European Union Network for the Implementation and Enforcement of Environmental Law

Project WODA: Water Over Abstraction & Illegal Abstraction Detection and Assessment

Pilot Feasibility Study Lombardy

Final Report: March 2016

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Summary

1 Introduction

This document describes the Pilot Feasibility Study related to Lombardy, in the framework of WODA project (Water Over-abstraction and illegal abstraction Detection and Assessment).

In the WODA project three Pilot Feasibility Studies were carried out in order to assess the technical feasibility and operational use of Earth Observation data to identify and quantify situations of over-legal or illegal extraction of water. Two of these feasibility studies (Malta and Romania) were related to the use of optical satellite data, and applied in the geographical context of two of the project partners; the third feasibility study, which is summarized in this report, refers to the use of satellite interferometric SAR data, in the geographical context of Lombardy.

The general concept of EO monitoring of groundwater over abstractions through SAR Interferometry is described in Figure 1.

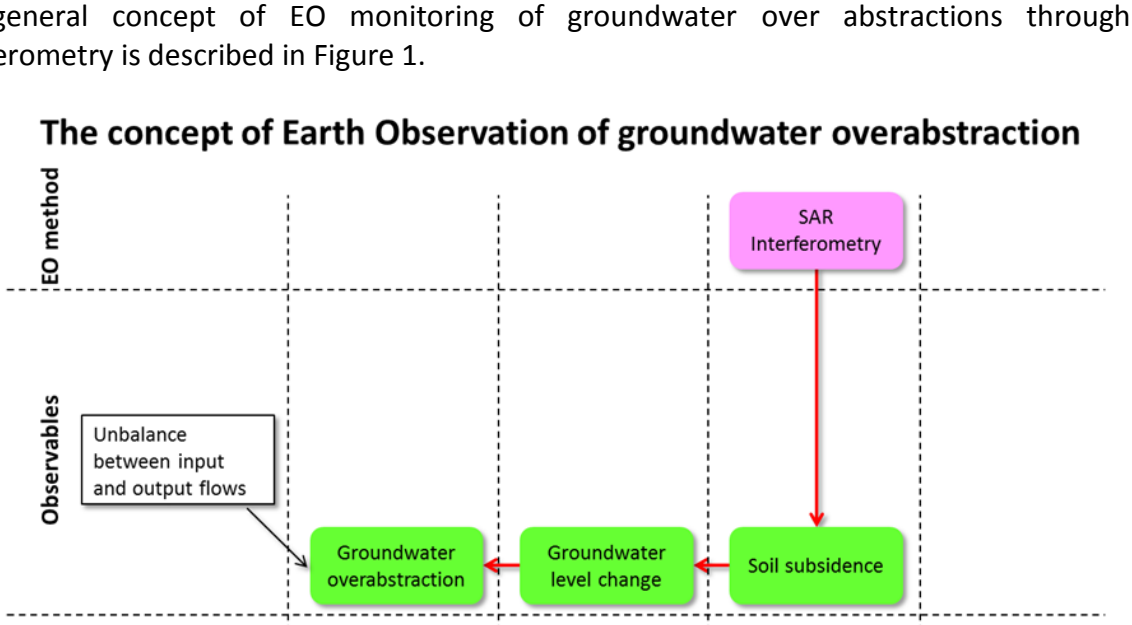

Figure 1: Conceptual scheme of satellite SAR Interferometric monitoring of groundwater overabstractions, versus the DPSIR model.

As a first general reference (see Figure 1), it should be emphasized that the observation method (satellite SAR interferometry), measures with high accuracy the movements of the land (subsidence), which are actually the overall and combined effect of several competing phenomena (in the DPSIR framework terms, this leads to an "impact"). The variation of the piezometric levels of underground aquifers (the "state", according to the DPSIR framework) is however only one of the possible causes of the possible observed subsidence; moreover, the piezometric variations may be subject to water over-abstractions (the "pressures"), or unbalances between abstractions and recharges of groundwater resources.

2 Objectives and contents of the feasibility study

The technical feasibility of ground movements monitoring with satellite SAR Interferometry, with high accuracy, is widely proven in literature and in numerous operational monitoring applications; within the WODA project and through this feasibility study, the objective is to assess the observability, in the geological context of Lombardy lowland, of subsidence induced by groundwater abstraction (and possibly over-abstraction). This kind of phenomenon has already been observed and monitored in the past in other regions, even proximal to Lombardy (for example, in Emilia Romagna), but this approach is not yet applied operationally in Lombardy's context.

In addition to this technical feasibility evaluation (focused on the observability of the phenomenon), we also want to investigate the "operative" feasibility, in terms of availability of SAR data and interferometric time series, and of auxiliary data availability for the correct interpretation of the observed ground movements.

The feasibility analysis is structured in the following different components:

- assessment of the current / future satellite data availability and SAR interferometric time series in Lombardy's lowland,
- assessment of the availability of auxiliary information in order to properly interpret the observed ground movements, and in order to relate them correctly, among other possible reasons, to the groundwater abstraction
- observability analysis of the phenomenon in the geological context of the Lombardy's lowland, with some specific ground movement analysis from available SAR data, linked with groundwater abstraction informations.

The aspects of "non-technical" feasibility, e.g. the ones relating to organizational aspects, data acquisition, SAR data pre-processing in order to obtain interferometric series, etc., aren't object of this report.

3 SAR interpherometric data – state of the art and data availability in Lombardy

This section of the document refers to the evaluation of the current and future availability of SAR satellite data and of SAR interferometric time series, relatively to Lombardy Region.
From the SAR satellite data availability point of view, the following figure summarizes the essential characteristics (length of time series, revisit time, bandwidth) of the main SAR constellations that operated in the past decades, or are currently in operation, or are expected in the next years.

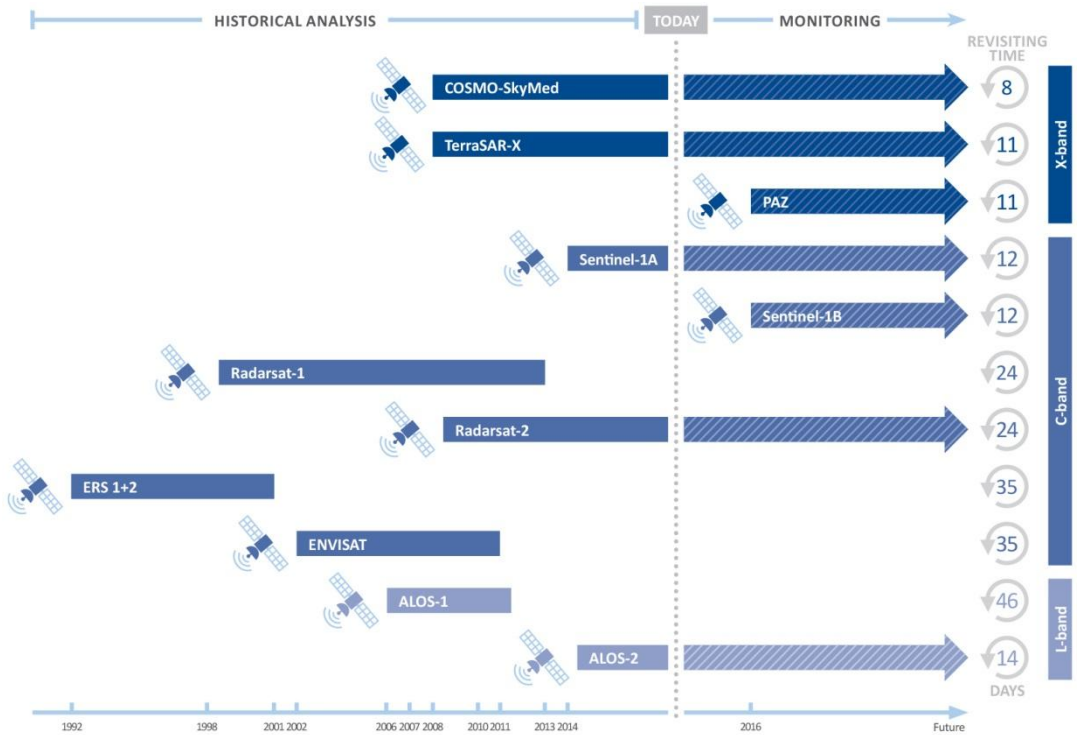

Figure 2: Essential scheme of the main SAR satellites (image courtesy: TRE s.r.l.)

The main SAR satellites that worked in the past, useful for historical analysis of ground movements, are the european satellites ERS1 and ERS2 (1992-2000 time series) and ENVISAT (2002-2008 time series) and the Canadian Radarsat1 (1999-2012 time series). Right now, different SAR constellations are fully operating with different characteristics, like Cosmo-SkyMed (ASI), TerraSAR-X (DLR), and in particular the first SAR satellite from the ESA COPERNICUS Program (Sentinel-1A, operating from April 2014). In 2016 Sentinel-1B will also be launched, providing half of the current time revisit of this constellation (from 12 days to 6 days).
From the operational point of view, it should be emphasized that, for the purpose of the actual usability of SAR data for the monitoring of ground movements, more than the "simple" availability and accessibility of data, the main limiting factor is SAR data processing (particularly onerous from the computational point of view) in order to derive the interferometric time series.

The following paragraphs briefly describe the essential characteristics of the SAR interferometric time series currently available in Lombardy.

3.1 SAR Interferometric time series provided by Environmental Ministry

A first baseline is represented by the SAR interferometric time series provided at national level by the Environmental Ministry, in the framework of the National Remote Sensing Plan (PST). The data are related to the processing of ERS1, ERS2 and ENVISAT data, and are available through the National Geoportal and specific map services. The following figures show the coverage of the ERS and ENVISAT SAR time series coverages. In particular, Lombardy is covered almost entirely by time series for 1992-2000 period (ERS) and 2003-2008 period (ENVISAT).

