SUBSIDENCE DUE TO PEATLAND OXIDATION IN THE VENICE LAGOON CATCHMENT

GIUSEPPE GAMBOLATI[1], MARIO PUTTI[1], PIETRO TEATINI[1], MAURIZIO BONARDI[2], MATTEO CAMPORESE[3], STEFANO FERRARIS[4], GIUSEPPE GASPARETTO STORI[5], VINCENZO NICOLETTI[6], FEDERICA RIZZETTO[2], PAOLO SALANDIN[7], SONIA SILVESTRI[6] AND LUIGI TOSI[2]

[1] *Dipartimento di Metodi e Modelli Matematici per le Scienze Applicate, Università di Padova*
[2] *Istituto di Scienze Marine, CNR*
[3] *Dipartimento di Ingegneria Idraulica, Marittima, Ambientale e Geotecnica, Università di Padova*
[4] *Dipartimento di Economia e Ingegneria Agraria, Forestale e Ambientale, Università di Torino*
[5] *Consorzio Bonifica Adige-Bacchiglione*
[6] *Sistema Informativo, Magistrato alle Acque di Venezia*
[7] *Istituto di Idraulica e Infrastrutture Viarie, Università Politecnica delle Marche*

Riassunto.

La Laguna di Venezia è caratterizzata da una morfodinamica apprezzabile non solo su periodi geologici ma anche in tempi storici e moderni. Un importante cambiamento nell'area meridionale lagunare si è verificato nel secolo scorso con la bonifica di vaste zone e la loro trasformazione in fertili territori agricoli. I suoli bonificati contengono elevati quantitativi di torbe che, a contatto con l'aria, si ossida rilasciando in atmosfera anidride carbonica e causando una continua perdita di massa dal terreno. La subsidenza antropica indotta da questo processo geochimico ha abbassato l'altimetria di molte zone ben al di sotto del livello medio del mare e della laguna, con problemi crescenti di rischio idrogeologico e maggiori costi di gestione della bonifica. La subsidenza in oggetto è stata quantificata in 1.5 m durante gli ultimi 70 anni, con una velocità attuale di abbassamento di 1.5-2 cm/anno. La reazione geochimica che controlla l'ossidazione della torba dipende principalmente dalla temperatura e dall'umidità del terreno. A questo riguardo le pratiche agronomiche ed il franco di bonifica giocano un ruolo assai importante. All'interno di un piccolo bacino (24 km^2) posto in prossimità del margine lagunare e ben delimitato dal punto di vista idrologico (Bacino Zennare) è stato allestito un campo sperimentale per la misura dei movimenti del terreno e delle principali grandezze idrologiche che controllano il processo di ossidazione. Le misure in-situ, integrate con dati telerilevati, hanno consentito la modellizzazione della subsidenza antropica e dei principali processi di interesse e l'individuazione di possibili strategie di mitigazione.

Abstract.

The Venice Lagoon is characterized by a fast morphodynamics appreciable not only over the geological scale but also in historical and modern times. The lagoon environment proves very sensitive to even minor modifications of the natural and anthropogenic controlling factors. An important human endeavor accomplished in the past century is the reclamation of the southernmost lagoon area that has been turned into a fertile farmland. The reclaimed soil is reach in organic matter (peat) that may oxidize with release of carbon dioxide to the atmosphere. The continuous loss of carbon is causing a pronounced settlement of the farmland that lies below the present sea/lagoon level. This enhances the flood hazard and impacts noticeably on the maintenance and operational costs of the drainage system. Total peatland subsidence is estimated at 1.5 m over the last 70 years with a current rate of 1.5-2 cm/year. The geochemical reaction is primarily controlled by soil water content and temperature, and is much influenced by agricultural practices, crop rotation, and depth to the water table. A small (24 km^2) controlled catchment located in the area has been instrumented for accurately monitoring the basic parameters and recording the ground motion. The in situ measurements have been integrated with the combined use of remote sensing data to help cast light on the process and identify the mitigation strategies.

