Investigating land subsidence trend in the major coastal cities of Europe

R. Bonì[1], P. Teatini[2], C. Zoccarato[2], P. Minderhoud[2,3], L. Tosi[4], M. Béjar-Pizarro[5], C. Guardiola-Albert[5], G. Bru[5], P. Ezquerro[5], G. Herrera[5], R. Tomás[6], M.I. Navarro-Hernández[6]

1 Department of Pure and Applied Sciences, University of Urbino "Carlo Bo", Urbino, Italy.
2 Department of Civil, Environmental and Architectural Engineering, University of Padua, Padua, Italy.
3 Soil Geography and Landscape Group, Wageningen University, Wageningen, The Netherlands
4 Institute of Geosciences and Earth Resources, National Research Council, Padova, Italy
5 Geohazards InSAR Laboratory and Modeling Group, Instituto Geológico y Minero de España, Madrid, Spain.
6 Universidad de Alicante, Dpto. de Ingeniería Civil, Escuela Politécnica Superior de Alicante, Alicante, Spain.

Correspondence to: Roberta Bonì (roberta.boni@uniurb.it)
Session: Measuring and Monitoring of land subsidence

Abstract
Major coastal cities in the world are threatened by land subsidence due to natural and anthropogenic causes. These phenomena can exceed global sea-level rise by one order of magnitude. While sea-level rise has received great consideration by the scientific community, land subsidence and its effect on the relative sea-level rise in coastal cities have not. The aim of this work is to show the comparison of the recent trends of land subsidence in the major coastal cities of Europe by exploiting the advanced differential interferometric SAR (A-DInSAR) data provided by the European Ground Motion Service (EGMS) developed by the European Union's Earth observation programme. The results will be exploited to investigate the driving forces of the different land subsidence mechanisms.

Keywords: land subsidence; coastal areas; A-DInSAR; EGMS; relative sea-level rise

Introduction
Land subsidence is a worldwide problem as reported by a recent study that has evaluated how 90% of the global population may face a high probability of subsidence (Herrera et al., 2021) with an increasing exposure to sea-level rise. Different authors have evaluated the risk associated to future coastal flood in Europe due to global warming and socioeconomic development (e.g., Paprotny et al., 2018; Vousdoukas et al., 2018).

It is well known that the combined effect of land subsidence and sea level rise increases flood risk and that several coastal cities, such as Jakarta in Indonesia (Abidin et al. 2011), Shanghai in China (Yue et al. 2015), along with many other densely populated areas in the world (Yan et al. 2022), are sinking faster than the sea level is rising. However, information on current land subsidence dynamics and rates at a global scale is often not available. In addition, the spatio-temporal variability of the coastal land subsidence, due to the different causes, makes the integration of its contribution to future relative sea-level rise challenging.

In 2016, a European initiative was developed to provide A-DInSAR measurements at a continental scale (Crosetto et al. 2020). This service, named European Ground Motion Service (EGMS), represents the most important wide-area deformation monitoring system ever developed. The aim of this work is to give insight into i) the use of the EGMS products (displacement time series and average velocities) for the monitoring of land subsidence in 16 coastal metropoles in Europe characterized by a population over one million, and ii) the interpretation of the driving mechanisms using cross-correlations with subsurface geospatial information (e.g., geology, hydrogeology, etc.).

Data and Methods

Major coastal cities selected in Europe

In the selected coastal cities/metropoles, more than 1 million people are at risk from climate change and natural hazards (Figure 1). Thirteen cities were considered as the most vulnerable in Europe as of 2005 (Hallegatte et al., 2013) and three more were lately included (Antwerp, Oslo and Valencia) as they have surpassed 1 million inhabitants in recent years (Siegel, 2020).

Land subsidence is triggered by a variety of factors, many of which are related to hydrogeologic processes. Some natural processes causing land subsidence are influenced by human activities related to land and water use and by climatic variability (Galloway et al., 2016). To interpret the land subsidence in the selected cities, these drivers were investigated through a literature review and cross-correlation with subsurface geospatial information.