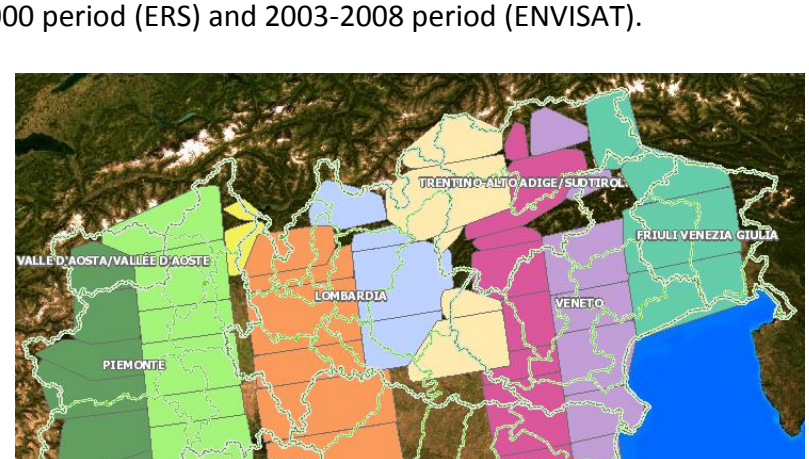

Figure 3: coverages over Northern Italy of ERS Ascending Interferometric time series (from PST, Environmental Ministry)

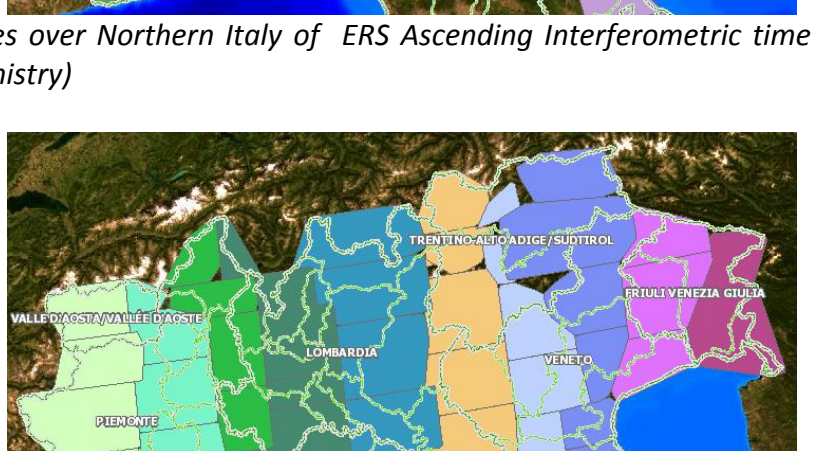

Figure 4: coverages over Northern Italy of ENVISAT Ascending Interferometric time series (from PST, Environmental Ministry)

Through specific map services it's possible to check the individual PS (Permanent Scatterers) identified in the different areas. One limitation of these series is that the identified Permanent Scatterers are generally themed only by the average vertical displacements (mm/year) during the period, thus highlighting only mean movements during the available time series; disaggregated data referred to single satellite acquisitions are not available, which would enable a more complete interpretation of observed subsidence movements (for example, possible acceleration in specific periods, seasonal fluctuations, etc ..).

3.2 Regional SAR Interferometric time series

At Regional level, other SAR interferometric time series are available, commissioned by ARPA or Lombardy Region , in particular in the framework of landslide monitoring activities. The temporal coverage and the type of SAR satellite data is different (in particular ERS and Radarsat series, and, in more recent years and in smaller areas, even with Cosmo-SkyMed data); the territorial coverage of these data is mostly related to the mountainous and hilly areas of the Lombardy (Figure 5).

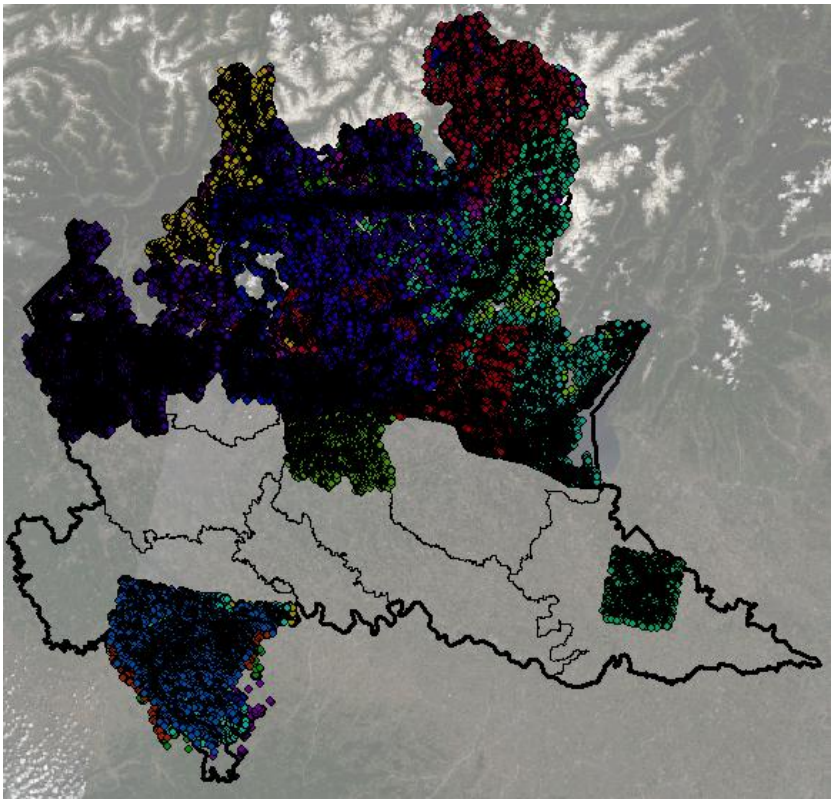

Figure 5: Coverages over Lombardy of the available SAR Interferometric series, provided in the framework of landslides monitoring

Some of these SAR Interferometric time series cover, almost partially, the higher part of Lombardy's lowland or the main alpine valleys (characterized in general by the presence of local aquifers); moreover for these data the specific information of the ground movements observed in every satellite acquisition, for the single Permanent Scatterer, is generally available; for these reasons, these data provide potentially a good level of information.

3.3 SAR interferometric time series at the Underground Gas Storage (UGS)

A further source of available information, evaluated in this feasibility study, are the interferometric series available for some of the Underground Gas Storages (UGS) facilities active in Lombardy. Currently in Lombardy six different UGS concessions are active; for four of them ground movements and subsidence is monitored with SAR Interferometry; these data are required to the Environmental Ministry and to ARPA. The following figure shows the location of the six active UGS concessions in Lombardy, and the PS points available from SAR monitoring.

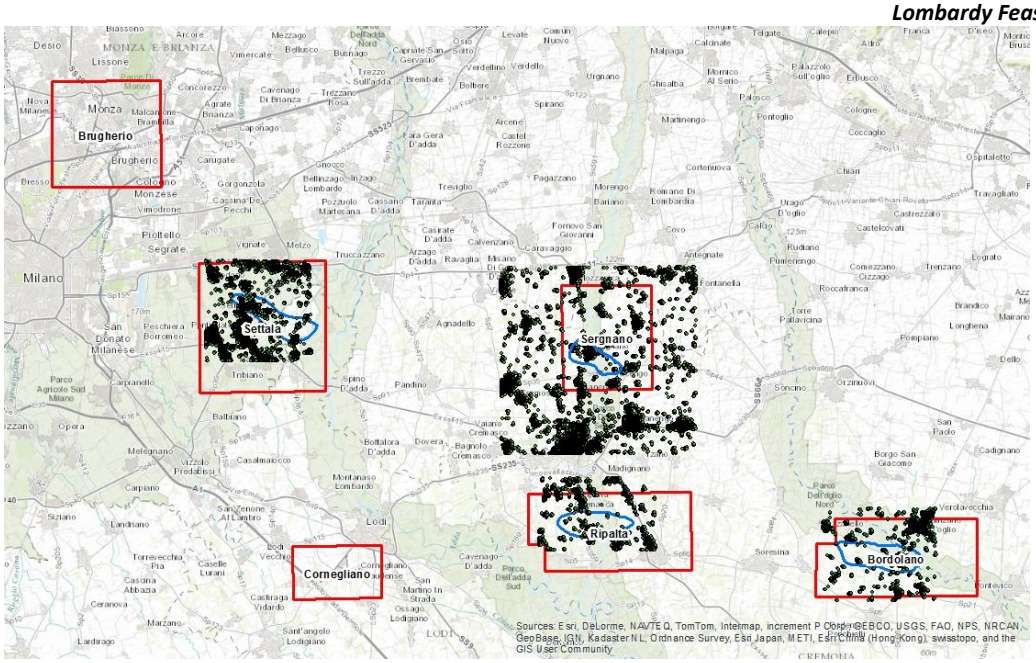

Figure 6: Location of the six active UGS concessions in Lombardy, and the permanet scatterers available from SAR Interferometric monitoring.

Such interferometric series are currently referred to Radarsat data, with time series available since 2003, and with the acquisition frequency of 24 days.

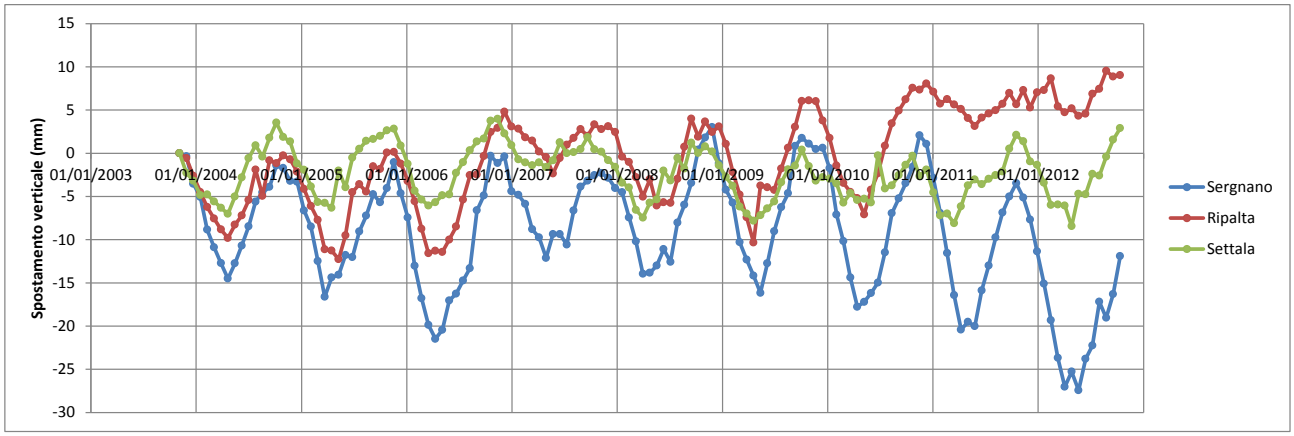

Figure 7: Pattern of ground deformation measured at the three underground gas storage sites of Sergnano, Ripalta and Settala: these measures, referred to the area immediately above the gas storages, highlight the periodic oscillation of the ground in relation to the annual cycles of injection and extraction of gas.

For the purposes of this feasibility study, such data are of interest, as well as from the methodological point of view, exclusively in the marginal portions of the monitored areas, where the observable ground movements are not caused by the gas storage activities.

