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A NEW MONITORING STRATEGY TO CONTROL LAND MOVEMENTS. THE VENETO REGION TEST AREA, ITALY

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Abstract

Anthropogenic land subsidence has widely been affecting the Veneto Region, northern Italy, since the past century. Groundwater withdrawals for industrial, domestic, and agricultural uses, exploitation of mineral water, thermal water for health treatment, methane-bearing water, and peat oxidation in reclaimed farmlands produced a land settlement varying in time and space throughout the area. Moreover, natural consolidation of the Quaternary deposits and tectonics of the pre-Quaternary basement contribute to increase ground surface lowering. Different survey techniques, with different characteristics, have been adopted to control land subsidence. To overcome the limits that characterize each single method and to enlarge the knowledge on regional land subsidence, an integrated monitoring method has been designed to accurately and reliably keep land movements under control in the study area. We combine five earth observation techniques, i.e. spirit leveling, Continuous Global Positioning System (CGPS), Differential GPS (DGPS), Interferometric Synthetic Aperture Radar (InSAR), and Interferometric Point Target Analysis (IPTA), together over about the last ten-years, and homogenized and integrated their results in both the time and space domains. The application of this Subsidence Integrated Monitoring System (SIMS) provides a new complete and dependable picture of the vertical displacements in the Veneto Region never available before.

Keywords: monitoring, leveling, GPS, remote sensing, data integration, Veneto Region (Italy)

1. INTRODUCTION

The subsidence of the city and the lagoon of Venice, known all over the world, has been studied in every aspect for decades (e.g. CNR, 1971a, 1971b; Carbognin et. al., 1977, 1995a, 1995b, 2000a, 2004; Gatto and Carbognin 1981; Bortolami et al., 1984; Teatini et al., 1995; Tosi et al., 2002; Brambati et al., 2003).

Particularly significant is the relative drop of 23cm in land elevation that has taken place in Venice over the last 100 years. This elevation loss is the result of about 12cm of land subsidence (3cm natural and 9cm anthropogenic after 3cm of rebound occurred following the shutdown of artesian wells) and 11cm of sea level rise due to climatic changes occurring on a global scale. In other words the level of the sea has risen by about 23cm with respect to the ground level, yielding a more than seven-fold increase in the frequency of floodings (locally called acqua alta) by sea surges. Each centimeter of elevation is precious for Venice: the famous St. Mark's Square, the city's lowest section, is today only 40cm above the m.s.l. Recent studies have shown that the city of Venice and its nearby mainland are at present almost stable. In the ambit of the lagoon, on the other hand, geological subsidence is mainly due to compaction of recent deposits and anthropogenic components has been caused by groundwater withdrawal from the multiaquifer system well developed down to a 320m depth.

Once complying with the demand for a complete understanding of the Venice subsidence by local authorities managing the solutions to preserve the lagoon environment, further developments of study have been addressed to the entire region and to the monitoring techniques and program.

2. LAND SUBSIDENCE IN THE EASTERN VENETO REGION

Land subsidence is a phenomenon involving many areas all over the regional territory. The most severe environmental impacts caused by land subsidence in the Veneto Region are areas presently lying below the mean sea level, flooding, contamination of coastal phreatic aquifers by saltwater intrusion with problems to the agriculture development, and damages to buildings and other man-made structures.

Data collected in the past, knowledge on the region geological setting, human activities, and cause-and-effect relationships have confirmed that land subsidence is due to a number of factors acting individually or together. Natural causes of settlement are compaction of fine-grained deposits referable to the river deltas located at the North and South lagoon edges and that increase from the mainland toward the sea, and substratum deformation due to tectonics and geostatic load. Anthropogenic subsidence is varying in time and space throughout the Veneto Region. It is due to groundwater pumping for industrial, domestic, and agricultural uses, mineral and thermal water withdrawal, over-exploitation of gas-bearing water, peat oxidation in reclaimed farmlands. It is worth recalling that methane-bearing water pumping from the Quaternary formations performed in the Po River Delta from the 1950s to the 1960s induced a very huge subsidence ranging between 50cm and 3m with a strong environmental impact (Carbognin et al., 2000b). Rather new research development in the Veneto Region regards land subsidence caused by the loss of sediment mass due to biochemical oxidation of organic soils in response to drainage for agricultural purposes (Gambolati et al., 2005).

