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A scoping review of the vulnerability of Nigeria's coastland to sea-level rise and the contribution of land subsidence

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A scoping review of the vulnerability of Nigeria's coastland to sea-level rise and the contribution of land subsidence

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Abstract

Nigeria's low-lying coastal region, with its various economic activities, is vulnerable to global sea-level rise triggered by climate change. In some areas, this threat can be amplified by land subsidence, which can severely hamper coastal resilience. Several studies have investigated the vulnerability of Nigeria to global sea-level rise, but only few studies have investigated the role of increasing subsidence rates in some low-lying coastal cities, and none has provided a comprehensive review of the combined effects of these two phenomena. We propose here a synthesis of available literature on land subsidence and relative sea-level rise along the Nigerian coasts and identify current knowledge gaps. In addition, this study provides an in-depth analysis of land subsidence in the Port Harcourt area, using recently acquired Sentinel-1 satellite data. The findings indicate that land subsidence occurs in four coastal area: Lagos, Port Harcourt, Uyo, and Warri. However, the absence of active GNSS stations to calibrate and validate InSAR measurements poses the results quite uncertain. Another significant knowledge gap is the lack of records of groundwater withdrawals and piezometric evolution in recent decades. This information is necessary for reliable quantification of the link between groundwater extractions and land subsidence. Integrating measurements of recent sea-level changes with vertical land motion and piezometric data would be necessary to improve knowledge on land subsidence in Nigeria and provide relative sea-level rise projections. It is necessary to separate processes occurring on a global scale, such as sea-level rise, which are not directly under the control of the Nigerian authorities, from processes occurring locally, such as anthropogenic land subsidence, which could be mitigated. This study is a first step towards the development of effective mitigation and adaptation strategies against relative sea-level rise in Nigeria.

Keywords

Gulf of Guinea; Land subsidence; Nigeria; Sea-level rise; SBAS-InSAR.

Acknowledgements

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Résumé
Les régions côtières de faible altitude du Nigéria, avec leurs diverses activités économiques, sont vulnérables à la montée du niveau marin global causé par le changement climatique. Dans certaines zones, cette menace peut être amplifiée par la subsidence, qui peut sévèrement affecter la résilience côtière. Plusieurs études ont examiné la vulnérabilité des zones côtières nigérianes à la montée du niveau marin global, mais peu se sont penchées sur le rôle des taux de subsidence croissants dans certaines villes côtières de basse altitude, et aucune n'a fourni un examen complet des effets combinés des deux phénomènes. Nous proposons ici une synthèse de la littérature disponible sur la subsidence et la montée du niveau marin relatif le long des côtes nigérianes, et identifions les lacunes dans les connaissances actuelles sur ce sujet. Cette étude fournit également une analyse approfondie de la subsidence dans la région de Port Harcourt, basée sur des données satellitaires récentes de Sentinel-1. Les résultats indiquent que quatre régions côtières sont affectées par la subsidence : Lagos, Port Harcour, Uyo et Warri. Cependant, l'absence de stations GNSS actives pour calibrer et valider les mesures InSAR rend les résultats incertains. Une autre lacune importante est le manque de données sur l'exploitation des eaux souterraines et l'évolution du niveau piézométrique au cours des dernières décennies. Cette information est nécessaire pour quantifier de façon fiable le lien entre extractions d'eau souterraines et subsidence. Combiner des mesures récentes de changement du niveau marin avec les mouvements verticaux du sol et des données piézométriques serait nécessaire pour améliorer la connaissance sur la subsidence au Nigéria et fournir des projections de montée relative du niveau marin. Il est nécessaire de distinguer les phénomènes d'échelle globale - comme la montée du niveau marin - qui ne sont pas directement contrôlables par les autorités nigérianes, et les processus locaux, comme la subsidence d'origine anthropique, qui pourraient être atténués. Cette étude est une première étape vers le développement de stratégies d'atténuation et d'adaptation efficaces face à la montée relative du niveau marin au Nigéria.

Mots-clefs
Golfe de Guinée; subisence; Nigéria; niveau marin; SBAS-InSAR.

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Introduction

General context

The soft coastline of the Gulf of Guinea is lowly elevated and is particularly vulnerable to erosion and sea-level rise (PRLEC-UEMOA, 2010). Many capital cities are located along the coast, including megacities with millions of inhabitants such as Lagos, Abidjan and Accra. Population projections for these cities suggest a staggering demographical increase in the coming decades (United Nations, 2018). In Ghana, Benin, Togo, and Nigeria, most of the economic activities are located within the coastal zone.

The entire coastline is currently experiencing alarming coastal erosion rates, up to several meters per year (e.g. Croitoru et al., 2019). The main causes of these phenomena are generally linked to human activities: sand extraction, decrease in sedimentary input from rivers due to upstream dams, port developments or even coastal protection structures that accentuate erosion downstream (Abessolo et al., 2021). As a result, the problem is well-studied in the region and various programs aim to put in place coastal protection measures, such as the West African Coastal Areas Management Program (WACA) from the World Bank.

On the other hand, studies of impacts and vulnerability to sea-level rise (SLR) in the context of climate change appear to be more limited. One can find in the literature various studies conducted on a very local scale (e.g. Addo & Adeyemi (2013); Idowu & Home (2015); Dossou & Glehouenou-Dossou (2007)) or sub-regional (e.g. Onwuteaka (2014) and Musa (2018) for the Niger Delta). Some global studies also give orders of magnitude on the risks of submersion for the countries of the Gulf of Guinea (Dasgupta et al. (2007); Brown et al. (2011); Kulp & Strauss (2019)). However, this work suffers from important limitations, linked among other things to the use of inaccurate satellite altimetry data. Recent advances in global elevation data (Hooijer & Vernimmen, 2021; Hawker et al., 2022) provide exciting opportunities to re-evaluate coastal elevation and assess potential sea-level rise vulnerability of this fast-developing region.

In addition, new research shows that while sea level is rising as a result of global warming, the majority (51-70%) of the present-day *relative* sea-level rise (rSLR) experienced by people worldwide is caused by land and coastal city sinking, i.e. land subsidence (Nicholls et al., 2021). Globally coastal land subsidence is critically under-quantified and the Gulf of Guinea region, where data on subsidence is completely lacking (Herrera-Garcia, et al., 2021), is no exception to this. This underlines the importance of including vertical land motion component to climate change-driven SLR to assess the complete effect of rSLR.

In this context, the ENGULF[1] (Coastal land subsidENce in the GULF of Guinea) research program aims at improving the assessment of exposure to relative sea-level rise along the Gulf of Guinea's coastline by providing new data and knowledge on coastal subsidence in the area. Preliminary work of this program was conducted with three main objectives: 1) Improving the coastal elevation assessment and assessing current scientific literature on coastal vulnerability for the Gulf of Guinea region; 2) Identifying the main knowledge gaps and critical geographical areas; 3) Assessing current knowledge on coastal land subsidence in Nigeria and Ghana. This study presents the results of the Nigeria case while the regional assessment and the Ghana case are presented in Hauser et al. (2023) and Avornyo et al. (2023) respectively.

Nigeria socio-economic context

Nigeria has one of the largest populations in the world, with an estimated 212 million residents in an area of approximately 923,768 km². Because of its high birth rate, early marriage occurrences, and net migration rates, partly from migrants coming from neighboring countries through Nigeria's porous borders, the population of Nigeria is rising dramatically, with an estimated growth rate of 3.1% per year (United Nations, 2019). Based on

[1] https://www.afd.fr/en/carte-des-projets/engulf-program-assessing-exposure-relative-sea-level-rise-along-gulf-guinea

this estimate, Nigeria's population will reach more than 400 million by the end of 2050s and become the third largest in the world by 2047 (United Nations, 2019).

The country is bounded to the south by the Atlantic Ocean and has the largest amount of coastline among the countries in the Gulf of Guinea, with an approximate length of 853 km. The coastline is low-lying and predominantly a combination of Pleistocene and Holocene sands and recent muddy silts. Low-lying coasts are typically exposed to various anthropogenic and natural hazards such as storm surges, tsunamis, flooding, and coastal erosion (Odunuga et al., 2014; Agboola & Ayanlade, 2016; Ohwo, 2018; Efiong & Ushie, 2019). Despite this, most of the world's population resides on coastal regions because of the various economic benefits they offer, including improved revenue bases from tourism, international trade, fishery, sand mining, and lumbering (Ikuemonisan & Ozebo, 2020; Shirzaei et al., 2021). The Nigerian lowly coastland is a large, diverse area where several commercial and industrial activities are concentrated, ranging from seaport activities to oil and gas exploitation, forestry activities and sand mining. Over 65% of the country's businesses are in the coastal cities and all the Nigerian major seaports (including Lagos Port, Warri Port, and Calabar Port) are located along the coast. Nearly all oil and gas exploitation in Nigeria occurs along the coastline and the adjoining low-lying areas.

Nigeria's coastal cities are marked by rapid population growth because of their location at the land-sea interface and the development of commercial activity in the coastal areas. Approximately 25% of the Nigerian population lives along the coast, which corresponds to over 50 million people, of which nearly 67% live in informal accommodations with restricted access to basic amenities and infrastructure (Guarneri et al., 2020). Because most of the coastal cities are located on a cluster of creeks and islands with flanked lagoons, their urban sprawl has not been adequately managed (Olajide et al., 2018). There is a massive deficit in the functional drainage system and public water supply system. Furthermore, groundwater access is mostly unregulated, and many homes depend on water wells or boreholes for drinking water (Balogun et al., 2017; Healy et al., 2020; Shiru et al., 2020; Ikuemonisan et al., 2021a). All of these can seriously impact the ecosystem if adequate and timely countermeasures are not implemented.