4 Auxiliary data availability and data quality in support to the interpretation of interpherometric series

Theoretically, with constant extraction of groundwater, the observable effect to the ground, in terms of subsidence, is highly variable in function of many factors, in particular depending on different geological conditions, on sediments granulometry, on the thickness of the aquifer, etc...
The proper knowledge, as thorough as possible, of these aspects is therefore an essential prerequisite for the proper interpretation of observable ground movements by SAR interferometry technique. In the following paragraphs a brief review of the main data available, in order to support the analysis and interpretation of movements, is summarized .

4.1 Geo-litology and sediments structure

Regarding data and information about geology, geolitology, and sediment structures in the lowland the basic maps available are shown in the following point.

- Geological map:

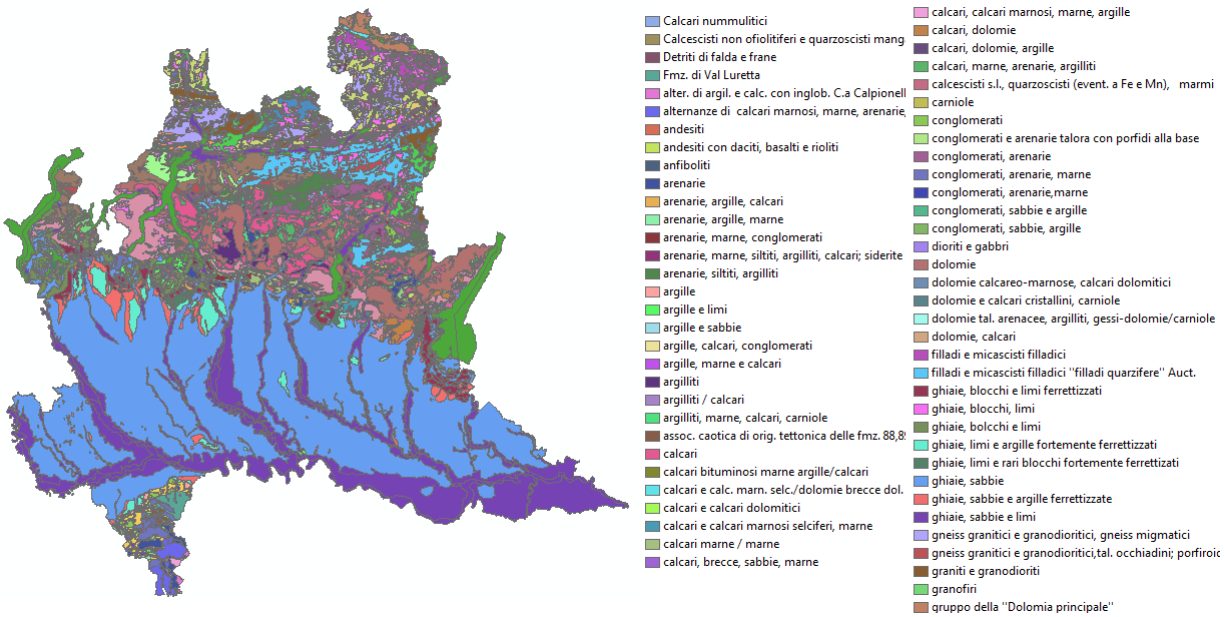

Figure 8: Lombardy geological map (scale 1:250.000), thematized by the main lithologies

- Pedological map:

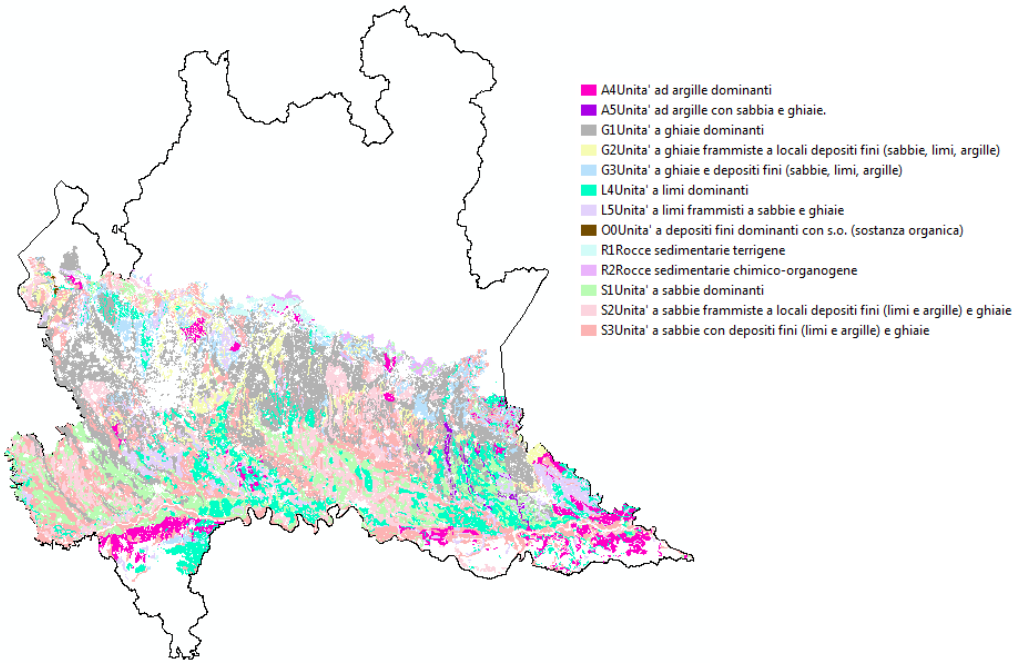

Figure 9: Lombardy pedological map (scale 1:50.000), thematized by the main soil type and prevalent granulometry in the upper stratus

- Geological surveys database, sediments stratigraphy:

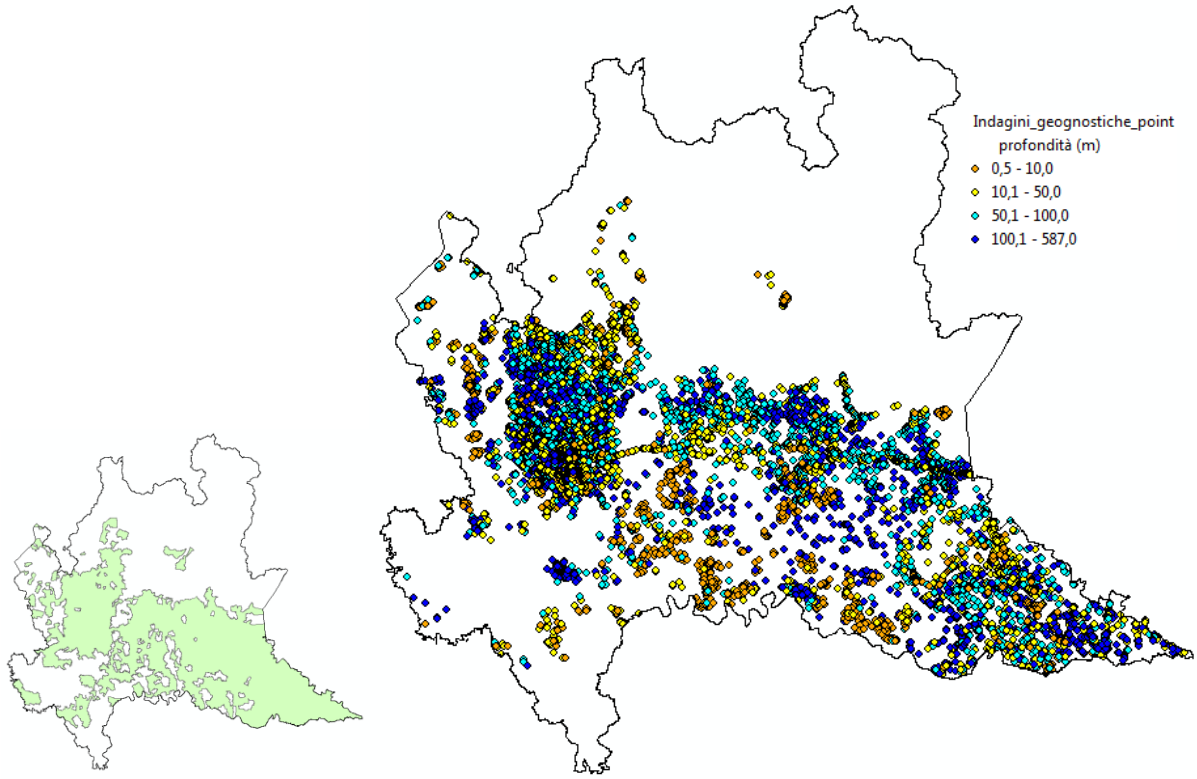

Figure 10: Coverage of the available information about local geological surveys and stratigraphy in the lowland of Lombardy ("Banca Dati Sottosuolo").

In particular, the Subsoil database in Lombardy (“Banca Dati Sottosuolo”) is composed of a total of 12306 points with geological surveys (of which 8015 related to stratigraphy of wells, and 3985 relating to direct surveys).
For each point of the database stratigraphic analysis with horizons definition and granulometry analysis are available.

4.2 Aquifers and Ground Water Bodies definition and monitoring

Regarding the knowledge of the aquifers and their spatial development, the reference database is the "Geology of aquifers" regional database, available through the Regional Geoportal. In this database, for different defined aquifers groups (Group A, B, C, D), the information relating to extension of the aquifers, depth of the basal surfaces, thickness of sandy deposits, recharge areas, are available. For example, the next figures show two extracts of the database "Geology of aquifers" relatively to the Group A and Group B.

