Insights into increasing land subsidence along Nigeria's Gulf coast

Femi Emmanuel Ikuemonisan[1,2,*], Philip S.J. Minderhoud[3,4,5], Leon Hauser[6], Vitalis Chidi Ozebo[1], Roberta Boni[7], Claudia Zoccarato[4], Marie-Noëlle Woillez[8], Pietro Teatini[4]

1 Department of Physics (Geophysics Research Group), University of Lagos, Nigeria
2 School of Pre-Degree Studies (Physics Unit), Lagos State University, Lagos, Nigeria *Correspondence to Femi Ikuemonisan (femi.ik@yahoo.com),
3 Soil Geography and Landscape Group, Wageningen University, Wageningen, The Netherlands,
4 Department of Civil, Environmental and Architectural Engineering, University of Padova, Padova, Italy,
5 Department of Subsurface and Groundwater Systems, Deltares Research Institute, Utrecht, The Netherlands
6 Leiden University (check), Leiden, The Netherlands,
7 University of Urbino, Urbino, Italy,
8 French Development Agency (AFD), Paris, France

Session: Measuring and Monitoring of land Subsidence
Focus: Coastal areas

Abstract

Land subsidence is a threat to environmental sustainability and can pose greater dangers with a proportionate rise in bordering sea levels. Nigerian low-lying coastal region and the various economic activities around the coast are vulnerable to rising sea level because of global warming. However, no existing study has examined sea-level rise combined with land subsidence. This study reviews available literature on land subsidence and consequential relative sea-level rise along Nigerian coastlines and identifies research gaps. Subsidence occurs, at least, in four Nigerian coastal cities – Lagos, Port Harcourt, Uyo, and Warri. The highest observed subsidence (up to 520 mm/year) is found in the Harcourt area, which is likely due to continued groundwater pumping and oil and gas extraction.

Keywords: Subsidence; Relative sea-level rise; InSAR; Nigeria; Gulf of Guinea; Port Harcourt

Introduction

Nigeria is bounded to the south by the Atlantic Ocean and has the longest coast among the countries in the Gulf of Guinea, with an approximate length of 853 km. The country has one of the largest populations in the World, with an estimated 212 million inhabitants and a projected growth rate of 3.1% per year (United Nations, 2019). With this projection, Nigeria will become the third largest country by population within the next three decades. Most of country's industries are situated along the Gulf of Guinea, including seaports and harbors a significant number of facilities to develop oil fields. This has led to a dramatic increase in population. Consequently, the rate of groundwater pumping and swampland reclamation, which are known causes of land subsistence worldwide, are accelerating dramatically.

Subsidence is a major environmental issue impacting coastal cities of the World and threatening environmental sustainability. Efficient modelling of RSLR, i.e. the combined impact of sea-level rise (SLR) and land subsidence, is a critical step to mitigate the risk of RSLR-induced hazards in coastal cities, as continuous monitoring and observation are cost-prohibitive and time-consuming. Both monitoring and modelling raise awareness for environmental authorities and residents about the hazards of the contribution of land subsidence to rising sea levels. In addition, modelling can provide significant insights into future trends (Shirzaei et al., 2021).

This study synthesizes previous topical research work relating to land subsidence evolution and sea-level change in the Nigerian low-lying coast to identify knowledge gaps and for further studies. In addition, this study reveals recent subsidence trends in the Port Harcourt area, which is one of the areas where the highest subsidence rates have been estimated over the last years using recently acquired Sentinel-1 data.