From the climatic point of view, six cities are localized in the maritime North climatic zone (i.e., Dublin, London, Rotterdam, Amsterdam, Antwerp, Hamburg), seven cities in the Mediterranean climatic zone (i.e., Porto, Lisbon, Valencia, Barcelona, Marseille, Naples, Athens), two cities (i.e., Oslo and Helsinki) are in the nemoral climatic zone, and one (i.e., Copenhagen) in the continental climatic zone (EEA, 2022).

Most of the cities (i.e., Athens, Barcelona, Marseille, Valencia, Hamburg) are sit above highly productive aquifers low and moderately productive aquifers (i.e., London, Lisbon, Amsterdam, Rotterdam). One and two cities are located in regions with highly (i.e., Copenhagen) and low to moderately productive *fissured* aquifers (i.e., Napoli, Dublin), respectively.

Non-aquiferous rocks characterized the regions of Oslo and Helsinki, with Porto and Antwerpen placed above locally aquiferous rocks (Figure 1).

Available scientific literature suggests the selected cities are experiencing land subsidence due to natural and/or anthropogenic causes. In some cases, the main cause of the detected subsidence could be due to excessive groundwater extraction, but detailed studies are lacking.

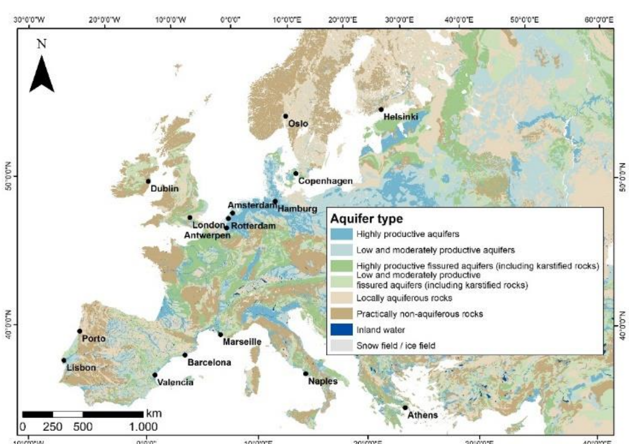

Figure 1. Location of the selected coastal cities positioned on the hydrogeological map of Europe (modified from Duscher et al. 2015).

EGMS dataset

The land subsidence rates have been investigated in the 16 cities using the EGMS products. This is a service developed by Copernicus, the European Union's Earth observation programme, that provides A-DInSAR data obtained using SAR images acquired by the Sentinel-1 satellites in ascending and descending geometries over Europe in the period from 2016 to 2020 (Figure 2).

The vertical displacement rates for each city were extracted from the EGMS Viewer by using the available "Ortho" level of product. The values represent absolute displacements, with the A-DInSAR outcome calibrated using GNSS records. Additional information about the dataset is available through the dedicated webpage (https://land.copernicus.eu/pan-european/european-ground-motion-service).

The tool "Compute average" was used to extract the mean velocity, the standard deviation associated to the mean velocity, the average displacement times series and the associated standard deviation in areas of the city most affected by land subsidence as detected by visual inspection.

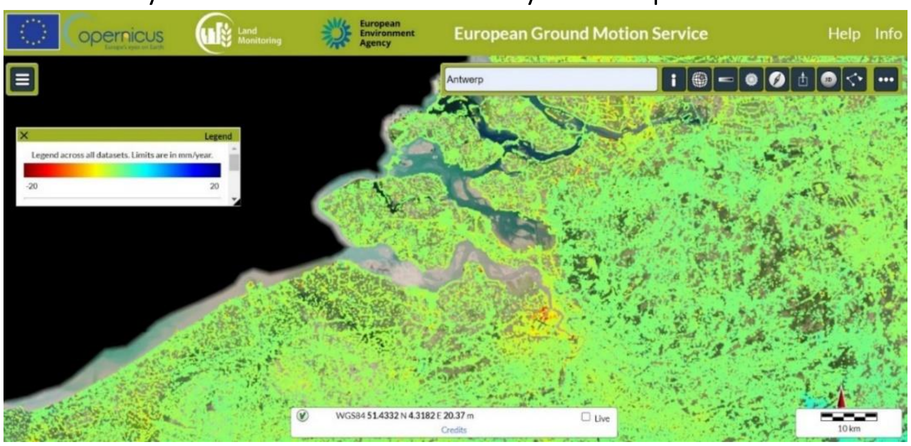

Figure 2. View of the EGMS products for Antwerp in Belgium. Negative and positive values stand for land subsidence and uplift, respectively.