3. MONITORING TECHNIQUES: THE EASTERN VENETO REGION NETWORKS

Ground-surface elevation in the Veneto Region has been measured by leveling with sufficient accuracy and reliability since the end of 1800, chiefly on the national topographic network (IGM surveys). During the last decades Global Positioning System (GPS) techniques, has been also adopted. More recently significant progress in measuring ground displacements was achieved using Synthetic Aperture Radar-based techniques (SAR).

3.1 Leveling

Leveling is the traditional subsidence monitoring technique used all over the world because of its accuracy in providing point-wise measurements. However, it is intrinsically time-consuming and hence expensive.

The IGM network in the Veneto Region has been enriched during the second half of the 1900 with new regional/municipal leveling lines, established by CNR and "Venice Protection Committee" (Comitato per la Difesa della città di Venezia) to keep under control the lagoon subsidence. Reduced leveling networks were established over 20th century in the region by land reclamation authorities ("Consorzi di bonifica") to cope with local needs. Except for IGM and CNR, the other agencies established and controlled its own benchmark network with a genera lack of homogeneity between the measurements performed by the different in stitu tions.

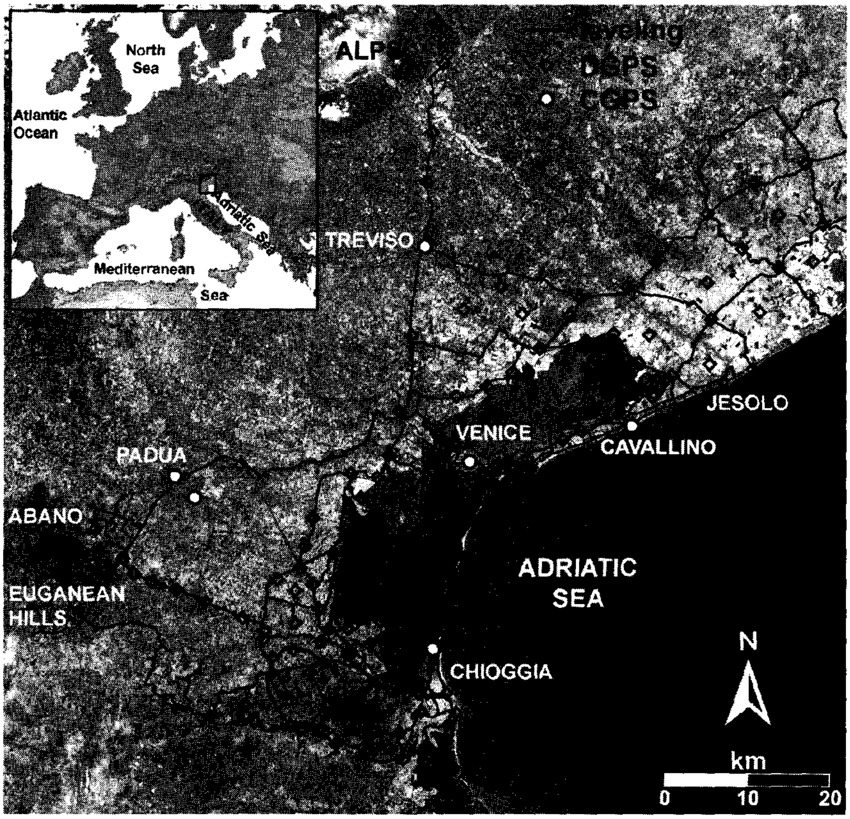

Fig.1 Networks of leveling, CGPS, and DGPS presently available in the eastern Veneto Region

Starting from 2000 a program has been carried out to homogenize the regional leveling nets. The existing coarse network has been refined especially in the southern and the northern parts of the coastal plain where the surveys carried out in 1993 and 2000 along the historical lines showed the highest subsidence rates equal to 2-3 mm/a in Chioggia and 4-5 mm/a in Jesolo (Tosi et al., 2000). Presently, the overall leveling network is about 1,200km long, consisting of about 1,300 benchmarks, usually about 1 km apart, with about 50 closed polygons few tens of kilometers long (Fig.1). The original net, connected before 2000 only to the stable area of Treviso in the Alpine foothills, is also linked today to the Monte Venda in the stable Euganean Hills.

