Giornale di Geologia Applicata 1 (2005) 5 –11, doi: 10.1474/GGA.2005-01.0-01.0001

Land Subsidence in the Venetian area: known and recent aspects

Carbognin Laura[1], Teatini Pietro[2], Tosi Luigi[1]

[1] ISMAR (ex ISDGM) - Italian National Research Council, San Polo 1364, 30125 Venezia, Italy
[2] DMMMSA, University of Padova, via Belzoni 7, 35131 Padova, Italy

ABSTRACT. The paper reviews three major factors responsible for the relative land settlement occurred in the Venice lagoon area over the XX century. The anthropogenic geomechanical subsidence, induced by groundwater over-exploitation, the geological subsidence, and the eustatic sea level rise have lowered Venice of about 23 cm with respect to the m.s.l.. Other causes deeply studied over the last years are: a) land sinking due to the expected gas production from the Chioggia-Mare reservoir, but the development project is to date shelved despite the reassuring results obtained by a modeling analysis, and b) geochemical subsidence due to peat oxidation and salinisation of clayey sediments taking place in the southern catchment of the Venice lagoon. Finally, an integrated subsidence monitoring system, based on leveling, GPS, and InSAR techniques, has been elaborated and used to provide a comprehensive image of the land displacements in the Venice region over the past decade.

Key terms: Geological subsidence, Geomechanical subsidence, Geochemical subsidence, Eustacy, Saltwater intrusion, InSAR

Introduction

The subsidence of Venice is a problem which came to light at the beginning of the 1960s, since when the city has been ever more frequently subjected to *acqua alta* events (a local idiom meaning flooding). This case history is surely one of the most famous in the world, due not to the amount of sinking but to the special prestige of the city, which risks to disappear into the lagoon. The physical structure of the city is, in fact, characterized by the presence of historic buildings – some of which were constructed more than six centuries ago – in direct contact with the lagoon water and with the ground level only a few tens of centimeters above normal high tide level.

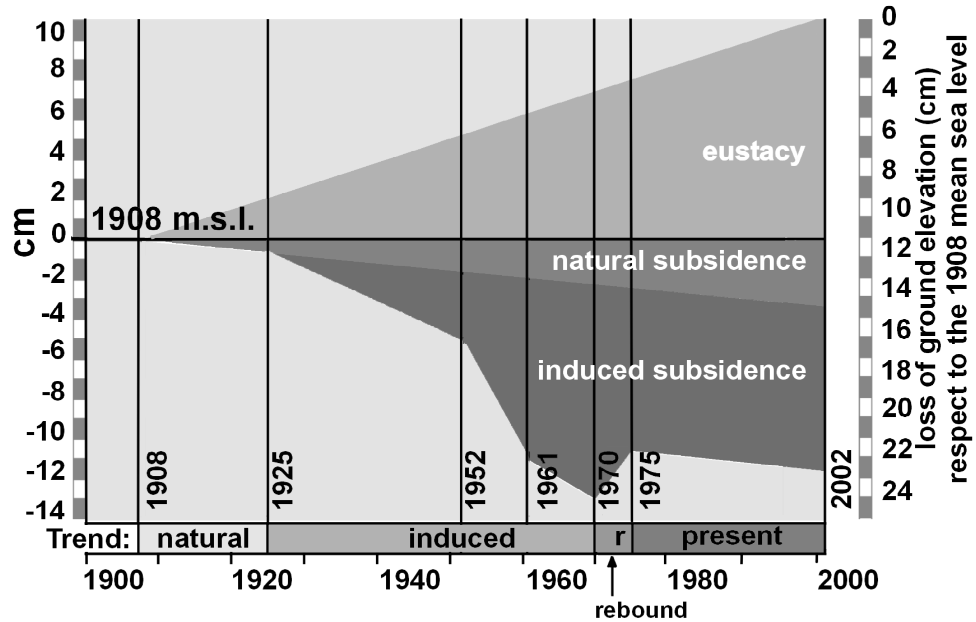

FIG. 1 - Graphical representation of the three components of the relative ground elevation loss at Venice consisting of about 3 cm of natural subsidence, 9 cm of anthropogenic subsidence, and 11 cm of sea level rise (updated after GATTO & CARBOGNIN, 1981).

