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A scoping study on coastal vulnerability to relative sea-level rise in the Gulf of Guinea

Coastal elevation assessment and literature review

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Abstract
The Gulf of Guinea's low-lying soft coastline is highly vulnerable to coastal erosion and relative sea-level rise (rSLR). Large capital cities and core economic activities are concentrated along the coastline, and potentially exposed to unforeseen risk. Currently, there is limited research on the impacts and vulnerability to rSLR (i.e. including land subsidence). Recent advances in satellite-derived global digital elevation model (DEM) data offers exciting opportunities to assess coastal elevation at large scale and identify "hotspots" of potential sea-level rise vulnerability. Hereto, this study presents first a literature review on coastal vulnerability to rSLR in the Gulf of Guinea region. Secondly, this study use recent global satellite-based DEMs for a coastal elevation assessment of the Gulf of Guinea to identify low-lying geographical areas needing more detailed investigations. Findings from satellite remote sensing are validated with in-situ data points in the Volta Delta.

The results from the literature review highlights that very few publications investigate the combined effects from global SLR and land subsidence in the studied area. None investigates the drivers of land subsidence. Our analysis on satellite-based DEMs shows that there are large uncertainties on coastal elevation in the area, with considerable discrepancies between DEMs (>1m). These results highlight the importance of validation, either through ground-truthing or advanced approaches such as incorporating multiple DEMs. Unfortunately, field data that can be used as reference are scarce in the region, emphasizing the need for more field measurements and publicly available data. Incorporating newer data – e.g. LiDAR or high resolution optical stereogrammetry – is expected to improve assessments significantly and should be further explored. Based on the combination of FABDEM and CoastalDEM_v2.1, several coastal hotspots of vulnerability to SLR have been identified, including Lagos, Niger Delta, Cotonou, Western Accra, the Volta region, and urban areas surrounding the Ebrie lagoon within Abidjan. We conclude our study with concrete suggestions for future research and projects on rSLR in the region.

Keywords
Gulf of Guinea, Sea-level rise, subsidence, DEM, coastal vulnerability, Ghana, Togo, Benin, Nigeria, Côte d'Ivoire.

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Résumé

Le littoral à faible altitude et sédiments meubles du Golfe de Guinée est très vulnérable à l'érosion côtière et à la hausse relative du niveau marin. Les grandes capitales et les principales activités économiques sont concentrées le long du littoral, et potentiellement exposées à des risques imprévus. Actuellement, les recherches sur les impacts et la vulnérabilité face à la hausse relative du niveau marin (i.e. incluant la subsidence) sont limitées. Les progrès récents des modèles numériques d'élévation (MNE) globaux, basés sur les données satellitaires, offrent des possibilités intéressantes pour évaluer l'élévation des côtes à grande échelle et identifier les « points chauds » de vulnérabilité potentielle face à la hausse du niveau marin. Dans ce contexte, cette étude présente d'une part une revue de la littérature sur la vulnérabilité côtière à la hausse du niveau marin dans la région du Golfe de Guinée. D'autre part, cette étude utilise des MNE globaux récents basés sur des données satellitaires pour évaluer l'élévation côtière du Golfe de Guinée et identifier des zones géographiques de faible altitude nécessitant des investigations plus poussées. Les résultats de la télédétection par satellite sont validés avec des points de données in situ du delta de la Volta.

Les résultats de la revue de littérature soulignent que très peu de publications étudient les effets combinés de la hausse du niveau marin global et de la subsidence pour la zone d'étude. Aucune n'étudie les moteurs de la subsidence. Notre analyse des MNE satellitaires montre qu'il existe de fortes incertitude sur l'élévation des zones côtières de la zone, avec d'importants écarts (> 1m) d'un MNE à l'autre. Ces résultats soulignent l'importance de la validation, soit avec des données de terrain, soit par des approches avancées telles que l'incorporation de plusieurs MNE. Malheureusement, les données de terrain pouvant servir de référence sont rares dans la région, ce qui souligne le besoin pour davantage de mesures de terrain et de données publiquement accessibles. L'incorporation des nouvelles données dans les MNS – p. ex. LiDAR ou stéréogrammétrie optique de haute résolution – devrait améliorer les évaluations de manière significative, perspective qui devrait être approfondie. En combinant les données de FABDEM et CoastalDEM_v2.1, plusieurs points chauds de vulnérabilité à la hausse du niveau marin ont été identifiés, notamment Lagos, le Delta du Niger, Cotonou, Accra Ouest, le delta de la Volta, et les zones urbaines entourant la lagune d'Ebrie à Abidjan. Nous concluons cette étude en proposant des pistes concrètes pour de futures recherches et projets sur la hausse relative du niveau marin dans la région.

Mots-clés

Golfe de Guinée, hausse du niveau marin, subsidence, modèle numérique d'élévation, vulnérabilité côtière, Ghana, Togo, Benin, Nigeria, Côte d'Ivoire.

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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). Economic activities are also concentrated at the coastline. For instance, coastal areas in Nigeria are home to 85% of industry and more than 200 million people (United Nations World Population Prospects, 2022) whereas the coastal areas of Ghana house around 80% of its industrial firms (Amlalo, 2006).

The entire coastline is currently experiencing alarming coastal erosion rates, ranging from 1 to 15 m/year between Côte d'Ivoire and Nigeria (e.g. Croitoru et al., 2019; Anthony 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); Almar et al. (2021)). 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 (Coastal land subsidENce in the GULF of Guinea) research program aims at improving the assessment of exposure to relative sea-level rise along the coast of Guinea 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 regional assessment case while the Ghana case and Nigeria case are presented in Avornyo et al. (2023) and Ikuemonisan et al. (2023) respectively.

Objectives of the study

A literature review on coastal vulnerability to rSLR in the Gulf of Guinea region was performed to assess the availability of local knowledge and data and identify crucial knowledge gaps which impede proper coastal risk assessment in the region (section 2). In addition, for the correct assessment of coastal exposure to rSLR, the availability of good quality elevation data is of paramount importance. As shown in previous studies for other coastal plain regions (e.g. Minderhoud et al., 2019; Almar et al., 2021;

Seeger et al., 2023), digital elevation models (DEM) derived from satellite altimetry data may have significant biases in low-lying coastal areas. The study presented here aims to assess several recent global DEMs and provide a satellite-based remote sensing multi-source coastal elevation assessment of the Gulf of Guinea region to suggest key low-lying geographical areas (hotspots) where detailed investigations are required (section 3). Geospatial findings from satellite remote sensing are validated with in-situ data points in the Volta Delta. Based on these results, we propose concrete suggestions for follow-up research actions and project(s) on coastal subsidence and rSLR for the Gulf of Guinea region.

1. Literature review

1.1. Methodology

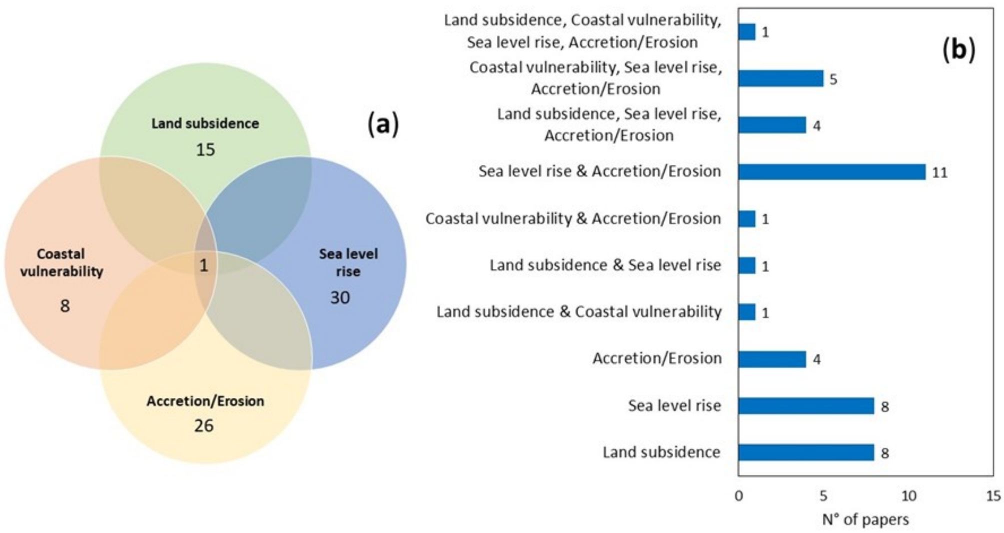
The literature review was conducted using: Scopus, Web of Science and Google Scholar as search engines. Initially, we collected original articles, book chapters, conference proceedings, extended abstracts written in English and published by international journals after peer review and also thesis and reports written in French.

The papers were collected using different keywords such as “Land subsidence”, “Coastal vulnerability”, “Sea level rise”, “Accretion”, “Erosion”, and “Gulf of Guinea”, “Nigeria”, “Ghana”, “ Côte d'Ivoire”. Afterward, we identified the publications with the selected keywords for the purposes of the work and a database of selected works was created.

1.2. The literature database

A total number of 44 papers were identified (the list is provided in Appendix). These documents were subdivided into groups based on the content of the publications and using four research topics: “Land subsidence”, “Coastal vulnerability”, “Sea level rise”, “Accretion/Erosion”. Publications dealing with more than one research topic were also noted and the number of papers overlapping different topics are shown in the Venn diagram and a histogram (Figure 1). The results show that only one document covers all the selected research topics, suggesting additional efforts should be devoted to the integration of different phenomena such as land subsidence, SLR and accretion/erosion in studies for the assessment of the coastal vulnerability of the Gulf of Guinea. The mentioned paper was developed by Addo (2013) and evaluated the coastal vulnerability index to climate change around Accra (Ghana). In this work, local subsidence trend and accretion/erosion rates are included as relative risk factors to assess the coastal vulnerability. SLR rates extracted from previous works were used to discuss the vulnerable areas of the Accra coast by distinguishing three categories such as low, medium and high vulnerable stretches of the coast.

Figure 1. Venn diagram and histogram of the literature review.



(a) Venn diagram of the literature study with the total number of papers grouped using four keywords and their intersections of the four topics. (b) Histogram of the number of papers that have been tagged with one or more than one keyword.

1.3. Database analysis

Most of the papers (30) deal with SLR. Among these papers, eight do not connect to other topics. Fashae and Onafeso (2011) examined the historical trend in storm tide along the coast of Lagos, and projects the potential impact on coastline change considering scenario-based climate change predictions from three different general circulation models (GCMs). The change in erosion rates and storm surge progression were evaluated using satellite imageries from LANDSAT Thematic Mapper for 1999 and 2009. Idowu and Home (2015) carried out empirical predictions considering the probable effects of anthropogenic effects such as the land reclamation activities coupled with projected SLR in the stretches of Lagos coast. In this work, the data come from a literature review across various disciplines, predictions and reports from monitoring agencies, global organizations, and real-life experiences. The authors state that on the global scale, various predictions on SLR indicate values of 1 m by the end of the century, but the high uncertainty related to the existing models based on continental ice melting is a challenge for predicting SLR. Furthermore, excessive and uncontrolled land reclamation activities on the lagoon side of the city, will aggravate the situation. Musa et al. (2015a, 2015b and 2016) considered the effects of the SLR on flood duration, flooding reach and water depth in the Niger river basin and along the lower Niger delta. The authors used SRTM DEM from NASRDA data archives to assess the elevation of the Niger delta, but these satellite-derived DEMs have less vertical accuracy, higher bias and higher RMSE than other DEMs derived from airborne lidar and airborne as explained in section 3.2 of this report. The effect of different SLR scenarios was also studied by Onwuteaka (2014) to assess the flood exposure of the Nigerian coastal areas.

Without specific quantitative measurements, SLR was considered to assess submersion risks at a world scale and in West Africa by Tessler et al. (2015) and Alves et al. (2020), respectively. In particular, Tessler et al. (2015) introduced a systematic global-scale assessment of the changing risk profiles of coastal deltas, whereas Alves et al. (2020) carried out a review on coastal erosion and flooding risks, together with best management practices in West Africa.

Eleven papers deal with SLR and accretion/erosion rates. Three papers (Addo et al., (2008); Addo and Adeyemi (2013) and Evadzi et al., (2017)) include SLR rate of 2 mm/yr in conformity with the global trend, with historic rate of erosion equal to 1.13 m/yr (±0.17 m/yr) in Accra, Ghana. The large range of SLR used for future scenarios ranging from 2 to 6 mm/yr affects the uncertainty of the results. The authors found that the western and the eastern regions areas of the Accra coast are eroding more rapidly than the central region (-0.2 m/yr) reaching values of -1.7 and -1.9 m/yr, respectively. This evidence should be due to the geomorphic and geological features and the engineering interventions (reclamation and construction of groynes and revetments) that could be responsible for stabilisation and accretion. The authors stated that the overall bounds of the possible recession rates are -2.45 m/yr and -1.27 m/yr. The predictions show that some important infrastructures will be lost in the future such as the Kwame Nkrumah Mausoleum in 2152, the Independence Square between 2082 and 2112, and Christianborg Castle in 2052. Addo et al. (2015) evaluated for the same area the interactions between SLR, hydrodynamic forces, seabed, beach morphology and potential sediment transport as well as anthropogenic activities. The report produced by the United Nations Environment Programme (UNEP) in 1985 described the control factors (i.e., the physical structure and the nature of the rocks) of the erosion and the regional historical trends of the SLR along the Coast in West and Central Africa. However, currently, the anthropic pressure in the study area is very different. In the work by Giardino et al. (2018) the areal land losses due to erosion and coastal retreat as a result of man-made interventions and climate change with respect to a reference scenario were quantified and a large-scale sediment budget was developed using a numerical model for the Gulf of Guinea. The authors found that the effects of the current major ports on coastal erosion will be of the same order of magnitude as the effect of lower SLR scenarios (RCP 4.5 climate scenario). Future local accretion or erosion of the shoreline up to 1–2 m/y, may be caused by climatic effects on offshore wave conditions (i.e., wave height and incoming wave direction) and in river catchments (e.g., precipitation or temperature). Overall, the study gave insight into the interdependency between different interventions along the rivers and at the coast on the sediment budget, suggesting that a large-scale integrated sediment management plan is needed for sediment management.

