2nd International Workshop on Coastal Subsidence

Programme
Book of Abstracts

May 30th - June 1st, 2016

Arsenale, Tesa 102
ISMAR - CNR
Venice, Italy

Welcome - 2nd International Workshop on Coastal Subsidence

This is the second event of a series of International Workshops on Coastal Subsidence initiated in 2013 at New Orleans, LA.

Subsidence is generated by numerous natural and anthropogenic processes. Land subsidence is a widespread phenomenon, particularly relevant to transitional environments, such as wetlands, deltas, and lagoons, characterized by low elevation with respect to the mean sea level. The influence of land subsidence on hydrogeological hazard and sustainable development of coastlands is often under-estimated with respect to sea level rise. However, in many places human-induced subsidence (often superimposed on subsidence due to natural processes) is orders of magnitude higher than sea-level rise, increasing vulnerability for flooding and salt-intrusion, threatening agriculture and ecological functions. Quite often, especially at the onset of the occurrence, land subsidence goes unnoticed as it affects a large portion of the territory (up to thousands of square kilometres) and usually occurs at slow velocity, only discovered when severe damages are observed. At this stage, undertaking effective remedial measures to mitigate the associated environmental and socio-economic impacts may prove tremendously expensive.

The goal of this workshop series is to assemble a team of international experts to re-examine our understanding of coastal subsidence drivers, to explore new paths forward in subsidence prediction, and to define best practices for integration of subsidence science into coastal risk assessments. With the new millennium, improved methods for measuring changes of land surface elevation, the application of geophysical modeling, the development of advance mathematical models have greatly advanced our understanding of potential rates and mechanisms of subsidence and provide valuable tools for planners and resources managers in coastal areas throughout the world. However, many uncertainties remain about the rates and spatial distributions of present and future subsidence at a time when low elevation coastal areas are under increasing threat from rising sea levels and severe storms. Also today, large coastal cities and deltaic regions, mainly in the developing or newly-development countries, are strongly threatened by large subsidence rates.

Programme Committee

Pietro Teatini	Dept. of Civil, Environmental and Architectural Engineering, University of Padova, Padova, ITALY
Luigi Tosi	Institute of Marine Sciences, Italian National Research Council, Venice, ITALY
Torbjörn Törnqvist	Dept. of Earth and Environmental Sciences, Tulane University, New Orleans, Louisiana, USA
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Pietro Teatini and Claudia Zoccarato	Dept. of Civil, Environmental and Architectural Engineering, University of Padova, Padova, ITALY

About Venice

Venice is the capital of the Veneto Region, Italy. It is located in the marshy Venetian Lagoon which stretches along the shoreline, between the mouth of the Po and the Piave Rivers. Venice is built on an archipelago of 117 islands formed by 177 canals in a shallow lagoon, connected by 409 bridges. In the old center, the canals serve the function of roads and almost every form of transport is on water or on foot.

Venue

Conference Hall in ISMAR-CNR

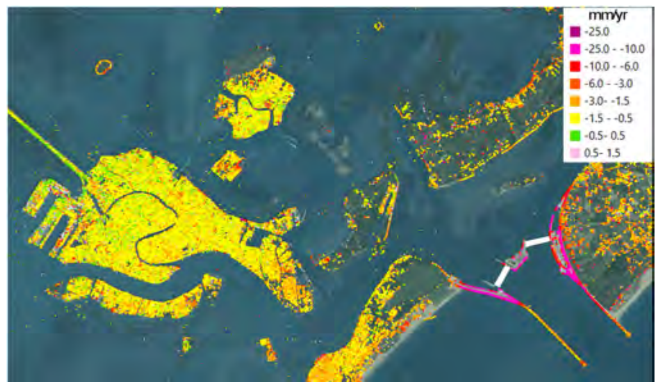
The workshop is held in Venice, Italy, beginning Monday, May 30th, and concluding Wednesday, June 1st, 2016.

Venice is one of the most beautiful and famous cities in the world, well known because relative land subsidence has seriously compromised the heritage and the safety of the city in relation of its small elevation above the Adriatic Sea.

The venue of the workshop is the ISMAR-CNR (Institute of Marine Sciences of the Italian National Research Council) headquarter. ISMAR-CNR is located in four covered pavillons (“tese” in Italian) recently renovated in the Arsenale, a complex of former shipyards and armories clustered together. The Arsenale was the pulsing heart of the power and military strength of the Republic of Venice from the XII century.

Guided Tour to the Control Room of MOSE

During the afternoon of June, 1 2016, a guided tour to the control room of the MOSE system is organized for the Workshop participants. The MOSE barriers consist of flap gates, installed in the bottom of the inlets. The gates allow to separate temporary the lagoon from the sea during an event of high tide. A brief description of the MOSE system is provided at the Puntomose (Arsenale Nord, building 63) followed by a guided tour to the control room of the MOSE system and at one of its modules.



Average land displacements (2008-2011) of the historical center of Venice and the Lido inlet obtained by PSI on TerraSAR-X images. The MOSE system at Lido inlet consists of two rows of flap gates: 21 gates at the barrier of North Lido (total lenght 420 m) and 20 gates at the barrier of South Lido (total lenght 400 m). The barriers are separated by an artificial island.

Sponsorship

European Geosciences Union

MATHEMATICAL METHODS and MODELS for ENGINEERING

Workshop Programme

Day 1: Monday, May 30

9:00 - 10:15: Registration

10:15 - 10:30: Opening Remarks and Welcome

10:30 - 12:30: Session 1 - New and Revisited Case Studies of Coastal Land Subsidence

11:15 - 11:30: Coffee Break

12:30 - 14:00: Lunch Break

14:00 - 17:00: Session 1 - New and Revisited Case Studies of Coastal Land Subsidence

15:30 - 15:45: Coffee Break

Poster

17:00 - 18:00: Session Wrap Up/Discussion

Day 2: Tuesday, May 31

09:30 - 12:15: Session 2 - Drivers of Land Subsidence in Coastal Areas

09:30-10:15 Keynote
Modelling post-glacial deformations and sea-level along the Mediterranean coasts
Spada G. 18

10:15-10:30
Subsidence due to Holocene sediment load in the Ganges-Brahmaputra-Meghna delta: effect of faults
Krien Y., Karpytchev M., Ballu V., Calmant S., and Shum, C.K. 19

10:30-10:45
Coastal and see level changes detected from InSAR and ground based measurements: analysis of potential drivers and future scenarios
Stramondo S., Anzidei M., Bignami C., Brunori C.A., Montuori A., Moro M., Polcari M., Vecchio A., Serpelloni E., Civico R., and Pizzimenti L. 20

10:45 - 11:00: Coffee Break

11:00-11:15
Differential subsidence due to peat compaction in Holocene coastal deltas
van Asselen S. 21

11:15-11:30
Evidence of 3-D coastal subsidence
Stiros S.C. 22

11:30-11:45
Land subsidence monitoring and mechanism research over the Yellow River Delta, China
Liu Y., Huang H. 23

11:45-12:00
Multi-sensors Advanced DInSAR analysis of the land subsidence pattern from 1992 to 2016 in the Ravenna area (Italy)
Boní R., Fiaschi S., Meisina C., Ibrahim A., Calcaterra D., Di Martire D., Ramondini M., Borgstrom S., Siniscalchi V., Achilli V., and Floris M. 24

12:00-12:15
Surface displacement estimation through the P-SBAS automatic chain on the ESA's Grid Processing on Demand (G-POD) web
Berardino P., Manunta M., Del Luca C., Zinno I., Casu F. 25

12:15 - 13:45: Lunch Break

13:45 - 15:00: Session 3 - Contemporary Subsidence Management in Coastal Areas

13:45-14:30 Keynote
Flooding projections from elevation and subsidence models for the Rajang Delta peatlands, Malaysia
Hooijer A., Vernimmen R. (presenter Erkens G.) 26

14:30-14:45
Shallow subsidence and sediment accretion in the Ganges-Brahmaputra natural and poldered regions
Wilson C., Steckler M.S., Goodbred Jr. S. 27

14:45-15:00
Dealing with subsidence in the Dutch delta: do current management strategies fit todays challenge of mitigating subsidence?
Stouthamer E., Groothuijse F. 28

15:00 - 15:15: Coffee Break

15:15 - 17:15: Session 4 - Coastal Land subsidence vs Sea Level Rise

15:15-16:00 Keynote
Global estimates of the effects of subsidence on coastal flood risk
Nicholls R.J., Brown S., Hanson S., Hinkel J., Lincke D., and Vafeidis A. 29

16:00-16:15
Influence of mechanical compaction and biodegradation on salt-marsh sediment and relative sea-level change
Brain M.J., Kemp A.C., Hawkes A.D., Vane C.H., Cahill N., Donnelly J.P., Horton B.P., Engelhart S.E., and Parnell A.C. 30

16:15-16:30
Shallow subsurface process controls on wetland elevation and relative sea-level rise rates
Cahoon D.R. 31

16:30-16:45
Holocene subsidence history in the Ganges Brahmaputra Delta
Grall C., Goodbred S., Sincavage R., Pickering J., Steckler M.S., Spiess V., and Paola C. 32

16:45-17:00
Managing subsidence of the Wadden Sea tidal flat area due to gas production: a probabilistic approach
van Thienen-Visser K., Breunese J.N. 33

17:00-17:15
Coastal GPS vertical velocity field available from SONEL (www.sonel.org) data assembly center
Wöppelmann G., Gravelle M., and Santamaría-Gómez A. 34

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Disaster risk reduction of land subsidence in Jakarta

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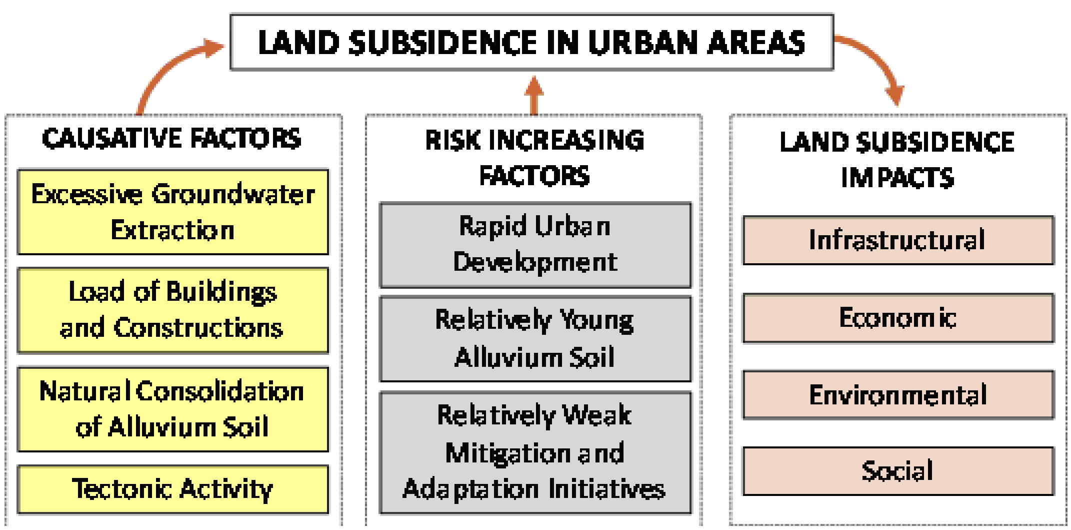
Keywords: land subsidence, disaster reduction, Jakarta

Jakarta is the capital city of Indonesia located in the west-northern coast of Java island, within a deltaic plain and passes by 13 natural and artificial rivers. This megapolitan has a population of about 10.2 million people inhabiting an area of about 660 square-km, with relatively rapid urban development. It has been reported for many years that several places in Jakarta are subsiding at different rates. The main causative factors of land subsidence in Jakarta are most probably excessive groundwater extraction, load of constructions (i.e., settlement of high compressibility soil), and natural consolidation of alluvial soil. The results obtained from leveling surveys, GPS surveys and InSAR technique over the period between 1974 and 2014 show that land subsidence in Jakarta has spatial and temporal variations with typical rates of about 3 to 10 cm/year. The observed land subsidence along the coastal areas of Jakarta are relatively have larger rates than the inland areas. The subsidence impacts can be seen already in the field in forms of cracking and damage of housing, buildings and infrastructure; wider expansion of (riverine and coastal) flooding areas, malfunction of drainage system, changes in river canal and drain flow systems and increased inland sea water intrusion. These impacts can be categorized into infrastructural, environmental, economic and social impacts (see Figure). Rapid urban development, relatively young alluvium soil, and relatively weak mitigation and adaptation initiatives, are risk increasing factors of land subsidence in Jakarta. This paper discusses and analyzes the disaster risk reduction management of land subsidence in Jakarta, especially related to its prevention, mitigation, adaptation and preparedness aspects.



The causative factors, risk increasing factors and impacts of land subsidence in Jakarta

Living on peat soils for a 1000 years

G. Erkens[1], M.J. van der Meulen[2], and H. Middelkoop[3]

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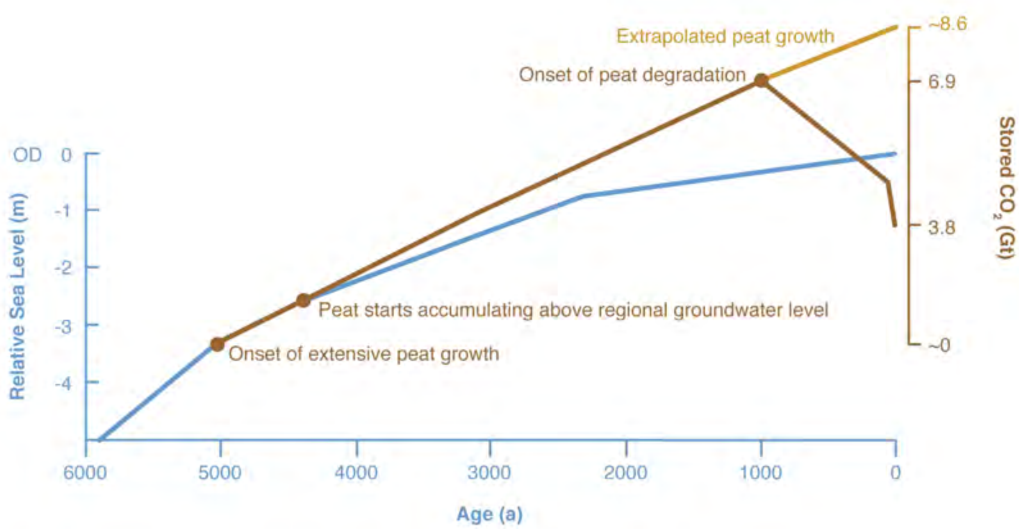
Keywords: coastal peatlands, CO_2 emissions, subsidence

Many coastal peatlands are currently drained to create arable land. This is not without consequences; physical compaction of peat and its degradation by oxidation lead to subsidence, and oxidation also leads to emissions of carbon dioxide (CO_2). The continuously increasing scale of human impact on coastal peatlands is in strong contrast with the limited spatial and temporal scales of the available measurements. This study complements existing studies by quantifying total land subsidence and associated CO_2 respiration over the past millennium in the Dutch coastal peatlands, to gain insight into the consequences of cultivating coastal peatlands over longer timescales. Results show that the peat volume loss was 19.8 km^3, which lowered the Dutch coastal plain by 1.9 m on average, bringing most of it below sea level. At least 66% of the volume reduction is the result of drainage, and 34% was caused by the excavation and subsequent combustion of peat. The associated CO_2 respiration is equivalent to a global atmospheric CO_2 concentration increase of $\sim$0.39 ppmv. Cultivation of coastal peatlands can turn a carbon sink into a carbon source (see figure). If the path taken by the Dutch would be followed worldwide, there will be double trouble: globally significant carbon emissions and increased flood risk in a globally important human habitat. The land subsidence history forced the Dutch to adapt their land and water management practices a couple of times over the last 1000 years and ongoing land subsidence continues to present the Dutch some major challenges for the future, which will both be discussed.



Approximate CO_2 sequestration and subsequent emission from the Dutch coastal peatlands over the last 6000 years. Due to their thick peat deposits (compared to upland peatlands) particularly coastal peatlands become - when converted to arable land - long lasting sources of CO_2

The contribution of land subsidence to the increasing coastal flooding hazard in Miami Beach

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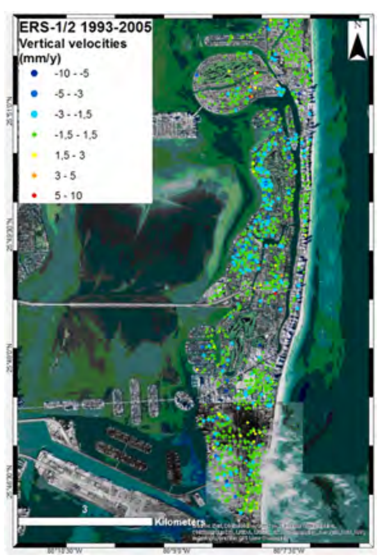
Keywords: subsidence, InSAR, Miami Beach

South Florida is one of the most vulnerable areas to Sea Level Rise (SLR) due to its low elevation, large population, and economic importance. Recently, the City of Miami has been identified as the economically most vulnerable city to SLR in the world (US National climate assessment). Heretofore, the effect of SLR has felt mostly in low-lying coastal communities, such as the City of Miami Beach. A recent flooding hazard study of Miami Beach have shown that the flooding frequency after 2006 increased by 400% compared with flooding events during the previous decade (Wdowinski et al., 2016). This study attributed the flooding frequency increase to a decadal-scale accelerating rates of SLR that occurred most likely due to the weakening of the Florida Current/Gulf Stream system. However, some of the increased flooding frequency might have caused by local land subsidence affecting the sections of the city built on reclaimed swamps. In this study we evaluate the contribution of land subsidence to the flooding hazard of Miami Beach using Interferometric Synthetic Aperture Radar (InSAR) observations. We analyzed 23 ERS-1/2 images acquired during the period 1993-2005 using two InSAR techniques, Permanent Scatterer (PS) and Small Baseline Subset (SBAS). Preliminary results yield localized subsidence at a rate of 2-3 mm/yr, mostly along the western section of the city. Although the detected subsidence velocities are quite low, their effect on the flooding hazard is significant, because (1) houses originally built 80 years ago on higher ground have subsided by 16-24 cm down to flooding hazard zones; and (2) the combined effect of subsidence and SLR further expose the subsiding areas to higher flooding hazard than the rest of the city.