Results and discussion

The results show that the mean velocity of studied cities ranges from -0.48 mm/yr up to -4.89 mm/yr. The highest values were detected for the cities of Antwerp, Hamburg, Barcelona and Rotterdam (Figures 3 and 4).

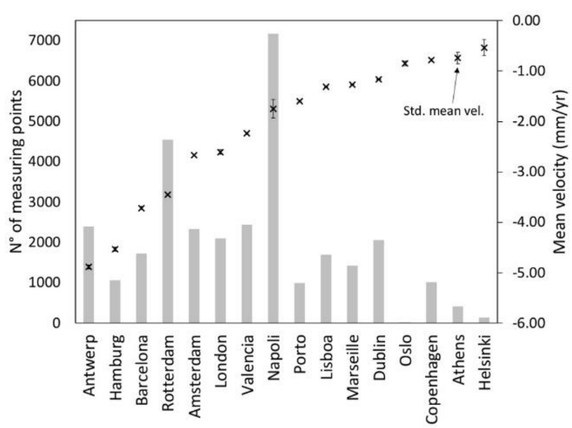

Figure 3. Mean velocities for the major coastal cities of Europe extracted in areas of interest. The grey columns and the black crosses represent the number of measuring points and the mean velocity, respectively. The standard deviation of the mean velocity and the number of measuring points for each area is also reported. Oslo shows only very local vertical movements and

21 measuring points were selected.

The highest subsidence rate is measured in Antwerp (Belgium), which is located in the alluvial plain of the Scheldt River where fluvial deposits are overlain by human-made landfills. The recent intensive urbanization could be the primary cause of the consolidation of these compressible deposits (Declercq et al., 2021). A similar land subsidence mechanism is reported for the port of Barcelona (Spain), which was built on Quaternary and Tertiary River alluvial compressible deposits of the Llobregat river delta (Pros et al., 2014).

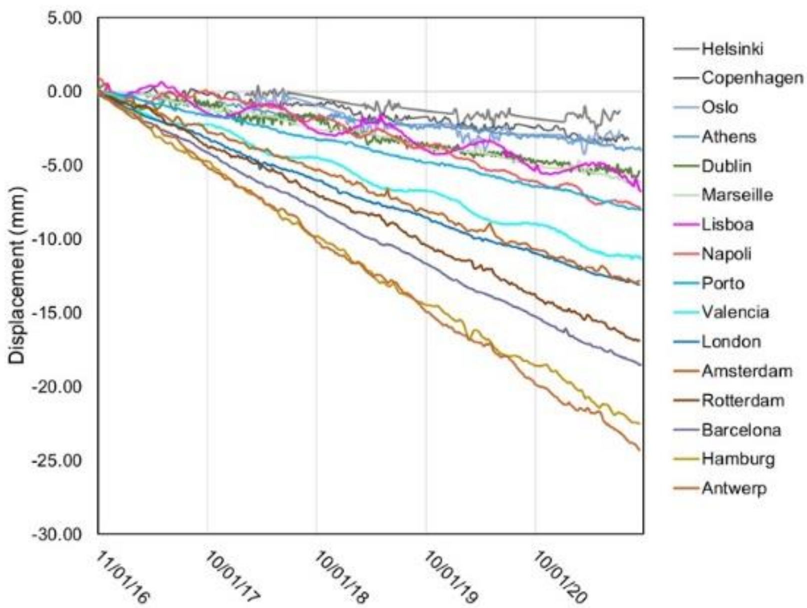

Figure 4. Average displacement time series for the selected areas of the coastal cities of interest.