An area exposed to relative sea-level rise

Nigerian low-lying coastal region and its various economic activities is vulnerable to global SLR induced by global warming (Nwankwoala, 2012; Obia et al., 2015; Croitoru et al., 2020; Danladi et al., 2017, 2020). According to the latest Assessment Report of the Intergovernmental Panel on Climate Change (IPCC, 2021), global mean sea level increased by 0.20 [0.15 to 0.25] m between 1901 and 2018. Average rate of SLR is accelerating and now reaches about 3.7 mm/year. The rise will continue over the 21st century; current projections by 2100 compared to 1995-2014 range from 0.28-0.55 m under a very low greenhouse gas (GHG) emission scenario, (SSP1-1.9) to 0.63-1.01 m under a very high GHG emission scenario (SSP5-8.5) but higher values cannot be ruled out given the high uncertainties on the evolution of polar ice sheets. On longer time-scales (several centuries to millennia), sea level is committed to further rise by several meters.

However, in some areas, the local SLR will be greater than the global average due to changes in ocean circulations or local salinity values and climate variability (Cazenave & Cozannet, 2014). In addition, land subsidence can considerably worsen SLR by sinking the low-lying regions (Minderhoud et al., 2020, Liu et al., 2020; Sarah et al., 2021). It is therefore crucial to also consider local processes which can drive vertical land movement to correctly assess people's exposure to rising sea level.

The vertical land motion can be classified into upward ground displacement (uplift) and downward ground displacement (land subsidence). In this review, henceforth, the combined downward motion of various vertical land motion processes will be referred to as land subsidence. Land subsidence is one of the environmental problems affecting major urban cities of the world (Nicholls et al., 2021) and is widespread in coastal low-elevation areas, populated cities, and irrigated areas (Osmanoğlu et al., 2011; Teatini et al., 2011). The drivers of land subsidence can be natural or anthropogenic (Shirzaei et al., 2021). Natural drivers of land subsidence include sediment loading and isostasy (Wolstencroft et al., 2014), volcanic eruption, tectonic activities (Kobayashi et al., 2015; Leeper et al., 2017), natural compaction of unconsolidated sediments (Zoccarato et al., 2018), and peatland oxidation (van Asselen et al., 2018). On the other hand, anthropogenic drivers of land subsidence include aquifer overexploitation, oil and gas withdrawals, and earth surface loading due to urbanization (Husnayaen et al., 2018).

Land subsidence is a serious threat to environmental sustainability, particularly in coastal cities (Hamdani et al., 2021). It can cause a variety of ecological risks in vulnerable areas and accelerates the exposure to local SLR-related disasters in low-elevation coastal cities (Bott et al., 2021), increasing the risk of climate change-induced hazards such as flooding and coastal erosion. Land subsidence can also cause damage to civil infrastructures (Andreas et al., 2017; Ohenhen & Shirzaei, 2022), increase saline water intrusion in groundwater and surface freshwater, and reduce aquifer storage capacity (Koster et al., 2018). In the absence of effective mitigation and adaptation strategies, continued land subsidence can aggravate the submergence of vulnerable areas and make their protection unsustainable.

Relative sea-level rise (rSLR) is the combination of "absolute" SLR triggered by climate change and the various vertical land motion processes, as expressed in Equation 1:

$$rSLR = SLR + VLM \qquad (1)$$

where $rSLR$ is *relative* sea-level rise, SLR global sea-level rise and VLM the vertical land motion.

On the Nigerian coastland, rSLR is expected to be much higher than global mean SLR, particularly in the Niger-Delta area where oil and gas extraction has been taking place, as well as in Lagos, where a larger proportion of industries and population heavily depends on groundwater. Although previous studies have provided useful insight into the vulnerability of the Nigerian low-lying coast to local SLR, the contribution of subsidence to SLR experienced by people has received little or no attention.

The combined effects of anthropogenic and natural process along the Nigerian coastal regions have caused various ecological problems for the coastal cities. Because of the dynamic nature of coastlines and the varying driving forces of VLM and global SLR, there is a pressing need for modeling and continued monitoring of the coastlines. Such monitoring would raise awareness for the government authorities and the people about the risks and impacts of the contribution of land subsidence to the rising sea level.

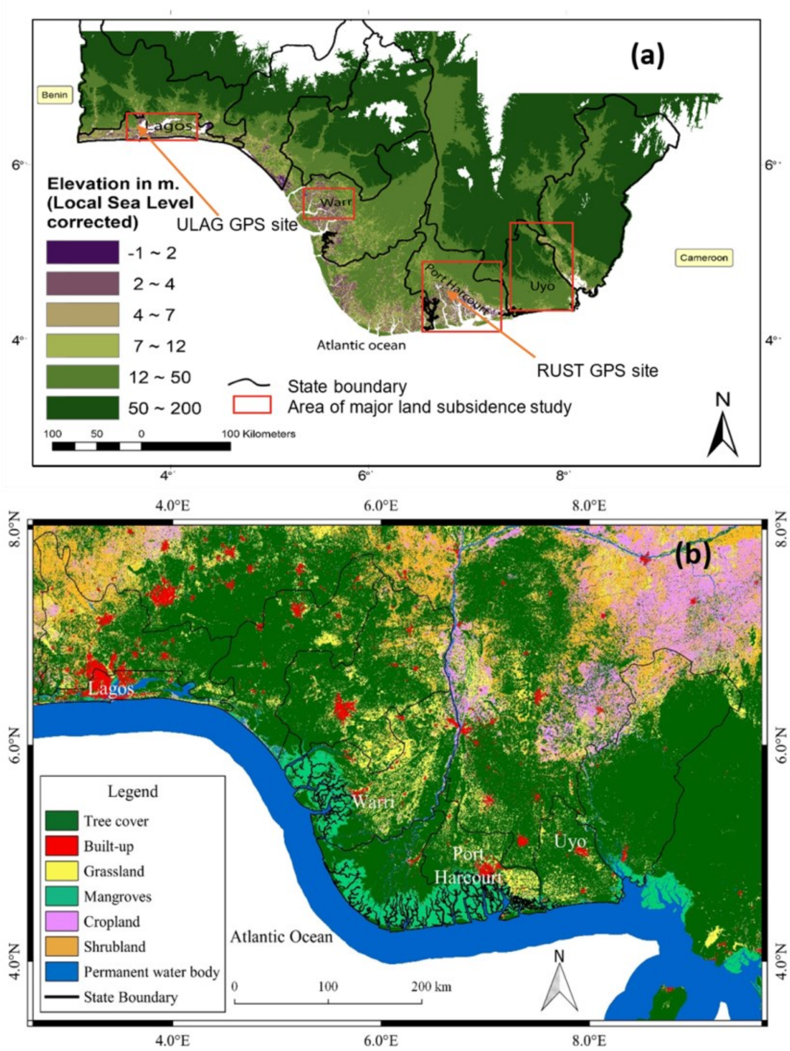
Objectives of the study

While a few studies have focused on land subsidence, others have only focused on global SLR. No previous study has reported the contribution of land subsidence to rSLR along the Nigerian coastline. In this review, we synthesize previous research work on coastal vulnerability assessment, land subsidence, and SLR along the Nigerian low-lying coastline. Specifically, this study reviews the available scientific knowledge and data and identifies gaps in existing studies that may be impeding adequate coastal risk assessments of the Nigerian coastlines. Additionally, this study provides a more detailed analysis of land subsidence in the Port Harcourt area, where the largest subsidence rates have been reported over the last years, using recently acquired Sentinel-1 satellite images, thanks to the Copernicus Programme satellite constellation conducted by the European Space Agency.

1. Study area

Nigeria's coastline runs along Africa's west coast, in the Gulf of Guinea. It stretches from the Nigeria-Benin Republic border at Seme, Lagos State, to the Nigeria-Cameroon border at Ikang, Cross River State, tilting into the Atlantic Ocean. The coastline is located between latitude 4º10′–6º20′ N and longitude 2°45′–8º32 E; it can broadly be divided between the western coast (the Lagos-Ogun axis) and the eastern coast (the Niger Delta region), spanning eight southern Nigerian states, and is host to several coastal cities. These include Lagos, one of the World's most rapidly-expanding megacities in addition to Warri and Port Harcourt, located in the Niger Delta region and home to Nigeria's oil and gas sector (Elum et al., 2016; Bello & Nwaeke, 2020). Across the Niger Delta region, there are more than 800 oil and gas field establishments in various towns, with nearly 900 operational oil wells (Onyena & Sam, 2020). In Lagos, the current population is estimated 25 million. With an annual projected population growth rate of 5% (Lagos Bureau of Statistics, 2018), access to public water systems will remain a huge challenge. Port Harcourt has an estimated population of over three million, and it will increase by approximately 5% a year.

Figure 1. Topographic and land cover distribution of the study area



(a) Surface elevation map showing Nigeria's low-lying coastal; data source: 30 m digital elevation model of the Japan Aerospace Exploration Agency. (b) A 10 m resolution land cover map for low-lying Nigerian coast. Data source: 2020 European Space Agency (ESA) WorldCover, at 10 m of spatial resolution.

