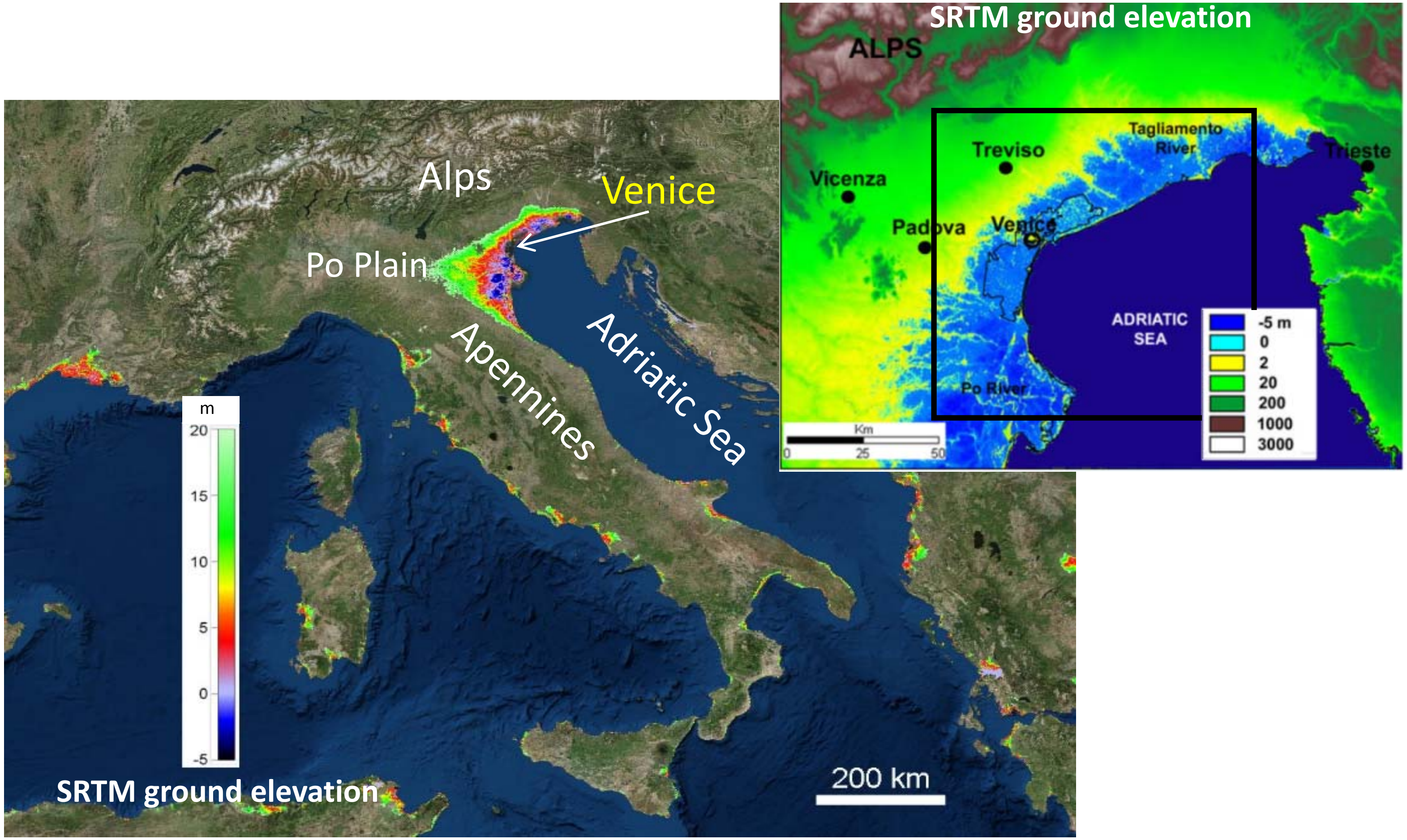
Workshop for
Land Subsidence Prevention
May 14th, 2019

FROM LEVELING TO SAR-BASED INTERFEROMETRY: ADVANCES IN KNOWLEDGE AND UNDERSTANDING OF CAUSES, PREVENTION AND MITIGATION COASTAL SUBSIDENCE IN VENICE

Luigi Tosi

Institute of Geosciences and Earth Resources – National Research Council, Italy

Venice Region: Morpho-physiographic setting

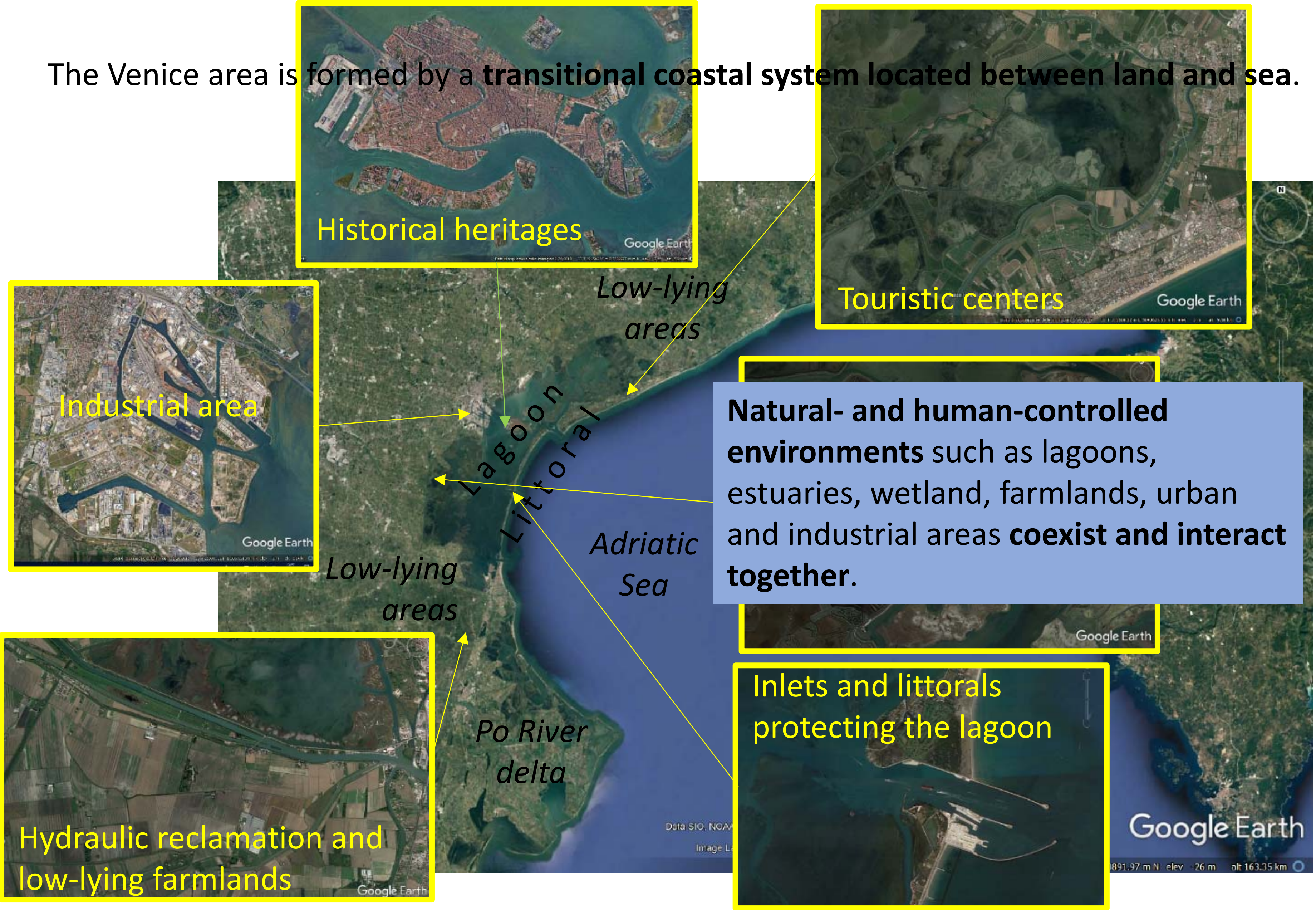


The Venice Region is located in the northwestern Adriatic coastland between the Po River delta and the Tagliamento River.

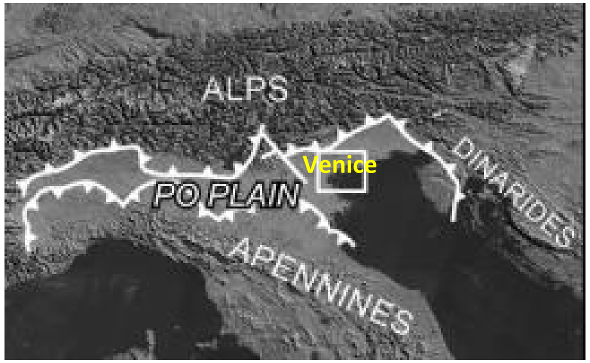
The Venice coastland is part of the largest Italian low-lying plain with ground elevation up to 5 m below the sea level or only 2-3 m above it.

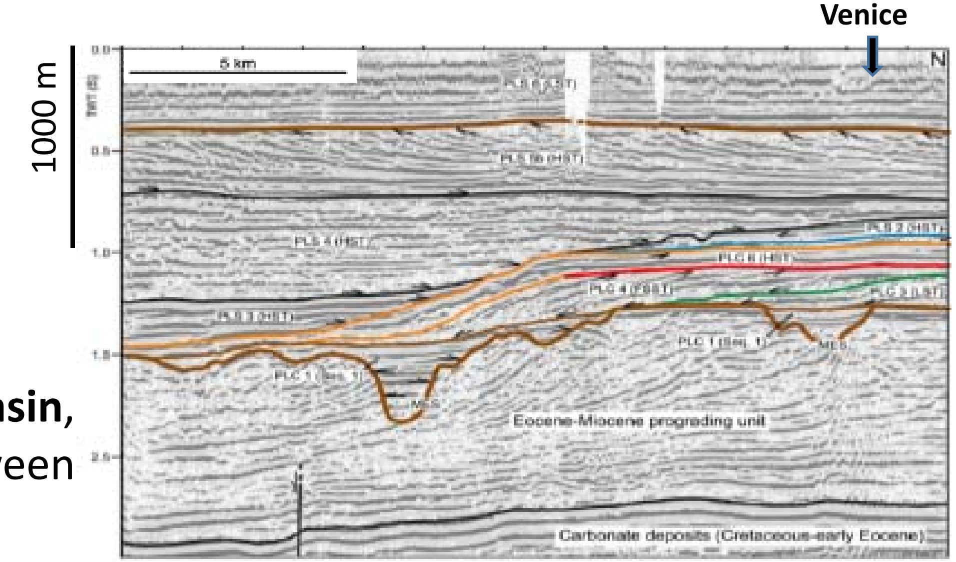
The Venice coast: heterogenous transitional environment

The Venice area is formed by a **transitional coastal system located between land and sea**.



Natural- and human-controlled environments such as lagoons, estuaries, wetland, farmlands, urban and industrial areas **coexist and interact together**.





The Venice area lies in a **natural subsidence basin**, which is part of a foreland region located between the Apennine and Alpine mountain chains.

For this reason, **Venice experienced land subsidence since its foundation**.

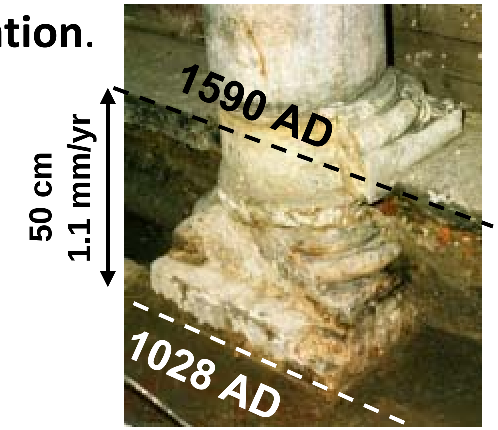
Causes of land subsidence well known in the past

Natural components:

- Tectonics: deformation of the bedrock
- Compaction of the Plio-Pleistocene deposits: about 1,500 m thick of sandy and silty-clayey layers of alluvial and marine origin.

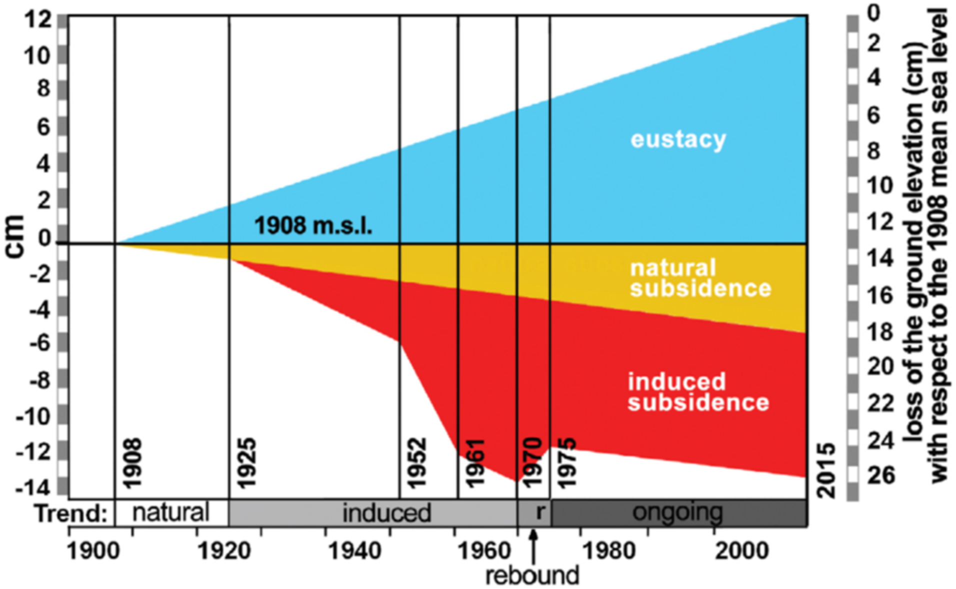
Anthropogenic activities:

- Subsurface fluid exploitations: mainly groundwater
- Hydraulic reclamations of ancient lagoon and wetland sectors



Evidence of natural subsidence: Rising of the base of an ancient column after 562 yr due to 50 cm of land subsidence and sea level rise

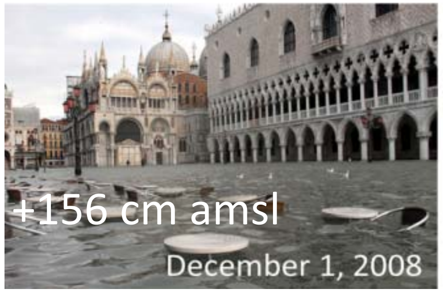
Land subsidence also contribute to the Relative Sea Level Rise (RSLR) exacerbating the effect of flooding due to the high tides.



Land **subsidence in the Venice area is in the order of a few mm/yr**, hence, it is not high in magnitude compared to other cases in the world that reach up to several cm/yr.

However, **land subsidence combined with the small ground elevation** above the mean sea level **and the eustatic rise** of the North Adriatic Sea **has made Venice increasingly prone to flooding**.

