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Groundwater Pumping and Land Subsidence in the Sarno River Plain (Campania)

Emungimenti e subsidenza nella piana del fiume Sarno (Campania)

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ABSTRACT - The present paper focuses on the analysis of large scale deformation phenomena, that take place in many Italian regions. The traditional approach is based on earth surface (terrestrial) measures of relevant parameters and on the specialistic review of their time series. On the other hand, National and International technological scenery is characterized by a fast development and offers a number of interesting options in the field of satellite technologies. This is the background of an innovative and multi-disciplinary research activity, that has been issued in order to provide a methodological contribution to the integration of the different competences needed to manage subsidence phenomena. Based on INSAR measures by CNR-IREA on a sample area, located in the Campanian Plain and the Vesuvian Area, a correlation between geological, hydrogeological and geotechnical relevant parameters has been assessed.

KEY WORDS: Groundwater Resources, Land Subsidence, SAR Interferometry, Satellite Technologies.

RIASSUNTO - Il tema del presente lavoro è l'analisi dei fenomeni deformativi del suolo su larga scala, che interessano molte aree italiane. L'approccio tradizionale è basato su misure terrestri dei parametri di interesse, e sull'esame specialistico delle loro serie temporali. D'altro canto, il panorama nazionale ed internazionale dal punto di vista tecnologico si è fortemente evoluto e propone tecniche, di grande interesse applicativo, basate sulle infrastrutture satellitari destinate a scopi civili. È apparso dunque importante impostare un'attività di ricerca multidisciplinare e fornire un contributo metodologico capace di integrare le competenze coinvolte nella gestione dei fenomeni di subsidenza. Con riferimento ad un'area campione collocata nella piana Campana adiacente alla zona vesuviana, coperta fin dai primi anni '90 dal CNR-IREA con acquisizioni ed elaborazioni di misure interferometriche SAR, è possibile dimostrare l'esistenza di correlazioni tra i parametri di deformazione osservati e gli aspetti locali di natura geologica, idrogeologica e geotecnica.

PAROLE CHIAVE: Risorse idriche sotterranee, Subsidenza, Interferometria SAR, Tecnologie satellitari.

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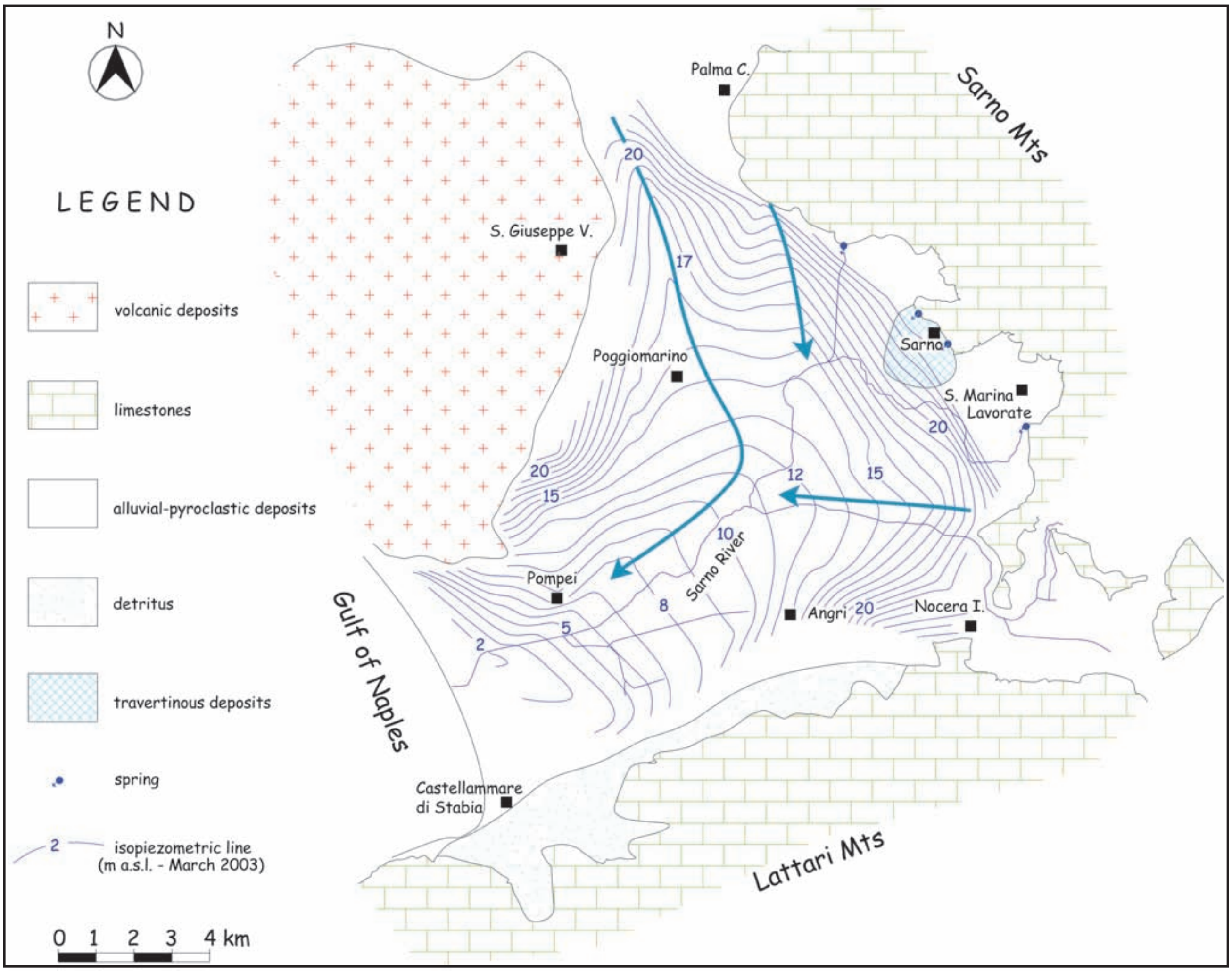

Fig. 1 - Water table map of the Sarno River Plain (March 2003).
- Carta a curve isopiezometriche della piana del F. Sarno (Marzo 2003).

1. - INTRODUCTION

Hydrogeological risk assessment is a key topic for the international scientific research community. Improvement of suitable techniques to identify the decline of ground water quantity and quality is certainly of interest.

This paper presents the framework of the research, theoretical and experimental in nature, under development by a cooperative multidisciplinary group of the Department of Earth Sciences - University of Naples Federico II and of the Institute for Electromagnetic Sensing of the Environment (IREA) of Naples.

The aim is to analyse land subsidence phenomena due to over-pumping of groundwater resources in a number of river plain test areas using advanced technologies to measure surface displacements.

In particular this paper presents the revision of geological, geotechnical and hydrogeological data on the Sarno River Plain (Campania) and of the evaluation of surface level variations measured by Interferometric Synthetic Aperture Radar (InSAR) techniques.

2. - GEOLOGIC AND HYDROGEOLOGIC SETTING

The Sarno River Plain is located in South-Eastern area of the Campanian Plain (Southern Italy) and is bounded by the Somma-Vesuvio volcanic pile to the North-East and by the Sarno Mts and Lattari Mts to the South. This plain represents a peri-Tyrrhenian graben formed during the Plio-Pleistocene extensional tectonic which involved the Apenninic chain.

