remote sensing

Editorial

Editorial for Special Issue "Monitoring Land Subsidence Using Remote Sensing"

Massimo Fabris [1,*], Nicola Cenni [2] and Simone Fiaschi [3]

1 Department of Civil, Environmental and Architectural Engineering—ICEA, University of Padova, 35131 Padova, Italy
2 Independent Researcher, 35131 Padova, Italy; ncenni@gmail.com
3 UCD School of Earth Sciences, University College Dublin, D4 Dublin, Ireland; simone.fiaschi@ucd.ie
* Correspondence: massimo.fabris@unipd.it

1. Introduction

Land subsidence is a geological hazard that affects several different communities around the world. The main consequences of subsidence can be related to environmental degradation, damage to buildings, and interruption of services [1]. The effects produced by the lowering of the ground level on building and infrastructure can be considered as a major problem in many countries. More than 150 cities all over the world have endured land subsidence with rates up to tens of centimeters per year ([2] and references therein).

Land subsidence can have both natural and anthropogenic origin: natural subsidence can be due to the compaction of lithological layers of the soil, the oxidation of peat, and geodynamic processes (e.g., tectonic-plate movements, volcanism [3]); anthropogenic subsidence derives mainly from the compaction of aquifers associated with groundwater/oil/natural gas extractions, drainage of organic soils, underground mining, hydrocompaction, sinkholes, stress provided by newly-built man-made structures, and thawing permafrost ([4,5] and references therein); the combination and coexistence of these factors have a strong negative impact on the territory [1]. The effects of this global problem are more evident along transitional environments, such as coastal areas, deltas, wetlands, and lagoons, which are becoming increasingly vulnerable to flooding, storm surges, salinization, and permanent inundation [6]. In these areas, the effects of subsidence are linked also to the retreat of coastlines and disappearance of emerged surfaces [7,8].

The ground surface movements due to anthropogenic activities have been deeply investigated, particularly in critical environments such as high-urbanized areas and coastal zones [9].

The monitoring activities allow to acquire useful information that can be used to prevent damage to buildings and infrastructures, plan more sustainable urban development, and mitigate the risk; the knowledge of the temporal and spatial distribution of the ground surface deformations is essential to delineate the areas most affected by subsidence and to understand the involved mechanisms [1].

In the past, only the traditional leveling technique was used for the monitoring of land subsidence; however, despite its high accuracy, its use has been reducing with time due to the high costs and limited number of points potentially measurable.

The monitoring of ground movements made great progress in the last decades with the development of Global Positioning System (GPS)–Global Navigation Satellite System (GNSS) [10] and Interferometric Synthetic Aperture Radar (InSAR) [11] technologies together with the use of different approaches, from analytical to 3D numerical, for the analysis of the involved physical processes [9]. Starting from the 2000s, further advances in the satellite-borne and in-situ technologies made the monitoring of Earth surface motions an easier and more common geodetic task [12].

check for updates

Citation: Fabris, M.; Cenni, N.; Fiaschi, S. Editorial for Special Issue "Monitoring Land Subsidence Using Remote Sensing". *Remote Sens.* **2021**, *13*, 1771. https://doi.org/10.3390/rs13091771

Received: 22 April 2021
Accepted: 28 April 2021
Published: 1 May 2021

The GPS/GNSS technique allows the 3D monitoring of points based on continuous or repeated surveys with lower costs in comparison with the leveling approach, but, generally, with low spatial resolution.

The Differential Interferometric Synthetic Aperture Radar (DInSAR) approach, which was developed from the InSAR technique, has the advantages of wide spatial coverage, high spatial resolution, all-weather working conditions, and cost effectiveness [13].