Effect of Relative Sea Level Rise in Venice

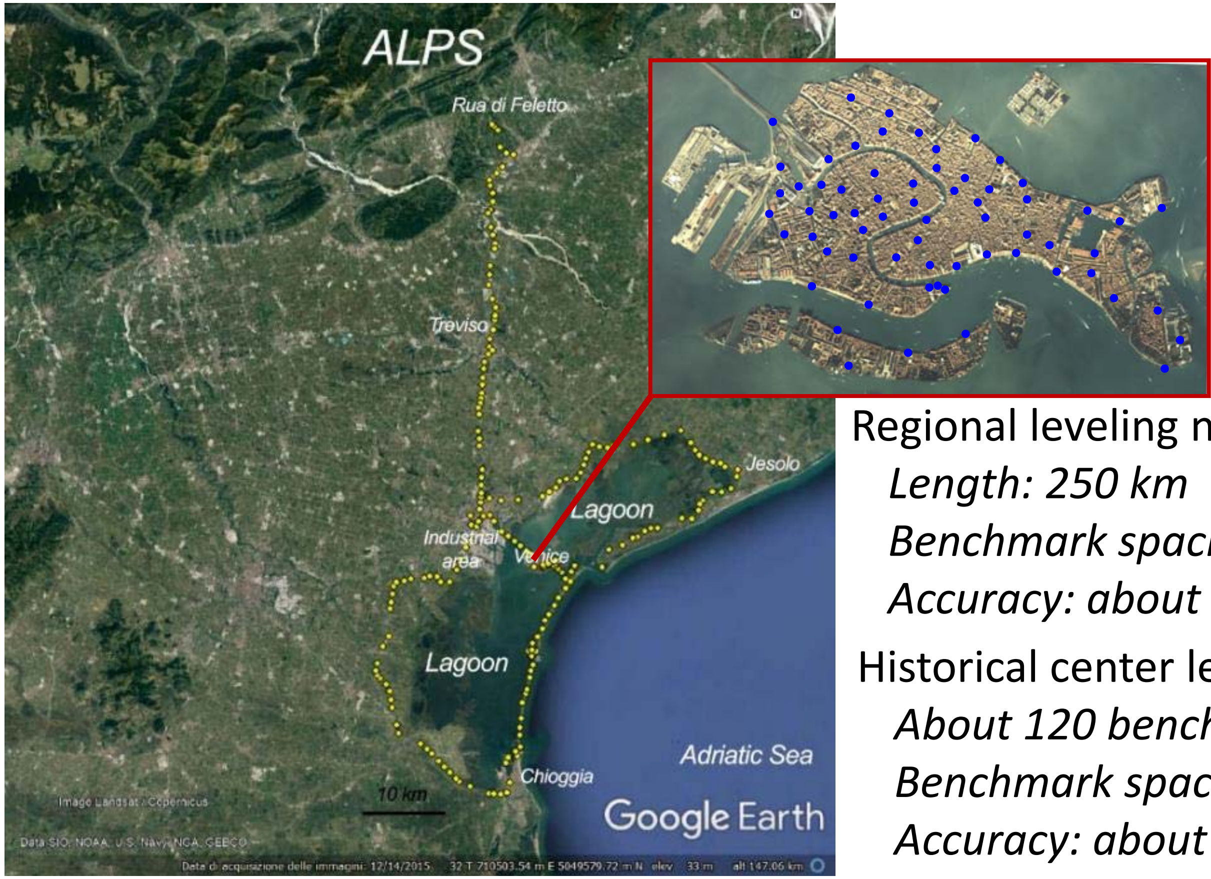


Given that:

- ground surface of the historical center of Venice is only a few decimeters higher than that of the average tide level,
- ground surface of the coastal plain is mostly below the mean sea level,
- elevation lost due to land subsidence is irreversible,
- sea level rise due to climate changes is increasing,

even a few mm loss of ground elevation seriously compromise the survival of the historical and natural heritage of **Venice and its lagoon** and highly concerns the safety of the **low-lying farmlands** in the mainland.

Past Land Subsidence monitoring: First leveling network



The first subsidence monitoring network was established in the 1950s when the Venice area began to experience serious sinking rates due to groundwater exploitation.

Regional leveling network

Length: 250 km

Benchmark spacing: 1 km

Accuracy: about 1.5 mm (first order spirit leveling)

Historical center leveling network

About 120 benchmarks

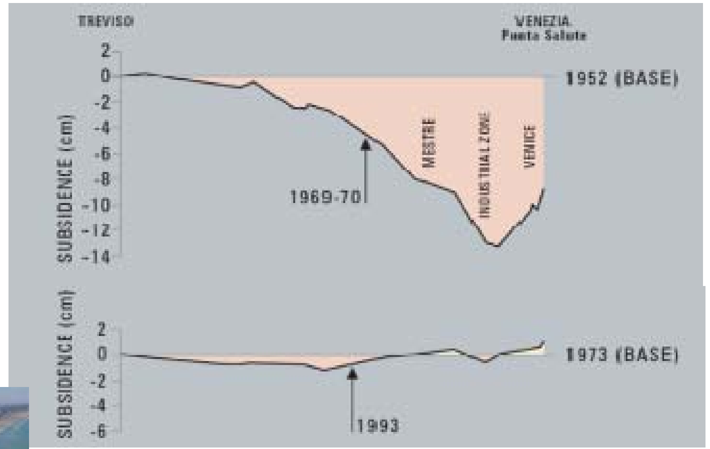
Benchmark spacing: 150-300 m

Accuracy: about 1.5 mm (first order spirit leveling)

Because of the fragility and the high value of Venice and its lagoon, land subsidence has always been a major issue that requires high accuracy in monitoring ground movements and a deep knowledge of cause-effect relationships.

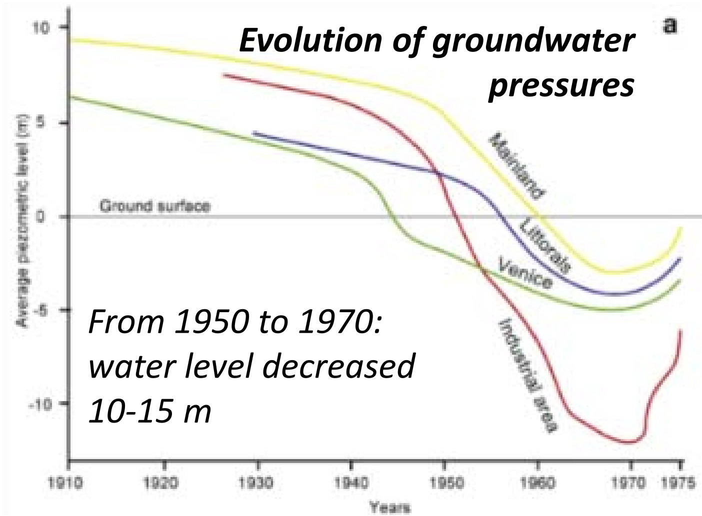
Past Land Subsidence monitoring: groundwater exploitation

Past groundwater pumping areas



1952-1970
Groundwater exploitation
Induced subsidence

1973-1993
Exploitation ban
Natural subsidence

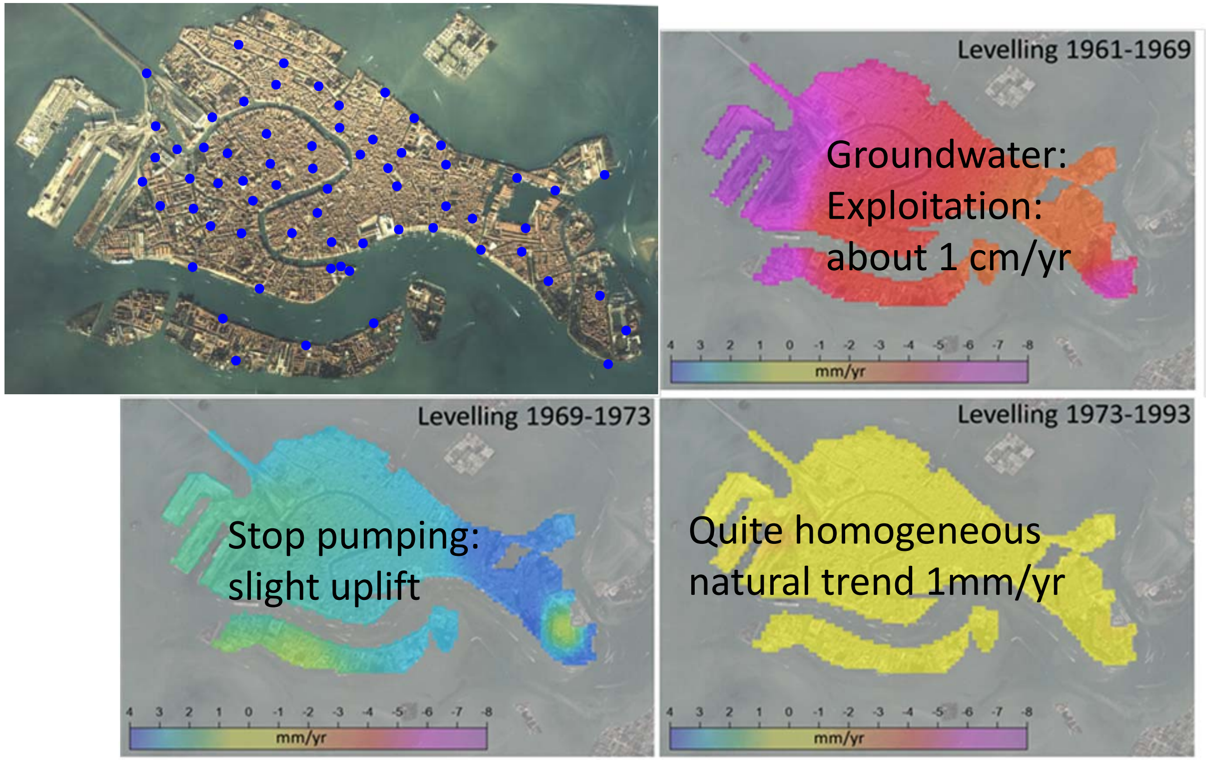


In the 1960s anthropogenic land subsidence due to the groundwater exploitations (industrial use and touristic purpose) seriously affected Venice.

From 1950 to 1970 the groundwater level decreased by 10-15 m.
In 1970 groundwater pumping in Venice was prohibited and the subsidence of the City significantly reduced.

Past Land Subsidence monitoring: from induced to natural rates

The leveling network allowed an **accurate monitoring of ground displacements in the historical center** over the period 1961-1993.

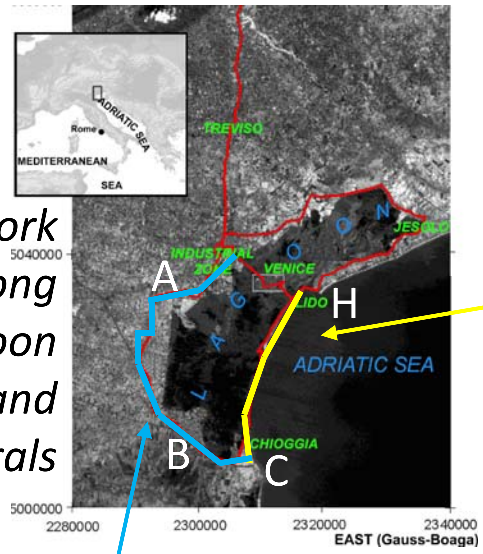


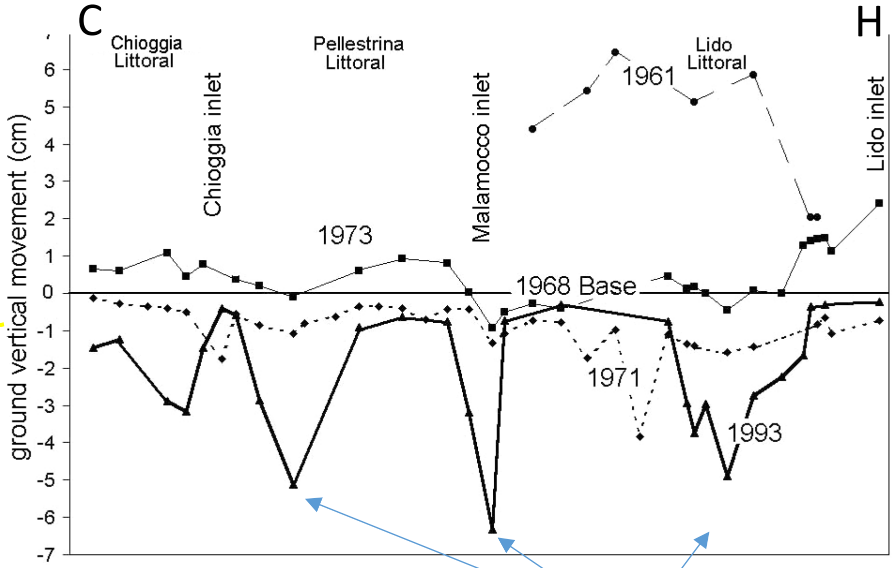
- 1969: Maximum subsidence rate due to groundwater exploitation.
- 1970: Closure of the wells.
- 1973-1993: Natural subsidence

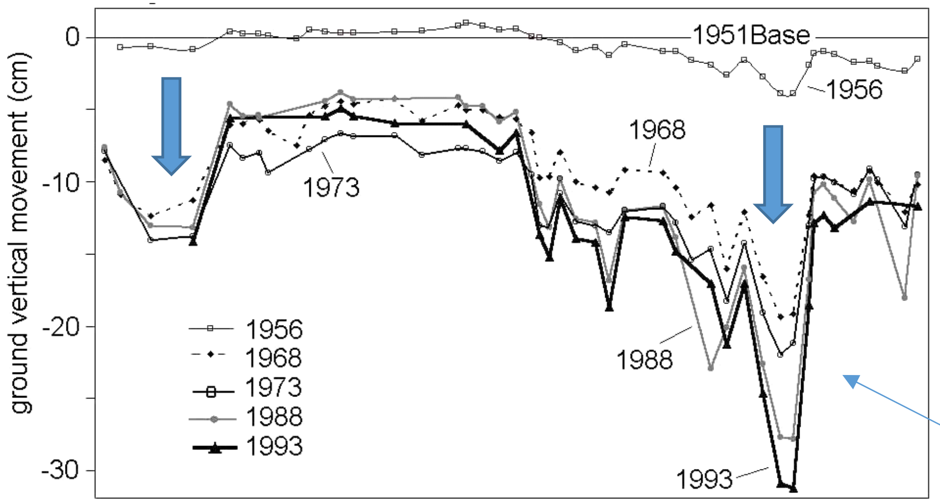
- Severe land subsidence in the 1960s due to **groundwater exploitation, up to 1 cm/year**.
- **A slight rebound** of a few mm for a short period, i.e., 1969-1973, **as consequence of the closure of the wells.**
- Natural subsidence rates from 1973 to 1993, i.e. less than 1.5 mm/year, **as consequence of the groundwater exploitation ban** in the Municipality of Venice.