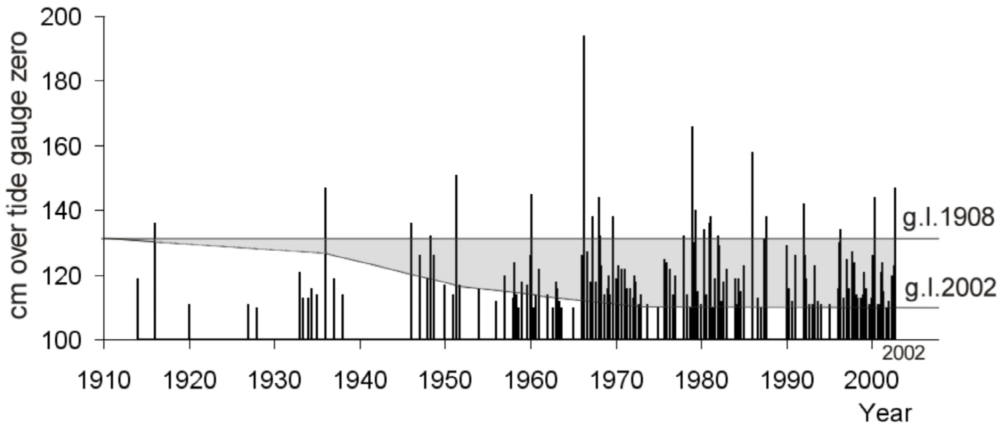

FIG. 2 – The frequency increase of the *acqua alta* events greater than 110 cm above tide gauge zero induced at Venice by the relative land settlement (updated after GATTO & CARBOGNIN, 1981).

TABLE 1- General plan of interventions: implementation as of 31 December 2002 (updated after CARBOGNIN *ET ALII*, 2000).

SHORELINE DEFENCE WORKS	The nourishment of 38 km of the coastal strip provides a safeguard against flooding for events with return period of 300 years. Restoration of 8 km of coastal dunes
LOCAL FLOODING DEFENCE WORK Waterfront recostructions 70 km Defence of populated centres 1,100 ha	Passive defence works against more frequent flooding, to al level of 110 cm in the historic town center of Venice and 170 cm in the minor populated centers of the lagoon.
ENVIRONMENTAL INTERVENTIONS **Recovery of the lagoon morphology** Channel maintenance (120 km; 7,5 million m^3 dredging volume) Construction and reinforcement of wetlands (700 ha; volume 6,5 million m^3 reuse of dreging sediments) Arrest of erosion on 11 smaller islands **Arrest of deterioration of the lagoon environment** Clearing of four dumps Embanbkments - industrial channels (8,4 km) Dredging - industrial channels (280,000 m^3) Costruction of two areas for phytopurification	The **wetlands** consist of *mudflats* and *saltmarshes*: the mudflats are areas in the shallow which emerge under certain tide conditions; the saltmarshes are the areas situated at an elevation comprised within the tidal excursion range (between 0 and 40 cm a.s.l.). The planned interventions are aimed at withstanding the tendency toward erosion, triggering at the same time processes of rinaturalization, which would determine an improvement in the quality of the water and the environment.
EXCLUSION OF OIL - TANKER TRAFFIC Preliminary design approved	Reduction of the risk of serious accidents in the lagoon building an off - shore terminal.
OPENING OF THE FISH FARMS Working design completed Pilot project - 1 fish farm (Valle Figheri) opened under varying conditions.	Assessment of the enviromental effects of reopening the fish farms along the mainland shore of the lagoon.
INTERNAL NAVIGATIONAL AIDS Illuminated route along the oil - tanker channel (12 km).	Navigation aids have been installed, allowing the safe transit of shipping at night and in fog conditions.
MOSE SYSTEM Propaedeutic study; REA design; Preliminary design; E.I.S.; Final design; Executive design of the breackwaters of Malamocco and Chioggia (complementary works)	The breackwater of Malamocco are under construction; by the end of 2003 constructing of the breackwater of Chioggia will start.

Detailed studies on subsidence in Venice, its lagoon, and its hinterland have been performed starting around 1970 by a team of scientists at the Venice C.N.R. (Italian National Research Council). As a main result, the role played by three factors, which have induced a loss in land elevation over the last 100 years of about 23 cm, has been quantified (FIG. 1). In other words, the Adriatic Sea level *has risen* by 23 cm with respect to the ground level and has contributed not only to flooding intensification (FIG. 2), as the most "spectacular" consequence in the historical city, but has also triggered erosion and other unfavorable hydraulic processes inside the lagoon basin. The relative land lowering has also led to greater fragility in the littoral, increasing the nearshore bottom slope (CARBOGNIN *ET ALII*, 1995a) and the risk of flooding from overtopping; thus, expensive interventions are required for the environmental protection and restoration planned by Venice Water Authority (TABLE 1).