Velocity map over Miami Beach obtained with the PS technique

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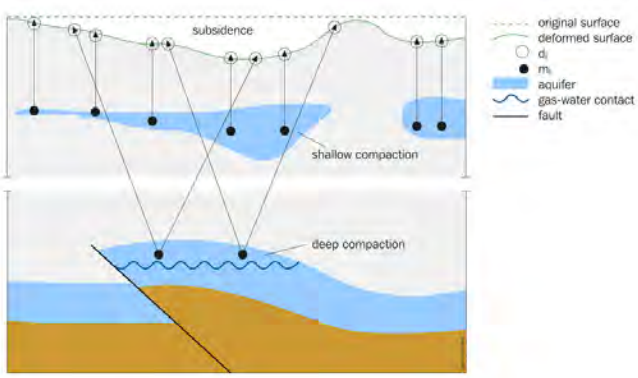
Monitoring of gas reservoirs with surface movement data

P.A. Fokker[1] and T.G.G. Candela[1]

[1]TNO - Geological Survey of The Netherlands

Keywords: PS-InSAR, leveling, inversion, gas field

A complementary tool for reservoir production monitoring is the use of surface movement measurements. Such measurements can come from various sources, like classical levelling, GPS, or PS-InSAR. Inverting the surface movement measurements can help to assess the global reservoir behavior in time and space, and is thus complementary to the very local well production information. The goal of such an inversion scheme is to constrain the driving parameters of the prior model. With the improved parameter estimates, the reservoir behavior can be better assessed and subsidence predictions can be improved. In this contribution we will show possible applications of subsidence inversion using some recent field cases. Two main complications need to be carefully handled in the use of subsidence estimates for reservoir characterization. First, the inverse problem is often ill-posed, as the number of parameters may be larger than the number of measurements. Second, the influence of reservoir compaction is distributed over a relatively large area of the surface (see the Figure). We will show key results from three Dutch cases to highlight some of the problems and possibilities related to subsidence inversion. In a first application we show the importance of prior knowledge. We show an inversion in which a pressure depletion field that is known from reservoir simulations is multiplied by an uncertain compaction coefficient and thus propagated toward surface movement using a linear elastic model. The effect of different choices for the smoothness of the compaction coefficient over the field is shown. In the second application we demonstrate how ascending and descending tracks of InSAR give additional information. Indeed, InSAR measurements are taken along a line of sight at an angle with the vertical; data collected in the ascending and descending satellite passes thus provide surface movements into different directions. In the third application we show how forward modelling with the use of subsidence data at the present date can be used to improve subsidence predictions and support future development choices. The key here is to map all pertinent uncertainties and evaluate their effect on the subsidence prediction. One can think of (i) uncertainties in the reservoir model, like undetected aquifer activity; (ii) uncertainties about the compaction behavior of the reservoir rock; and (iii) uncertainties of the geomechanical response of the reservoir overburden, like viscoelastic behavior of an evaporite seal or variability of the elastic parameters.



Schematic view how reservoir compaction influences the surface movement over large areas, and how deep and shallow causes of surface movement interfere at the surface

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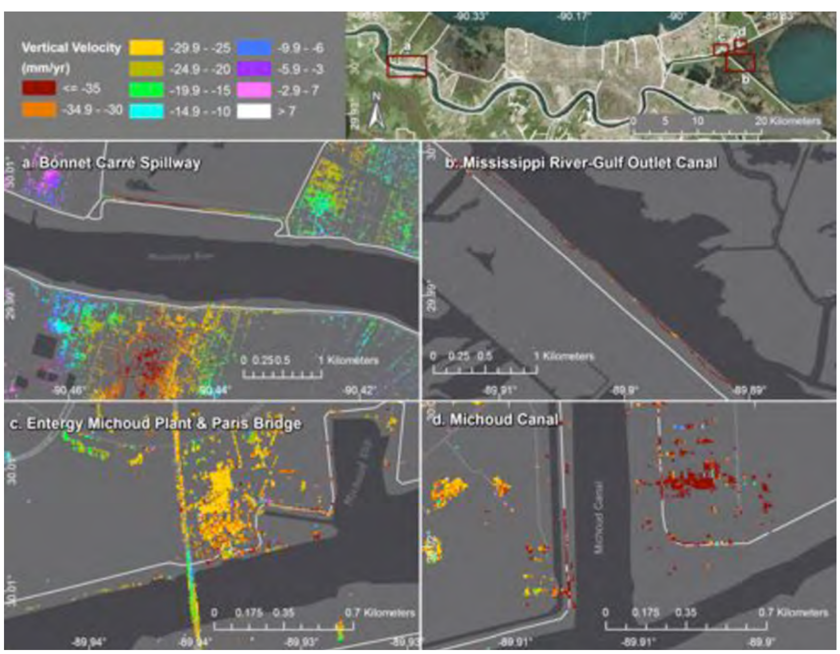
Anthropogenic and geologic influences on subsidence in the vicinity of New Orleans, Louisiana

C.E. Jones[1], R. Blom[1], E. Ivins[1], D. Bekaert[1], K. An[2], and J. Kent[3]

[1]Jet Propulsion Laboratory, California Institute of Technology — [2]Univ. of California, Los Angeles — [3]Louisiana State Univ.

Keywords: New Orleans subsidence, groundwater withdrawal, dewatering

We present an InSAR analysis of Uninhabited Aerial Vehicle Synthetic Aperture Radar (UAVSAR) data acquired on 16 June 2009 and 2 July 2012 covering New Orleans, Louisiana (USA) and two upriver communities situated near major industrial complexes. The results are used to determine the areas showing greatest subsidence, and to evaluate proximate causes for subsidence in those areas. The measured subsidence trends are similar to those reported by Dixon et al. (2006) for 2002-2004 in parts of New Orleans where observations overlap. The analysis differs from previous work in using L-band SAR and having much higher spatial resolution (6 m). The geographic associations of cumulative surface displacement suggest that the most likely drivers of susidence are groundwater withdrawal and drainage/dewatering activities. High subsidence rates are observed localized around some major industrial facilities, and appear in some cases to affect flood control infrastructure at distances >1 km. Rapid subsidence from shallow compaction is observed to occur in highly localized areas, showing that this source of subsidence could be missed in surveys relying on point measurements collected at limited locations and/or infrequent time intervals.



Subsidence of flood control infrastructure in relation to subsidence of the adjacent areas. (top) Overview of area showing levees (white) and outlined areas of (a) the Bonnet Carré Spillway; (b) the Mississippi River-Gulf Outlet Canal); (c) the power plant in Michoud; and (d) east of the NASA Michoud facility

Land subsidence in deltaic areas

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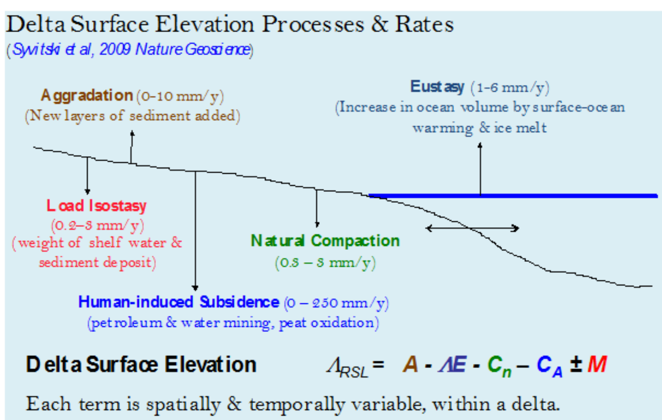
Keywords: deltas, InSAR, sediment reduction

As sea level rises, concern is mounting regarding the impacts of land subsidence in the coastal zone. Concern is not only on the rates and elevation of the land topography, but also with the connectivity to the ocean given the magnitude of storm surges, and locally tsunamis. River deltas, with their compressible substrates and large populations, are particularly vulnerable to subsidence caused by fluid extraction and reduced sediment supply. In deltas, however, surface elevation change is a complex phenomenon involving many interwoven processes: crustal motion, climate and runoff, vegetation dynamics, sediment supply and sediment compaction, and sediment remobilization by waves, tides, currents and storms. These processes cross the more traditional disciplinary boundaries, requiring methods from sedimentology, solid-earth geology and geodesy, oceanography, biology, hydrology, and engineering. Tide gauges, leveling surveys, surface elevation tables, marker horizons and sediment cores have historically allowed long-term estimates of subsidence and sedimentation rates, while advances in InSAR, LiDAR and GPS now allow unprecedented measurements of short-term change. Each method can resolve pieces of the delta balance at certain spatial and temporal scales. Meeting the highest goal of operational elevation forecasting will require combining techniques to resolve the full surface elevation balance in coastal areas. This balance includes deep motion, sedimentation and vegetation processes. Accurate predictions will require decomposing subsidence measurements into each of these components and then blending them in reasonable extrapolations. The frontiers of research will lie in the discovery, characterization and modeling of couplings between each of these processes and the activities of humans that live in the coastal zone.



Elevation Balance of a typical coastal delta (after Syvitski et al 2009, Nature Geoscience)

Impact of land subsidence due to residual gas production on surficial infrastructures: the Dosso degli Angeli field study (Ravenna, Northern Italy)

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Keywords: land subsidence, infrastructures instabilities, differential displacements, geomechanical model, hydrological and hydraulic models

The impacts of the expected land subsidence caused by gas production from the Dosso degli Angeli reservoir, Northern Italy, were analyzed over the periods from 2013 to 2018 and between 2018 and 2023. The Dosso degli Angeli reservoir is located along the coast of the Adriatic Sea, approximately 20 km north of Ravenna. The field was discovered in 1968 and the production started in 1971. The production strongly decreased from 1998 to 2004 and suspended in 2004. In 2012 Eni, the oil company managing the reservoir, has planned to complete the exploitation of the residual reserves. The impacts of the residual land subsidence on roads and other susceptible structures (bridges, pumping stations, lagoon embankments, historical buildings, power plants and a power lines) as well as on the drainage network of the reclamation basins have been evaluated. The expected subsidence values were derived from a non-linear FE model provided by Eni. The subsidence maps over the periods 2013-2018 and 2018-2023 (characterized by a maximum value equal to 1.6 cm and 1.0 cm, respectively) were used to calculate the displacement gradients in correspondence of the sensitive structures in order to assess possible damages. Since the maximum gradient value for both periods is 3.5×10^{-6} no damage is expected. Hydrological (HEC-HMS) and hydraulic (HEC-RAS) models were used to assess the effects on the drainage network. These models calculate the flows variation and the influence of subsidence on the network geometry. The results indicate that the hydraulic levels and the management of the pumping stations will not be affected significantly. To maximize the early warning plan during the extraction activities, an integrated monitoring system has been planned consisting of levelling surveys, installation of GPS permanent stations and LiDAR reflectors in the most sensible areas and the acquisitions of satellite radar (X-band) and LiDAR images.

Location of Dosso degli Angeli reservoir (in red)

The subsiding Mekong Delta; 3D numerical simulation on the impact of groundwater exploitation

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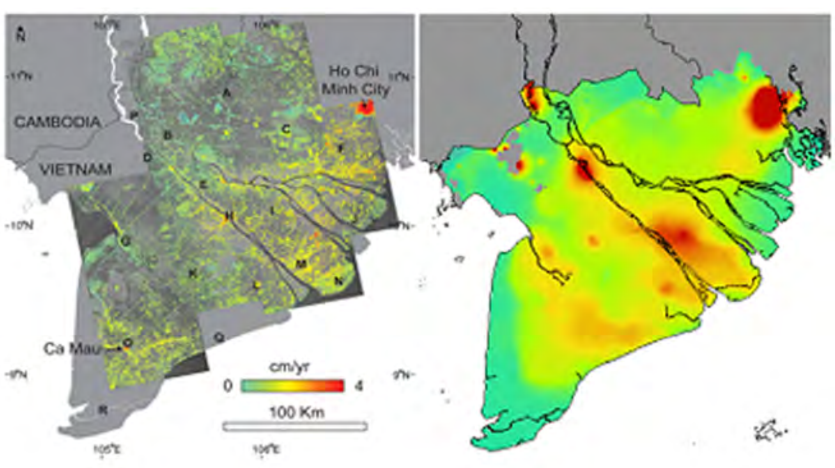
[1]Utrecht University — [2]Deltares Research Institute — [3]DWRPIS - Division of Water Resources Planning and Investigation for the South of Vietnam (DWRPIS)

Keywords: Land subsidence, numerical modelling, groundwater extraction, Mekong delta

The Vietnamese Mekong Delta, the third largest delta in the world, is facing land subsidence rates of 1-4.7 cm/yr^{-1} (Erban et al., 2014). These relatively high subsidence rates are largely attributed to groundwater extraction, which has drastically increased over the past decades due to growing domestic, agricultural and industrial demands. Hydraulic heads in the aquifers drop on average 0.3-0.7 m/yr^{-1}, causing aquifer-system compaction. With over 50% of the delta surface elevated less than 1 meter above sea level, this poses a real threat to its inhabitants, enhancing flood risk and salinization in river channels. To determine the contribution of groundwater extraction induced subsidence to total subsidence in the Mekong delta, we built a 3D numerical groundwater flow model. This model simulates hydraulic heads over the past 25 years based on the groundwater exploitation history. Subsequently, we calculate corresponding aquifer-system compaction using a coupled land subsidence module (SUB-CR), which includes a direct, elastic component and a secondary, viscous component (i.e. creep). Where InSAR is limited to the build-up environment, our approach enables modelling groundwater extraction induced subsidence in both the urban and rural part of the Mekong Delta. Even though, not all measured subsidence is explained by the model, the calculated spatial subsidence patterns largely correlate with the measurements. This identifies groundwater extraction as a major subsidence driver, yet also other drivers seem to contribute to the total subsidence balance. Furthermore we found that delta-wide subsidence initiated around two decades ago. Since then subsidence accelerated, with present rates exceeding previous measured values.



Left: Subsidence rates measured by InSAR for the period 2006-2010 (Erban et. al., 2014). Right: Modelled aquifer-system compaction due to groundwater exploitation (preliminary)

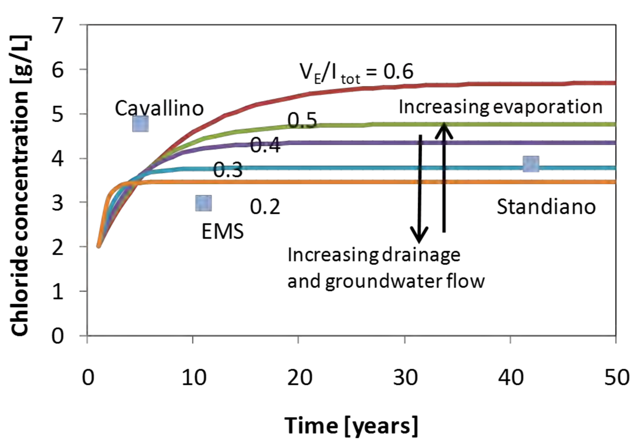
How subsidence and sea level rise influence the water budget and chloride concentration of coastal gravel pit lakes: implications for ecology

P. N. Mollema[1,2] and M. Antonellini[1]

[1]University of Bologna, Italy — [2]TU Delft, The Netherlands)

Keywords: water budget modeling, polder, gravel pit lakes

Land subsidence and sea level rise influence the artificial drainage of coastal low lying basins or polders. As a result, the hydrologic budgets of coastal surface waters including wetlands and gravel pit lakes along the Adriatic Coast (Ravenna) are affected. Groundwater flow into the gravel pit lakes is driven by high evaporation and pumping rates required for drainage. Land subsidence here can be up to 12 mm/year (Regione Emilia-Romagna 2005). Enhanced drainage required in the near future to counteract the hydraulic pressure of sea level rise, will increase the hydraulic gradient towards the lakes. The water of the gravel pit lakes is currently characterized by a high salinity (TDS 5-12 g L-1). We present a water budget model using stable water isotopes as well as Cl as a conservative tracer to simulate various scenarios of increasing evaporation- and pumping rates. The results show that the final Cl concentration in the gravel pit lakes depends strongly on the ratio of evaporation (VE) to the sum of precipitation and ground water inflow (Itot). If the Cl concentration of ground water is lower than that of lake water, the resulting lake Cl concentration will decrease under enhanced drainage while increasing evaporation would at the same time increase Cl concentration. Changing Cl concentrations will strongly affect the ecology of the gravel pit lakes as well as of other surface waters since specific plant and animal communities are tolerant of a small range of salinity.



Modeled chloride concentration in water of the gravel pit lakes as a function of time and different VE/ Itot ratios. Modified from Mollema et al.(2015), doi: 10.1002/lno.10147

Integrated geological approach to coastal subsidence in Emilia-Romagna

L. Perini[1], L. Calabrese[1], P. Luciani[1], and P. Severi[1]

[1]Geological, Seismic and Soil Survey – Emilia-Romagna Region, Italy

Keywords: subsidence, coastal risk, information system

The Emilia-Romagna coastal zone is affected by subsidence phenomena which enhances beach erosion, sea and channels flooding, and contributes to the onset of several risks of this territory. Emilia-Romagna has recently developed a dedicated Information System and monitoring network (called in_Move) in order to collect the available data and create a solid tool for elaborations and specific studies such as analyze the subsidence rate evolution and discriminate both natural and anthropic influences. Data stored are historical and more recent monitoring measurements (levelling, GPS, SAR, settlement gauges log) and they were acquired from regional sources and Oil and Gas companies. The rich dataset allows approaching the study of the subsidence at different scales and considering several drivers. Insights about the contribution of compaction of recent deposits are currently undertaken. The monitoring network has been recently implemented with two settlement gauges respectively at Gorino (Ferrara coastal zone) and Lido di Classe (close to Ravenna); they have the capability of measuring the compaction of Holocene sequence, which is also studied through a geotechnical analysis of more compressible layers. Other topics under development are the relationship between subsidence and the impact of urbanization and the mining history of the gas fields.