Past Land Subsidence monitoring: from induced to natural rates

Leveling network installed along the lagoon margin and littorals

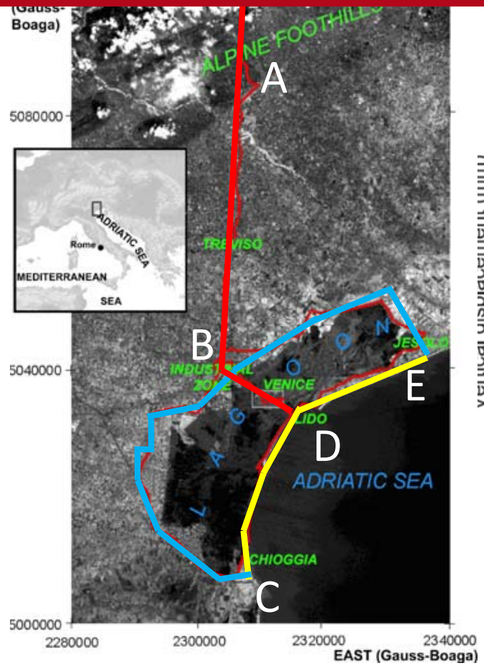


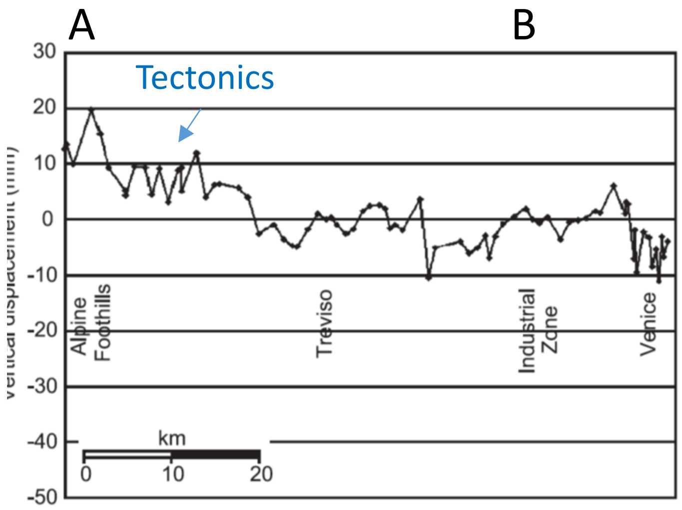


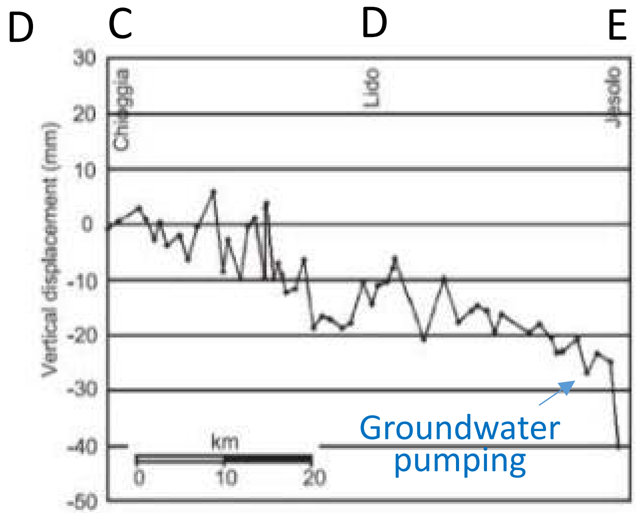


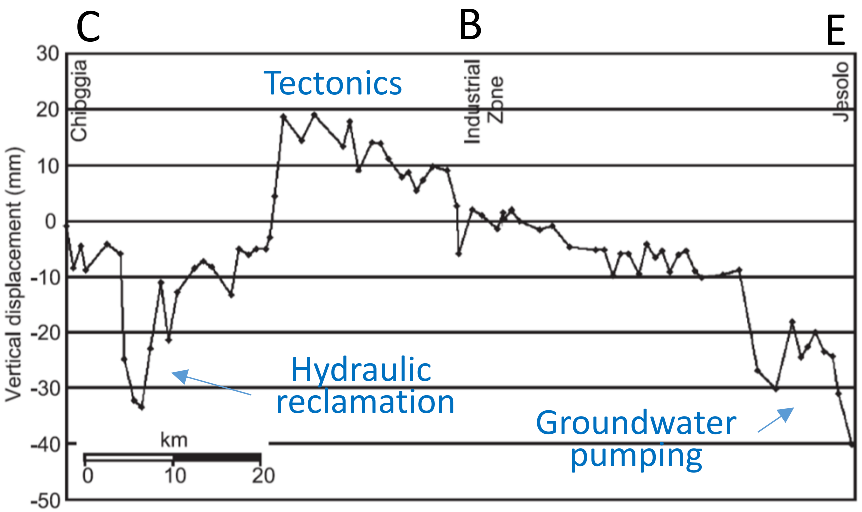
The lagoon margins and the littorals were also monitored in detail. The reduction of the subsidence rates in the industrial zone have been confirmed over the 1973-1993 period, while sinking sectors have been observed in correspondence of low-lying farmlands and the inlets.

Past Land Subsidence monitoring: natural rates and new induced sinking sectors



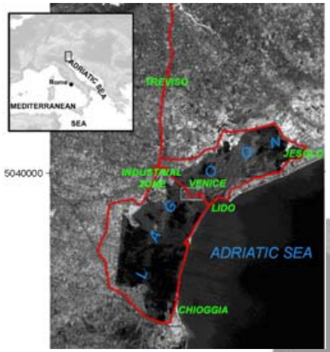


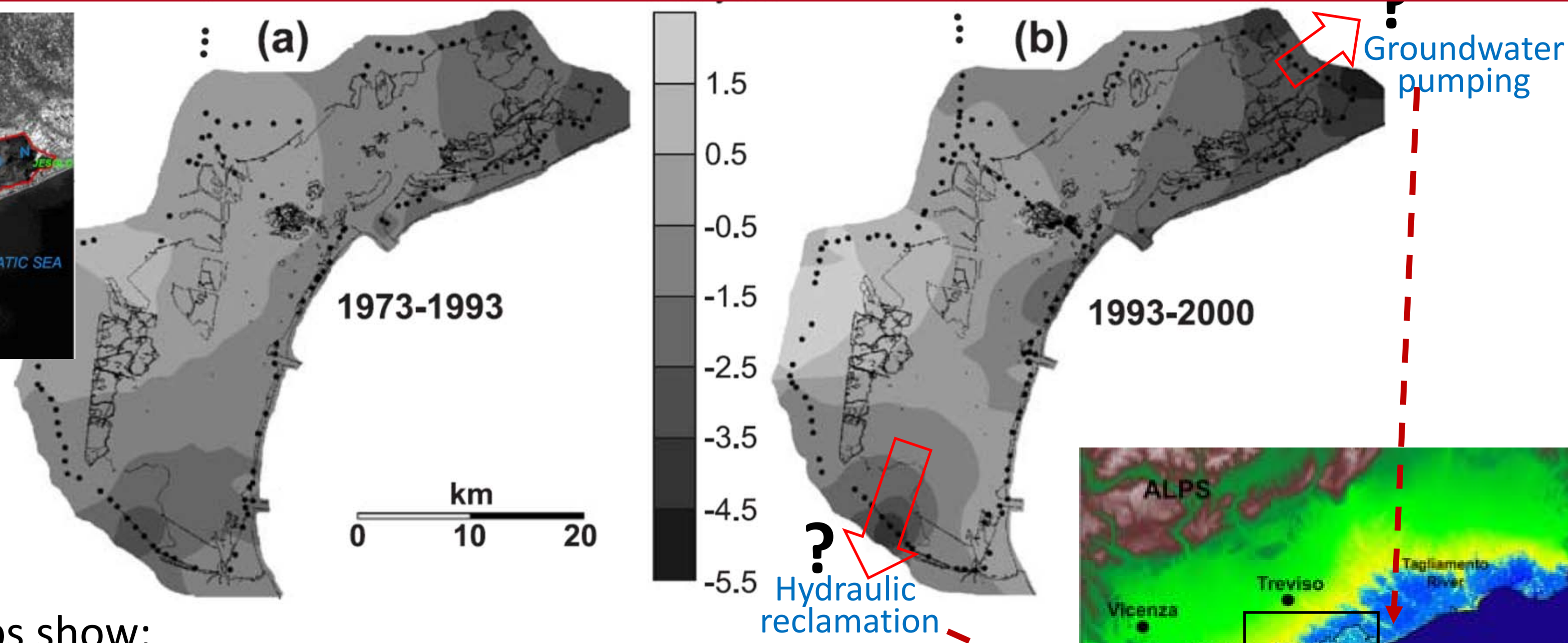


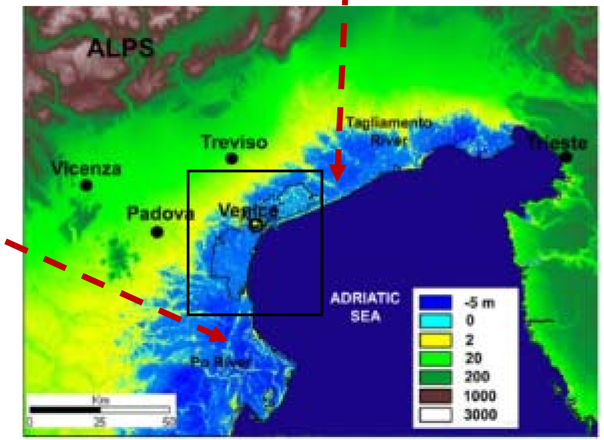


Ground movements measured in the 1993-2000 period confirmed the stability of historical center and industrial zone, and highlighted an increase in sinking rates towards the northern and southern lagoon margins because of hydraulic reclamation and groundwater pumping.

Past Land Subsidence monitoring: natural rates and new induced sinking sectors







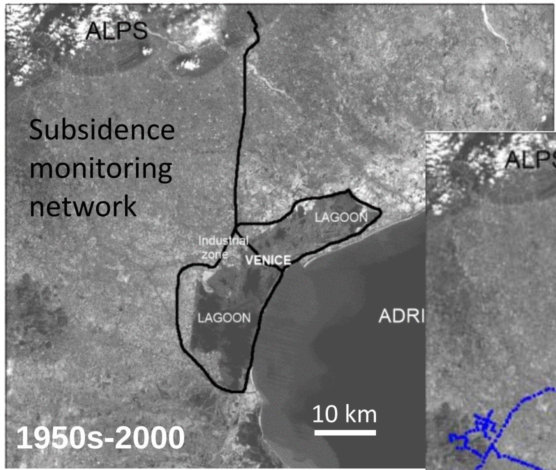
Both maps show:

- Similar subsidence images obtained for both periods.
- Negligible subsidence in the central lagoon.
- Sinking trends increasing northward and southward to more than 5 mm/year in correspondence of low-lying coastland sectors with high hydrogeological risk.

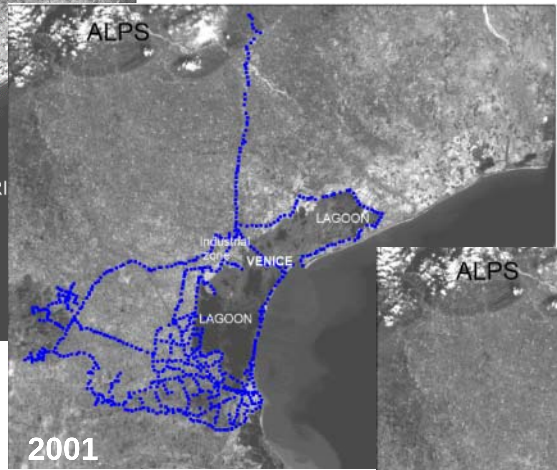
These results raised new concerns on land subsidence and in 2000, the **Authorities** responsible for the costal management (e.g., water authority of Venice, land reclamation authorities, municipalities) **joined together to support a research project aimed to update the knowledge of the process, including the extension of the monitoring network** in areas never investigated before.

Land Subsidence monitoring in the 2000s: new leveling network

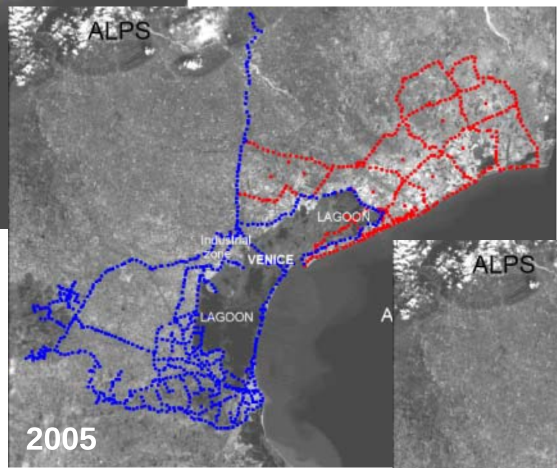
A continuous effort has been devoted to improve the subsidence monitoring network from 2001 to 2009



Leveling network: 250 km
Benchmark spacing: 1 km



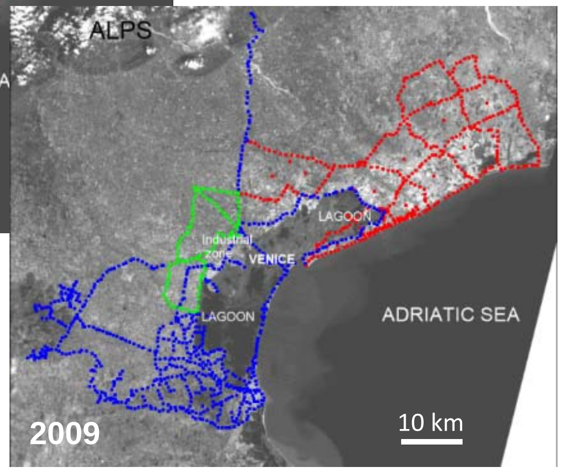
Leveling: 1200 km
GPS benchmark: 120



Leveling: 2000 km
GPS benchmark: 180

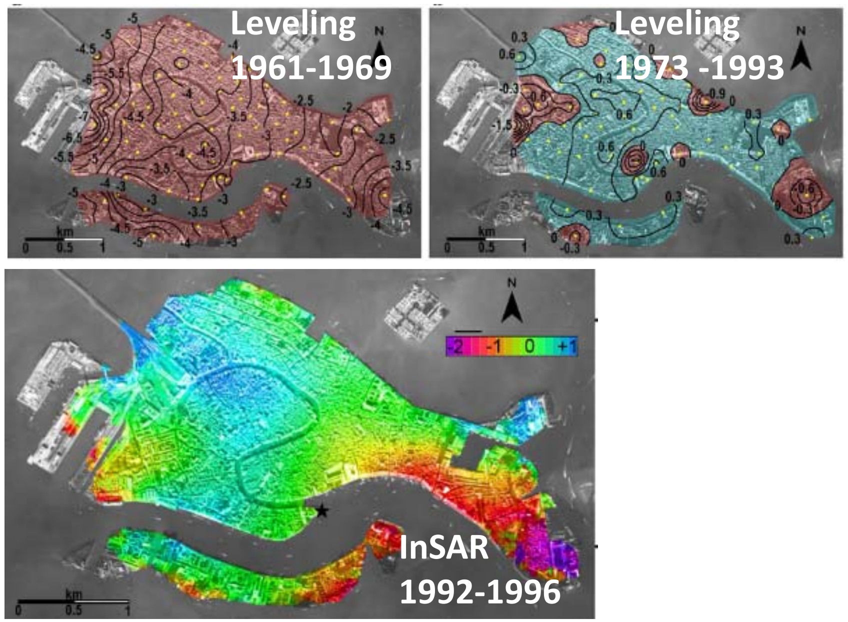
From a few hundreds leveling benchmarks to more than 2500 leveling benchmarks, 200 of which also for DGPS measurements

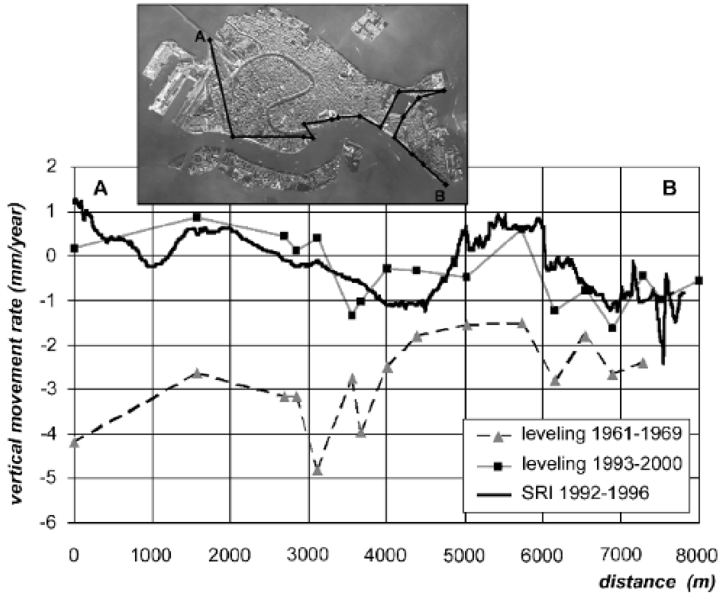
Once ascertained that land subsidence is still in progress in the southern and northern Venice coastal areas and in the nearby mainland, **the ground movement monitoring network has been progressively extended to cover areas never been investigated in the past**



Leveling: 2100 km (2500 benchmarks)
GPS benchmark: 200

Land Subsidence monitoring in the 2000s: First test of SAR-based interferometry application in Venice