1. Introduction.

According to some authors [Bortolami *et al.*, 1984; Brambati *et al.*, 2003] the Venice Lagoon was born about 6000 years and was much smaller than it appears today [Gatto and Carbognin, 1981]. The lagoon communicates with the Adriatic Sea through three inlets (Fig. 1) that were nine around 1000 AD. The original inflowing rivers, i.e. Adige, Bacchiglione, Brenta, Piave and Sile, were diverted to the sea by the "Serenissima" Republic to avoid the lagoon fill-in. More recently natural and anthropogenic land subsidence, mean sea level rise and deepening of a few channels for internal navigation have promoted a dominant marine-type environment [Gatto and Carbognin, 1981]. The southernmost part of the lagoon catchment was progressively reclaimed starting from the end of the XIX century and finishing in the late thirties (Fig. 1). As a major result the area was turned into a fertile farmland at present kept dry by a distributed drainage system that collects the water from a capillary network of ditches and canals and pumps into the lagoon or the sea. By its very origin this area lies below the sea level and progressively lowers in close connection with the agricultural practices on the reclaimed farmland. Anthropogenic land subsidence raises a number of serious environmental concerns and economical issues ranging from the enhanced risk of inundation during the frequent Adriatic winter storms, to a larger salt contamination from the intruding sea water [Tosi *et al.*, 2004], to the need for increasing the power of the pumping stations and the depth of the canal beds, i.e. the maintenance cost [Gambolati *et al.*, 2005a].

To study the land settlement that plagues this area of high economical value for the Venice watershed the VOSS (Venice Organic Soil Subsidence) project was undertaken with the primary objective to understand the process underlying the anthropogenic event, quantifying the past and present subsidence rate and advancing possible remedial measures without penalizing the economy of the area. The study, conducted in close collaboration with the Land Reclamation Authority (Consorzio di Bonifica) and the farmland owners, is focused on a hydrologically controlled catchment, the Zennare Basin, located just south of the Venice Lagoon and characterized by the presence of wide peat areas.