The tectonic structure of the basement rocks is represented by step-fault blocks of the

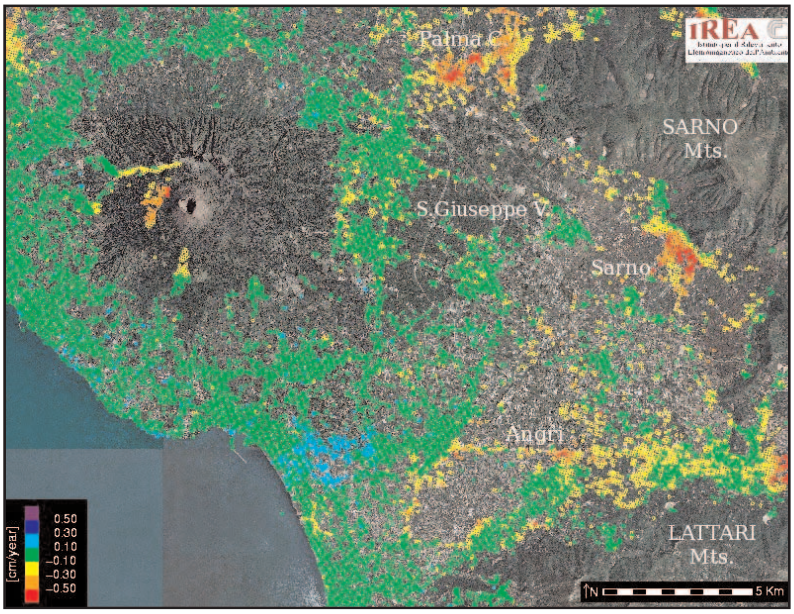

Fig. 2 - Mean-velocity values of ground surface deformations superimposed to an optical image (orthophoto courtesy of C.I.R.AM., Italy) of the Sarno River Plain test-site. The colour scale represents surface displacement expressed in cm/year.
- *Carta delle velocità medie di deformazione della superficie nella piana del F. Sarno, sovrapposta ad ortofoto, gentilmente concesse dal C.I.R.A.M. La scala di colori rappresenta la dislocazione della superfice terrestre, espressa in cm/anno.*

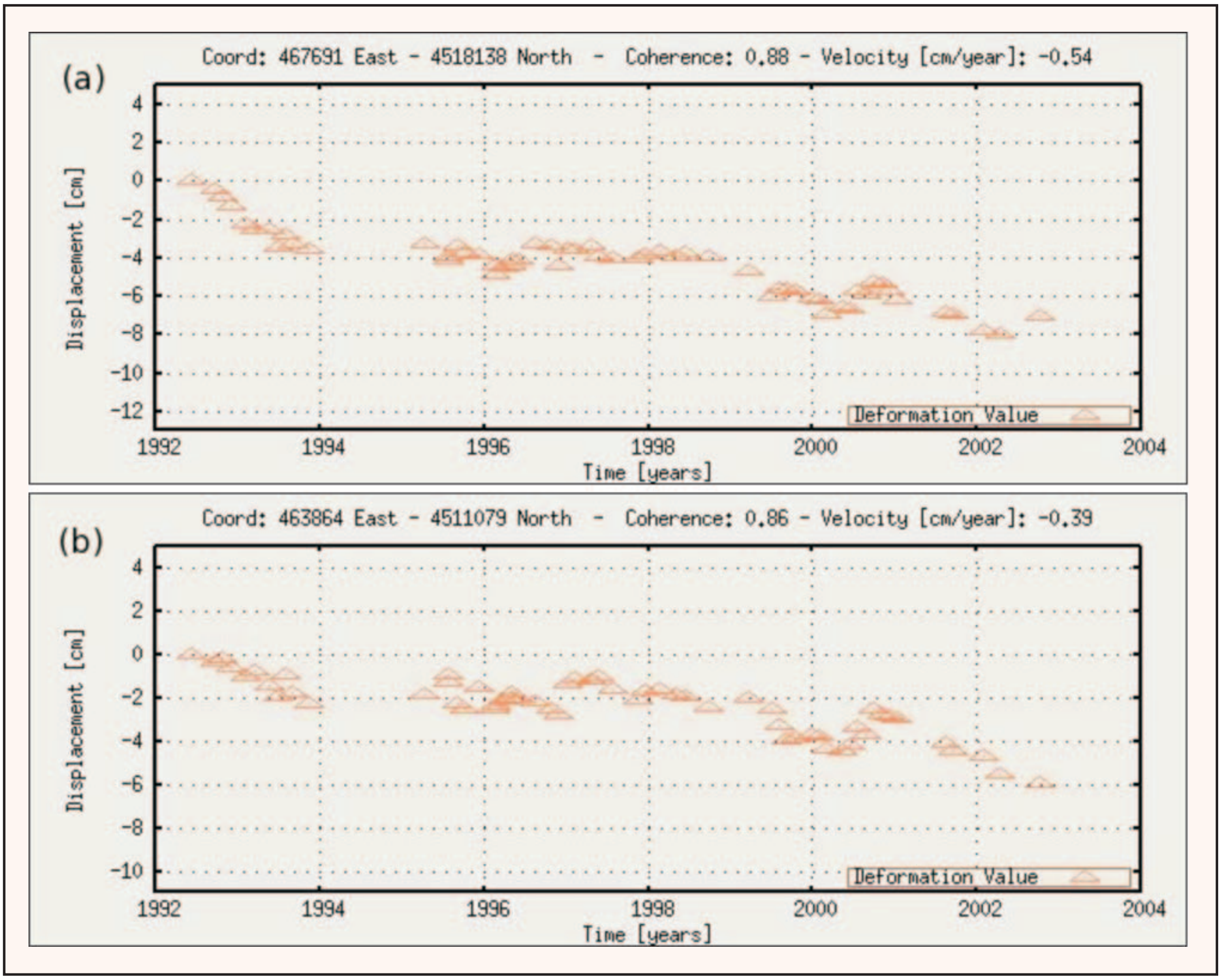

Fig. 3 - DInSAR deformation time-series relevant to the Sarno (a) and Angri (b) urban areas (see fig. 2).
- *Significative serie temporali delle deformazioni DInSAR nelle aree urbane di Sarno (a) e Angri (b); cfr. fig. 2.*