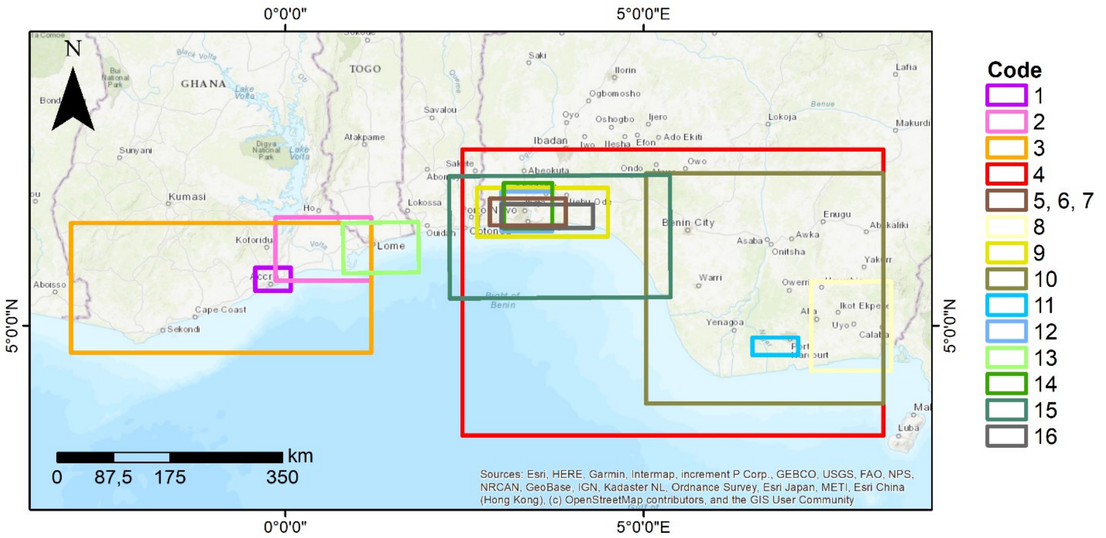
Furthermore, Evadzi et al. (2018) evaluated the awareness of sea-level response to climate change in the coast of Ghana using semi-structured interviews at national, municipal/district and coastal community scales. The authors reported that most communities on the coast of Ghana are aware of SLR and the coastal erosion impact on their communities, but the causes of this problem were mainly attributed to God indicating the need for educational outreach programs on SLR. Some communities stated that the sea defense wall in their area does not allow drains to flow easily from the mainland into the sea, resulting in favorable conditions for mosquitoes that increased malaria cases. Fishing communities expressed a negative opinion about the sea defense project because landing sites are not provided. The authors stated that there is a need of facilitated discussion learning programs to improve cooperative relationships between national, district, and local authorities with coastal research scientists and engineers, and communities along the coast of Ghana.

Two papers provided measurements of the SLR in the Western African region using satellite altimetry data (Melet et al., 2016; Marti et al., 2021) and mentioned that this data will be important to further assess if the coastal regression will be mainly due to natural or anthropogenic factors. Ozer et al. (2017) used high spatial resolution images available in open access on Google Earth to evaluate the coastal dynamics. The study found that 34% of the coastal area of Togo and Benin is stable, 14% is characterized by accretion in upstream of harbor infrastructures, but a large part (52%) experiences erosive processes, sometimes exceeding annual average retreats of 10 m/yr. In addition, a recent study proposed by Dada et al. (2021) mentioned that SLR and changes in the frequency and power of extreme meteorological events are increasing the impact on coastal flooding and erosion, thus acceleration of land loss in the Western African coast. A rise greater than the global average is expected for this area, but a gap in SLR data does not allow to generate future projections with high confidence. For example, few regional climate models or empirical downscaling were produced to create climate change scenarios for this region (Dada et al., 2021).

Regarding the topic of land subsidence, a detailed study was performed to extract relevant characteristics of the previous works. A summary of the land subsidence studies is listed in Table 1, including the subsidence values and the different drivers. The geographic location of the studied areas is represented in Figure 2. In particular, the literature review shows that land subsidence hotspots were detected in Lagos, Niger delta, Port Harcourt, Warri and Volta delta. No specific studies were found about land subsidence in Abidjan, Accra, Togo and Benin areas that were indicated as affected by subsidence by Cian et al. (2019). In Lagos, the authors recognized different drivers of the land sinking such as groundwater extraction, natural loading isostasy, peatland reclamation and loading by building (Ikuemonisan et al., 2021a,b). Two papers reported that land subsidence in Lagos is mainly due to the over-abstraction of groundwater (Ikuemonisan and Ozebo, 2020, Mahmud et al., 2016a). Available groundwater data indicated a general decline in hydraulic head between 2011 and 2017, but studies about the amounts of withdrawn groundwater are unavailable. Land subsidence is also due to land reclamation as observed at the Lekki peninsula. Furthermore, Ikuemonisan and Ozebo (2020) suggest that the settling of Holocene sediments and isostatic deformation resulting from the passive continental margin of an African plate are possible factors influencing the subsidence rate. The direct negative effects experienced in Lagos are damage to infrastructure, increased occurrence of flooding, and increased coastal erosion (Ikuemonisan et al., 2020). Satellite-based estimates of ground settlement in some parts of the Lagos metropolis is very severe with reported rates up to -94 mm/yr (Ikuemonisan et al., 2021 a, b), however a recent satellite-based analysis reported much lower vertical land movements for the city (Ohenhen & Shirzaei et al., 2022), revealing the need for ground truth data to validate these spaceborne estimates. In both analyses the settlement rate is unevenly distributed because of heterogeneous geotechnical soil properties and different groundwater extraction rates and land use. In the Nigerian delta, Port Harcourt and Warri are subsiding not only for natural drivers such as tectonic movements and compaction of recent sediments but also for the fluid withdrawal from aquifers and hydrocarbon reservoirs (Fabiyi and Enaruvbe 2014; Ericson et al., 2006; Uko et al., 2018; Mahmud et al., 2016 b).

Unfortunately, no comprehensive publication provides relevant information on the contribution of different drivers of land subsidence. This knowledge is relevant for distinguishing between natural and anthropogenic land subsidence and enable projections of it following different drivers and processes, of which some are more or less linear while other can be high non-linear in time and space (e.g. Shirzaei et al., 2021). Increasing this understanding is crucial to enable inclusion of land subsidence into reliable projections of rSLR and to think of better suited adaptation plans.

Figure 2. Land subsidence studies previously performed in the study area.



The locations of the study sites reported in Table 1 are represented by polygons.

Table 1. Summaries of the case histories characteristics of the previously reported land subsidence studies.

Code	Authors	Study area	Method	Data	Monitored period	Range of subsidence* rates (mm/year)	Max. subsidence rates (mm/year)	Drivers
1	Addo (2013)	Accra, Ghana	Tide gauge	Takoradi tide gauge station	-	≥ -1 and ≤ 1	-	-
2	Addo et al. (2018)	Volta delta, Ghana	Not measured	-	-	from -1 to -2 (hypothesis)	-	-
3	Boateng et al. (2016)	Ghana	Tide gauge	Takoradi and Tema tide gauge stations	-	≤ -1	-	-
4	Fabiyi and Enaruvbe (2014)	Nigeria	Space-based	ASTER (2001) and SRTM (2008)	2001-2008	from -20 to -50	-100	Hydrocarbon extraction
5	Ikuemonisan and Ozebo (2020)	Lagos, Nigeria	GPS and SBAS-InSAR	GPS** ENVISAT Sentinel-1	2011-2014 2004-2011 2015-2019	-3.3 -15 from -4.9 to -64		Groundwater extraction Natural loading Isostasy
6, 7	Ikuemonisan et al. (2021)a, b	Lagos, Nigeria	SBAS-InSAR	Sentinel-1	2015-2019	-8.7	-94	Groundwater extraction Peatland reclamation Loading by building
8	Udoh & Udofia (2014)	Akwa Ibom State, Nigeria	-	-	-	-	-	Groundwater extraction
9	Mahmud et al. (2016)a	Lagos, Nigeria	StaMPS	ENVISAT	2003-2010	from -4 to -7	-	Groundwater extraction

								Peatland reclamation Loading by building
10	Ericson et al. (2006)	Niger delta, Nigeria	-	-	-	-	-	Hydrocarbon extraction
11	Uko et al. (2018)	Niger delta, Nigeria	Leveling data	-	1988-2003	from -66.67 to 200	-	-
12	Cian et al. (2019)	Lagos, Nigeria	SNAP and StaMPS	ENVISAT Sentinel-1 TerraSAR-X	2004-2010 2015-2018 2009-2013	from -2 to -5	-	-
13	Guerrera et al. (2021)	eastern Ghana and western Benin gulf	-	-	-	-	-	Tectonic movements Groundwater extraction
14	Wu et al. (2022)	Lagos, Nigeria	SNAP and StaMPS	Sentinel-1	2015-2020	≤ -2	-	-
15	Ibe & Quelennec (1989)	Gulf of Guinea	-	-	-	-	-25	Tectonic movements
16	Tay et al. 2022	Lagos, Nigeria	InSAR ARIA-SG	Sentinel-1	2014-2020	From 5 to -13	-13	-

2. Elevation assessment

2.1. Study area

The coast of Gulf of Guinea comprises several geologic formations of different eras. These range from the earliest Archean to the Quaternary period. The geology of the various parts of the coast determines the "resistance" to erosion and land subsidence. Soft geological formations such as the unconsolidated Quaternary materials are less resistant than stronger geological formations like plutonic and metamorphic rocks (Heckmann et al. 2022).

In the study area, the beach evolution is controlled by natural and anthropogenic factors, which cause shoreline recession (erosion) and/or accretion, depending on prevailing exogenic and endogenic processes (UEMOA, 2017). The main anthropogenic factors that control beach evolution in the Gulf of Guinea include coastal development, the construction of nearshore infrastructure as a result of demographic pressure, as well as the construction of seawalls and other coastal structures, and human activities that lead to changes in sediment supply, such as sand mining, hydropower and river dams, dredging and land-use changes (Almar et al., 2015). Wind, waves and marine currents are natural forces that easily move the unconsolidated sediments along the beach, causing rapid modifications. The short-term beach evolution is determined by small-scale processes such as storms, wave action, tides and wind control, whereas the long-term evolution depends on large-scale processes such as climate changes and tectonic activity. The latter causes vertical movements which may be increased by anthropogenic land subsidence due to groundwater withdrawal, building load, etc. (e.g. Shirzaei et al., 2021) contributing to rSLR.

2.2. Advantages and disadvantages of satellite-derived digital elevation models

Digital Elevation Models (DEMs) are crucial inputs for SLR exposure and risk assessments. As global SLR projected for the 21st century are in the order of several decimeters, ranging from 30 cm to 80 cm or more by 2100 (IPCC, 2021), ideally the DEM should provide a similar vertical accuracy as is the case for DEMs created using high-accuracy elevation observations like airborne-based laser altimetry (LiDAR) or ground measurements from geodetic surveys. However, such data are not often available at a regional scale, or when they exist are not publicly available for the scientific community, especially in countries of the Global South. As a result, global or regional assessment of SLR exposure usually rely on DEMs derived from radar satellite altimetry data such as the NASA's SRTM DEM (Farr et al., 2007) and more recently on LiDAR satellite data (Vernimmen et al., 2020). However, satellite radar data may have large biases, up to several meters in some areas. Errors may arise from the presence of canopy cover, buildings or artefacts (Minderhoud et al., 2019; Almar et al., 2021; Hooijer and Vernimmen, 2021), which may lead to an over- or underestimation of exposure to SLR. On the other hand, LiDAR can penetrate vegetation canopy to create more reliable DEM in region with dense vegetation data. A new DEM interpolated from LiDAR (ICESAT-2) satellite data (that provides incomplete spatial coverage) have recently lead to an upward reassessment of coastal population exposed to SLR (Hooijer and Vernimmen, 2021), however the horizontal accuracy is only ~5 km, i.e. much lower than the 90m or 30m spatial resolution of the SRTM for instance. High-resolution on demand missions now also offer a promising at regional scale and hotspots (500 km^2) to assess fine scale morphological features such as protections and dunes (Almeida et al. 2019; Salameh et al. 2019; Taveneau et al. 2021). As new satellite increasingly accurate data will become available in the coming years, updated assessments with higher accuracy are expected, and represent a real game changer in West Africa (Almar et al. 2022). In addition, to the above-mentioned issues, global satellite-derived DEM are usually referenced to a geoid, which requires the correction of the vertical datum to local sea level, an step often forgotten in SLR impacts assessments (as highlighted by Minderhoud et al., 2019). This omission can lead to additional vertical biases in coastal elevation assessment as the global geoid models can deviate from local SLR up to several meters in extreme cases.

2.3. Datasets

2.3.1. Characteristics of the DEMs considered in this study

A wide variety of space-borne digital elevation models (DEM) based on Radar and/or LiDAR data became publicly available recently. The combination and comparison of multiple elevation models help to arrive at a superior assessment of local elevation. In the study, we compare and assess the potential offered by open-access and recently released DEMs, for an up-to-date coastal evaluation for the Gulf of Guinea region. These include: CoastalDEM version 1.1, CoastalDEM version 2.1, SRTM-ACE2, ALOS DEM (AW3D30), and FABDEM. The characteristics of the different DEMs are presented in the overview of Table 2. We have highlighted the specifications of the different DEMs considered advantageous for the study in green.

