Unsustainable use of groundwater resources in agricultural and urban areas: a persistent scatterer study of land subsidence at the basin scale

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Abstract

Multi-temporal analysis of space-borne radar images through Persistent Scatterer Interferometry (PSI) is exploited for mapping subsidence at basin scale in the Gioia Tauro plain (Italy), a densely urbanized coastal area whose land deformation are controlled by aquifer overexploitation. Both historical (1992–2001; ERS1/2 images) and present (2002-2006; ENVISAT images) scenarios are analyzed to solve the spatial variability and temporal evolution of ground displacements affecting the plain. Average deformation rates as high as 10–15 mm/yr are observed from 1992 to 2006, with highest velocities (i.e. 22.8 mm/yr) occurred between 1992 and 2000 within the central part of the basin, in the area of Rizziconi (5 km ESE of Gioia Tauro). The outcomes of this PSI study will support the future improvement of groundwater management and the implementation of best strategies for risk mitigation, land use planning, sustainable use of groundwater resources, and consequent reduction of economic and social impacts.

Keywords: subsidence, groundwater overexploitation, Permanent Scatterers (PSInSAR), Persistent Scatterer Interferometry, SAR Interferometry, Gioia Tauro, Calabria.

1 Introduction

Densely urbanized and heavily industrialized areas are frequently affected by land subsidence, often caused by human activities and, in particular, subsurface

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water withdrawal. In many urban areas, subsidence induced by groundwater overexploitation and associated aquifer compaction has strong economic impacts and usually causes building damaging, road cracking, well-casing failure and deformation of water supply and sewage networks. Moreover, in low-lying coastal areas, decrease of ground elevation, combined with a global sea-level rise, may lead to severe flooding and inundations.

Advanced remote sensing techniques, such as multi-temporal InSAR (Synthetic Aperture Radar Interferometry), may contribute to the understanding of spatial and temporal patterns of ground subsidence, exploiting long time series of satellite images acquired at different times over the investigated areas, and reconstructing their deformation history.

We exploit the contribution of Persistent Scatterer Interferometry (PSI) through the multi-temporal analysis of space-borne radar images, for mapping land subsidence at basin scale in the Gioia Tauro plain (Italy), a densely urbanized coastal area built over unconsolidated fine-grained sediments. Available archives of satellite SAR images acquired since 1992 and currently operational SAR missions allow the study of both past and present ground displacements; the main objectives are to facilitate the analysis of hazard and risk scenarios, and to support the improvement of groundwater management in order to minimize future subsidence, and to help the implementation of best strategies for risk mitigation, land use planning and consequent reduction of economic and social impacts.

2 Persistent Scatterer Interferometry

Differential InSAR (DInSAR), a technique that exploits the phase difference of two SAR images gathered at different times on the same target area, has been widely used since late ‘80s [1, 2] to detect, map and quantify surface deformations with centimetre precision over large contiguous areas [3, 4]. In the last two decades, space-borne DInSAR techniques have demonstrated and improved their capability and their potential as ground deformation measurement tools in a wide range of application fields.

Conventional DInSAR is limited by temporal and geometrical decorrelation. Moreover, the impossibility of removing phase distortions introduced by atmospheric effects can degrade and limit the accuracy of the results.

Multi-interferometric approaches, such as PSI techniques, overcome the main limitations encountered in single-pair interferograms; the use of long temporal series of SAR data makes possible the removal of atmospheric artefacts or, at least, the reduction of their impact on the estimated displacement values.

PSI techniques represent powerful tools for identifying and mapping man-induced surface movements and for reconstructing the temporal evolution of the investigated areas, considerably improving the applicability of SAR Interferometry for the measurement of ground motions [5–9]. Extracting phase information from multiple SAR images, these techniques are able to identify ground resolution elements (pixels) dominated by single scatterers, the so-called PS (Persistent Scatterers). For this reason, PSI methods have successfully been exploited for the analysis of urban areas, where stable targets produce strong reflectors, typically corresponding to man-made structures (e.g. buildings, roads, dams, pipelines, pylons) or stable natural reflectors (e.g. rock outcrops). These targets allow the measurement of deformation velocities (both average ground deformation rate and displacement time series, acquisition by acquisition) along the satellite Line Of Sight (LOS), with millimetre precision [10, 11].