High subsidence rates are observed also in Hamburg (Germany). In this case, the subsidence is due to the dynamics of evaporites (Kersten et al., 2017). Volcanic inflation/deflation is the main mechanism responsible for the movements in Napoli (Italy) although other causes were identified (Terranova et al., 2015). Athens (Greece) experiences land subsidence due to mining activities (Parcharidis et al. 2006). Land subsidence in Amsterdam and Rotterdam (The Netherlands) is due to compaction and oxidation depending on the subsurface lithology, the loading and groundwater table history (Koster et al., 2018; Van Asselen et al., 2018). Subsidence due to groundwater withdrawal is observed in London (UK) (Bonì et al., 2016) and suggested for Valencia (Spain) (Ruiz-Armenteros et al., 2018). The cities of Lisbon and Porto (Portugal) show movements probably due to the natural compaction of alluvial deposits and anthropogenic materials (Catalao et al., 2011; Sousa et al., 2012), although subsidence may also be due to aquifer overexploitation. Further studies and groundwater monitoring data are required to understand the cause of the detected movements in these cities. It is worth noting that Copenhagen (Denmark), Helsinki (Finland) and Oslo (Norway) show low subsidence rates in reclaimed areas and restricted zones where aquifer drainage operations for underground construction were carried out (Dehls and Nordgulen, 2004). In Dublin (Ireland), local compaction of unconsolidated shallow sediments such as peat or lacustrine deposits due to the load induced by the recent construction of roads and buildings could be the main cause of the observed phenomena (Fiaschi et al., 2019). Low subsidence rates are observed in Marseille (France).

Conclusions

This work shows the preliminary results of an investigation aimed at quantifying land subsidence in major coastal cities in Europe using EGMS products and understanding its potential driving mechanisms using geomatic layers such as geological, and hydrogeological maps. The approach could be applied to identify hotspots of land subsidence that will require further investigations to disentangling the governing mechanisms and implementing mitigation strategies and sustainable land management plans. Future studies will be performed to simulate projections of future subsidence trends and variabilities and to combine these measurements into relative sea-level rise scenarios with the final aim to estimate the flooding potential in these densely populated areas.

Acknowledgments

The activity has been developed within the scientific collaboration of the UNESCO Land Subsidence International Initiative (LaSII, https://www.landsubsidence-unesco.org/). This is a contribution of the IGCP-663 project of the IUGS and UNESCO, and SARAI project (Project PID2020-116540RB-C22 funded by MCIN/ AEI /10.13039/501100011033).

References

Abidin, H. Z., Andreas, H., Gumilar, I., Fukuda, Y., Pohan, Y. E., & Deguchi, T. (2011). Land subsidence of Jakarta (Indonesia) and its relation with urban development. *Natural hazards*, 59(3), 1753-1771.

Bonì, R., Cigna, F., Bricker, S., Meisina, C., & McCormack, H. (2016). Characterisation of hydraulic head changes and aquifer properties in the London Basin using Persistent Scatterer Interferometry ground motion data. *Journal of Hydrology*, 540, 835-849.

Catalao, J., Nico, G., & Conde, V. (2011, April). Detection of ground subsidence in the city of Lisbon: comparison of InSAR and topographic measurements. *In 2011 Joint Urban Remote Sensing Event* (pp. 417-420). IEEE.

Crosetto, M., Solari, L., Mróz, M., Balasis-Levinsen, J., Casagli, N., Frei, M., ... & Andersen, H. S. (2020). The evolution of wide-area DInSAR: From regional and national services to the European Ground Motion Service. *Remote Sensing*, 12(12), 2043.

Declercq, P. Y., Gérard, P., Pirard, E., Walstra, J., & Devleeschouwer, X. (2021). Long-term subsidence monitoring of the Alluvial plain of the Scheldt river in Antwerp (Belgium) using radar interferometry. *Remote Sensing*, 13(6), 1160.

Dehls, J. F., & Nordgulen, Ø. (2004). Evaluation of the use of PSInSAR for the monitoring of subsidence in Oslo region.

Duscher, K., Günther, A., Richts, A., Clos, P., Philipp, U., & Struckmeier, W. (2015). The GIS layers of the "International Hydrogeological Map of Europe 1: 1,500,000" in a vector format. *Hydrogeology journal*, 23(8), 1867-1875.

EEA, 2022. https://www.eea.europa.eu/data-and-maps/figures/observed-climate-zones-in-the

Fiaschi, S., Holohan, E. P., Sheehy, M., & Floris, M. (2019). PS-InSAR analysis of Sentinel-1 data for detecting ground motion in temperate oceanic climate zones: a case study in the Republic of Ireland. *Remote Sensing*, 11(3), 348.

