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PRESENT AND FUTURE EXTREME COASTAL WATER LEVELS AND FLOODING EXTENTS ON NIGERIA'S MAHIN MUD COAST

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ABSTRACT

In the context of global warming marked by rising sea levels and extreme meteorological events, it is imperative to gain a comprehensive understanding of coastal vulnerability to flooding, as this knowledge is essential for safeguarding both communities and ecosystems. Using high-resolution satellite-derived digital elevation models and global ocean reanalysis, the degree to which a part of Nigeria's Mahin mud coast in the Gulf of Guinea of the North Atlantic Ocean is vulnerable to coastal flooding is assessed. The results show that the study area is at risk of being affected by both present and future extreme coastal flooding events, which poses a significant threat to coastal integrity and stability. It faces potential deterioration in coastal flooding due to future SLR consequences. Mean ECWLs are projected to increase from 1.6 m in 1993-2015 (present) to 2.1 and 2.2 m by 2050, with further acceleration to 2.4 and 2.85 m by 2100, under SSP2-4.5 and SSP5-8.5, respectively. This increases the risk of extreme coastal water levels, with land submerged by 125 km² and 170 km² under SSP2-4.5 and SSP5-8.5 climate scenarios by 2100. The study area's exposure to ECWF increased from 2181 to 2312 buildings in 2050 and 3003 in 2100 under SSP2-4.5 and SSP5-8.5, with potential exposure increasing from 24,856 to 128,083 people in 2100 under SSP5-8.5, highlighting the area's high vulnerability to sea level rise. It is therefore crucial to develop a sustainable strategy to protect the mud coast from degradation and promote sustainable development, thereby mitigating the present and future coastal retrogradation.

Keywords: Extreme Coastal Flooding, Extreme Coastal Water, Mahin Mud Coast, Sea Level Rise, Nigeria Coast, Climate Change.

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INTRODUCTION

Over billions of years, coastal regions have seen tremendous changes which have evolved alongside huge climatic changes. The Intergovernmental Panel on Climate Change (IPCC) notes in its sixth and most recent report that climate change is happening faster than initially anticipated, with unprecedented rises in sea levels, heat waves, and the rapid melting of polar ice caps (Zhu et al., 2021). Humanity is currently attempting to adapt to and cope with rapid climate change, which affects ocean currents, winds, precipitation, temperatures, and dramatically altered landscapes (Mousavi et al., 2010).

Coastal flooding is one of the greatest threats to the environmental and socio-economic developments of West African coastal countries (Alves et al., 2020; Cisse et al., 2022; Dada et al., 2021, 2023, 2024; Vousdoukas et al., 2022) as most West African coastal cities are exposed to flooding. Studies have shown that sub-Saharan African coastal areas due to their low elevation would be among those that will be most affected by sea level rise (Giardino et al., 2018; Marti et al., 2021). Extreme Coastal Water Level at the coast is the result of several coastal processes (Eq. 1), including the regional sea level anomaly caused by the steric effect, ocean circulation, and the movement of mass from the continents (ice sheets, glaciers, and land water) into the ocean, storm surge or dynamic atmospheric correction caused by atmospheric pressure and winds, astronomical tide (Almar et al., 2021; Almeida et al., 2019; Dodet et al., 2019; Melet et al., 2018).

There is a dearth of studies on marine flooding and the anticipation of its impact and mitigation/ adaptation in Nigeria, despite the projection of increased climatic instability in the context of continuing climate change (Breilh et al., 2012). Understanding the vulnerability of coastal areas to flooding is crucial for decision-making as well as for the protection of coastal communities and assets (Bernadino et al., 2023; Tebaldi et al., 2012).

Digital elevation models have been utilized for large-scale studies of coastal morphology mapping for a long time, allowing for the mapping of shoreline/coastline position and the analysis of its evolution (e.g., Gardel and Gratiot, 2006). This study seeks to determine the degree to which the Mahin mud coast of Nigeria is susceptible to potential coastal flooding using data derived from a digital elevation model and model hindcasts.