3.2 GPS

Two GPS techniques are presently used: the continuous (CGPS) and the differential one (DGPS). Although costly, CGPS is based on a restricted number of stations providing long time series that can be used to monitor the displacement rates of few reference benchmarks in the vertical as well as the two horizontal directions. On the contrary, DGPS is generally applied on a coarse benchmark net and is faster and cheaper than leveling but less accurate. Its application appears particularly interesting to connect the subsiding areas to stable reference points and to perform expeditious surveys aimed at a preliminary process detection or at verifying displacement trends already known.

The six CGPS stations existing in the study area are placed in Padua (one managed by the University of Padova and one by Consorzio Venezia Nuova), at the northern (Cavallino) and southern (Chioggia) lagoon extremities and in, Treviso (Consorzio Venezia Nuova) and in Venice (Italian Space Agency) (Fig.1).

The DGPS network is nowadays composed of one hundred and fifty suitable selected benchmarks of the leveling net (Fig.1). All the nodal points and the polygon centers of the leveling network have been used as DGPS stations, and some benchmarks have been located on the stable Euganean Hills and Alpine foothill (Tosi et al., 2000). The benchmarks have been connected by intersecting and redundant baselines and a few stations with an optimal satellite visibility have been selected as points of strategic relevance. These latter have been linked by long baselines measured by dual frequency receivers with prolonged observing sessions and used as reference stations for local sub-networks, each of them characterized by short baselines of similar length. The DGPS network has been connected to the five continuous GPS stations and the surveys carried out in static mode in 2000 and 2003 have confirmed the subsidence trends shown by leveling

3.3 InSAR

Interferometric Synthetic Aperture Radar (InSAR) has been introduced as a tool to measure land subsidence at the beginning of 1990. InSAR allows mapping land movements at high spatial resolution, sub-cm accuracy, relatively low cost, i.e. with characteristics complementary to the in-situ surveys. It is powerful chiefly in urban areas.

InSAR was employed in the Veneto Region to complement leveling and GPS surveys. A time series of six interferometric radar images of the ERS-1 and ERS-2 satellites from 1993 to 2000 was analyzed. In order to generate a single subsidence map with reduced errors, the interferometric radar images have been combined by a stacking technique (Strozzi et al., 2001). Although temporal decorrelation does not permit the interferometric phase analysis in agricultural and rural areas, the InSAR investigation in the Venice Region has pointed out many locations with a coherent signal because of the high urbanization in this area (Fig.2a). InSAR outcome confirms the leveling results and moreover supplies very detailed information over major cities, e.g. Venice, Padua, and Treviso, smaller urban centers such as Chioggia, Conegliano, Abano, and many small rural villages with an areal extent of the order of 1 km^2. All of them constitute a sort of InSAR net with an overall number of about 380,000 coherent pixels (Strozzi et al., 2003).

3.4 IPTA

In order to overcome the main InSAR limitation, i.e. the incomplete spatial coverage limited to urban areas, new techniques to interpret the interferometric phase of stable reflectors have recently been developed on long time series of SAR images (Werner at al., 2003). One possibility to obtain this goal is to consider only targets that exhibit a point-like scattering behavior and remain phase-coherent over time for a large number of SAR acquisitions. Through the use of many scenes, even if separated by large baselines, Interferometric Point Target Analysis (IPTA) is particularly effective to monitor land displacements also for