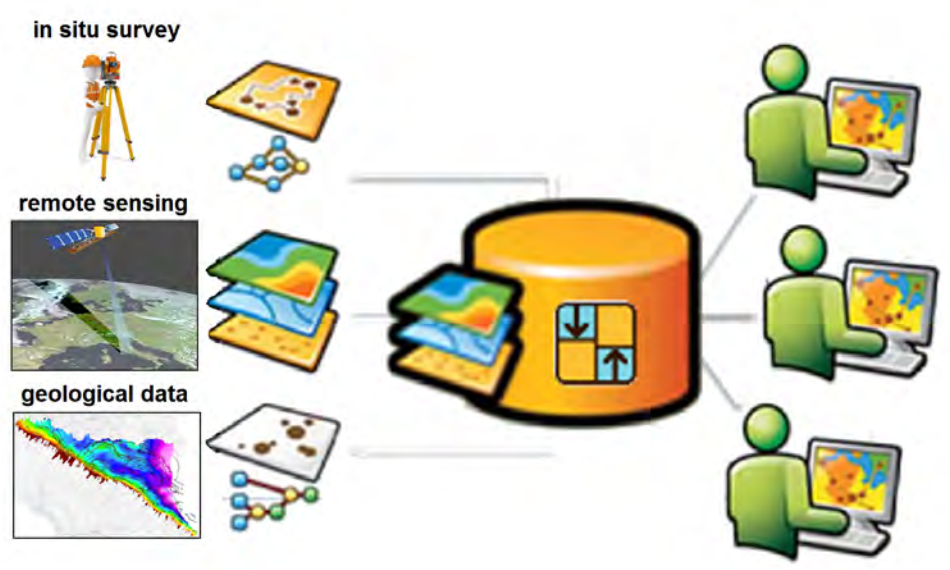


Diagram of the geodatabase in_Move

2nd International Workshop on Coastal Subsidence
May 30 - June 1, 2016 - Venice (Italy)

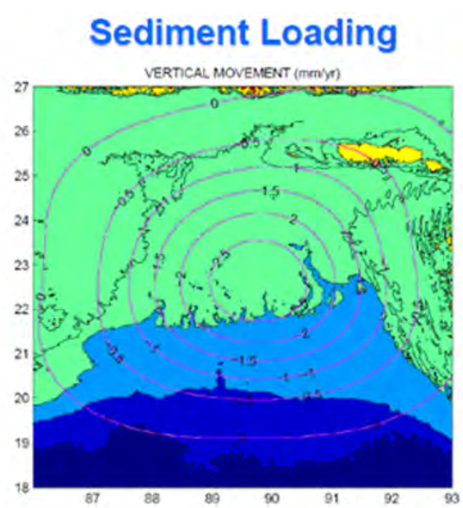
Subsidence of the Ganges-Brahmaputra delta due to Holocene sedimentation

M. Karpytchev[1], Y. Krien[1], V. Ballu[1], M. Becker[1], S. Calmant[2], G. Spada[3], J. Guo[3], Z. Khan[5], and C.K. Shum[4]

[1]CNRS UMR7266 LIENSs - University of La Rochelle, La Rochelle, France — [2]Institut de Recherche pour Développement, Toulouse, France — [3]University of Urbino “Carlo Bo”, Urbino, Italy — [4]School of Earth Sciences, Ohio State University, Columbus, OH, USA — [5]Institute Of Water Modeling, Dhaka, Bangladesh

Keywords: Ganges-Brahmaputra delta, sedimentation, subsidence

The large variability of the subsidence rates in the Ganges-Bangladesh delta estimated from both sediment cores and modern geodetic techniques suggests interplay of different natural and anthropogenic processes including tectonics, sediment loading and sediment compaction, groundwater extraction among many other vertical land movement drivers. In this study, we focus on evaluating the subsidence rates due to sediments transported by the Ganges-Brahmaputra since the last 18000 years. The delta subsidence induced by the sediment loading and the resulting sea level changes are modeled by the TABOO and SELEN software (Spada, 2003; Stocchi and Spada, 2007) in the framework of a gravitationally self-consistent Earth model. The loading history was obtained from the available sediment cores and from the isopach map of Goodbread and Kuehl (2000). The results reveal that the delta loading enhanced by the Holocene sedimentation can be responsible for a regular subsidence across the Ganges-Brahmaputra delta with amplitude of 1-5 mm/yr along the Bengal coast. These estimates demonstrate that the contribution of the Holocene as well as of the modern sediment loading should be taken into account in elaborating the climate change mitigation policy for Bangladesh.



The present-day vertical movements driven by Goodbred-Kuehl (2000) sediment loading

2nd International Workshop on Coastal Subsidence
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Subsidence in the coastal zone of Bangladesh from GPS, tide gauges, and historical sites

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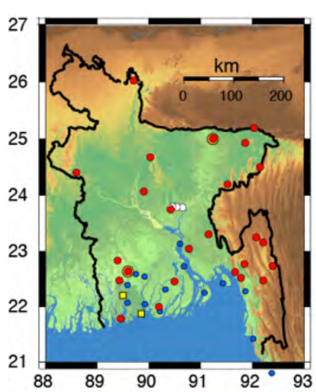
Keywords: Coastal subsidence, GPS, compaction, Ganges-Brahmaputra Delta

In the face of rising sea levels, the balance of land subsidence, sea level rise and sedimentation is critical for low-lying deltaic regions. Deltas commonly experience subsidence due to compaction of their thick sediment accumulations and other processes. Many are susceptible to growth faulting and seaward collapse of the sediment pile on detachment layers (salt and/or shales) leading to even greater subsidence. We present evidence for moderate longer-term subsidence rates and continuing active sedimentation at the Ganges-Brahmaputra Delta in Bangladesh. Subsidence rates are based on continuous GPS, including three new coastal stations established in 2012, hourly tide gauge data for 1977-2012 at 16 sites, two historical sites with ages of 300 years (salt-making kilns) and 400 years (Hindu temple), and sedimentation accumulation rates of near-sea-level deposits from hand-drilled tube wells. Results so far suggest that rates near the sandy Brahmaputra (Lower Meghna) river mouth are subsiding at 3-4 mm/y Historic Sites with timescales of 300-400 y also show rates of 3-4 mm/y. Tide gauges show significant variability in rates that raise questions about their reliability. Higher rates appear to be associated with muddier settings and may reflect near-surface consolidation and organic matter oxidation. Two sets of vertical optical strainmeters record sediment compaction and inform its variation with depth. Sedimentation rates in natural settings are adequate to keep up with subsidence so that areas most at risk are where anthropogenic changes have cut off sediment supply. We hypothesize that the moderate subsidence rate of the delta is due to buttressing of the margin by the continental rise. The slope-rise break is shallow at 1 km water depth due to the high sediment supply feeding the Bengal Fan. Thus the thick wedge of continental rise sediments rise higher than the top of the weak overpressured sediments in the delta that could act as a décollement surface. This prevents the seaward collapse of the delta and associated higher rates of subsidence.



(Left) Map of continuous GPS sites (red), campaign GPS sites (white), tide gauges (blue), historical sites (yellow) and compaction meters (orange) that inform subsidence rates in Bangladesh. (Right) Photo of a GPS antenna in coastal zone

Toward a InSAR continuous monitoring over large areas

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Keywords: InSAR, surface monitoring, subsidence, Sentinel-1

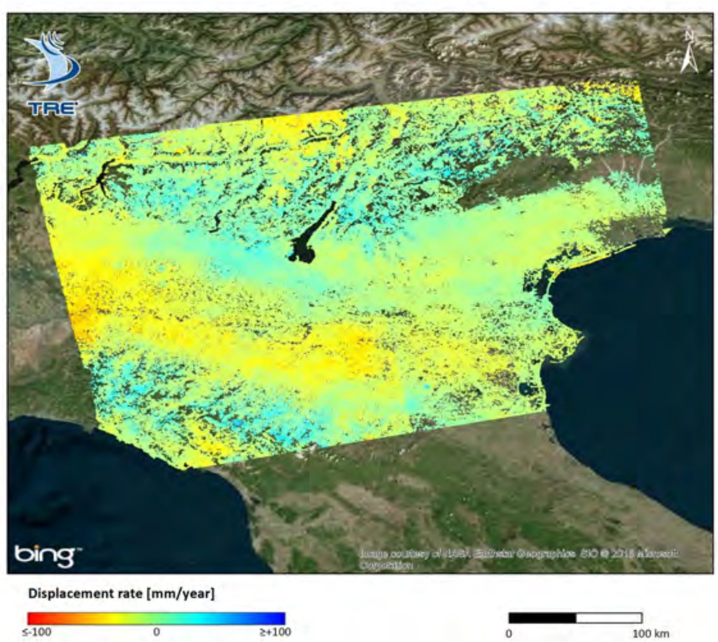
SAR interferometry (InSAR) has widely proven its effectiveness in the analysis of subsidence phenomena based on multi-temporal radar images. Thanks to its capability to detect millimeter level displacements over wide areas, numerous case studies report the integration of advanced InSAR data in coastal subsidence studies and risk assessment.

The challenge for the future is to move from the historical analysis (off-line) of SAR scenes already acquired into a near real-time monitoring program on regional and national scale, where up to date deformation data is routinely provided to final users.

A near-real time InSAR monitoring is now possible thanks to. 1) the recent advances in processing algorithms; 2) the advent of cloud computing; 3) the launch of new satellite platforms.

A great opportunity arises from Sentinel-1A, operating since late 2014 by the ESA. It is the first (civilian) sensor specifically designed for surface deformation monitoring over large areas. The Sentinel-1A regularly acquires over Europe with a repeat cycle of 12 days. It images ares of 250x250 km each, more than double the previous ERS and ENVISAT satellites, and the access to the collected imagery is free.

Homogeneous and reliable InSAR measurements, updated regularly at any new SAR acquisition, can help decision makers in characterizing and addressing areas prone to risk, such as highlighting areas affected by displacement rate variations. In addition, a continuous InSAR monitoring can provide new information to design early warning systems on regional and national scale in synergy with ground-based instruments.



Example of an Advanced InSAR analysis performed over the North Italy using Sentinel-1 data

Impacts of river linking on sediment transport to Indian Deltas

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Keywords: changes in sediment transport, river diversions, Indian deltas

In response to water scarcity and a growing population, the Indian government has begun a project to link India's largest rivers together in the most ambitious water diversion scheme ever proposed. The Indian Rivers Interlink project has been under consideration since 1980, but the plan has new momentum since a 2012 Supreme Court decision ordered the project to move forward. The first link was completed in Sep. 2015, transferring water from the Godavari to the Krishna River. If the interlinking project is fully realized, fourteen canals will ultimately divert water from tributaries of the Ganges and Brahmaputra rivers to areas in the west, where fresh water is needed for irrigation. Additional canals would transport the water more than 1000 km south to the southern tip of the Indian subcontinent. Here, we investigate the impacts of the proposed diversions on water and sediment transport to the Ganges-Brahmaputra, Mahanadi, Godavari, Krishna, and Kaveri river deltas. We map the changing river network and all proposed new nodes and connections. Additionally, we present the cumulative potential impact of the project's new dams on population displacement and forest land. Changes in sediment due to the proposed canals are simulated using HydroTrend, a climate-driven hydrological water balance and transport model that incorporates drainage area, discharge, relief, temperature, basin-average lithology, and anthropogenic influences. Simulated river discharge is validated against current observations from the Central Water Commission of the Government of India. We also quantify changes in contributing areas for the outlets of nine major Indian rivers, showing that more than 50% of the land in India will contribute a portion of its runoff to a new outlet should the entire canal system be constructed.

Summary of proposed link canals and major rivers. From the National Perspective Plan, National Water Development Agency (NWDA), www.nwda.gov.in

Monitoring natural and anthropogenic components of the land movements in Venice by RADARSAT-2 and COSMO-SkyMed

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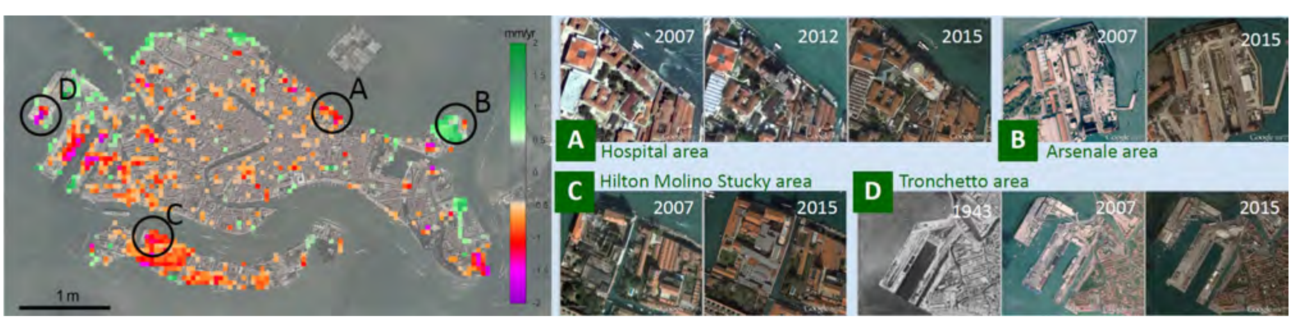
Keywords: RADARSAT-2, COSMO-SkyMed, natural and induced subsidence, Venice

The subsidence of Venice seriously jeopardized the heritage and the safety of the city in relation of its small elevation above the sea. The recent challenge of researches is the quantification of the natural subsidence and the ground movements induced by anthropogenic activities. The former is strictly related to the reference period (i.e. geological- and modern- term) and its quantification was obtained through various methodologies and not uniquely quantified. However, it is much more interesting to evaluate the natural displacement over the last few decades, than that averaged values over geological periods. Although subsidence due to groundwater pumping ceased in the 1970s, others anthropogenic activities such as restoration works for the conservation of the historical palaces and the embankment walls and the waves induced by the boat and ship traffic, potentially induce "local ground movements". This research is aimed at testing the capability of RADARSAT-2 (C-band) and COSMO-SkyMed (X-band) to distinguish between natural and induced ground movements. Preliminary results quantified the present average natural subsidence in 0.9-1.1 mm/yr, however, a certain variability has been detected because of the heterogeneity of the shallow subsoil. The ground movements due to human activities act at very local scale up to 2 mm/yr. About 20-30% of the city has experienced in 2013-2015 some movements due to anthropogenic causes. The calculated average natural subsidence is comparable with a previous study (Tosi et al., 2013, doi:10.1038/srep02710) based on ENVISAT-ASAR and TerraSAR-X images (COA0612©DLR and COA1800©DLR), while average anthropogenic ground movements are underestimated of 30-40%. This is probably due to the limited number of archive images made available from the COSMO-SkyMed/RADARSAT-2 Initiative. This research is ongoing under the umbrella of the RADARSAT-2 and COSMO-SkyMed, Project 2940©ASI and 5266©SOAR and the Flagship Project RITMARE - The Italian Research for the Sea.



Map of the man-induced displacements experienced in 2013-2015 obtained by removing the C-band (RADARSAT-2) interpolated map from the X-band (COSMO-SkyMed) interpolated solution. The insets show some examples of building restoration

Regional and local land subsidence at the Venice coastland by TerraSAR-X PSI

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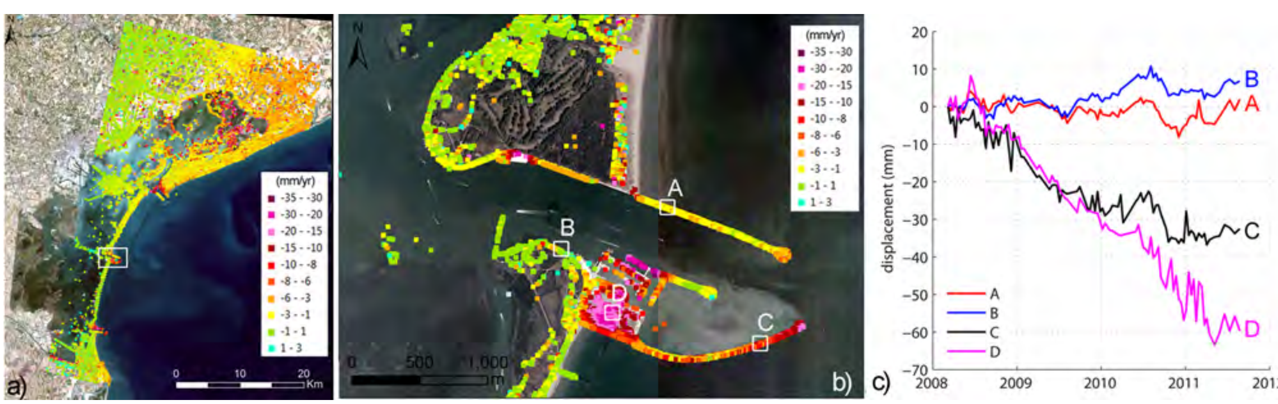
Keywords: TerraSAR-X, Regional and local land subsidence, Venice

Land subsidence occurred over the 2008-2011 period has been investigated by Persistent Scatterer Interferometry (PSI) using a stack of 90 TerraSAR-X stripmap images with a 3-m resolution and a 11-day revisiting time. The regular X-band SAR acquisitions over more than three years coupled with the very-high image resolution has significantly improved the monitoring of ground displacements at regional and local scales, e.g., the whole lagoon respectively the historical palaces, the MoSE large structures under construction at the lagoon inlets to disconnect the lagoon from the Adriatic Sea during high tides, and single small structures scattered within the lagoon environments. Our results show that subsidence is characterized by a certain variability at the regional scale with superposed important local displacements. The movements range from a gentle uplift to subsidence up to 35 mm/yr. For instance, settlements of 30-35 mm/yr have been detected at the three lagoon inlets in correspondence of the MoSE works and local sinking bowls up to 10 mm/yr connected with the construction of new large buildings or restoration works have been measured in the Venice and Chioggia historical centers. Focusing on the city of Venice, the mean subsidence of 1.1 ± 1.0 mm/yr confirms the general stability of the historical center. Data courtesy: (1) TerraSAR-X, Project COA0612©DLR; (2) Flagship Project RITMARE - The Italian Research for the Sea.