Table 2. Key characteristics of the DEMs.

	CoastalDEM v1.1	**CoastalDEM v2.1**	**SRTM-ACE2**	**ALOS-DEM (AW3D30)**	**FABDEM**
Base data (radar)	SRTM	NASADEM (modernized version of SRTM)	SRTM	ALOS-PRISM	COPDEM30 (itself based on TanDEM)
Calibration data	airborne lidar-derived elevation data in the U.S. and Australia	NASA's ICESat-2 LiDAR Globally	ERS1, ERS2, Topex, EnviSat and Jason-1	ICESat-2, cross-calibration: SRTM, ASTER GDEM, PRISM (airborne)	LiDAR DTM, ICESat-2
Elevational range of corrections	1-20 m	-10m-120m	-	-	-
Tree height bias removed	V	V	x	X	V
Building removal	x	x	x	X	V
Ellipsoid	WGS84	WGS84	WGS84	WGS84	WGS84
Geoid	EGM96	EGM96	EGM96	EGM96	EGM2008
Spatial resolution (m)	30	30	90	30	30
Model architecture	perceptron neural network	convolutional neural network	Data fusion	Void Filling	Random forest
Released	2019	2021	2010	2021 (Ver. 3.2)	2022
Reference	Kulp & Strauss (2019)	Kulp & Strauss (2021)	Berry et al. (2010)	Jaxa (2021)	Hawker et al. (2022)

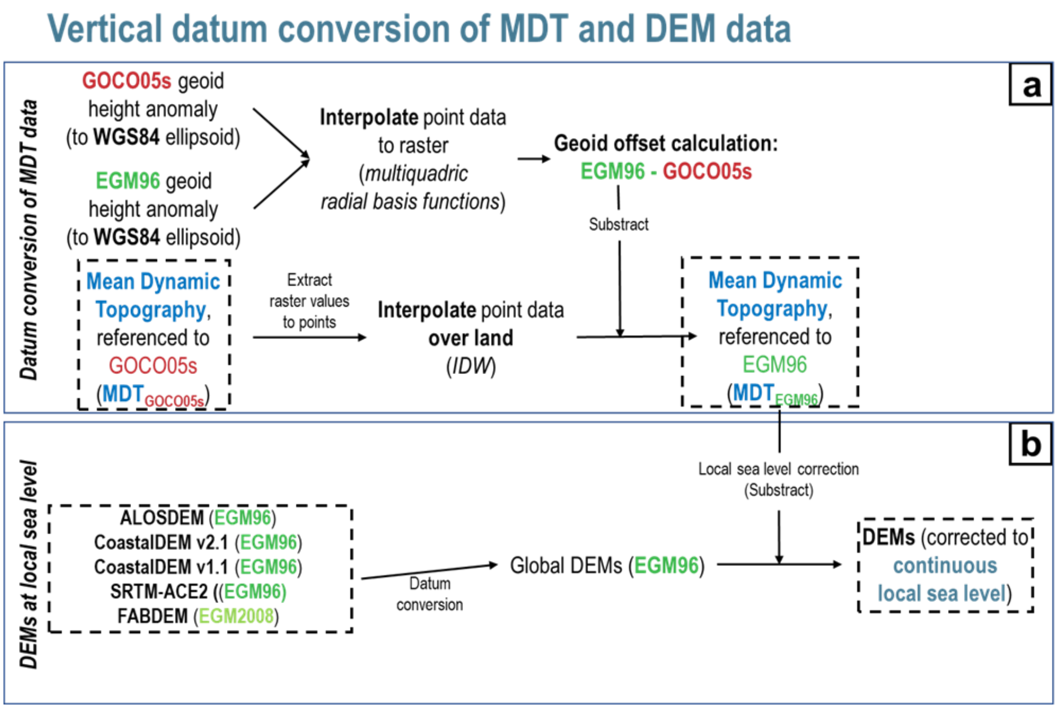
Overview of key characteristics of the satellite-based DEMs considered in this study. Key specifications have been indicated based on a colour scheme for features considered advantageous (green) or limiting (orange) for our study purpose.

In terms of calibration data, the use of global data is important to ensure representativeness. For instance, initial calibration of CoastalDEM v1.1 on data from the US, and validation in Australia resulted in an overfit and limited transferability to other coastal regions globally (Kulp & Strauss, 2019). Moreover, the ingestion of LiDAR (spaceborne: ICESAT-2) and precise airborne measurements are considered superior for calibration. In general, LiDAR systems are considered to offer higher precision for the estimation of coastal elevation as compared to the more widely available radar instruments due to its generally higher vertical resolution, direct measurement techniques, and being less affected by surface roughness and vegetation cover compared to Radar systems (Vernimmen et al., 2020). However, satellite-based LiDAR mission still offer limited data availability, as few satellites are equipped with LiDAR sensors and tend to have smaller swath lengths, moreover its performance is weather dependent, and data processing and storage is computational more intensive compared to satellite-based Radar inferences (Salameh et al., 2019). The tree height bias removal is relevant as densely vegetated areas can result in DEMs that overestimate the elevation height due to the scattering effects of vegetation. For instance, the presence of dense mangrove forests can inflate the height of the shoreline. In addition to tree height bias removal, the recent FABDEM also corrects for buildings (Hawker et al. 2022). The spatial resolution is preferable high to add detail to the spatial variation in coastal elevation. Most of the DEMs studied here are available at a 30m spatial resolution.

2.3.2. DEM correction

All five DEMs have been vertically referenced to local mean sea level of the Gulf of Guinea as opposed to the standard global vertical reference datums. Local mean sea level data have been derived from AVISO's Mean Dynamic Topography (MDT) datasets describing the mean sea surface height above geoid computed on a 20 years period (1993-2017). The MDT dataset was produced by CLS and distributed by Aviso+, with support from CNES (https://www.aviso.altimetry.fr/). The MDT data integrates ocean mean geostrophic currents as mean sea level heights differ across the global. The MDT covers the seas and oceans globally. To correct the DEMs also at inland positions, the mean local sea level points along the coast were interpolated for the inland region using Inverse distance weighted (IDW) interpolation, similar to the approach by Vernimmen et al. (2020).

Figure 3. Workflow for DEM correction.



Workflow to convert all DEM and MDT data to the EGM96 geoid model (vertical datum) (a) and correction of global DEMs to local mean continuous sea level (b) (modified from Seeger et al., 2023).

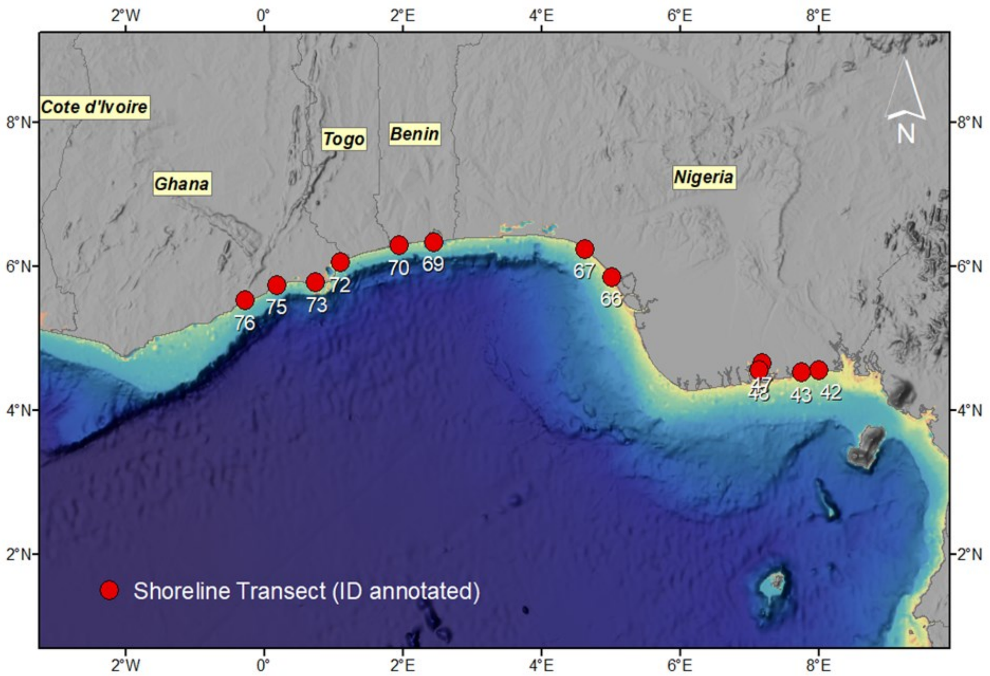
The initial global DEMs were referenced to different geoid models (vertical datum). Four DEMs were projected to the EGM96 model, whereas FABDEM was referenced to the EGM2008 geoid, and the MDT data to the the GOCO05s vertical datum. To convert the DEMs to local mean sea level in the Gulf of Guinea as well as the cross-comparison of the different DEMs, a harmonization of the vertical datum was needed. As such, all data was converted to be consistently projected vertically to the EGM96 geoid model. The diagram in Figure 3 overviews the workflow to correct DEMs to local mean sea level (b) as well as the prior conversion of all datasets to the EGM96 geoid model (a). For the calculation of gravity field functionals on ellipsoidal grids, we made use of the ICGEM conversion computation (available through: http://icgem.gfz-potsdam.de/calcgrid). This allows comparison of different vertical datum (geoids) against the WGS84 projection (ellipsoid) to enable conversions. Point data has been interpolated using multiquadric radial basis functions as the use of multiquadric RBF has been established to be the most suitable for geoid data interpolation in Doganalp and Selvi (2015) and a number of studies reviewed by Foroughi et al. (2018).

2.4. Methodology

2.4.1. Shoreline profile for DEM comparison

For visual comparison of the different corrected DEMs we made use of shoreline profiles, running perpendicular to the coastline, as presented in Diaz et al. (2019) and Almar et al. (2021). Shoreline profiles offer a valuable tool for visual comparison of the different DEMs in a harmonized way that is easy to comprehend visually and targeted to low-lying coastal regions in our study area. By comparing the profiles, we can observe how the DEMs differ from each other in terms of relative skewness or discrepancies. In other words, the method provides a quick and easy way to visually and comprehensibly evaluate the (dis)agreement of different DEMs in low-lying coastal regions.

Figure 4. Location of the shoreline transects.



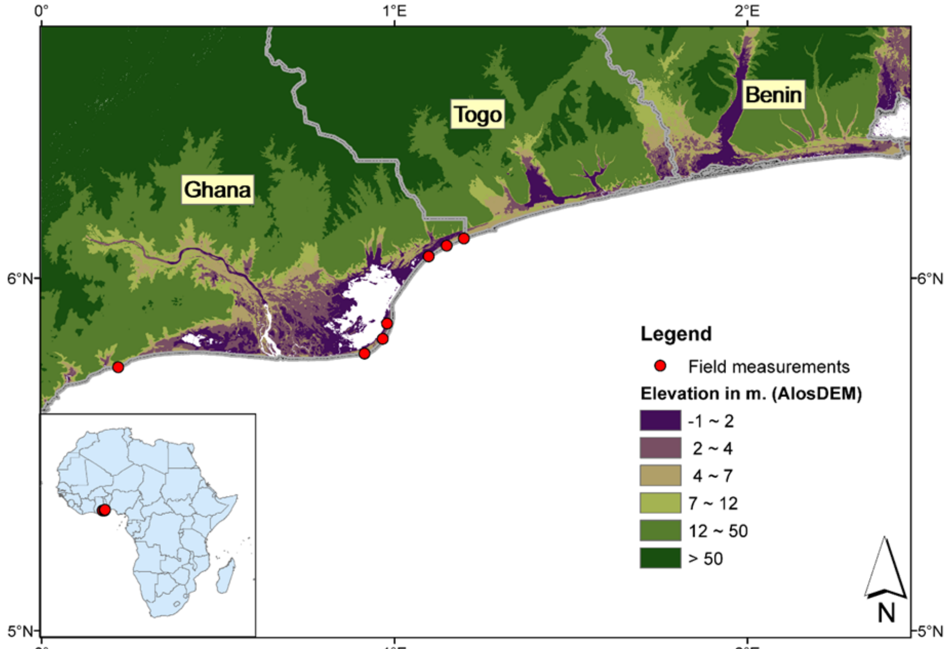
Overview of the shoreline transects (12 a piece; 6 pairs) sampled across lowly elevated coasts of Ghana, Togo, Benin and Nigeria. Base layer comprises of the combined bathymetric/topographic digital elevation models stewarded at NOAA's National Centers for Environmental Information (NCEI), available through: ArcGIS Online (https://gis.ngdc.noaa.gov/arcgis/rest/services/DEM_mosaics/DEM_global_mosaic_hillshade/ImageServer)

The Global Self-consistent, Hierarchical, High-resolution Geography Database (GSHHG) coastline, which contains the latitude/longitude coordinates of the coastline, was used to draw sample locations (Wessel & Smith, 1996). The database consists of 14,140 transects along the open coasts of the world of which 106 are located in our study area. Twelve transects with the lowest average coastal elevation according to the GSHHG and located in Ghana, Togo, Benin and Nigeria were selected (Fig.4). The 12 elevation profiles were then extracted from the DEM using the coordinates from the GSHHG. The coastal shoreline and topography are highly variable alongshore. Therefore,in order to obtain reasonably robust estimates, regional profiles are constructed by averaging two neighbouring elevation transects. All transects lead up to 2 km of sample points inland, with 20 m intervals, totaling 100 points which are plotted using 3 points moving average so ensure smooth profiles (Fig.8).