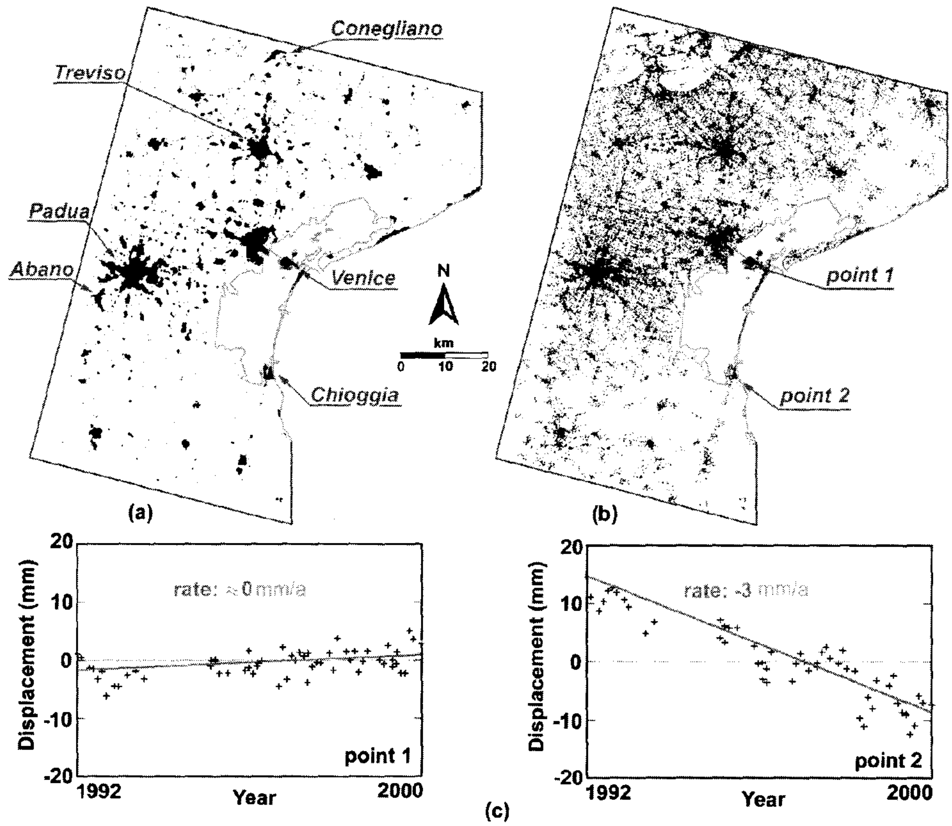

Fig.2 (a) InSAR and (b) IPTA networks in the eastern Veneto Region over the time period 1992-2000. Logs of subsidence for points 1 and 2 are shown in (c)

Tab.1 Comparison of the major characteristics of leveling, DGPS, DGPS, InSAR and IPTA for monitoring regional ground displacements

	Spatial resolution	**Spatial characteristics**	**Vertical accuracy**	**Main limits**
Leveling	250 - 1000 m	leveling lines	≦ 1 mm	time consuming / expensive
CGPS	tens - hundreds of km	few permanent stations	≦ 2 mm/a	expensive / long time series
DGPS	5 - 10 km	scattered network	≦ 5-10 mm/a	accuracy
InSAR	25 m	built-up areas	≦ 2 mm/a	signal decorrelation in rural areas
IPTA	5×25 m	point targets	≦ 1-2 mm/a	expensive/ requires filtering

isolated man-made structures with high temporal sampling. However, IPTA is more expensive than InSAR requiring much more SAR scenes to fulfill a reliable analysis. Moreover, filtering is required to remove point-wise movements related to local processes for a correct evaluation of regional land subsidence trends. Finally, in extreme rural zones IPTA can fail to retrieve subsidence information and only leveling and GPS can presently be used.

IPTA has been used in the Veneto Region using 59 ERS-1 ERS-2 SAR images between 1992 and 2000 with stable Doppler centroid. More than 120,000 point targets (PT) with valuable subsidence information have been detected in the area and are scattered over cities, suburban areas, and isolated farm structures in rural areas (Fig.2b). IPTA has clearly shown its capability in monitoring land subsidence at punctual scale with millimeter accuracy (Fig.2c).

4. SUBSIDENCE INTEGRATED MONITORING SYSTEM (SIMS)

To overcome the main limitations characterizing each of the five techniques briefly compared in Tab.1, a new monitoring system based on their integration (SIMS) has been developed to draw a comprehensive subsidence picture at regional scale (100km×100 km area).

Measurement cross-validation is a very important SIMS step. After the selection of a common reference benchmark, whose stability or movement trend is well known by leveling over decades, the land displacement rates obtained over similar time intervals by the various techniques are compared using a significant number of points. Basic statistic analysis on the record differences provides an estimate on the SIMS accuracy and can suggest some adjustments (e.g., the reference point change and the outlier elimination) to enhance data homogenization. Statistics can be carried out at the globa l scale as well as in local zones around the leveling and GPS benchmarks. Moreover, the partition of the study region into a number of sub-areas, each of them characterized by the presence of a few ground-based monitoring points to be used as a local reference, has proved useful in resolving the problem of phase unwrapping for the remote sensing analysis.

Once calibrated, the superimposition of the movement rates recorded at the leveling/GPS points with the InSAR/IPTA response on the pixels/PT intersecting the leveling lines provide a straightforward visualization of the validation results.