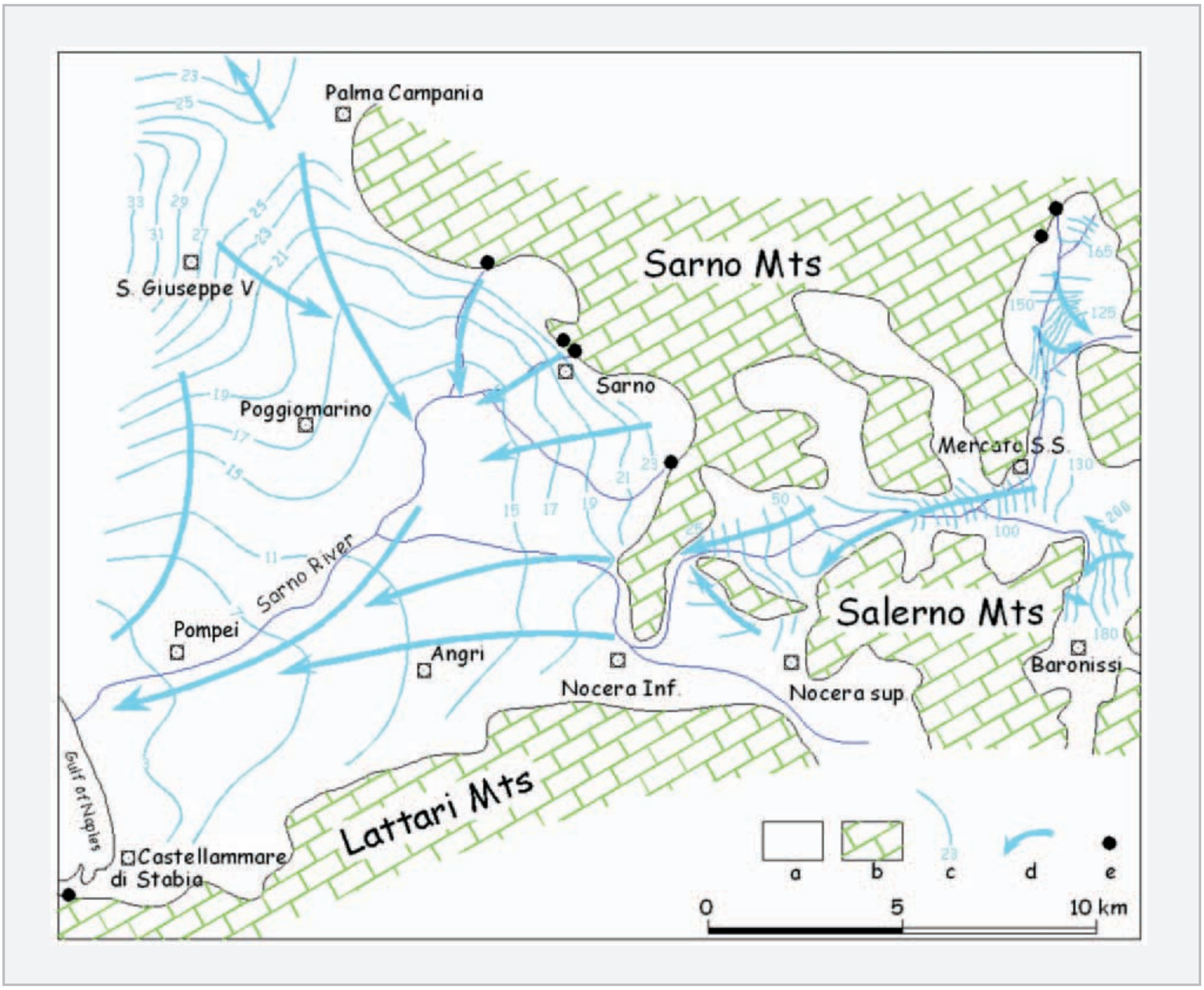

Fig. 4 - Water table map of the Sarno River Plain (fill period - year 1992), after CELICO & PISCOPO (1995); a) alluvial-pyroclastic deposits; b) carbonate rocks; c) isopiezometric line (m a.s.l.); d) groundwater flow direction; e) spring.
- Carta a curve isopiezometriche della piana del F. Sarno (periodo di piena-anno 1992), da CELICO & PISCOPO (1995); a) complesso alluvionale-piroclastico; b) complessi calcareo, calcareo-dolomitico e dolomitico; c) curva isopiezometrica (m s.l.m.); d) direttrice di flusso; e) sorgente.

Mesozoic carbonates. The top of the Mesozoic basement in the Campanian Plain is depicted by seismic refraction experiments performed during 1994-1997 (ZOLLO *et alii,* 1996, 1998, 2000, 2001; GASPARINI, 1998; DE MATTEIS *et alii*, 2000). The basement surface generally dips from the eastern and southern margin of the Campanian Plain towards the Vesuvio volcano, consistent with the Bouger anomaly pattern (CASSANO & LA TORRE, 1987; BERRINO *et alii*, 1998).

The fill of the Sarno Plain is composite and incorporates volcanic, alluvial and marine deposits. Its complex stratigraphic architecture causes strong spatial variations of permeability. In addition, a semipervious tuff horizon, intercalated among above-mentioned deposits in the Central-Eastern area of the plain, generates two overlying ground water flows, recharged by precipitations and indirect intake from bordering hydro-structures. However leakance phenomena between two overlying aquifers exist and are characterized by an upward flow in natural conditions (CELICO & PISCOPO, 1995).

At large scale only one ground water flow is detected due to natural hydrogeologic conditions and well completion at multiple depths, that mix the two distinct aquifers. In particular the water table map (fig. 1) shows that groundwater outflows into the sea with the main flow paths directed North-North East South-South West. The interaction between ground water and surface water changes from the high reaches to the river mouth; in the former the stream is gaining, in the latter the stream is losin.