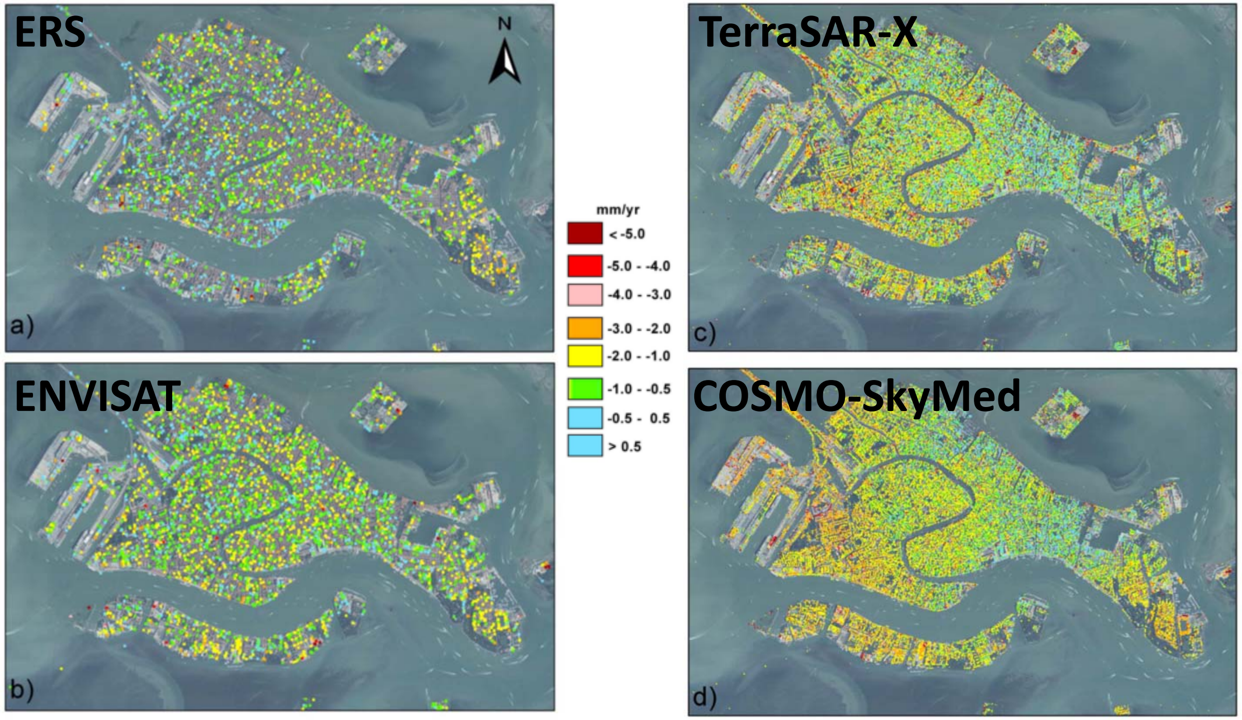
Validation of the interferometric data through leveling.

Together with the extension of the leveling and GPS networks, SAR-based interferometry was applied for monitoring land subsidence.

The first test of SAR interferometry in Venice was carried out in the historical center. Results highlighted:

- The stability of Venice historical center,
- A good accuracy of the interferometric products.

Land Subsidence monitoring in the 2000s: SAR-based interferometry has become a practice for Venice

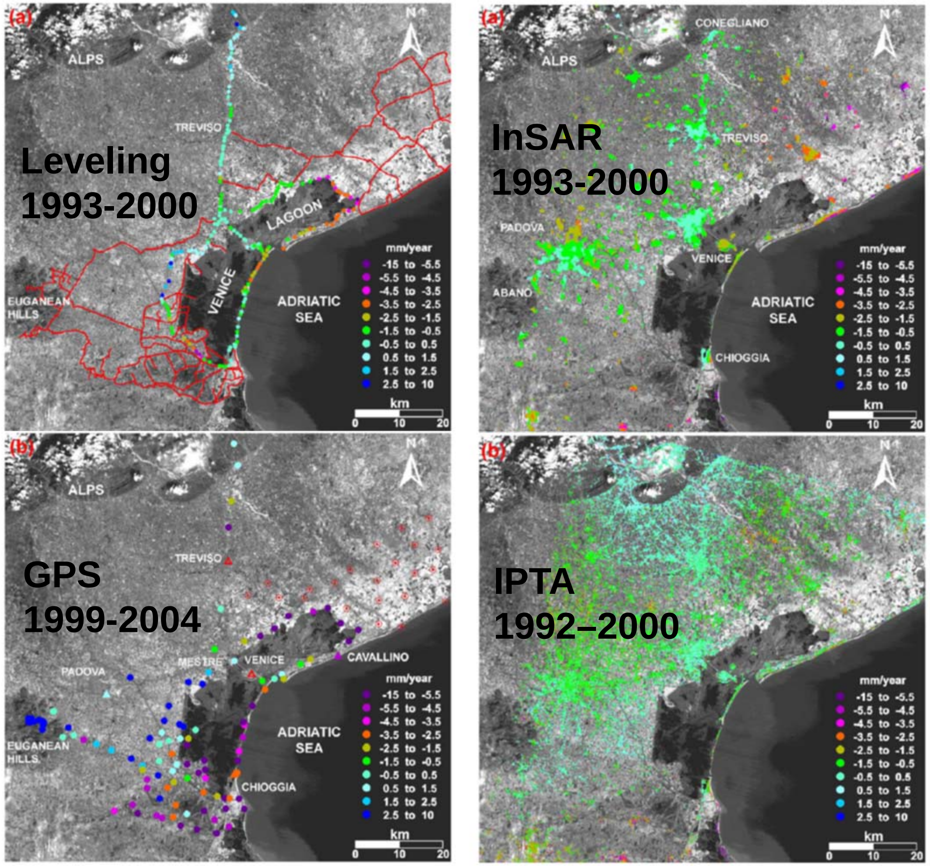


The number of Persistent Targets and their spatial resolution increased from less than 100,000 obtained by ERS/ENVISAT (20-m pixel resolution) to more than 300,000 by TerraSAR-X and COSMO-SkyMed (3-m pixel resolution).

Over the time SAR-based interferometry has continued and **most of the SAR satellites have been used**.

The **high spatial resolution** of the SAR-based interferometric products provided a **new picture of the land subsidence process**. In particular a **high heterogeneity** of the subsidence not detectable by the leveling network has been observed.

Land Subsidence monitoring in the 2000s: The Subsidence Integrated Monitoring System (SIMS), a new strategy to control land movement at regional scale

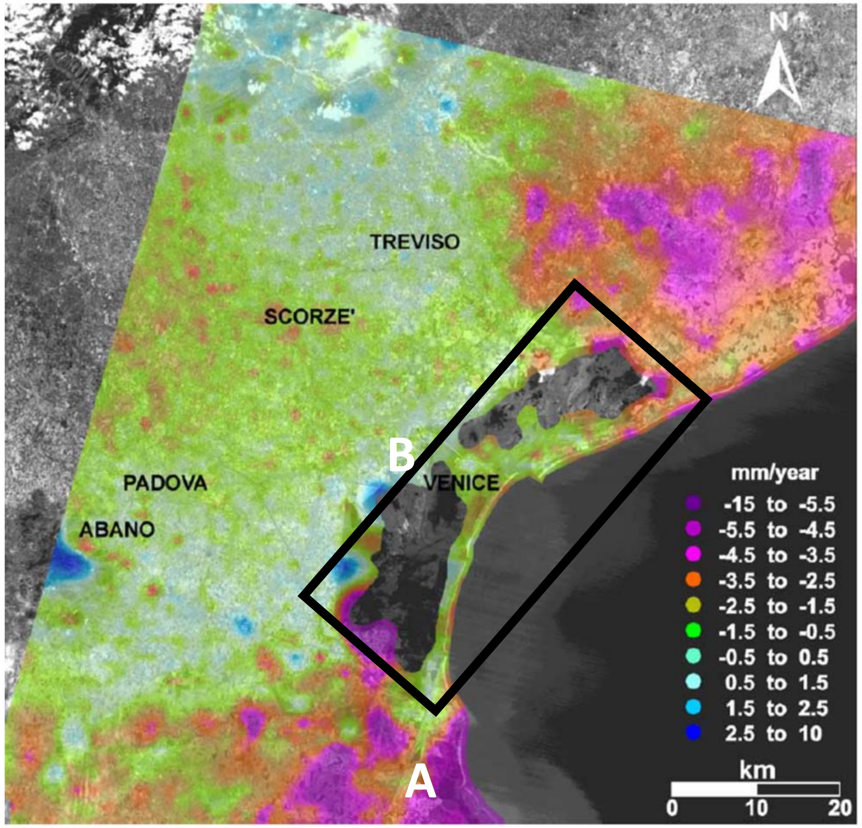


The first subsidence integrated monitoring system (SIMS) was set up in 2003 and included Leveling, Differential GPS, Continuous GPS, InSAR, and PSI (IPTA) networks.

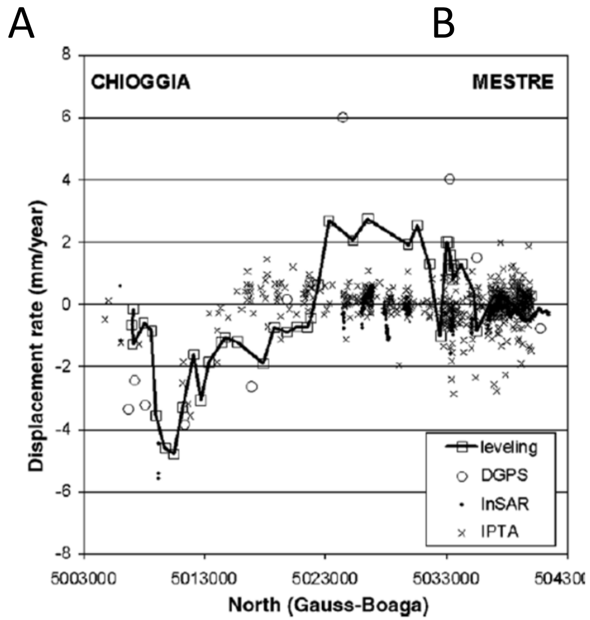
In the early 2000s, following the positive results obtained by SAR-based interferometry, **national, regional and local authorities** in charge to manage the Venice coastland issues **required to set up a new land subsidence monitoring system** capable for:

- providing a **comprehensive image** of ground vertical displacements both at regional and local spatial scale,
- **updating the knowledge** on land subsidence controlling mechanisms,
- **planning solutions to reduce the hydrogeological hazard** in hydraulic reclamation areas,
- **controlling the effect** of groundwater exploitations,

Land Subsidence monitoring in the 2000s: Mapping regional land displacements by SIMS



Synoptic map of the average displacement rates (1992-2002) of the Venice region obtained by the integration of the data sets acquired through the Subsidence Integrated Monitoring System (SIMS).

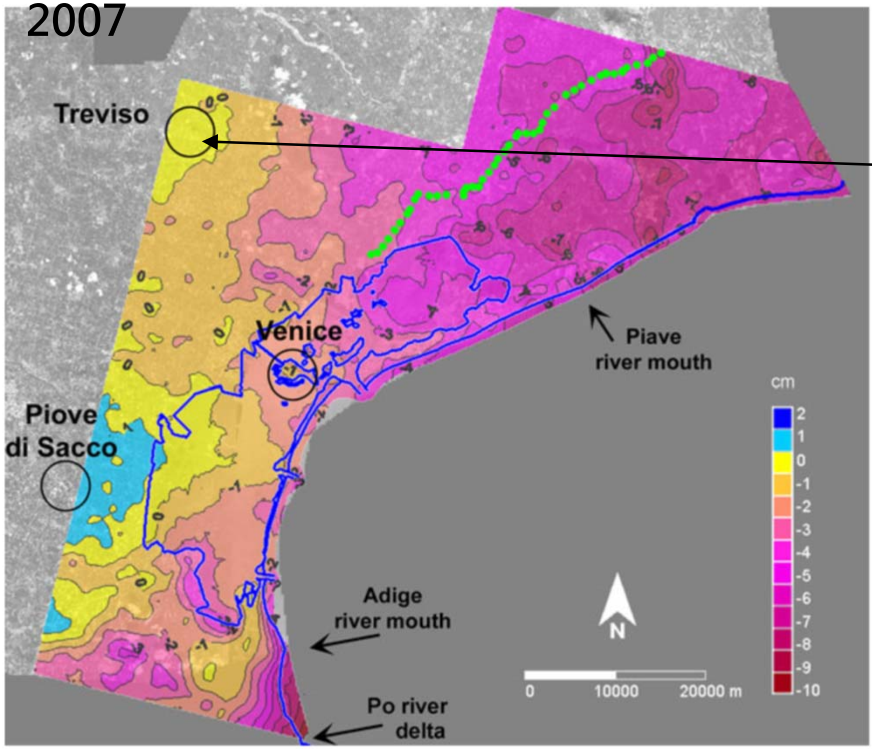


Cross-validation of leveling, GPS, InSAR, and IPTA results along the southern lagoon margin.

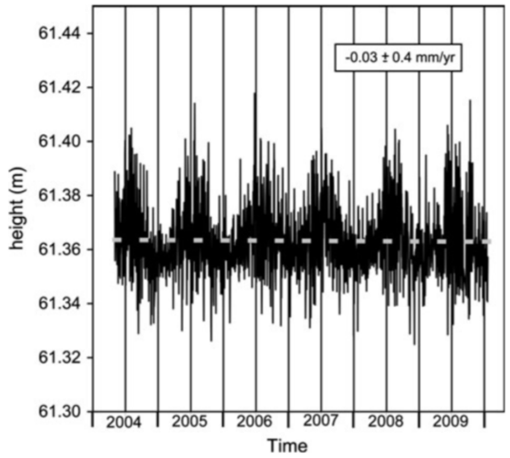
The **SIMS allowed mapping regional land displacements over the whole Venice coastland and mainland**. Notice that previous knowledge on land subsidence was limited to the area included in the black rectangle.

Land Subsidence monitoring in the 2000s: Mapping regional land displacements by SIMS

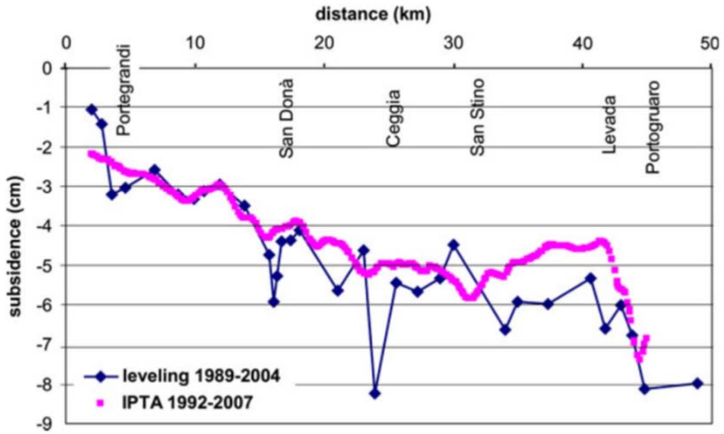
ERS 1992-2000 and ENVISAT 2003 - 2007



Cumulative 1992-2007 displacements (cm) as obtained by the integration of ERS-1/2 and ENVISAT IPTA results.