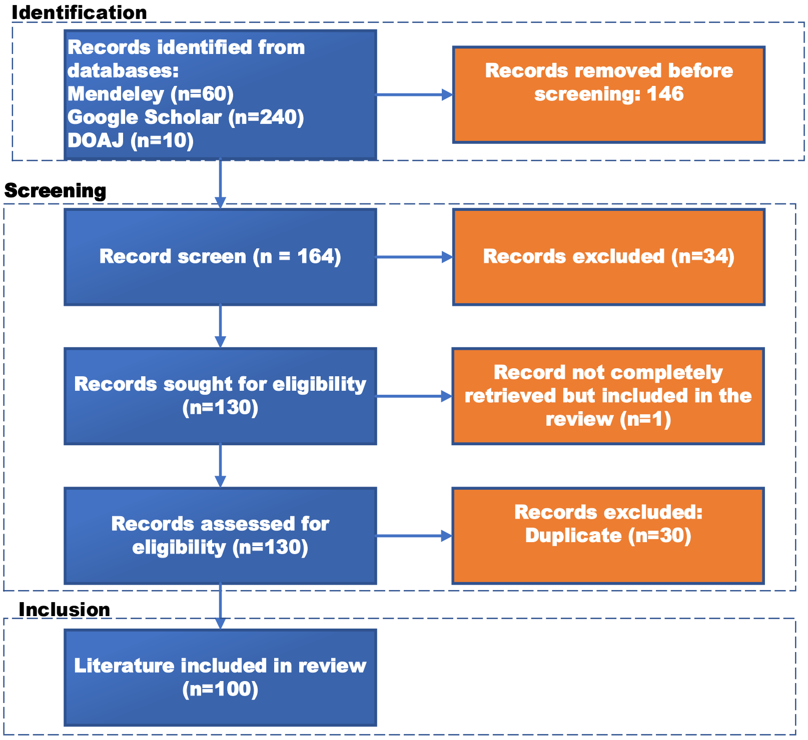
The continued rise in population and industrialization have triggered the upswing in groundwater usage, as access to drinking water remains a major problem in almost every Nigerian coastal city. Besides, to meet the demands posed by the rising population, the oil and gas industry and the import/export trade significant expanses of swampland, lagoon, and seashore have been reclaimed, resulting in increased dredging and redistribution of sediments along the coastlines (Nwankwoala, 2012; Olajide et al., 2018; Olatinsu et al., 2019). While dredging has enhanced the navigability of waterways in some cities (Adejare et al., 2013), it has accelerated changes in the topographic gradients of vulnerable areas, leading to the expansion of flood zones and shoreline erosion (Akukwe & Ogbodo 2015; Salami et al., 2016; Kabari & Mazi, 2020).

The coastline is low-lying, including a vulnerable mangrove system that has progressively been eradicated because of numerous anthropogenic activities (Ekanade et al., 2008; Fabiyi & Yesuf, 2016). According to the 30 m Advance Land Observation Satellite digital elevation model (ALOS DEM) provided by the Japan Aerospace Exploration Agency (JAXA, 2021), inland elevations with an average altitude of 3 m extend from Lagos towards the Niger Delta (Adeaga, 2014; Fabiyi & Enaruvbe, 2014) (Figure 1.a). Considering the geomorphological, vegetation and beach type characteristics, the Nigerian coastland can be divided into four major categories: from west to east (specifically, from Seme in Lagos State to Ikang in Cross River State), there is the barrier lagoon coast complex, the Mahin transgressive mud coast, the Arcuate Niger Delta, and the strand coast (Benson & Fred-Ahmadu, 2020). The coastline comprises inshore waters, coastal lagoons, estuaries, and mangroves, which are present particularly in the Niger Delta region. Figure 1.b shows the land cover map of the study area as revealed by the European Space Agency (ESA) WorldCover 10 m 2020 data.

2. Research methods

A literature review is an effective approach for evaluating and synthesizing previous studies to understand the available knowledge, identify research gaps, and lay the groundwork for future research (Arksey & O'Malley, 2005). The five-stage scoping review framework proposed by Arksey and O'Malley (2005) and Preferred Reporting Items for Systematic Review and Meta-Analysis extension for scoping reviews (PRISMA-ScR) were adopted in this study. This approach helped us formulate research questions, identify relevant studies, and chart, collate and synthesize the data. It also enabled us to highlight the available evidence and knowledge gaps on the topic. The flow chart for the method used in the study is shown in Figure 2.

Figure 2. PRISMA review flow chart adopted for this study.



2.1. Identification of the research questions

The first stage in conducting a scoping review is to outline the research questions to be addressed in the study. This study addresses the following research questions:

i. What is known from the existing literature about land subsidence along the Nigerian coastlines?
ii. Does the existing literature provide sufficient evidence for the contribution of land subsidence to rSLR?
iii. What are the most significant knowledge gaps in the available literature?
iv. Is there sufficient data for a full-scale assessment of the contribution of land subsidence to rising sea levels along Nigeria's coastlines?

Answering these questions will aid the development and implementation of a comprehensive plan for a full-scale investigation of the contribution of land subsidence to rSLR along Nigerian coastlines.

2.2. Identification of relevant studies

Database searches were conducted in three major databases: Google Scholar, Mendeley, and the Directory of Open Access Journals (DOAJ). The last literature search was completed on August 4, 2022, and only articles published after the year 1999 were selected, except French et al. (1995) because of its close relevance to this study. The research strategy was built by selecting groups of keywords combined with the Boolean operator “AND”. The words “Land subsidence” AND “Nigeria”, “sea-level rise” AND “Nigeria”, and “vulnerability” AND “sea-level rise” AND “Nigeria” were used as search queries in the three databases. The databases, particularly Google Scholar, were selected because they store a range of scholarly publications, including journal articles, review articles, books, and opinion letters, from various fields of study. This review is divided into three general sections, namely studies on land subsidence, on SLR, and on coastal vulnerability assessments.

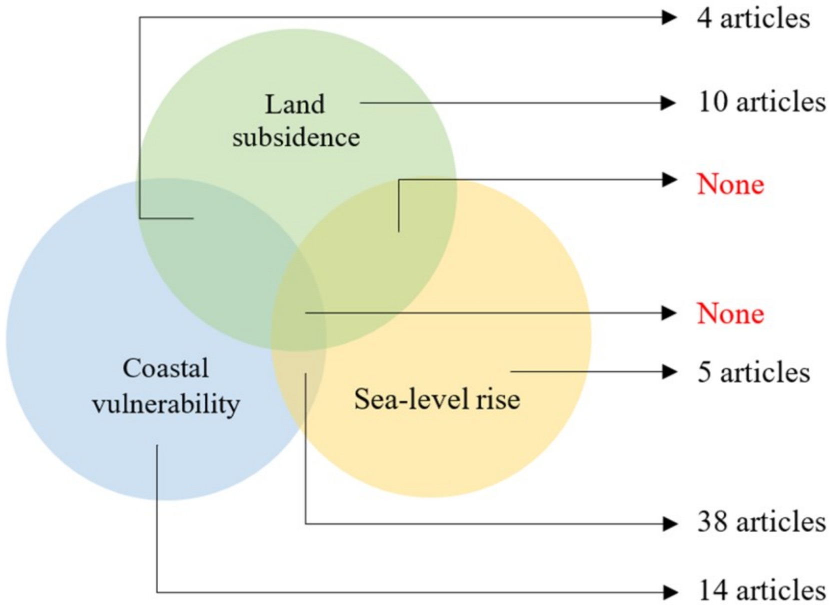
2.2.1. Selection of relevant studies

The data pulled from the three databases were combined. 240 articles from Google Scholar, 60 articles from Mendeley, and 10 articles from DOAJ were initially identified (Figure 2). However, because Google Scholar and Mendeley incorporate a wide range of literature, the search results were sorted manually, with the search threshold manually scaled down to 164 of the most salient articles based on their relevance to the keywords. This was further iterated using the following criteria: no duplicate studies, and studies essentially addressing land subsidence, SLR, or the link between them in Nigeria. Ultimately, 100 articles were chosen for review in this report, including 29 that provided a general overview of the topics of land subsidence, SLR, coastal vulnerability assessment, and Nigeria's geographic and social-economic contexts.

2.2.2. Charting the data

To address the research questions, we created a data charting form with the following elements: authors, year of publication, objective of the study, method/data and findings. The information from the data charting form was to summarize the overall number of studies, years of publication, state where studies were conducted, and the focus and purpose of the studies. Figure 3 shows the distribution of various studies reviewed. Although 100 papers were analyzed for the study, Figure 3 only includes articles that primarily focused on the issues of land subsidence, SLR, coastal vulnerability assessment, and the link between them in Nigeria.

Figure 3. Venn diagram of studies relating to coastal vulnerability assessment, sea-level rise, and land subsidence in low-lying coastal Nigeria.



3. Collating, synthesizing and reporting the results

We reviewed 10 studies mainly focusing on land subsidence, 5 focusing mainly on SLR, and 14 studies focusing on coastal vulnerability. In addition, this study reviewed 38 studies focusing on coastal vulnerability assessment and SLR, 4 studies partly combining land subsidence and coastal vulnerability assessment.