Study area and approach

Nigeria coastline runs along Africa west coast in the Gulf of Guinea. The coast is situated in a low-lying elevation between latitude 4°10′–6°20′ N and longitude 2°45′–8°32 E. The elevation map of the study area is shown in Figure 1. The Nigeria low-lying coast can be classified as the western coast and the eastern coast, spanning eight southern Nigerian States and is host to several coastal cities. These include Lagos, one of the world most rapidly expanding megacities, Warri and Port Harcourt, located in the Niger Delta region and home to Nigeria’s oil and gas sector. Across the Niger Delta region, there are over 900 oil and gas field establishments in various towns and communities, with nearly 800 operational oil wells. Available literature is reviewed following the five-stage review framework by Arksey and O’Malley (2005). For the Port Harcourt case study, 217 Sentinel-1 images (Track 30, Ascending orbit) were processed on the Geohazard Thematic Exploitation Platform (Geohazard TEP) using the Parallel Small BAseline Subset (P-SBAS) algorithm (Casu et al., 2014) to generate a map of average land displacement and displacement time series.

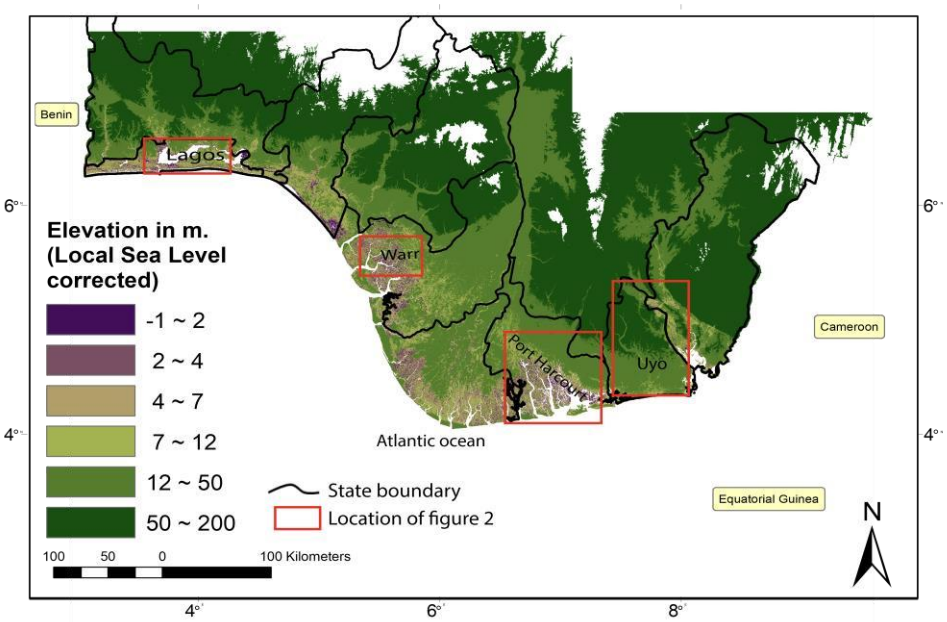

Figure 1 Elevation map of the study area

Results and discussions

The literature review yielded few studies reporting on land subsidence for four major areas along the Nigerian low-lying coast: Port Harcourt, Lagos, Warri, and Uyo, see Figures 1 for their location. Figure 2 shows the spatial distribution of land subsidence in these areas and Table 1 presents a summary on the temporal coverage and methods used to monitor land subsidence.

Land subsidence in the Port Harcourt area

The Port Harcourt area experiences the highest land subsidence rates presently known along the Nigerian coast (Figure 2a). Land subsidence rates at selected oil well locations in this area accelerated dramatically from 33 mm/year in 1982 to 550 mm/year in 2000 (Abija et al., 2020). In a related study by Uko et al. (2018), land subsidence in the Port Harcourt area varied between 67 to 200 mm/year at some levelling sites in 2018. The observed high subsidence rate is attributed to reservoir compaction caused by hydrocarbon production in the area. The compaction of onshore oil fields is predicted to reach staggering 15.5 m at near optimal reservoir pressure drawdown, with a possibility to extend significant land subsidence toward the coastline (Abia & Abam, 2022). As shown in Figure 1, the elevation of this area is approximately 4 m above msl.