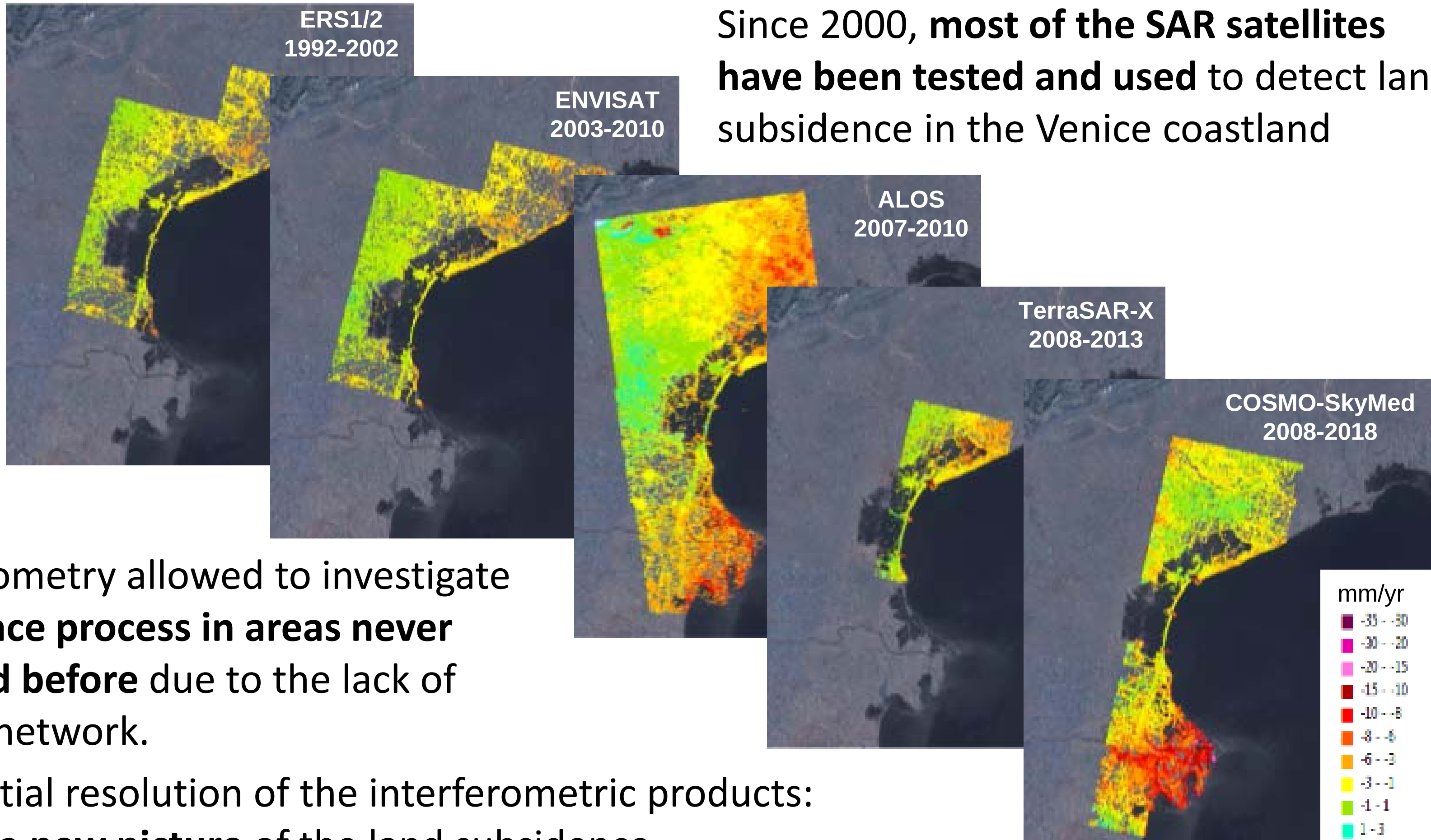
GPS time series used for SAR data calibration



Validation: Comparison between leveling and IPTA results

Land Subsidence monitoring in the 2000s:
More than 25 years of SAR-based interferometry over the Venice coast

Since 2000, **most of the SAR satellites have been tested and used** to detect land subsidence in the Venice coastland

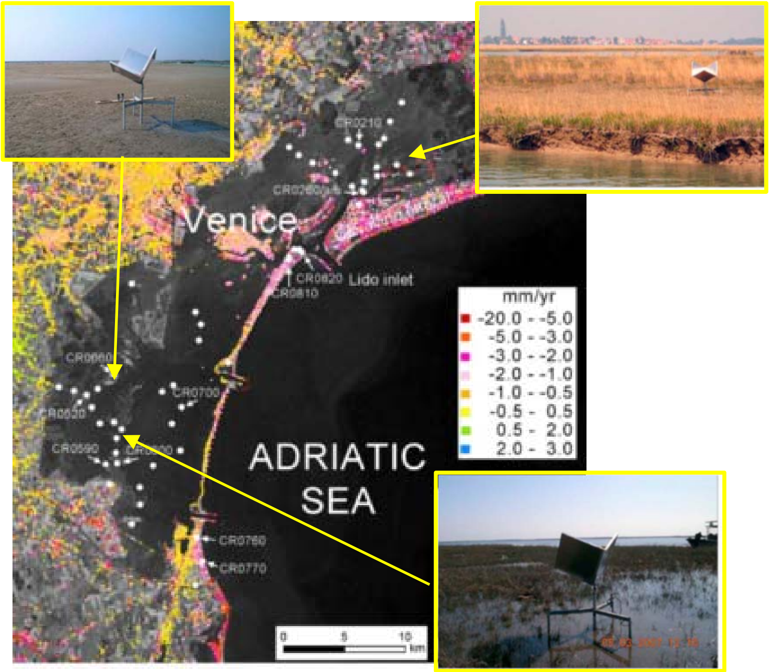


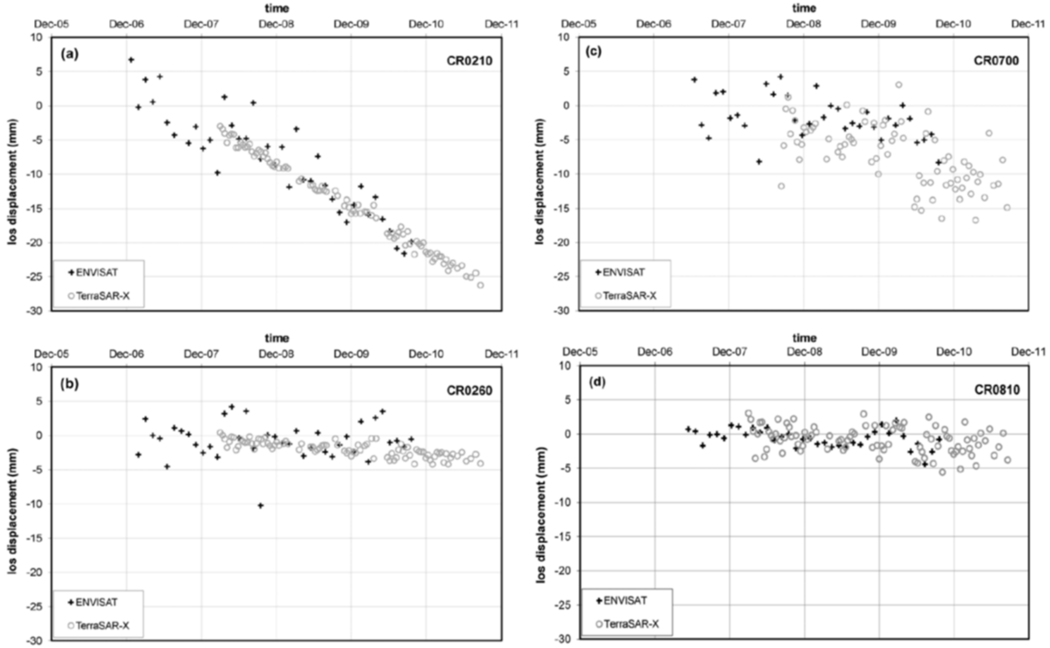
SAR Interferometry allowed to investigate the **subsidence process in areas never been studied before** due to the lack of the leveling network.

The high spatial resolution of the interferometric products:

- provided a **new picture** of the land subsidence
- revealed **mechanisms** that drive land subsidence, which have not been properly considered in the past
- revealed a **high heterogeneity** of the subsidence in transitional coastal environments, not detectable by the leveling network

Land Subsidence monitoring in the 2000s: Improving knowledge of ground dynamics in the lagoon basin by artificial corner reflectors





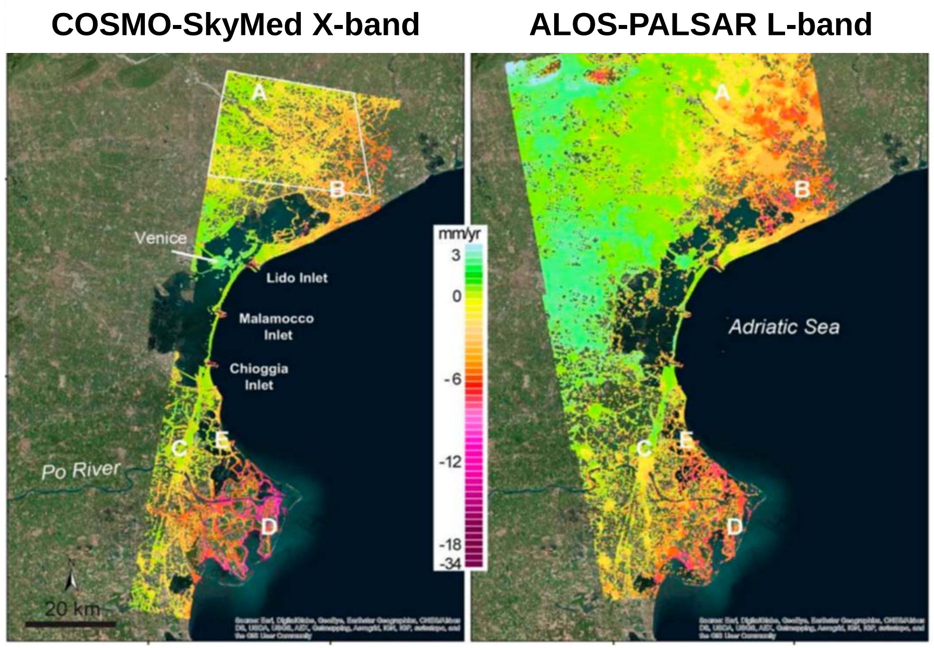
Time series of TCR displacements obtained using ENVISAT and TerraSAR-X data.

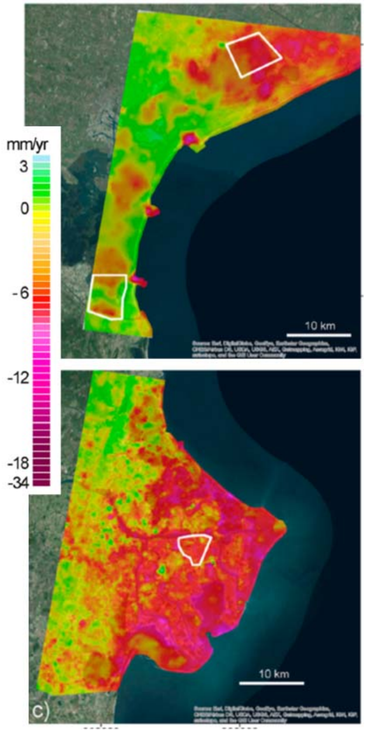
An important **limitation of SAR-based interferometry is the incomplete spatial coverage** especially in lagoon and wetlands because of:

- Decorrelation does not permit a reliable analysis of the interferometric phase for parts of the area (INSAR).
- Loss of coherence in vegetated areas and wetlands (PSI).

In order to overcome or at least reduce the limits of SAR interferometry **in 2007** about **60 trihedral corner reflectors have been installed in tidal flats and salt marshes**

Land Subsidence monitoring in the 2000s: Improving knowledge by combining SAR data from different band sensors





X-band and L-band products combined at ***regional scale***

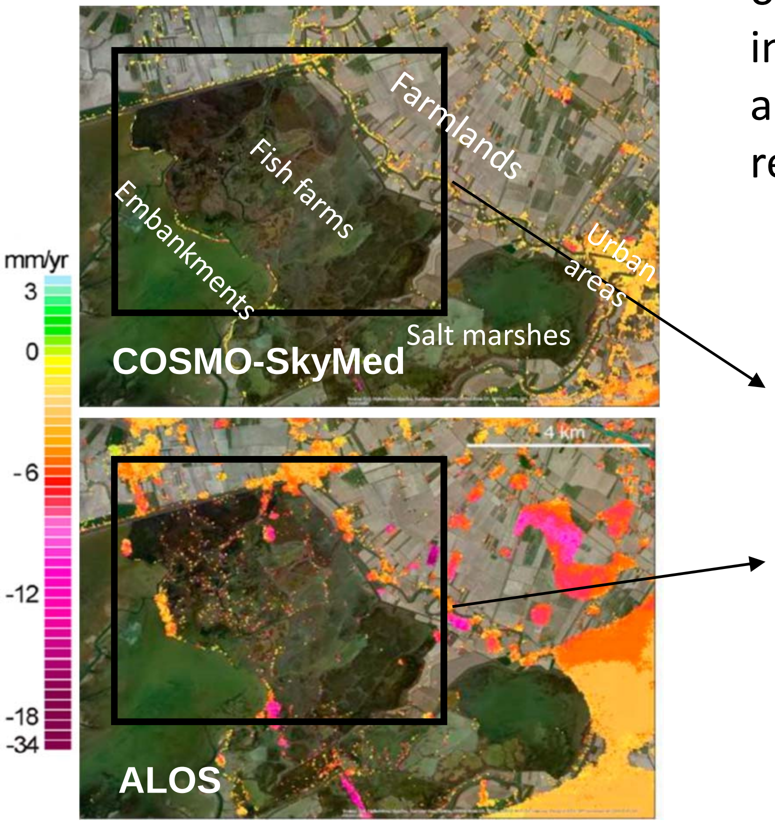
The synergic use of X-band and L-band satellites was tested with the aim to take advantage of the different potentialities of the two sensors:

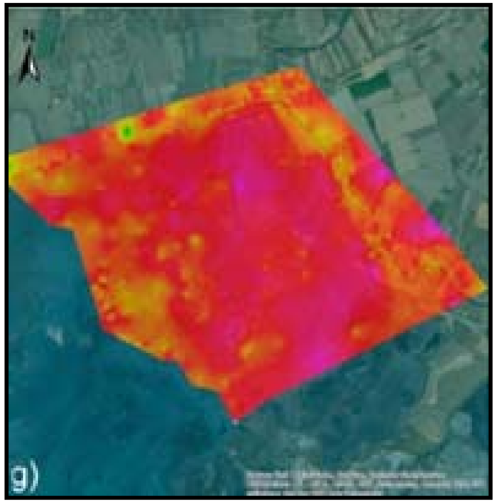
- the high accuracy of the displacements detected by X-band on even small-size anthropogenic structures;
- the high temporal coherence over the long time of L-band allowing detecting displacements over marshlands and crop-fields.

The proper combining of the L- and X-Band SAR Interferometric products has improved the spatial coverage of ground displacement data in heterogeneous coastal environments, both at regional and local scale.

Land Subsidence monitoring in the 2000s: Improving knowledge by combining SAR data from different band sensors

The L- and X-band datasets have been combined in order to gather together the best subsidence information in both the vegetated and constructed areas that can be extracted from the two satellites, respectively.

