Land subsidence dynamics and inundation simulation in the Volta Delta: An application of InSAR and the Bathtub model

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Abstract

Deltas are important coastal landforms that are home to diverse services. However, population growth and climate change along with their cascading impacts have had profound impacts on their topography and evolution. Consequently, many deltaic regions are subsiding and are incessantly plagued with hazards that are increasing in both magnitude and frequency. Coastal hazards such as flooding and erosion are already apparent in Ghana's Volta Delta. To provide a holistic understanding of the surge in inundation and erosion events in the Volta Delta, this study assessed altimetric changes in the Volta Delta to establish the subsidence regime and measure this against increasing rates of Sea Level Rise (SLR). Using Interferometric Synthetic Aperture Radar (InSAR) technique and Global Positioning System (GPS) surveys, interferograms of Sentinel-1 data from 2016 to 2020 indicated deformation rates ranging from -9.16 mm/yr to 1.77 mm/yr. The highest subsiding areas were within the floodplains of the dominant lagoons and along the Bight of Benin—areas heavily influenced by human activities. Albeit recording upliftment in fault-controlled areas, the Delta is considered a subsiding delta. The surface geology, which extensively (~70% areal coverage) constitutes compressible alluvial sand, silt and clay is posited to be a major natural driver of subsidence in the Delta. An inundation risk assessment using a simple Bathtub model and IPCC projections was investigated for both SLR and Relative SLR (rSLR) scenarios. Under the SLR scenarios, projections are that 25.29%, 26.29% and 29.68% of the Delta will be flooded by 2040, 2060 and 2100 respectively whereas 26.02% (2040), 27.09% (2060) and 30.78% (2100) of the Delta area will be flooded under the rSLR scenarios. Coupled with climate change, subsidence will increase the flood extents of the Delta by 19.79 km^2 and exacerbate the vulnerability of the Delta to other coastal hazards. To mitigate impacts, the study recommends the use of alternative and environmentally-friendly energy and water sources; a continuous and long-term monitoring framework for drivers of change; a hybrid approach and review of coastal management strategies; and the establishment of continuous GPS stations, tidal stations, and elevation benchmarks.

Introduction

Coastal areas are regions of essential value that provide a myriad of services. Consequently, little over half of the world's major urban communities are situated in coastal zones, and living within 100 km of these zones is forty percent of the global population (Nicholls et al., 2007). Chances are that these numbers may have surged based on global population growth rates of 0.9% as of 2021 (World Bank Group, 2022). However, coastal zones are increasingly having their makeup features, functioning, existence and services being threatened to points of complete collapse (Stouthamer & Asselen, 2015). Due to their settings, elevations and proximities to the sea, several human interventions and climate change amongst other natural occurrences, have been major factors impacting the sustainable usage of coastal zones, and their ecosystem services and landforms (Danladi et al., 2017). Additionally, coastal areas are being confronted with a far more immediate threat of sinking, thus subsidence which is exacerbating prevalent coastal hazards and devastating impacts of climate change (Brown & Nicholls, 2015; Johnston et al., 2021; Restrepo-Ángel et al., 2021). Globally, deltas—one of several coastal landforms—are not exempted. Population growth in deltaic regions coupled with infrastructure developments and rising sea levels have had a profound impact on their topography (Styvitski et al., 2009). Many deltaic regions around the globe are losing land and subsiding (Brown et al., 2018; Nienhuis and van de Wal, 2021).

The study, therefore, seeks to establish the subsidence regime in Ghana's Volta Delta using geodetic methods, to provide a holistic understanding of the frequent flooding and erosion events in the Delta. Additionally, it seeks to assess the future flood vulnerability of the Delta by simulating future Sea Level Rise (SLR) and Relative Sea Level Rise (rSLR) scenarios.