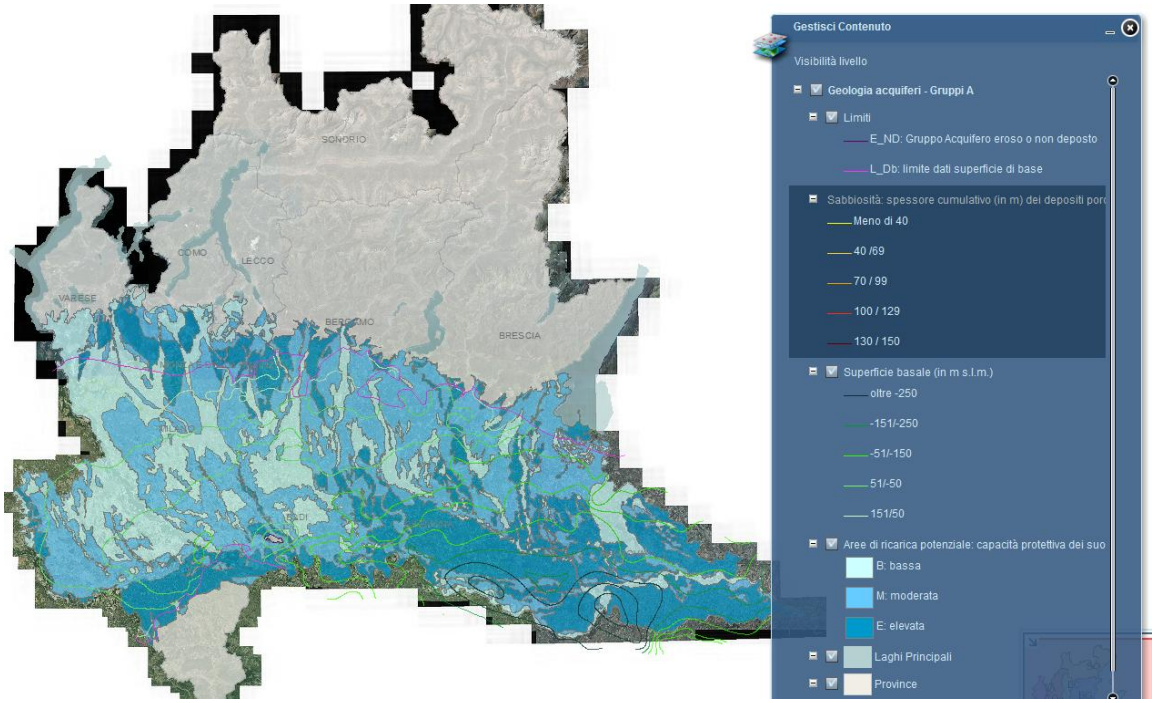

Figure 11: Example, from the Regional Geoportal webservice, of the"Geology of aquifers" database, in this case referred to the upper aquifers (“Gruppo A”).

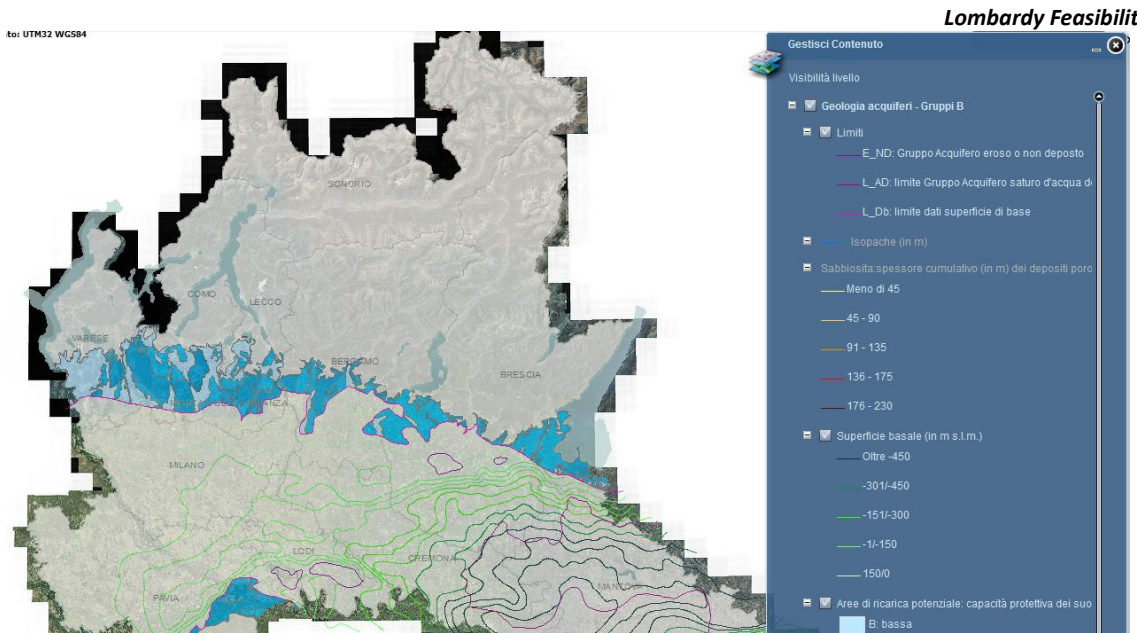

Figure 12: Example, from the Regional Geoportal webservice, of the"Geology of aquifers" database, in this case referred to the medium aquifers ("Gruppo B").

Regarding the Groundwater bodies (GWB) definition and classification, and their qualitative and quantitative monitoring as required by the Water Framework Directive (WFD), in Lombardy 23 groundwater bodies (GWB) are defined (Figure 13).

Figure 13: Limits and codes of groundwater bodies (GWB) defined in Lombardy, under the Water Framework Directive; the map shows the superficial groundwater bodies (GWB ISS) and the local GWB in the main alpine valley (GWB F).

Focusing now the attention only on the quantitative aspects, from the point of view of the classification of the status of groundwater bodies as specified in the Framework Directive, it must be stressed that currently all the defined GWB are classified in Good status.
The defined water bodies are monitored through the ARPA monitoring network (groundwater quality and quantity network). The following figure shows the location and the type of qualitative and quantitative groundwater monitoring network stations.

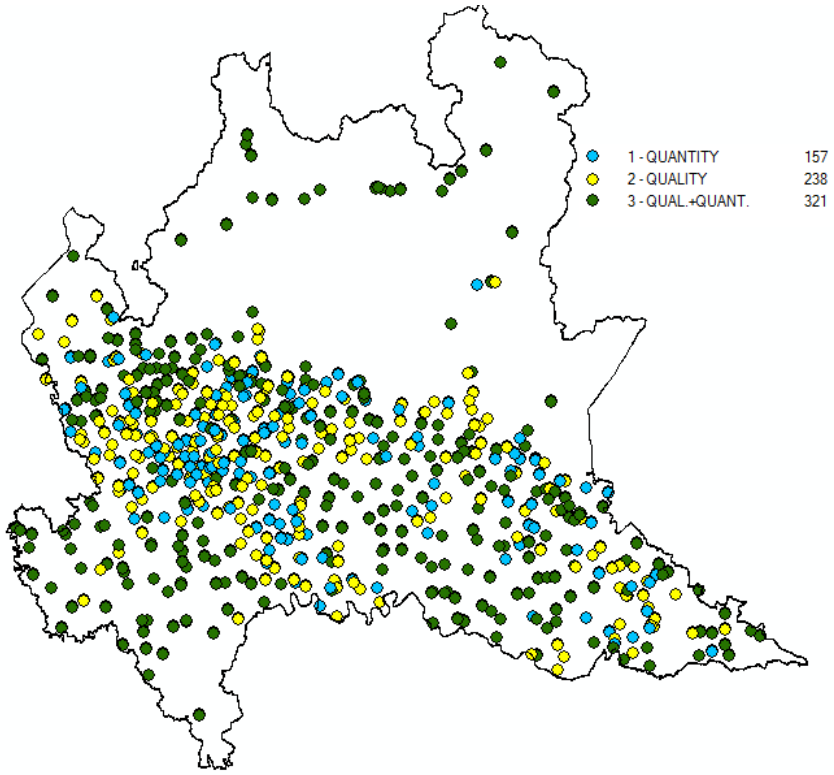

Figure 14: Location and type of qualitative and quantitative groundwater monitoring network stations.

The frequency and length of the time series of quantitative piezometric measurements is variable (generally monthly measures).

4.3 Quantitative informations about actual groundwater abstractions

Generally, in Lombardy there aren't direct and systematic measurements about the amount of actual groundwater abstractions (such measures are planned and available only on a small part of the major abstraction points). The reference database about active licenses and concessions for the extraction of groundwater in Lombardy is represented by CUI (Catasto Utenze Idriche, Water Utilities Cadastre), that is currently being updated and under revision (towards the new SIPUI database). The CUI database is characterized by a certain degree of dishomogeneity in terms of type and completeness of the information (in particular referring to the distinction between large and small concessions, characterized by different authorization process and competences).
For example, the following figure shows the active water concessions, extracted and georeferenced from CUI database, distinguished between large and small concessions.

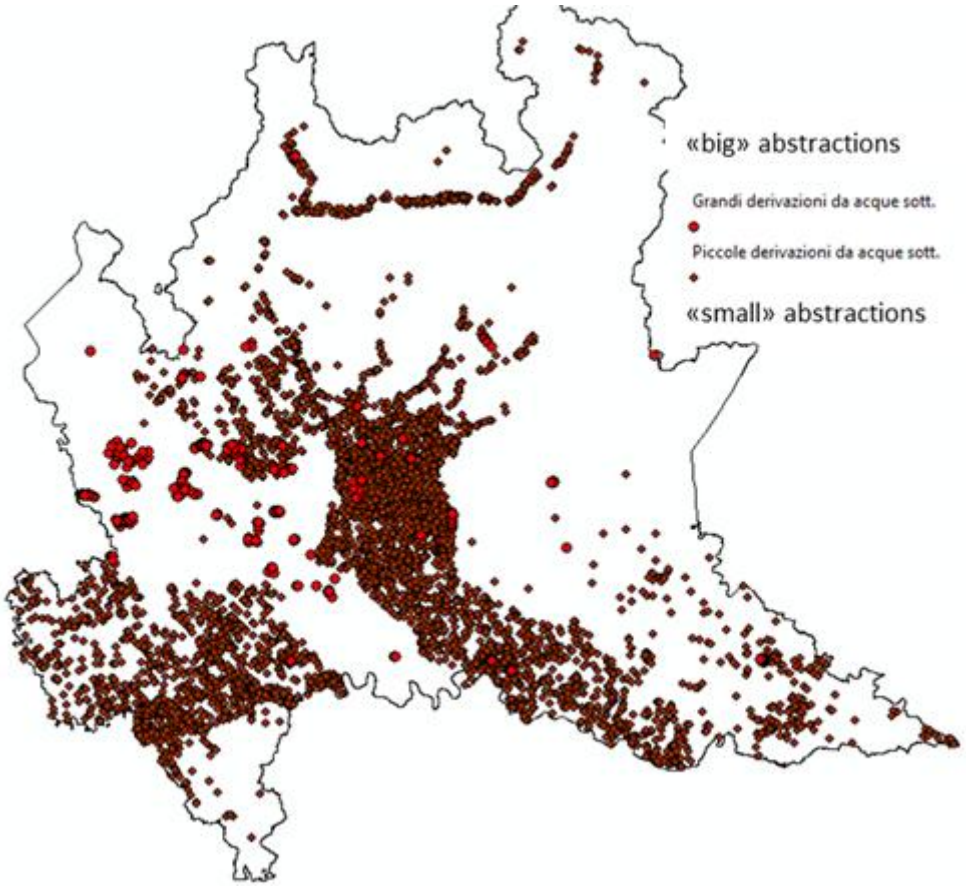

Figure 15: Groundwater abstraction concessions in Lombardy, extracted and georeferenced from CUI, and distinguished by "big" (> 100 l/sec) and "small" (< 100 l/sec) abstractions.