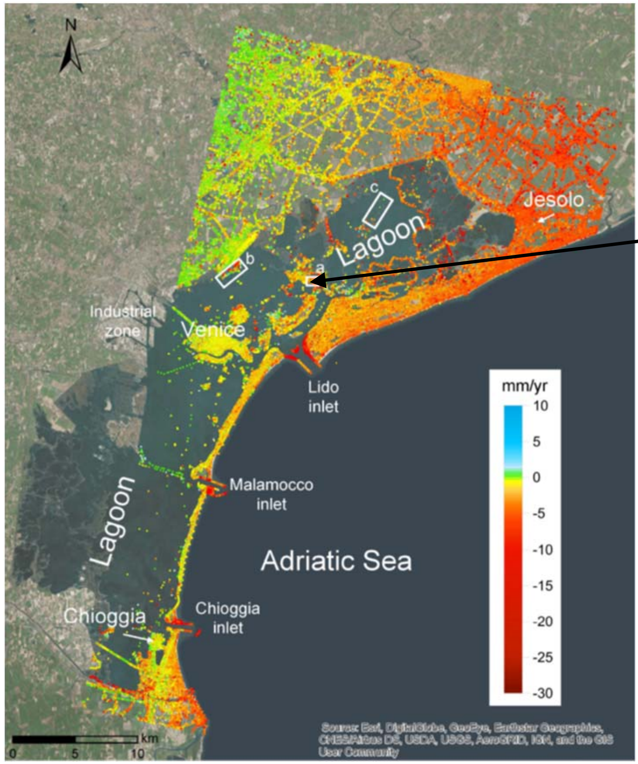


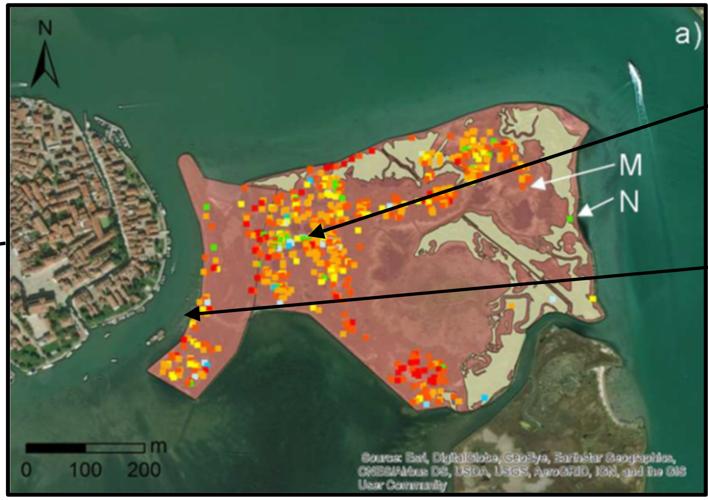


*X-band and L-band products combined at **local scale***

The L- and X-band datasets show **complementarity characteristics** in term of spatial distribution of the detected monitoring points.

Land Subsidence monitoring in the 2000s: Improving knowledge using high resolution, high frequency and long-time data series





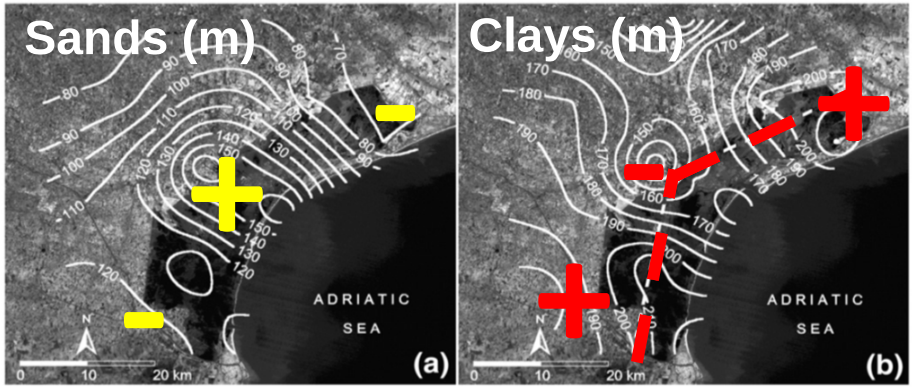
Rich-shell silty deposits, construction remnants, wood posts, and stone-filled rolls provide PTs

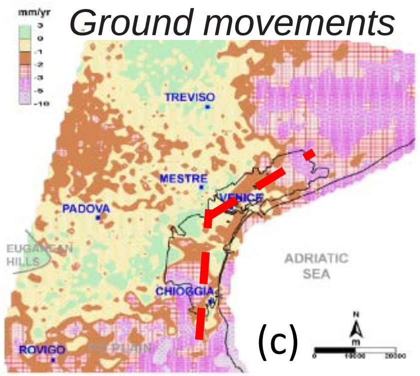
PSI technique on a **5-year long stack of X-bandwidth SAR acquisitions** (143 images from TerraSAR-X) **regularly acquired** with **short satellite revisiting time** (11 days) and **high image resolution** (~3 ×3 m), allowed detecting thousands of persistent targets (PTs) in salt marshes.

Monitoring land subsidence in saltmarshes is challenging due to the peculiar features of these morphological forms: e.g., **they are difficult to access**, made of largely **unconsolidated deposits**, **without anthropogenic structures**, and become **submerged by high tides**.

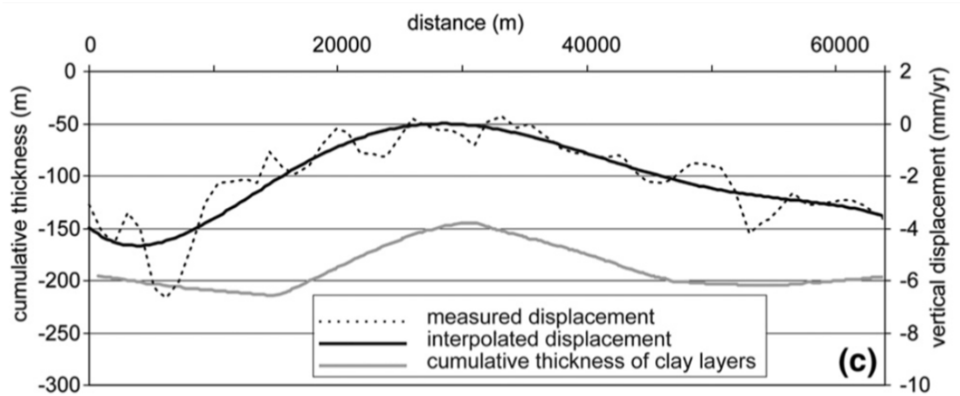
Knowledge advance in subsidence mechanisms and causes: Architecture of the subsoil

The integrated analysis of ground movements and subsoil characteristics allowed to find a relationship between ground movements and deep subsoil architecture.





Cumulative thicknesses of the sandy (a) and clayey (b) deposit of the in the upper 400 m of the subsoil; ground movements (c).

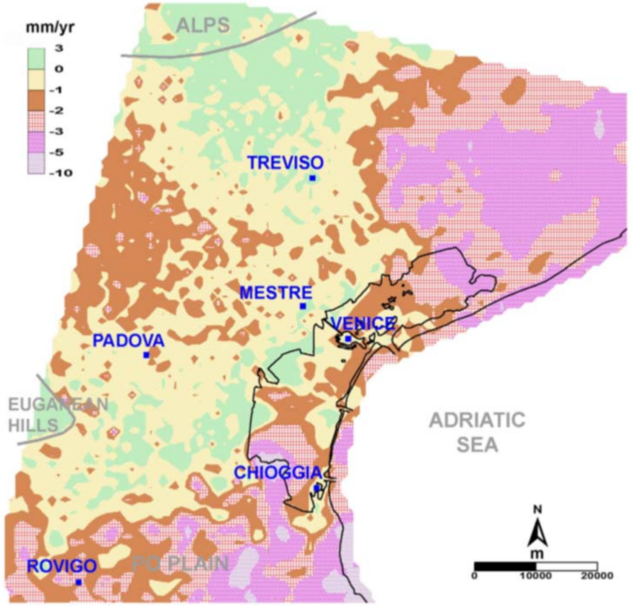


Comparison between the cumulative thickness of the clay and the subsidence rates (slices along the red dashed lines).

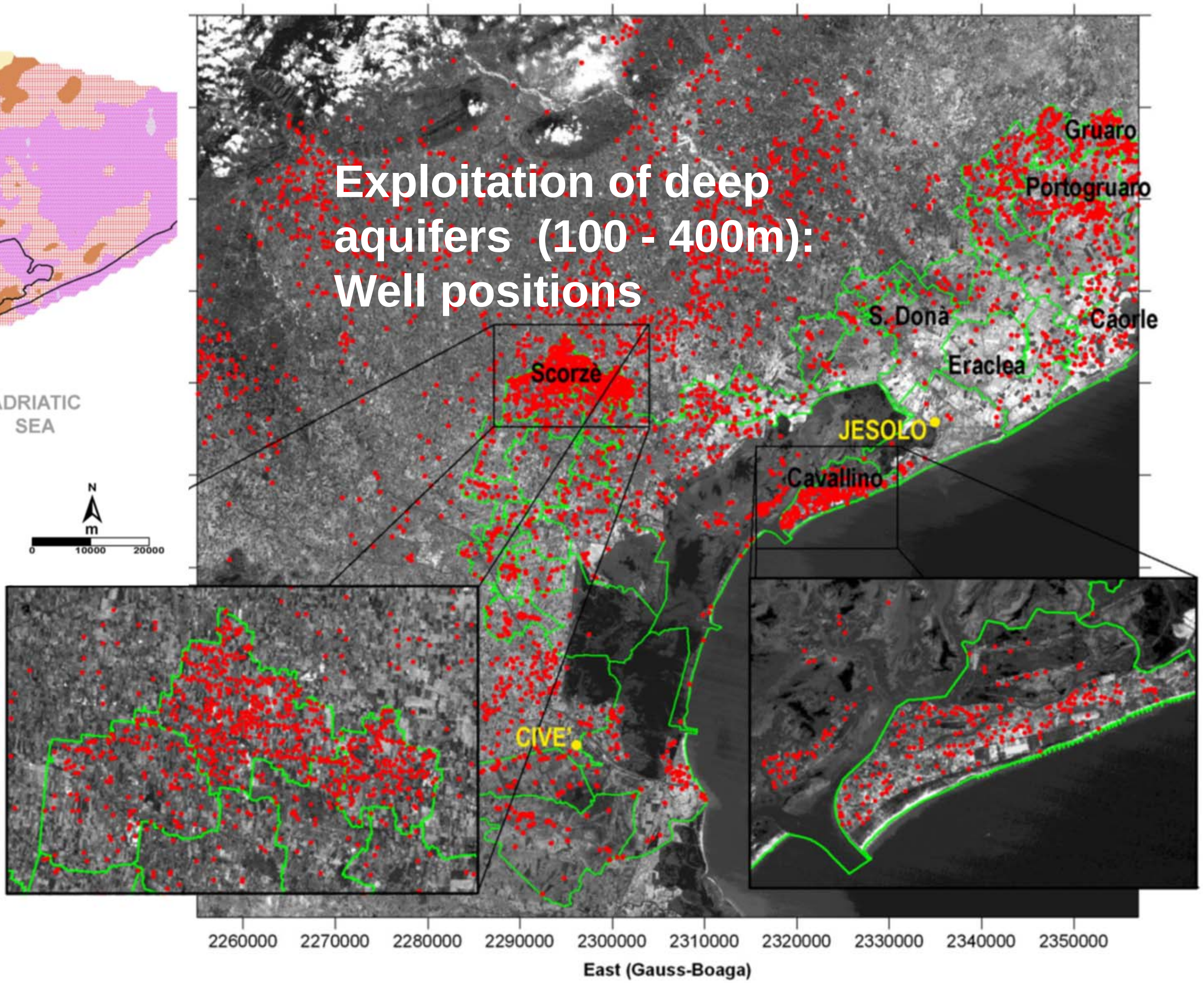
The areas of greatest subsidence rates correspond to those of greater cumulative thickness of clays (i.e. the northern and southern coast), conversely lowest displacement rates occur in the central area where there is the greatest cumulative thickness of sands.

Knowledge advance in subsidence mechanisms and causes: the emergence of new groundwater exploitation areas

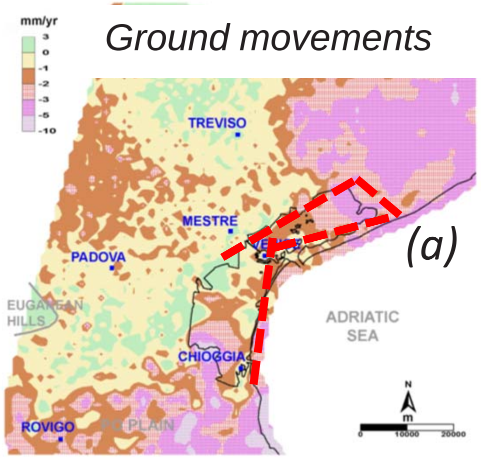
Ground movements

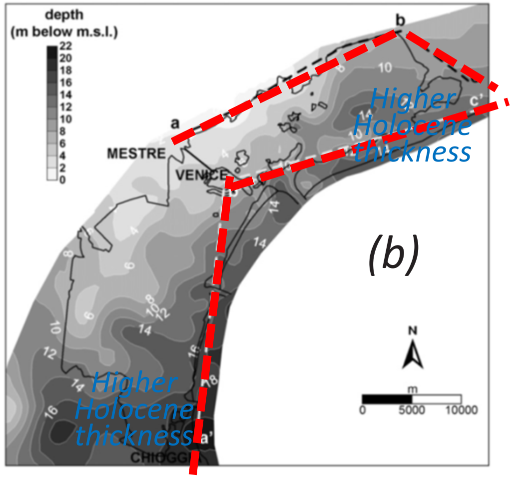


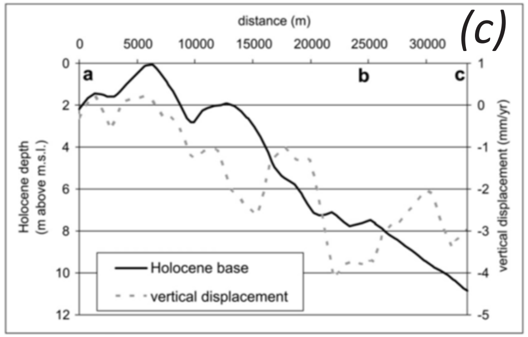
Deep mechanisms: groundwater pumping

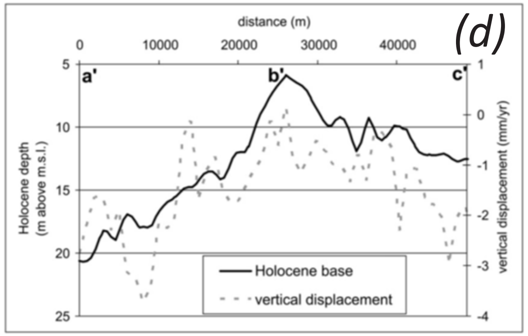


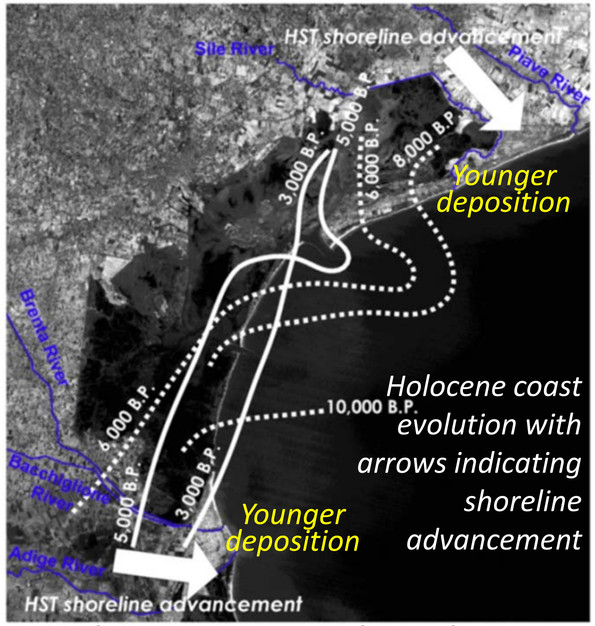
Knowledge advance in subsidence mechanisms and causes: Compaction of Holocene deposits











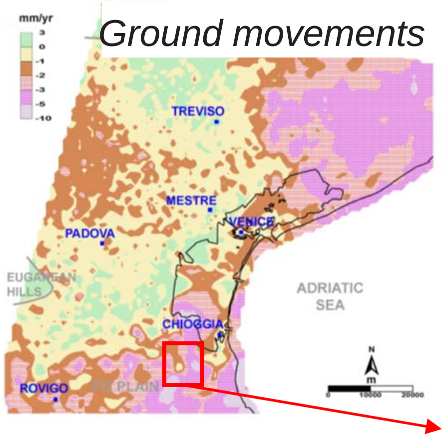
Holocene coastal evolution

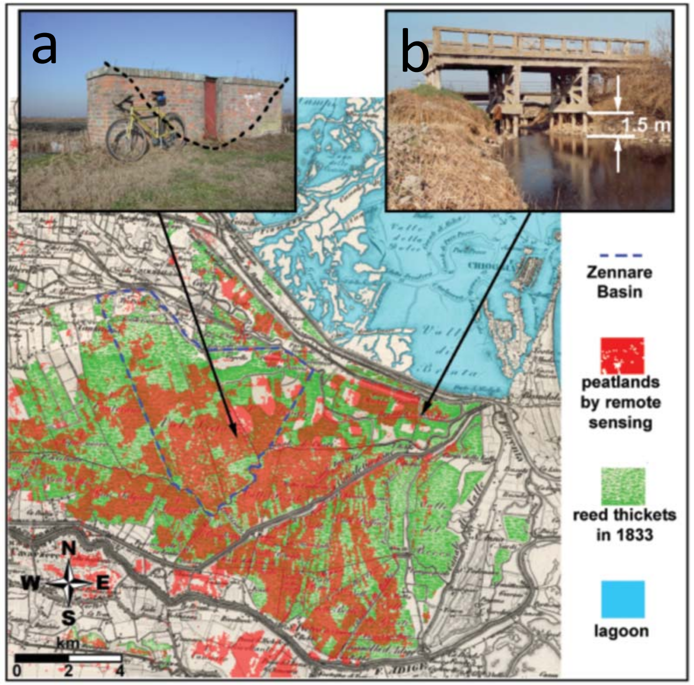
(a) Ground movements and (b) thickness of the Holocene deposits; ***(c) (d) correlation between vertical displacements (mm/yr) and thickness of the Holocene deposits (m)***

The **areas of greatest subsidence rates correspond to those of greater thickness of younger deposits** (i.e. the northern and southern coast), conversely lowest displacement rates occur in the central area where Pleistocene well consolidate alluvial deposits are close to crop out.