However, the standard DInSAR technique is strongly limited by the presence of atmospheric effects that reduce the accuracy, and by the lack of time-series [1,2]. These limitations were overcome by the development of multi-temporal DInSAR techniques such as the Permanent Scatterer Interferometry (PSI, which looks for point-like scatterers) and the Small Baseline Subset (SBAS, which looks for distributed scatterers within the cell resolution) that allow improved time-series analysis with millimetric accuracies [2,14]. Both methods are based on the analysis of stacks of SAR acquisitions from which are extracted suitable measure points. The PSI and SBAS approaches can be successfully applied over many different ground targets such as buildings, infrastructures, outcrops, base soils, low-vegetated area, etc. [11], and in several research fields, such as tectonics and volcanology [15], landslides [10,11,16], clay deposits deformations [5,17], and groundwater/oil/natural gas depletion [9,18].

The possibility to combine the results obtained from the analysis of SAR images acquired in both ascending and descending geometries allows the computation of the vertical and east–west components of movement, which is fundamental for data interpretation and for the integration with other techniques [18].

Despite the large advantages of the multi-temporal DInSAR methodology, the acquisition of ground-based data, mainly from leveling and GNSS techniques, is crucial for validation and integration of the satellite measurements. Nowadays, the land subsidence monitoring mostly relies on the integration between available and reliable InSAR data and sparse, but highly accurate, GNSS measurements, which are often compared to other geodetic observation methods [9–12,15,19,20].

This Special Issue consists of nine individual works that used different approaches and methodology for land subsidence applications. In the next section, each work is presented and the general contribution to this Special Issue is summarized.

2. Overview of Contributions

The papers included in this Special Issue cover a wide spectrum of applications related to the land subsidence monitoring in different areas of the world using remote sensing techniques integrated with ground-based data. The accepted works are presented here in order of publishing.

Zhou et al. [2] analyzed the overexploitation of groundwater in the Beijing–Tianjin–Hebei (BTH) area in China, in the 2012–2018 period, using the Interferometric Point Target Analysis (IPTA) with Small Baseline Subset (SBAS) technique. Authors used 126 RADARSAT-2 and 184 Sentinel-1 images acquired in ascending and descending orbits, respectively, to derive land subsidence rates in the study area: they validated the results using 72 leveling benchmarks and compared the measured vertical land motion with data of groundwater monitoring wells from 2012 to 2015. Moreover, the authors correlate the detected land subsidence rates with eleven subsidence features and land use types: the results showed serious vertical land motion with rates up to 131 mm/y. They demonstrate that the land subsidence changes are consistent with the seasonal trends of the groundwater level changes.

Gido et al. [5] used the Permanent Scatterer Interferometry (PSI) technique and historical leveling data to study the ground surface deformation of Gävle city in Sweden: two ascending and descending Sentinel-1A/B datasets (91 images in total), collected between January 2015 and May 2020, were processed and analyzed together with a long record of a leveling dataset (4 leveling lines), covering the period from 1974 to 2019. The authors performed the comparison between the obtained data at some locations showing a close agreement between the subsidence rates extracted from precise leveling and PSI. Land subsidence rates were compared also with the geological information of the analyzed area: they suggest that the land subsidence (with maximum displacement rate that reaches up to -6 ± 0.46 mm/y in the LOS direction and only in localized deformation zones) occurred due to relatively weak subsurface layers (hazard zone reported as an artificial fill area) that either was affected by loading of new constructions or by hydro-compaction.

Doke et al. [15] performed an InSAR time series analysis of the Hakone Volcano (Japan) from 2006 to 2011 using the SBAS method and ALOS-PALSAR scenes (24 from the ascending and 22 from the descending orbits, respectively). The authors corrected the obtained InSAR displacements using the available GNSS data. The results showed highly localized subsidence (500 m in diameter, with maximum vertical rates of about 25 mm/y) to the west of Owakudani from 2006–2011. The authors suggested that the land subsidence was caused by a reservoir contraction at approximately 700 m above sea level. Based on the structure of the hot spring wells and their chemical components, they suggested that the contraction source can be considered as a reservoir containing hydrothermal fluids, which demonstrates the feasibility of the InSAR technique to monitor hydrothermal activity in shallow parts of volcanic areas.

