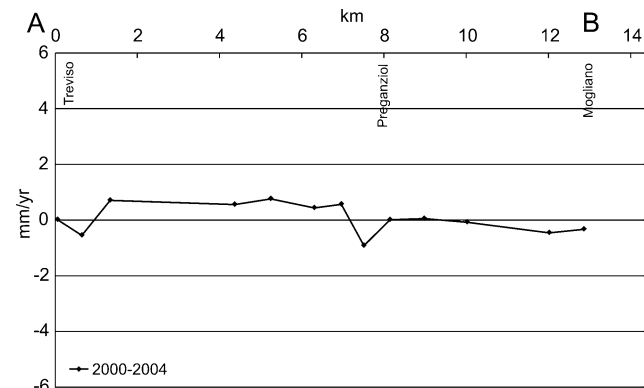


Fig. 12 Vertical displacements between 2000 and 2004 along the section Treviso–Mogliano (see A–B position in Fig. 7)

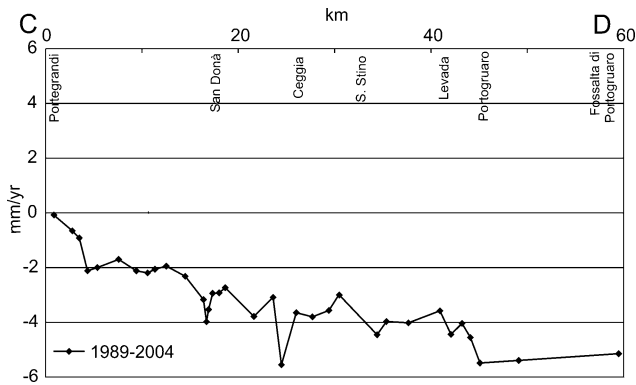


Fig. 13 Land settlements measured from 1989 to 2004 along the Portegrandi-Fossalta di Portogruaro section (see C–D position in Fig. 7)

Comparison between Figs. 14 and 10 points out a higher variability of the 2000–2004 displacements than those of the 1993–2000 period. This is likely due to the difference through time of settlement sources (i.e., land reclamation, local ground-water pumping, overloads, non homogeneous lithology) in this portion of the Venice territory. The movements are now captured with a better detail because of the re-establishment of several benchmarks in 2000.

Analysis was also carried out for the few IRMA GPS benchmarks shared with the 2000 ISES network. Table 1 shows that the 2000–2004 displacements and the relative standard deviations are similar to the values computed from 2000 to 2003 (Fig. 11). Presently the overall IRMA plus ISES DGPS network shows a well-distributed geometry that should guarantee more precise measurements.

The simultaneous levelling and DGPS measurements on a significant number of points allow the

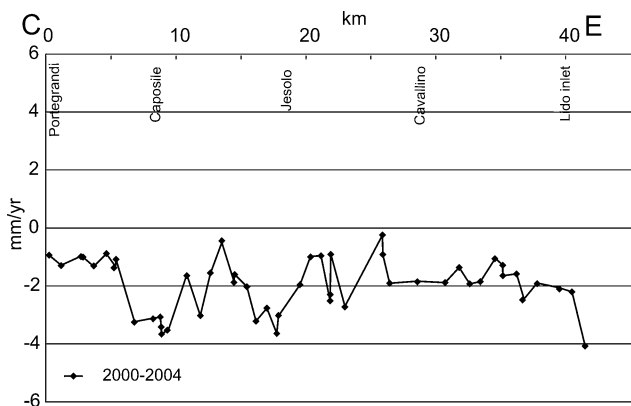


Fig. 14 Vertical displacements measured between 2000 and 2004 along the section from Portegrandi to Lido inlet (see D–E position in Fig. 7) around the margin of the northern Venice Lagoon

computation of the geoid undulation (or height) N in the IRMA area, with a higher accuracy than that characterizing national models (Barzaghi et al. 1996). The difference between the WGS–84 ellipsoid altitude measured by GPS and the topographical altitude provided by levelling has been computed for 34 GPS benchmarks of the IRMA network and 11 benchmarks of the ISES network.

The local model of the geoid undulation has been computed interpolating the scattered data by the quadratic function:

$$N(x,y) = -1779.3296511907 + 1.929432920457E - 4 \cdot x - 6.182702159473E - 4 \cdot y - 2.2513789561156E - 10 \cdot xy + 2.0108841741628E - 10 \cdot x^2 - 7.5082897388345E - 12 \cdot y^2 \quad (3)$$

with N in m, and x and y are the east and north Gauss-Boaga (East fuse) coordinates of the generic point. The high accuracy of this model is confirmed by the low residuals in the measured positions, always less than 1 cm in modulus. A contour line map of the above model is given in Fig. 15a.

Preliminary interpretation of land subsidence

Natural and man-induced processes are responsible for the vertical ground movements recently come to light in the study area, and each factor contributes differently to the total displacement.