Most recent research topics on land subsidence in the Venice region deal with the geochemical subsidence caused both by soil loss due to peat oxidation and the sediment salinization induced by a spread in saltwater intrusion, the expected land settlement due to a program of offshore natural gas withdrawal, and the development of an integrated monitoring approach to accurately check land movements in the whole territory surrounding the lagoon.

Geological subsidence

Land subsidence (η) has forever been occurring in the Venetian region at variable rates depending on the geological events. The average long-term subsidence rate is less than 0.5 mm/yr and reflects mainly tectonic processes (KENT ET *ALII,* 2002), while that of the Late Pleistocene-Holocene period, $\eta_{mean} \cong 1.3$ mm/yr, reflects mainly the consolidation of sediments, which has played the major role during the lagoon's natural evolution stage. The average rate of 1.3 mm/yr decreased over recent centuries, reaching the current figure $\eta_{mean} \leq 0.5$ mm/yr (GATTO & CARBOGNIN, 1981; BORTOLAMI *ET ALII*, 1984; BRAMBATI *ET ALII,* 2003).

Anthropogenic subsidence

Geomechanical subsidence

Geomechanical subsidence refers to the sediment compaction as the result of subsurface fluid removal.

Groundwater withdrawal

Progressive exploitation of the six artesian aquifers, located in the upper 350 m of the 1000-m-thick unconsolidated Venetian Quaternary formation, began in the 1930s with the first industrial installations, grew with the post-war industrial development, and peaked in the 1950-1970 period, together with the subsidence velocity ($\eta_{mean} \cong 2,5$ mm/yr). Drastic measures to curtail artesian overexploitation were taken starting from 1970; the subsidence rates slowed down, coming to a stop in 1973 and a slight but significant rebound of about 2 cm was measured in Venice by the 1975 leveling survey (see FIG. 1) (CARBOGNIN *ET ALII*, 1977; CARBOGNIN *ET ALII*, 1995b). A further piezometric increase was measured thereafter, and the stability of Venice and the adjacent mainland was also verified in 2000 by a regional leveling survey (TOSI *ET ALII*, 2000) and in 2002 by an integrated monitoring system (TOSI *ET ALII*, 2002; STROZZI *ET ALII,* 2003). The subsidence rates (1-3 mm/yr) recorded recently along the coastline and at the furthermost northern and southern lagoon boundaries are correlated with local processes, such as restricted groundwater exploitations and a more active sediment consolidation caused by the subsoil depositional history of these areas.

Land subsidence due to groundwater withdrawal has also been studied with mathematical models. The first 2-D mathematical model to simulate the anthropogenic land subsidence in Venice was developed in the 1970s. A two-step simulation approach consisting of a regional hydrologic model and a local subsidence model was used (GAMBOLATI & FREEZE, 1973; GAMBOLATI *ET ALII*, 1974). Simulation results showed a land settlement of about 15 cm in Venice over the period during which there were extensive groundwater withdrawals (1930-1973), with the main responsibility for the subsidence of the historical city placed on the heavy industrial pumping at Marghera. Moreover, the model demonstrated the almost complete irreversibility of the aquitard compaction ($\cong$ 85%) and the efficacy of a partial or total shutdown of the artesian wells to stop the process. A more recent quasi 3-D nonlinear finite element model was developed in the 1990s removing the main limitations of the previous study, i.e. the linearity of the hydro-geologic parameters characterizing the formations and the simplified aquifer system geometry (TEATINI *ET ALII*, 1995; GAMBOLATI & TEATINI, 1996). The new model confirmed the results obtained in the 1970s.

Gas Withdrawal

Land subsidence is also to be expected as a consequence of the gas production planned in the *Chioggia Mare* field. It is the largest reservoir in the Upper Adriatic coastal area, whose gravity center is about 25 km from Venice and 10 km from the city and littoral of Chioggia (see location in Fig. 5). A very accurate reconstruction of the complex geological structure of the *Chioggia Mare* reservoir and the hydraulically connected aquifer was made. A three-dimensional finite element model was developed to simulate the compaction of both the gas-bearing formations and the lateral/bottom aquifer and the transference of the deep compaction to the ground surface. The major results obtained from the study were that the largest settlement of 12 cm occurred offshore over the reservoir at the end of the planned field production life (13 years), while Venice is not expected to subside, and the Chioggia and the littoral may subside to approximately 1 cm (BAÙ *ET ALII*, 2000; TEATINI *ET ALII,* 2000). In any case, the Minister of the Environment has forbidden the exploitation of the *Chioggia Mare* reservoir and the planned project is to date shelved.