3 Gioia Tauro plain

3.1 Geological and geomorphologic setting

The Gioia Tauro plain, also known as "Rosarno Plain", is an urbanized coastal area located in southern Calabria Region, Italy (Fig. 1), including 33 municipalities (entirely belonging to Reggio Calabria district), with a total extension of about 500 km^2. The area has nearly 150,000 inhabitants, with a very high population density (300 inhabitants/km^2).

From a geological point of view, the Gioia Tauro basin is a 25-30 km long, NNE–SSW oriented half-graben, spreading from the Valley of Mèsima to the Massif of the Aspromonte and elongated between the Calabrian Arc Mountains and the Tyrrhenian Sea [12]. The uplifted Aspromonte and Serre ridges form the structural backbone of southwest part of the Calabrian Arc.

The main geological feature of the Calabrian Arc is the 180 km long normal fault belt that strongly controls the morphology of western-facing mountain slopes, separating the main uplifted mountain range from a series of extensional sedimentary basins (i.e. Mesima, Gioia Tauro, Reggio Calabria and Barcellona basins), located on the Tyrrhenian side of the arc [13–18].

To the east, the Gioia Tauro basin is bounded by Cittanova fault, a 35 km normal fault juxtaposing the basement of the uplifted Aspromonte and Serre mountains with the Pleistocene deposits of the plain. S. Eufemia fault, an 18 km ENE-striking normal fault bounds to the south the basin. To the NE, the Coccorino and Nicotera normal faults abruptly truncate and separate the plain area from the uplifted promontory of Capo Vaticano.

While the uplifted blocks and the bedrock are characterized by crystalline basement rocks (gneiss and granites), the basin is filled by a 700 m thick succession of marine and continental sediments of Pliocene and Quaternary Age. The Late Pliocene-Early Pleistocene marine sequence consists of about 70 m of sands and calcarenites, overlaid by a layer of compacted clays and silty clays of great thickness (500 m or more), capped by 100 m of regressive sands and conglomerates.

The marine sequence is unconformably overlain by the most superficial layers of the plain (up to a depth of 50-70 m from the ground level), that is prevalently constituted by granular saturated soils consisting of Middle-Upper Pleistocene alluvial conglomerates and sands, truncated by a wide planation surface [13, 15].