2.4.2. In situ validation

Ground truth validation is extremely valuable to assess the bias and uncertainty involved in satellite-derived coastal height estimates. In-situ validation has been conducted based on a small dataset of ground control point (GCP) height measurements in the Volta Delta, Ghana. In total the measurements consist of seven GCP data measured in June 2009 and April 2021[1]. We have taken the average of both time moments to increase the robustness of the measurements and provide versatility to the temporal variation and composite nature of the different satellite-based DEMs. The in-situ measurements have been recorded on EGM2008 vertical data, and hence transformed to EGM96 for this study's purpose. Commonly used accuracy metrics are applied to understand the error and deviance of the DEMs against the in-situ measurements. These include root mean square error (RMSE), Mean absolute error (MAE), and the rank-based correlation (Kendall's tau) between in-situ and space-borne elevation measures. An overview for the location of the GCP for in-situ measurement of coastal elevation can be found in Figure 5. One of the GCP (located in Great Ningo, westernmost point) has been measured very close to the shoreline. The Great Ningo GCP's vincinity to the coastline produced missing values across all five satellite datasets and therefore was omitted from of the analysis.

Figure 5. Overview of the in-situ ground control points for validation of elevation estimates.



Datapoints are located along the coast of Ghana's Volta Delta region.

[1] Note : there is virtually no difference between the values measured in 2009 and 2021.

2.4.3. Coastal vulnerability analysis

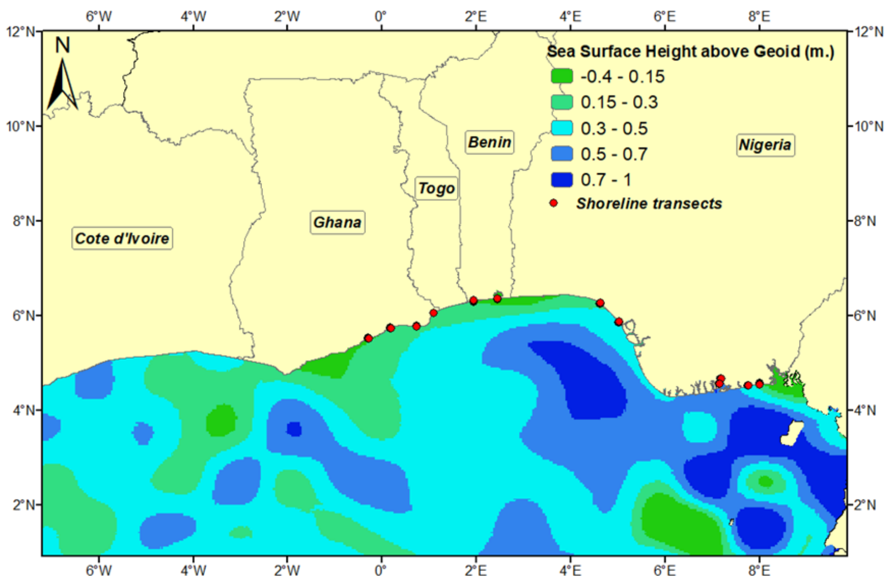
After validation and shoreline profile analysis, we focused on the most promising DEMs to scope potential coastal vulnerability hotspots. The key variables to determine potential vulnerability include the DEM-derived coastal elevation itself in combination with land use types. Cropland and built-up land cover types are considered as focal points given that these host the largest number of inhabitants and land-based economic activity, and thus potentially the highest vulnerability to human damage and loss. In addition, these land cover types are generally characterized by the highest anthropogenic land subsidence rates, thus posing a greater future risk to relative sea level rise (e.g. Abidin et al. (2011); Minderhoud et al., (2017)). The land cover type map is based on the Copernicus WorldCover dataset which provides a baseline global land cover product at 10 m resolution for 2020 based on Sentinel-1 and 2 satellite data (Zanaga et al., 2021). WorldCover offers ten land cover classes and a minimum overall accuracy of 75%. Hence, vulnerability hotspots are defined by a coastal elevation height of less than 2 m above local sea level and characterized by cropland and built-up land cover zones.

2.5. Results

2.5.1. MDT local sea-level map

An overview of the local sea height deviation above the EGM96 geoid can be found in Figure 6. Most relevant are the values close to the shoreline as these determine the actual coastal sea level and are subsequently used to fill in values inland following interpolation. Figure 7 shows the distribution (N=1200) of sea surface height above geoid for the selected shoreline transects (Fig. 4). Directly along the shoreline, deviations of 0.1 m to 0.7 m from the global geoid model are not uncommon within our study area. Such deviations can stem from ocean circulation, temperature and salinity, tides, wind, waves amongst other factors. Together, Figure 6 highlights the importance of converting the reference of the data from the global geoid to the local sea level. Neglecting to do so can lead to large biases in the assessment of coastal elevation to local sea level and thus rSLR impact assessments. This is especially important for the low-lying coastal regions we focus on as the observed differences in sea surface height (up to multiple decimetres) can be several magnitudes larger than global SLR.

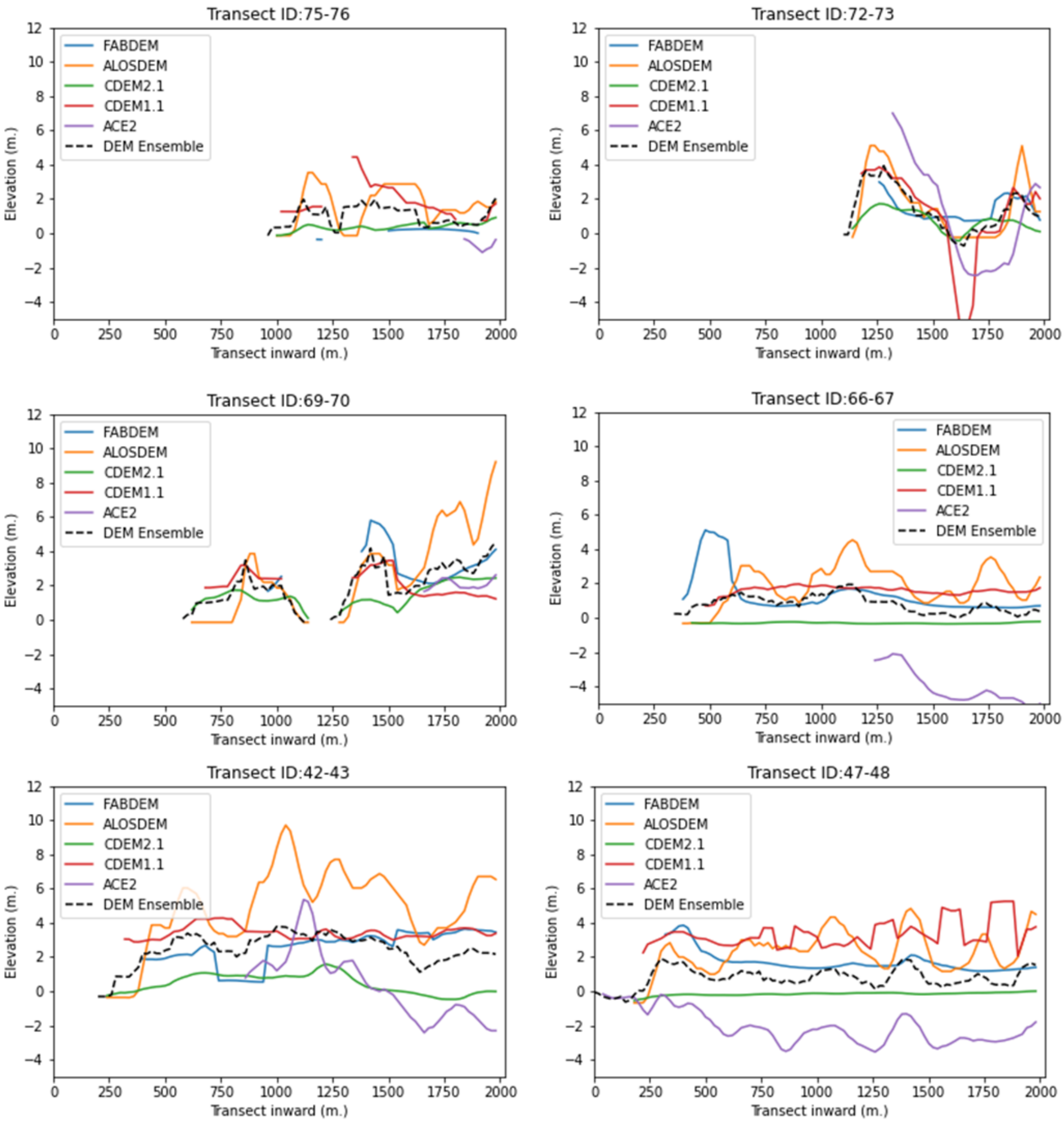
Figure 6. Sea Surface Height above geoid (EGM96) based on AVISO's Mean Dynamic Topography MDT-CNES-CLS18 is an estimate of the mean over the 1993-2017 period.



Data source: AVISO's Mean Dynamic Topography MDT-CNES-CLS18, which is an estimate of the mean sea surface height above the geoid over 1993-2017.

2.5.2. Coastal elevation assessment along shoreline profiles

Figure 7. Shoreline elevation profiles.



Shoreline elevation profiles (2000 m transects) of six paired low-lying coastal areas along the Gulf of Guinea as observed by the five different DEMs (FABDEM, AlosDEM (AW3D30), CoastalDEM v2.1, CoastalDEM v1.1, SRTM-ACE2) and computed as ensemble average. The location of paired shoreline transects can be found in Fig. 4.

The coastal elevation profiles of six paired shorelines are presented in Figure 7. The data acquisition starts further or closer to the shoreline depending on the DEM. Interrupted lines generally indicate the shoreline transact crosses inland water surface (e.g.: lagoons, estuaries). The coastal elevation in inundated and sea-covered areas was unable to be mapped in the DEMs, however, differences exist across the different data sources in the starting point of detectable shoreline. In general, we find that ACE-2 tends to report values much further inland along the transects as opposed to the other DEMs.

In general, we observe relatively large differences between DEMs over the same transects. These differences are in the range of meters (magnitude of the deviation between 1.1 and 3.4 m, Table 3). The shoreline profiles illustrated by ACE-2 in these low lying transects deviate the strongest from others and the ensemble median value (RMSE: 3.43, Table 3). The bias of estimation tends to negative (-2.7 m) for ACE-2 which could have to do with the initial coarser resolution (90 m). CoastalDEM_v2.1 tends to give structurally lower estimations of coastal elevation as well yet to a lesser extent. AlosDEM, on the other hand, tends to give higher estimates of coastal elevation compared to the other DEMs. The lack of tree height bias removal could be underlying this overestimation. FABDEM, and to lesser extent CoastalDEM_v2.1, seems to fall most frequently in the middle of the pack, leading to the lowest error and deviation of the mean of all elevation models.

Table 3. Comparison of the DEM performances along the shoreline profiles.

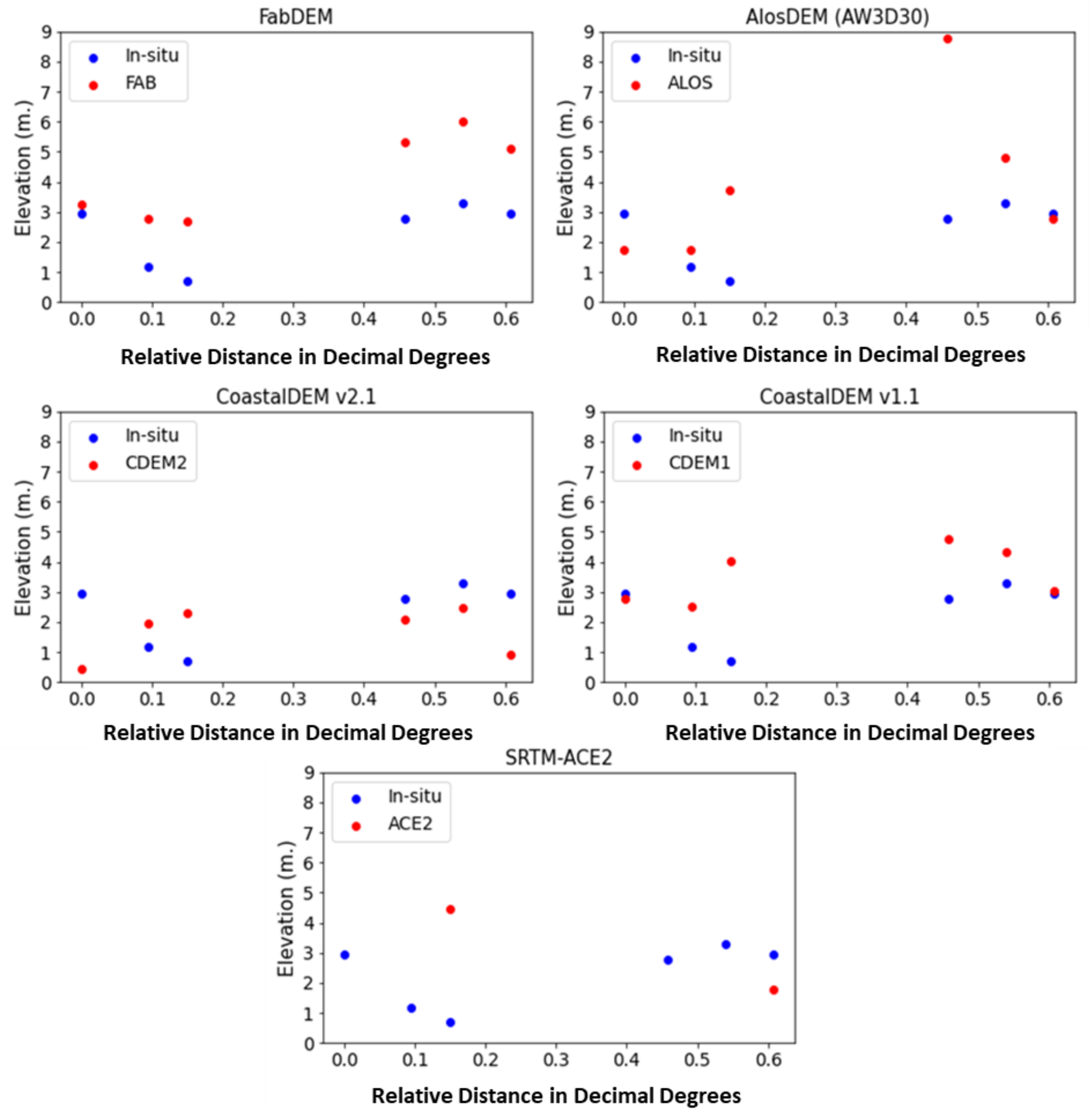
		FABDEM	AlosDEM (AW3D30)	CoastalDEM v2.1	CoastalDEM v1.1	SRTM-ACE2
	Mean	2.22	3.15	0.63	2.78	-0.84
	Median	1.87	3.00	0.46	2.79	-1.40
	Std. Deviation	1.44	2.66	0.82	1.57	2.25
versus median ensemble	**Bias**	0.20	1.34	-1.20	0.81	-2.74
	MAE	0.70	1.58	1.29	1.14	2.98
	RMSE	1.13	2.36	1.66	1.68	3.43

Table 3: Descriptive and error metrics (Bias, Mean Absolute Error (MAE), Root Mean Square Error (RMSE) and rank-based correlation (Kendall's tau) calculated between the five individual DEMs and the median ensemble of all DEMs across the six low-lying coastal transects. NaN occurrences are omitted from analyses.