Geochemical subsidence

Land sinking induced both by peat soil oxidation and salinization of clayey sediments has been studied for the last five years.

Peat oxidation

Land subsidence involves peaty areas in response to drainage for agricultural purposes. Drainage of reclaimed lands leads the organic soils to aerobic conditions, and thus the microbial activity can oxidize the carbon in the peat causing carbon loss in the form of gaseous CO_2 and hence land settlement. This process has induced worldwide subsidence rates varying from about 1 to more than 10 cm/yr.

Agricultural reclaimed lands characterized by the presence of soils with high organic content are located in the southeastern part of the Veneto Region. A test-area of about 23 km^2, located in the south of the Venice Lagoon and approximately 10 km from the Adriatic Sea, has been selected to study the process by means of field experiments and mathematical models. It has been proved that an overall local settlement of about 1.5 m has occurred during the last fifty years (nowadays, the ground surface lies here almost entirely below mean sea level, mostly between -2 and -4 m). The research has demonstrated that the present average subsidence rate caused by organic soil oxidation is between 2 and 3 cm/yr (FORNASIERO *ET ALII*, 2003; GAMBOLATI *ET ALII*, 2005 a and b). This result is somehow confirmed by the significantly smaller displacement rates (less than 1 cm/yr) measured by high precision leveling surveys since the end of the 19th century along a leveling line adjacent to the study basin and running on a street embankment where oxidation of organic soils is precluded (TOSI *ET ALII*, 2000).

Saltwater intrusion

It is known that a change in the chemical character of the clayey interstitial water, i.e. the substitution of freshwater with saltwater, enhances the sediment compaction because of electrochemical processes (U.S. GEOLOGICAL SURVEY, 1964). Earlier knowledge has suggested that the research should be carried out using different criteria for the different