S/N	**Location**	**Temporal coverage**	**Method: data**	**Max. Subsidence rate (mm/year)**	**References**
1	Lagos	2002 – 2011	InSAR: Envisat-ASAR	7.0	Mahmud et al. (2016)
		2002 – 2019	InSAR: Sentinel-1, TerraSAR-X, COSMOSkyMed	9.5	Cian et al. (2019)
		2015 – 2019	InSAR: Sentinel-1	94.0	Ikuemonisan et al. (2021)
2	Port Harcourt area	1988 – 2003	Analytical modelling, Leveling, GPS	520.0 (expected estimate) 200	(Abia & Abam, 2022) Uko et al. (2018) Uko & Otugo (2016)
3	Uyo area	-	Modelling: Groundwater extraction	Very High (qualified in classes)	Udoh & Udofia (2014)
4	Warri	2006 - 2010	InSAR: Envisat-ASAR	5.0	Mahmud et al. (2016)

Table 1 Summary of land subsidence observations in Nigerian coastal cities

Land subsidence in the Lagos area

Various methods and satellite data have been deployed to monitor subsidence in Lagos. The maximum known subsidence rate as estimated by InSAR in the Lagos area is 94 mm/year, and is predicted to increase by over 20% in the coming years partly due to groundwater over-exploitation (Ikuemonisan et al., 2021). However, none of the methodologies provides exactly the same results. The observations cover consecutive time periods and show an accelerating trend towards present. InSAR-based study shows high subsidence rates for the southern part of Lagos, notably the areas along the Atlantic Ocean coast and the Lagos lagoons. As shown in the Figure 2b, approximately 340 km^2 of Lagos experiences severe subsidence, about 68% of the city's area. Major subsidence bowls developed across the Lagos causing frequent flooding as water inundates subsiding areas when precipitation exceeds infiltration.

Although various factors have been attributed to cause land subsidence in Lagos, a linear regression analysis between subsidence and groundwater level change (as estimated by Gravity Recovery and Climate Experiment (GRACE)) indicates a fair correlation between the two parameters (Ikuemonisan et al., 2021). The statistical correlation coefficient is in the order of ≈ 0.45, suggesting that groundwater extraction is one of the causes of land subsidence in Lagos. It is worth mentioning that GRACE provides coarse resolution of groundwater level change. Other drivers of land subsidence in this area may include natural compaction of unconsolidated sediments and compaction of the reclaimed wetland due to the weight of the overburden structure, as Lagos is predominantly set on a sedimentary formation.