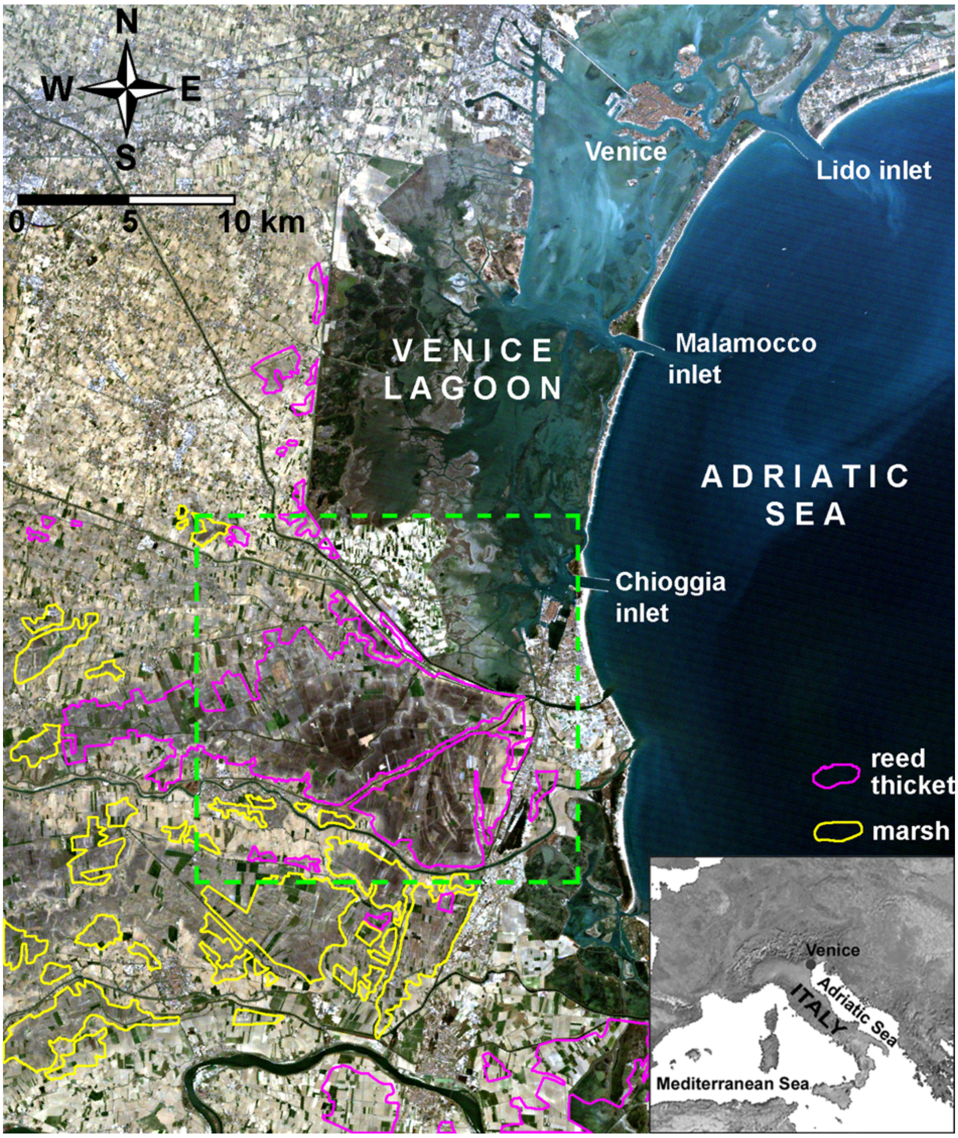

Fig. 1 – View of the Venice watershed with the map of the reedy and marshy areas drawn in 1833 during the Lombardo-Veneto kingdom and reclaimed in the past century. The green dashed box identifies the location of the map reported in Fig. 3 (after Gambolati *et al.* [2005b]).

2. Geochemical Land Subsidence.

Land subsidence is a major consequence of the oxidation of the soil organic fraction in the upper aerated agricultural zone and has been reported from other similar areas around the world as well [Stephens *et al.*, 1984; Rojstaczer and Deverel, 1995;

Nieuwenhuis and Schokking, 1997; Wösten *at al.*, 1997]. The geochemical reaction of interest can be represented as follows:

$$C_6H_{12}O_6 + 6O_2 = 6CO_2 + 6H_2O \quad (1)$$

The release of carbon dioxide to the atmosphere causes a soil mass loss which manifests itself as land subsidence. The organic soil is in the form of amorphous granular peat derived from the accumulation and decomposition of reeds (*Phragmites Australis*) grown in the ancient marshy area of the lagoon surroundings, where the above reaction could not occur due to anaerobic conditions. After reclamation, aerobic conditions were established in the upper soil (few tens of centimeters). Moreover the seasonal ploughing contributes to the exposition of new organic material to the atmosphere promoting new subsidence. The reaction is controlled by temperature and is limited by the presence of oxygen. Therefore, the lower the degree of water saturation in the subsoil and the higher the ambient temperature the faster the reaction rate. The depth of the subsurface water table affects the soil water content and the zone of aeration and hence the exposure of soil to oxygen. Since the water table is sensitive to the amount of precipitation, we can conclude that dry and hot seasons are most favorable to the occurrence. By contrast in winter soil oxidation slows down almost to zero. In light of the above we expect that anthropogenic land subsidence in the future might increase should the extreme climate events (i.e. hotter and dryer seasons) become more frequent, as the most recent meteorological records seem to indicate.

3. The VOSS Project.

The area under study was reclaimed from 1897 to 1937 and cumulative average settlement to date varies from 1.5 and 2 m (according to the thickness of the outcropping peaty layer) as is derived from indirect evidence including the protrusion of old structures from the ground (Fig. 2). Comparison of a 1983 DEM (Digital Elevation Model) of the area, obtained from aerophotogrammetry, and a 2002 kinematic DGPS (Differential Global Positioning System) campaign shows an average settlement rate of 2-3 cm/year, or more, over the last 20 years. Recent SAR (Synthetic Aperture Radar) surveys [Strozzi *et al.*, 2003] suggest that the areas where peat is not present are subject to natural subsidence only at a much smaller rate, estimated at a few mm/year [Gatto and Carbognin, 1981; Gambolati and Teatini, 1998; Kent *et al.*, 2002].

The areal extent of peatlands has been investigated using satellite data [Nicoletti *et al.*, 2003]. Several images from the IKONOS, ASTER, and LANDSAT-7ETM+ satellites, which combine high geometric (1 m^2 for IKONOS) and high spectral (6 bands for LANDSAT and 14 for ASTER) resolution, have been analyzed and calibrated against a detailed geomorphologic map of the study area and a large dataset of peat spectral signatures collected in situ using a portable spectrometer. The best results of the spectral analysis have been obtained from a density slice of the synthetic Brightness band obtained from the Tasseled Cap analysis of the LANDSAT data. Scenes collected between February and May provide the best data source as the farmland is already ploughed, so that no crop residues are present on the surface, and vegetation is only partially developed. The delineated peat areas well compare with a 1833 map of the local marshes drawn by government officials of the Lombardo-Veneto kingdom (Fig. 3).