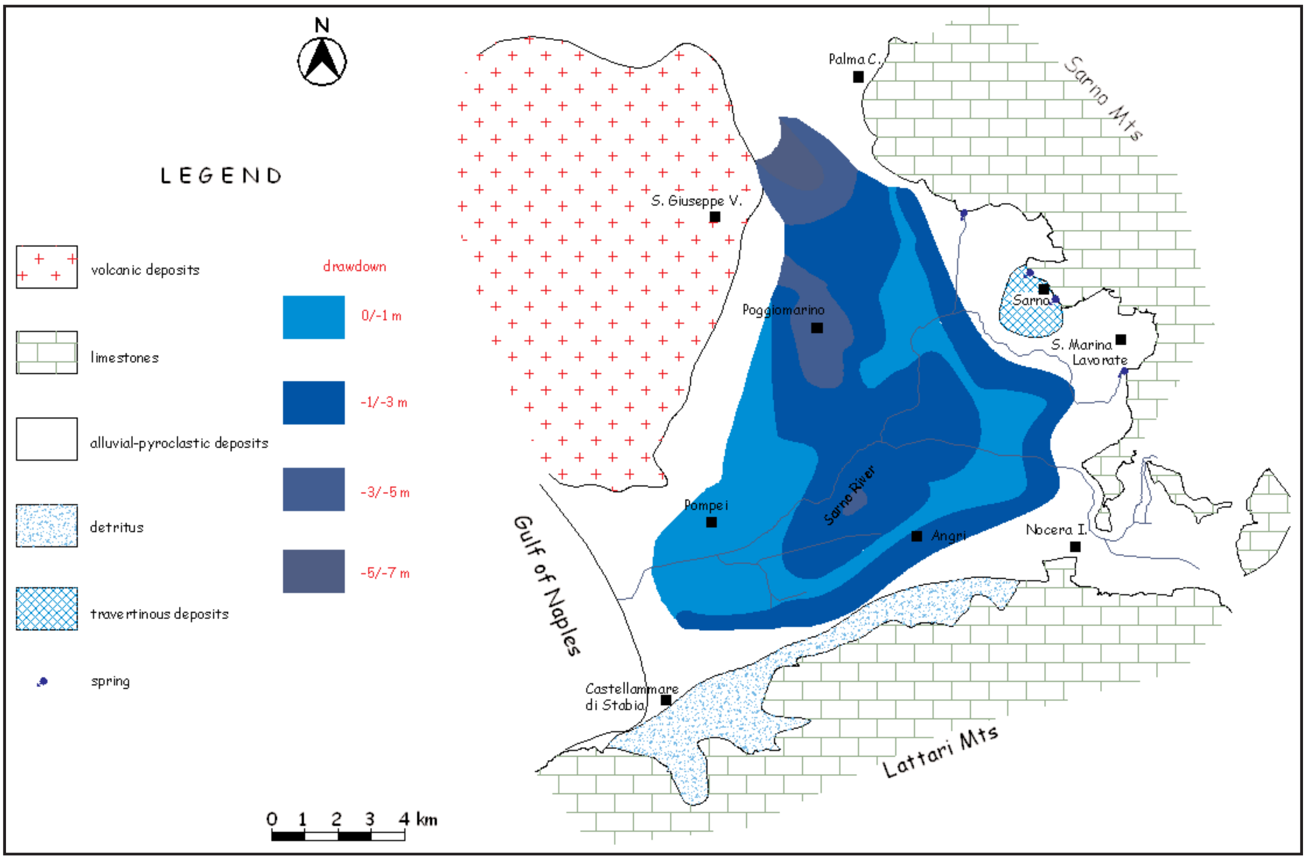

Fig. 5 - Lowering of the water table with reference to years 1992-2003.
- *Abbassamenti della superfice piezometrica registrati tra il 1992 ed il 2003.*

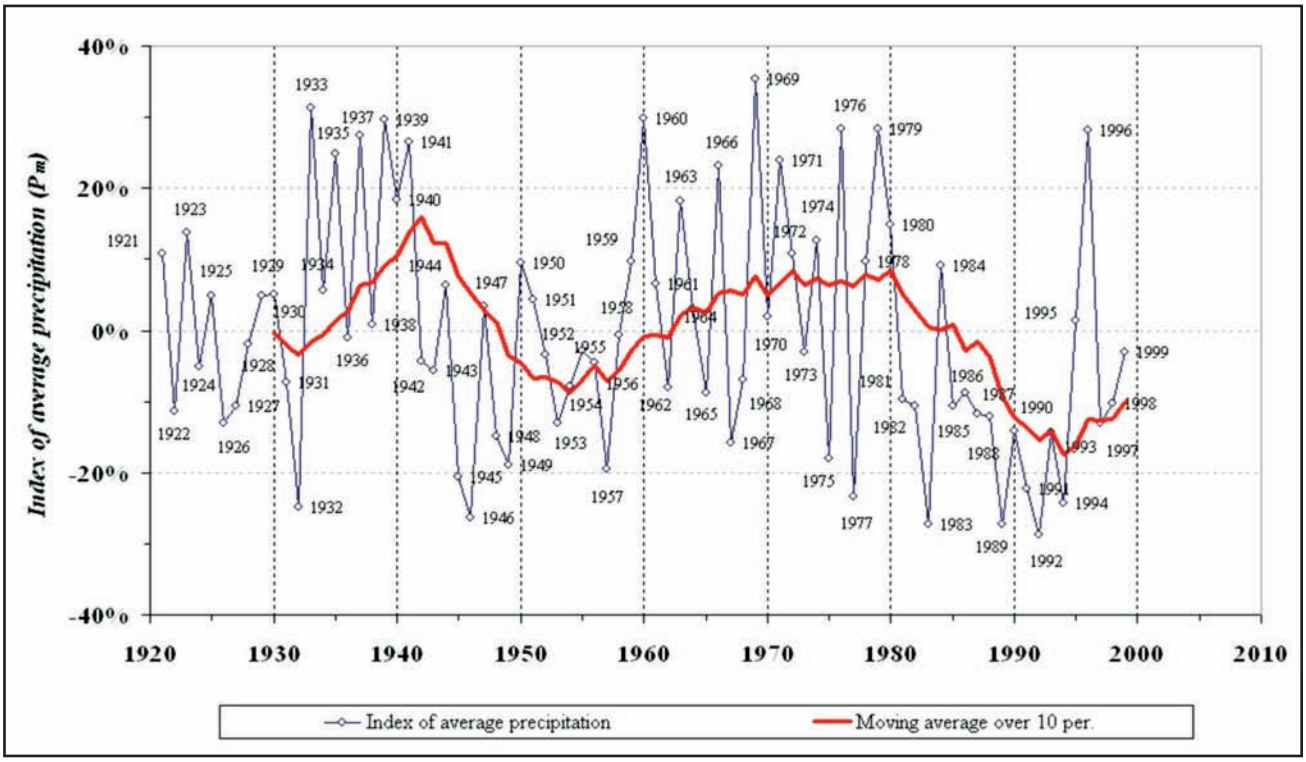

Fig. 6 - Variation of the average precipitation index (Pm) in time with reference to 18 pluviometric stations located in Campania. (After DE VITA, 2001, modified).
- *Variazione temporale dell'indice di precipitazione annua media (Pm) per la Campania (1921-1999).* (*Da* DE VITA, *2001, modificata).*

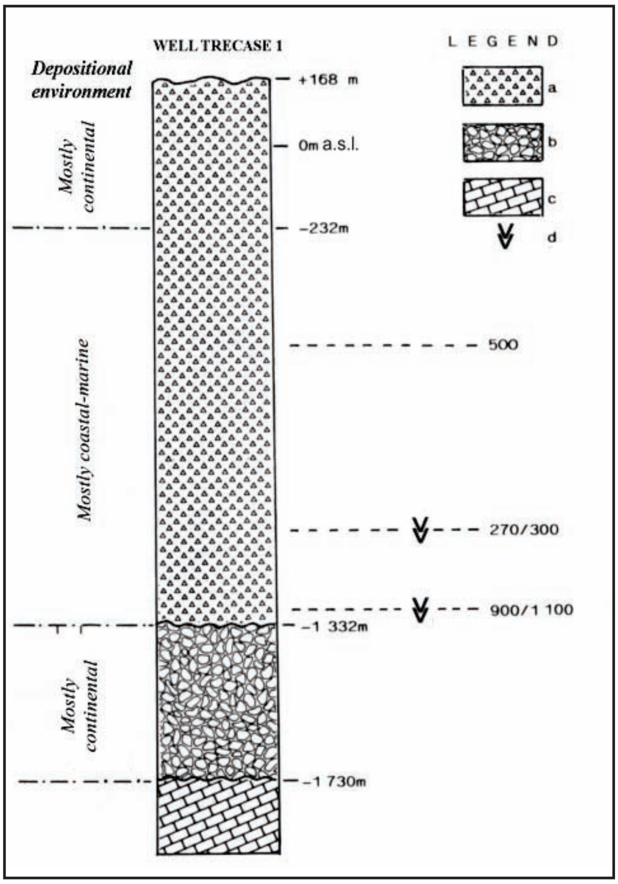

Fig. 7 - Stratigraphy of the Trecase 1 well (after BALDUCCI *et alii,* 1983; BERNASCONI *et alii*, 1981; CINQUE *et alii,* 1987); a) volcanic deposits; b) carbonate conglomerates; c) Mesozoic carbonate substratum; d) intervals with reversed magnetic polarity.
- *Colonna stratigrafica del pozzo Trecase 1 (da* BALDUCCI *et alii, 1983;* BERNASCONI *et alii, 1981;* CINQUE *et alii, 1987); a) vulcaniti e vulcanoclastiti; b) conglomerati ad elementi calcarei; c) substrato carbonatico mesozoico; d) livelli con polarità magnetica invertita.*

3. - SATELLITE OBSERVATIONS

Land subsidence is the sinking of ground surface due to endogenetic causes. Surface deformation may be caused by tectonic movements, solution and compaction of sediments due to sediment load and ground water withdrawal.