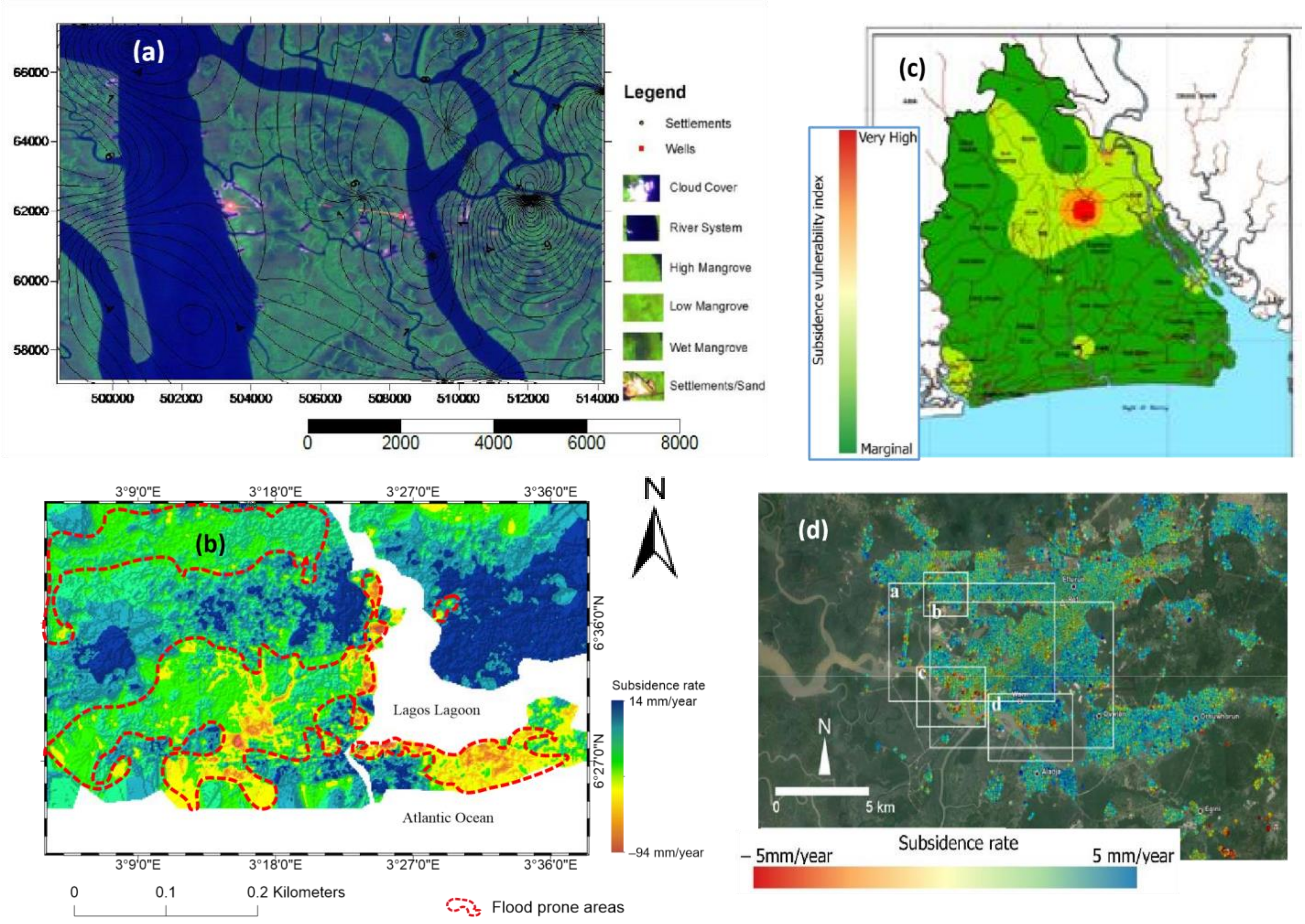

Figure 2 Spatial distribution of land subsidence in Nigerian low-lying coasts: (a) subsidence rate over baseline map of 1988 in the Port Harcourt area, southeast Niger Delta [After Uko et al., 2016]; (b) land displacement in Lagos as estimated by Sentinel-1 satellite between 2015 and 2020, showing subsidence bowls [Modified after Ikuemonisan et al., 2021]; (c) land subsidence in the Uyo area [After Udoh & Udofia (2014); (d) land displacement in the Warri area as estimated by Envisat-ASAR (2002 –2011) [After Mahmud et al., 2016].

Land subsidence in the Warri and Uyo areas

Previous studies also focused on land subsidence in the Warri and Uyo areas. Time series analysis of InSAR images acquired over Warri between 2006 and 2010 indicates that average subsidence amounts 5 mm/year. Subsidence in the area can predominantly be ascribed to excessive groundwater pumping and oil and gas extraction (Mahmud et al., 2016). In the Uyo area, land subsidence vulnerability has been assessed by Udoh and Udofia (2014) using water extraction data collected at the scale of the Akwa Ibom State. The study found that the Uyo area, particularly the built-up areas, are mostly vulnerable to land subsidence due to groundwater depletion, as shown in Figures 2(c) and (d).