1. STUDY AREA

The study focuses on the Transgressive Mahin mud sector of the Nigerian coastline in the Gulf of Guinea of the North Atlantic (Figs. 1-2). This section of the Nigerian coastline is situated between the West African Barrier-Lagoon system and the Western Flank of the Niger Delta Basin, and runs for approximately 88 km, between latitudes 5° 45' N and 6° 30' N and longitudes 4° 30' E and 5° 07' E (Dada et al., 2020). Geologically, the Mahin mud coast belongs to the western Niger Delta Basin (Ebi-

semiju, 1987; NEDECO, 1954). According to Wright et al. (1985), the mud beach coast developed as the Niger Delta merged with the Gulf of Guinea after a brief Paleocene transgression.

The population of the study area was estimated to be 391,200 in 2016, with a 3% yearly population change (Brinkhoff, 2020). Due to the swampy condition of the location and limited access roads, this population may have been underestimated. The towns in the study area are made up of many villages that live along the riverbanks and estuaries, which connect several perennial streams and rivers that finally flow into the Atlantic Ocean via the Oke Siri, Abereke, and Awoye estuaries (Nubi et al., 2022), and the newly-opened Idi Ogba estuary.

The study area is highly vulnerable to coastal hazards such as erosion and flooding (Adesina et al., 2020, 2022, 2023, 2024; Badru et al., 2017; Dada et al., 2019, 2020; Daramola et al., 2022a, b; Ebisemiju, 1987; Komolafe et al., 2021; Ogunrayi et al., 2024; Olorunlana, 2013; Oyedotun, 2015; Popoola, 2022). This vulnerability stems from a combination of natural and human-induced factors leading to continual degradation (Dada et al., 2019, 2020). The area, apart from the Lagos Lagoon-barrier coast, is one of the most densely settled portions of the Nigerian coast with clusters of first-line settlements. Due to active forest removal and extensive decimation of mangrove forests, the region experiences perennial flooding and continuous ocean attacks on the adjacent coastal community (Dada et al., 2019, 2020).

The coastal plain is undulating, about 3 m above sea level and < 700 m wide, with 19 km-50 km of freshwater marshes and swamps behind it, joined by creeks, swamps, and lacustrine marshes (Olorunlana, 2013; Ebisemiju, 1987). The upper beach is distinguished by steep mud or organic-rich peaty scarps, whilst the more active areas of the beach face have mild slopes of approximately 0.025 (Sexton and Murday, 1994). The most common beach sediment compositions are silt and clay (Adesina et al., 2020, 2022, 2023) while the shoreline is scarped/grooved or tidal flats that merge with the high-water line (Dada et al., 2020; Ebisemiju, 1987; Olorunlana, 2013; Sexton and Murday, 1994).

The Mahin mud shore sees semi-diurnal tides with tidal ranges of up to 1.8 m. The wave climate along Nigeria's Atlantic coast is mainly influenced by wet and dry seasons (Dahunsi et al., 2022). The wet season (from May to October) is characterized by strong winds (8-12 m/s) and energetic waves, whereas the dry season (from November to April) is characterized by gentle winds and waves (Dahunsi et al., 2022; Adesina et al., 2024; Dada et al., 2015, 2016a, b, 2018, 2019; Nubi et al., 2022). The Mahin mud coast has modest and short-crested waves (6 s) that hit the shoreline at a height of 0.5 m, making it the lowest breaker height on the Nigerian coast (Dahunsi et al., 2022; Adesina et al., 2024; Sexton and Murday, 1994). Longshore currents from the west and east converge on the eastern section of this mud coast (Dahunsi et al., 2023; Sexton and Murday, 1994).