The subsidence data sets are then integrated taking into account their intrinsic features, mainly the spatial density of the SAR-based information that is orders of magnitude higher than that of the ground-based measurements. The following steps are implemented (Fig.3): (1) InSAR data re-sampling on a regular grid to reduce the number of measurements within the urban areas. The grid extent depends on the dimension of the investigated area; (2) IPTA data filtering to reduce their intrinsic variability. Filtering is performed by a geostatistic technique using a spatial autocorrelation model characterized by the presence of a "nugget effect" C in order to reduce the inherent data incoherence (De Marsily, 1986); (3) set up of a single database containing the post-processed InSAR and IPTA information and the leveling and GPS records; and (4) interpolation of the overall database over the study region by kriging (De Marsily, 1986).

5. LAND SUBSIDENCE IN THE EASTERN VENETO REGION BY SIMS

Using the SIMS with the available data described in Section 3, a comprehensive image of ground vertical displacements has been drawn for the Veneto Region.

Although recorded over a time period following that of the other monitoring techniques, the DGPS measurements have been used in the integration procedure because they are coherent with the information collected over the previous interval. The map of Fig.4 is therefore representative of the decade 1992-2002.

Fig.4 has been obtained by interpolating the available measurements on a 1000-m regular grid and using the stable area in Treviso as reference. InSAR data have been previously pre-processed on a 250×250 m grid and the IPTA measurement analysis has suggested a filtering variogram characterized by C values ranging between 0.4 to 1 mm^2/a. Difficulties in data homogenization have been found at the northern lagoon extremity and in the nearby coastland where DGPS and IPTA over- and underestimates, respectively, the average sinking rates up to a few mm/a, and therefore have been neglected in the mapping process. The reason for such an inconsistency is under investigation. However, it must be pointed out that these displacement values are in the range of the intrinsic accuracy of the technique.

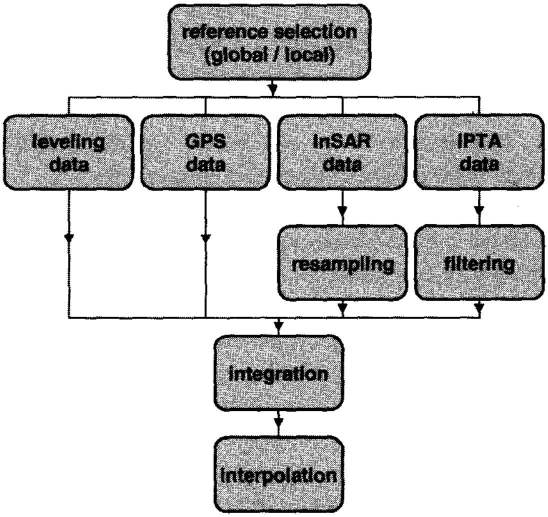

Fig.3 Flow chart of the integration process to map regional land displacements

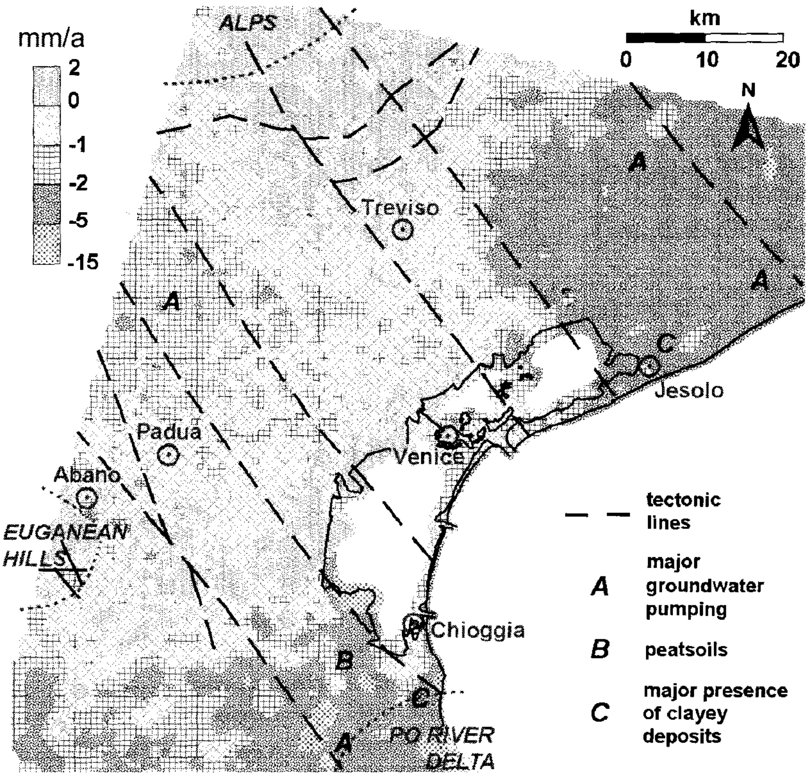

Fig.4 Vertical displacements (mm/a) in the Veneto Region over the period 1992-2002 obtained by SIMS. Negative values mean subsidence. Tectonic lines modified after Cavallin and Marchetti (1995)