Subsidence is generally a gradual lowering of the ground surface that may be measured by conventional levelling of established permanent benchmarks. Early traditional methods were also based on mechanical borehole extensometers, i.e. a deep set benchmark measured relative to the land surface.

Recently, thanks to the development of the Global Positioning System (GPS) technology, site specific location and elevation is provided by the GPS electronic device.

At present the approaches for ground deformation analysis based on remote sensing techniques and, in particular, on the Synthetic Aperture Radar (SAR) systems, are among those with a larger spatial coverage capacity. They are referred to as Differential Interferometric SAR (DInSAR) techniques and can produce spatially dense deformation maps where the measured displacement represents the line of sight (LOS) projection of the surface deformation.

An effective way to detect and trace the temporal evolution of the investigated deformation is the generation of time-series; to do this, the information available from each interferometric data pair must be properly related to other acquisitions in order to generate an appropriate sequence of so called InSAR interferograms (GABRIEL *et alii*, 1989).

The Small Baseline Subset (SBAS) algorithm (BERARDINO *et alii* 2002, LANARI *et alii* 2004), developed at IREA CNR in Naples, is a DInSAR technique that implements an appropriate combination of differential interferograms produced from image data pairs characterized by a small orbital separation (baseline). This technique allows to investigate the space-time characteristics of deformations; its application to an ERS-1/ERS-2 data set of 55 images, spanning the time-interval from 1992 until 2002, allowed the investigation of the Sarno River Plain area (fig. 2).

In order to highlight the temporal characteristics of the detected displacement, deformation time-series on selected areas are also showed in fig. 3; they indicate that a maximun deformation of about 4-8 cm can be identified in the given time interval.

4. - RESEARCH ACTIVITY

The approach to the assessment of the causes of the observed surface deformations is based on a detailed review of hydrogeological data combined with geological, morphological and geotechnical information.

The effects of ground water over-pumping are critical and need careful consideration. It is well known that land subsidence caused by fluid extraction from porous media is attributed to the non recoverable compaction of aquitards. When the reduction in pore-fluid pressure (due to the water table decline) causes an effective stress increase to values greater than the preconsolidation stress, the pore structure of vulnerable fine grained units in the aquifer-system may undergo significant reorganization. This circumstance produces a permanent reduction of pore volume and subsequent vertical compaction of aquitards accompanied by the vertical displacement of ground surfa.

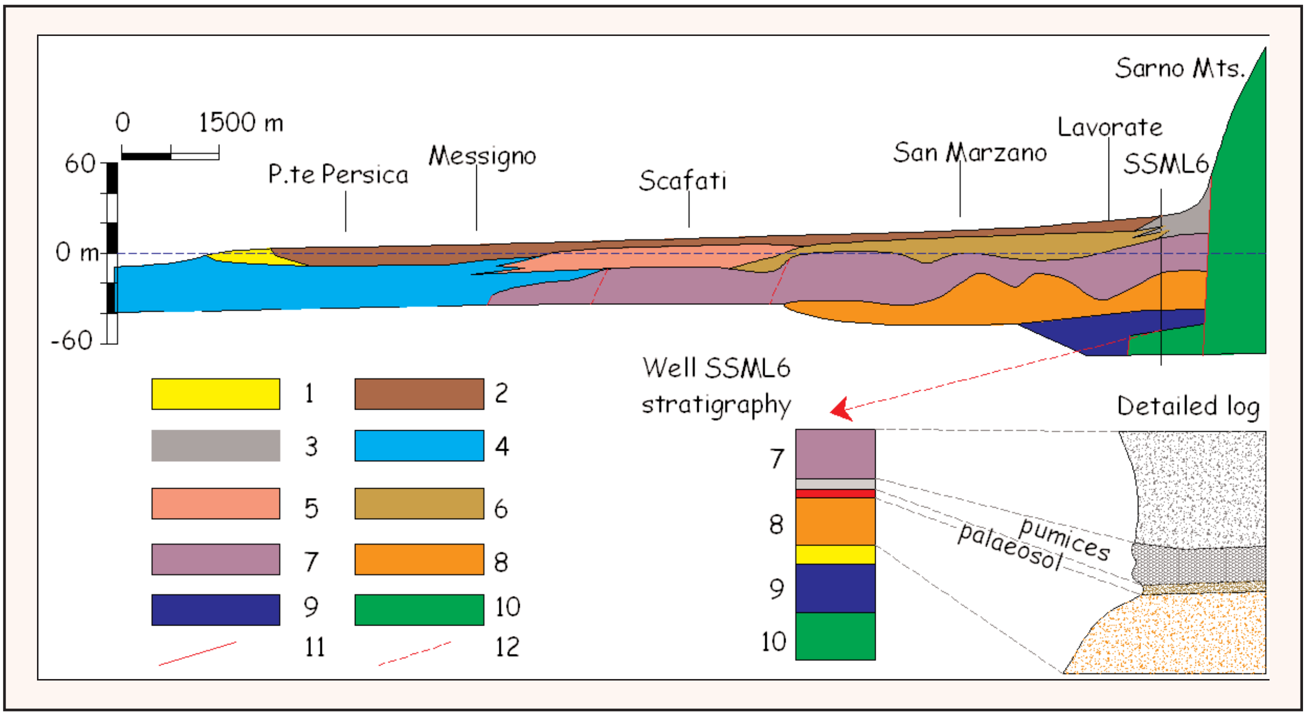

Fig. 8 - Geological cross-section along the Sarno River from its mouth to the Sarno Mts (after APRILE & TOCCACELI, 2002). 1) Beach and eolian recent deposits; 2) Alluvial deposits and recent sub-aerial pyroclastic products (in situ or reworked) of Somma-Vesuvius (AD. 79 - 1944); 3) Talus and slope deposits; 4) Beach and shore sediments with peat levels of Versilian age; 5) Palustrine and lagoonal deposits of Versilian age; 6) Alluvial deposits and undisturbed or reworked pyroclastic deposits of the Sarno (17 ky B.P.) and Ottaviano (8 ky B.P.) eruptions; 7) Campanian Grey Tuff (about 39 ky B.P.); 8) Taurano Yellow Tuff (about 157 ky B.P.); 9) Beach and marine deposits (Late Middle Pleistocene); 10) Dolomites and limestones (Mesozoic- Cenozoic); 11) Fault; 12) Uncertain fault.