Fig. 2 – Evidence of the anthropogenic land subsidence in the reclaimed area: (a) The protrusion of a sluice well above the bed of an old disappeared channel; (b) An old bridge hanging over the canal bank which settled by 1.5 m.

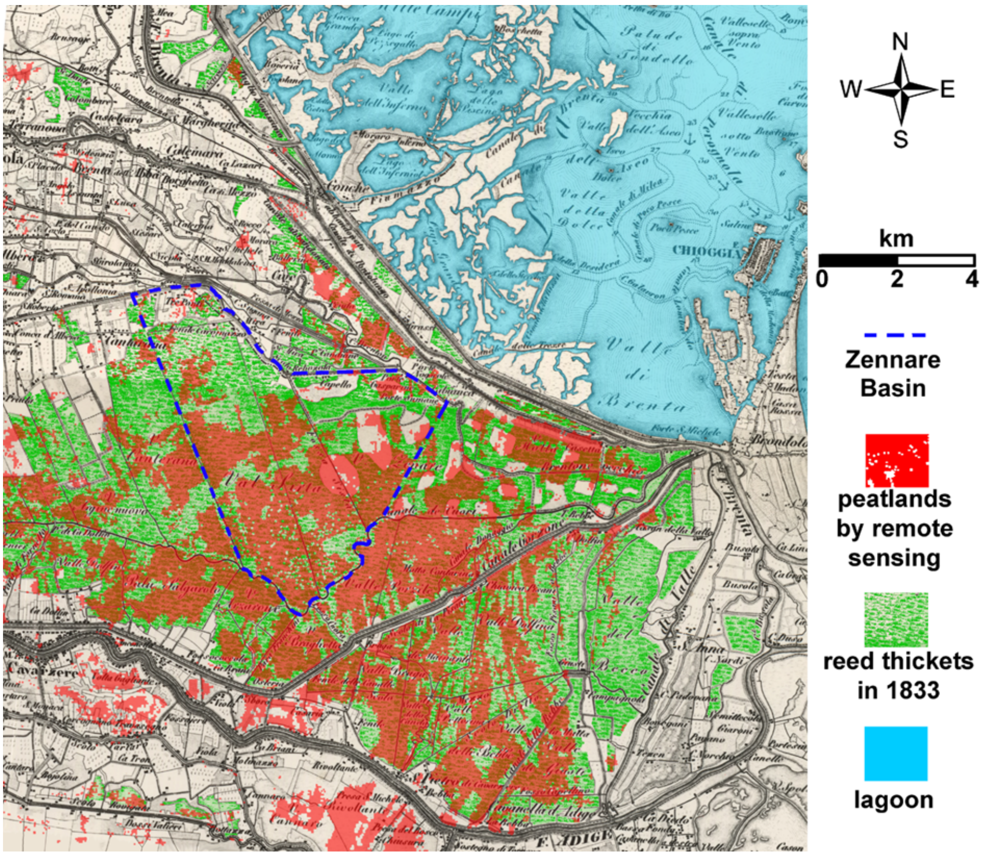

Fig. 3 – Peatland as derived from the spectral processing of the LANDSAT image of March 25, 2003, and superposed on the 1833 wet area. The boundary of the Zennare Basin is highlighted (after Gambolati *et al.* [2005b]).

A number of experimental fields have been instrumented in the Zennare Basin (Fig. 3), in the heart of the reclaimed farmland in the Venice watershed, to monitor the actual land settlement, help understand the process, and predict the future occurrence. The following devices were installed and operated for more than 2 years: rain gauges, anemometer, piezometers, soil temperature probes, tensiometers for capillary pressure, TDR probes for soil water content at 5 different depths, extensometer for land settlement, two NSS (Non Steady State) steel chambers for CO_2 fluxes [Hutchinson and Rochette, 2003] and a micrometeorological station based on the Eddy Covariance technique [Soegaard *et al.*, 2003]. The CO_2 fluxes are converted into an estimate of anthropogenic land subsidence η by the formula [Deveral and Rojstaczer, 1996]:

$$\eta = \frac{f_c}{\rho}\frac{p_c}{p_o} \qquad (2)$$

where:

- f_c is the carbon flux;
- ρ is the soil density (the peaty soil of the area has a ρ slightly larger than water);
- p_c is the percentage of carbon within the organic matter;
- p_o is percentage of organic matter within the soil (approximately equal to p_c).