3.1. Land subsidence

A total of ten articles on land subsidence in Nigeria were identified for review. Their findings are presented in the following sections. The review reveals that many areas of Nigerian coastlines have undergone land subsidence to different degrees, with the maximum potential cumulative deformation rate (predicted) reaching 520 mm/year (Abija et al., 2020), and that the area in which subsidence occur is expanding. Land subsidence along the coastline and adjoining low-lying areas is particularly severe. However, it is important to stress that there is a lack of adequate in situ data (GPS and levelling) to validate InSAR-derived subsidence, which makes the overall InSAR-based results summarized below somewhat uncertain.

3.1.1. Measuring land subsidence: overview

Accurate spatiotemporal measurement is the first step in tackling the threat of land subsidence. The fundamental approach to subsidence measurement is to determine ground elevation differences at a particular location between two dates. This can be done in different ways depending on the type of technique deployed and the scale of the investigation. Various techniques have been developed, including terrestrial levelling, global navigation satellite system/global positioning satellite (GNSS/GPS), interferometric synthetic aperture radar (InSAR), and the stratigraphic method. These techniques can provide a detailed understanding of the spatiotemporal variability of land subsidence. Moreover, when the results provided by the aforementioned techniques are integrated with mathematical models calibrated on the past occurrence, such as time series analyses, data-driven models, or physically-based simulators, the results can provide reliable estimates of future subsidence trends (Ikuemonisan et al., 2021b).

Early research on land subsidence along the Nigerian coastlines concentrated mainly on the use of InSAR data such as Envisat-ASAR (Mahmud et al., 2016; Cian et al., 2019, Ikuemonisan et al., 2020; Alademomi et al. 2020), Sentinel-1 (Cian et al., 2019; Ikuemonisan et al., 2021a), TerraSAR-X and COSMO-SkyMed (Cian et al., 2019). Till today, the preponderance of the studies documenting the spatial distribution and temporal trend of land subsidence in parts of Nigeria is individual-case study-based. No detailed review article on spatiotemporal variability of land subsidence has been published. In addition, only a few semi-large-scale or large-scale land subsidence studies have been conducted on the Nigerian coastline, with such studies covering four major areas along the coastline. These include the Lagos area (Cian et al., 2019; Ikuemonisan & Ozebo et al., 2020; Mahmud et al., 2016), the Warri area (Mahmud et al., 2016), the Port Harcourt area (Uko & Otugo, 2016) and the Uyo area (Udoh & Udofia, 2014). Table 1 summarizes the major available knowledge on land subsidence along the Nigeria coast. It is worth noting that in the case of the InSAR data, the values are not vertical velocities but measurements obtained along the line of sight of the satellite. In the following sections, we highlight the main features of the land subsidence occurrence in these areas.

Table 1. Summary of land subsidence observations in Nigerian coastal cities.

S/N	Location	Temporal coverage	Method: data	Maximum subsidence rate (mm/year)	References
1	Lagos area	2002 – 2011	InSAR: Envisat-ASAR	7.0	Mahmud et al. (2016)
		2002 – 2019	InSAR: Sentinel-1, TerraSAR-X, COSMO-SkyMed	9.5	Cian et al. (2019)
		2015 – 2019	InSAR: Sentinel-1	94.0	Ikuemonisan et al. (2021)
2	Port Harcourt area	-	Geertsma nucleus of strain: predicted reservoir pressure	Predicted cumulated subsidence at the end of reservoir production life: 15.5 m	Abija & Abam (2022)
		1988 - 2003	Time-lapse orthometric leveling measurements	200.0	Uko et al. (2018)
3	Uyo area	-	Modelling: Groundwater extraction	Very High	Udoh & Udofia, (2014)
4	Warri area	2006 – 2010	InSAR: Envisat-ASAR	5.0	Mahmud et al. (2016)

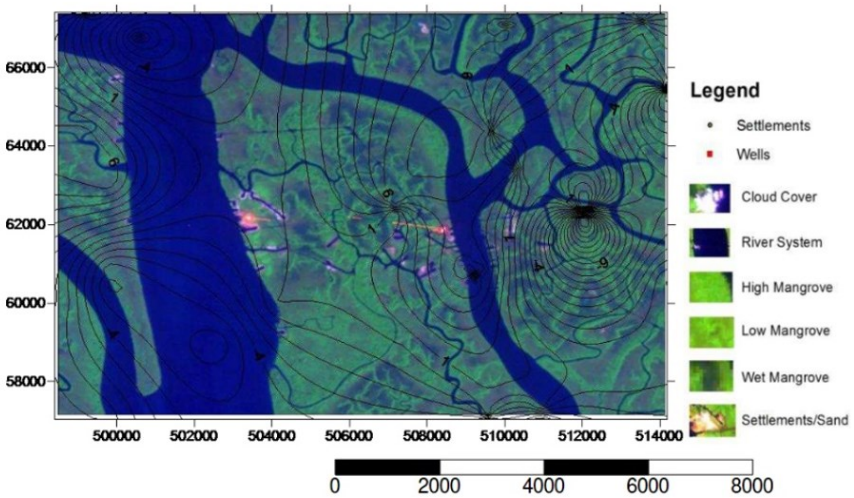
3.1.2. Land subsidence data in four regions

3.1.2.1. Port Harcourt Area

The Port Harcourt area experiences the highest land subsidence rates presently known along the Nigerian coast (Figure 4). Land subsidence rates at selected oil well locations in this area seems to show an accelerating trend from 33 mm/year in 1982 to 550 mm/year in 2000 (Abija et al., 2020). This latter value was estimated by the authors by comparing two ASTER DEMs (provided in 2018 and 2020), which are known to have vertical errors of multiple meters, consequently the reliability of these estimates is extremely low. In studies by Uko and Otugo (2016) and 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 compaction of onshore oil fields has been roughly predicted to reach 15.5 m at the end of the reservoir production life, with a possibility to extend significant land subsidence toward the coastline (Abija & Abam, 2022). If this is correct, this will have major implications because, as shown in Figure 1.a, the elevation of this area is approximately 4 m above mean sea level.

The high rate of subsidence in the Port Harcourt area is attributed to the reservoir compaction resulting from oil and gas extraction and groundwater pumping, with the first one dominating (Uko & Otugo, 2016; Uko, et al., 2018; Abija et al., 2020). The pore pressure decline associated with subsurface fluid removal increases the effective stress in the depleted horizons, which compact. Typically, compaction at depth causes the land surface to subside. Pressure depletion can propagate from the reservoir into the surrounding aquifer, possibly causing land to subside quite far from the producing wells. The extent to which subsidence can spread away from the producing wells is determined by a number of factors. These include the reservoir geometry, the geomechanical properties of the overburden, the volume of fluid (water, oil, and gas) withdrawn, and the magnitude of the associated pressure reduction.

Figure 4. Isoline (contour map) of land subsidence overlaid on a baseline map of 1988 in the Port Harcourt area, southeast Niger Delta.

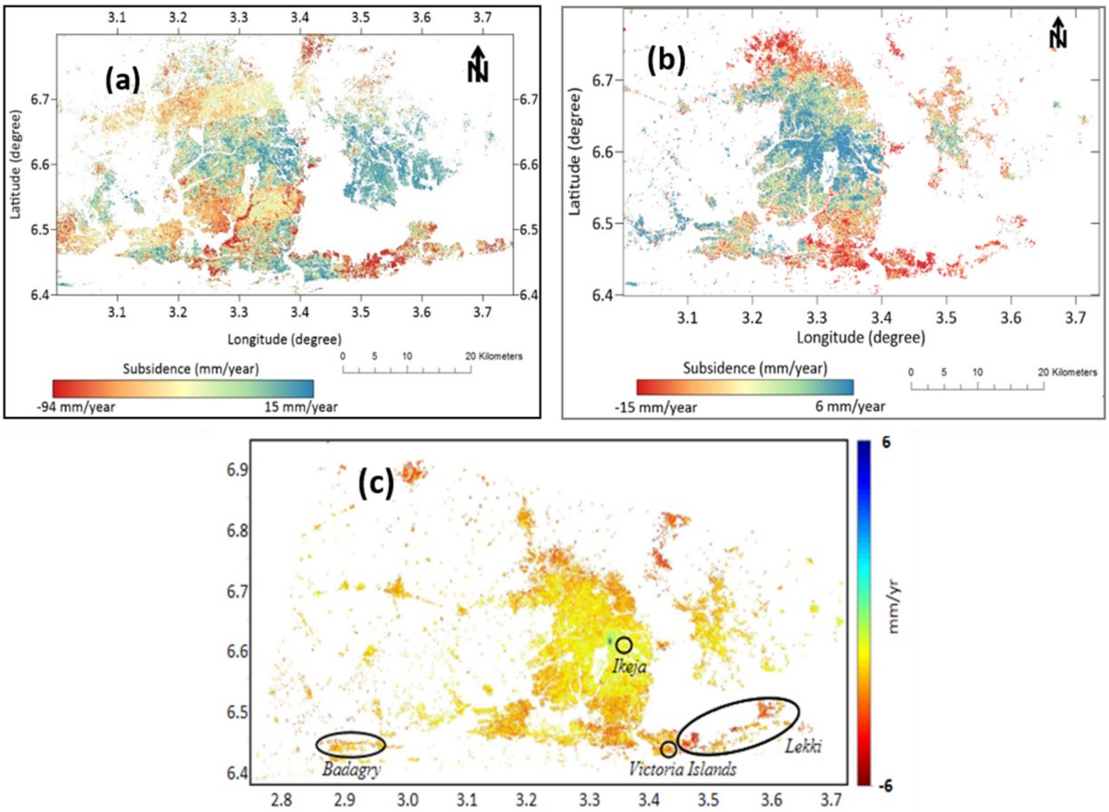


Unit: mm/year. temporal coverage: 1988-2003. Source: After Uko et al., 2018. Although the spatial scale of the map is not defined by Uko et al. (2018), the location of the study area is shown in Figure 1 (Port Harcourt).