Methods

PSI Analysis using the SNAP to StaMPS Approach

The satellite data used are Sentinel-1 (S1) Single Look Complex (SLC) Synthetic Aperture Radar (SAR) images which are freely accessible on the Copernicus Science Hub online platform—356 SAR images in total. The InSAR technique employed for this study was the Persistent Scatterer Interferometry (PSI) technique based on the Permanent Scatterer algorithm by Ferretti et al., (2001) and following the workflow of Höser (2018) and Cian et al. (2019). The PSI analysis was done using the Sentinel Application Platform (SNAP) software, Version 8 and the Stanford Method for Persistent Scatterers (StaMPS)/Multi-Temporal InSAR open-source toolbox, Version 4.1b (Hooper et al., 2012). Global Positioning System (GPS) survey on some Ground Control Points (GCPs) was employed as a geodetic method to calibrate the results obtained from the InSAR processing technique (Teatini et al. 2012; Amato et al., 2020).

Simple Bathtub (Inundation) Model

Based on the assumption that the InSAR-derived deformation rates remained linear with no horizontal land motion, the bathtub model was used as a simple inundation model to predict coastal flooding and inundation extents (Leal-Alvesm et al., 2020; Alarcon et al., 2022) in the Volta delta at varying timescales for both SLR and rSLR scenarios. The IPCC (2021) categorized 2021 to 2040 as near-term; 2041 to 2060 as mid-term; and 2081 to 2100 as long-term, thus informing the selection of the years 2040, 2060 and 2100 as prediction timelines. The DEM used was the Multi-Error-Removed Improved-Terrain (MERIT) DEM developed by Yamazaki et al. (2017). Errors such as absolute bias, stripe noise, speckle noise, and tree height bias were removed from available spaceborne DEMs (Yamazaki et al., 2017). The global sea level rise projections were obtained from the IPCC Sixth Assessment Report (AR6), Working Group I (IPCC, 2021)—all projections are relative to the year, 1900. The Shared

Socioeconomic Pathways (SSP) scenario 5-8.5 (central, medium confidence) characterized by very high greenhouse gas emissions was selected.

Results

The number of persistent scatterers (PS) generated from the PSInSAR methodology was 119,477 in total with an areal PS density of 66.52 PS/km2—excluding the water-covered surfaces. Along the Sentinel-1 line of sight (LOS), the PS deformation velocities (Figure 1) ranged from uplifting rates of 1.77 mm/yr to subsiding rates of -9.16 mm/yr. The number of PSs with uplifting rates was 0.19% of the total PSs obtained whereas the subsiding PSs made up the remaining 99.81% of the total PS number.

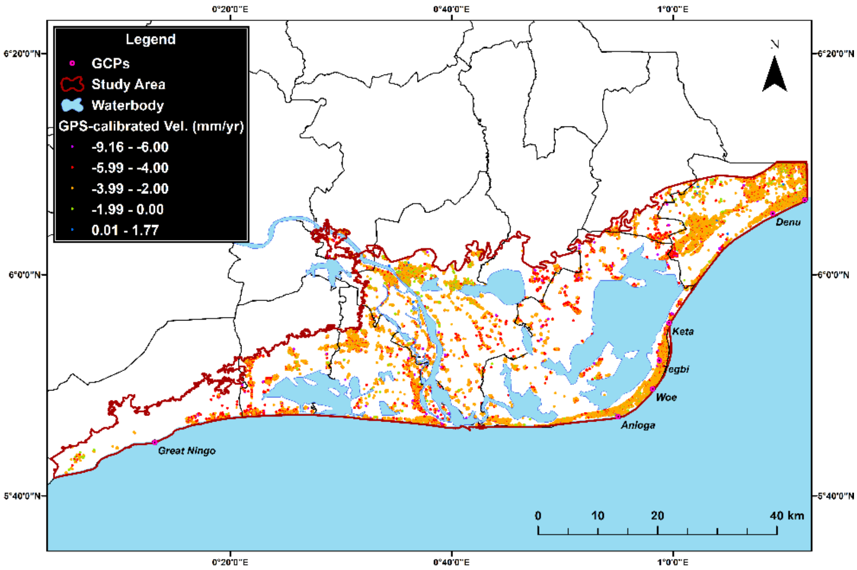

Figure 1 Map view of the line of sight (LOS) mean velocities of PSs in the Volta delta

Flood projections based on projected rSLR and SLR were done using the simple bathtub model to map out inundation-prone areas or hotspots within the Volta (Figure 2).