At the moment, the considerable lack of homogeneity of the available information about actual groundwater abstraction measurements and also about groundwater concessions appears a strong criticality, although this will be probably largely overcome by the future evolutions in water utilities databases.

4.4 Potentially interfering phenomena location

For the purposes of the correct interpretation of the observable ground movements, and in particular to properly attribute the main causes of local subsidence, we need to know as much as possible also about localization and extent of other possible interfering phenomena.
The main anthropogenic phenomena that potentially generate observable ground movements are the different exploitations of the subsoil: the following map (source MISE, Ministry for the Economic Development) shows the areas currently with active concession for exploitation, research or storage of mineral resources (oil and gas) in Lombardy. Among them, those with the greatest interest and potential impact in terms of observable ground movements, are the concessions for the production (extraction) and underground storage of natural gas.

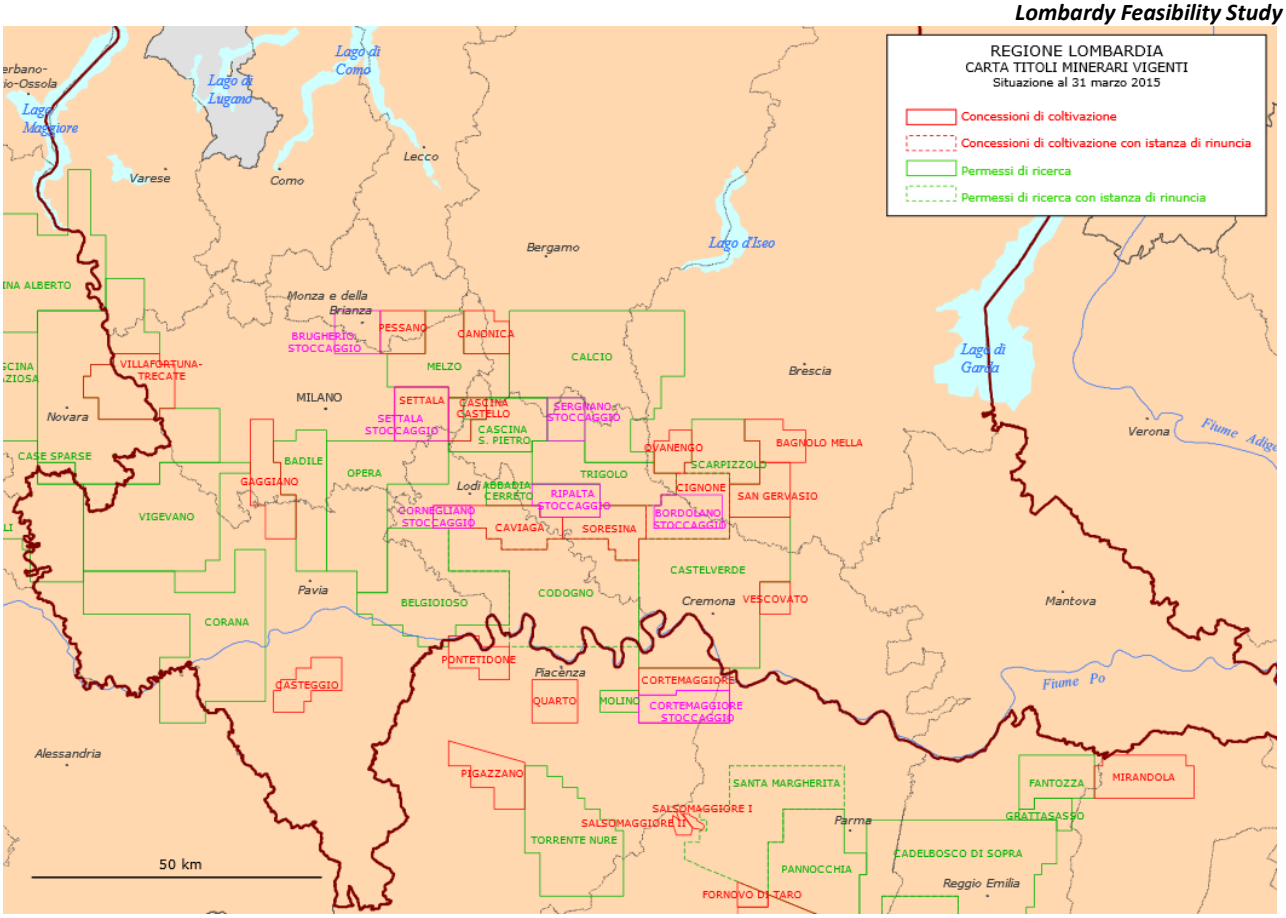

Figure 16: Map of Active Mining Titles in Lombardy (source MISE); in particular, in magenta the limits of concessions for underground gas storage, and in red the concessions for gas extraction are shown.

Other types of ground movements could be for example related to the local compaction of sediments, observable in particular in the recently built urban areas, or even related to the thermal expansion of the buildings; to minimize these “interfering signals", which in fact represent a disturbance to the proper interpretation of SAR interferometric series, the analysis should be always supported by local knowledge of the areas (eg., land use maps, more detailed information extracted from topographic databases, etc ..).

5 Case studies analysis

The following sections are related to some examples in Lombardy, where SAR interpherometric time-series analysis, jointly with auxiliary data analysis, led to the detection of areas with specific ground movements over time, potentially related to groundwater abstractions, despite significant differences about spatial extension and temporal development of the phenomena, and possible other interfering causes.

5.1 Oltrepò Pavese

A first potential interest area for the observed ground movements, is represented by the Oltrepò Pavese (Pavia Province). Since from the first SAR interferometric series analysis carried out under the PST with ERS (1992-2000) and ENVISAT (2003-2008), locally the Oltrepò Pavese plain showed some areas affected by local subsidence (see next figures)

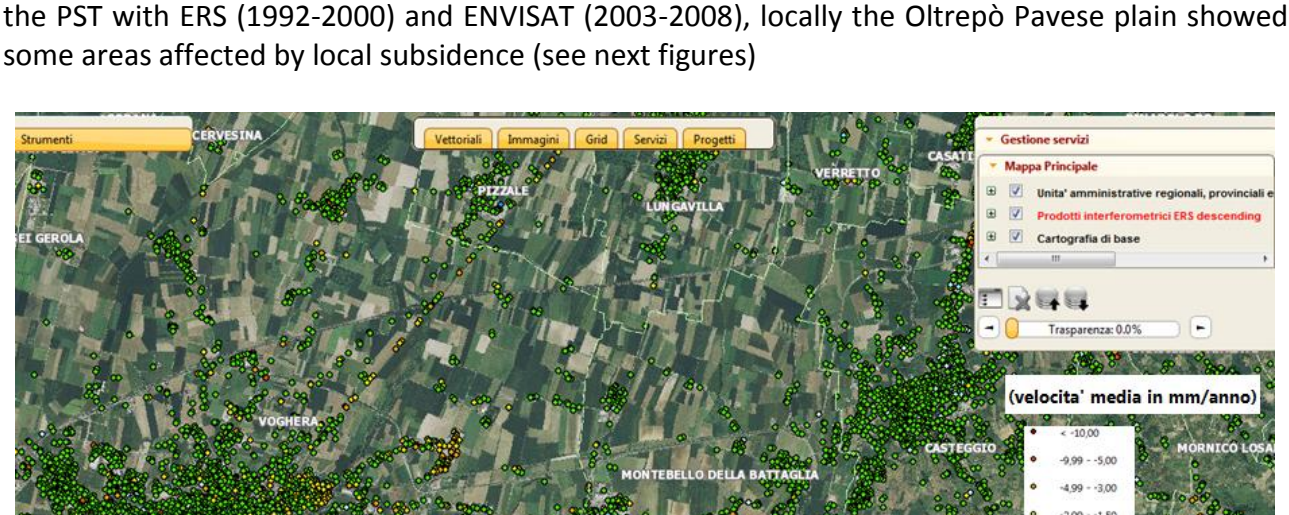

Figure 17: Extract, from the National Geoportal, of the SAR interferometric analysis from PST (ERS series 1992-2000), in a portion of Oltrepò Pavese; single Permanet scatterers (PS) points are themed as a function of their average speed of displacement (mm/y) along the line of sight of the satellite during the period of analysis; yellow-red colors denote local subsidence.

Figure 18: Extract, from the National Geoportal, of the SAR interferometric analysis from PST (ENVISAT series 2003-2008), in a portion of Oltrepò Pavese; single Permanet scatterers (PS) points are themed as a function of their average speed of displacement (mm/y) along the line of sight of the satellite during the period of analysis; yellow-red colors denote local subsidence.

The Oltrepò Pavese area, from the point of view of water resources, has very specific characteristics compared to the average Lombardy conditions: water uses from superficial network in this area are very limited, while most of the uses (especially for irrigation) are secured by groundwater.
For example, the following is an extract from the CUI, with the georeferencing of active groundwater concessions (all classified as “small concessions”), themed by use type and amount.

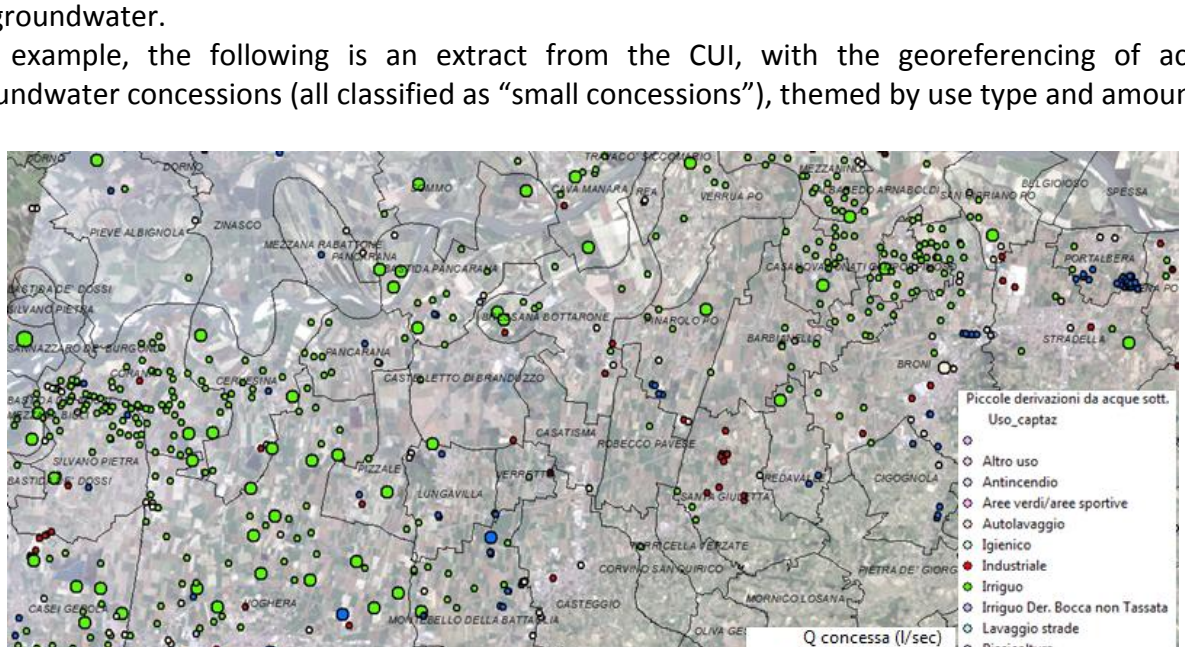

Figure 19: Extract, from the CUI, of the active groundwater concessions in the Oltrepò Pavese area (all classified as “small concessions”), themed by water use type and water concession (l/sec).