3.1.2.2. Lagos Area

Various studies used different methods to process the InSAR data over Lagos, and they all reported significant deformation rates. Mahmud et al. (2016) employed multitemporal InSAR (MT-InSAR) data to monitor land subsidence in Lagos State and found that some parts of Lagos State are subsiding at a rate up to 7 mm/year along the line of sight in the period from 2004 to 2010 (Figure 5). Cian et al. (2019) then used the Stanford method of employing Persistent Scatterer Interferometry (StaMPS PSI) to characterize land subsidence in parts of Lagos. Similar to previous findings, the study reported that parts of Lagos are subsiding at varying spatial rates, ranging between 1 mm/year and 9 mm/year. Based on the application of an integrated approach Ikuemonisan et al. (2020) mapped and characterized land subsidence in the Lagos metropolitan areas. The authors found that land subsidence of high rate is widespread across the study area, and that the cumulative subsidence is expected to continue rising significantly unless adequate mitigating strategies will be established. The maximum known average subsidence rate in this area, as estimated by InSAR technique between 2015 and 2019, is approximately 94 mm/year, with the cumulative subsidence projected to increase by 36.2 cm by the end of 2023, partly because of increasing groundwater extractions (Ikuemonisan et al., 2021b). However, GPS monitoring during 2011–2013 at University of Lagos campus showed a subsidence rate of 3 mm/year occurring in built-up areas (Ikuemonisan & Ozebo, 2020). The GPS measurement could not be reliably used to calibrate the InSAR results because of the gap with the time periods.

Figure 5. Spatial distribution of subsidence rates in Lagos as estimated by InSAR data.



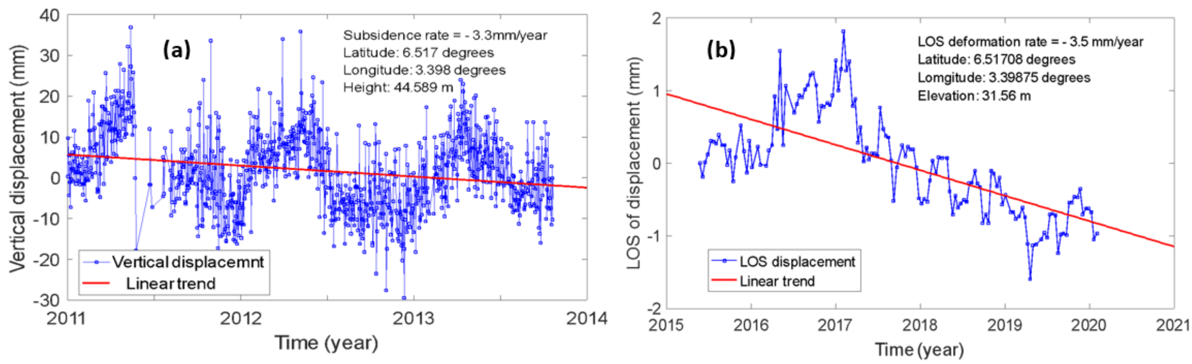
(a) Sentinel-1 (2015 –2019); (b) Envisat-ASAR (2002 –2011) [After Ikuemonisan et al., 2021b]; (c) Envisat-ASAR (2002 –2011) [After Mahmud et al., 2016]. Note the different ranges of the colour scales.

The various methodologies used for subsidence monitoring in Lagos appear to produce largely similar results mainly in terms of subsidence spatial spread (Figure 5). In some areas, the orders of magnitude of subsidence rates are similar, however in some others they can vary significantly. Table 2 shows average subsidence rates as estimated by Envisat-ASAR, Sentinel-1, and GPS at the center of the University of Lagos campus from 2002 to 2020 by the different approaches. The measurements were taken at different time steps, indicating that land subsidence exists in the Lagos area and is increasing. In this location, the various monitoring techniques provide consistent outcome in terms of land subsidence rate processing, suggesting that InSAR data are relatively reliable. The spatial distribution and temporal trend of land subsidence in Lagos are shown in Figure 5 and Figure 6.

Table 3. Land subsidence measured through various methods at ULAG GPS site in Lagos. The InSAR data reports line of sight velocity rates and the GPS data measures vertical velocity rates.

Temporal coverage	Average subsidence rate (mm/year)	Measurement method	Reference
2002–2011	2.6	Envisat–ASAR	Ikuemonisan & Ozebo (2020)
2011–2013	3.3	GPS	Ikuemonisan & Ozebo (2020)
2015–2020	3.5	Sentinel-1	Ikuemonisan et al. (2021a)

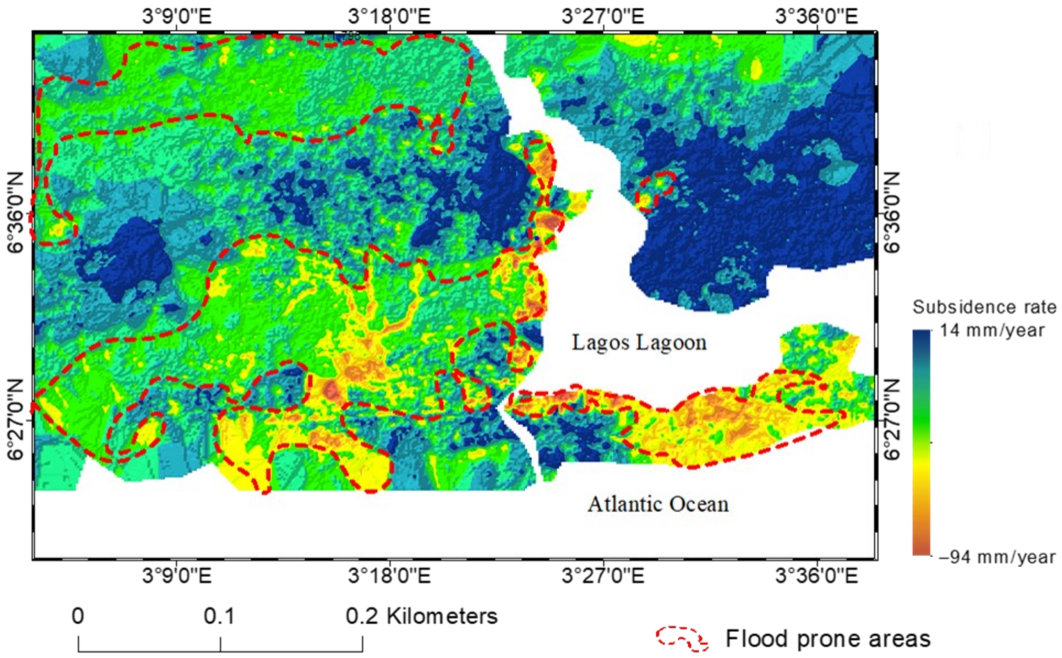
Figure 6. Temporal evolution of land subsidence at GPS site (ID: ULAG) in Lagos



(a) measurements based on GPS; (b) measurement based on Sentinel-1. [Modified after Ikuemonisan et al., 2020].

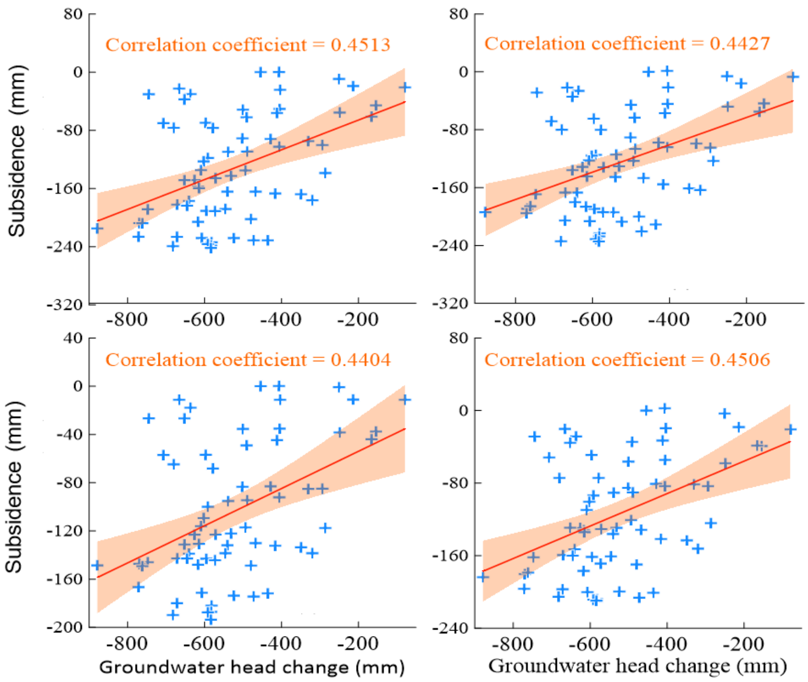
In all the InSAR-based studies, Envisat-ASAR and Sentinel-1 results show that the southern part of Lagos, notably the areas along the Atlantic Ocean coast and the Lagos lagoons, is characterized by high subsidence rates. Spatial estimation analysis reveals that land subsidence at varying rates (differential subsidence) affects approximately 340 km² of land (Figure 7), accounting for approximately 68% of the city landmass, with subsidence bowls spreading proportionately. As can be seen in Figure 7, major subsidence bowls are emerging across the city of Lagos, with floods as a major visible effect of subsidence phenomenon. Indeed, land subsidence can exacerbate flooding since when the precipitation rate is much greater than the infiltration rate, excess water will accumulate in the subsidence bowl, thereby causing the affected area to be inundated.