Even et al. [18] applied InSAR using both PS and SBAS approaches to study the complex displacement field caused by convergence and operational pressure changes of the natural gas storage field at Epe (N–W Germany). The authors processed 86 and 118 SAR images, respectively, in ascending and descending orbits; they compared the InSAR results with leveling data acquired during three surveys between 2015 and 2017 (517 points in total) and ground water measurements at 97 locations. The authors combined separately the different components of the phase model (geometric orbit combination) for a better understanding of the phenomena that contribute to the displacement field; in addition, a method that allows to perform an orbit combination based on simplistic geomechanical modeling of the spatial displacement field was presented (Multi-Mogi approach). They demonstrated that the InSAR-derived displacements were in reasonable agreement with the leveling data taking into account the geometric orbit combination, and in good agreement with the Multi-Mogi approach; for the vertical components, the comparison with leveling data provided Root Mean Square (RMS) of 3.41 mm/y and 2.39 mm/y for the geometric orbit combination and for the Multi-Mogi approach, respectively.

Benetatos et al. [9] presented a multi-physics investigation of the ground movements related to the cyclical and seasonal injection and withdrawal of natural gas in/from a depleted reservoir located in the Po Plain area (Italy) using the Persistent Scatterer Pairs InSAR (PSP-InSAR) approach and GNSS data. The authors developed an integrated geological, fluid-flow, and geomechanical numerical modeling approach to reproduce the main geometrical and structural features of the involved formations. They processed 432 and 428 SAR scenes (from 2003) in both ascending and descending orbits, respectively, from RADARSAT-1/2 and Sentinel-1 satellites, and daily data from a continuous GNSS (CGNSS) station (from 2008), using the Network approach and the Precise Point Positioning data processing. They found (i) agreement between the InSAR and the GNSS results; (ii) gentle long-term subsidence trends; (iii) a strong correlation between the cumulative volumes curve of the gas storage and the historical series of the ground displacements above the reservoir, considering both the vertical and east–west planimetric components; and (iv) cyclical subsidence/uplift limited to the field area.

Grgić et al. [12] showed the conjoint analysis of vertical land motion of the Dubrovnik area (Croatia) using 75 ascending Sentinel-1 images from 2014 to 2020, continuous GNSS observations at Dubrovnik site obtained starting from 2000, differences of the sea-level change derived from all available satellite altimeter missions for the study area and tide gauge measurements in Dubrovnik starting from 1992. The data from the CGNSS station were used to correct the obtained InSAR ground motion rates and to reference the motions with respect to an absolute reference frame. They compared and analyzed trends obtained with the different techniques in the overlapping period, from 2014 to 2020: the results showed vertical land motion velocities in the order of some mm/y with only some limited areas characterized by rates exceeding −5 mm/y.

Sopata et al. [3] focused on describing vertical surface displacements related to seven mining-induced tremors in the Upper Silesian Coal Basin in the south of Poland using the standard DInSAR approach. The authors processed 15 interferograms of Sentinel-1A/B satellites from March to May 2017 in ascending orbit, which overlap with seven reported tremors of the rock mass of magnitude M_L = 2.3–2.6. As a result that the obtained land subsidence isolines showed residual signal noise, the authors developed a procedure to eliminate the occurring irregularities interpolating the subsidence profile by means of eighth-degree orthogonal polynomials and manually entering the corrections to the surface distribution of isolines for each individual subsidence. Moreover, they evaluated the threats to building structures according to the classification used in mining areas. They found that the structures with resistance lower than the limit values of land subsidence speed can be exposed to higher damage risk.

Mancini et al. [21] developed a PSI-based workflow to process dual-orbit SAR observations with open-source tools complemented by the use of GNSS observations as constraints for the global reference frame and final accuracy assessment of the vertical and horizontal velocity maps. The authors investigated the land subsidence processes in the eastern sector of the Po Plain (Italy) and in particular in the metropolitan area of the Bologna city analyzing interferometric and GNSS observations acquired between 2015 and 2019. With respect to the InSAR analysis, they added a procedure to refer the LOS-projected velocities to the GNSS reference frame and an algorithm for decomposition analysis. The validation of the velocity maps through the comparison between the decomposed InSAR and GNSS annual rates provided differences at the millimeter level, which confirmed the substantial agreement between the PSI and GNSS measurements.