Average land displacements (2008-2011) of the Venice coastland (a) and the Malamocco inlet (b) obtained by PSI on TerraSAR-X images. (c) Displacement history of selected scatterers

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Salt marsh behavior in sinking areas of the Venice Lagoon

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Keywords: salt marshes, relative sea-level rise, Venice Lagoon

In the last century, the evolution of the Venice lagoon salt marshes (northwestern Adriatic Sea, Italy) has been largely affected by a complex variety of both natural and anthropogenic processes. As salt marshes grow in intertidal environments, very small changes in sea level can lead to pronounced geomorphological, sedimentological, and ecological modifications. In particular, they survive if they are able to accrete at a rate that produces a surface elevation sufficient to offset relative sea-level rise. In the Venice Lagoon, salt marshes have displayed different behaviors in response to the main local factors and processes. Anyway, the effects of relative sea-level changes have been clearly identified.

Evolution of the northern Venice lagoon salt marshes since the end of the 19th century: (a) historical map realized in the period 1887-1892; (b) recent satellite image (12/07/2015).

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Modelling post-glacial deformations and sea-level along the Mediterranean coasts

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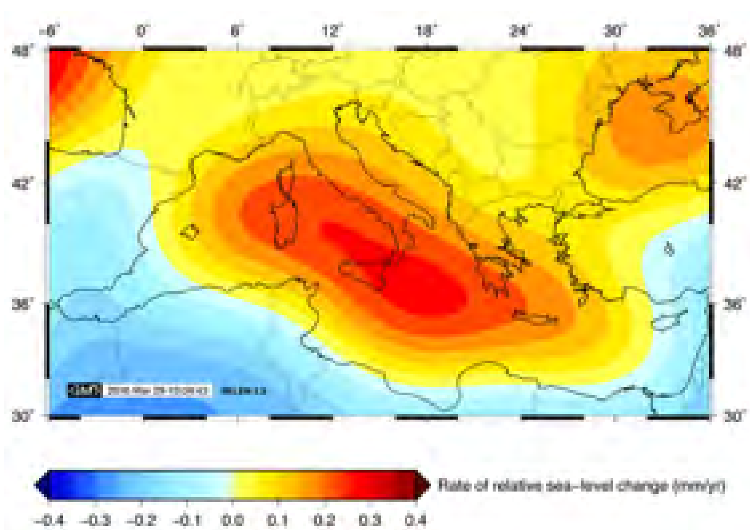
[1]DiSPeA, Urbino University, Italy

Keywords: Sea-level change, Glacial Isostatic Adjustment, Coastal subsidence, Mediterranean Sea

Short and long term sea-level signals are strongly affected, at any spatial scale, by Glacial Isostatic Adjustment (GIA), the response of the Earth to the melting of the late-Pleistocene ice sheets. GIA involves interactions between the solid Earth, the cryosphere and the oceans, driven by deformational, gravitational and rotational effects. The variability of GIA was recognised a long ago on the basis of field evidence and physical modelling, and since its discovery it has ben the subject of considerable attention. Presently, the effects of GIA on sea-level change and geodetic variations can be predicted by using advanced global models, but they cannot easily detected nor disentangled from the other components of observed sea-level change. The contribution of GIA, currently described in terms of sea-level "fingerprints", affects both to the long-term sea-level observations from tide gauges and those from space geodesy, retrieved during the "altimetry era" since the early 90s. The GIA fingerprints have a complex geometry, and show a remarkable variability even in small scale basins in the far field of the regions previously covered by ice sheets. In the Mediterranean Sea, the pattern of the GIA relative sea-level fingerprint is peculiar and presently shows maximum rates in the bulk of the basin (see Figure). At the same time, the rate of absolute sea-level change is fairly uniform across the basin, and a spatially variable subsidence is manifest and strongly anti-correlated with relative sea-level change. Using a multi-scale approach, here I describe the pattern of GIA sea-level change across the Mediterranean Sea at different time scales, and I compare them with simultaneous contributions to sea-level in the same region, also addressing existing uncertainties and open problems.



Rate of present day relative sea-level change expected from GIA across the Mediterranean Sea, based on model ICE-5G(VM2) of Peltier (2004)

Subsidence due to Holocene sediment load in the Ganges-Brahmaputra-Meghna delta: effect of faults

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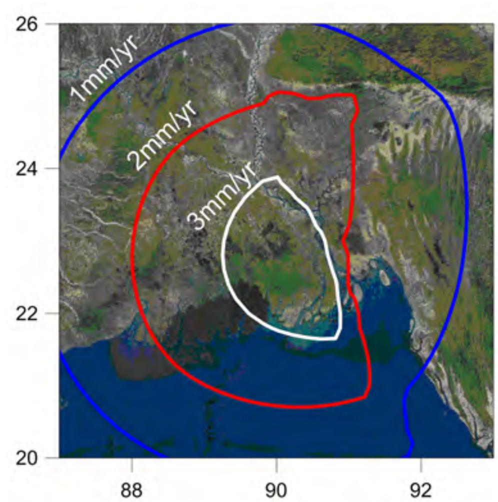
[1]JLEGOS, LIENSS, France — [2]LIENSS, Université de La Rochelle, France — [3]LEGOS, Toulouse, France — [4]Ohio State University, Columbus, USA

Keywords: Ganges-Brahmaputra-Meghna delta, subsidence, sediment load, 3D finite-element model, faults

The Ganges-Brahmaputra-Meghna (henceforth GBM) delta is a highly dynamic and vulnerable environment constituted by a network of interconnected channels exposed to large cyclonic-induced surges causing great loss of life and property. The risk could be magnified in the following decades because of land/ocean relative motions due to sea level rise or subsidence. In the GBM delta, the strong rates of subsidence (higher than 10mm/year in some places) are notably of great concern for large areas located just a few meters above mean sea level. Mechanisms responsible for subsidence are still a subject of debate, but it is widely admitted that tectonic and sediment compaction play a major role. In the framework of the international Band-Aid project funded by the Belmont forum (http://www.belmont-bandaid.org/), a preliminary model showed that subsidence due to Holocene sediment load may also contribute to the observed subsidence rate up to a few millimeters. We built up on this work to investigate the effect of faults represented as weak parts of the lithosphere on the vertical motion pattern. Using 3D-finite element model, we found that subsidence rates due to Holocene sediment load could be enhanced in the central part of the delta by about 1 mm/year.



Actual subsidence rate due to Holocene sediment load in the GBM delta, assuming a 80km-thick lithosphere, radial elastic properties taken from PREM, weak faults, and viscosity of 3.10^{19}, 10^{21} *and* 10^{22} *Pa.s for the asthenosphere, transition zone, and lower mantle respectively*

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Coastal and see level changes detected from InSAR and ground based measurements: analysis of potential drivers and future scenarios

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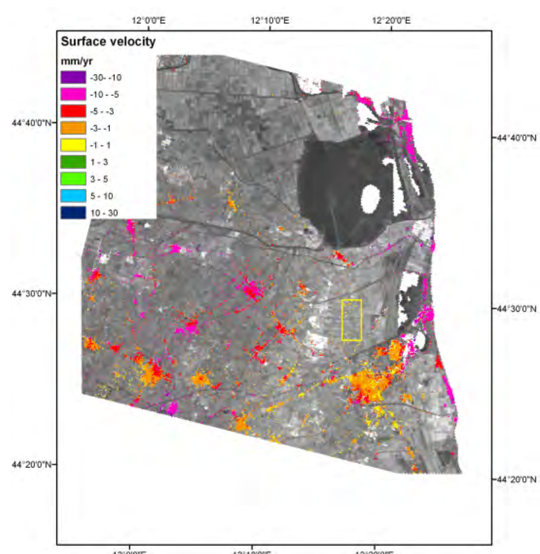
[1]Istituto Nazionale di Geofisica e Vulcanologia, Italy

Keywords: Sea level rise, Coastal Subsidence, InSAR

Coastal areas in the Mediterranean are densely inhabited and several infrastructures have been there established. In the last decades these areas suffer from the combined effect of sea level rise and land subsidence, that can be observed by tide gauges, GPS and InSAR observations. The former is caused by global changes and fostering critical effects in terms of coastal erosion, marine flooding, etc.. On the other side coastal subsidence or uplift is generally ascribable to natural or anthropogenic causes that can be deeply investigated in order to complete the analysis as well as to provide reliable scenarios of coastal retreat and flooding at medium-to-long term. To such aim, we propose the following case studies each one characterized by a different cause of relative sea level change and by a specific investigation technique based on GPS, InSAR and tidal data: 1- Venice Lagoon; 2- Ravenna coastline; 3- Fiumicino (Central Italy) subsidence. Finally, we analyzed the longest time series of sea level data collected at four tide gauge stations located in the Central-Northern Mediterranean Sea. Through the Empirical Mode Decomposition a simple model was built up to estimate sea levels and variabilities up to year 2100 for this region. These latter have been estimated for two different scenarios: i) global trend projected by the IPCC AR5 (2014) and ii) the Veermer and Rahmstorf (2009) dual model. For the most severe scenario, our analysis indicate a mean sea level rise of 131.1±7.0 cm by 2100, thus providing crucial information for this region that is prone to sea flooding, being characterized by coastal plains, lagoons and mouth of rivers.



Subsidence rate estimated from InSAR technique in the coastal area of Ravenna.

Differential subsidence due to peat compaction in Holocene coastal deltas

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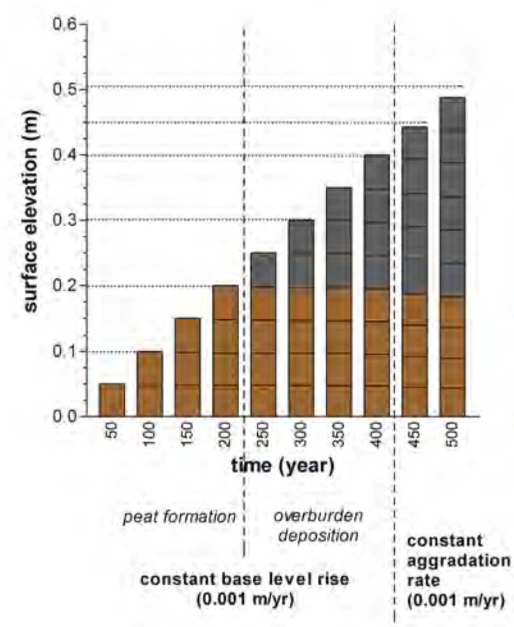
[1]Utrecht University

Keywords: subsidence, peat compaction, subsurface lithological composition, delta

Many Holocene coastal deltas comprise substantial amounts of peat, which is most compressible of all natural soils. In these organo-clastic deltas, that are often densely populated, natural and human-induced compaction of peat soils may cause substantial land subsidence. An extensive field-based research in the Rhine-Meuse delta (NL), Cumberland Marshes (CA) and Biebrza National Park (PL) showed that the amount and rate of subsidence due to peat compaction in deltaic settings are highly variable in time and space, and may be in the order of meters (amount; timescale 102-103) and cm/yr (rate; timescale 100-102). Key factors influencing this variability are the (1) effective stress, which is a function of the weight of the overburden and pore water pressure, (2) thickness of the peat layer, (3) organic-matter content of peat, and (4) occurrence of intercalated clastic layers. Groundwater table lowering may cause substantial additional subsidence due to oxidation of peat above the groundwater table. The collected field data has been used to develop and calibrate a peat compaction model, which can be used to predict subsidence due to peat compaction in different Holocene deltaic settings. The commonly heterogenic composition of deltaic sequences affects the present and future potential of subsidence due to peat compaction in deltas, and thus is important information for subsidence mitigation and management strategies.



Schematic representation of the peat compaction model. In this example, initially a peat sequence builds up (brown), followed by clay deposition (green). Accommodation space created by peat compaction and base level rise is completely filled each time step. During the final two time steps, aggradation is insufficient to keep up with base level rise, which illustrates a situation of reduced sedimentation in a delta, for example due to upstream damming, resulting in relative land subsidence

Evidence of 3-D coastal subsidence

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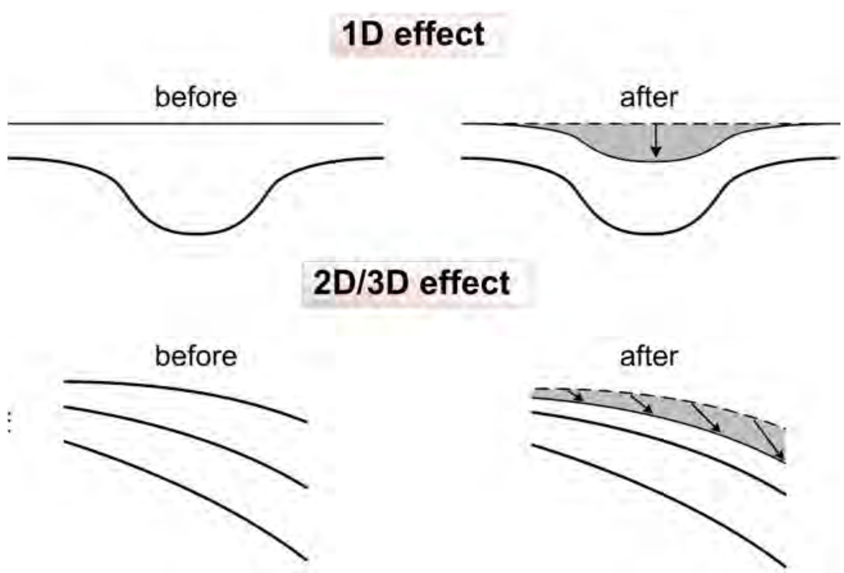
Keywords: GPS/INSAR, delta flow, non-elastic deformation

Apart from coastal land subsidence due to the global sea level rise, land subsidence is usually regarded as an essentially elastic effect due to geotechnical (near surface) processes and of geophysical (deep, seismic/tectonic, volcanic, etc.) processes. This corresponds to an essentially 1-D effect, although minor contraction due to differential compaction of sediments because of fluid extraction has been occasionally noticed.

However, evidence from certain areas provide evidence of two other causes of land subsidence. First, consolidation of sediments due to decay of their organic content, leading to non-elastic (permanent) ground deformation. Such effects are usually due to lowering of the aquifer as a result of over-pumping or poor feeding of deltas due to their partial abandonment; the latter can be due to natural processes or to engineering interventions and can also be described as a 1-D effect. Second, flow of masses of unconsolidated sediments towards depocenters, as high viscous fluids, usually above detachments. This is an effect noticed both for dry land and coastal areas, and in past, in some areas it has been assigned to tectonic/seismic effects. Such flows may also explain growth folds in deltas. An analogue can provide creeping landslides, the movement of which was derived by geodetic data and are characterized by extensional fissures because of their high content in course sediments. In coastal areas, on the contrary, with finer sediments prevailing and the aquifer at high levels, deformation is essential plastic and continuous. Growing evidence of this effect tend to provide GPS and eventually INSAR data from major and minor deltas.



Sketches of the proposed mechanisms of land subsidence in coastal areas.

Land subsidence monitoring and mechanism research over the Yellow River Delta, China

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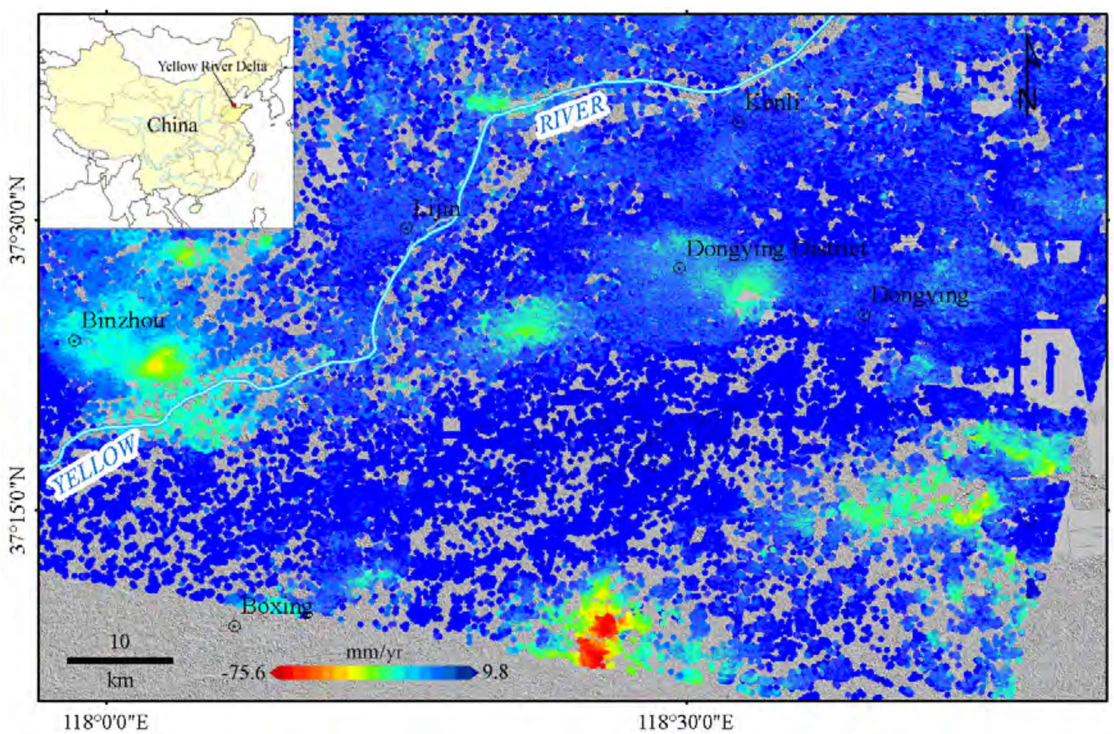
[1]Institute of Oceanology, Chinese Academy of Sciences, P.R. China

Keywords: deltaic subsidence, SBAS InSAR, groundwater

The Yellow River Delta, the largest and most rapidly growing delta in China, has been subsiding due to the combination effects of human and natural factors. Increasing anthropogenic activities, such as groundwater exploitation accelerate the subsidence, increasing vulnerability for natural hazards. However, little was known about the full spatial-temporal evolution of the subsidence and its primary causes. Here, the land subsidence pattern and causes are systematically characterized using Envisat/ASAR and corresponding groundwater data. The small baseline subset (SBAS) InSAR method is applied to retrieve time-series deformation and the full land subsidence pattern in the Yellow River Delta. The major subsidence regions, which have a maximum subsidence rate ranging from 20 to more than 70 mm/yr, cover a total of approximately 800 km^2, and are mainly concentrated in the groundwater source areas. An intimate connection of surface deformation with groundwater suggests that land subsidence is primarily caused by excessive exploitation of groundwater. Meanwhile, the seasonal land subsidence correlates with the rainfall rate. These findings not only provide new insights into subsidence mechanism, but enrich the theories disaster reduction system in the Yellow River Delta. A key policy priority should therefore be to plan for controlling anthropogenic activities and better management of groundwater.