This area of interest is also partly covered by a more recent SAR interferometric time series, from Radarsat (2003-2010 period), in which the disaggregated data referred to the movements of individual PS in the individual acquisition dates are available (extract in Figure 20).

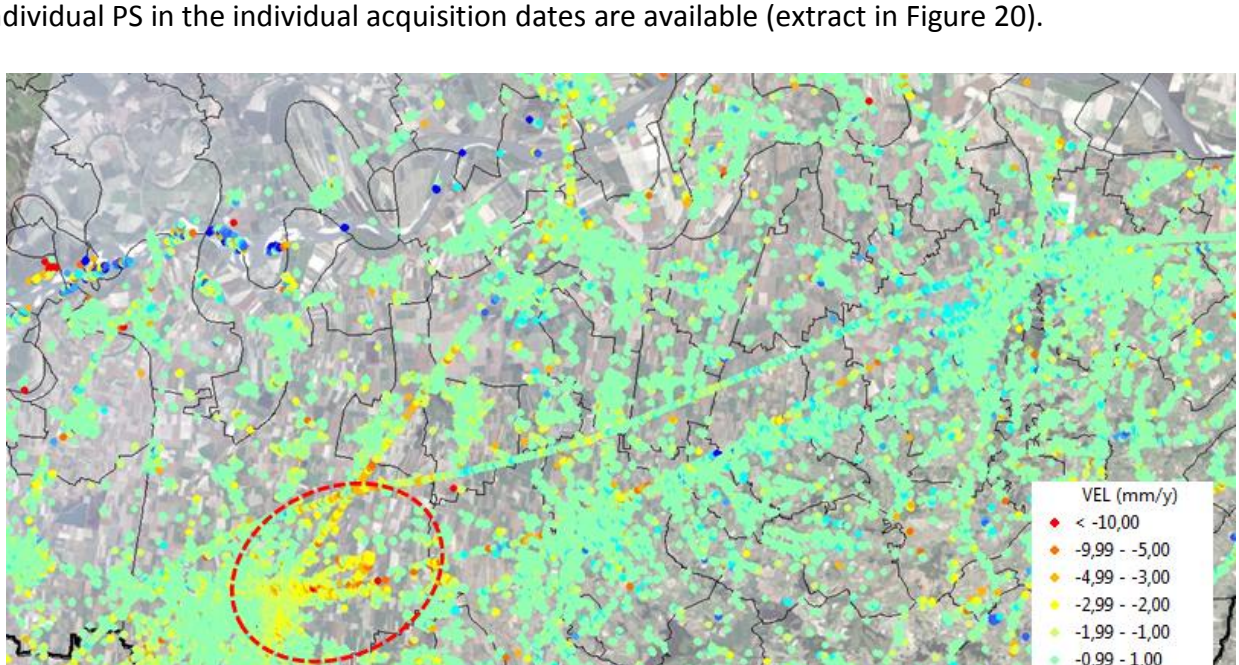

Figure 20: Extract of SAR interferometric analysis from Radarsat time series 2003-2010), in a portion of Oltrepò Pavese; single Permanet scatterers (PS) points are themed as a function of their average speed of displacement (mm/y) along the line of sight of the satellite during the period of analysis; yellow-red colors denote local subsidence.

Even in this case, and over this period of analysis, localized areas of light subsidence are observed; in particular, an area (e.g. ellipse in red in Figure 20) of local subsidence near the town of Voghera is highlighted, that could be caused by the combination of different potential causes; among them, it can be excluded the gas extraction (the nearby Casteggio Concession, now exhausted, is several km to the east); most likely a concomitant cause could be the sediments compaction effects (in particular for the PS points in slight subsidence aligned along transport infrastructures); the distributed “background signal" of subsidence trend appears likely related to groundwater abstractions (in the area there are several active concessions in particular for civil and irrigation uses).

Analyzing the Permanent Scatterers data from the statistical point of view, the group of PS in this area shows a substantially linear trend of slight subsidence in the investigated period, with no significant seasonal trend (Figure 21).

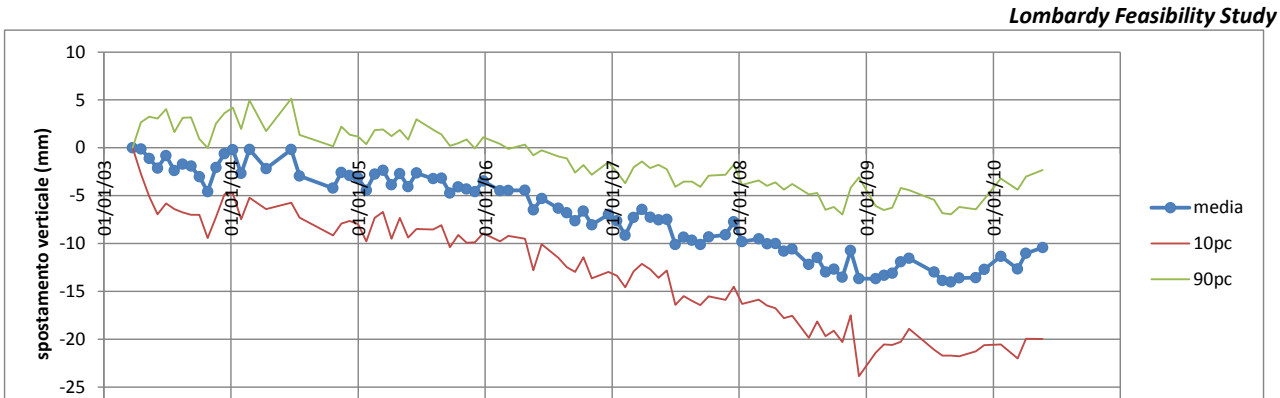

Figure 21: Statistical analysis of the vertical displacement trend of the PS points near Voghera; this group of PS shows a slight tendency to subsidence, with slightly higher rate in 2007-2008, without particular seasonal variations.

From the regional groundwater monitoring network point of view, unfortunately there are no close and significant stations nearby this local subsidence area, and in particular not relatively to the period covered by SAR data.
In this area the groundwater body (GWB), called MPOP ISS, is classified in "Good" quantitative status, but it should be emphasized that the GWB covers a very wide area, while the observable effects of potential "unbalance" of groundwater resources, caused by potential over-exploitation, could be very localized. Moreover, the monitoring of these observed subsidence phenomena appears potentially interesting for improve the knowledge and for the long-term management of water resources, as well in potential support to the authorization process for renewal or new concessions of permissions for water abstractions.

5.2 Local Phenomena

A second type of investigation and potentially interesting area for observed ground movements, is represented by localized areas in the main Alpine valleys.

The next figure shows the case of lower Valtellina valley (Sondrio Province), in which, already in the PST SAR interferometric series, very localized areas of long-term subsidence were observed.

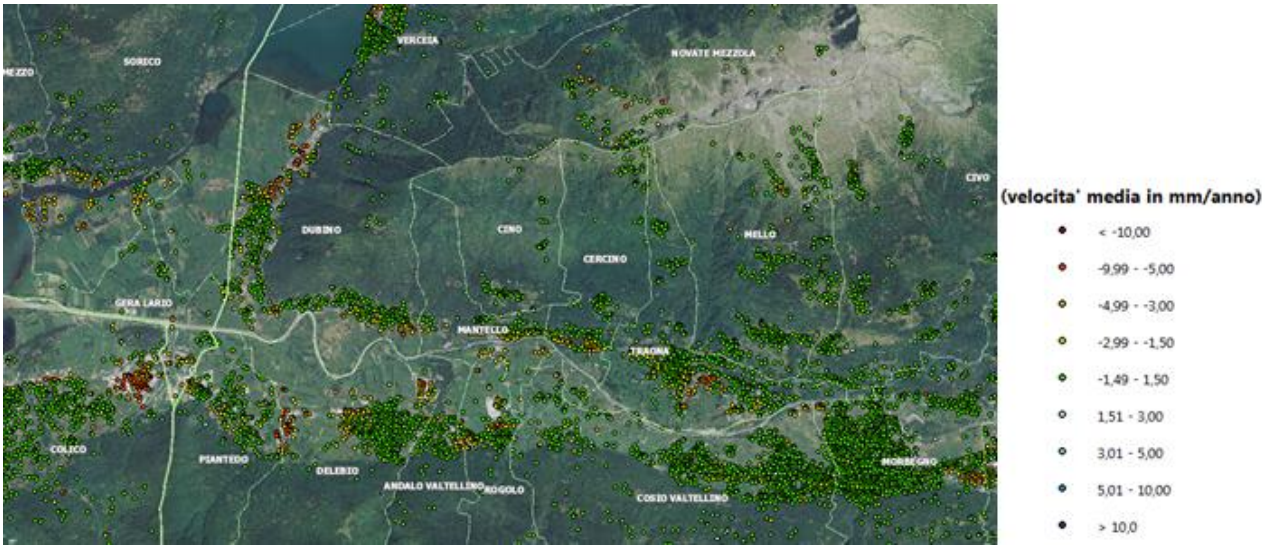

Figure 22: Extract of the Permanent Scatterers points identified by SAR interferometry (PST, ENVISAT series 2003-2008), in a portion of the Valtellina lower vally; PS points are themed the average speed of displacement (mm/y) along the axis of sight of the satellite during the period of analysis.