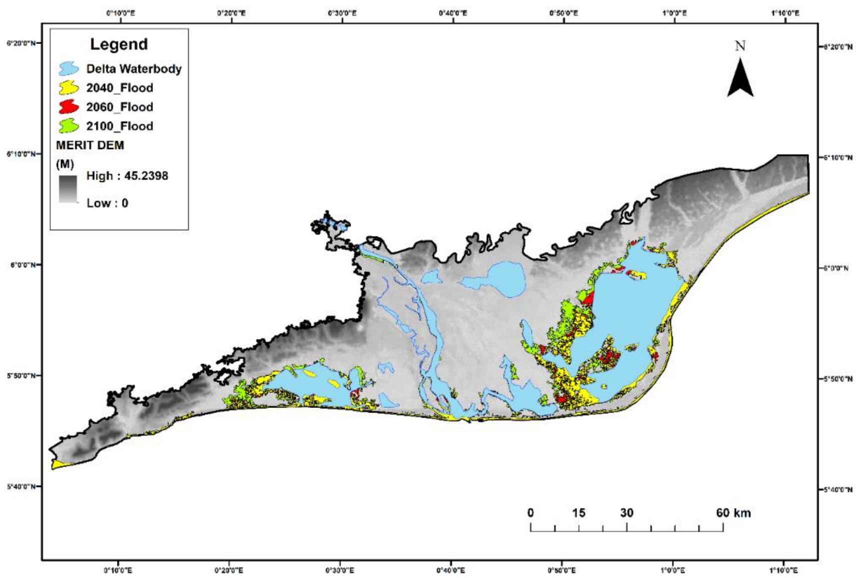

Figure 2 A map view of rSLR inundation projections in the Volta Delta using the bathtub model

The inundation risk assessment using a simple Bathtub model and IPCC projections was investigated for both SLR and rSLR scenarios. Under the SLR scenarios, projections are that 25.29%, 26.29% and 29.68% of the Delta will be flooded by 2040, 2060 and 2100 respectively whereas 26.02% (2040), 27.09% (2060) and 30.78% (2100) of the Delta area will be flooded under the rSLR scenarios (Figure 3A). The differences in the extent of areal flooding between rSLR and SLR show an inclining trend from 2040 to 2100 (Figure 3B).

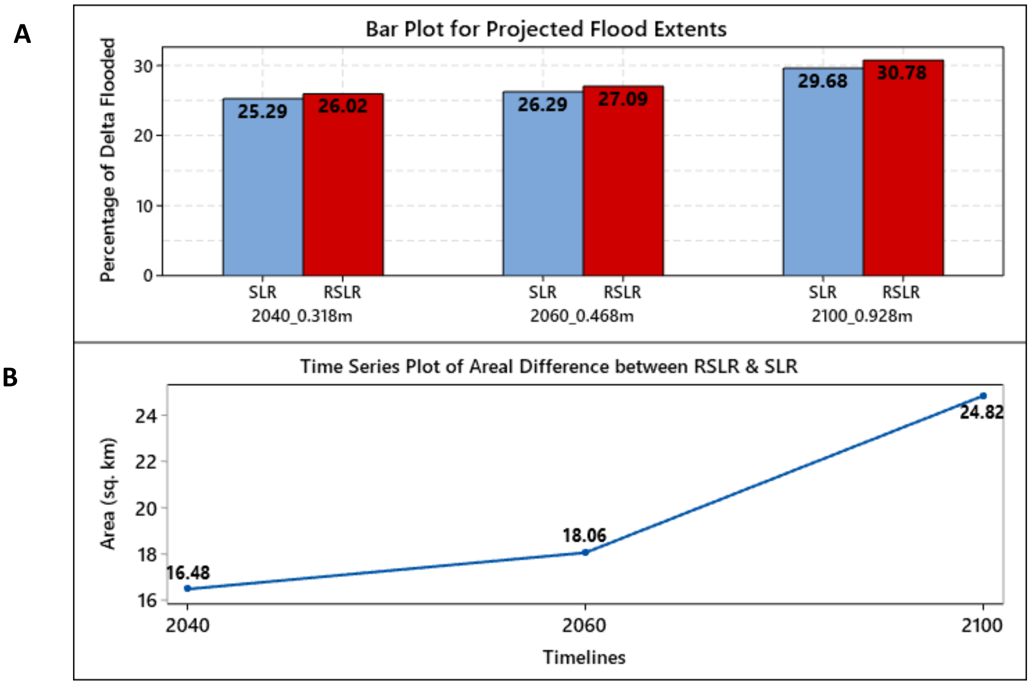

Figure 3 A graph showing projections of Delta flood extents and areal differences between SLR and rSLR scenarios