Mean displacement velocity field of the Yellow River Delta

Multi-sensors Advanced DInSAR analysis of the land subsidence pattern from 1992 to 2016 in the Ravenna area (Italy)

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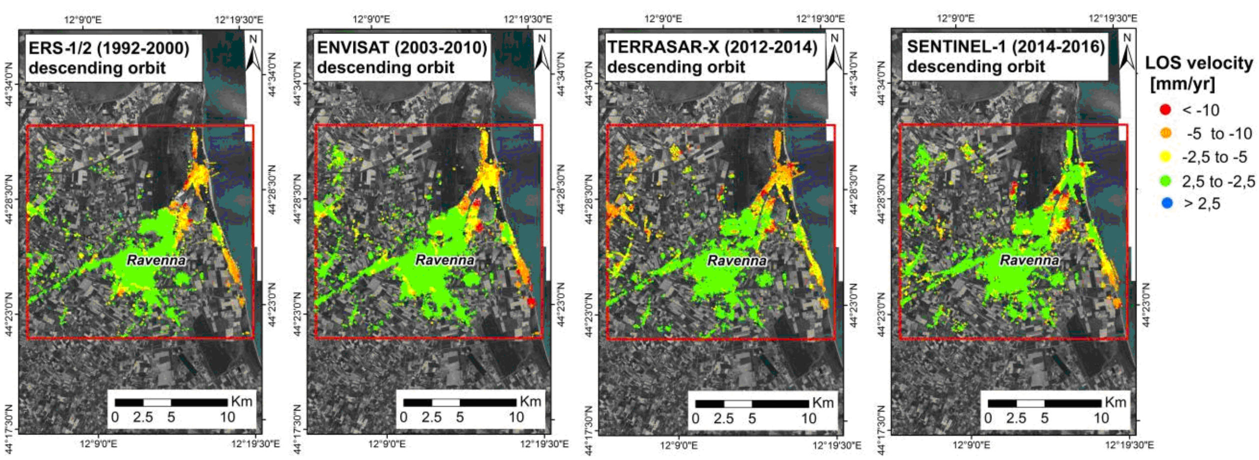
Keywords: A-DInSAR, land subsidence, Ravenna

Recent advances in satellite radar differential interferometry (DInSAR), have created new demands for more efficient methodologies aimed to analyse large datasets which consist of huge amounts of measuring points with high temporal resolution. In this work, a methodology is proposed to analyse multi-sensor A-DInSAR data, and to characterize the spatio-temporal evolution of the land subsidence affecting the coastal area of the Ravenna Municipality (NE of Italy). This methodology was applied to a set of SAR images acquired by C- band (ERS-1/2, ENVISAT and Sentinel-1) and X-band (TerraSAR-X) sensors, processed using the SBAS technique in order to estimate the land subsidence pattern in the study area for the period 1992-2016.



LOS velocity over the study area (red square) onto the Ortophoto AGEA 2011 (http://geoportale.regione.emilia-romagna.it/). ERS-1/2, ENVISAT and Sentinel-1 images were provided by ESA (respectively, CAT-1 Project: 14280 and free-downloadable) and TerraSAR-X images by DLR (Proposal GEO2478 and GEO3016)

Surface displacement estimation through the P-SBAS automatic chain on the ESAs Grid Processing on Demand (G-POD) web

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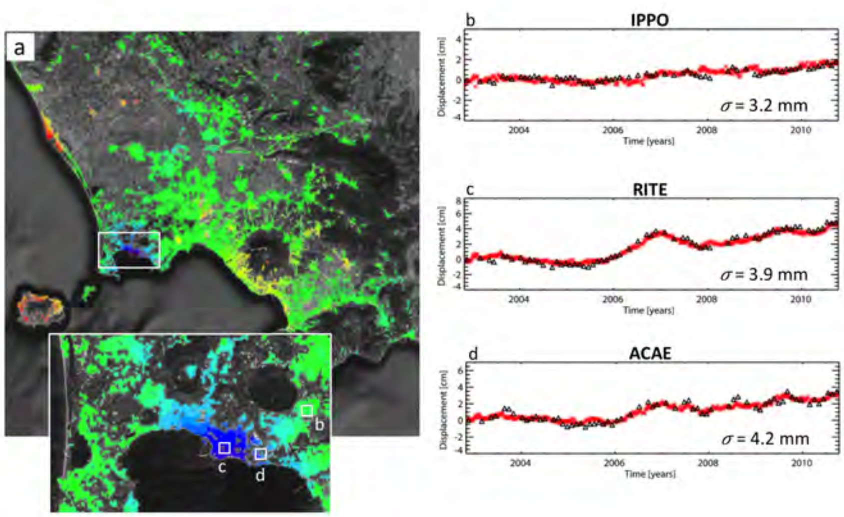
Keywords: DInSAR, P-SBAS, G-POD

The current EO scenario is characterized by a huge availability of Synthetic Aperture Radar data that have been acquired during the last 25 years by past and present sensors. Moreover, among the SAR data exploitation methodologies, we focus on the well known DInSAR algorithm Small BAseline Subset (SBAS), which is able to generate mean deformation velocity maps and displacement time series from multi-temporal SAR datasets; it is, besides, capable to perform analyses at different spatial scales and with multi-sensor data. Recently, an advanced algorithmic parallel computing solution, referred to as P-SBAS, that encompasses diverse parallelization strategies, has been developed. P-SBAS implements the whole SBAS processing chain, in a totally automatic way. Such an unsupervised implementation, besides, has been designed to effectively exploit High Performance Computing (HPC) and distributed computing infrastructure (cluster, grid, or cloud computing platforms). The P-SBAS algorithm has been already deployed within the ESA's Grid Processing on Demand (G-POD) and is fully accessible from the GEP. G-POD benefits from the access to the large ESA computing and provides a friendly web user interface that permits to set up an efficient and on-demand P-SBAS processing web tool addressed to scientists that are not expert on interferometric SAR data processing.



Unsupervised P-SBAS processing chain validation experiments on the Campi Flegrei caldera (Napoli) test site. The three plots show the very good agreement between SBAS-DInSAR (black) and GPS (red) measurements

Flooding projections from elevation and subsidence models for the Rajang Delta peatlands, Malaysia

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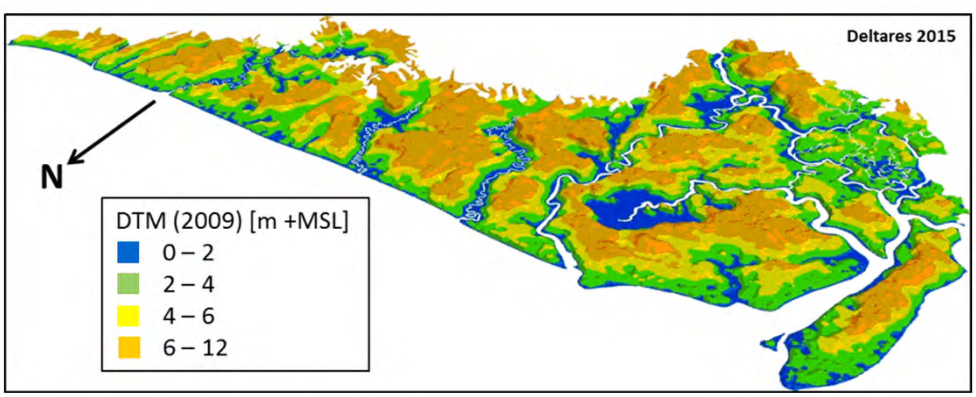
Keywords: peatland, elevation model, subsidence, flooding

Peat swamp forests in SE Asia have been subject to rapid conversion to drained land-uses, especially oil palm and *A*cacia plantations. As peatland is not really "land" in the common sense but an unstable mix of water (over 90 %) and organic matter from partly decomposed plant material, peatland drainage for agriculture inevitably leads to rapid land surface subsidence and carbon loss. From experience in Europe and the USA, we know that inundation and loss of agricultural production is to be expected in such areas. We have investigated at what rate the process of steadily increasing flood risk following peatland drainage proceeds in 850,000 hectares of peatland in the Rajang Delta of Sarawak, Malaysia. Here, the area of swamp forest decreased from 56% to less than 16% between 2000 and 2014. The remaining area is mostly oil palm plantation; the entire area may now be considered drained. An elevation model for the area was constructed from airborne IFSAR data collected in 2009 by filtering out vegetation and canal effects. Elevations corresponding to thresholds for drainability and flooding were defined following earlier assessments of the area. A subsidence rate of 3.5 cm per year was applied, in line with the latest science and with IPCC and FAO estimates of carbon emissions from such drained peatlands. Model results suggest that in 2009, 29% of existing plantations suffered from reduced drainability. Assuming no further oil palm expansion beyond 2014 in the area, we find that 42% of current industrial plantations will experience problems associated with reduced drainability by 2034, 56% by 2059 and 82% by 2109. For areas that are frequently flooded with river water, where the peat surface has subsided to below the High Water Level, the corresponding figures are 18% by 2009, 27% by 2034, 39% by 2059 and 64% by 2109. These areas are likely to experience considerably reduced productivity associated with first groundwater table depths less than those that are optimal for crop growth, and eventually floods. It is expected that agricultural production will be lost long before flooding becomes near-permanent. Eventually, nearly all peatland in the area is expected to be lost for production, much of it within decades and most within the next 100 years. For full report, see: https://www.deltares.nl/en/projects/flooding-projections-for-oil-palm-plantations-in-the-rajang-delta-peatlands-sarawak-malaysia/



Elevation model of peatland in the Rajang Sarawak River Delta, Malaysia, 2009

Shallow subsidence and sediment accretion in the Ganges-Brahmaputra natural and poldered regions

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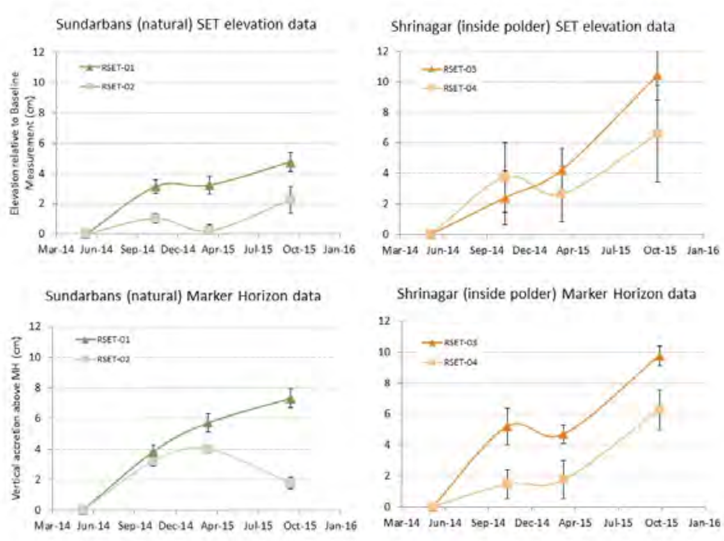
Keywords: elevation dynamics, sedimentation, shallow subsidence, Ganges-Brahmaputra delta

In the Ganges Brahmaputra tidal deltaplain, century-scale relative sea-level rise obtained from tide gauges is on the order of 4-6 mm/yr, however the natural mangrove forest (the Sundarbans) appears to be in equilibrium with hydroperiod and sediment supply conditions. In contrast, the extensive coastal embankment system (i.e., polders) has greatly reduced the regional tidal prism, led to an expansion of the tidal range by as much as 1 meter, and altered sediment distribution patterns. As a result, elevation loss due to sediment preclusion and accelerated subsidence severely increases the risk of coastal communities to storm surge or even regular tidal flooding. An array of Surface Elevation Tables (SETs) and corresponding marker horizons record elevation change and vertical accretion within both the Sundarbans and an adjacent polder. While results are preliminary (SETs installed Fall 2013), elevation gain within the polder area where some tidal exchange has been restored appears to be greater than within the natural forest (see Fig below), presumably due to the elevation deficit and greater hydroperiods. Vertical accretion within the Sundarbans is predominantly mineralogenic soil, as during the winter/dry season months the shallow groundwater table lowers, possibly oxidizing the subsurface and preventing substantial peat formation.



Elevation change (top) and vertical accretion (bottom) in the natural Sundarbans mangrove forest (left) and a rice paddy within polder #32 where seasonal tidal exchange has been restored (right)

Dealing with subsidence in the Dutch delta: do current management strategies fit todays challenge of mitigating subsidence?

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Keywords: delta subsidence, integrated subsidence management

In many deltas worldwide subsidence still is an underestimated problem, although, especially in urbanizing deltas, the consequences start to become noticeable at an accelerated rate. Subsidence is driven by multiple causes like *human-induced* extraction of hydrocarbons and groundwater, drainage of phreatic groundwater, and loading by buildings and infrastructure and *natural* tectonics and loading by sediments and water (e.g. Syvitski et al., 2009, Tosi et al., 2009, 2013, Stouthamer et al., 2015). The exact contribution of the different drivers to total subsidence spatially differs within a delta and also between deltas. To mitigate subsidence and its negative impacts requires the understanding of the relative contribution of the drivers to total subsidence, and good predictions of the subsidence potential of the subsurface under different management scenarios and its impacts. This knowledge enables the development of sustainable management strategies dealing with subsidence, ensuring future delta life. However, the knowledge on the quantitative contribution of the multiple drivers of subsidence is often lacking as well as a sustainable management strategy to deal with subsidence. Two reasons for this lacking management strategies are 1. that there is not a single problem owner or organized group of problem owners of subsidence, which makes it difficult to recognize this as a common societal issue and to develop and implement management strategies to mitigate subsidence, and related to this 2. it requires an integrated approach involving technical knowledge on the contributors to subsidence, water management, governance, legislation, socio-economic developments and spatial planning. In our presentation we show the drivers of subsidence in the central part of the Rhine-Meuse delta, its impacts (see Figure) and how this is currently dealt with and we discuss the current management approach and how management strategies could be optimized.

Subsiding peat area in the western part of the Netherlands. A. Rural area (photo: Berendsen). B. Historic city centre of Gouda with water levels that cannot be further lowered without causing oxidation of wooden foundation poles (photo: Erkens)

Global estimates of the effects of subsidence on coastal flood risk

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Keywords: coastal flood, broad-scale assessment, population, asset damage

It is widely recognised in multiple studies that climate-induced sea-level rise is raising extreme water levels around the world's coast and this will accelerate in the coming decades. In turn, this will lead to an increase in coastal flood risk, unless there is corresponding adaptation. In addition to this effect there are also important geological effects that are causing relative sea-level rise such as tectonics, neotectonics, and glacial-isostatic adjustment (GIA). As global models are available, GIA is often considered in global analyses, but other sources of land elevation change are ignored, and implicitly seen as a local problem. One of the biggest sources of geologically-induced sea-level rise is human-induced subsidence due to groundwater pumping and drainage of organic soils, compounded by the exclusion of sedimentary processes. As Syvitski et al (2009) among others has demonstrated, these effects are marked in many of the world's populous deltas, while the effects are even larger in many coastal cities on deltas. A number of cities have subsided several metres over large areas during the 20th Century. Well know examples include Tokyo, Shanghai and Bangkok, with Jakarta currently subsiding at alarming rates (Nicholls, 2014). Further subsidence is emerging as an issue in other expanding coastal cities. Using the available global estimates of such subsidence, the Dynamic Interactive Vulnerability Assessment (DIVA) model is used to assess the current and potential role of human-induced subsidence in enhancing coastal flooding in comparison to climate-induced effects. The methods that are employed have been described by Hinkel et al (2014). The analysis will include consideration of indicators based on coastal risk (exposed population and expected annual damage) as well potential adaptation results to counter the predicted flooding. Hence the relative role of subsidence will be evaluated in relation to climate-induced sea-level rise.

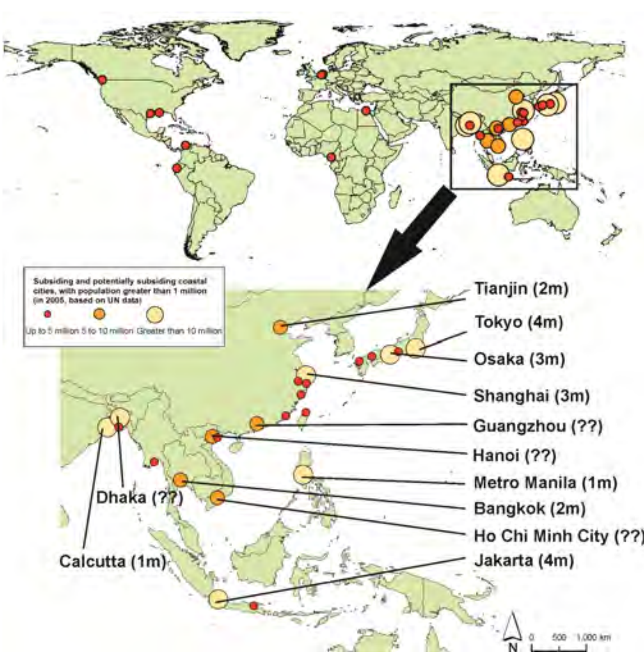

Figure 1: *Subsiding and potentially subsiding coastal cities (taken from Nicholls, 2014). The maximum observed subsidence (in metres) is shown for cities with populations exceeding 5 million people, where known. The maximum subsidence is reported as data on average subsidence is not available.*

Hinkel, J., Lincke, D., Vafeidis, A.T., Perrette, M., Nicholls, R.J., Tol, R.S.J., Marzeion, B., Fettweis, X., Ionescu, C. and Levermann, A. (2014) Coastal flood damage and adaptation costs under 21st century sea-level rise. Proceedings of the National Academy of Sciences (doi:10.1073/pnas.1222469111).
Nicholls, R.J. 2014. Adapting to sea level rise. In Ellis, J.T. and Sherman, D.J. (eds.) Coastal and Marine Hazards, Risks and Disasters, Elsevier, London, pp. 243-270.
Syvitski J.P.M., Kettner A.J., Hannon M.T, Hutton EW.H., Overeem I, Brakenridge G.R, Day J, Vörösmarty C, Saito Y., Giosan L, Nicholls R. J., (2009). "Sinking Deltas". Nature Geoscience, 2, 681-689.