Fig.4 shows that the central part of the Veneto Region, including the major cities of Venice, Padua, and Treviso is generally stable, with scattered local bowls of subsidence up to 2-3 mm/a. Conversely, land settlement is a widespread phenomenon in the northern and southern coastland bounding the lagoon extremities with rates up to 5 mm/a and 15 mm/a, respectively. Uplifts ranging from 0.5 to 1.5 mm/a have been measured in two different large areas located, respectively, north of Treviso and south of Padua, whereas higher values are restricted to the eastern sector of the Euganean Hills.

Various processes, both natural and man-induced, are responsible for the measured ground vertical movements and give different contributions to the displacement rates. The main causes are groundwater withdrawals, oxidation of outcropping peat soils, residual sediment consolidation due to the increased geostatic load in connection with the coastal progradation during the late Holocene and land reclamation carried out during the last two centuries. Moreover, the presence of tectonic lines, the occurrence of recent seismic events, and a larger thickness of clayey compressible deposits in the upper 400m depth at the lagoon extremities with respect to stiffer sandy formations in the central lagoon can be correlated with differential ground vertical movements. The 4-5 mm/a sinking rates along the coastland north of the lagoon are due to the superimposition of groundwater pumping, tectonics, and consolidation of recent and clayey deposits. The sector north of Treviso, corresponding to the outcropping front of the southern Alps, shows a general uplift due to the thrust tectonics. Some faults of this area are classified as seismogenic sources. In the inner portion of the study area, i.e., northwest of Treviso and Padua, and in the area of Abano several local bowls of subsidence up to 3 mm/a are mainly related to groundwater withdrawal for civil and thermal purposes, respectively, to which slight tectonic movements are superimposed. From the Euganean plain to the central lagoon margin, the uplift trend seems related to tectonic movements connected to the Alpine thrust belt (like WSW-ENE direction) and to a NW-SE fault system. The southern part of the study region is characterized by significant subsidence rates, ranging from 5 mm/a around the south lagoon margin to 15 mm/a toward the Po River Delta, with local zones of relative stability. Here an important role is play by tectonics, residual consolidation of clayey deposits, together with more local factors such as peat oxidation enhanced by the agricultural practices and natural compaction of fine-grained deposits in recently reclaimed lagoon sectors. Along the southern coast, sinking is mainly due to the increase of geostatic load because of the Po River Delta progradation.

6. CONCLUSIVE REMARKS

A new strategy to control wide-area vertical land displacements (SIMS) is implemented. Based on the integration of the conventional monitoring methods, SIMS allows optimizing the areally distributed remote-sensed information with the site-specific records measured by ground-based systems.

The SIMS is applied in the eastern Veneto Region and enhances the knowledge on land subsidence, complying with the increasing request by local authorities managing the area. Its application over the last decade allows to map ground displacements all over the Veneto Region with good accuracy and with spatial coverage never available in the past, even if the displacement rates are generally rather small and the study area large.

The SIMS results show that the general stability of the central part of the study area contrasts with the sinking trend of the northern and southern coastland extremities ranging between 5 and 15 mm/a. The geodynamic, geological, geomorphological characteristics of the region, the presence of human activities and the knowledge of the cause-and-effect relationships well support the displacement rates provided by SIMS. The outcome itself obtained by the SIMS allows for a significant review the Veneto regional geodynamics.

Continuous monitoring of land subsidence is a need both in the Venice lagoon, for the importance of the environment and historical heritage of the city, and in the adjacent coastal areas whose present sinking rates raise concern over the Veneto coastland.

An integrated survey like SIMS appears the best way to investigate the regional land vertical displacements, capable of keeping under full control the future evolution of the occurrence, improving the qualitative and quantitative analysis of subsidence.

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