2.5.3. In situ performance assessment

With six ground control points (GCP) in the Volta Delta, the in-situ validation is very limited in sample size. Yet, the measurements are conducted thoroughly over two moments in time (2009 and 2021) and averaged to create temporally more robust height estimates. Table 4 provides the key statistics to validate DEM performance against the ground data. The ACE-2 DEM is found to be problematic given that only two data points could be observed due to the earlier-mentioned data paucity at the coast. Moreover, there two points exhibit the strongest deviation from in-situ measurements compared to the other DEMs. AlosDEM has the second largest error size according to the used metrics, however this can largely be attributed to a single point strongly inflating overall MAE and RMSE, highlighting the need for more validation data to avoid large impact of a single datapoint. We observe that the CoastalDEMs perform very well in terms of error, with the latest version recording a slightly better accuracy (Table 4). In terms of relative differences along the Volta Region, FABDEM records a relatively strong correlation which highlights its accuracy in capturing relative changes in coastal height. Figure 8 is illustrative of how the different DEMs follow the coastal height curvature along the six coastal GCPs in the Volta Delta. Based on cross-validation against other DEMs (previous paragraph) and the validation against in-situ GCPs, FABDEM and CoastalDEMs tend to be the safest to the other DEMs in terms of error size of this preliminary analysis. When considering the ability to capture relative height differences, FABDEM appears to be the most consistent option.

Fig. 8: Scatterplots depicting in-situ measurements versus DEM estimates of coastal elevation along six geodetic control points (GCP) in the Volta Delta.



The x-axis shows the distance between GCPs, in relative decimal degrees, where 0° refers to the most westward GCP. See fig. 5 for the GCP locations.

Table 3. Comparison of the DEM performances at ground control points.

	FABDEM	AlosDEM (AW3D30)	CoastalDEM v2.1	CoastalDEM v1.1	SRTM-ACE2
MAE	1.89	2.08	1.41	1.32	2.45
RMSE	2.05	2.86	1.57	1.72	2.76
Kendall's tau	0.73*	0.14^{ns}	-0.07^{ns}	0.20^{ns}	-

*Performance assessments of the satellite-based DEM estimates against in-situ validation points (N=6) in the Volta Delta. The error metrics include Mean Absolute Error (MAE), Root Mean Square Error (RMSE) and rank-based correlation (Kendall's tau)). Kendall's tau could not be calculated for SRTM-ACE2 due to missing data. *= significant at alpha < 0.05 level.* ^{ns}= not significant.

2.5.4. Potential rSLR vulnerability hotspots

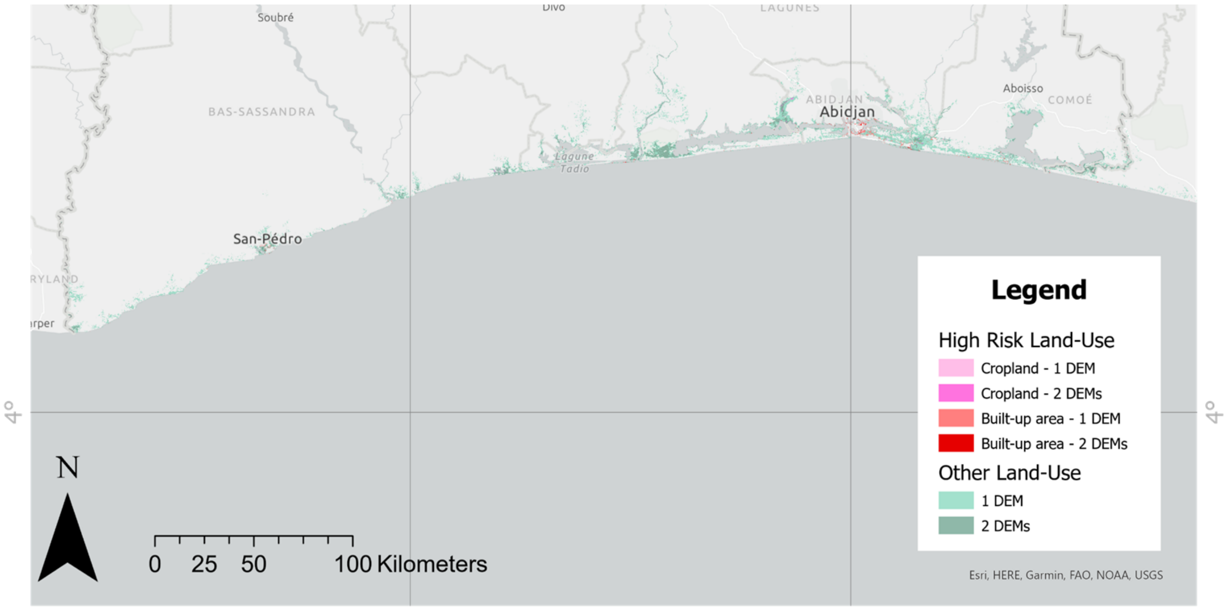
The FABDEM and CoastalDEM v2.1 perform best in our analyses and assumably represent the actual coastal land surface level (LSL) best. Hence, we decided to use both DEMs in the coastal vulnerability to rSLR hotspot analysis to delineate areas below 2-m LSL to reduce the dependency on a single DEM and potential errors herein. Maps are provided hereafter (Figures 9 to 18). The analysis was carried out at two levels of certainty following two approaches. The first, more precautionary approach, considers all areas identified below 2-m LSL in either of the two DEMs, while the second, higher certainty cross-validated approach, considers the areas identified below 2-m LSL by both DEMs. To add a first spatial assessment of coastal risk, we linked coastal land below 2-m LSL to high risk land-use types. We consider Built-up Areas and Cropland as land-use types with a higher risk to human loss and damage. This is given the generally higher probability of land subsidence in those areas due to compaction from heavy constructions and groundwater extraction for consumption and irrigation, both well-known causes for land subsidence and thus increased chance for rSLR (Shirzaei et al., 2021). In addition, built-up areas and cropland are tied to strong human presence and thus higher vulnerability through the effects of rSLR. Given the long stretch of coastline along the Gulf of Guinea, the results are presented for different national subsets.

Nigeria, in particular, contains large areas below 2-m LSL, most of which are located in areas with little built-up and cropland land use types. We observe, however, that large parts of the megacity of Lagos are below 2-m LSL as identified by both FABDEM and CoastalDEMv2.1. Therefore, large potential vulnerability is at stake given rSLR. The concerns can be extended across the border from Lagos into Benin, regarding the urban residential areas of capital Cotonou. Other cities within Nigeria such as the greater Lagos area, Bonny, Warri, Port Harcourt (the latter two sheltered within the delta) are facing similar vulnerability. Capital metropolitan areas of Accra and Abidjan also have distinct quarters of the city below 2-m LSL with consequential vulnerability to rSLR, especially West of Accra and surrounding the Ebrie lagoon within Abidjan.

The analysis focused on urban land and cropland as heavily relied upon areas for residence and food production while also subject to vulnerability risk in terms of anthropogenic land subsidence. Beyond these lands, natural and extensively used low-lying areas are potentially also vulnerable to accelerated rSLR. Anthropogenic land subsidence following oil extraction, for instance along the Niger Delta and surrounding coastal areas is likely, based on findings in oil extraction regions elsewhere (Zhang et al., 2015; Abija et al., 2020).Relative SLR in these natural regions can threaten biodiversity and relevant ecosystem services on which human and ecological communities rely (Furlan et al., 2022; Tregarot, 2021).

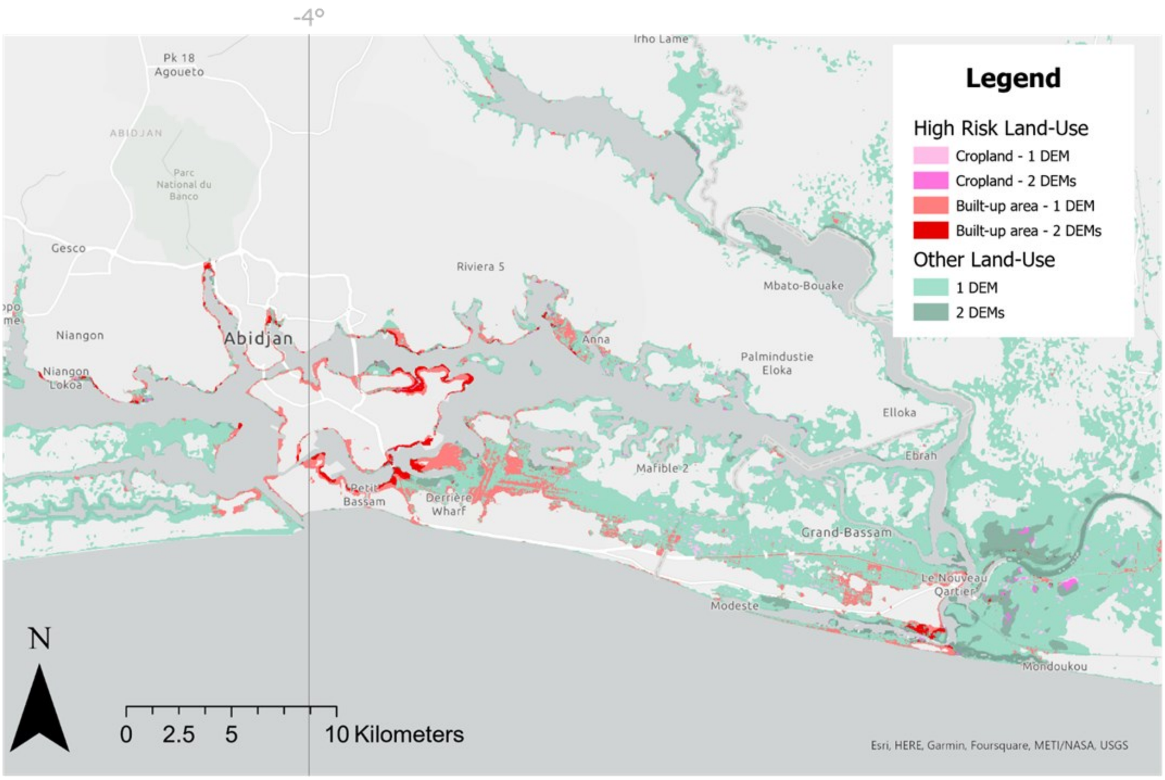
2.5.4.1. Côte d'Ivoire

Figure 9. Lowly-elevated coastal areas (elevation < 2 m above local mean sea-level) in Côte d'Ivoire.



Location of lowly-elevated coastal areas (elevation < 2 m above local mean sea-level), classified according to land-use types, in Côte d'Ivoire according to the DEMs FABDEM and CoastalDEM_v2.1. Land-use types are taken from Zanaga et al. (2021).