InSAR study of the Port Harcourt area

Port Harcourt city has progressively grown in population over the last ten years, causing a rapid expansion of physical infrastructure, including high-rise buildings, housing, and industrial estates. In addition, Port Harcourt has a relatively low surface elevation, ranging from 4 m to 7 m (Figure 1). Figure 3 shows the spatial distribution of land subsidence as estimated by InSAR in the Port Harcourt area. The Sentinel-1 spatiotemporal analysis showed widespread coastal subsidence in the area. The maximum subsidence rate projected in the vertical axis is 50 mm/year. In general, subsidence rates range in coastal regions from 50 mm/year above the oil production areas to 26 mm/year in industrial areas. The southern coastal areas of Port Harcourt city, Onne, which is home to a major Nigerian seaport with adjoining oil fields has the highest subsidence rate. The displacement time series for the Port Harcourt area is depicted in Figure 3(b). The largest cumulative subsidence amounted to 370 mm over the last 7 years. Calibration of InSAR results would require the availability of independent absolute measurements, generally made available through GNSS stations. Only one station (RUST) was located in the study area and the record was processed at the Nevada Geodetic Laboratory. Unfortunately, the recorded time series is short (from 2011 to 2013) with two considerable gaps, making it impossible to derive a reliable trend of land movement.

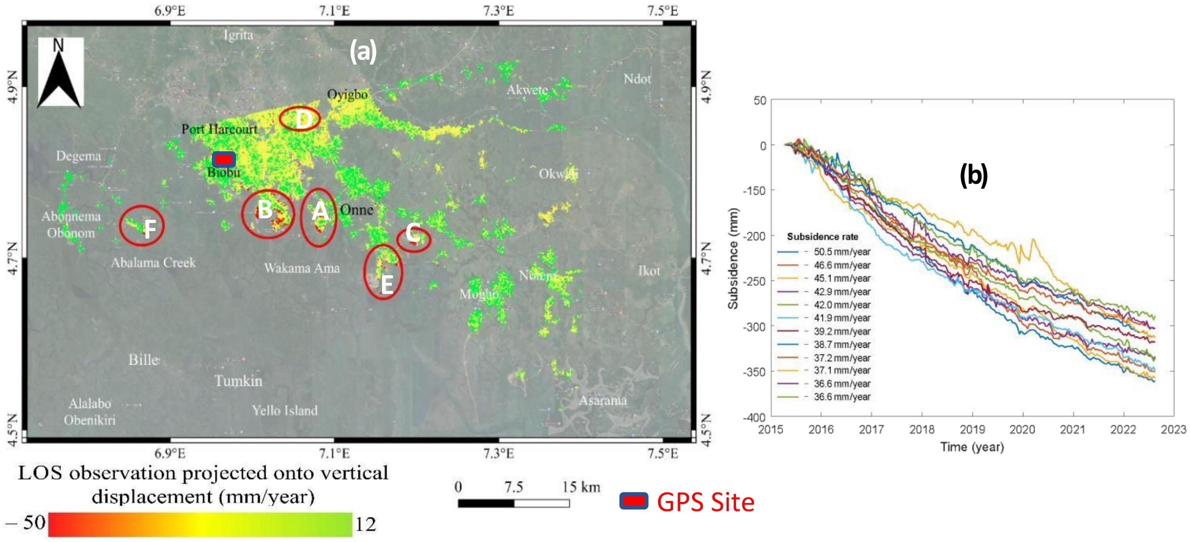

Figure 3 Spatial and temporal trend of land displacement in the Pot Harcourt area: (a) velocities based on Sentinel-1 observation (most subsided areas are highlighted with red ellipses). Features are underlain by a Google Earth map; (b) Displacement time series of the ten most subsided areas. Time series with subsidence rates of 50.5 mm/year and 46.6 mm/year belong to the ellipse A; time series with subsidence rates of 45.1 mm/year, 42.9 mm/year, and 42.0 mm/year belong to the ellipse B; time series with subsidence rates of 41.9 mm/year and 39.2 mm/year belong to the ellipse C; time series with subsidence rates of 38.7 mm/year belong to the ellipse D; time series with subsidence rates of 37.2 mm/year, 37.1 mm/year, and 36.6 mm/year belong to the ellipse E; time series for the ellipse F also have a subsidence rate of 36.6 mm/year.