Figure 7. Spatial distribution of land subsidence in Lagos as estimated by InSAR between 2015 and 2019, showing subsidence bowls in parts of Lagos.



Source: After Ikuemonisan et al. (2021a). The subsidence bowls have a strong correlation with the flood area extension map developed for Lagos by Kaoje and Ishiaku (2017).

Figure 8. Statistical relationship between land subsidence and groundwater level change in parts of Lagos.



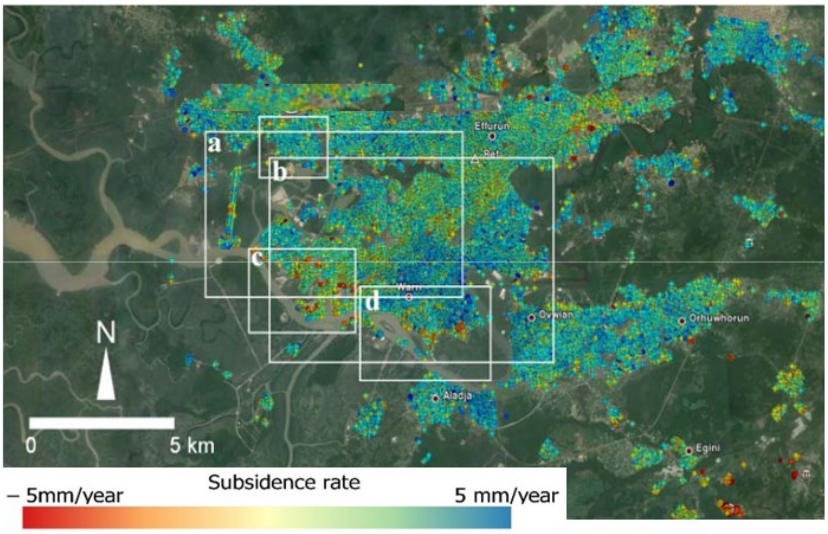
Source: Ikuemonisan et al. (2021a).

Although various factors have been attributed to cause land subsidence in Lagos, a linear regression analysis involving subsidence values and groundwater level change parameters (as estimated by Gravity Recovery and Climate Experiment (GRACE)) indicates a certain correlation between the two quantities (Ikuemonisan et al., 2021a). The statistical correlation coefficient is in the order of ~0.45 (Figure 8), suggesting that groundwater extraction is likely to be one of the causes of land subsidence in Lagos. It is worth noting that GRACE provides coarse resolution of groundwater level change. Other drivers of land subsidence in this area include natural compaction of unconsolidated sediments and the compaction of reclaimed wetland due to the weight of the overburden structure (Cian et al., 2019).

3.1.2.3. Warri area

Limited information is available from published literature and reports regarding land subsidence in Warri. However, monitoring studies have revealed that land subsidence occurred in the Warri area. The spatial distribution of land subsidence in the Warri area is shown in Figure 9. Displacement time series analysis of InSAR images acquired between 2006 and 2010 reveal that subsidence occurred in Warri at a maximum rate of 5 mm/year. This was suspected to have been caused by groundwater withdrawal (Mahmud et al., 2016).

Figure 9. Spatial distribution of land subsidence in the Warri area.

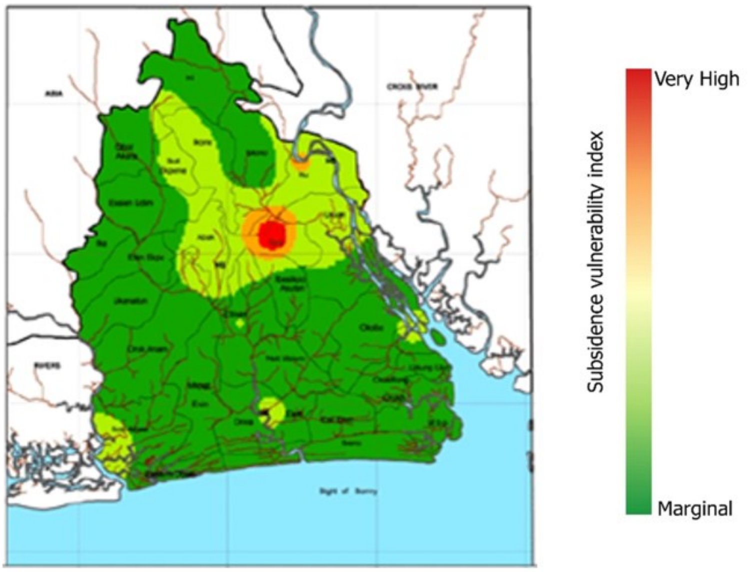


Source: Modified after Mahmud et al., 2016. The location of the study area is shown in Figure 1 (Warri).

3.1.2.4. Uyo area

Until present day, land subsidence in the Uyo area has been extensively investigated from a single perspective: groundwater extraction. Udoh and Udofia (2014) modelled the land subsidence vulnerability of the entire Akwa Ibom State using water extraction data obtained from the Akwa Ibom Water Company and the State's Ministry of Rural Development. The total amount of water extracted in the study area was calculated by combining various extraction parameters (annual discharge for all hand pump boreholes; annual discharge for all mini water schemes; and annual discharge for all of the Akwa Ibom Water Company) in each local government area. Subsidence vulnerability index for the Uyo area is shown in Figure 10. The vulnerability index measures the ground exposure to land subsidence. The study reported that the Akwa Ibom State of Nigeria is vulnerable to subsidence due to complex interactions between anthropogenic activities and natural processes.

Figure 10. Subsidence vulnerability map for the Uyo area



Source: Udoh & Udofia (2014). The location of the figure is presented in Figure 1 (Uyo).

3.2. Sea-level rise and coastal vulnerability In the Nigerian coast

Global SLR and its effect on coastal cities have become a topical issue in recent times, not only within the scientific community but also among the general public. This is particularly prevalent in the media sphere (Cazenave & Le Cozannet, 2014). However, there is still serious uncertainty about the future of this trend and its implications locally for the coastland of Africa, particularly Nigeria. Monitoring and modelling SLR are somewhat complex due to uncertainties associated with the input variables that define the modelling scenario, such as the thermal expansion of seawater and the melting of glaciers and ice sheet. Nonetheless, this section reviews the current knowledge regarding sea-level variability and future trends on the Nigerian coastline and the resulting impact. This was achieved by synthesizing the most up-to-date knowledge concerning SLR and its effects.

The impact of SLR in Nigeria has been documented by various authors (Ologunorisa, 2004; Akinro et al., 2008; Adelekan, 2010; Ozor et al., 2011; Odunuga et al., 2014; Ebele & Emodi, 2016; Dada et al., 2020). SLR poses a high environmental risk to adjoining low-lying areas (French et al., 1995; Ali & Hamidu, 2014; Mensah et al., 2017; Merem et al., 2019). According to Badru et al. (2012), Idowu and Home (2015) and Oloyede et al. (2021), Nigeria is highly vulnerable to SLR, which has caused many environmental problems for the ecosystem, including increased flooding risk, coastal erosion, inundation, and groundwater salinization (Fashae & Onafeso, 2011; Ogbo et al., 2013; Idowu & Home, 2015). All of these impose considerable socioeconomic and ecological disadvantages on cities along the coast (Obia et al., 2015) and threaten their economic potential.

Oloyede et al. (2021) used SimCLIM to simulate SLR under future climate scenarios along the Lagos lagoon coast using data provided by the Coordinated Regional climate Downscaling Experiment (CORDEX) as input variables. The results of this study indicated that sea level will rise by 0.12 m by 2025 and may reach 0.25 m at the end of 2050. A similar modelling scenario has been provided by Odunuga et al. (2014). The GIS-based inundation model, considering the - now old - IPCC SRES climate scenarios for global SLR (ranging 0.18 m to 0.59 m) as well as extreme SLR scenarios, shows that only 0.13% (9.44 ha) of the Badagry area of Lagos would be inundated in case of a 1 m SLR, which would be negligible. SLR above 3-4 m would be required for significant parts of the study area (>8%) to be inundated. However, the study used Shuttle Radar Tomography Mission (SRTM) 90 m digital elevation data, which could lead to significant biases in this exposure assessment, even if the SRTM was updated using spot height area. Indeed, the projection of the Badagry areas that would fall under sea level in a scenario of 1 m of SLR appears much more significant when considering the elevation data from the Coastal DEM (Kulp & Strauss, 2018), recently updated on https://coastal.climatecentral.org (last access in december 2022).