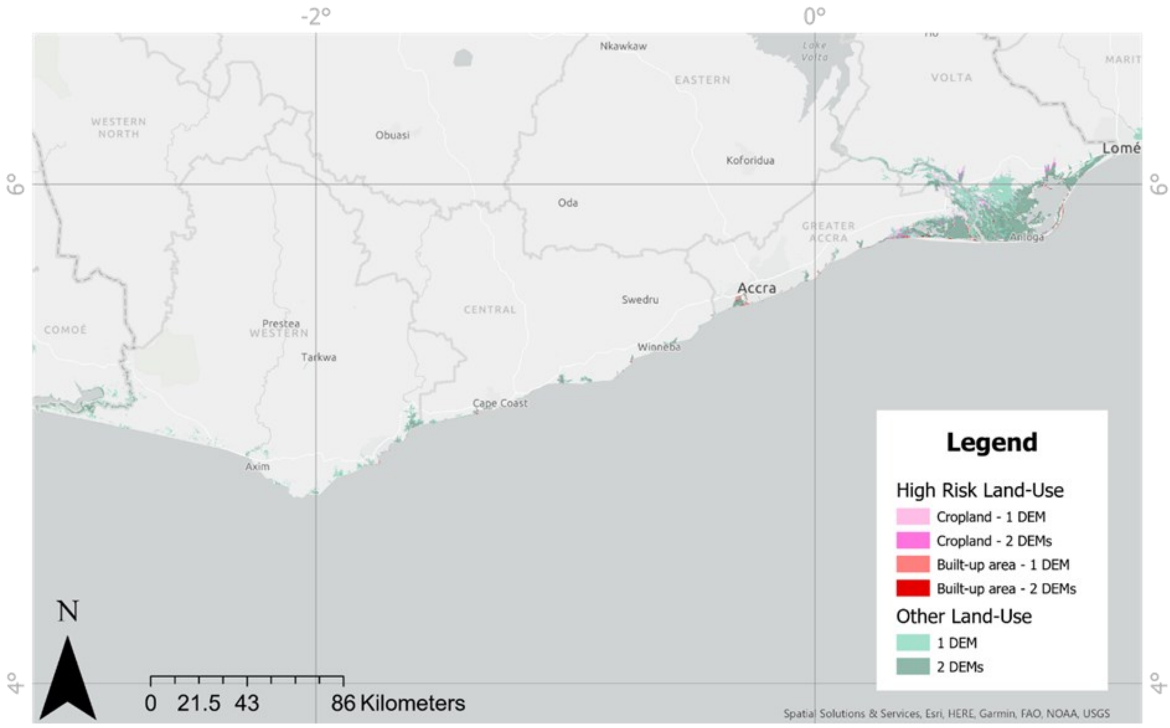
Figure 10. Lowly-elevated coastal areas (elevation < 2 m above local mean sea-level) in Abidjan.



Location of lowly-elevated coastal areas (elevation < 2 m above local mean sea-level), classified according to land-use types, in Abidjan according to the DEMs FABDEM and CoastalDEM_v2.1. Land-use types are taken from Zanaga et al. (2021).

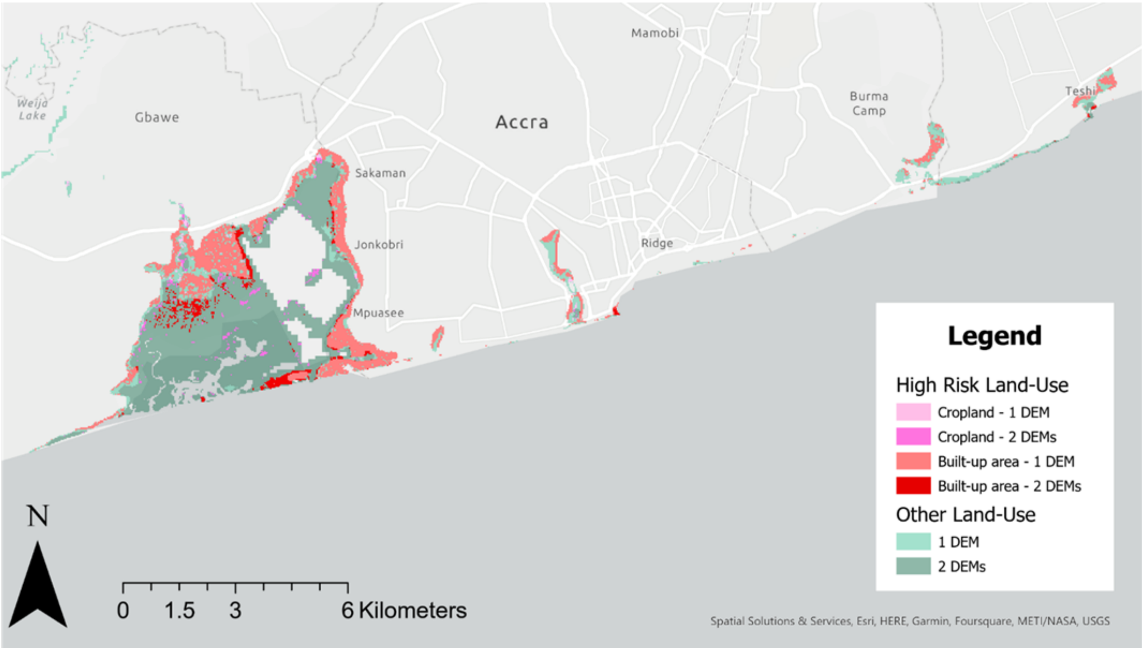
2.5.4.2. Ghana

Figure 11. Lowly-elevated coastal areas (elevation < 2 m above local mean sea-level) in Ghana.



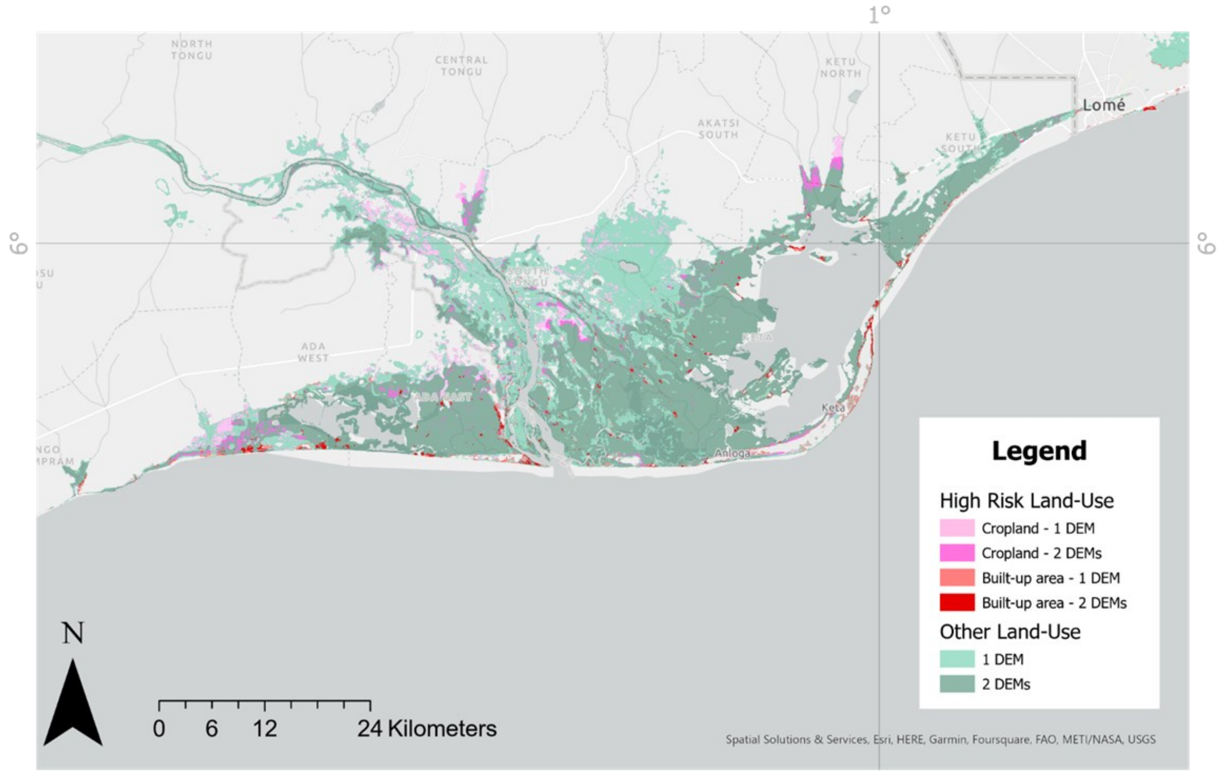
Location of lowly-elevated coastal areas (elevation < 2 m above local mean sea-level), classified according to land-use types, in Ghana according to the DEMs FABDEM and CoastalDEM_v2.1. Land-use types are taken from Zanaga et al. (2021).

Figure 12. Lowly-elevated coastal areas (elevation < 2 m above local mean sea-level) in Accra.



Location of lowly-elevated coastal areas (elevation < 2 m above local mean sea-level), classified according to land-use types, in Accra according to the DEMs FABDEM and CoastalDEM_v2.1. Land-use types are taken from Zanaga et al. (2021).

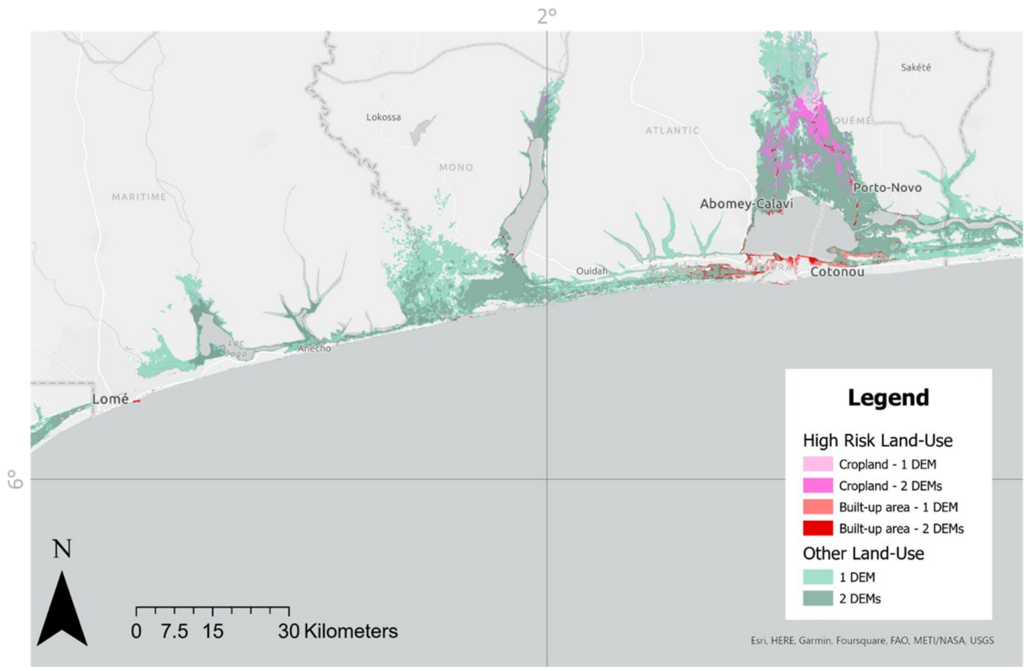
Figure 13. Lowly-elevated coastal areas (elevation < 2 m above local mean sea-level) in the Volta Delta.



Location of lowly-elevated coastal areas (elevation < 2 m above local mean sea-level), classified according to land-use types, in the Volta delta according to the DEMs FABDEM and CoastalDEM_v2.1. Land-use types are taken from Zanaga et al. (2021).

2.5.4.3. Togo and Benin

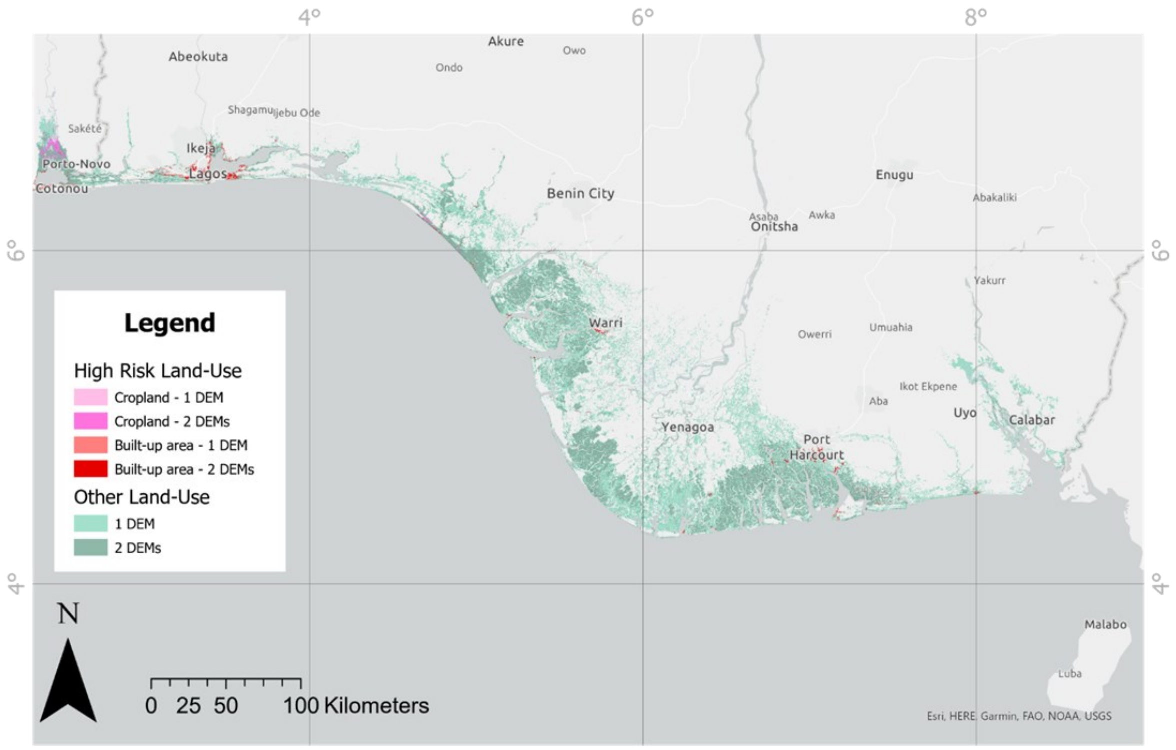
Figure 14. Lowly-elevated coastal areas (elevation < 2 m above local mean sea-level) in Togo and Benin



Location of lowly-elevated coastal areas (elevation < 2 m above local mean sea-level), classified according to land-use types, in Togo and Benin according to the DEMs FABDEM and CoastalDEM_v2.1. Land-use types are taken from Zanaga et al. (2021).