- Sezione geologica lungo il fiume Sarno, dalla foce ai Monti di Sarno (da APRILE & TOCCACELI, 2002). 1) Depositi di spiaggia ed eolici attuali e recenti; 2) Depositi alluvionali e piroclastiti subaeree (in posto e/o rimaneggiate) recenti del Somma-Vesuvio (periodo 79 DC. 1944); 3) Detriti di falda e di versante; 4) Depositi litorali di spiaggia con livelli di torba del "Complesso Versiliano"; 5) Depositi palustri e lagunari associati al "Complesso Versiliano"; 6) Depositi alluvionali e piroclastiti in posto o rimaneggiate attribuibili alle eruzioni di Sarno (17 ky B.P.) e Ottaviano (8 ky B.P.); 7) Tufo grigio campano (circa 39 ky B.P.); 8) Tufo giallo di Taurano (circa 157 ky B.P.); 9) Depositi di spiaggia e marini del tardo Pleistocene medio; 10) Termini calcareo-dolomitici mesozoico-terziari; 11) Faglia; 12) Faglia presunta.

4. 1. - HYDROGEOLOGY

The hydrogeological research is aimed to assess the spatial and temporal evolution of ground water dynamics in the investigated period (from 1992 to 2002). The collection of hydrogeological data, in particular water table levels, points out the deficiency of piezometric monitoring in the study area. In fact only the hydrogeological conditions checked during the fill period of the year 1992 (CELICO & PISCOPO, 1995) are well known (fig. 4).

The examination of hydrogeological data provided by well and drilling stratigraphies shows the temporal and spatial discontinuity of piezometric observations and the need of a fitting piezometric monitoring network. So in the recharge season of March 2003 a water table levelling survey was established (fig. 1). Although no significant changes in the hydrogeological regime of the plain were detected, it was possible to recognize a general lowering of the water table, with different range of values in the various zones (fig. 5).

The maximum values of water table lowering (about 7 m) is observed in the area located between Palma Campania and S. Giuseppe Vesuviano. Three metres represent the maximum decrease of piezometric levels found in most areas of the plain as well as in the area close to the carbonate ridges. This circumstance seems to be validated by the data (up to 1993) on spring discharge and water level measurements (CASCINI & DI MAIO, 1994).

The uncontrolled withdrawal from carbonate and pyroclastic-alluvial aquifers causes the decrease of springs discharge and piezometric levels. The effect of this condition dramatically evident since 1989, when precipitations in the plain decreased up to 30% with respect to the average value of the reference period 1921-1999 (fig. 6).

In the years 2001 - 2002 the pluviometric data from a large set of stations located in Campania, provide a Standardized Precipitation Index (SPI) of -2 (Hydrographic and Sea State Department, 2002) indicating an extremely dry period.

In conclusion the analysis of the available hydrogeological data enables to recognize a significant decrease of piezometric levels in the Sarno

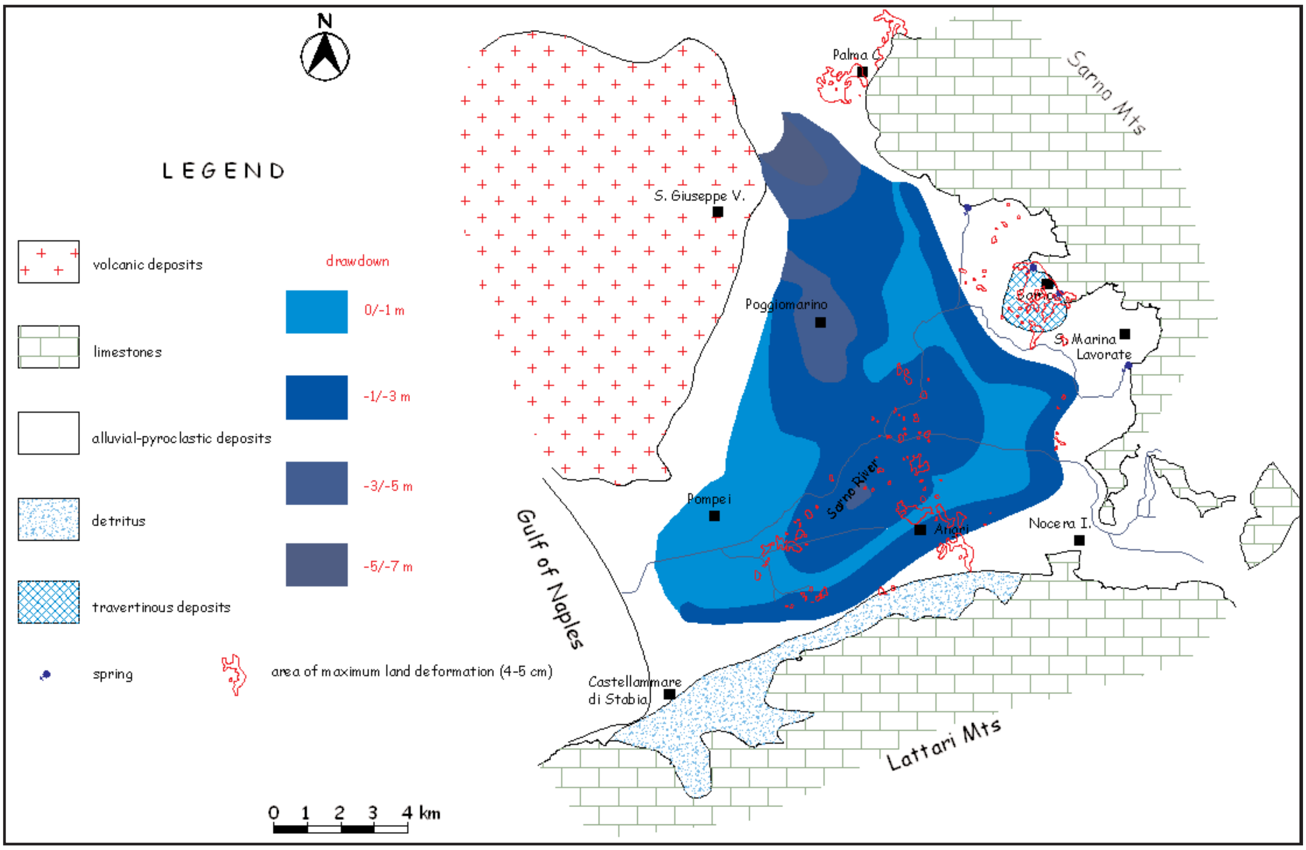

Fig. 9 - Water table lowering combined with maximum land displacements (reference period 1992-2003).
- *Sovrapposizione delle aree di massima deformazione della superficie terrestre con gli abbassamenti della superficie piezometrica (periodo di riferimento 1992-2003).*

River Plain during the years 1992-2002 caused by the uncontrolled intense pumping of ground water combined with the decrease of precipitations.

4.2. - SEDIMENT DEFORMATION

The fill of the Sarno River Plain graben is composed of a 2000-3000 m thick sequence of Plio-Quaternary continental, deltaic and marine sediments, intercalated with volcanic deposits. This sequence is explored by the almost 2000 m deep AGIP well Trecase 1 (fig. 7) located in the SE slope of the Vesuvio volcanic cone (BALDUCCI *et alii*, 1983; BERNASCONI *et alii*, 1981; CINQUE *et alii*, 1987).