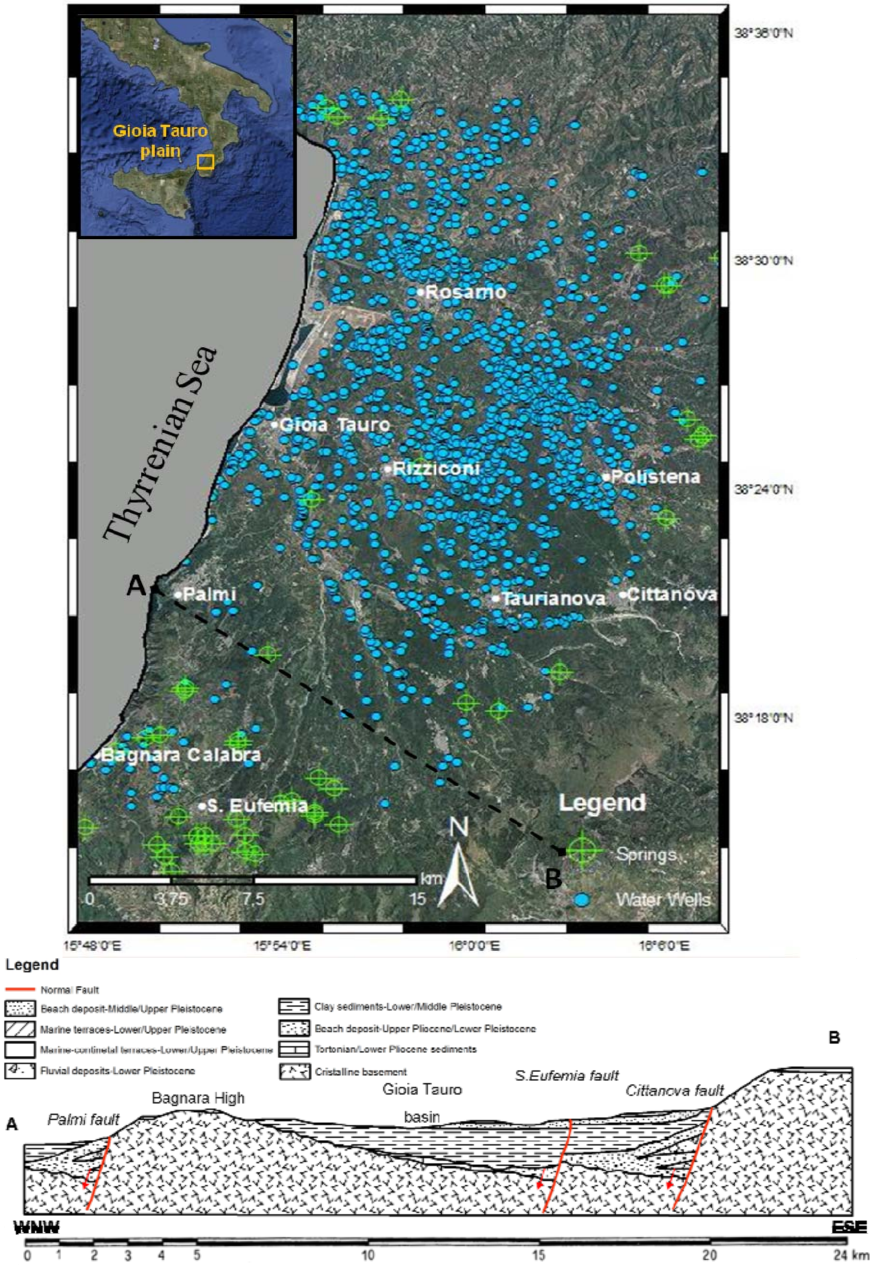

Figure 1: Geographical setting of the area of Gioia Tauro, Italy (above). Simplified geological cross-section of the basin (below), modified from Jacques et al. [15].

3.2 Agricultural activities and groundwater management

Agriculture is the most important economic activity in the area: olive trees and seed crops (mainly wheat) are cultivated extensively. The citrus cultivation represents a key factor for the economic livelihood of local population. In the whole plain, the yearly production of citrus (especially tangerines and oranges) amounts to 700,000 tons, i.e. 3% of the total product of Mediterranean countries or 0.7% of the world product [19].

The farming system in Calabria is based on a much fragmentized model, with hundreds of small plots, self-sufficient from the water supplying point of view. Farms and estates of less than 2 ha made up 69% of the total in 2000 [19].

In addition to the municipal network for water supply and distribution (Fig. 1), that has serious inefficiencies, many independent and usually uncontrolled water wells have been recently constructed and, in the whole plain, 45% of water needs are currently provided by private water wells [19]. Recently increased groundwater demands for irrigation purpose have caused the gradual lowering of the water table, with related compaction of the aquifer deposits, to progressively accelerate.

Different elements at risk are present in the plain, such as the Gioia Tauro Harbour, the largest container terminal of the Mediterranean Sea (about 440 ha of land and 1.8 million m^2 of stocking yards), the road infrastructure with the State Road n.18 and the motorway A3, and the railway network through the Rosarno Station. Many new works, aimed at improving the harbour and the industrial activity of the area have also been designed and are currently being built or under feasibility studies. In 2008, after the submission of an Environmental Impact Assessment, authorization for the construction of a huge liquefied natural gas terminal in the Gioia Tauro port area has also been obtained. The construction is planned to start in 2011 and the system is expected to be operative in 2014, with a capacity of 12 billion m^3 of gas per year, over 10% of the Italian gas demand.

3.3 Satellite data and PSI analysis

The satellite analysis of land subsidence in the Gioia Tauro basin was performed using the PSInSAR (Permanent Scatterers InSAR) technique, which belongs to the multi-interferometric approaches [5], and integrating several datasets of satellite SAR data acquired by different ESA (European Space Agency) missions.