Knowledge advance in subsidence mechanisms and causes: Hydraulic reclamation and oxidation of organic soil

Hundreds of pumping station keep drained large low-lying farmlands.
These areas correspond to former wetlands and lagoons rich in organic soil.



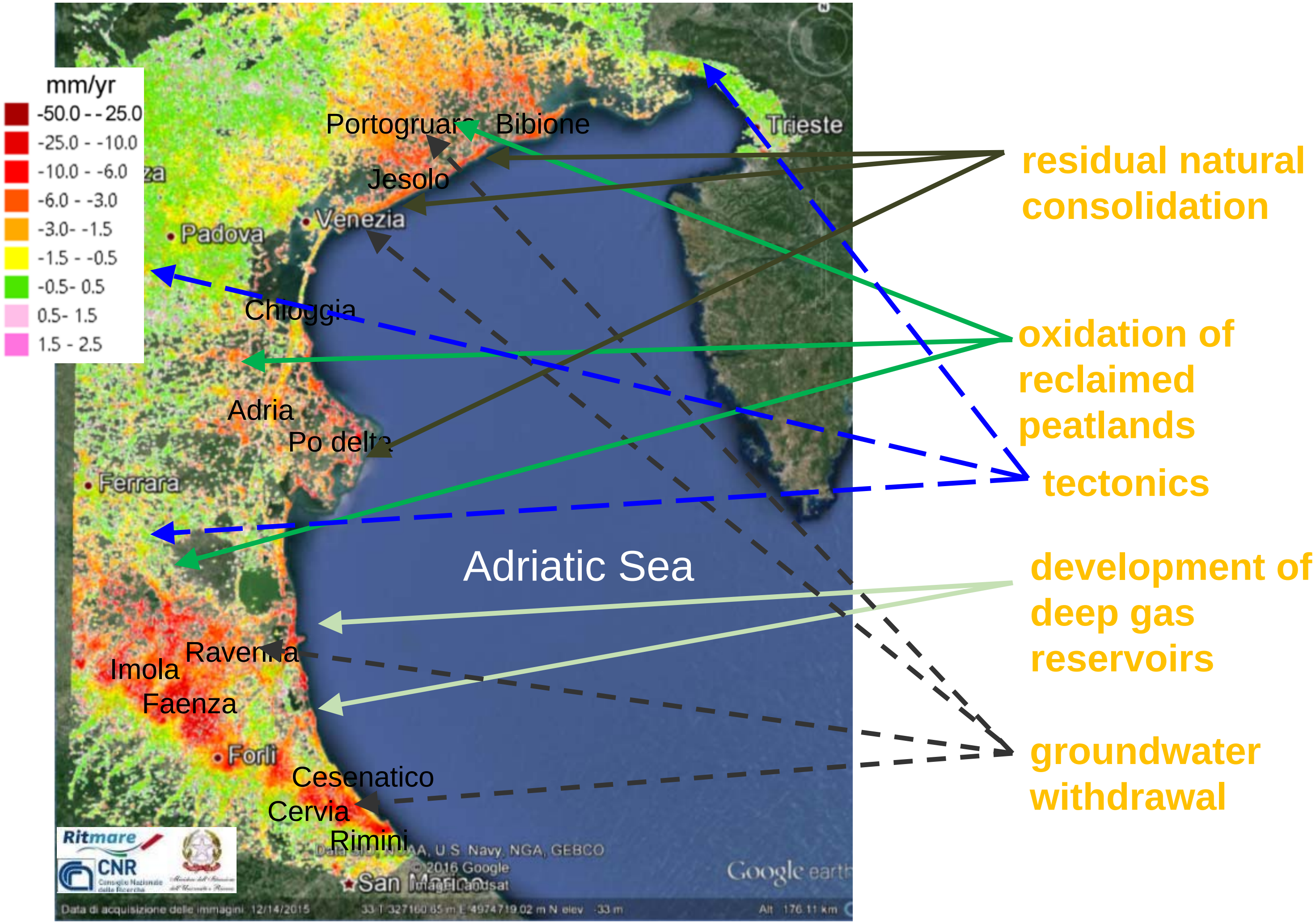


a. Protrusion of a sluice above the ground surface. Dashed line shows the trace of the disappeared channel.

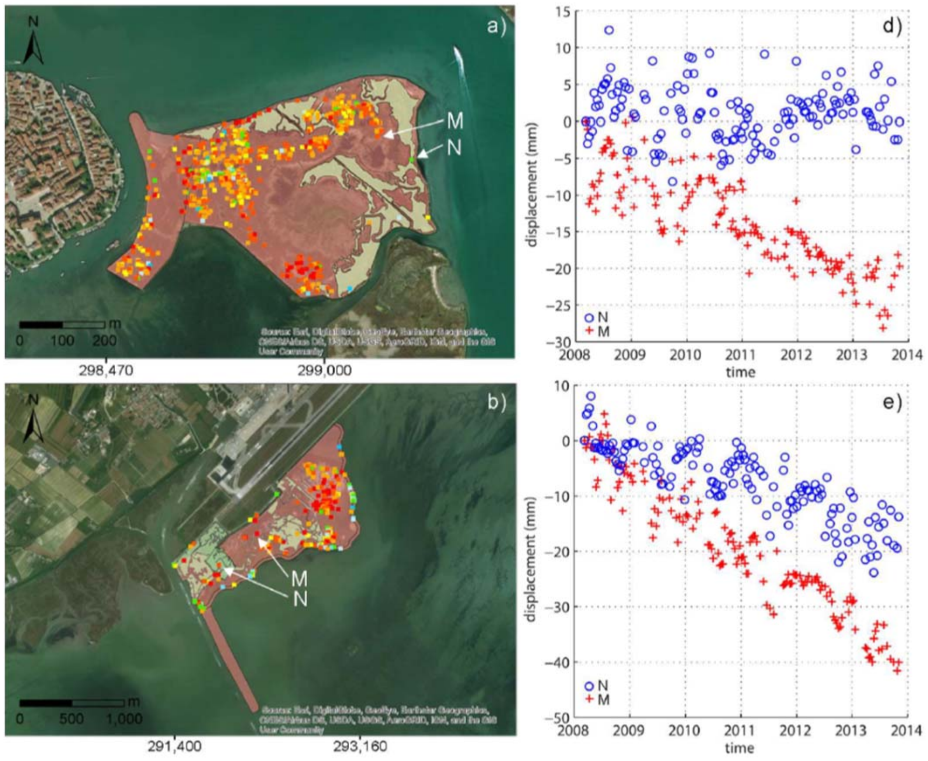
b. An old bridge hanging over the canal bank which settled by 1.5 m.

Land subsidence involves peaty areas in response to drainage for agricultural purposes. Drainage of reclaimed lands induces aerobic conditions in soils and oxidation of the carbon of organic matter. This lead to carbon loss in the form of gaseous CO2, and hence, land settlement. The **oxidation of organic soil has induced subsidence rates up to 2 cm/yr**.

Knowledge advance in subsidence mechanisms and causes: Mapping land subsidence causes at regional scale



Knowledge advance in subsidence mechanisms and causes: ground dynamics of salt marshes



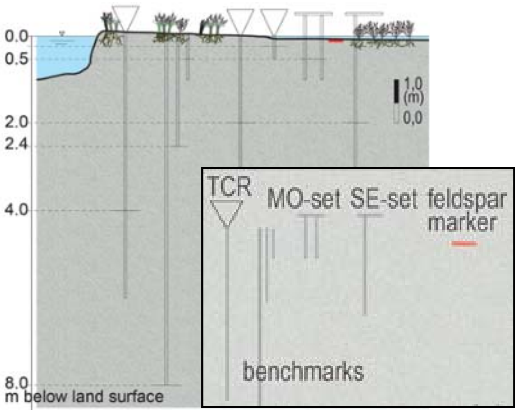
High frequency and long-time data series from TerraSAR-X allowed to quantify land subsidence in natural (N) and man-made (M) salt marshes.

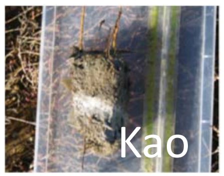
There is a **good correlation between sinking rates and formation age of the salt marshes**. Man-made salt marshes dated 2007, 2002 and 1992 show median subsidence rate amounting to 4.0, 2.8 and 1.3 mm/year, respectively. Natural salt marshes that are approximately 500–1000 year old are characterized by a median subsidence equal to 0.4 mm/year

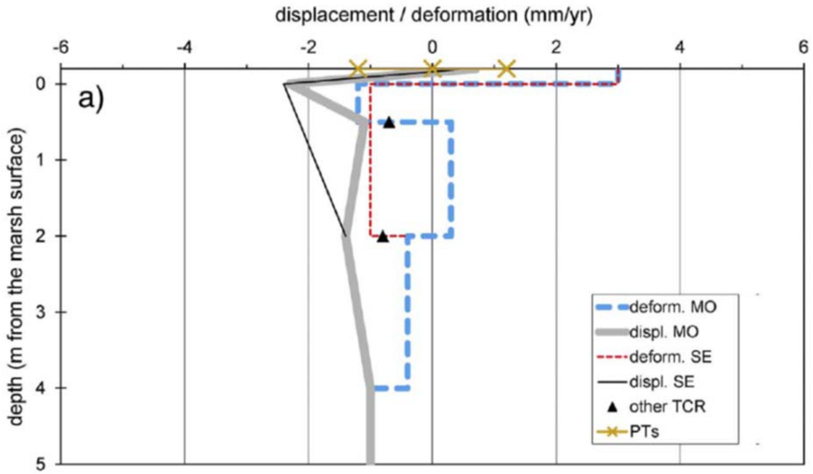
The **existence of salt marshes is strictly connected to their elevation** with respect to the mean sea level.
Quantifying land subsidence of these high-value environments is therefore crucial to investigate their long-term possible survival, also **in view of the expected climate changes**.

Knowledge advance in subsidence mechanisms and causes: the real/net loss of ground elevation in salt marshes

The ability of salt marshes to counteract land subsidence and sea level rise also depends by other processes such as sedimentation and erosion.







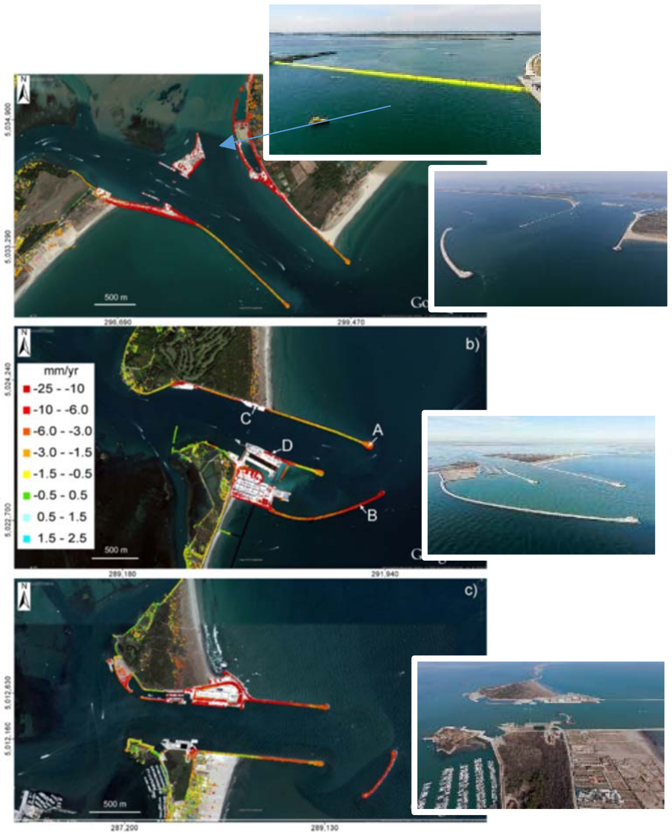
The **Integration of SAR Interferometry and ground-based investigations** such as:

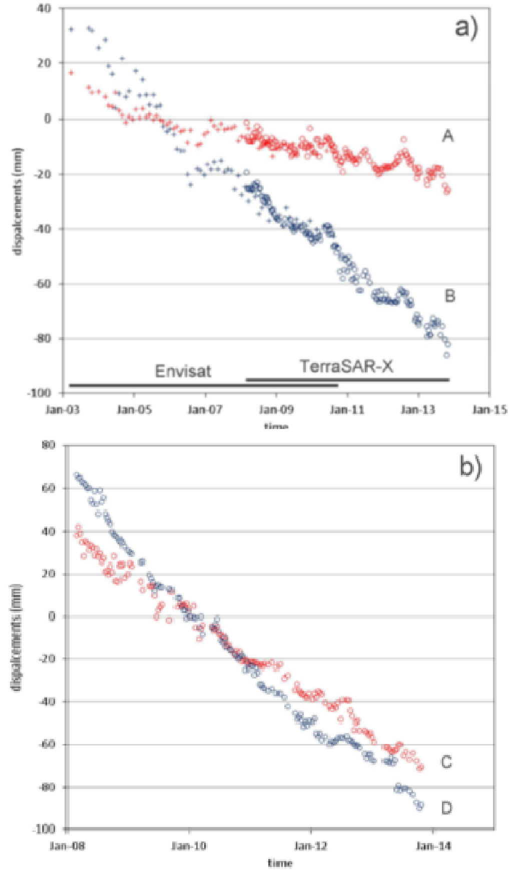
- Multi-level benchmarks,
- Multi-level Trihedral Corner Reflectors,
- PTs,
- Surface Elevation Table,
- Kaolin layers.

allowed obtaining differential compaction rates of the subsoil layers at different depths and the real/net loss of ground elevation.