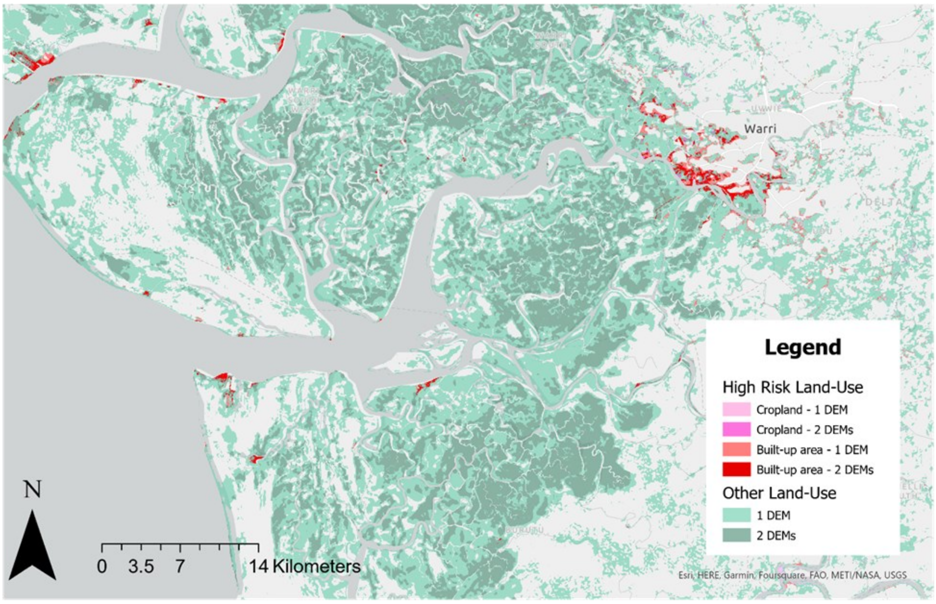
2.5.4.4. Nigeria

Figure 15. Lowly-elevated coastal areas (elevation < 2 m above local mean sea-level) in Nigeria.



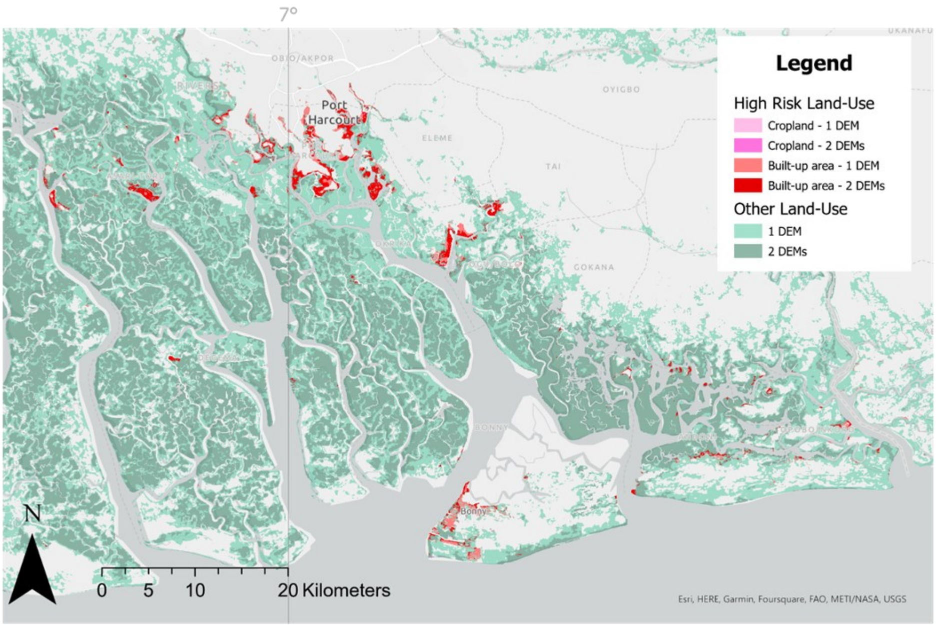
Location of lowly-elevated coastal areas (elevation < 2 m above local mean sea-level), classified according to land-use types, in Nigeria according to the DEMs FABDEM and CoastalDEM_v2.1. Land-use types are taken from Zanaga et al. (2021).

Figure 16. Lowly-elevated coastal areas (elevation < 2 m above local mean sea-level) in Warri.



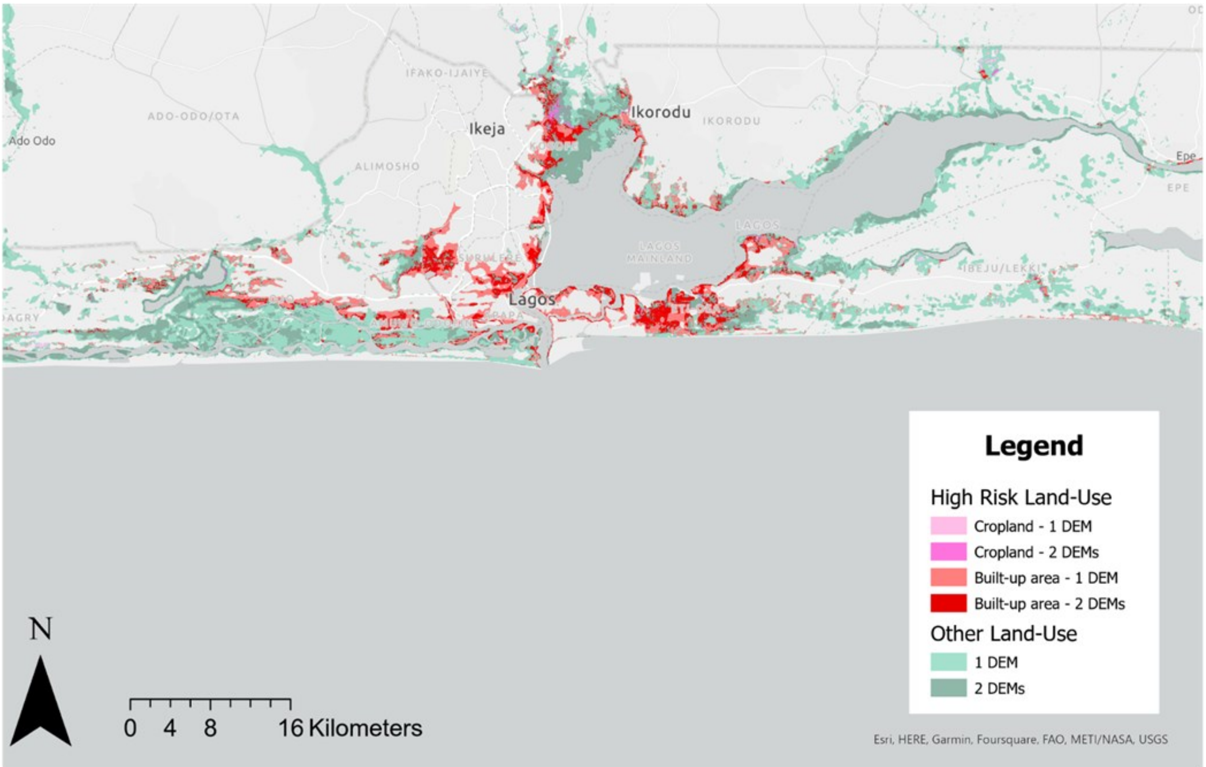
Location of lowly-elevated coastal areas (elevation < 2 m above local mean sea-level), classified according to land-use types, in Warri according to the DEMs FABDEM and CoastalDEM_v2.1. Land-use types are taken from Zanaga et al. (2021).

Figure 17. Lowly-elevated coastal areas (elevation < 2 m above local mean sea-level) in Warri.



Location of lowly-elevated coastal areas (elevation < 2 m above local mean sea-level), classified according to land-use types, in Port Harcour according to the DEMs FABDEM and CoastalDEM_v2.1. Land-use types are taken from Zanaga et al. (2021).

Figure 18. Lowly-elevated coastal areas (elevation < 2 m above local mean sea-level) in Warri.



Location of lowly-elevated coastal areas (elevation < 2 m above local mean sea-level), classified according to land-use types, in Lagos area according to the DEMs FABDEM and CoastalDEM_v2.1. Land-use types are taken from Zanaga et al. (2021).

3. Discussion

3.1. DEM performances

The coastal communities and ecosystems along the Gulf of Guinea are increasingly facing challenges in averting impeding hazards driven by global climate change and direct impacts from local human interventions (Almar et al., 2022). The scale of vulnerability to hazards and coastal changes has been difficult to assess due to limited spatially explicit understanding of local and regional processes and the challenges of obtaining detailed data. Recent advances in satellite remote sensing for digital elevation mapping has opened opportunities to address data gaps with spatially continuous coastal information from space-borne sensors. Global satellite-based datasets increasingly offer high spatial resolution (~30 m), calibration with varying degrees of global representativeness, and algorithms to remove tree height biases and buildings (see overview in Table 2). In this scoping study, we ingested data from five global satellite-based DEMs; CoastalDEM version 1.1, CoastalDEM version 2.1, SRTM-ACE2, ALOS DEM (AW3D30), and FABDEM.

The global satellite-based DEMs were vertically referenced to the same global geoid model (EGM96) to enable comparison. Firstly, we show the importance of correcting to local sea level as for the Gulf of Guinea which deviate between 0.1 and 0.7 m above the presumed global sea level average based on the EGM96 geoid. Secondly, comparison of the shoreline profiles derived from the different DEMs leads to results that can differ several meters. The limited agreeability between DEMs emphasizes the need for vigilance when purely relying on satellite-based coastal elevation estimates. Taken together, the initial results of the geospatial elevation study conducted here underpins that the message of global satellite based DEMs needs to be met with caution in low-lying and flat coastal regions (Minderhoud et al., 2019).

We found that in this region the availability of relevant in-situ measurements to validate the space-borne observations is scarce, hard to access and poorly documented. With the wide range of differences in coastal elevation estimates by different DEMs, such information is crucial to understand the size of vertical error and uncertainty, to assess the quality of the different DEMs for application in the Gulf of Guinea, and facilitate local/regional calibration. Based on a limited (N=6) yet thoroughly measured ground control points in the Volta Delta (Ghana), we find an average error size (RMSE) of between 1.5 and 2.9 m depending on the DEM deployed for analysis. Further validation across the other countries and regions of the Gulf of Guinea is needed. Moreover, a much larger dataset of ground truth control points is required to draw solid conclusions on the performance of the different DEMs for this.

Across global datasets, the confidence in coastal elevation estimation and the assessment of coastal vulnerabilities against relative sea-level rise projections is generally constraining (Minderhoud et al., 2019). The accuracy of satellite radar data remains relatively low. In our study, CoastalDEM v2.1 has an accuracy of about 1.6 m (RMSE) against our GCPs, which is in correspondence to the RSME of ~1.4 m (CoastalDEM v2.1) reported by Vernimmen at al. (2020) for three validation sites (Vietnam, Netherlands and Florida) reports. Newer satellite-based DEMs or version of improved error-removal are continuously being developed and released (Hawker et al., 2022). In combination with field data, this leaves potential for ensemble and calibration techniques to locally optimize the estimates of global satellite-based DEMs. Potentially even more promising is the increasing availability of satellite-based LiDAR data which generally holds an improved accuracy compared to satellite radar based DEMs (Vernimmen et al., 2020). Recently, Hooijer & Vernimmen (2021) have released global LiDAR lowland DTM (GLL_DTM_v1) at 0.05-degree resolution which currently still contains vertical reference conversion flaws (Seegers et al., 2023). The newest version (GL_DTM_v2) published during the final preparation of this report (Vernimmen & Hooijer, 2023), reportedly greatly improve both horizontal as vertical accuracy, which provides a promise to future coastal elevation assessments.

In this report, to preliminarily assess the vulnerability of different regions to coastal changes, we relied on an analysis based on two of the more recent DEMs: CoastalDEM_v2.1 and FABDEM. These datasets provide coastal elevation information at high spatial resolution (30 m), offer algorithms to remove tree height biases (FABDEM: also buildings), and ingest global ancillary data for the calibration of the underlying digital elevation models (see Table 2 for an overview). Moreover, based on the small sample size validation, CoastalDEM_V2.1 and FABDEM performed above-average in absolute (in meters), and relative (profile of elevation) coastal elevation assessment (Figures 8 and 9). Yet, these conclusions are based on six ground control points only therefore not conclusive but indicative only.

3.2. Coastal vulnerability to relative sea-level rise and hotspot analysis

The assessment of areas of potential vulnerability to rSLR was conducted by focusing on coastal areas elevated below 2-m LSL as observed through the respective FABDEM and CoastalDEM_v2.1. We applied both a more precautionary approach which considers all areas identified below 2-m LSL by *either* DEM as well as a higher certainty cross-validated approach which highlights areas below 2-m LSL identified by *both* DEMs. With the exception of the coastline of Côte d'Ivoire, large spatial agreement can be observed between CoastalDEM v2.1 and FABDEM for the areas below 2 m in Ghana, Togo, Benin and Nigeria.

Secondly, the coastal elevation data was combined with land cover information. Emphasis was placed on urban land and cropland as a demographic proxy and these land cover types are associated with higher risks in terms of anthropogenically-induced land subsidence. Large capital cities and major metropolitan hubs were found to be near the coast and elevated below 2-m LSL. We specifically highlight; 1) Lagos, a megacity, with large parts below 2-m LSL as identified by both FABDEM and CoastalDEMv2.1; 2) other cities within Nigeria such as the greater Lagos area, Bonny, Warri, Port Harcourt; 3) Benin's capital Cotonou enclosed between the Atlantic Ocean and Lake Nokoué; 4) Western Accra in Ghana; 5) and urban areas surrounding the Ebrie lagoon within Abidjan, Cote D'Ivoire. In addition to the geospatial analysis, the literature review on land subsidence highlights observed hotspots in Lagos, Niger delta, Port Harcourt, Warri and Volta delta. No specific studies were found about land subsidence in Abidjan, Accra, Togo and Benin areas that were indicated as affected by subsidence by Cian et al. (2019).