The data from the NSS chambers, having footprints of a fraction of square meter (Fig. 4a), have been compared with records from the micrometeorological station, characterized by a footprint of the order of few hundreds of square meters. The average rates provided by these two techniques satisfactorily agree over the range 0.02-0.7 mg CO_2/m^2s, i.e. minimum (winter) and maximum (summer) value, respectively [Camporese *et al.*, 2004a]. From this data we readily obtain an estimate of the current anthropogenic land subsidence which ranges between 0.1 and 2 cm/year in winter and summer, respectively.

Experiences carried out with the extensometer (Fig. 4b) indicate that elastic soil deformations superpose on the long trend settlement (Fig. 4c) because of soil swelling (and subsequent shrinkage) that may occur in winter due to freezing and all year long due to rainfall [Camporese *et al.*, 2004b]. The peat soil expansion during a precipitation event can be experimentally related to groundwater table oscillations at a rate of 0.3-0.4 mm per 1 cm increase of the water table level. It is followed by a slower but completely reversible shrinkage (Fig. 4c). An original model fpr the simulation of the swelling/shrinking process in peat soil has been developed. Starting from the experimental observation that most of the deformations take place in the unsaturated zone, the model takes into consideration the variation of porosity with moisture content. A good agreement with published experimental data from laboratory analysis has been found. The model has been implemented into a Richards equation-based numerical code. This code has been applied for the simulation of the peat soil dynamics as measured in the Zennare Basin. The modelling results match very well with a large set of field data and demonstrate that the proposed model allows for an accurate reproduction of soil dynamics (Fig. 5).

On a larger scale (2 years) cumulative anthropogenic subsidence on the order of 2-3 cm is shown. Small or negligible rates characterize the summer and winter periods of the year 2002, when persistent and intensive rainfall events were recorded. Most of the settlement occurred in the very dry and hot summer of 2003. Application of a model developed by Stephens *et. al.* [1984], which relates the subsidence rate to soil temperature and groundwater table depth, allows for reasonably capturing the long term behavior of the settlement process (Fig. 4c).