Cenni et al. [22] highlighted the spatial and temporal evolution of the land subsidence in the Po River Delta (PRD) area (Italy) analyzing time-series obtained from CGNSS stations using a moving window approach temporally overlapping with both the surveys of a new GNSS network (PODELNET—PO DELta NETwork) (46 non-permanent sites measured in 2016 and 2018), and InSAR data (SBAS processing of Sentinel-1A/B images from 2014 to 2017). The authors investigated the integration between these data: since the InSAR technology does not perform well in high vegetated areas or areas with high temporal variability, the PODELNET sites represent an important improvement for the monitoring of the land subsidence in the PRD. Moreover, they highlighted that an integrated monitoring system, combining GNSS and InSAR data, permit to overcome the limits of the two techniques. The obtained results suggested that the land subsidence velocities in the easternmost part of the area of interest (of about −10 mm/y) were characterized by values greater than the ones located in the western sectors (in the order of −5 mm/y), which can be linked to the different morphological characteristics of the subsoil in the PRD.

Author Contributions: The three authors contributed equally to all aspects of this Editorial. All authors have read and agreed to the published version of the manuscript.

Funding: This research received no external funding.

Data Availability Statement: Not applicable.

Acknowledgments: The guest Editors would like to sincerely thank all the Authors who contributed to this Special Issue and the Reviewers who dedicated their time and provided the Authors with valuable and constructive recommendations. They would also like to thank the Editorial team of Remote Sensing for their support.

Conflicts of Interest: The authors declare no conflict of interest.