Forty-eight SAR images acquired in 1992-2001 by ERS1/2 satellites along descending (when satellite passes over the target area approximately from north to south) and ascending (south to north) orbits were used to study past ground displacements. Eighteen SAR images acquired by ENVISAT satellite along descending orbits and twenty-six images along ascending orbits were then used to monitor recent land deformation.

The PSInSAR analysis provided estimates of yearly deformation velocity, referred to both historical (1992–2001; ERS images) and recent (2002–2007;

ENVISAT images) scenarios (Tab. 1), allowing the analysis of the spatial variability and temporal evolution of Gioia Tauro subsidence.

The density of PS turned out to be significantly higher in urbanized areas in comparison to the agricultural and woodland sectors: according to the 1st classification level of the land cover map (CORINE Land Cover, 2000), PS density is distributed as ca. 350 PS/km^2 in urban and artificial lands, 20 PS/km^2 in agricultural and pasture areas, and only 5 PS/km^2 in the woodland and semi-natural areas.

Table 1: Number of images, time period, number of identified PS and average PS density (differentiated for land cover categories) for ERS and ENVISAT data stacks used for the PSI analysis. Desc, descending; Asc, ascending.

Satellite and orbit	N° images	Time range	N° PS	PS density (PS/km^2)		
				Urban areas	Agricul. areas	Wood Land
ERS_desc	48	20/10/1992-05/01/2001	34,064	532	24	7
ERS_asc	48	08/09/1992-24/11/2000	31,935	473	25	7
ENVI_desc	18	26/12/2003 01/09/2006	8,161	129	6	1
ENVI_asc	26	29/11/2002-08/12/2006	22,192	325	18	6

3.4 Results and discussion

ERS1/2 and ENVISAT PSI data, both in ascending and descending geometry, allows the analysis of the spatial variability and, through the displacement time series, the temporal evolution of Gioia Tauro subsidence in 1992-2006.

PSInSAR results for ERS dataset (Fig. 2 and Fig. 3) show that subsidence was widespread throughout Gioia Tauro basin in the time period from 1992 to 2000, with a mean rate of 11 mm/yr. In particular, an ellipse-shaped area, SW-NE oriented, corresponding to the central part of the plain, is affected by intense subsidence, with mean deformation velocity of 15 mm/yr. Two areas of maximum deformation located at Rizziconi (within the central part of the basin, 5 km ESE of Gioia Tauro) and Rosarno (in the northern part of the plain) are observed in 1992-2000, whose higher measured deformation velocities are 22.8 mm/yr and 18.8 mm/yr, respectively.

PSInSAR results for ENVISAT dataset (Fig. 4 and Fig. 5) indicate, in the time period from 2002 to 2006, a general subsidence decrease, for both intensity and extension of the affected area. Compared with the previous period, average ground deformation rate highlights that the SW-NE oriented ellipse-shaped area corresponding to the central part of the Gioia Tauro basin, is affected by a subsidence with a mean value of 7 mm/yr. Maximum land deformation