In these areas, the highest subsidence rates are generally observed nearby the urbanized areas with mainly industrial and commercial landuse (often areas of recent construction): likely in these cases an important interfering phenomenon is represented by the sediments compaction, moreover in these valley areas more "young" from a geological point of view.

From the perspective of groundwater resources, generally these areas are characterized by local and superficial aquifers: for these GWB, also, currently is not possible to determine the quantitative status under the Framework Directive.

Often, in correspondence of the local subsidence areas, there are also concentrated the most active licenses for groundwater abstractions (see for exampleFigure 23).

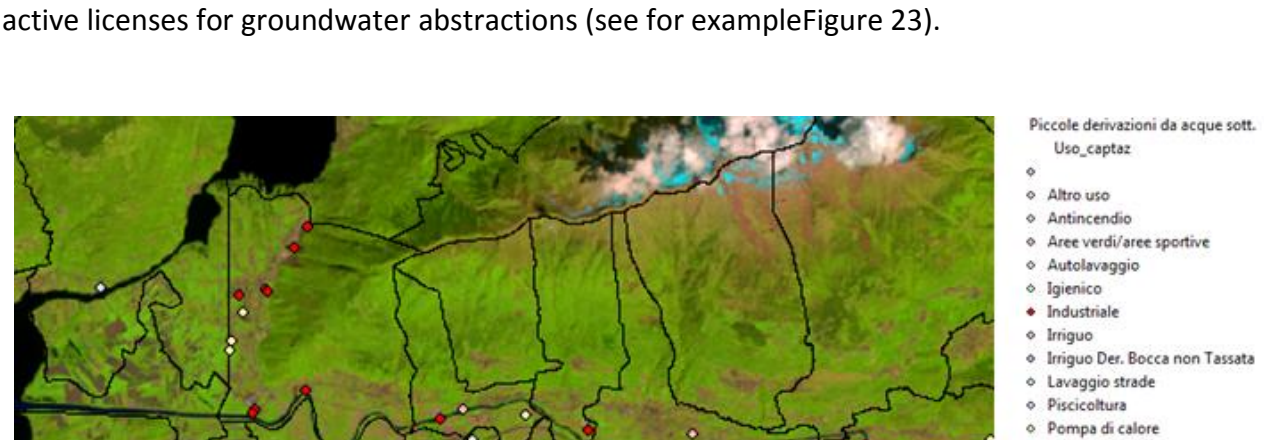

Figure 23: Overlapping, in the lower part of Valtellina valley, of the georeferenced concessions for groundwater abstractions, themed for main use (e.g: red: industrial uses).

In this case, in particular, there are many water concessions for industrial use, localized in the areas subject to slight subsidence.
This type of very localized phenomenon of subsidence takes place in different similar contexts alpine valley or high plains. In many cases, the concomitant presence of concessions for groundwater abstarctions (often for industrial use) suggests a potential situation of cause/effect relationship (at least in terms of one of the contributing causes).
The following example refers to a similar situation in the Val Cavallina valley (Bergamo Province), nearby the Endine lake.

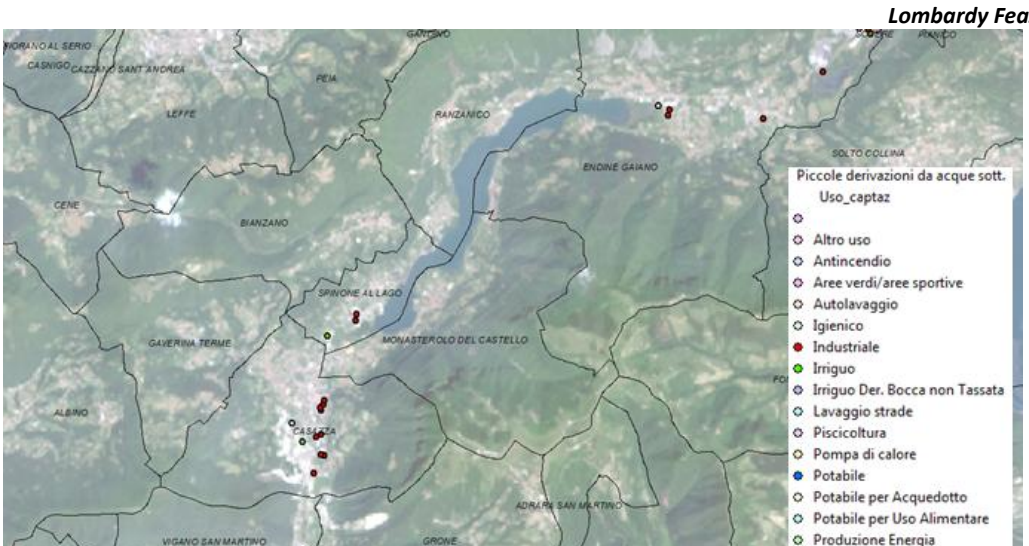

Figure 24: Overlapping, in Val Cavallina valley, of the georeferenced concessions for groundwater abstractions, themed for main use (e.g: red: industrial uses).

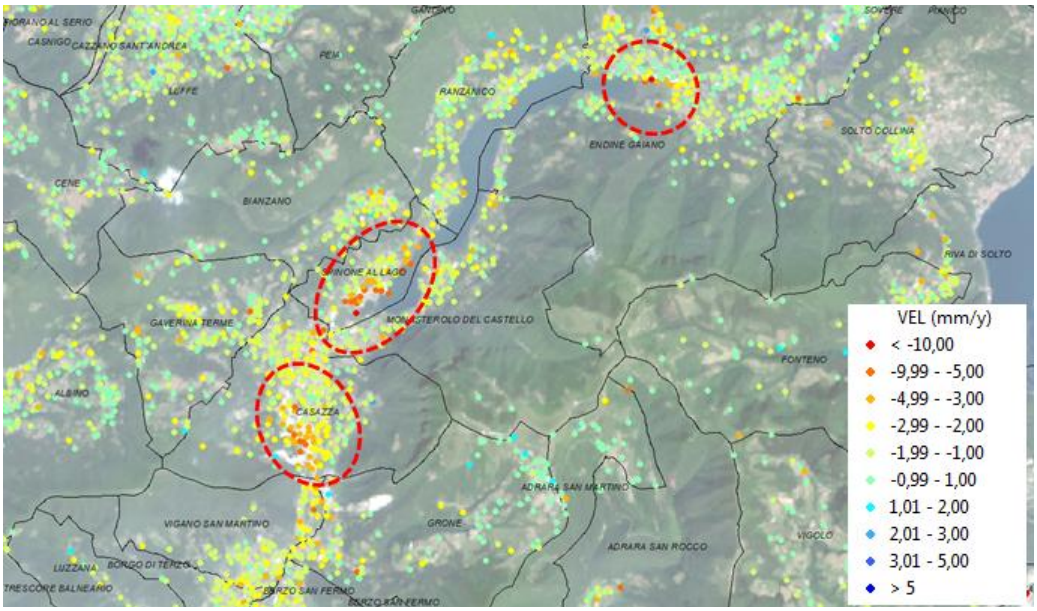

Figure 25: Extract of the Permanent Scatterers points identified by SAR interferometry (Radarsat time series 2003-2010), in a portion of the Val Cavallina vally; PS points are themed the average speed of displacement (mm/y) along the axis of sight of the satellite during the period of analysis.

In similar contexts, local subsidence could be detected and localized, but there are no enough informations about actual local abstractions and water concessions data; in Figure 26, an example of two situations of very localized subsidence in the valley of Val Sabbia (Concesio) and in the high plain of Brescia (Gussago).

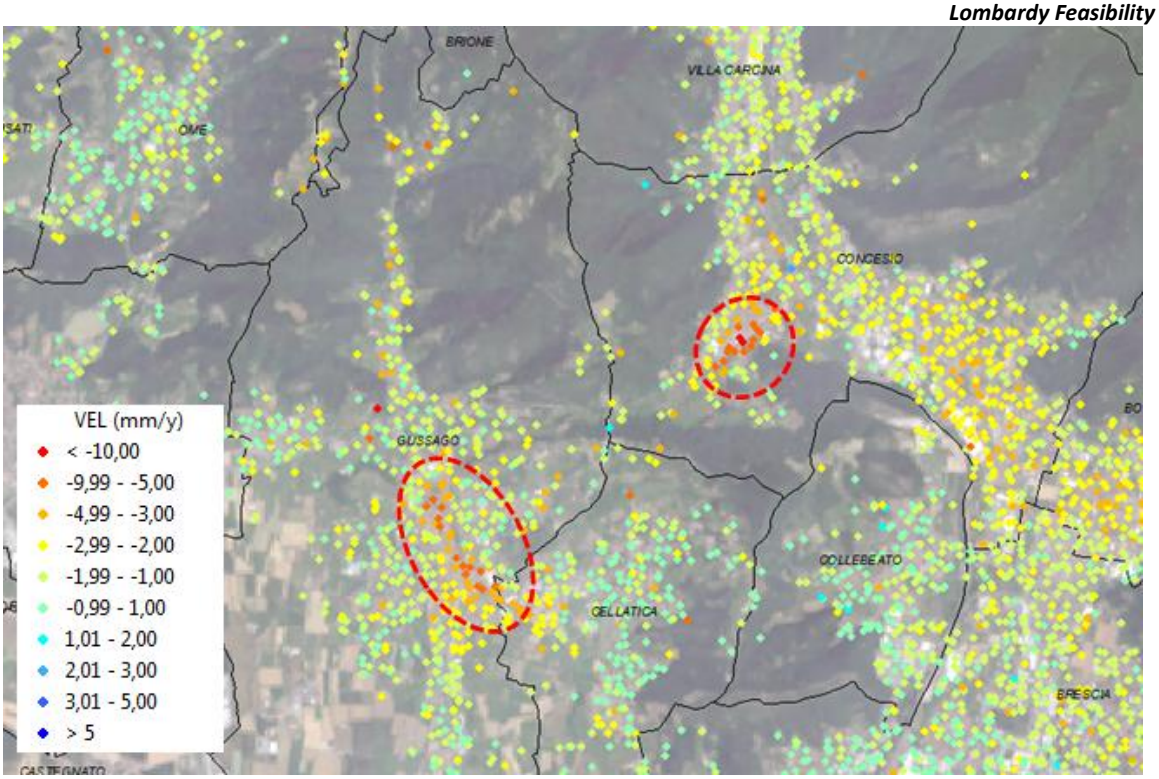

Figure 26: Extract of the Permanent Scatterers points identified by SAR interferometry (Radarsat time series 2003-2010), in the valley of Val Sabbia and the high plain of Brescia; PS points are themed the average speed of displacement (mm/y) along the axis of sight of the satellite during the period of analysis.