While built up area and cropland were emphasized in the analysis, other land use types can still be highly vulnerable despite being less extensively populated, in particular, in consideration of biodiversity and ecosystem services (Furlan et al., 2022; Tregarot, 2021). Large rural areas of the Niger delta are subject to subsidence due to oil and gas (hydrocarbon) extraction and the withdrawal from underground aquifers imposed heighted vulnerability to these low-lying regions (Ericson et al., 2006; Fabiyi & Enaruvbe. 2014).

4. Future outlook and conclusions

These efforts to improve our estimates on coastal elevation are valuable and very timely for this region, as assessments of vertical land movement by InSAR (Interferometric Synthetic Aperture Radar) for the entire coastline of the Gulf of Guinea are performed currently in the ENGULF project. This will improve our understanding on the spatial (and temporal) contemporary coastal subsidence which in combination with coastal elevation will enable to include for the first time land subsidence in future rSLR projections and improve coastal vulnerability assessments.

The lack of specific hydrogeologic information and uncertainty in the actual coastland elevation presently hampers our ability to understand the mechanisms responsible for the observed land movements (e.g. by InSAR) and developing scenarios of coastal hazard and risk over the next decades.

The inclusion of land cover to predict vulnerabilities should be expanded to fully understand the spatial relationships between elevation, land use and land subsidence potential to assess coastal vulnerability. Future analysis needs to include a wider range of spatially explicit information on population densities, major infrastructure, the distinction between different types of cropland (irrigated vs. non-irrigated), the extraction of groundwater and other underground fluids (e.g. hydrocarbons), coastal buffers including mangrove forests, coastal erosion/accreditation dynamics, and relevant geological information based on sedimentation and soil types. Rocky and sandy shores will respond differently to extraction of subsurface fluids with negligible or possibly significant subsidence rates. Including this information will improve future analyses. However, data availability, reliability and especially high resolution spatially continuous data will be challenging to acquire for this region.

To conclude, we summarize the following messages from this preliminary scoping analysis on coastal elevation for the Gulf of Guinea:

- Satellite-based DEMs provide a first indications of the low-lying coastal areas along the Gulf of Guinea
- Estimates between DEMs differ considerably (> 1 m), which highlights the importance of validation (e.g. ground truthing) or advanced approaches incorporating multiple DEMs in the absence of ground-truth data, as done in this study.
- Ground-truth data for the Gulf of Guinea is very scarce. This emphasizes the value of future field campaigns (e.g. monitoring or installing GPS stations) and the sharing of available data between relevant institutes.
- Incorporation of the newest published LiDAR DEM (Vernimmen & Hooijer, 2023) and other satellite optical missions (e.g. Pleiades, Pleiades Neo) is expected to improve future assessments further.
- Several coastal hotspots of vulnerability to rSLR along the coast have been identified based on the combination of the FABDEM and CoastalDEM_v2.1 in conjunction with land cover data. These include: Lagos and its greater metropolitan area, the Niger Delta including Bonny, Warri, Port Harcourt (Nigeria), Cotonou (Benin), Western Accra, the Volta region (Ghana), and the urban areas surrounding the Ebrie lagoon within Abidjan (Cote D'Ivoire).
- Here, only static morphologies were considered while this stretch of soft material coast is undergoing a massive erosion (up to tens of meters per year) under climate and anthropogenic influences. It is thus key to set an efficient monitoring plan at regional scale from satellite with revisit to also account for morphological evolution in any risk assessment evolution (Taveneau et al. (2021); Almar et al. (2022); Vousdoukas et al., (2022)).

Urbanized areas and cropland as a demographic and "risk" proxy can be expanded in future vulnerability assessments taking into consideration present land subsidence rates, hydrogeological setting, population densities, major infrastructures among other geospatial information.

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Acronyms and Abbreviations

ALOS-PRISM	Advanced Land Observing Satellite – Panchromatic Remote-sensing Instrument for Stereo Mapping
DEM	Digital Elevation Model
DTM	Digital Terrain Model
ENGULF	Coastal land subsidENce in the GULF of Guinea
FABDEM	Forest And Buildings disabled Copernicus DEM
GCM	General Circulation Model
GCP	Ground Control Point
GPS	Global Positioning System
GSHHG	Global Self-consistent, Hierarchical, High-resolution Geographic database
InSAR	Interferometric Synthetic Aperture Radar
LiDAR	Light Detection And Ranging
LSL	Land Surface Level
MDT	Mean Dynamic Topography
MAE	Mean Absolute Error
RCP	Representative Concentration Pathway
RMSE	Root Mean Square Error
rSLR	relative Sea-Level Rise
SBAS	Satellite-Based Augmentation Systems
SLR	Sea-Level Rise
SNAP	Sentinel Application Platform
SRTM	Shuttle Radar Topography Mission
StaMPS	Stanford Method for Persistent Scatterers
UNEP	United Nations Environment Programme
WACA	West African Coastal Areas Management Program

Appendix

Table A.1. List of the papers included in the literature database. For each paper, the tagged keywords are indicated using the number one.

Authors	Title	DOI	Keywords			
			Land subsidence	Coastal vulnerability	Sea level rise	Accretion/Erosion
Abam (2001)	Regional hydrological research perspective in the Niger Delta	https://doi.org/10.1080/02626660109492797	0	0	0	1
Addo (2013)	Assessing Coastal Vulnerability Index to Climate Change the Case of Accra – Ghana	https://doi.org/10.2112/SI65-320.1	1	1	1	1
Addo and Adeyemi (2013)	Assessing the impact of sea-level rise on a vulnerable coastal community in Accra, Ghana	http://dx.doi.org/10.4102/jamba.v5i1.60	0	0	1	1
Addo (2015)	Monitoring sea level rise-induced hazards along the coast of Accra in Ghana	https://doi.org/10.1007/s11069-015-1771-1	0	0	1	1
Addo et al. (2008)	Detection, measurement and prediction of shoreline recession in Accra, Ghana	https://doi.org/10.1016/j.isprsjprs.2008.04.001	0	0	1	1
Addo et al. (2018)	A Biophysical and Socioeconomic Review of the Volta Delta, Ghana	https://doi.org/10.2112/JCOASTRES-D-17-00129.1	1	0	1	1
Alves et al. (2020)	A review on coastal erosion and flooding risks and best management practices in West Africa: what has been done and should be done	https://doi.org/10.1007/s11852-020-00755-7	0	0	1	0
Aman et al. (2019)	Physical Forcing Induced Coastal	https://doi.org/10.4236/jep.2019.109071	0	1	1	1

	Vulnerability along the Gulf of Guinea					
Anthony et al. (2019)	Response of the Bight of Benin (Gulf of Guinea, West Africa) coastline to anthropogenic and natural forcing, Part 2: Sources and patterns of sediment supply, sediment cells, and recent shoreline change	https://doi.org/10.1016/j.csr.2018.12.006	0	0	0	1
Boateng et al. (2016)	Mapping vulnerability and risk of Ghana's coastline to sea level rise	https://doi.org/10.1080/01490419.2016.1261745	0	1	1	1
Cian et al. (2019)	Sentinel-1 for Monitoring Land Subsidence of Coastal Cities in Africa Using PSInSAR: A Methodology Based on the Integration of SNAP and StaMPS	https://doi.org/10.3390/geosciences9030124	1	0	0	0
Dada et al. (2021)	"Towards West African coastal social-ecosystems sustainability: Interdisciplinary approaches"	https://doi.org/10.1016/j.ocecoaman.2021.105746	0	0	1	1
Danladi et al. (2017)	Vulnerability of the Nigerian coast: An insight into sea level rise owing to climate change and anthropogenic activities	https://doi.org/10.1016/j.jafrearsci.2017.07.019	0	1	1	1
Ericson et al. (2006)	Effective sea-level rise and deltas: Causes of change and human dimension implications	https://doi.org/10.1016/j.gloplacha.2005.07.004	1	0	1	1
Evadzi et al. (2017)	Quantifying and Predicting the Contribution of Sea-Level Rise to Shoreline Change in Ghana: Information for Coastal Adaptation Strategies	https://doi.org/10.2112/JCOASTRES-D-16-00119.1	0	0	1	1

Evadzi et al. (2018)	Awareness of sea-level response under climate change on the coast of Ghana	https://doi.org/10.1007/s11852-017-0569-6	0	0	1	1
Fabiyi & Enaruvbe (2014)	Coastal Land Subsidence and Morphological Changes within Nigerian Coastal Areas	-	1	0	1	0
Fashae and Onafeso (2011)	Impact of climate change on sea level rise in Lagos, Nigeria	https://doi.org/10.1080/01431161.2011.581709	0	0	1	0
Giardino et al. (2018)	A quantitative assessment of human interventions and climate change on the West African sediment budget	https://doi.org/10.1016/j.ocecoaman.2017.11.008	0	0	1	1
Guerrera et al. (2021)	Shoreline Changes and Coastal Erosion: The Case Study of the Coast of Togo (Bight of Benin, West Africa Margin)	https://doi.org/10.1016/j.ocecoaman.2017.11.008	1	0	1	1
Ibe and Quelennec (1989)	Methodologie d' inventaire et de controle de l'erosion cotiere dans la region de l' Afrique de l'Ouest et du Centre	-	1	0	1	1
Idowu and Home (2015)	Probable effects of sea level rise and land reclamation activities on coastlines and wetlands of Lagos Nigeria	-	0	0	1	0
Ikuemonisan and Ozebo (2020)	Characterisation and mapping of land subsidence based on geodetic observations in Lagos, Nigeria	https://doi.org/10.1016/j.geog.2019.12.006	1	0	0	0
Ikuemonisan et al. (2021)	Investigating and modelling ground settlement response to groundwater dynamic variation in parts	https://doi.org/10.1016/j.sesci.2021.03.001	1	0	0	0

	of Lagos using space-based retrievals					
Ikuemonisan et al. (2021)	Investigation of Sentinel-1-derived land subsidence using wavelet tools and triple exponential smoothing algorithm in Lagos, Nigeria	https://doi.org/10.1007/s12665-021-10020-1	1	0	0	0
Jonah et al. (2016)	Coastal Erosion in Ghana: Causes, Policies, and Management	https://doi.org/10.1080/08920753.2016.1135273	0	0	0	1
Jonah et al. (2017)	Coastal zone management challenges in Ghana: issues associated with coastal sediment mining	https://doi.org/10.1007/s11852-017-0511-y	0	0	0	1
Mahmud et al. (2016)	Application of Multi-Temporal Interferometric Synthetic Aperture Radar (MT-InSAR) technique to Land Deformation Monitoring in Warri Metropolis, Delta State, Nigeria	https://doi.org/10.1016/j.procs.2016.09.150	1	0	0	0
Marti et al. (2021)	Altimetry-based sea level trends along the coasts of Western Africa	https://doi.org/10.1016/j.asr.2019.05.033	0	0	1	1
Melet et al. (2016)	What dominates sea level at the coast: a case study for the Gulf of Guinea	https://doi.org/10.1007/s10236-016-0942-2	0	0	1	1
Musa et al. (2014)	The Niger Delta's vulnerability to river floods due to sea level rise	https://doi.org/10.5194/nhess-14-3317-2014, 2014	0	1	1	1
Musa et al. (2015a)	Sensitivity analysis of the 2D SOBEK hydrodynamic model of the Niger River	-	0	0	1	0
Musa et al. (2015b)	A review of applications of satellite SAR, optical, altimetry and DEM	https://doi.org/10.5194/hess-19-3755-2015, 2015	0	0	1	0

	data for surface water modelling, mapping and parameter estimation					
Musa et al. (2016)	Approach on modeling complex deltas in data scarce areas: a case study of the lower Niger delta	https://doi.org/10.1016/j.proeng.2016.07.566	0	0	1	0
Oloyede et al. (2022)	Coastal Vulnerability Assessment: A Case Study of the Nigerian Coastline	https://doi.org/10.3390/su14042097	0	1	0	1
Onwuteaka (2014)	GIS Modeling of Flooding Exposure in Nigerian Coastal Areas from Sea Level Rise	-	0	0	1	0
Ozer et al. (2017)	Recent evolution of the coastline in the Bight of Benin. Example of Togo and Benin	-	0	0	1	1
Tano et al. (2016)	Assessment of the Ivorian Coastal Vulnerability	https://doi.org/10.2112/JCOASTRES-D-15-00228.1	0	1	1	1
Tay et al. (2022)	Sea-level rise from land subsidence in major coastal cities	https://doi.org/10.1038/s41893-022-00947-z	1	1	0	0
Tessler et al. (2015)	Profiling risk and sustainability in coastal deltas of the world	https://www.science.org/doi/10.1126/science.aab3574	0	0	1	0
Udoh & Udofia (2014)	Land Subsidence Monitoring Using Geographic Information System (GIS) Techniques in Akwa Ibom State, Nigeria	http://dx.doi.org/10.12944/CWE.9.1.01	1	0	0	0
Uko et al. (2018)	Estimation of Land Surface Subsidence Induced by Hydrocarbon Production in the Niger Delta, Nigeria, using Time-Lapse Orthometric Leveling Data	http://dx.doi.org/10.2139/ssrn.3214967	1	0	0	0

UNEP (1985)	Coastal Erosion in West and Central Africa	https://wedocs.unep.org/20.500.11822/29369	0	0	1	1
Wu et al. (2022)	Subsidence in Coastal Cities Throughout the World Observed by InSAR	https://doi.org/10.1029/2022GL098477	1	0	0	0
		Total count	15	8	30	26

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