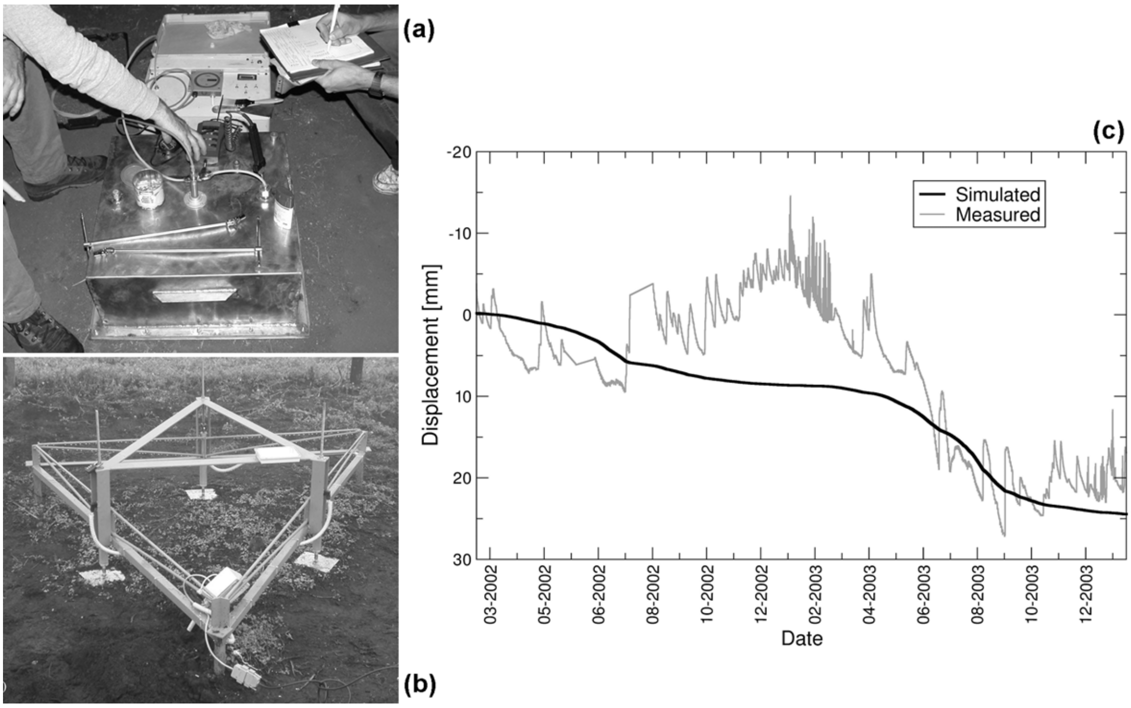

Fig. 4 – (a) NSS (Non Steady State) steel chamber used to measure the pointwise CO_2 released from the soil being oxidized. (b) Extensometer designed to measure the anthropogenic land subsidence due to peat oxidation. (c) Vertical displacement measured by the extensometer from February 2002 to January 2004 and compared with the prediction made by Stephens *et al.* [1984] formula which relates the reaction (and hence settlement) rate to temperature and depth to water table.

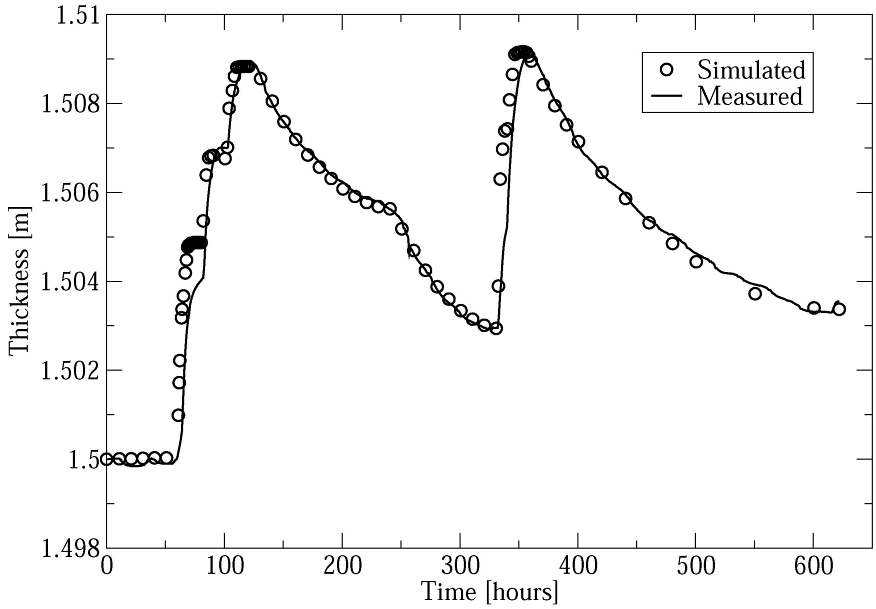

Fig. 5 – Measured and simulated reversible displacement of the peat surface over the period 08/10/2002 – 02/11/2002 (after Camporese *et al.* [2004b]).

4. Concluding Remarks.

Field experiments, data analysis, and modeling applications point to the following conclusions. The reclaimed farmland in the Venice watershed is subject to peat oxidation which has induced a cumulative anthropogenic subsidence between 1.5 and 2 m over the last century. Ground and remote sensed records provide evidence that land settlement has progressed at the rate of 2 cm/year or more during the last 20 years. The ad hoc extensometer exhibits a present trend of 1.5 cm/year while direct CO_2 measurements indicate up to 2 cm/year. These three independent measurement techniques agree very satisfactorily. Elastic reversible deformations related to soil freezing and rainfall may superpose on the long trend ground motion and make its pointwise interpretation very difficult.