Knowledge gaps and future research

A few previous studies revealed widespread land subsidence in parts of Nigeria's lowly coastal cities, but no detailed study provides useful information on the contribution of land subsidence to rising sea levels or the future trend of RSLR. The lack of operational GNSS stations to calibrate and validate InSAR measurements makes the entire InSAR outcome somewhat uncertain. Another significant knowledge gap is the lack of records of groundwater withdrawals and piezometric evolution over the last decades, which are necessary for efficient quantification of the role of groundwater depletion on land subsidence. For accurate local SLR projection and RSLR estimation, up-to-date observational studies are essential to assess the local sea-level changes and continuous piezometric measurements. Combined measurements of the recent sea-level changes with vertical land motion and piezometric data will significantly improve our capability to predict land subsidence and RSLR over the next decades.

Funding

This project is funded by the France Development Agency (AFD).

The Sentinel-1 datasets used for the Port Harcourt case study were processed on the Geohazard Thematic Exploitation Platform (Geohazard-TEP), supported by the European Space Agency (ESA) Network of Resources Initiative (NoR)''

References

Abija, F. & Abam, T. (2022). Predicting Ground Subsidence Due to Long Term Oil/Gas Production in A Niger Delta Basin, Nigeria: Implications for CO2 EOR and Geosequestration, (Preprint) https://doi.org/10.21203/rs.3.rs-357959/v1

Abija, F.A. Abam, T.K.S. Teme, S.C. Eze, C.L, (2020) Relative Sea Level Rise, Coastline Variability and Coastal Erosion in the Niger Delta, Nigeria: Implications for Climate Change Adaptation and Coastal Zone Management. J Earth Sci Clim Change 2020 11:9.

Casu, F., Elefante, E., Imperatore, P., Zinno, I., Manunta, M., De Luca, C., Lanari, R. (2014) SBAS-DInSAR Parallel Processing for Deformation Time Series Computation. IEEE JSTARS, doi: 10.1109/JSTARS.2014.2322671

Ikuemonisan, F. E., Ozebo, V. C., & Olatinsu, O. B. (2021). Investigation of Sentinel-1-derived land subsidence using wavelet tools and triple exponential smoothing algorithm in Lagos, Nigeria. *Environmental Earth Sciences*, 80(21). https://doi.org/10.1007/s12665-021-10020-1.

Mahmud, M. U., Yakubu, T. A., Adewuyi, T. O., Sousa, J. J., Ruiz-Armenteros, A. M., Bakoň, M., … Perissin, D. (2016). Subsidence monitoring in the coastal region of Nigeria using multi temporal interferometric synthetic aperture radar (MT-Insar). *In European Space Agency, (Special Publication)* ESA SP (Vol. SP-740). European Space Agency.

Shirzaei, M., Freymueller, J., Törnqvist, T. E., Galloway, D. L., Dura, T., & Minderhoud, P. S. J. (2020). Measuring, modelling and projecting coastal land subsidence. Nature Reviews Earth & Environment, 2(1), 40–58. https://doi.org/10.1038/s43017-020-00115-x

Udoh, F., & Udofia, E. (2014). Land Subsidence Monitoring Using Geographic Information System (GIS) Techniques in Akwa Ibom State, Nigeria. *Current World Environment Journal*, 9(1), 1–6. https://doi.org/10.12944/cwe.9.1.01.

Uko, E. D., Famuyibo, D. A., & Okiongbo, K. (2018). Estimation of Land Surface Subsidence Induced by Hydrocarbon Production in the Niger Delta, Nigeria, Using Time-Lapse Orthometric Levelling Data. *SSRN Electronic Journal*. https://doi.org/10.2139/ssrn.3214967.

United Nations, Department of Economic and Social Affairs, Population Division (2019). World Population Prospects 2019: Data Booket. ST/ESA/SER.A/424.