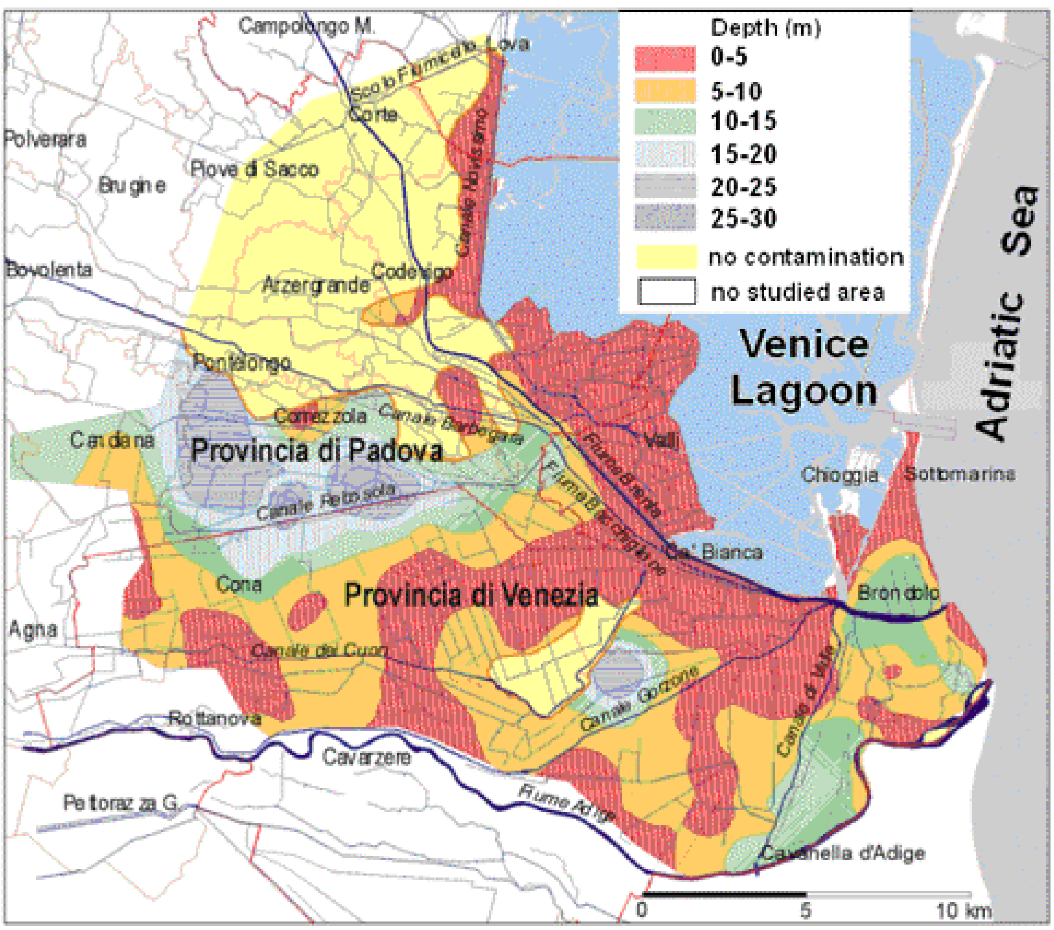

FIG. 3 –Depth (m) of the fresh-salt water interface in the southern catchment of the Venice Lagoon (CARBOGNIN & TOSI, 2003).

parts of the Venetian territory. The northern area seems not to be significantly involved by the phenomenon. In the central zone the risk of saltwater intrusion involves the exploited multiaquifer system, which might be threatened by a vertical encroachment from the overlying lagoon and the underlying fossil saltwater, and laterally from the seawater. In the southern areas, mostly in the lagoon southern catchment, saltwater contamination mainly involves the phreatic water used especially for agriculture purposes.

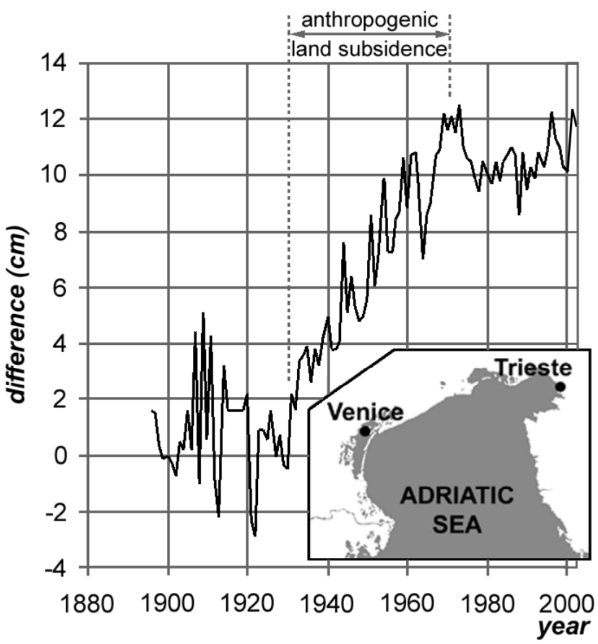

FIG. 4 - Difference between the mean sea level at Venice and Trieste vs. time (updated after TOSI *ET ALII*, 2002). The increasing difference in the period 1931-1970, during which anthropogenic subsidence occurred, seems to indicate an anomalous rise of sea level at Venice with respect to Trieste, while no such anomaly is recorded before and after (after CARBOGNIN & TARONI, 1996). The constancy in the differences from 1971 up to 2002 confirms that land vertical movements in Venice have been negligible for the last 30 years. The location of Trieste with respect to Venice is shown in the inserted map.

Saltwater intrusion in the central part of the lagoon area was studied with a 2-D finite element model coupling water flow and salt transport. The results showed negligible saltwater intrusion in the aquifer system on a short time-scale, whereas on a century time-scale the contamination could progressively involve the coastal area up to the mainland. In the upper part, down to a depth of 200 m, a ≥3.5 g/l salt concentration could occur mainly due to the vertical seepage from the lagoon, while a higher concentration (3.5 - 14 g/l) caused by intrusion of fossil waters might affect the deeper strata (BIXIO *ET ALII*, 1998).

In the territories bounding the southern lagoon and the Chioggia littoral the research has been developed by a number of interrelated multidisciplinary studies that have allowed the extent, the modality, and the causes of the aquifer saltwater intrusion to be evaluated. Although not the whole area is presently subject to saline contamination, a very serious situation has been brought to light: the freshwater/saltwater interface is between 0 to 10 m deep, varying with hydraulic and weather conditions, and extends up to 20 km inshore (FIG. 3). Both the tide-water flowing upward within the watercourses and the influence of many geological and sub-surface geomorphological structures play an important role in the dynamics of the process. (CARBOGNIN & TOSI 2003; RIZZETTO *ET ALII*, 2003).