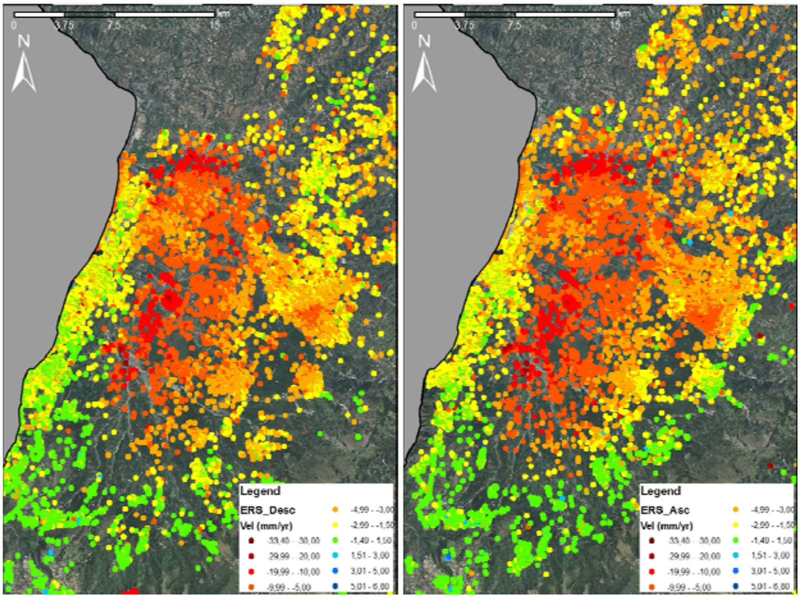

Figure 2: Average displacement rates along the LOS of ERS satellites in 1992-2000.

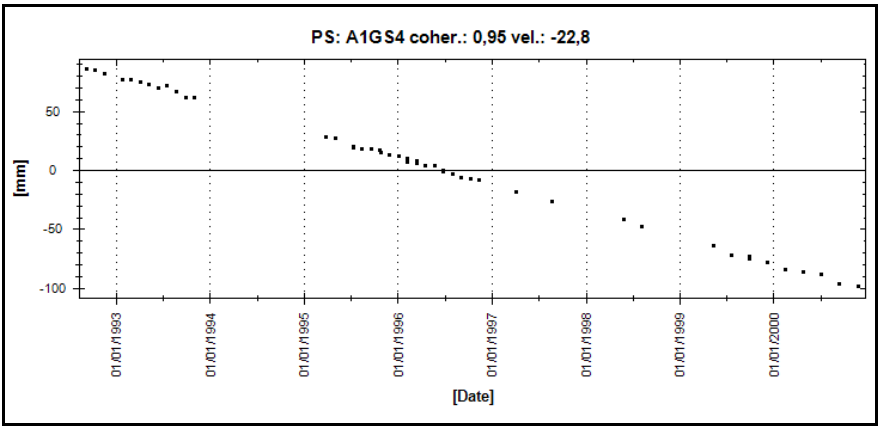

Figure 3: Example of displacement time series of a PS located in the area of highest deformation.

velocities, detected in 2002-2006 are 17.7 mm/yr and 11 mm/yr, measured at Rizziconi and north of Rosarno, respectively, which remain the areas of maximum subsidence rate.

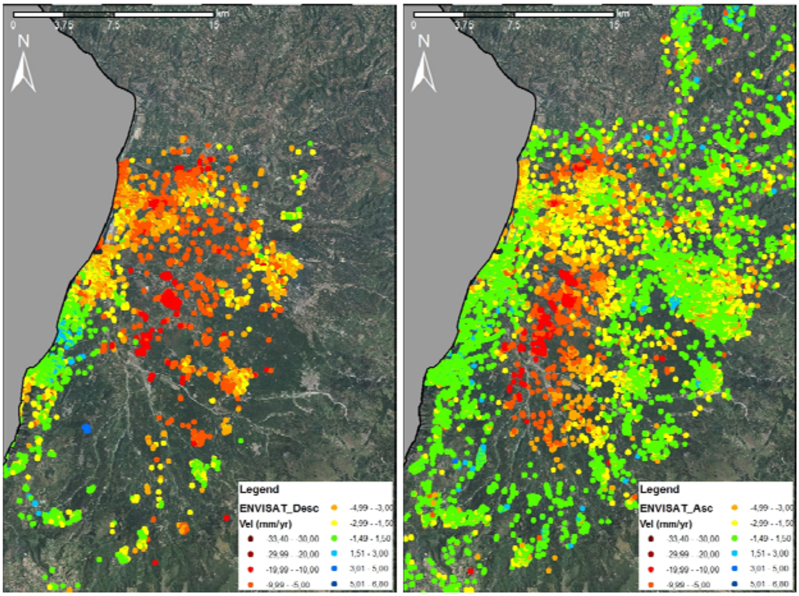

Figure 4: Average displacement rates along the LOS of ENVISAT satellite in 2003-2006.