Knowledge advance in subsidence mechanisms and causes: long-term consolidation of subsoil in relevant structures and works

Improving monitoring ground displacements in areas of strategic works: MoSE construction yards



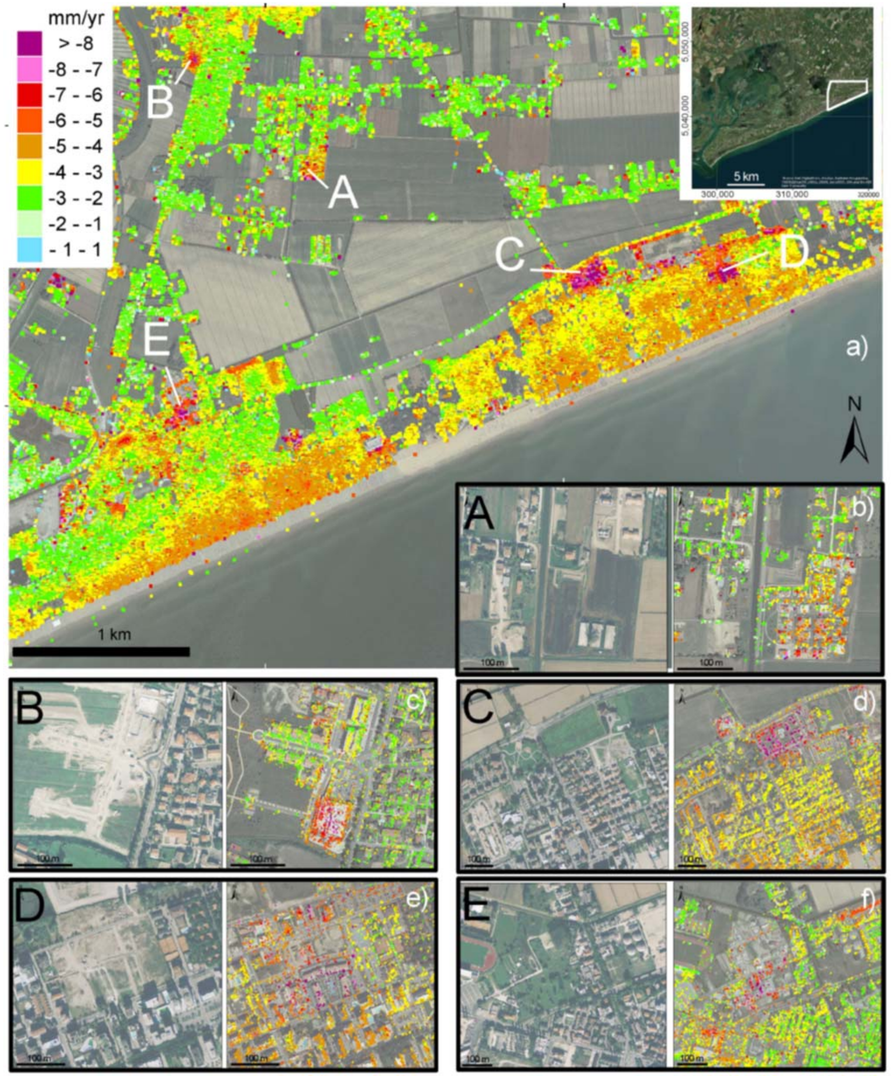


The construction of the mobile barriers at the three inlets raised **concerns about possible important settlements caused by the load of the complementary structures** (e.g., jetties, breakwaters, locks, and an artificial island) on the Quaternary deposits.

Sinking rates less than 3 mm/year were measured in the parts of the jetties not affected by the restoration works; conversely, sinking rates up to 30 mm/year are detected in the newer structures

The geomechanical characterization of coastal soils is of considerable interest to geotechnical and geo-environmental researchers in relation to the stability of large coastal structures.

Knowledge advance in subsidence mechanisms and causes: Long-term consolidation of subsoil in newly built up areas



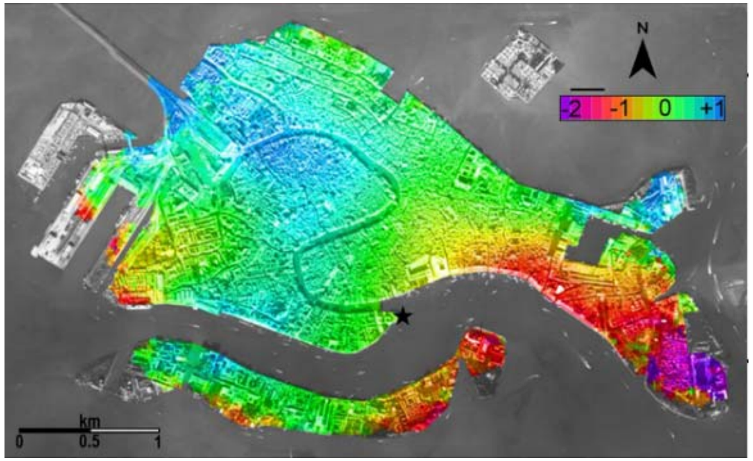
The new buildings exert heavy loads on relatively recent coastal deposits and lead to consolidation of the shallow subsoil below their foundations.

The new urbanization is responsible for subsidence bowls spread all over the Venice coastland, wherein several urban suburbs and industrial/commercial sites have grown rapidly by changing farmland use.

Over the last decades, newly built-up areas have been developed on the Venice coastland with residential, touristic and industrial purposes.

Knowledge advance in subsidence mechanisms and causes: long-term consolidation in the historical center

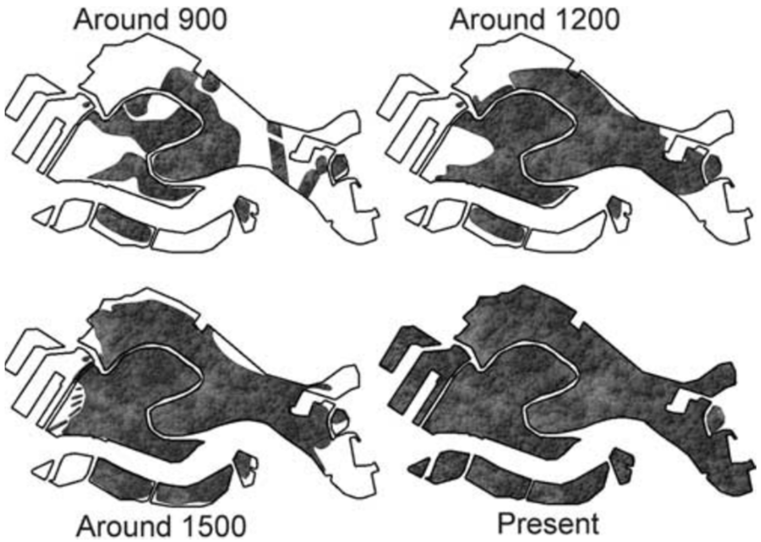
Rates of ground vertical displacement (mm/year) at Venice



The city developed over ancient well-consolidated sandy islands during the first millennium, and the following expansions were done by reclaiming and filling parts of the lagoon and channels.

The high spatial resolution of the interferometric data provided a new picture of the subsidence of Venice and revealed that the **sectors with higher sinking correspond to those of the last urbanization**:

- Stable sectors generally correspond with the city development before 1500.
- Secondary consolidation is still active in the newer sectors.



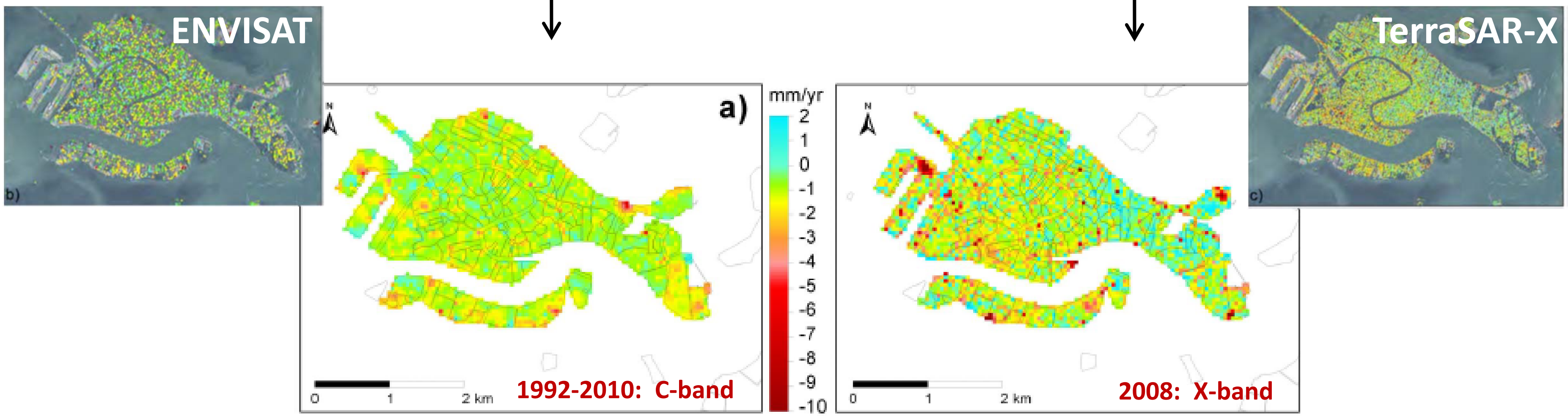
Sketch of the growth in area of Venice from 900 A.D. to present.

Knowledge advance in subsidence mechanisms and causes: ground movements induced by anthropogenic activities

The combined use of interferometric products obtained by sensors with different bandwidth extends the capability of the SAR-based Interferometry

Long-term displacements (1992-2010) by C-band SAR sensors (ERS/ENVISAT):
The 20 m pixel resolution and 35-day revisiting time poorly capture and significantly smooth the short-term anthropogenic subsidence (in VENICE). **We can assume that the 1992-2010 mean velocities are reasonably the picture of the present natural subsidence**

Short-term displacements (2008) by X-band SAR sensor (TerraSAR-X):
The X-band sensor with 3 m pixel resolution and 10-day revisiting time detects rapid movements, which in VENICE are **primarily ascribed to the anthropogenic causes superposed to the natural background**

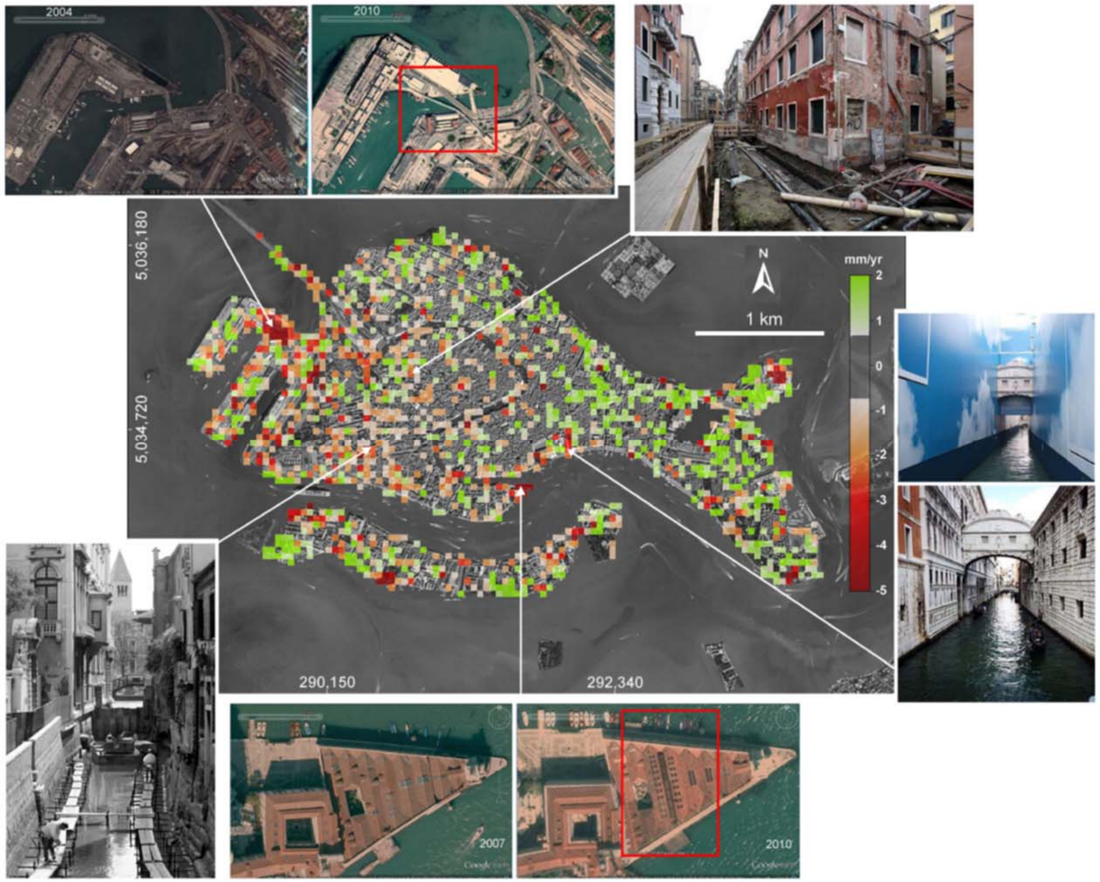


The quantification of the ground displacements is obtained by removing the long-term interpolated map (1992-2010) from the short-term interpolated solution (2008)

Knowledge advance in subsidence mechanisms and causes: ground movements induced by anthopogenic activities

During the last two decades, many interventions have been carried out for safeguarding the city and some of them likely produced short-term ground displacements

Anthropogenic ground movements (2008)



Restoration works for the conservation of the historical palaces and the embankment walls (e.g., new loads, consolidations, jet grouting, well-points), dredging the canals, etc.

Waves induced by the boat and ship traffic on the embankment walls and sidewalk next to the canals.

Conclusive Remarks

The city of Venice and its surrounding lagoon is presently one of the sites most sensitive to land subsidence worldwide. **Even a few mm loss of ground elevations** with respect to the mean sea level can **significantly change the natural lagoon environments and threaten the city's survival**.

The **monitoring of land subsidence** in the Venice area **began in the 1960s using spirit leveling and over the last decades has been significantly improved using space-borne observation techniques** based on synthetic aperture radar (SAR) interferometry.
The subsidence **monitoring network** of the Venice coastland **progressively increased from a few hundreds of leveling benchmarks to more than one million of SAR reflectors**. This reduced the use of in-situ measurements to calibrate and validate interferometric products.

The increased spatial coverage allowed:

- Investigating the subsidence process in **areas never been studied before**;
- A much **wider and accurate quantification** (space/time) of ground dynamics;
- An improvement of the **knowledge on** the various **factors driving land subsidence**.

Conclusive Remarks

Driving factors known in the past

Natural components

- *Tectonics*: *deformation of the bedrock*
- *Compaction of the Plio-Pleistocene deposits*: *about* 1,500 m thick of sandy and silty-clayey layers of alluvial and marine origin

Anthropogenic activities:

- *Subsurface fluid exploitations:* mainly groundwater

Driving factors that came out recently

Natural components

- *Differential compaction because of the variability of the deep subsoil architecture at regional scale.*
- *Compaction of the shallow subsoil: in particular the Holocene sediments, mostly lagoon muds and unconsolidated clay and silts*

Anthropogenic activities:

- *Hydraulic land reclamations (ancient lagoon and wetland sectors) leads to* organic soil oxidation and saltwater intrusion
- Newly built-up areas
- Restoration works

Conclusive Remarks

The **strategies for prevention and mitigation of the effects of the land subsidence** in the Venice coastlands are **based on technical and governance aspects**.

- **Set up of a proper systems for monitoring land subsidence** integrating satellite- and ground- based methodologies such as multi-band interferometry, continuous CGP stations, differential GPS measures and spirit levelling;
- Implementation of **pilot projects for improving knowledge** of the process and developing updated monitoring methods;
- analysis of the **effects and identification of stakeholder requirements**;
- a continuous **knowledge improvement of the subsoil** setting and architecture.
- proposing **best practices, procedures and guidelines** such as:
    - the regulation of groundwater exploitations combined with the monitoring of the groundwater levels;
    - the proper management of the hydraulic land reclamation of low-lying farmlands reducing the oxidation of organic solid;
    - appropriate irrigation practices by watercourses and precision method;

Conclusive Remarks

Among the mitigation measures to counteract the land subsidence effects there are:

- Ground floor rising of the historical centers;
- Beach nourishments;
- Reconstruction of salt marshes;
- The construction of the mobile gates at the lagoon inlets;
- Continuous improving of the pumping stations for guarantee the drainage of the low-lying coastal sectors;
- Freshwater injection in shallow aquifers contaminated by saltwater intrusion because of the ground elevation loss in low-lying farmlands;
- The assessment of vulnerability to land subsidence.

Thank you