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Influence of mechanical compaction and biodegradation on salt-marsh sediment and relative sea-level change

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Keywords: salt marsh, compaction, biodegradation, post-depositional lowering, basal peat

Compaction is a significant driver of land subsidence in some coastal locations, contributing to long-term, ongoing relative sea-level rise and capable of causing rapid, widespread coastal submergence. As such, projecting rates of compaction-driven subsidence into the future is an important scientific goal. This can be done using numerical models that describe compaction and its effects on coastal stratigraphies and surface elevation. However, the accuracy of numerical models is critically dependent on a robust understanding of the compaction processes in operation. Many compaction models consider mechanical compression processes only, rarely incorporating the potentially significant effects of biodegredation processes on volume changes in organic strata; these processes are poorly constrained. To address this, we consider the stratigraphic record, which can provide considerable insight into the rate and magnitude of biodegradation processes over decadal to millennial timescales. We compare and contrast two late Holocene relative sea-level reconstructions obtained from salt-marsh deposits at East River, Connecticut, USA. The first reconstruction is compaction-free, obtained from basal peat deposits overlying an incompressible basement. The second reconstruction was obtained from a compaction-prone sediment core from the same location. The observed differences between the records can feasibly only be attributed to sediment compaction. We demonstrate that mechanical compression alone cannot explain the observed offset. Through simulation of biodegradation- and bioturbation-induced softening of core sediments, the accuracy of our compaction model is greatly improved, accounting for the offset between records. Our study illustrates the significance of syn- and post-depositional alteration of biogenic strata in driving compaction, subsidence and relative sea-level changes.

East River Marsh, Long Island Sound, Connecticut, USA

Shallow subsurface process controls on wetland elevation and relative sea-level rise rates

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Keywords: shallow subsidence, shallow expansion, wetland relative sea-level rise

The importance of shallow (< 25 m) land subsidence processes in coastal wetland substrates was first described quantitatively by Kaye and Barghoorn (1964) more than 50 years ago. The Rod Surface Elevation Table (RSET) device (Cahoon et al. 2002) measures wetland elevation change with a millimeter scale of resolution for the top 25 meters of the wetland substrate. These wetland elevation change measures (VLMw) are independent of and complement measures of land subsidence (VLMc) derived from the tide gauge benchmark network located on uplands near a tide gauge (see Figure). A large majority of coastal wetlands instrumented with RSET devices exhibit dynamic surface elevation change up to 20 mm/y, both positive and negative, not recorded at tide gauges. To better estimate wetland submergence potential, relative sea-level rise (RSLR) must be calculated at the local wetland by subtracting the wetland elevation trend from the nearby tide gauge RSLR trend, the term for which is wetland RSLR (RSLRwet). A review of 89 wetlands reveals that 39% experienced an elevation rate surplus and 58% an elevation rate deficit (e.g., sea level becoming lower and higher, respectively, relative to the wetland surface). When RSET data are combined with surface accretion measures from marker horizons (MH), shallow subsurface process controls on wetland elevation can be distinguished from surface sediment deposition and erosion. Subsurface process controls include a) root zone expansion from increased root volume, b) root zone collapse from reduced root production, increased decomposition of roots, and loss of root volume, c) shrink-swell related to ground-water level changes, and d) compaction. Environmental drivers influencing shallow subsidence processes include storms, plant herbivory, fire, drought, river stage, tides, elevated atmospheric CO_2 concentrations, and nutrient enrichment. Thus wetland elevation trends and shallow subsidence-expansion processes exert critical influence on wetland sustainability to sea-level rise.

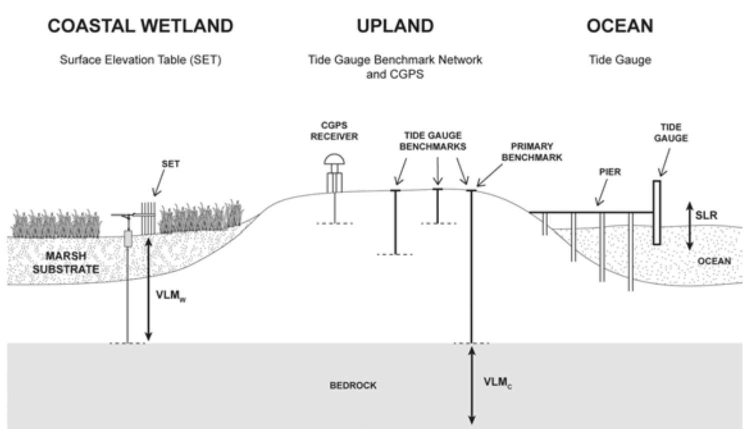

Diagram showing the relationship among vertical land motion recorded by a tide gauge bench mark network on upland (VLMc) and the rod surface elevation table (RSET) method in a wetland (VLMw) [from Cahoon 2015]

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Holocene subsidence history in the Ganges Brahmaputra Delta

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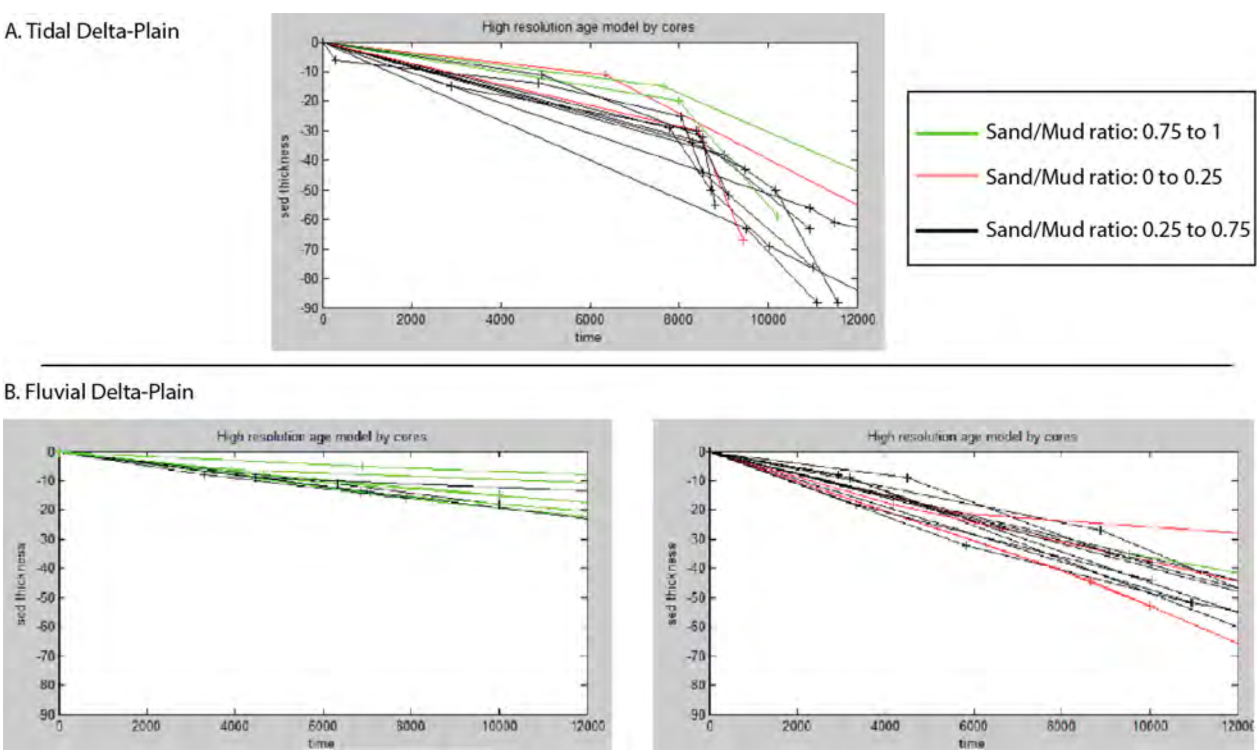
Keywords: Holocene subsidence, sand vs. mud ratio, Holocene sea-level rise

Over 182 radiocarbon ages combined to constraints on the Holocene/Pleistocene transition allow us to provide age-model of sediment accumulation over 92 sites. Also, seismic reflection data collected along the Meghna and the Brahmaputra-Jamuna valleys gives insights about the regional trend of sediment accumulation. Most of the sites in the Fluvial Delta Plain do not display strong contrast between the early high sea-level rise period and the late slow sea-level rise history. In contrast, the sea-level history appears to strongly modulate the sediment accumulation in the tidal delta-plain, while the sediment accumulation is much higher during the early than the late Holocene. Over Holocene sediment sections here analyzed, we distinguished sites by the sand vs. mud ratio, and shows that the sediment accumulation is consistently most of twice higher within channel than within the alluvial plain. We wonder if this difference accounts only from the differential between sand and mud of grain rearrangement in the near surface, or if it can also be the result of channel cut effect.



Sediment accumulation in the tidal Delta Plain (A) and in the Fluvial Delta Plain (B). Three categories regarding the Sand/Mud ratio are here considered: 1. sand dominated (in red); 2. Mud dominated (in green) and 3. Mixed (in black). Sediment thicknesses are in meters

Managing subsidence of the Wadden Sea tidal flat area due to gas production: a probabilistic approach

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[1]TNO-Geological Survey of the Netherlands

Keywords: subsidence, gas production

Sea bed subsidence and sea level rise co-exist in many coastal areas, potentially giving rise to changes in the natural habitat. One of these cases is the Wadden Sea which is a shallow tidal sea behind a chain of coastal barrier islands situated in the north of the Netherlands. In this area gas is being extracted from gas fields below the Wadden Sea (see figure below). Gas pressure depletion causes compaction in the reservoir, that manifests itself as sea bed subsidence.

The Wadden sea has been on UNESCO's World Heritage list since 2009 because of its unique morphodynamic features and wildlife habitat. Due to the sensitive nature of the Wadden Sea, the gas fields below it are produced within the so-called "effective subsidence capacity". The effective subsidence capacity is defined as the maximum volume rate of relative subsidence available for (planning of) human activities. The relative sea level rise and the combined effect of the sea level rise and the subsidence due to gas production, has to be compensated by the natural sedimentation in order to prevent drowning of the shallow sea.

The probability that the effective subsidence capacity would be exceeded was calculated for the tidal basins of Pinkegat and Zoutkamperlaag in the Wadden Sea. For the period up to 2012, the possible exceedance of the effective subsidence capacity was first tested in a deterministic way. In this test it was concluded that the effective subsidence capacity was not exceeded in this period. The test, however, did not take into account the parameter uncertainties. Therefore, for the period from 2012 to 2050, the probability of exceeding the effective subsidence capacity was determined at 2.8% for the tidal basin of Zoutkamperlaag and 1% for the tidal basin of Pinkegat. Relative sea level rise dominates these numbers and subsidence due to gas depletion only plays a minor role.

The tidal basins of Pinkegat and Zoutkamperlaag as well as the gas fields (in green) from left to right Ameland, Nes, Metslawier, Moddergat, Anjum, Ezumazijl, Lauwersoog-Oost, -Centraal en –West, and Vierhuizen

Coastal GPS vertical velocity field available from SONEL (www.sonel.org) data assembly center

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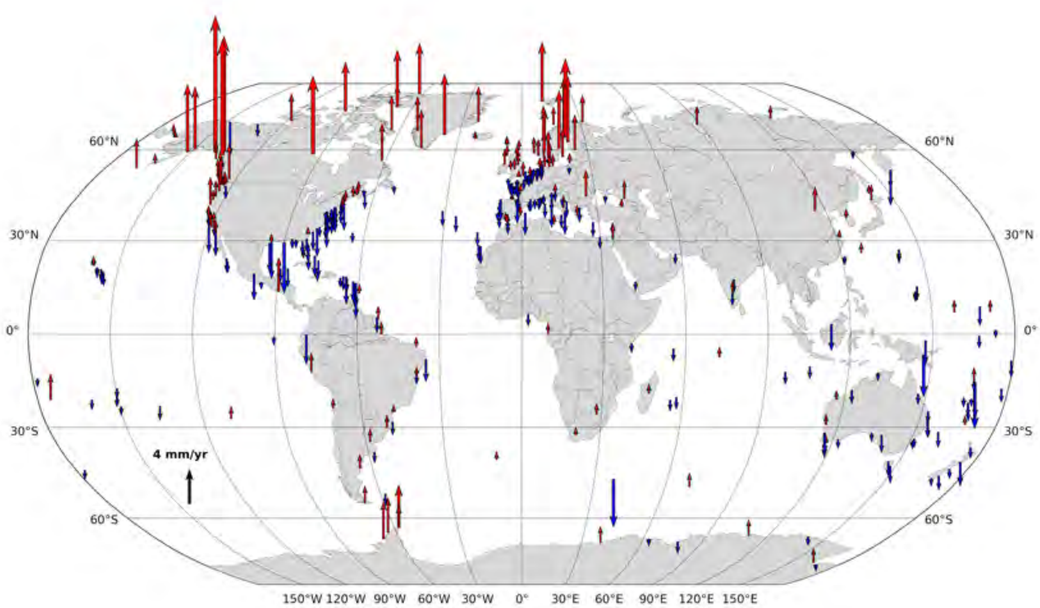
Keywords: GPS, tide gauges, SONEL

In 2012, the Global sea level observing system (GLOSS) program of the Intergovernmental Oceanographic Commission (IOC) of UNESCO called for the important upgrade of its core network of tide gauges with continuous GPS (GNSS) stations, and that their observations be provided to its dedicated data assembly center (SONEL; www.sonel.org), so that the observations and generated products be *public and free to anyone in line with the IOC/UNESCO oceanographic data exchange policy.* The latest coastal GPS vertical velocity field available from SONEL will be presented. It was produced by the University of La Rochelle (ULR) within the second reprocessing campaign of the International GNSS Service (IGS). This velocity field comprises 391 GPS stations (see Figure) for which the entire dataset of measurements available between 1995.0 and 2014.0 was reprocessed using the most up-to-date models and corrections available. Note that not all the stations cover that period of 1995 to 2014. A minimum of three continuous years without a discontinuity (e.g., due to an equipment change or an earthquake) in the time series were required to estimate a "robust" vertical velocity. This duration is the minimum to limit introducing biases from the seasonal cycles. The median formal uncertainty on the estimated vertical velocities is about 0.4 mm/year. Here, we will show its main characteristics and its possible application for long term sea level studies while outlining its limitations.



Vertical velocity field from GPS data analysis over 1995.0 to 2014.0 in the ITRF2014

Surveying techniques and their evolution for subsidence monitoring

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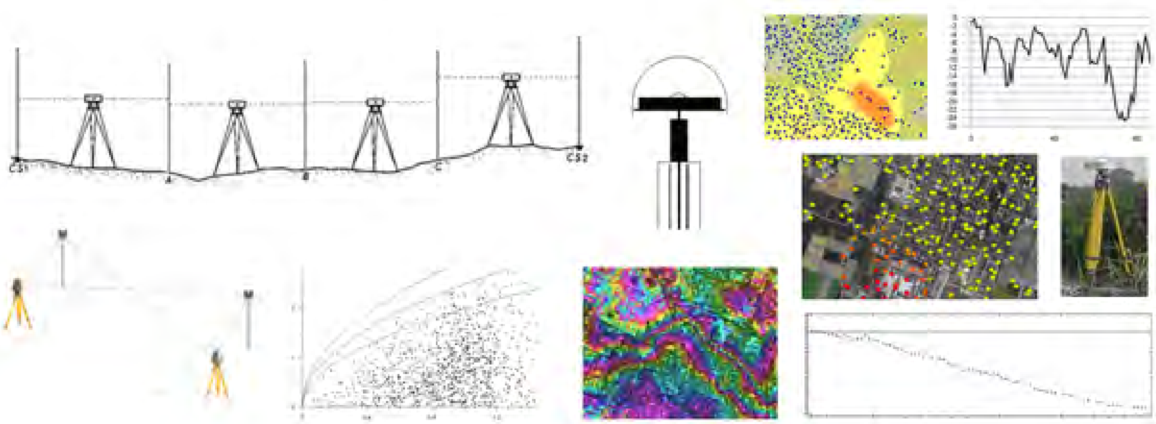
Keywords: subsidence, surveying, geomatics, remote sensing

The geometrical monitoring of subsidence for coastal and inner areas has been carried out in the last decades by different techniques and methodologies, starting from the traditional topographic methods to the currents advanced approaches offered by Remote Sensing and by the integration of different geomatic methods. Aim of the work is to present a review of the different methodologies applied, involving geodetic/trigonometric levelling, GNSS in various configurations, interferometric analysis of radar imagery. Different case studies will be used to discuss their characteristics following several aspects: accuracy and precision, issues related to the link of relative measurements to terrestrial reference frames and to velocities datums, questions about absolute and relative monitoring, data management by specific databases, interoperability, standardization procedures for surveying and data processing, quality evaluation and testing, efficiency and rapidity in data acquisition and data handling, information spatial density and interpolation issues, time series analysis and homogenization with historical data, logistic and economic requirements and constraints, skills involved at different levels, etc. A correct integration of different techniques can be today envisaged, with development of common well established methods and standardization regarding materialization of the benchmarks/points, data acquisition rules, procedures for data processing, validation of the results.