The collection and re-interpretation of exiting data represented by well and drilling stratigraphies, hydrogeological and geotechnical field investigations and laboratory tests on undisturbed samples, as well as surface deformation data enables a comprehensive picture of field conditions.

Several stratigraphical, volcanological and geomorphological studies, carried out in the last decades, describe the complex setting of the Quaternary deposits of the Sarno River Plain. A geological cross section, after APRILE & TOCCACELI (2002), is outlined in fig. 8; it shows the presence of the tuff horizon (Campanian Grey Tuff and Taurano Yellow Tuff) at shallow depth in the South-Eastern portion of the plain. Shallow marine deposits reaching the foot of the eastern marginal relief, are recognized and are related to a number of sea ingression. In particular the most widespread are the Middle Pleistocene (APRILE & TOCCACELI, 2002), Eu-Tyrrhenian and Versilian ones (CINQUE *et alii* 1987; CINQUE, 1991). In terms of depositional environments, lacustrine and palustrine (peat and silt) deposits are recognized. Clearly all these sediments are interlayered with products of the neapolitan volcanic region.

A number of studies highlight local subsidence phenomena, that in some conditions may cause structural damages to buildings (APRILE *et alii*, 1998; CASCINI & DI MAIO, 1994). In particular CASCINI & DI MAIO (1994) analyse the subsidence occurred in the town of Sarno and define the compressibility of soils represented by peat, pyroclastics associated with peat and loose pyro-

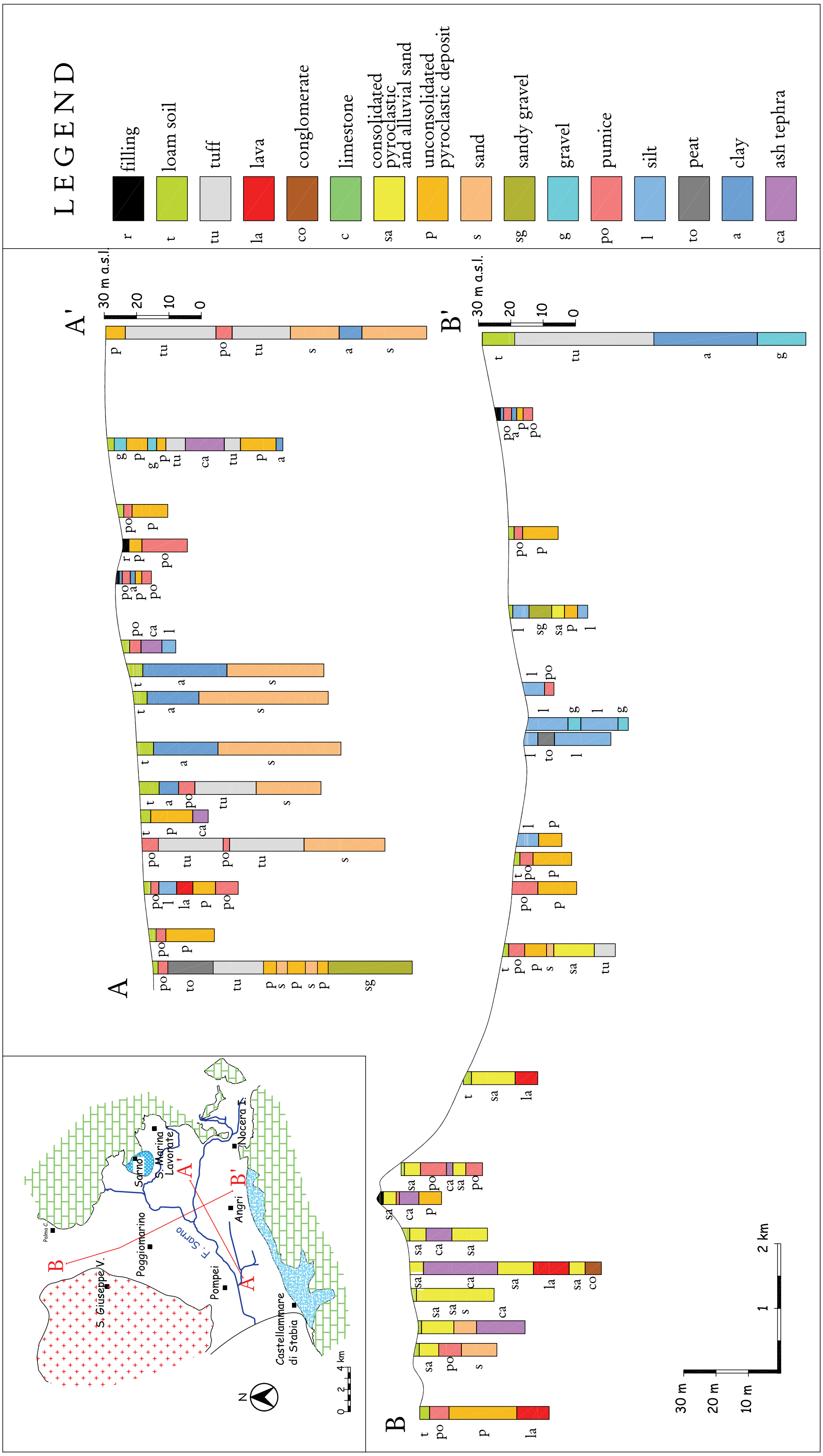

Fig. 10 - Key alignments of stratigraphic columns.
- *Principali allineamenti delle colonne stratigrafiche.*

clastic deposits (ash, lapilli and pumice tephra).

Mechanical and physical properties of unconsolidated pyroclastic deposits arise from the specific extensive literature (PELLEGRINO, 1967; RIPPA & VINALE, 1982, 1986; VINALE, 1983, 1988) combined with laboratory and survey tests. CASCINI & DI MAIO, 1994 assess an E_{ed} about 5 x 10^3 kPa. The rheologic behaviour of peat and its variability according to environmental chemical-physical conditions is known. In particular the highly permeable fibrous peat deposits recognized in the subsoil of the Sarno River Plain have a viscous behaviour (CASCINI & DI MAIO, 1994). In addition their compressibility increases when the chemical composition of interstitial fluid changes. This means that deformations can be related to past stress state changes and enlarged by groundwater contamination.

5. - CONCLUSION

Surface deformation data indicate that subsidence phenomena are presently active in the Sarno River Plain; this research shows that they can be profitably combined with geological, geotechnical and hydrogeological data.

Maximum deformations, together with drawdowns, are depicted in figure 9 and two alignments of stratigraphic columns are reported in figure 10.

The analysis of data carried out in the period 1992-2003 enables to identify spatial correlations between maximum land deformations and geological-hydrogeological information as follows:

- maximum surface deformations are located in areas characterized by draw-downs ranging from 1 to 3 meters and also in the zones of moderate drawdowns (0-1m) characterized by the presence of peat;

- land subsidence occurs where at least two compressible lithologies are present and increases with increasing thickness of compressible deposits;

- in areas of maximum drawdowns (>3m) no deformations occurs where compressible lithologies are missing and only non compressible rocks (lava) are present.

Summarizing, the extension and rate of surface deformation depends on local hydrogeological and lithostratigraphic conditions, i.e. water table lowering, thickness and properties of compressible soils; in the reference period, subsidence phenomena of the Sarno Plain can be related to the tensional state changes caused by water table lowering.