Conclusion

Based on the dominance of PSs (over two-thirds of total PSs) with subsiding rates, the Volta Delta is classified as a subsiding delta. Areas mostly located within the floodplains of the two dominant lagoons and lower Delta plain recorded subsiding velocities exceeding -8 mm/yr. The coastal stretch from Keta to Hlorve has been identified as one of the most subsiding areas and is already a hotspot for periodic floods and erosion. Subsidence in coastal hotspots will increase the depth and coverage extent of the floods. The inundation projections in this study for both SLR and rSLR scenarios suggest a substantial surge in Delta inundation along with more devastating impacts even in the near term (2040). The projection timelines show an inclining trend in areal inundation for both SLR and rSLR with a minimum of 29.68% of the Delta area being inundated by the end of the century. Averagely, subsidence (rSLR) will increase the flood extents of the Delta by 19.79 km^2 when compared to SLR scenarios. These findings, therefore, accentuate the need to implement measures to stall the impending threats subsidence poses to the sustainable use of the Volta Delta.

References

Alarcon, V. J., Linhoss, A. C., Kelble, C. R., Mickle, P. F., Sanchez-Banda, G. F., Mardonez-Meza, F. E., ... & Ashby, S. L. (2022). Coastal inundation under concurrent mean and extreme sea-level rise in Coral Gables, Florida, USA. *Natural Hazards*, 111(3):2933-2962, https://doi.org/10.1007/s11069-021-05163-0

Amato, V., Aucelli, P. P. C., Corrado, G., Di Paola, G., Matano, F., Pappone, G., & Schiattarella, M. (2020). Comparing geological and Persistent Scatterer Interferometry data of the Sele River coastal plain, southern Italy:

Implications for recent subsidence trends. *Geomorphology*, 351, 106953. https://doi.org/10.1016/j.geomorph.2019.106953

Brown, S., & Nicholls, R. J. (2015). Subsidence and human influences in mega deltas: The case of the Ganges–Brahmaputra–Meghna. *Science of the Total Environment*, 527–528, 362–374. https://doi.org/10.1016/j.scitotenv.2015.04.124

Brown, S., Nicholls, R. J., Lázár, A. N., Hornby, D. D., Hill, C., Hazra, S., … Tompkins, E. L. (2018). What are the implications of sea-level rise for a 1.5, 2 and 3 °C rise in global mean temperatures in the Ganges-Brahmaputra-Meghna and other vulnerable deltas? *Regional Environmental Change*, 1–14. https://doi.org/10.1007/s10113-018-1311-0

Cian, F., Blasco, J. M. D., & Carrera, L. (2019). Sentinel-1 for monitoring land subsidence of coastal cities in Africa using PSInSAR: A methodology based on the integration of SNAP and staMPS. *Geosciences (Switzerland*), 9(3). https://doi.org/10.3390/geosciences9030124

Danladi, I. B., Kore, B. M., & Gül, M. (2017). Vulnerability of the Nigerian coast: An insight into sea level rise owing to climate change and anthropogenic activities. *Journal of African Earth Sciences*, 134, 493–503. https://doi.org/10.1016/j.jafrearsci.2017.07.019

Ferretti, A., Prati, C., Rocca, F., Inf, D.E., 2001. Permanent scatterers in SAR interferometry. IEEE *Transactions on Geoscience and Remote Sensing* 39 (1), 8–20.