Galloway, D. L., Erkens, G., Kuniansky, E. L., & Rowland, J. C. (2016). Preface: Land subsidence processes. *Hydrogeology Journal*, 24(3), 547-550.

Hallegatte, S., Green, C., Nicholls, R. J., & Corfee-Morlot, J. (2013). Future flood losses in major coastal cities. *Nature climate change*, 3(9), 802-806.

Herrera-García, G., Ezquerro, P., Tomás, R., Béjar-Pizarro, M., López-Vinielles, J., Rossi, M., ... & Ye, S. (2021). Mapping the global threat of land subsidence. *Science*, *371*(6524), 34-36.

Kersten, T., Kobe, M., Gabriel, G., Timmen, L., Schön, S., & Vogel, D. (2017). Geodetic monitoring of subrosion-induced subsidence processes in urban areas. *Journal of Applied Geodesy*, 11(1), 21-29.

Koster, K., Stafleu, J., & Stouthamer, E. (2018). Differential subsidence in the urbanised coastal-deltaic plain of the Netherlands. *Netherlands Journal of Geosciences*, 97(4), 215-227.

Paprotny, D., Sebastian, A., Morales-Nápoles, O., & Jonkman, S. N. (2018). Trends in flood losses in Europe over the past 150 years. *Nature communications*, 9(1), 1-12.

Parcharidis, I., Lagios, E., Sakkas, V., Raucoules, D., Feurer, D., Le Mouélic, S., ... & Cooksley, G. (2006). Subsidence monitoring within the Athens Basin (Greece) using space radar interferometric techniques. *Earth, planets and space*, 58(5), 505-513.

Pros, F., Gonzalez-Lopez, S., Martínez-Benjamin, J. J., Palau, V., & Duro, J. (2014, July). Breakwater settlement monitoring with InSAR data. *In 2014 IEEE Geoscience and Remote Sensing Symposium* (pp. 414-417). IEEE.

Ruiz-Armenteros, A. M., Manuel Delgado, J., Ballesteros-Navarro, B. J., Lazecky, M., Bakon, M., & Sousa, J. J. (2018, July). Deformation monitoring of the northern sector of the Valencia Basin (E Spain) using Ps-InSAR (1993–2010). *In IGARSS 2018-2018 IEEE International Geoscience and Remote Sensing Symposium* (pp. 2244-2247). IEEE.

Siegel, F. R. (2020). An example of coastal cities hazard exposure and economics. *In Adaptations of coastal cities to global warming, sea level rise, climate change and endemic hazards* (pp. 63-69). Springer, Cham.

Sousa, J. J., Bastos, L. C., Ruiz, A. M., Hooper, A. J., & Hanssen, R. (2012). Detection Of Ground Deformation In The Oporto Metropolitan Area With Multi-Temporal Interferometry (MTI). *Fringe 2011*, 697, 92-9092.

Terranova, C., Ventura, G., & Vilardo, G. (2015). Multiple causes of ground deformation in the Napoli metropolitan area (Italy) from integrated Persistent Scatterers DinSAR, geological, hydrological, and urban infrastructure data. *Earth-science reviews*, 146, 105-119.

Van Asselen, S., Erkens, G., Stouthamer, E., Woolderink, H. A., Geeraert, R. E., & Hefting, M. M. (2018). The relative contribution of peat compaction and oxidation to subsidence in built-up areas in the Rhine-Meuse delta, The Netherlands. *Science of the Total Environment*, 636, 177-191.

Vousdoukas, M. I., Mentaschi, L., Voukouvalas, E., Bianchi, A., Dottori, F., & Feyen, L. (2018). Climatic and socioeconomic controls of future coastal flood risk in Europe. *Nature Climate Change*, 8(9), 776-780.

Yan, X., Xu, Y., Yang, T., Tosi, L., Stouthamer, E., Minderhoud, P., ... & Bonì, R. (2022). Sustainable development of coastal cities through control of land subsidence: activities of IGCP Project 663 in Jakarta. *Episodes Journal of International Geoscience*, 45(1), 101-108.

Yue, L. U. O., Shujun, Y. E., Jichun, W. U., Xun, J. I. A. O., & Hanmei, W. A. N. G. (2015). Characterization of land subsidence during recovery of groundwater levels in Shanghai. *Geological Journal of China Universities,* 21(2), 243.