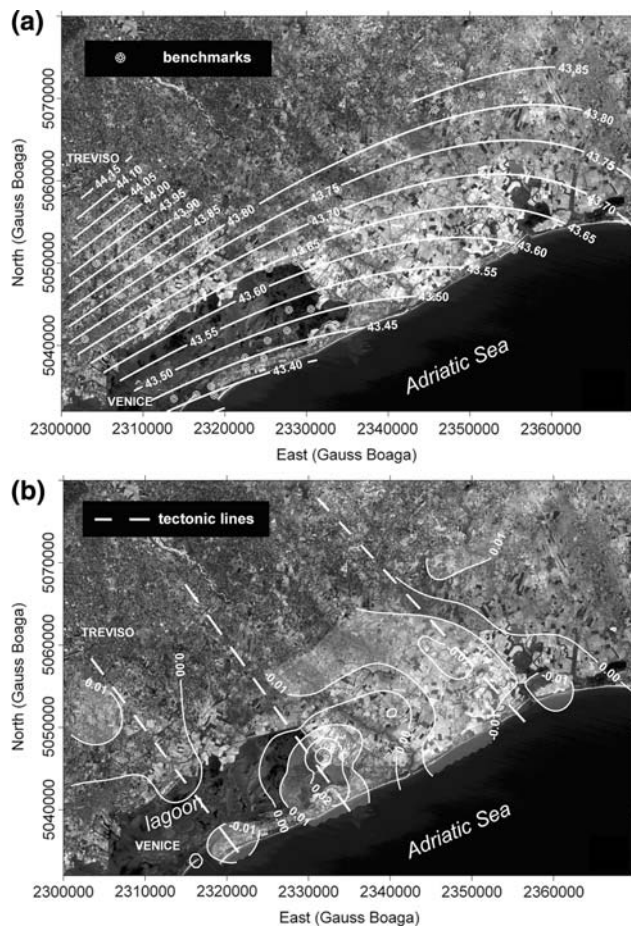
A deep knowledge about the hydro-geological structure refers to the IRMA area closest to the Venice Lagoon (Carbognin et al. 1977; Teatini et al. 1995), while the scarce information allows only a coarse reconstruction of the aquifer-aquitard system in the rest of the area (Provincia di Venezia 2000; Consorzio di bonifica Pianura Veneta tra Livenza e Tagliamento and Provincia di Venezia 2001). The available data are derived from wells drilled to groundwater pumping and show a significant spatial correlation of the deep confined aquifers, in spite of a certain variation of their top and bottom burial depth. On the contrary the phreatic and shallow semi-confined aquifers are locally extended. The average depth of the main aquifers in the southern, central, and northern sectors of the IRMA area is shown in Table 2.

The large number of existing wells in the area from Portogruaro to the coast between Caorle and Bibione (Provincia di Venezia 2000; Consorzio di bonifica Pianura Veneta tra Livenza e Tagliamento and Provincia di Venezia 2001) suggests that groundwater

Table 1 Subsidence rate and corresponding standard deviation for the DGPS measurements between 2000 and 2004

Benchmark	East (Gauss Boaga)	North (Gauss Boaga)	Subsidence (mm/year)	Standard Deviation (mm/year)
Mestre	2302865.264	5040796.64	-0.64	5.19
Cavallino	2324760.685	5038493.75	-2.04	4.38
Jesolo	2335719.655	5045183.882	-9.87	5.08
Caposile	2328720.765	5050167.885	-11.22	6.16
Tessera	2309682.335	5042589.791	-5.13	4.33

The benchmark location is provided in Fig. 11



established prior to the late 1990s in this part of the Venice territory. Degradation of the coastal environment, coastline regression, nearshore depth and slope rise, flooding increase due to storm surge events, and instability and destruction of littoral protection structures have been the first warning signs.

A preliminary recognition of the seriousness of the subsidence process was obtained by levelling on a pair of lines bounding the area and an InSAR analysis in the 2000–2001 period. As a result the authorities and administrations managing the territory funded the establishment of a new subsidence monitoring network. Within the IRMA Project a 480 km long levelling network was established in 2004. The net is composed of 527 benchmarks spaced about 1 km apart, and 45 of these points are also suited for DGPS measurements.

The first network survey was carried out in 2004 and the comparison with a few past records has pointed out a significant sinking trend in most of the north Venice coastland, with rates up to 5 mm/year. A number of important urban centers such as Caposile, Jesolo, Eraclea Mare, Caorle, Bibione, Torre di Mosto, San Donà di Piave, Ceggia, S. Stino, Levada, Portogruaro, and Fossalta di Portogruaro are experiencing a serious loss in land elevation.

Although an accurate investigation to understand the factors controlling the phenomenon has not yet been carried out, preliminary analyses show that various natural and man-induced processes are responsible for the land subsidence affecting the zone. A next step will be the improvement of the geological, sedimentological, and hydrogeological characterization of the area, including the use of mathematical models to quantify the cause–effect relationships.

Presently, land subsidence in the Venice coastland is monitored by a network (whose acronym is ISES-IRMA) that is composed of about 1,500 levelling benchmarks, 160 of which used also for DGPS measurements, with a cumulative length of 1,300 km. Integration of these traditional measurements with SAR-based techniques will ensure an accurate control of the elevation changes in the Venice coastal area over the next decades.

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