Hooper A; Bekaert D; Spaans K; Arikan M (2012), Recent advances in SAR interferometry time series analysis for measuring crustal deformation, *Tectonophysics*, 514-517, pp.1-13. doi:10.1016/j.tecto.2011.10.013

Höser, T. (2018). Analysing the Capabilities and Limitations of InSAR using Sentinel-1 data for Landslide Detection and Monitoring. *University of Bonn*. https://doi.org/10.13140/RG.2.2.35085.59362

IPCC, 2021: Summary for Policymakers. In: *Climate Change 2021: The Physical Science Basis. Contribution of Working Group I to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change* [Masson-Delmotte, V., P. Zhai, A. Pirani, S.L. Connors, C. Péan, S. Berger, N. Caud, Y. Chen, L. Goldfarb, M.I. Gomis, M. Huang, K. Leitzell, E. Lonnoy, J.B.R. Matthews, T.K. Maycock, T. Waterfield, O. Yelekçi, R. Yu, and B. Zhou (eds.)]. Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA, pp. 3−32, doi:10.1017/9781009157896.001.

Johnston, J., Cassalho, F., Miesse, T., & Ferreira, C. M. (2021). Projecting the effects of land subsidence and sea level rise on storm surge flooding in Coastal North Carolina. *Scientific Reports*, 11(1), 1–13. https://doi.org/10.1038/s41598-021-01096-7

Leal-Alves, D. C., Weschenfelder, J., da Guia Albuquerque, M., de Almeida Espinoza, J. M., Ferreira-Cravo, M., & de Almeida, L. P. M. (2020). Digital elevation model generation using UAV-SfM photogrammetry techniques to map sea-level rise scenarios at Cassino Beach, Brazil. *SN Applied Sciences,* 2(12), 1-19.

Nicholls, R.J., Wong, P.P., Burkett, V., Codignotto, J., Hay, J., McLean, R., Ragoonaden, S.; Woodroffe, C. D.; Abuodha, P. A. O.; Arblaster, J.; Brown, B.; Forbes, D.; Hall, J.; Kovats, S.; Lowe, J.; McInnes, K.; Moser, S.; Rupp-Armstrong, S.; Saito, Y., 2007. Coastal systems and low-lying areas. In: Parry, M.L., Canziani, O.F., Palutikof, J.P., van der Linden, J.P., Hanson, C.E. (Eds.), # Climate Change 2007: Impacts, Adaptation and Vulnerability: Contribution of Working Group II to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change. *Cambridge University Press*, Cambridge, UK, pp. 315–356. http://ro.uow.edu.au/scipapers/164

Nienhuis, J. H., & van de Wal, R. S. W. (2021). Projections of Global Delta Land Loss From Sea-Level Rise in the 21st Century. *Geophysical Research Letters*, 48(14), 1–9. https://doi.org/10.1029/2021GL093368

Restrepo-Ángel, J. D., Mora-Páez, H., Díaz, F., Govorcin, M., Wdowinski, S., Giraldo-Londoño, L., … Duque-Trujillo, J. F. (2021). Coastal subsidence increases vulnerability to sea level rise over twenty-first century in Cartagena, Caribbean Colombia. *Scientific Reports*, 11(1), 1–13. https://doi.org/10.1038/s41598-021-98428-4

Stouthamer, E., & Asselen, S. V. A. N. (2015). *DRIVERS OF DELTA SUBSIDENCE*. In IAHR World Congress (pp. 1–2). https://doi.org/10.1038/ngeo629.2

Syvitski, J. P. M., Kettner, A. J., Overeem, I., Hutton, E. W. H., Hannon, M. T., Brakenridge, G. R., … Nicholls, R. J. (2009). Sinking deltas due to human activities. *Nature Geoscience*, (September), 1–6. https://doi.org/10.1038/ngeo629

Teatini, P., Tosi, L., Strozzi, T., Carbognin, L., Cecconi, G., Rosselli, R., & Libardo, S. (2012). Resolving land subsidence within the Venice Lagoon by persistent scatterer SAR interferometry. *Physics and Chemistry of the Earth*, 40–41, 72–79. https://doi.org/10.1016/j.pce.2010.01.002

World Bank Group. (2022). Population growth (annual %). Retrieved from https://data.worldbank.org/indicator/SP.POP.GROW (Accessed on 26th July, 2022).

Yamazaki, D., Ikeshima, D., Tawatari, R., Yamaguchi, T., O'Loughlin, F., Neal, J. C., … Bates, P. D. (2017). A high-accuracy map of global terrain elevations. *Geophysical Research Letters*, 44(11), 5844–5853. https://doi.org/10.1002/2017GL072874