Sea Level Rise

The average linear eustatic rate of 1.13 mm/yr characterizing the Adriatic Sea behavior during the last century (see FIG. 1) is comparable with the data provided by other tide gauges in the Mediterranean. Actually, tide gauge measurements clearly show an up-and-down behavior in the mean sea level depending upon short-term climatic fluctuations. In particular, the existence of a non-unique secular trend for Venice due to the influence of anthropogenic subsidence was statistically verified (CARBOGNIN & TARONI, 1996). Differences between tide gauge values recorded at Venice and Trieste from 1896 to 2000 are shown in Fig. 4. The most recent measurements indicate that both at Venice and Trieste the mean sea level has undergone an abrupt rise in the last years (≅ 6.8 cm from 1994 to 2002). The mean rate linearly calculated for the period 1971-2002 has increased to about 1.5 mm/yr, a significant figure considering that no sea level rise occurred between 1971 and 1993 (CARBOGNIN *ET ALII*, 2004).

Conclusive remarks

Land subsidence mainly due to groundwater withdrawals has represented one of the most serious environmental problems for the Venice Lagoon during the last decades, increasing the vulnerability of the historical city, the littorals and the nearby mainland. Once the cause-and-effect relationship was defined, and countermeasures were taken, the induced subsidence at Venice stopped. The research is presently focused on improving the knowledge of the complex subsidence process which still today affects vaster areas outside the Lagoon, and to understand the different causes related to the geological regional history and human activities. The more compressible Holocene sediments located in the southern and northern sectors of the lagoon territory are responsible for natural settlement rates being greater than elsewhere (≅ 2 mm/yr); the organic soil oxidation in reclaimed southern areas led to an overall local settlement of about 1.5 m during the last fifty years and has been inducing sinking rates of up to 3 cm/yr; the tectonics, the consequences of the saltwater intrusion, the role covered by sea level rise and the expected land subsidence due to gas production from offshore fields are also topics of studies. Particular attention has recently been addressed to the monitoring systems. Until 1993, surveys in the Venice region were based on a few leveling lines starting inland and running along the coast and the lagoon edges, with only the city of Venice controlled by a fine grid of benchmarks. In recent years, the altimetric network has been updated to cover all the southern part of the lagoon, and a network covering also the northern sector is being set up. The same network used for the leveling surveys was adopted for differential GPS measurements. In addition, differential SAR interferometry and interferometric point target analysis (IPTA) have been used as an integrated system to check land displacements at a high spatial resolution.