References

1. Fiaschi, S.; Fabris, M.; Floris, M.; Achilli, V. Estimation of land subsidence in deltaic areas through differential SAR interferometry: The Po River Delta case study (Northeast Italy). *Int. J. Remote Sens.* **2018**, *39*, 8724–8745. [CrossRef]
2. Zhou, C.; Gong, H.; Chen, B.; Gao, M.; Cao, Q.; Cao, J.; Duan, L.; Zuo, J.; Shi, M. Land Subsidence Response to Different Land Use Types and Water Resource Utilization in Beijing-Tianjin-Hebei, China. *Remote Sens.* **2020**, *12*, 457. [CrossRef]
3. Sopata, P.; Stoch, T.; Wójcik, A.; Mrocheń, D. Land Surface Subsidence Due to Mining-Induced Tremors in the Upper Silesian Coal Basin (Poland)—Case Study. *Remote Sens.* **2020**, *12*, 3923. [CrossRef]
4. National Research Council. *Mitigating Losses from Land Subsidence in the United States*; The National Academies Press: Washington, DC, USA, 1991; p. 58. [CrossRef]
5. Gido, N.A.A.; Bagherbandi, M.; Nilfouroushan, F. Localized Subsidence Zones in Gävle City Detected by Sentinel-1 PSI and Leveling Data. *Remote Sens.* **2020**, *12*, 2629. [CrossRef]
6. Saleh, M.; Becker, M. New estimation of Nile Delta subsidence rates from InSAR and GPS analysis. *Environ. Earth Sci.* **2018**, *78*, 6. [CrossRef]
7. Fabris, M. Coastline evolution of the Po River Delta (Italy) by archival multi-temporal digital photogrammetry. *Geomatics Nat. Hazards Risk* **2019**, *10*, 1007–1027. [CrossRef]
8. Fabris, M. Monitoring the Coastal Changes of the Po River Delta (Northern Italy) since 1911 Using Archival Cartography, Multi-Temporal Aerial Photogrammetry and LiDAR Data: Implications for Coastline Changes in 2100 A.D. *Remote Sens.* **2021**, *13*, 529. [CrossRef]
9. Benetatos, C.; Codegone, G.; Ferraro, C.; Mantegazzi, A.; Rocca, V.; Tango, G.; Trillo, F. Multidisciplinary Analysis of Ground Movements: An Underground Gas Storage Case Study. *Remote Sens.* **2020**, *12*, 3487. [CrossRef]
10. Cenni, N.; Fiaschi, S.; Fabris, M. Integrated use of archival aerial photogrammetry, GNSS, and InSAR data for the monitoring of the Patigno landslide (Northern Apennines, Italy). *Landslides* **2021**. [CrossRef]
11. Chen, X.; Achilli, V.; Fabris, M.; Menin, A.; Monego, M.; Tessari, G.; Floris, M. Combining Sentinel-1 Interferometry and Ground-Based Geomatics Techniques for Monitoring Buildings Affected by Mass Movements. *Remote Sens.* **2021**, *13*, 452. [CrossRef]
12. Grgić, M.; Bender, J.; Bašić, T. Estimating Vertical Land Motion from Remote Sensing and In-Situ Observations in the Dubrovnik Area (Croatia): A Multi-Method Case Study. *Remote Sens.* **2020**, *12*, 3543. [CrossRef]
13. Fuhrmann, T.; Garthwaite, M.C. Resolving Three-Dimensional Surface Motion with InSAR: Constraints from Multi-Geometry Data Fusion. *Remote Sens.* **2019**, *11*, 241. [CrossRef]
14. Chen, B.; Gong, H.; Lei, K.; Li, J.; Zhou, C.; Gao, M.; Guan, H.; Lv, W. Land subsidence lagging quantification in the main exploration aquifer layers in Beijing plain, China. *Int. J. Appl. Earth Obs. Geoinf.* **2019**, *75*, 54–67. [CrossRef]
15. Doke, R.; Kikugawa, G.; Itadera, K. Very Local Subsidence Near the Hot Spring Region in Hakone Volcano, Japan, Inferred from InSAR Time Series Analysis of ALOS/PALSAR Data. *Remote Sens.* **2020**, *12*, 2842. [CrossRef]
16. Dai, K.; Peng, J.; Zhang, Q.; Wang, Z.; Qu, T.; He, C.; Li, D.; Liu, J.; Li, Z.; Xu, Q.; et al. Entering the Era of Earth Observation-Based Landslide Warning Systems: A Novel and Exciting Framework. *IEEE Geosci. Remote Sens. Mag.* **2020**, *8*, 136–153. [CrossRef]
17. Fryksten, J.; Nilfouroushan, F. Analysis of clay-induced land subsidence in Uppsala City using Sentinel-1 SAR data and precise leveling. *Remote Sens.* **2019**, *11*, 2764. [CrossRef]
18. Even, M.; Westerhaus, M.; Simon, V. Complex Surface Displacements above the Storage Cavern Field at Epe, NW-Germany, Observed by Multi-Temporal SAR-Interferometry. *Remote Sens.* **2020**, *12*, 3348. [CrossRef]
19. Song, X.; Jiang, Y.; Shan, X.; Gong, W.; Qu, C. A Fine Velocity and Strain Rate Field of Present-Day Crustal Motion of the Northeastern Tibetan Plateau Inverted Jointly by InSAR and GPS. *Remote Sens.* **2019**, *11*, 435. [CrossRef]
20. Weiss, J.R.; Walters, R.J.; Morishita, Y.; Wright, T.J.; Lazecky, M.; Wang, H.; Yu, C. High-resolution surface velocities and strain for Anatolia from Sentinel-1 InSAR and GNSS data. *Geophys. Res. Lett.* **2020**, *47*, e2020GL087376. [CrossRef]
21. Mancini, F.; Grassi, F.; Cenni, N. A Workflow Based on SNAP–StaMPS Open-Source Tools and GNSS Data for PSI-Based Ground Deformation Using Dual-Orbit Sentinel-1 Data: Accuracy Assessment with Error Propagation Analysis. *Remote Sens.* **2021**, *13*, 753. [CrossRef]
22. Cenni, N.; Fiaschi, S.; Fabris, M. Monitoring of Land Subsidence in the Po River Delta (Northern Italy) using geodetic networks. *Remote Sens.* **2021**, *13*, 1488. [CrossRef]