Oloyede et al. (2022) examined the vulnerability of the Nigerian coastal zone using the coastal vulnerability index (CVI) method to characterize vulnerability to SLR in detail by using geomorphological and physical variables (such as coastal gradient, wave height, bathymetry, mean tidal range, shoreline change rate, as well as the rSLR) and socioeconomic indicators (population, road network, and land use characteristics). The study showed that the entire Nigerian coastal region has been subjected to moderate to high vulnerability to SLR, with high vulnerability dominant in the Lagos and Port Harcourt areas. The analysis of the sea-level data provided by the Nigerian Institute of Oceanography and Marine Research (NIOMR) reveals an accelerating absolute SLR trend for the Nigerian coastline with an average of 2.1 mm/year over 1986-2015. The IPCC (2021) reports higher rates for global mean SLR, with 2.3 mm/year for 1971–2018 and 3.7 mm/year for 2006–2018, but the disparity with the time period considered in Oloyede et al. (2022) does not allow to assess to what extent SLR along the Nigerian coastlines varies from the global average.

With the increasing rate of global SLR, rSLR will possibly inundate a wide area of the adjoining Nigerian cities and islands in the coming years (Danladi et al., 2017; Musa, 2018). Oyegun et al. (2016) proposed a vulnerability assessment along similar lines. They found that the area from the mid-Niger Delta region down to the end of the eastern flank falls within the CVI range of high vulnerability to very high vulnerability. Musa et al. (2014) also investigated the vulnerability of the Niger Delta region to river floods due to SLR. Their study revealed that over 40% of the Niger Delta region is highly susceptible to SLR. The most affected areas are those associated with low coastal slopes, low landscapes and high average wave heights, as well as the areas characterized by unconfined aquifers.

Given the upsurge in socioeconomic development on the Nigerian coast, especially with the creation of the seaport at Badagry and the expansion of oil fields in the Niger Delta region, the future trends of sea level change and the potential implications of the resultant sea-land interaction needs to be examined more closely. Nigeria's coastal cities are expanding rapidly in low-lying areas where there are no detailed investigations, and these cities are highly threatened by SLR and growing land subsidence. In view of the aforesaid, there is an urgent need for a holistic assessment of the future trends of not only SLRs but also how land subsidence will affect rising sea levels along the Nigerian coast.

3.3. The link between sea-level rise and vertical land motion - relative sea-level rise

Vertical land motion resulting from natural and/or anthropogenic forces can change local sea level relative to the seafloor and coastal land surface (Wöppelmann & Marcos, 2012), which can, in turn, seemingly increase or decrease the sea level (Raucoules et al., 2013). However, until date, no published work has reported the role of vertical land motion, particularly land subsidence, in rising sea levels along the coastline of Nigeria. However, previous works in other coastal areas worldwide (Ingebritsen & Galloway, 2014; Passeri, et al., 2015; Wöppelmann & Marcos, 2016; Hung et al., 2018; Liu et al., 2020; Minderhoud et al., 2020) have clearly shown how important is to disentangle between "absolute" and relative SLR.

4. A case study: InSAR study of Port Harcourt area

A large-scale spatiotemporal analysis of land subsidence in the Port Harcourt area has not been conducted until now. The few relevant studies published have been limited to analyzing oil well observation data. Although reservoir compaction analyses conducted by Uko and Otugo (2016), Uko et al. (2018), and Abija et al. (2020) have provided a captivating narrative, analyses of oil wells provide information about land subsidence primarily in and around the observation points. There is no large-scale study involving InSAR spatiotemporal analysis across the Port Harcourt area. In this study, we performed an InSAR time-series analysis on Sentinel-1 data gathered between 2015 and 2022 using the small baseline subset (SBAS) technique. InSAR measures surface displacement along the line of sight of the satellite with millimeters accuracy over wide area. Different factors may contribute to land subsidence in addition to oil field development.

4.1. Data and Method of InSAR Processing

For the Port Harcourt case study, this work used SAR images acquired by the Copernicus C-band Sentinel-1 A/B SAR constellation between October 2015 and July 2022. A total of 217 (ascending orbit) images spanning the monitored period were processed to generate long-term deformation time series and maps. The Sentinel-1 data were acquired with 5.405 GHz center frequency and approximately 5.55 cm wavelength in the right-looking mode based on the Interferometric Wide (IW) imaging mode, characterized by 250 km swath width, 2.3 m pixel spacing in slant range and 14.1 m in azimuth. The IW imaging mode has a ground range and an azimuth single-look resolution of 5 m and 20 m, respectively. The imaging mode relies on the Terrain Observation with Progressive Scans (TOPS) technique to scan the target (ground surface), with radar incidence angles varying from approximately 31° to 46°. The InSAR data processing was performed on the Geohazard Thematic Exploitation Platform (Geohazard-TEP) using the Parallel Small BAseline Subset (P-SBAS) interferometry chain algorithm (software version: CNR-IREA P-SBAS 28) to retrieve ground deformation history using the reference point: Longitude (6.92352810) and Latitude (5.95086170), which is the approximately at the centre of Port Harcourt.

The P-SBAS interferometry chain algorithm was developed and incorporated into the Geohazard TEP by the Italian National Research Council-Institute for Electromagnetic Sensing of the Environment (CNR-IREA) for the processing of Sentinel-1 SAR data, in a project funded by the European Space Agency (ESA) Network of Resources (NoR) initiative. P-SBAS is an advanced differential InSAR (DInSAR) processing chain designed for the generation of average deformation velocity maps and deformation time series from stacks of Copernicus Sentinel-1A/B single-look complex (SLC) data for land deformation temporal evolution monitoring. Although the SBAS algorithm was originally proposed by Berardino et al. (2002) to process SBAS-InSAR time series, it has been successfully enhanced to handle the parallel computation of large datasets in a non-supervised environment (Casu et al., 2014; De Luca et al., 2015) with considerable accuracy (Cigna & Tapete, 2022).

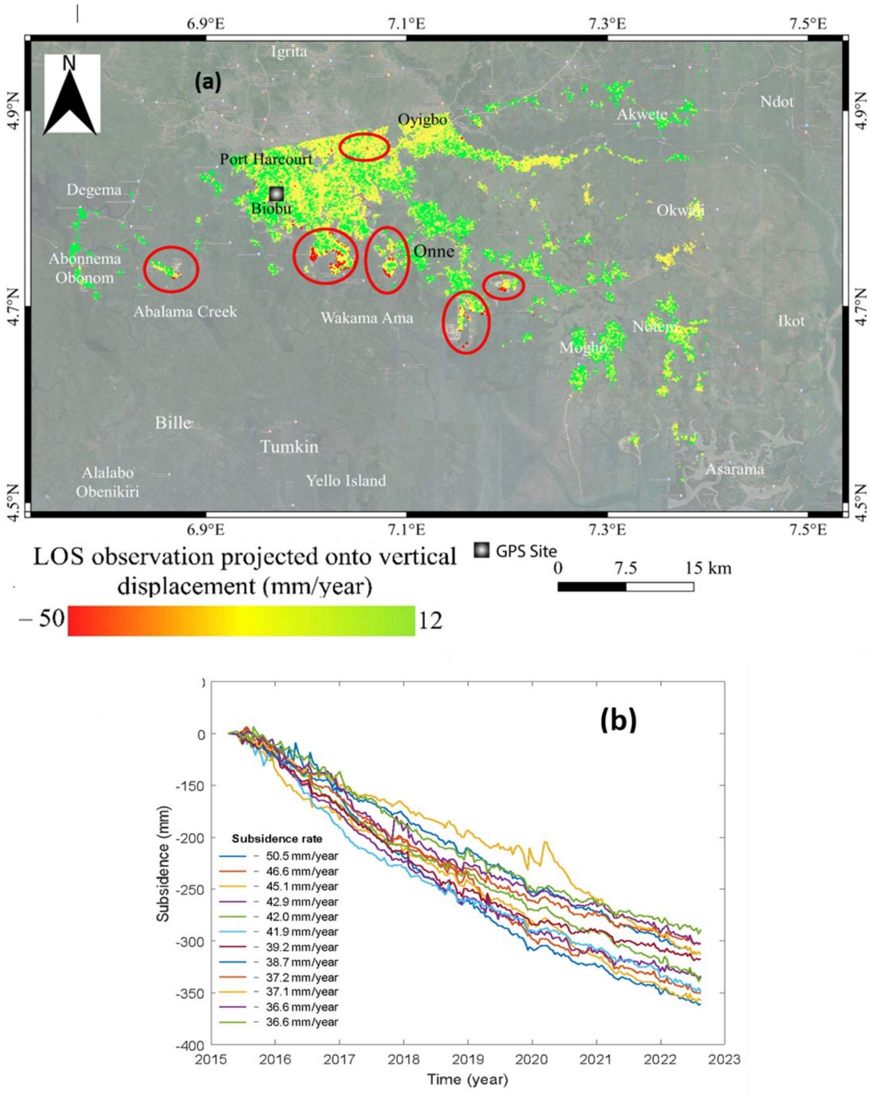
Because Sentinel-1 measures surface displacement along the line of sight, we projected line of sight observation onto the vertical direction to generate a subsidence map of the Port Harcourt area. The line of sight deformation was projected along the vertical direction using the following equation:

$$\Delta d = \frac{\Delta LOS_d}{cos\theta}$$

where Δd is the vertical land displacement, ΔLOS_d is the line of sight displacement, and θ is the Sentinel-1 incident angle, which is approximately 39.60. The equation can be applied considering the assumption of a non-relevant horizontal component of the movement.