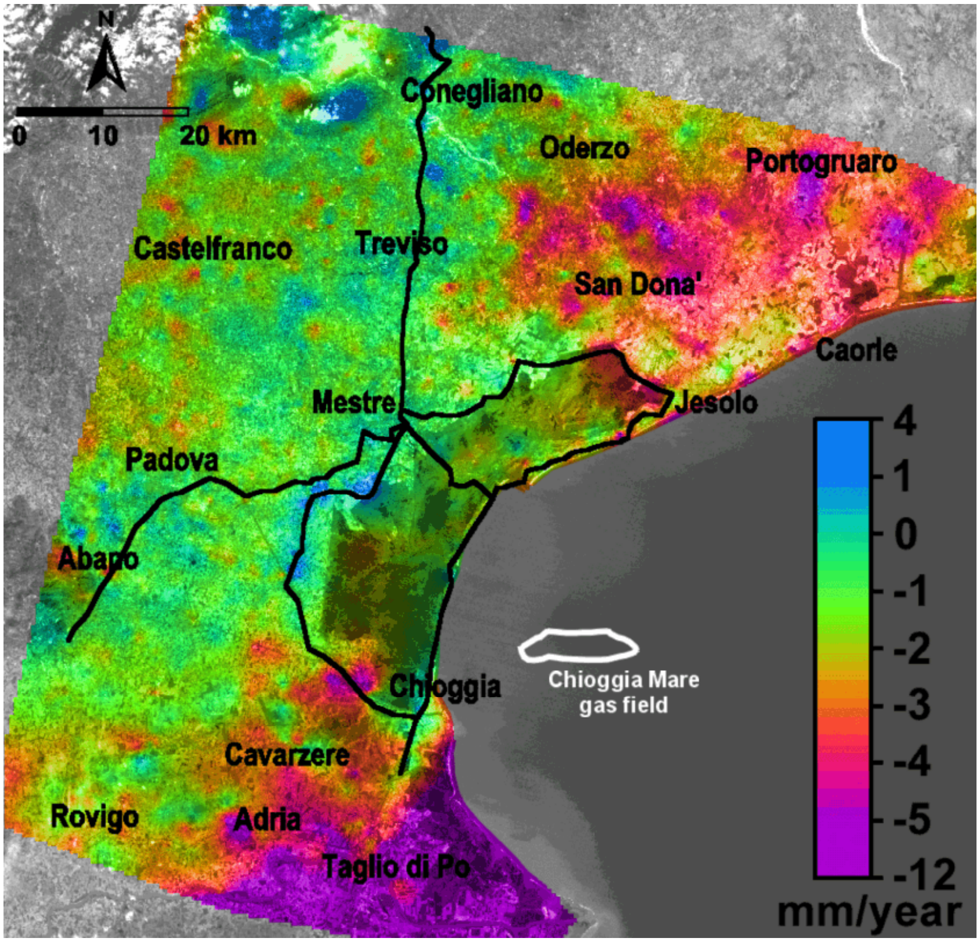

FIG. 5 – Map of vertical regional movement rates during the period 1993-2000 obtained through the integration of the INSAR and leveling measurements (after STROZZI *ET ALII,* 2003). The black lines represent the leveling trace; negative (green to violet) and positive (blue) velocities indicate land subsidence and land uplift, respectively.

A regional pattern of the overall land subsidence, i.e. including all components, has been drawn (FIG. 5) confirming the stability of the central areas, where groundwater overexploitation was the main factor responsible for land subsidence, concurrently with the seriousness of the southern and northern sectors where different components enhance the sinking process. Further studies of this integrated monitoting system are currently underway.

Acknowledgments

Both the 2000 leveling and saltwater intrusion measurements were carried out within the framework of the ISES Project. The monitoring integrated system is performed under the umbrella of the "Venice Project" supported by the European Space Agency (ESA). The Authors thank Jane Frankenfield Zanin, CNR-ISMAR, Venice for her efficient editing of the paper.

References

BAÙ D., GAMBOLATI G. & TEATINI P. (2000) - *Can gas withdrawal from Chioggia Mare field affect the stability of the Venetian littoral*? In: CARBOGNIN L., *et al.* (2000, eds.) - *Land Subsidence,* Vol. II, 421-433, La Garangola, Padova (Italy).

BIXIO A.C., PUTTI M., TOSI L., CARBOGNIN L. &

GAMBOLATI G. (1998) - *Finite Element Modeling of Salt water Intrusion in the Venice Aquifer System.* In: BURGANOS V. N., *et alii* (1998, eds.) - *Computational Methods in Water*

Resources, Vol. II, 193-200, Computational Mechanics Publications, Southampton, UK and Boston, USA.

BRAMBATI A., CARBOGNIN L., QUAIA T., TEATINI P. & TOSI L. (2003) - *The Lagoon of Venice: geological setting, evolution and land subsidence.* Episodes, 26 (3), 264-268.

BORTOLAMI G., CARBOGNIN L. & GATTO P. (1984) - *Natural subsidence in the lagoon of Venice.* In: JOHNSON A. I., *et alii* (1984, eds.) - *Land Subsidence*, 777-784, IAHS Publ. No. 151, Proc. 3rd Int. Symp. on Land Subsidence.

CARBOGNIN L. & TOSI L. (2003) - *Il Progetto ISES per l'analisi dei processi di Intrusione salina e Subsidenza nei territori meridionali delle province di Padova e Venezia*. 94 p & 12 Tavv. f.t. Grafiche Erredici, Padova.

CARBOGNIN L. & TARONI G. (1996) - *Eustatismo a Venezia e Trieste nell'ultimo secolo (Eustasy at Venice and Trieste in the last century)*. Atti Istituto Veneto SS.LL.AA., Classe di Scienze Fis., Mat. e Nat., Tomo CLIV, 33-52 (in Italian).

CARBOGNIN L., CECCONI G. & ARDONE V. (2000) - *Interventions to safeguard the environment of the Venice Lagoon (Italy) against the effects of land elevation loss*. In: CARBOGNIN L., *et alii* (2000, eds.) - *Land Subsidence,* Vol. I, 113-126, La Garangola, Padova (Italy).

CARBOGNIN L., GATTO P., MOZZI G., GAMBOLATI G. & RICCERI G. (1977) - New *trend in the subsidence of Venice.* In: J. C. Rodda (Ed.), *Land Subsidence* (Proc. 2nd Int. Symp. on Land Subsidence), 65-81, IAHS Publ. No. 121.

CARBOGNIN L., MARABINI F., & TOSI L. (1995a) - *Land subsidence and degradation of the Venice littoral zone, Italy.* Keynote lecture in: BARENDS J.F., *et alii*. (1995, eds.) - *Land Subsidence*, 391-402, IAHS Publ. No. 234.