If no remedial strategies are implemented in the near future and soil oxidation continues at the present rate, the entire peat layer is bound to disappear in about 50 years. This might cause an additional 75-100 cm of anthropogenic land subsidence with extremely negative consequences for the environment and the economy of the area. Since the process is accelerated during dry and hot summers, climate events, such as the 2003 summer, have a highly adverse impact. The extensometer data obtained in 2002 indicate that settlement can be mitigated by keeping a very low groundwater table depth. Scenarios using Stephens *et al.* model [1984] and calibrated on the available records suggest that, if the 2003 temperatures are projected into the future, the remaining peat layer will completely disappear in approximately 65 years for a constant water table depth of 60 cm. On the other hand, about 200 years would be needed to oxidize the peat if a more reduced water table depth of 20 cm is constantly maintained (Fig. 6).

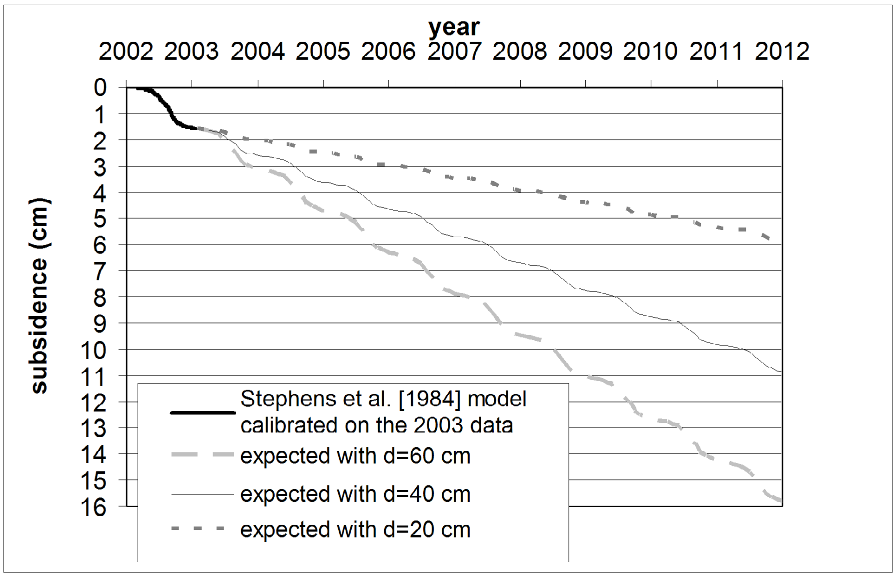

Fig. 6 – Expected land subsidence over the next decade as computed by the Stephens *et al.* [1984] model calibrated on the 2003 measurements collected at the Zennare Basin. The three scenarios assume the 2003 temperature and a constant water table depth of 20, 40, and 60 cm. Based on these data a 1 m thick peat layer would vanish in about 180, 90, and 65 years, respectively.

However, to become a management strategy of a practical use, shallow phreatic surface needs to coexist with the local agricultural practices. This can be achieved only if an accurate and timely control of the drainage system and the pumping station is planned, possibly with the aid of forecasting models, so that the water table depth can be kept at the minimum level consistent with the crop requirements. Introduction of different agricultural practices may also help reduce land settlement. For example, conservative tilling as a substitute to ploughing may help decrease the exposure of unmineralized peat to atmosphere while the introduction of cover crops may partially counterbalance the loss of organic material, as is also indirectly suggested in a much more general analysis of soil carbon sequestration at the global worldwide scale [Lal, 2004].

Acknowledgments.

This work has been funded by CORILA Research Programme 2000-2003. The contributions from Sistema Informativo MAV-CVN, Consorzio di Bonifica Adige – Bacchiglione, Te.Ma S.n.c., A.T.A. Studio Associato, Pergeo S.n.c., GeoTea S.r.l., Comune di Cavarzere, Comune di Chioggia, and Comune di Cona are gratefully acknowledged.

References.