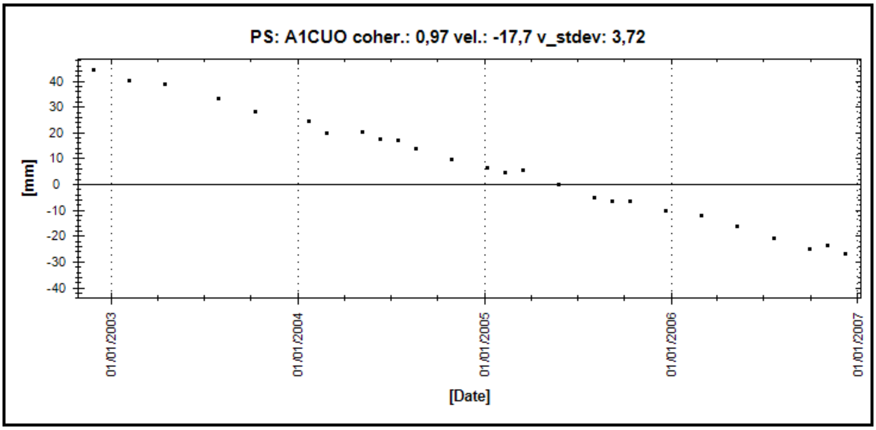

Figure 5: Example of displacement time series of a PS located in the area of highest deformation.

Analysis of PS displacement time series enable the analysis of the temporal variability of ground displacements, highlighting that, during both 1992-2001 (Fig. 3) and 2003-2006 (Fig. 5), subsidence is characterized by a constant rate of deformation.

Cumulating in time the displacement measured through the PS time series in 1992-2000 (ERS dataset), a maximum subsidence of 184 mm and 162 mm was observed at Rizziconi and Rosarno, respectively. On the other hand, for the 2003-2006 interval (ENVISAT dataset), a slightly lower deformation was measured, with maximum subsidence of 74 mm and 48 mm, observed at Rizziconi and Rosarno, respectively.

Fig. 6 and Fig. 7 show a 3D view of the cumulated LOS displacement field in 1992-2000 and 2003-2006 in the whole basin of Gioia Tauro. The ground deformation surface is interpolated with the IDW (Inverse Distance Weighted) method, assigning values to unmeasured locations by using the displacement values from scattered sets of surrounding PS.

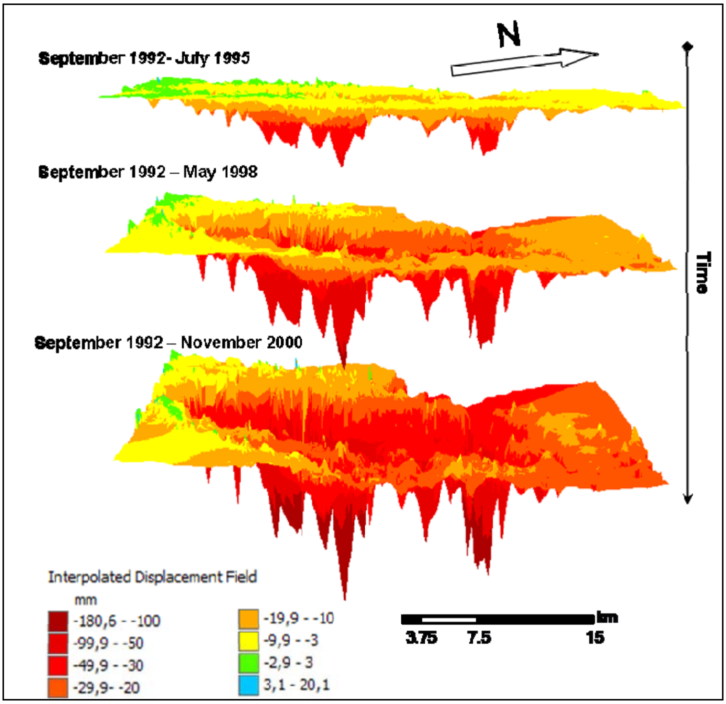

Figure 6: 3D view of cumulated LOS displacement in 1992-2000.

The three snapshots of Fig. 6 represent the interpolated ground deformation surface, corresponding to three different time intervals (whose length is about 950 days) during 1992–2000: September 1992–July 1995; September 1992–May 1998; September 1992–November 2000.