CARBOGNIN L., TOSI L. & TEATINI P. (1995b) - *Analysis of actual land subsidence in Venice and its hinterland (Italy).* In: BARENDS J.F., et alii (1995, eds.) - Land Subsidence, 129-137, A. A. Balkema, Rotterdam.

CARBOGNIN L., TEATINI P., & TOSI L. (2004) - *Eustasy and land subsidence in the Venice Lagoon at the beginning of the new millennium.* Journal of Marine Systems, in press.

FORNASIERO, A., PUTTI M, TEATINI P, FERRARIS S, RIZZETTO F & TOSI L. (2003) - *Monitoring of hydrological parameters related to peat oxidation in a subsiding coastal basin south of Venice, Italy.* In: SERVAT E., *et alii* (2003, eds.) - Hydrology of Mediterranean and Semiarid Regions, 458 - 462, IAHS Publ. No. 278.

GAMBOLATI G. & FREEZE R.A. (1973) - *Mathematical simulation of the subsidence of Venice. 1: Theory.* Water Resour. Res., 9 (3), 721-733.

GAMBOLATI G. & TEATINI P. (1996) - *A block iterative finite element model for non-linear leaky aquifer systems*. Water Resour. Res., **32** (1), 199-204.

GAMBOLATI G., GATTO P., & FREEZE R.A. (1974) - *Mathematical simulation of the subsidence of Venice.2: Results.* Water Resources Research, **10** (3), 563-577.

GAMBOLATI G., PUTTI M., TEATINI P., FERRARIS S., GASPARETTO STORI G.,NICOLETTI V., RIZZETTO F., SILVESTRI S. & TOSI L.(2005a) – *Peatland oxidation enhances subsidence in the Venice watershed.*EOS Transactions AGU, in press.

GAMBOLATI G., PUTTI M., TEATINI P., & GASPARETTO STORI G.(2005b) - *Subsidence due to peat oxidation and impacts on drainage infrastructures in a farmland catchment south of the Venice Lagoon.* Environmental Geology, in press.

GATTO P. & CARBOGNIN L. (1981) - *The Lagoon of Venice - natural environmental trend and man-induced modification*. Hydrological Sciences Bulletin, **26**/4/12, 379-391.

KENT V.D., RIO D., MASSARI F., KUKLA G. & LANCI, L. (2002) – *Emergence of Venice during the Pleistocene*. Quaternary Science Review, **21,** 1719-1727.

RIZZETTO F., TOSI L., CARBOGNIN L., BONARDI M. & TEATINI P. (2003) – *Geomorphic setting and related hydrogeological implications of the coastal plain south of the Venice Lagoon (Italy)*. In: SERVAT E., *et alii* (2003, eds.) – *Hydrology of Mediterranean and Semiarid Regions*, 458-462, IAHS Publ. No. 278.

STROZZI T., TOSI L., WEGMÜLLER U., WERNER C., TEATINI P. & CARBOGNIN L. (2003) – *Land subsidence monitoring service in the Lagoon of Venice*. IGARSS'03, Toulouse, France, 21-25 July 2003, Proceedings in CD-ROM.

TEATINI P., BAÙ D. & GAMBOLATI G. (2000) – *Water-gas dynamics and coastal land subsidence over Chioggia Mare field, Northern Adriatic Sea*. Hydrogeology Journal, **8** (5), 462-479.

TEATINI P., GAMBOLATI G. & TOSI L. (1995) - *A new 3-D non-linear model of the subsidence of Venice.* In: BARENDS J.F., *et alii* (1995, eds.) - *Land Subsidence,* 353-361, IAHS Publ. 234, UK.

TOSI L., CARBOGNIN L., TEATINI P., ROSSELLI R. & GASPARETTO STORI G. (2000) - The *ISES Project: subsidence monitoring of the catchment basin south of the Venice Lagoon, Italy*. In: CARBOGNIN L., *et alii* (2000, eds.) - *Land Subsidence*, Vol. II, 113-126, La Garangola, Padova (Italy).

TOSI L., CARBOGNIN L., TEATINI P., STROZZI T. & U. WEGMÜLLER (2002) - *Evidences of the present relative land stability of Venice, Italy, from land, sea, and space observations*. Geophys. Res. Lett. **29** (12) 10.1029/2001GL013211, 2002.

U.S. GEOLOGICAL SURVEY (1964) – *Removal of Water and Rearrangement of Particles During the Compaction of Clayey Sediments-Review*. (By Meade R.H.). U.S.G.S Professional Paper 497-B, 23p, U.S. Gov. Print. Office, Washington, D.C. 20402.