Bortolami G., Carbognin L. and Gatto P., 1984. The natural subsidence in the Lagoon of Venice, Italy. In: Johnson A. I. *et al.* (Eds.), *Land Subsidence (Proc. III Int. Symp. on Land Subsidence)*, IAHS Publ. No.151, 777-784

Brambati A., Carbognin L., Quaia T., Teatini P. and Tosi L., 2003. The Lagoon of Venice: geological setting, evolution and land subsidence. *Episodes* 26, 264-268

Camporese M., Putti M., Salandin P. and Teatini P., 2004a. Spatial and temporal variability of CO_2 flux from a peatland south of Venice. In: J. Päivänen J. (Ed.), *Wide Use of Peatlands* (*Proc. XII Int. Peat Congress)*, Int. Peat Society Publ., Vol. 1, 117-123

Camporese M., Putti M., Salandin P. and Teatini P., 2004b. Modeling peatland hydrology and related elastic deformation. In: Miller C. T. *et al.* (Eds.), *Computational Methods in Water Resources*, Elsevier, Vol. 2, 1453-1464

Deverel S.J. and 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

Gambolati G. and Teatini P., 1998. Numerical analysis of land subsidence due to natural compaction of the Upper Adriatic Sea basin. In: Gambolati G. (Ed.) *CENAS, Coastline Evolution of the Upper Adriatic Sea due to Sea Level Rise and Natural and Anthropogenic Land Subsidence*, Kluwer Academic Publ., Water Science & Technology Library n.28, 103-132

Gambolati G., Putti M., Teatini P. and Gasparetto-Stori G., 2005a. Subsidence due to peat oxidation and its impact on drainage infrastructures in a farmland south of the Venice Lagoon. *Environ. Geol.* In press

Gambolati G., Putti M., Teatini P., Camporese M., Ferraris S., Gasparetto Stori G., Nicoletti V., Rizzetto F., Silvestri S. and Tosi L., 2005b. Peatland oxidation enhanced subsidence in the Venice watershed. *EOS Trans. AGU*. Submitted

Gatto P. and Carbognin L., 1981 The Lagoon of Venice: natural environmental trend and man-induced modification. *Hydrol. Sci. B.* 26, 379-391

Hutchinson G.L. and Rochette P., 2003. Non-flow-through steady-state chambers for measuring soil respiration: Numerical evaluation of their performance. *Soil Sci. Soc. Am. J.* 67, 166-180

Lal R., 2004. Soil carbon sequestration impacts on global climate change and food security. *Science* 304, 1623-1627

Kent D.N., Rio D., Massari F., Kukla G. and Lanci L., 2002. Emergence of Venice during the Pleistocene. *Quat. Sci. Rev.* 21, 1719-1727

Nicoletti V., Silvestri S., Rizzetto F., Tosi L., Putti M. and Teatini P., 2003. Use of remote sensing for the delineation of surface peat deposits south of the Venice Lagoon (Italy). In: *IGARSS 2003 - Int. Geoscience and Remote Sensing Symp.*, IEEE, CD-ROM, Vol. IV, 2881-2883

Nieuwenhuis H.S. and Schokking F., 1997. Land subsidence in drained peat areas of the Province of Friseland, The Netherlands. *Q. J. Eng. Geol.*, 30, 37-48

Rojstaczer S. and Deverel S.J., 1995. Land subsidence in drained histosols and highly organic mineral soils of California. *Soil Science Soc. of American J.* 59, 1162-1167

Soegaard H., Jensen N.O., Boegh E., Hasager C.B., Schelde K. and Thomsen A., 2003. Carbon dioxide exchange over agricultural landscape using eddy correlation and footprint modelling. *Agr. Forest Meteorol.* 113, 159-183

Stephens J.C., Allen L. H. and Chen E., 1984. Organic soil subsidence. In: Holzer, T.L. (Ed.), *Man-induced Land Subsidence*, Geological society of America Reviews in Engineering Geology, v. 6, 107-122

Strozzi T., Tosi L., Wegmüller U., Werner C., Teatini P. and Carbognin L., 2003. Land subsidence monitoring service in the Lagoon of Venice. In: *IGARSS 2003 - Int. Geoscience and Remote Sensing Symp.*, IEEE, CD-ROM, Vol. I, 212-214

Tosi L., Carbognin L., Teatini P., Rosselli R. and Gasparetto Stori G., 2000. The ISES project subsidence monitoring of the catchment basin south of the Venice Lagoon, Italy. In: Carbognin L. *et al.* (Eds), *Land Subsidence (Proc. VI Int. Symp. on Land Subsidence)*, La Garangola, Padova, Italy, Vol. II, 113-126

Wösten J.H.M., Ismail A.B. and van Wijk A.L.M., 1997. Peat subsidence and its practical implications: A case study in Malaysia. *Geoderma* 78, 25-36