5.3 Bordolano area

In this case the available SAR interferometric time series is part of the monitoring data provided by the dealer of one of the underground gas storage sites (UGS) active in Lombardy, specifically the Bordolano site (Cremona and Brescia Province). This UGS site is not yet productive (i.e. a complete input/output cycle has not yet been completed), but for the purposes of the ex-ante evaluation interferometric series (from Radarsat) have been made available; these data are very complete, with disaggregated data for individual PS, and ground movement data relative to each satellite scenes analyzed (one every 24 days, in the 2003-2013 period).

From the point of view of the interferometric analysis, the area nearby the UGS is not affected by significant ground movements, except for the marginal portion of the monitored scene (extreme North-East, in the province of Brescia). In this area the identified PS points show, in addition to a light long-term subsidence trend, a particular seasonal oscillation, with very evident minimums (higher subsidence) in summer (Figure 27).

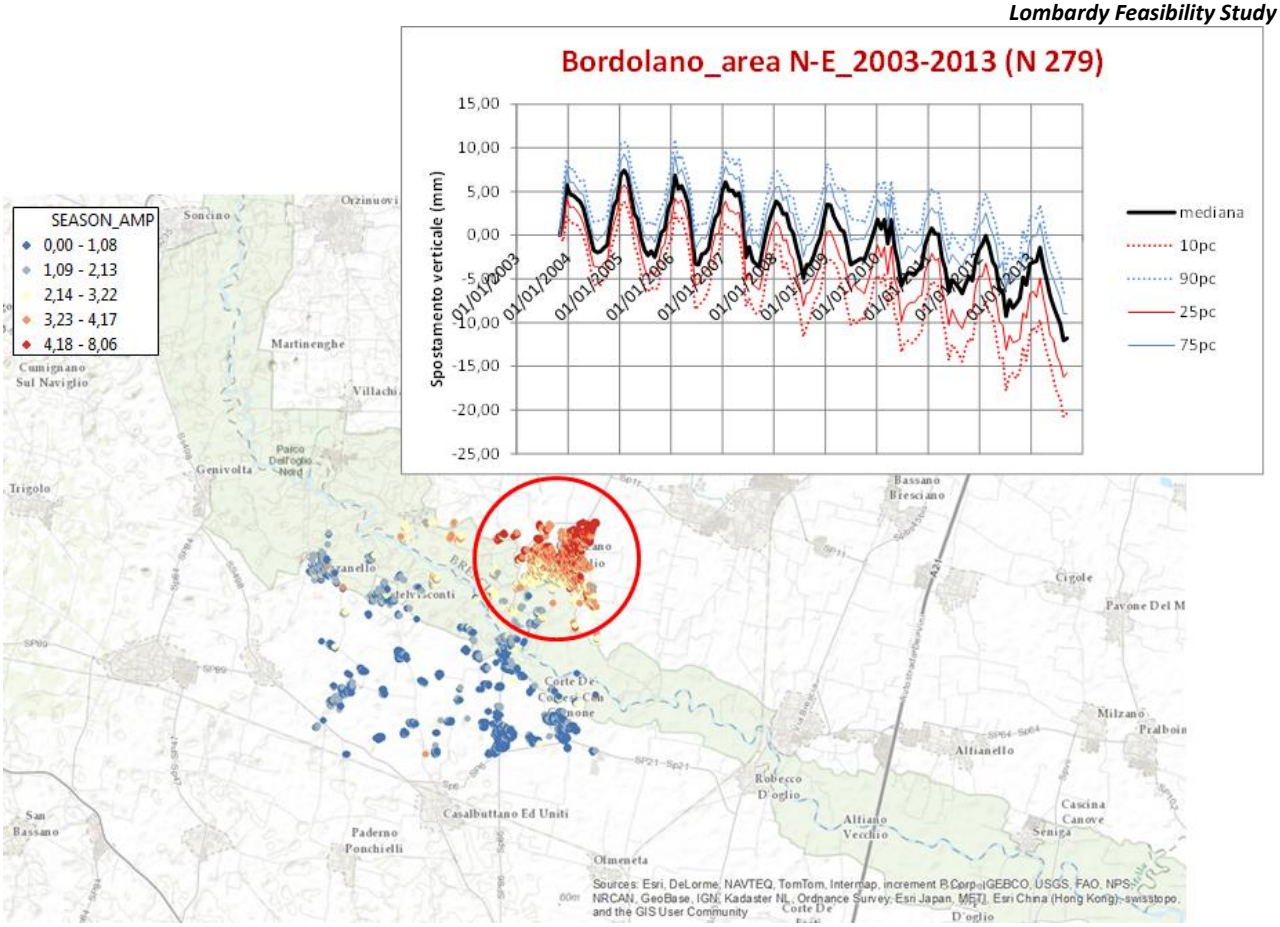

Figure 27: Focus over the area monitored with SAR interferometry near the UGS Bordolano site, and highlighting of the statistical trend of the group of PS points in the portion N-E of the scene; these point are affected by slight long-term subsidence and a seasonal variation.

This part of the lowland is particularly complex from the geological point of view, with succession of different sedimentary formations and the presence of different aquifers (at different depths and with different confinement degree); the area is characterized by intensive agriculture, with irrigation predominantly covered by surface water but also by groundwater (particularly in periods of scarcity of surface water resources); moreover, the area is characterized by high population density and by a great number of highly water demanding livestock farms.
In Figure 28, in addition to the graph related to the statistical trend of ground movements in the N-E portion of the scene, the trends of piezometric levels derived from three nearby groundwater monitoring stations are shown.

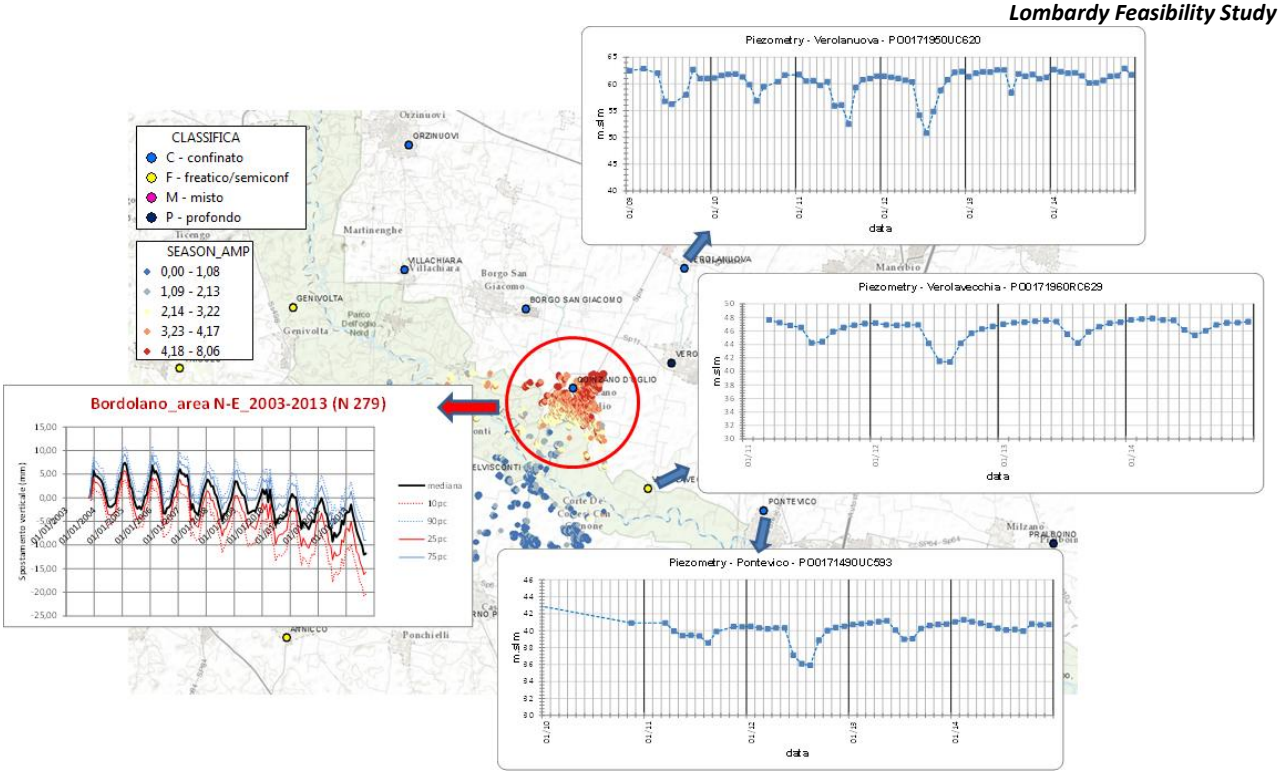

Figure 28: Statistical summary of the ground movement in the N-E portion of the scene, and trends of piezometric levels derived from three nearby groundwater monitoring stations

The piezometric time series measured at the three wells nearby the area of interest show, in addition to a substantially constant trend in the long term, several summer minimums, probably caused by the increased water abstractions in the summer period (in particular for irrigation and zootechnical water requirements); the summer deacreases in the water table are also more evident in particular in the summer of 2012, which was particularly dry.

In this case, the cause/effect relationship between groundwater abstractions and local subsidence (although localized and not irreversible) appears very likely, although it must be stressed that there could be other interfering phenomena (related in particular to the observed long term-trend of subsidence).

6 Conclusions

This report describes one of the feasibility studies carried out within the Project WODA; this particular feasibility study refers to the potential use of satellite SAR interferometric data for the identification of potential groundwater over-abstractions in the geographical context of Lombardy.

SAR Interferometry methodology measures with high accuracy ground movements (subsidence), which in fact is the overall effect potentially of several competing phenomena: for this reason, a first part of the analysis was focused on the overview of the auxiliary and supporting data that should be exploited in order to correctly interpret SAR interferometric series.

Another overall objective of the feasibility study was to assess the observability of subsidence in the geographical context of Lombardy (in the lowland and in the alpine valleys), potentially induced by groundwater abstraction and over-abstraction in most contexts the potential observability of the phenomenon appears guaranteed by actually operating SAR constellations.

In different contexts of Lombardy, some observed local subsidence appear, although with very different degrees in terms of scale and frequency, connected to groundwater abstractions; in order to further assess whether and in what situations these findings correspond to actual over-extraction (in terms of unbalances, in the long term, between abstraction and recharge) more complete analysis are necessary, as well as more complete availability SAR interferometric series on wider areas, updating the analysis and integrating them with different sources of information.

In general, improving the monitoring capabilities of the observed effects of local subsidence appears of interest for the purposes of knowledge improvement and of long-term management of the water resources, as well as in potential support to the authorization process for renewal or new concessions of permissions for water abstractions.