The two snapshots of Fig. 7 correspond to two different time intervals (whose length is about 750 days) during 2003–2006: November 2002–January 2005; November 2002–December 2006.

The observed subsidence in the Gioia Tauro plain is thought to be induced by groundwater overexploitation, with related water table decline and fine-grained aquifer compaction. Land subsidence is a displacement phenomena characterized by very high vertical component, hence ground deformation measurements have

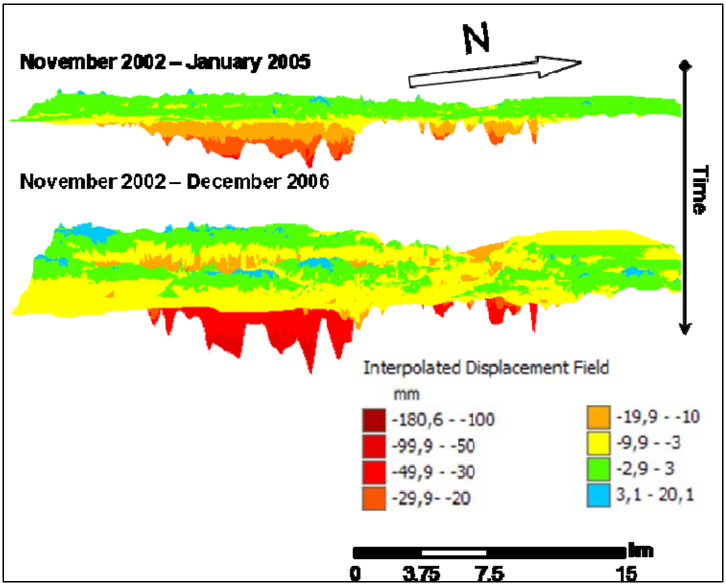

Figure 7: 3D view of cumulated LOS displacement in 2002-2006.

to be considered mainly vertical–subsidence (negative values, when PS move away from the sensor) and uplift (positive values, when PS move towards the sensor). Considering also the flat geometry of the plain, ascending and descending geometries provide very similar values of mean deformation rates of the same target areas.

Comparing the geographic location of water extraction sites (Fig. 1) and the deformation maps provided by the PSI analysis (Fig. 2 and Fig. 4), it is possible to highlight a slight correlation between the occurrence of intense subsidence and the distribution of water wells and springs. However, significant spatial variability of deformation velocities throughout the whole basin is also observed. Such variability may be induced by differences in both the geotechnical properties of the aquifer sediments and the compressible layer thickness and, secondarily, the water amounts pumped from the different water wells in the plain. Moreover, an incomplete census of water extraction sites cannot be ruled out for this area.

Identification of independent wells and respective water extraction rates, will be an urgent topic of discussion and analysis in the future, to better understand subsidence causes and patterns, and consequently improve water and land management strategies for a future sustainable use of groundwater resources.

4 Conclusions

The PSI analysis allowed the analysis of the spatial variability and temporal evolution of ground displacements affecting the Gioia Tauro plain in 1992-2006.

Both historical (1992-2001; ERS1/2 images) and present (2002-2006; ENVISAT images) scenarios reveal the occurrence of significant ground displacements affecting the unconsolidated fine-grained sediments of the plain. Average deformation rates as high as 10-15 mm/yr are observed in 1992-2006, with highest velocities (i.e. 22.8 mm/yr) occurred between 1992 and 2000 within the central part of the basin, in the area of Rizziconi (5 km ESE of Gioia Tauro).

Land deformation is probably controlled by groundwater overexploitation and consequent aquifer compaction. Slight correlation of intense subsidence with the distribution of water wells and springs is observed. Nevertheless, significant spatial variability of deformation patterns throughout the whole basin is also registered and justified by the differences in the geotechnical properties and thickness of the compressible layer, water extraction rates, and a probable incompleteness of the water well census.

The outcomes of this PSI study will support the future improvement of groundwater management and the implementation of best strategies for risk mitigation, land use planning, sustainable use of groundwater resources, and consequent reduction of economic and social impacts.

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