The aim of future work is the improvement of the outlined phenomenological model by the identification of a number of test-sites inside the plain.

To achieve this, it is necessary set up a specific monitoring network for the assessment of the stratigraphical, structural, physical, mechanical and hydrogeological properties of the surveyed aquifers.

Acknowledgments

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REFERENCES

APRILE F., ORTOLANI F. & TOCCACELI R.M. (1998) - *Proposta di restauro geoambientale della piana del Sarno (Salerno). Modalità di inquinamento delle acque e dei terreni. Subsidenze locali connesse alla presenza di torbe.* Geol. Tec. e Amb., **2**: 31-38

APRILE F. & TOCCACELI R.M. (2002) - *Nuove conoscenze sulla stratigrafia e distribuzione dei depositi ignimbritici quaternari nel sottosuolo della piana del Sarno (Salerno-Campania) - Italia meridionale.* Il Quaternario, **15**: 169-174.

BALDUCCI S., VASELLI M. & VERDINI G. (1983) - *Esploration well in the Ottaviano permit, Italy, Trecase 1.* Eur. Geot. Update, 3rd Int. Sem., Munich, 29 Nov. - 1 Dic., 407-418.

BERARDINO P., FORNARO G., LANARI R. & SANSOSTI E. (2002) - *A new Algorithm for Surface Deformation Monitoring based on Small Baseline Differential* SAR Interferograms. IEEE Transactions on Geoscience and Remote Sensing, **40** (11): 2375-2383.

BERNASCONI A., BRUNI P., GORLA L., PRINCIPE C. & SBRANA A. (1981) - *Risultati preliminari dell'esplorazione geotermica profonda nell'area vulcanica del Somma-Vesuvio.* Rend. Soc. Geol. It., **4**: 237-240.

BERRINO G., CORRADO G. & RICCARDI U. (1998) - *Sea gravity data in The Gulf of Naples: a contribution to delineating the structura pattern of the Vesuvian areal.* J. Volcanol. Geotherm. Res., **82**: 139-150.

CASCINI L. & DI MAIO C. (1994) - *Emungimento delle acque sotterranee e cedimenti nell'abitato di Sarno: analisi preliminare.* Rivista Italiana di Geotecnica, **3**: 217-231.

CASSANO E.& LA TORRE P. (1987) - *Geophysics, in Somma-Vesuvius.* CNR Quad. Ric. Sci., Ed. Santacroce, 175-196.

CELICO F. & PISCOPO V. (1995) - *Idrodinamica sotterranea e vulnerabilità intrinseca all'inquinamento delle piane del Sarno e del Solofrana (Campania).* Quad. Geologia Applicata, **2**: 407-415.

CINQUE A. (1991) - *La trasgressione versiliana nella piana del Sarno (Campania).* Geogr. Fis. Dinam. Quat., **14**: 63-71.

CINQUE A., ALINAGHI H.H., LAURETI L. & RUSSO F. (1987) - *Osservazioni preliminari sull'evoluzione geomorfologia della piana del Sarno (Campania, Appennino Meridionale).* Geogr. Fis. Dinam. Quat., **10**: 161-174.

DE MATTEIS R., LATORRE D., ZOLLO A. & VIRIEUX J. (2000) - *1-D P-velocity models of Mt. Vesuvius volcano from the inversion of TomoVes96 first arrival time data.* Pageoph, **157**: 1643-1661.

DE VITA P. (2001) - *Variabilità climatica e "rischio idrogeologico".*

In*:* A. Vallario (Ed.)*, "Il dissesto idrogeologico in Campania".* CUEN Napoli, 117-127.

Gabriel K., Goldstein R.M. & Zebker H.A. (1989) - *Mapping small elevation changes over large areas: Differential interferometry.* J. Geophys. Res., **94**: 9183-9191.

Gasparini P. (1998) - *Looking inside Mt Vesuvius. EOS* Trans. Am. Geophys. Un., **79**: 229-232.

Hydrographic and Sea State Department (2002) - *Rapporto sulla siccità 2001-2002 nel territorio del compartimento di Napoli del SIMN. Rapporto Tecnico 1/2002.*

Lanari R., Mora O., Manunta M., Mallorqui J.J., Berardino P. & Sansosti E. (2004) - *A Small-Baseline Approach for Investigating Deformations on Full-Resolution Differential SAR Interferograms.* IEEE Transactions on Geoscience and Remote Sensing, **42** (7): 1377-1385.

Lanari R., Zeni G., Manunta M., Guarino S., Berardino P. & Sansosti E. (2004) - *An Integrated SAR/GIS Approach for Investigating Urban Deformation Phenomena: A Case Study of the City of Naples, Italy.* Int. J. Remote Sensing, **25** (14): 2855-2862.

Pellegrino A. (1967) - *Proprietà fisico-meccaniche dei terreni vulcanici del napoletano.* Atti VIII Convegno di Geotecnica, Cagliari, 113-145.

Rippa F. & Vinale F., (1982) - *Experiences with CPT in Eastern Naples Area.* Proc. of the second European Symposium on Penetration Testing*,* Amsterdam.

Rippa F. & Vinale F. (1986) - *Primi contributi per la caratterizzazione geotecnica del sottosuolo dell'area flegrea ai fini di una microzonazione sismica.* Giornate di Studio Bradisismo e fenomeni connessi, Napoli.

Vinale F. (1983) - *Contributo alla conoscenza delle proprietà dinamiche dei terreni del napoletano.* XV Convegno Nazionale di Geotecnica, Spoleto.

Vinale F. (1988) - *Caratterizzazione del sottosuolo di un'area campione di Napoli ai fini d'una microzonazione sismica.* Rivista Italiana di Geotecnica, **2**: 77-100.

Zollo A., Gasparini P., Virieux J., Le Meur H., De Natale G., Biella G., Boschi E., Capuano P., De Franco R., Dell'Aversana P., De Matteis R., Guerra I., Iannacone G., Mirabile L. & Vilardo G. (1996) - *Seismic Evidence for a Low-Velocity Zone in the Upper Crust Beneath Mount Vesuvius.* Science, **274**: 592-594.

Zollo A., Gasparini P., Virieux J., Biella G., Boschi E., Capuano P., De Franco R., Dell'Aversana P., De Matteis R., De Natale G., Iannacone G., Guerra I., Le Meur H. & Mirabile L. (1998) - *An image of Mt. Vesuvius obtained by 2D seismic tomography.* J. Volcanol. Geotherm. Res., **82**: 161-173.

Zollo A., De Matteis R., D'Auria L. & Virieux J. (2000) - *A 2-D non linear method for travel time tomography: application to Mt.Vesuvius active seismic data.* In: Boschi E., Ekstroem G. & Morelli A. (Eds) "*Problems in geophysics for the next millennium".* ING-Ed Compositori, Bologna.

Zollo A., D'Auria L., De Matteis R., Herrero A., Virieux J. & Gasparini P. (2001) - *Bayesian estimation of 2-D P-velocity models from active seismic arrival time-data: imaging of the shallow structure of Mt. Vesuvius (Southern Italy).* Geophysics J. Int., **151**: 506-582.