4.2. Results of InSAR Analysis for the Port Harcourt area

Figure 11. Spatial and temporal trend of land displacement in the Pot Harcourt area:

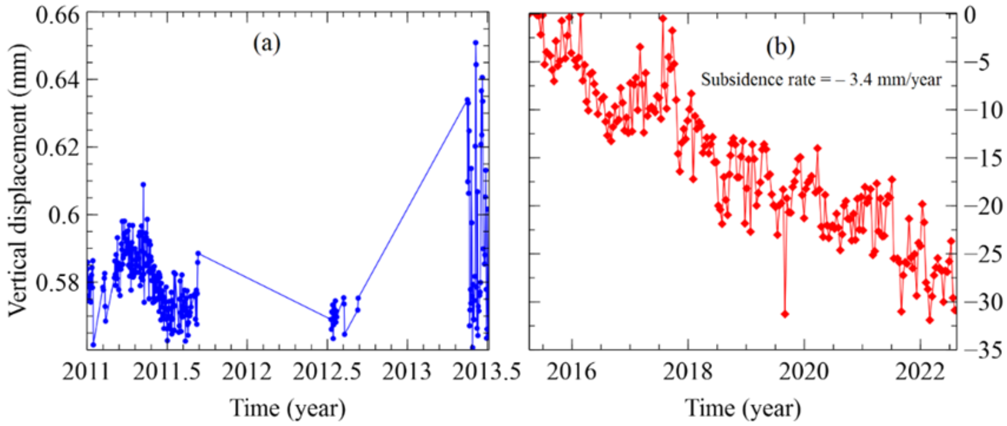


(a) Velocities based on Sentinel-1 observation (most subsided areas are highlighted with ellipses). Features are underlain by a Google Earth map; (b) Displacement time series of the ten most subsided areas.

Port Harcourt city has become a progressively growing population in the last four years, with a rapidly growing expansion of physical infrastructure, including high-rise building, housing, and industrial estates expansion. Figure 11.a shows the spatial distribution of land subsidence as estimated by InSAR in the Port Harcourt area. The Sentinel-1 spatiotemporal analysis showed widespread coastal land subsidence in the area. The maximum subsidence rate projected in the vertical direction 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, have been subjected to cumulative subsidence of approximately 370 mm between 2015 and 2022. The deformation time series for the Port Harcourt area is depicted in Figure 11.b. As can be seen in the figure, the ten highest cumulative subsidence areas vary significantly between 270 mm and 370 mm in the last seven years. The observed rise and fall in the time series signal during the dry and rainy seasons, respectively, suggested that land subsidence is influenced by seasonal factors like rain, increasing soil wetness and infiltration.

The displacement time series of Sentinel-1 and GPS measurements at the GPS site is shown in Figure 12. Usually, calibration and validation 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 deduce a reliable trend of land movement.

Figure 12. Displacement time series at RUST site in Port Harcourt.



(a) GPS; (b) Sentinel-1. (GPS Data from the Nevada Geodetic Laboratory).

5. Research gaps and data availability for further studies

Although previous studies provide some knowledge on land subsidence rates and spatial distribution, the damages caused by land subsidence along the Nigerian coastline have not been well documented, and no specific countermeasures to mitigate the potential impacts have been proposed, which may be attributed to stakeholders' lack of awareness about the impact of rSLR. This review identified several issues regarding the assessment of the vulnerability of the Nigerian coastline to rising sea levels, which require further investigations:

- Although a few previous studies revealed the existence of widespread land subsidence and increased sea levels in parts of the Nigerian coastline, there is no comprehensive paper or report that provides useful information on the contribution of land subsidence to rSLR. Therefore, additional observational studies on sea level changes at the local level are required to incorporate the findings with in situ tide gauge measurements, enhance the monitoring and prediction of vertical land motions and efficiently model rSLR by integrating sea level data with vertical land motion data.
- The lack of operational GPS stations to calibrate and validate InSAR measurements makes the entire InSAR outcome quite uncertain. This uncertainty is important because it seems to be on the same order (i.e., a few mm/year) as global SLR.
- The lack of open-access in situ hydrogeological data to ascertain hydrogeological trends, including records of groundwater withdrawals and piezometric evolution over the last decades, and the nature of subsurface lithology and the absence of a reliable framework to integrate sea level changes with vertical land motions.

Filling these knowledge gaps would provide an opportunity to better assess the exposure to relative SLR and the contribution of land subsidence.

The set of data required for a holistic investigation of coastal interactions and their associated impacts is composed of information from various fields of study and different agencies of government. In most cases, a number of government agencies both at the state and federal levels are saddled with the responsibilities of acquiring, archiving, and sharing different aspects of coastal variables. However, due to complex institutional bureaucracy and relationships and the lack of synergy, it is often difficult to access sufficient datasets that cover the entire Nigerian coast. This has made the effort of data collection a little more cumbersome. However, data published in previous related studies could be treated as proxy data to complement the various datasets readily available from the government agencies. Table 3 presents the list of datasets that would be needed for a full-scale investigation and modeling of land subsidence around the Nigerian low-lying coastal cities. In addition, this review identified various government agencies in Nigeria that are in charge of these data.

Table 3. List of data needed for a full-scale investigation and modelling of land subsidence in major Nigerian low-lying coastal cities.

Data	Description	Target City	Resolution	Data Points	Potential Source
Hydrogeological Data	Stratigraphic logs and sections (Lithology & thickness), hydrogeology map of Lagos; Hydro-geomechanical information on sediments at various depths (samples analyzed for geomechanical and hydrological properties, CPT, pumping tests)	Lagos, Warri & Port Harcourt	$\leq 0.01^0$ (spatial)	≥1000	Hydrogeology and Engineering Dept, Nigerian Geological Survey Agency (NGSA)
Groundwater Data	Groundwater level and piezometric head measurements over time (particularly in the industrial areas and in wellfields for domestic use), volume of groundwater consumption (daily)	Lagos, Warri & Port Harcourt	≤ 30 days (temporal)	≥1000	▪ Hydrogeology and Engineering Dept, NGSA ▪ Lagos State Ministry of Environment and Water resources
Borehole Data	Map showing location of boreholes (or coordinate of boreholes)	Lagos, Warri & Port Harcourt			▪ Lagos State Ministry of Environment and Water resources; ▪ Hydrogeology and Engineering Dept, NGSA
Sea Level and Land Displacement Data	Local relative sea level (RSL) records; GNSS acquisition on permanent stations or differential static mode acquisition on benchmarks	Lagos, Port Harcourt, Warri, & Uyo	≤ 24 hours (temporal)		▪ Centre for Marine Geosciences, NGSA ▪ Nigeria Meteorological Agency (NIMET), Oshodi, Lagos ▪ Nigerian Institute of Oceanography and Marine Research (NIOMR)

6. Conclusion and recommendations

This report synthesized the most up-to-date knowledge on recent sea level measurements, land subsidence development, and their contributed rSLR on Nigeria's coastal region. In this report, it is found that previous studies provided valuable contributions in the areas of coastal vulnerability assessment, sea level observations and the future trend, and preliminary assessments of subsidence occurrence. However, studies focusing on the contribution of land subsidence to rSLR are considerably lacking. Because of the damaging potential of the rSLR and the continued subsidence on coastal infrastructure, residents, and the entire ecosystem, there is a pressing need for a comprehensive country-wide assessment of the growing impacts of the rSLR on Nigeria's coastal region. This may require efficient modelling scenarios and/or continuous observation of both in situ measurements and space-borne observations. Consequently, contemporal subsidence need to be understood and the relative contribution of different, both natural and anthropogenic subsidence drivers disentangled. In addition, the effort to establish the link between rSLR and land subsidence is required for disentangling processes occurring at the global scale, i.e., climate-change driven SLR, and therefore not under the direct control of the Nigerian authorities, from those occurring at the local scale, i.e., anthropogenic land subsidence, which do provide opportunities for mitigation. If these two interlace phenomena are appropriately quantified, they can be considered for direct intervention and to limit their magnitude. This study is a first step of a complex procedure to develop effective mitigating procedures, risk management, and adaptation strategies against rSLR.

Based on the findings of this review, we make the following recommendations for future studies:

1. A thorough investigation of the coastline's response to rSLR, continuous monitoring of SLR and effective geomorphological models would improve our understanding of coastal dynamic variation. These investigations would provide valuable insight into future scenarios of coastline vulnerability to rSLR.
2. Measurements of recent sea-level changes with vertical land motion and piezometric data would significantly improve our expertise in quantifying rSLR along Nigeria's coastline. This kind of data is crucial for the development of numerical models.
3. Incorporating the effects of rSLR inundation with future surface topography changes would help to efficiently monitor both coastline erosion in affected areas and the effects of human-induced changes such as coastal defense and sand dredging.
4. It is of paramount importance to establish and maintain a network of several GPS permanent stations. Without them, we never really know how much subsidence is contributing to SLR. The stations must be put in safe locations (for example above the roof or in the courtyard of administrative buildings). It is not needed to put them on exposed and uncontrolled sites along the coastline. Their main aim is not to measure land subsidence in critical sites but to provide a reference system for InSAR analysis.
5. Integrating groundwater dynamic variations and hydrogeological parameters with sea-level measurements would help to develop a process-based numerical model of land subsidence. When such numerical models are calibrated properly, they can aid the development of a framework for groundwater withdrawal regulation, control measures, and disaster mitigation for land subsidence.
6. Estimation of socioeconomic implications and their incorporation into the overall synergistic process (e.g., amount and locations of future groundwater extractions) would help to quantify the growing land subsidence in affected coastal areas and the potential economic impacts of future rSLR for the Nigerian coastal zone.

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