Surveying for subsidence monitoring

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Combining GPS and PSI data for an improved evaluation of vertical land movements at the coast

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Keywords: vertical land movements, sea level trends, GPS, PSI, tide gauge, coast

Vertical displacements of the Earth surface crust are recorded by tide gauges along with sea level signals from climate change (thermosteric effects and continental ice melting), whose magnitude and temporal characteristics are similar. Dedicated observations of vertical ground motions are therefore required to separate these displacements from other long-term signals in sea levels. So far the best method to achieve this separation is by installing permanent Global Positioning System (GPS) stations at the tide gauges. However, there are little permanent GPS stations actually installed at the tide gauges. In many cases GPS data are available from distant stations, which raises the question of their relative stability with respect to the tide gauge. Furthermore, the density of GPS networks are too sparse to assess very localized vertical land movements. The interferometric synthetic aperture radar (InSAR) methods may provide a solution, in particular through the Persistent Scatterer InSAR (PSI) technique. In addition, InSAR can extend the pointwise GPS data to investigate the spatial structure of the vertical ground motions along the coastline. In this study, we examine the case of the city of Brest (France) on the Atlantic coast, where historical tidal observations have been recorded since the late 17^{th} century. The preliminary results suggest that the area of Brest as a whole is unaffected by vertical ground motions exceeding $+/-$ 1.5 mm/yr (Figure below). However, due to the low PS density near the GPS and the tide gauge, uncertainties remain regarding the existence of potential vertical ground motions within the 250 m around the tide gauge. Our findings advocate for the perspective of supplementing the natural geodetic network of points obtained by PSI with artificial corner reflectors in the vicinity of the geodetic instruments of interest.

PSI results around the tide gauge of Brest (France) on the Atlantic coast

Vulnerability to relative land subsidence in the Po River Delta - Venice region

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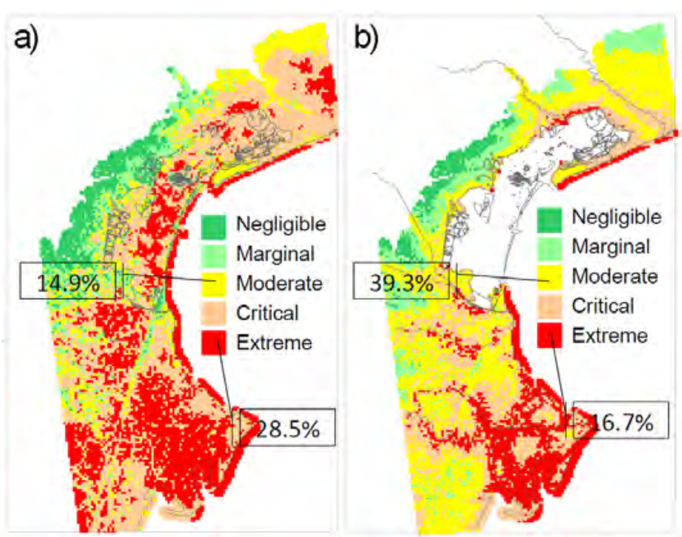
Keywords: Relative Land Subsidence, ALOS-PALSAR, Po River Delta, Venice region

The northern Adriatic coastal plain is characterized by low-lying environments such as deltas, lagoons, wetlands, and farmlands, and the interaction between land subsidence and eustacy represents the main threat for the survival of the coastland. This superposition effect, which is usually known as "relative sea level rise" (RSLR), is here termed "relative land subsidence" (RLS) because more suitable to visualize the process of loss in ground elevation with respect to the sea level not only in coastal sectors directly affected by the marine ingression but also in the inland coastal plain. In fact, because of its complex hydraulic setting, RLS may severely impact the northern Adriatic coastland, increasing the risk of river flooding, damages to buildings and other man-made structures, and enhancing the saltwater contamination of soils and aquifers, thus causing land desertification. In this work we provide the vulnerability maps to RLS and flooding of the Po River Delta - Venice region based on land displacements, eustacy, and the physiographic setting of the coastal region, e.g., ground elevation and distance to the sea. Ground vertical movements and the digital elevation model have been obtained by SAR-based Interferometry on ALOS-PALSAR and ENVISAT-ASAR images, respectively, and sea level rise scenarios have been derived from long time series of local tide gauge stations and the most updated IPCC projections. Vulnerability maps to RLS and flooding clearly outline that most of the coastland is in moderate to extreme conditions.



Vulnerability maps of Relative Land Subsidence (a) and Flooding (b), considering the actual rate of subsidence and SLR, and the actual ground elevation

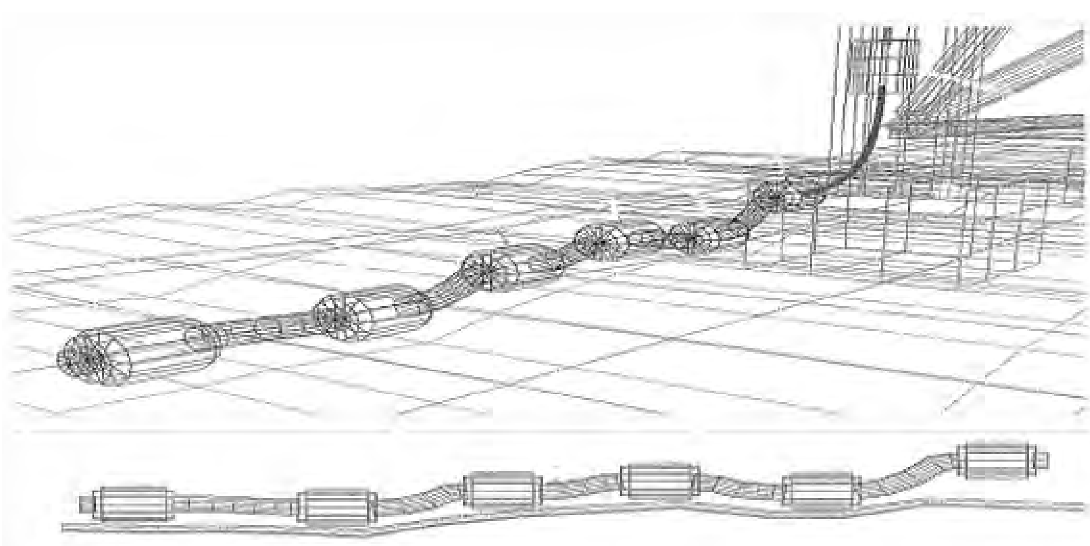
New methodologies in monitoring in-land and off-shore coastal land subsidence

A. Pozzoli[1] and A. Mosconi[1]

[1]Eni S.p.A.

Keywords: land subsidence, monitoring methodologies, sustainability

Land subsidence is a complex problem that involves different phenomena/causes. Therefore it is necessary to use innovative and diversified techniques in an integrate approach to take advantage from the best performances of each technique. Eni S.p.A. since the early '70 tested new methodologies in monitoring in-land and off-shore costal land subsidence. Next to the classical techniques as leveling, GPS and SAR surveying other systems supported the land subsidence monitoring: Satellite Survey Unit (S.S.U.) integrate Levelling, GPS and SAR measure with the calibration of the displacement; piezometers and assestimeters support the study of superficial compaction; Radioactive Marker Technique for reservoir compaction monitoring; Seabed Pressure gauges, Interferometric Synthetic Aperture Sonar, Hydrostatic Profile gauge for seabed vertical displacement. Only the full integration of all these techniques with available geological data, comparison with forecasting models and evaluation of natural historical subsidence component allows a correct computation of hydrocarbon-production effect and its regional and local sustainability.



Hydrostatic profile gauge schema

Advancements in the research of the land subsidence phenomena at the wider coastal area of Thessaloniki, Greece

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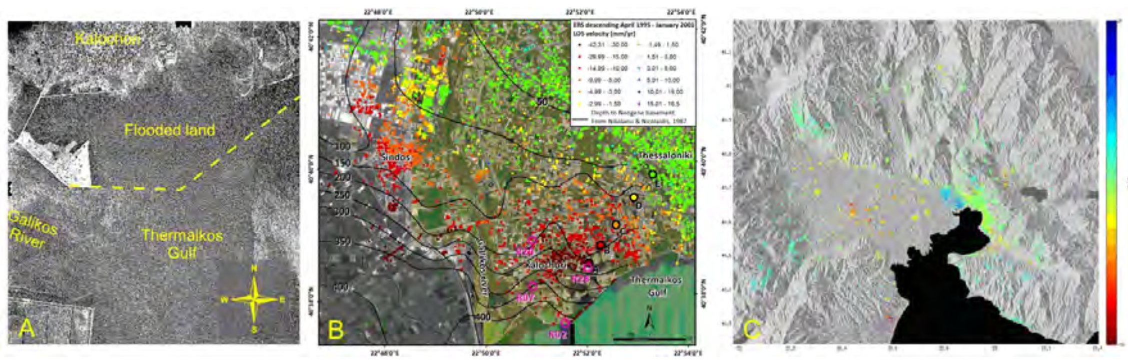
Keywords: overexploitation of aquifers, aquifer management, remote sensing

Land subsidence caused by the overexploitation of the aquifers manifest with an increasing frequency in several regions of Greece. In the broader Kalochori village region, at the west side of Thessaloniki, the first signs of subsidence were recorded in 1965 in the form of a progressive marine invasion. In 1969, during a period of intensive rainfall, the seawater reached the southern houses of the village, forcing the construction of embankments along the entire coastline. As a result of the continuous subsidence, reaching next to the coastline maximum values of 3-4 m, the embankments were destroyed and reconstructed several times (Fig. A). The land subsidence phenomena continue taking place since 2004, when sudden changes at the economic activities lead to the reduction of the water pumping and the gradual recharge of the aquifers. The aquifer recharge impressively changed the motion trend, from subsidence to uplift. Beside ground truth data the land subsidence trends have been also identified via multi-temporal InSAR techniques. In the framework of Terrafirma project, a set of SAR images acquired in 1995 - 2001 by the ESA satellites ERS1, 2 were processed with PSI technique identifying subsiding deformation rates of roughly 4.5 cm/year (Fig. B). Following research, using PSI and SBAS multi-temporal Interferometric approach, was also applied for the analysis of a 2 decades long ERS 1, 2 and ENVISAT dataset (1992 - 2010). The velocities estimated for the ERS dataset are in excellent agreement with previous studies. The intriguing output of the ENVISAT data archive (2003 - 2010) was an uplift motion trend, during the second decade (Fig. C).



A) Aerial photograph presenting the flooded area after the collapse of the embankment in 1973. B) land subsidence LOS deformation rates from ERS1/2 data (1995- 2001), C) PS results from Envisat data (2002-2010) indicating uplift due to ground water recharge

Superstation construction in the Mississippi Delta to examine rates and drivers of coastal subsidence

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Keywords: subsidence measurement, Mississippi delta, instrumentation

One of the outcomes of the inaugural International Workshop on Coastal Subsidence in 2013 was the recognition that there exists a pressing need for more coordinated efforts to reconstruct, monitor, and predict subsidence in low-lying coastal settings. One potential avenue is the creation of "superstations"– carefully selected localities within priority areas experiencing rapid subsidence such as deltas and coastal cities, where instrumentation, experiments, and data collection are focused. Here we report on a pilot study in the Mississippi Delta, an overall rapidly subsiding region where subsidence signals should be distinguishable from measurement noise within a matter of years. Funding from the U.S. Army Corps of Engineers has been utilized to construct an initial superstation in early 2016 sited near Myrtle Grove, Louisiana, co-located with a Coastal Reference Monitoring System (CRMS) station. The CRMS station monitors surface-elevation change and vertical accretion by means of the rod surface elevation table-marker horizon (RSET) technique. RSET data provides a record of shallow subsidence to the depth of the rod foundation (26 m at this site). Detailed stratigraphic information was obtained by means of a 12 cm diameter continuous core to provide information on sediment properties and geotechnical variables as well as age constraints on the local subsidence history. Low-power, interferometric, optical fiber strainmeters capable of continuous monitoring to micron resolution are being installed from the surface to 40 m (within the Pleistocene basement), 26 m and 10 m. These instruments, anchored to different depths to enable us to separate the various component processes that contribute to land-surface subsidence, are sufficiently sensitive to also record earth tides and earthquakes. GPS stations will be attached to either the base or the top of the strainmeters and tied to the Continuously Operating Reference Station (CORS) network that is operated by the U.S. National Geodetic Survey to provide a second data stream that monitors absolute subsidence in each well. The pilot superstation will be equipped later with reflectors (scatterers) to enable us to effectively calibrate the SAR solution using the superstation GPS to yield a total surface subsidence rate from later InSAR flyovers.

Borehole collection at the Mississippi Delta superstation site in February 2016

2nd International Workshop on Coastal Subsidence
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Cone Penetration Testing with pore pressure measurements, a new approach to assess land subsidence by peat compression

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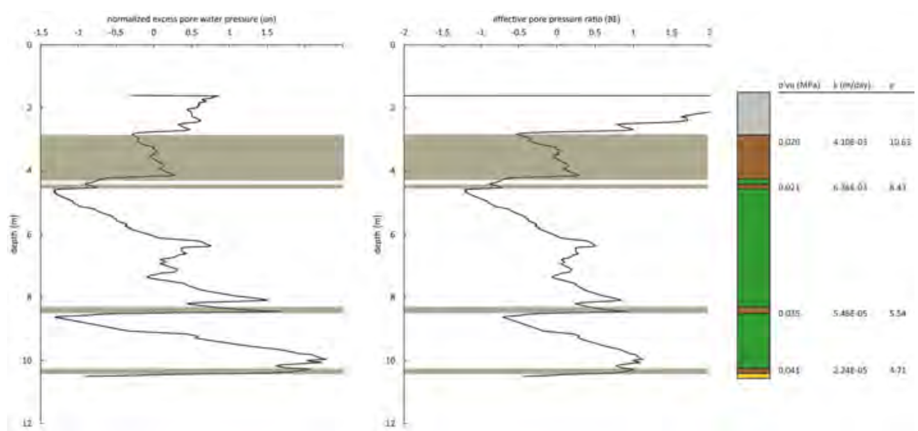
Keywords: Cone Penetration Test, peat, mechanical properties, land subsidence

The severity, rate, and spatial scale of coastal land subsidence demands new technological and methodological advancements, to assess the potential of subsurface units to future volume reduction when vertical stresses are changing. In many coastal areas, subsidence can be attributed to the loading and drainage of Holocene peat layers. These peat layers are often vertically and laterally differentially situated within the coastal sequences, therefore experiencing different in situ stresses, and as a result respond differently to changing vertical stresses by drainage and loading. We introduce Cone Penetration Testing with pore pressure measurements (CPTu) to assess the vulnerability of peat to land subsidence, by characterizing its mechanical properties. CPTu is a globally applied and internationally standardized geotechnical site investigation method that sounds mechanical properties of unconsolidated sediments with a continuous vertical interval of 2 cm. The method consist of the pushing of a cone, during which the mechanical resistance it experiences during penetration, as well as the excess pore water pressures that are generated during the sounding, are measured. We used two datasets of coupled CPTu with cored mechanical boreholes deriving from the coastal plain of the Netherlands. The first dataset derives from differentially loaded shallow peat layers (max. depth c. 6 m) adjacent and underneath an embankment (scale < 1 km^2). We found strong relations between volume loss/strain and increased mechanical properties expressed as cone resistance, caused by increasing stiffness under influence of compression. The second dataset derives from the entire Dutch coastal plain (scale c. 20.000 km^2) of Holocene peat layers situated at depths up to 25 m, of which permeability and void ratios were determined by samples taken from the cores. We predicted the permeability of peat layers using excess pore water pressures generated during the sounding, within one order of magnitude. Changes in void ratios were best related to cone resistance and excess pore water pressures. These peat properties are important input for consolidation calculations when vertical stresses change. Therefore, by CPTu, assessments can be made of peat bearing Holocene coastal sequences, regarding the amount of land surface lowering and the rate at which this will occur, when an area is loaded or drained. This makes CPTu a potentially powerful new contribution to the field of coastal land subsidence.



Calculated CPTu values: (left) normalized excess pore water pressure and (center) effective pore pressure ratio, respectively. (right) The corresponding lithological log from the core with effective stress, permeability and void ratio values. Peat is designated with brown shades. When peat is subjected to increasing effective stress, both CPTu values increase, whereas the permeability and void ratio decrease.

Satellite SAR interferometry on natural coastal areas

T. Strozzi[1], L. Tosi[2], C. Da Lio[2], and P. Teatini[3]

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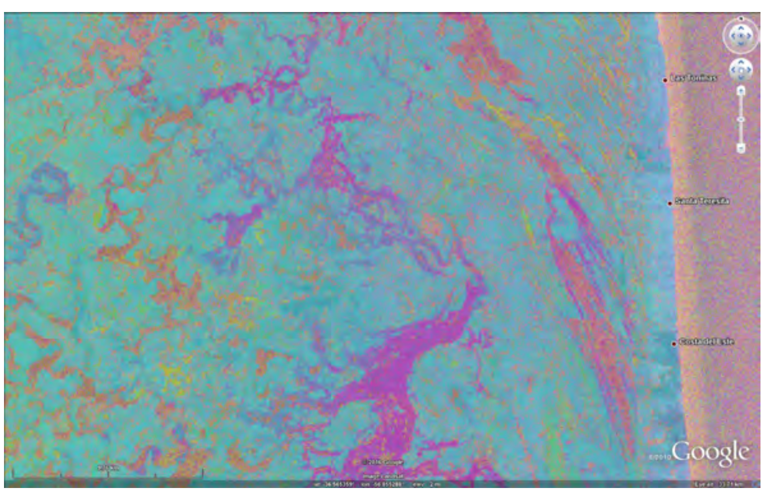
Keywords: SAR Interferometry, coastal areas, vegetated areas

Satellite SAR interferometry - using in particular multi-temporal processing approaches - is widely employed for the monitoring on land subsidence over coastal areas. Nonetheless, in vegetated areas such as wetlands, salt marshes and farmlands, ground movements are poorly detected because of temporal decorrelation and lack of point-like targets. In order to overcome this limitation, two approaches were attempted on the Venice Lagoon. In 2007, an innovative experimental network of about 50 artificial trihedral corner reflectors (TCR) was established on the salt marshes and tidal flats and ground movements detected with ENVISAT ASAR (C-band) and TerraSAR-X (X-band) images. The use of TCRs provided new insights on the ground movement of natural tidal environments and pointed out a large variability in the displacement rates. Another attempt has been carried out by using the L-band sensor ALOS PALSAR, which is characterized by a longer wavelength and is potentially able to retain in vegetated zones phase coherence over time periods longer than C- or X-band instruments. In some low coherence areas of the Venice Lagoon, as the coastal wetlands and farmlands, more persistent scatterers were identified allowing filling important information gaps. Now that ALOS PALSAR data are becoming freely available, a similar approach is much more easily possible in many coastal areas around the world, such as the Rio de la Plata Delta in Argentina where remarkable coherence was observed after 46 days (see Figure). In our presentation we will discuss the experiments performed so far in the Venice Lagoon for the estimation of land subsidence over vegetated coastal areas using satellite SAR interferometry and make an outlook over further possible applications in other coastal areas.



Differential ALOS PALSAR interferogram for the time period 2007.06.02

Present-day shallow subsidence rates and rates of relative sea-level rise in coastal Louisiana

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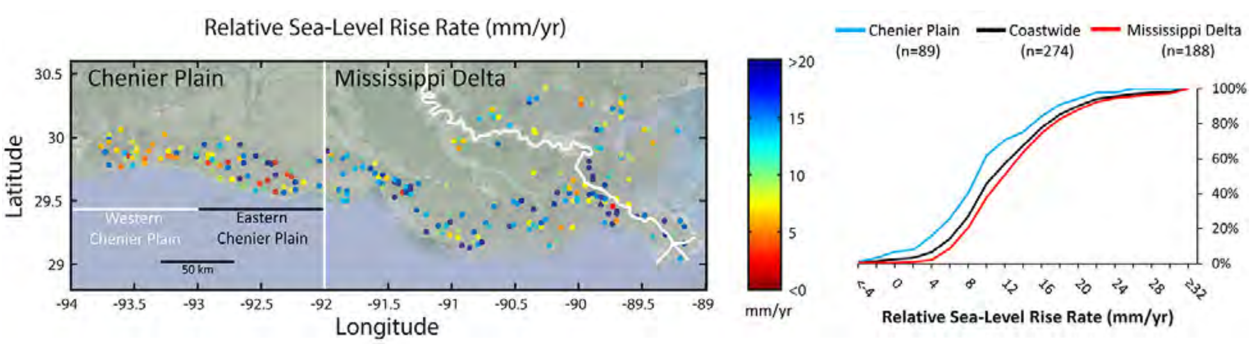
Keywords: relative sea level, compaction, Louisiana

Measuring present-day subsidence rates in the shallow (<20 m) subsurface of coastal wetlands is notoriously difficult. The rod surface-elevation table-marker horizon (RSET-MH) method has shown that such measurements can be made in principle. However, the limited number of RSET-MHs typically available, combined with the noisy nature of the time series produced, has often precluded more comprehensive, robust analyses. Here we present a dataset of unprecedented size, consisting of 274 records (5-10 years in duration) of shallow subsidence from across coastal Louisiana, including the Mississippi Delta and the Chenier Plain. While shallow subsidence rates exhibit large spatial variability, probability distributions for these two regions are almost identical with median rates of ∼6 mm/yr. Since the Chenier Plain consists of a veneer of Holocene strata <10 m thick and the underlying Pleistocene strata are highly consolidated, we conclude that compaction within the uppermost 5 to 10 m is the main contributor to the observed rates. We combine our new data with rates of deep subsidence (mainly from GPS data) to obtain total subsidence rates and find that shallow subsidence accounts for 60 to 85% of the total as recorded at the land surface. We add the mean rate of sea-level rise in the Gulf of Mexico from satellite altimetry (2 mm/yr) to obtain the rate of relative sea-level rise throughout the study area and find a median rate of 12 mm/yr for the Mississippi Delta. We stress the fact that unlike common practice, our analysis completely bypasses tide gauge data which tend to produce ambiguous data on subsidence rates in large deltas.



Present-day rate of relative sea-level rise at 274 sites across coastal Louisiana based on shallow subsidence rates (from RSET-MH data) plus deep subsidence rates (mainly from GPS data) plus regional sea-level rise (from satellite altimetry)

Hybrid interferometric time-series analysis over salt marshes: a case study in the Venice Lagoon (Italy)

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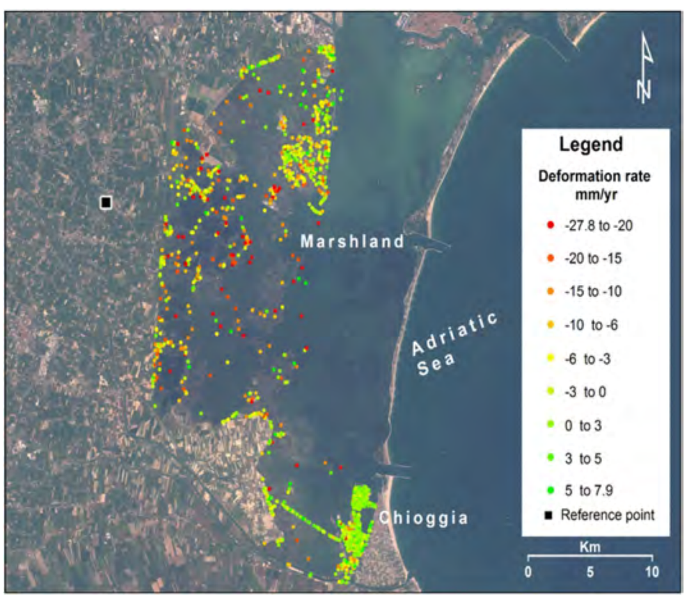
Keywords: hybrid interferometry, salt marshes, land deformation

Since the early nineties, Radar Interferometry has shown its maturity to monitor land displacements. Differential Synthetic Aperture Radar Interferometry (DInSAR) and Persistent Scatterer Interferometry (PSI), are widely applied for ground-motion monitoring. While PSI shows a great potential in mapping slow displacements in urban areas it shows relevant limitations concerning the spatial coverage in natural landscapes, e.g., wetlands and transitional coastal environments. In this contribution, we apply a synergistic approach using components from DInSAR and PSI methodologies, aiming at the improvement of the spatial coverage over the natural landscape in Venice Lagoon, Italy. ALOS-PALSAR data, covering a time period between January 2007 and July 2010, are used. For the selected area covered by salt marshes up to now no information about the land deformation was available, apart from a couple of tens corner reflectors that are installed within the lagoon. The proposed hybrid methodology shows a good potential to achieve an adequate spatial coverage of information over this marshland (see Figure). For the interpretation, the extracted values derived from the hybrid method (about 1350 pixels) are overlaid over auxiliary maps (morphology, evolution of the marshes etc.).



Hybrid interferometric result over the salt marshes in Venice Lagoon

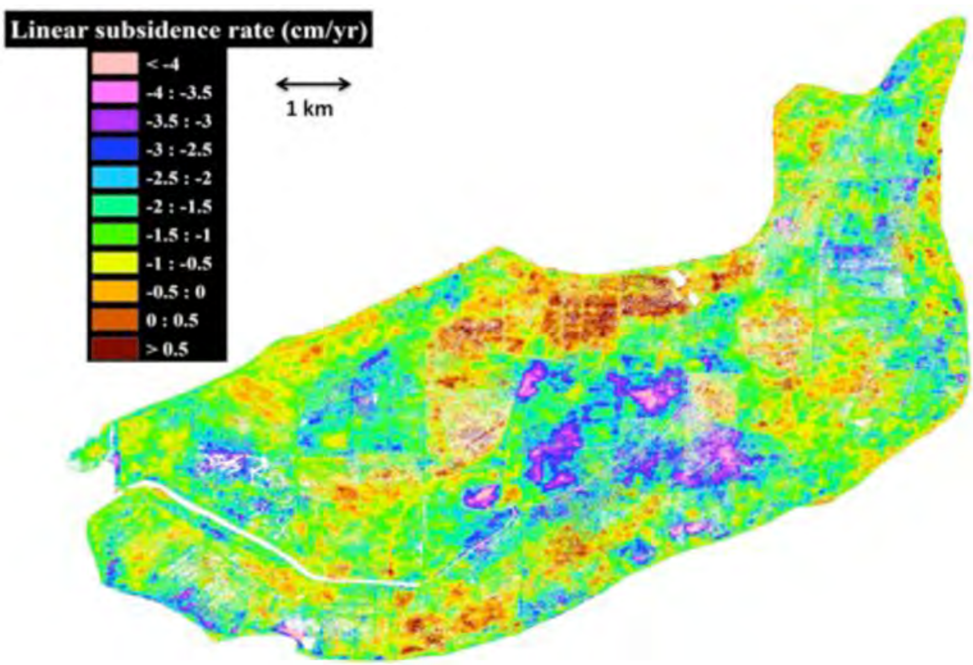
Subsidence of the Sacramento Delta (California, USA)

C.E. Jones[1], P. Sharma[1], D. Bekaert[1], and S. Deverel[2]

[1]Jet Propulsion Laboratory, California Institute of Technology, USA — [2]HydroFocus, Inc., Davis, California, USA

Keywords: Sacramento-San Joaquin Delta, subsidence, levees, InSAR

InSAR-based measurement of ground subsidence rates are notoriously challenging in agricultural areas because of rapid temporal decorrelation introduced by physical disturbance of the ground, vegetation growth, and changes in soil water content. Decorrelation noise can be mitigated by the use of longer wavelength instruments and time series techniques, but measurement remains a challenge particularly in areas where the deformation rates are low. Here we discuss techniques developed for low coherence data in a project to measure sub-island scale subsidence rates and levee movement across the Sacramento-San Joaquin Delta, based on SBAS processing of L-band Uninhabited Aerial Vehicle Synthetic Aperture Radar (UAVSAR) data. Determination of rates in this area is particularly valuable because of the Delta's critical importance as a water resource for the State of California and as a productive estuarine ecosystem. Subsidence across the region has left most of the man-made islands below mean sea level, and the levees maintaining the island integrity are subject to a wide range of threats, including localized nearby subsidence and earthquakes on nearby faults, which include the Hayward and San Andreas fault systems. We show that a dense acquisition of L-band images, processed with InSAR time series techniques, can achieve excellent spatial coverage and rate accuracy as low as 2 mm/yr even in this challenging area. Application of the technique to monitoring the levees and aqueducts in the area is shown, and he L-band airborne sensor results are compared to results obtained with TerraSAR-X and Radarsat-2.



Subsidence rates on Sherman Island, Sacramento Delta, California (USA) during 2009-2014, derived from InSAR applied to L-band airborne SAR (UAVSAR) data

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The Italian GNSS vertical kinematic pattern: spatial and temporal characteristics in the coastal areas

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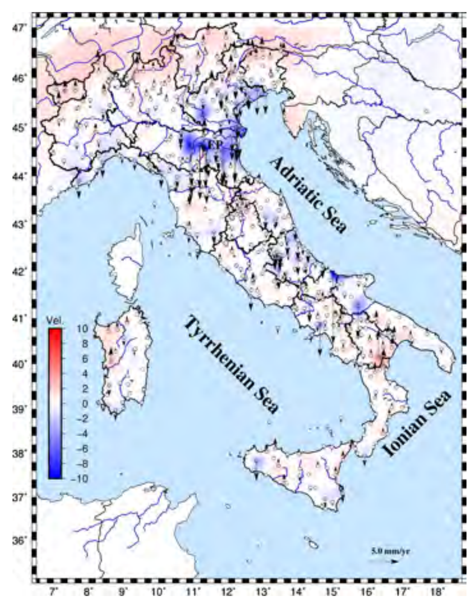
Keywords: GPS data, time series analysis, velocity changes

The aim of this work is the reconstruction of spatial and temporal variations of the vertical kinematic pattern in the Italian peninsula and in particular along the coastal areas, using the GNSS observation. The displacements observed by GNSS data can be considered as the result of different contributions, as: regional and local tectonic deformation, hydrologic processes and anthropogenic activities. In particular, the space distribution and time evolution of the last two processes can give a significant contribute to the heterogeneity distribution of vertical movements observed in the study area. The daily observation acquired in the period since 01-01-2001 to 31-12-2015 of more than 600 permanent stations are analyzed using GAMIT software in order to reconstruct the present kinematic pattern. At the end of the processing we have obtained the daily time series of the position components of each site in the ITRF2008 reference frame. The time series with an observation time span greater than 2.5 years are analysed with a procedure that at the same time compute: velocity, possible steps due to instrumental changes and/or seismic events and amplitudes of the first 5 seasonal signals. The vertical rates estimated are showed in Figure, where the relatively high density of the network provides a detailed spatial description. In particular, it can be noted that the velocity estimates for the land subsidence in the eastern sector of the Po Plain and in the Adriatic coast are significant lower than ones made in the second half of the 20^{th} century.



The present vertical kinematic pattern in the Italian peninsula obtained analyzing the observation acquired from 604 permanent GPS stations. The colours of circles indicate the velocity amplitudes, following the chromatic scale on the map, where the values are in mm/yr. The contour map has been obtained by a geostatistical method over a regular spaced grid (15 Km × 15 Km). EP = Easter Po Plain area.

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Efficient gPCE-based rock characterization for the analysis of a hydrocarbon reservoir

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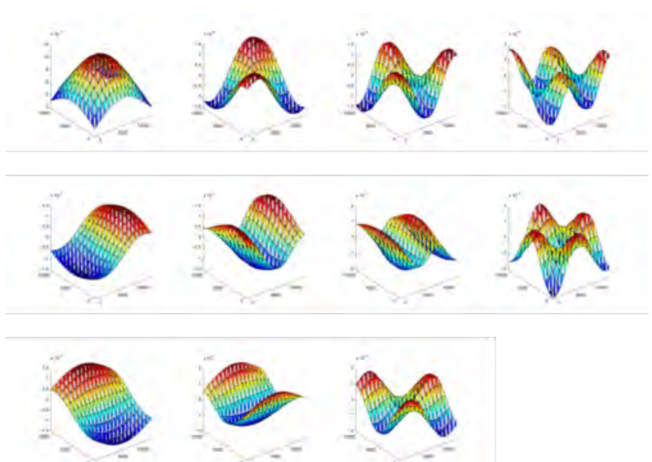
Keywords: land Subsidence, parameter estimation, heterogeneous material

Numerical modeling of anthropogenic land subsidence due to the exploitation of subsurface resources is of major interest to avoid significant environmental impacts on the ground surface. The reliability of the predictions depends on the different sources of uncertainty introduced into the modeling procedure. In this study, the focus is on the reduction of the model parameter uncertainty via assimilation of land surface displacements. In particular, a test case application on a deep hydrocarbon reservoir is considered. The land settlements are predicted with the aid of a 3D Finite Element (FE) model using a one-way coupled approach. The calibration focuses on the vertical uniaxial compressibility, c_M, which mostly controls the compaction of the rock formation caused by pressure depletion. Due to the geological compartmentalization of the reservoir into several blocks confined by sealing faults, c_M is assumed to vary both with the vertical effective stress and within the horizontal plane. The Ensemble Smoother (ES) as data assimilation technique can be easily implemented for parameter estimation problems. However, its convergence is guaranteed only with a large number of Monte Carlo simulations, which can be highly demanding from the computational viewpoint in large scale and complex systems. In this work, a meta-model is first built by using the generalized Polynomial Chaos Expansion (gPCE). Then, the ES is employed by sampling the ensemble members from the gPCE expansion. Because of the high computational cost of the forward model, the gPCE technique can be efficiently employed only with few random variables. Thus the discretization of the compressibility field is first achieved via the Karhunen-LoÃĺve expansion (KLE). Figure 1 shows the first L=11 eigenfunctions from the KLE of the random field assuming a Matern function to describe the field covariance. The proposed methodology is expected to reduce the overall computational cost of the original ES formulation and enhance the accuracy of the assimilation for parameter estimation. In fact, large ensembles can be sampled virtually at no additional cost, thus significantly reducing the associated errors.



Eigenfunctions from the KLE expansion truncated at 11 terms.

The Mose for the coastal and environmental defence of Venice and its lagoon

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[1]Pierluigi Rossetto, Engineer, Mose

Keywords: Management in Coastal Area, Sea Level Rise

In recent decades, floods have become ever more frequent and intense. Today the lagoon area is more than ever at risk of a catastrophic event such as that of 4 November 1966 when a tide of 194 cm completely overwhelmed Venice, Chioggia, towns and villages in the lagoon and the islands: cities and towns are, in fact, an average of 25 cm lower with respect to the water than at the beginning of the 20th century, due to a simultaneous rise in sea level and drop in land level. In the future, the phenomenon of flooding could worsen due to the predicted rise in sea level. The mobile barriers have been designed to protect the lagoon area, its inhabitants, its extraordinary towns and cities and its inestimable historical, artistic and environmental heritage from all high tides, including extreme events. The Mose is a far-ranging plan of measures to safeguard Venice and the entire lagoon area, implemented by the State (Ministero delle Infrastrutture e dei Trasporti - Provveditorato per le Opere Pubbliche del Triveneto) through the Consorzio Venezia Nuova. Adopting a systemic approach, the vast programme of activities combines physical protection from floods and sea storms with restoration of the morphological balance throughout the entire lagoon ecosystem in an unequalled work program for the size of the area involved, nature of the problems tackled and scale and characteristics of the measures implemented. The Mose is a model of action and of flexible management for the safeguarding of a complex system that represents a worldwide reference for the countries affected by the negative effects of climate change and involved in the challenge of coastal and environmental defence.

MOSE gates in operation

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