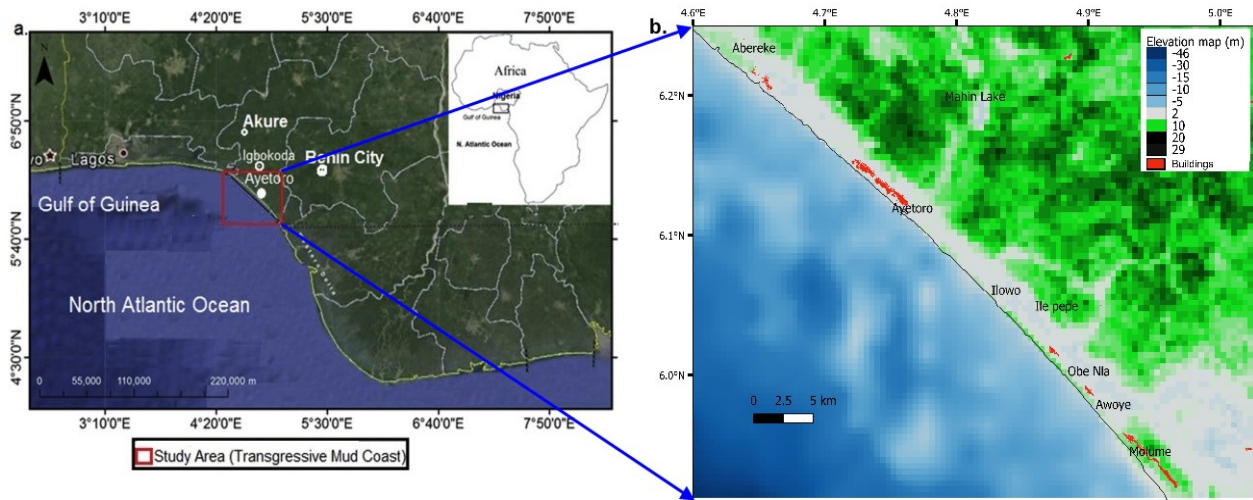


Figure 1. (a) Map of the Nigerian coast showing the study location (box) of the Mahin Mud Coast (modified from Dada et al., 2020). (b) Mahin Mud Coast elevation (in metres) with buildings.

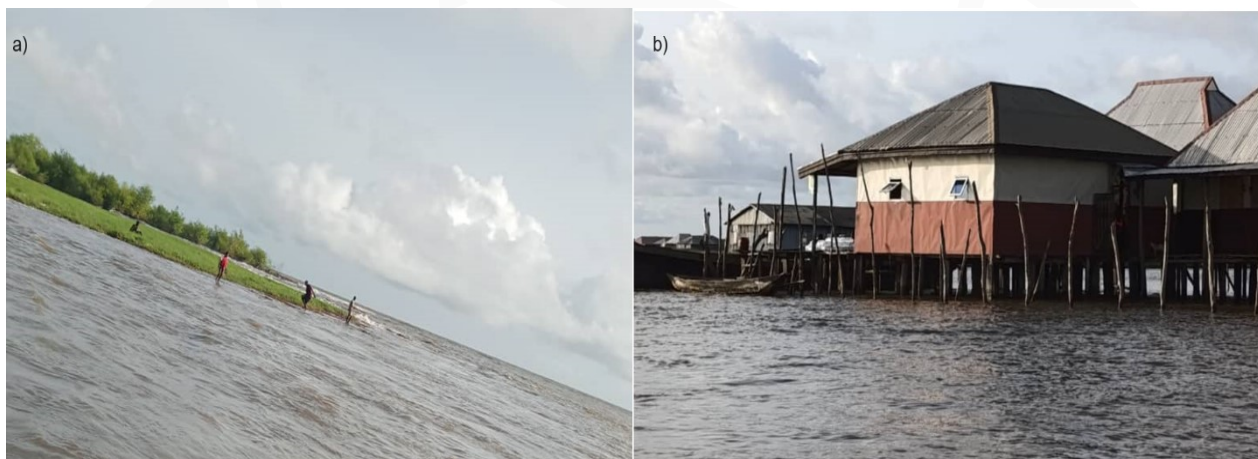


Figure 2. a) Flood phase at the Idi Ogba estuary inlet; b) along the estuary at the Idi Ogba community.

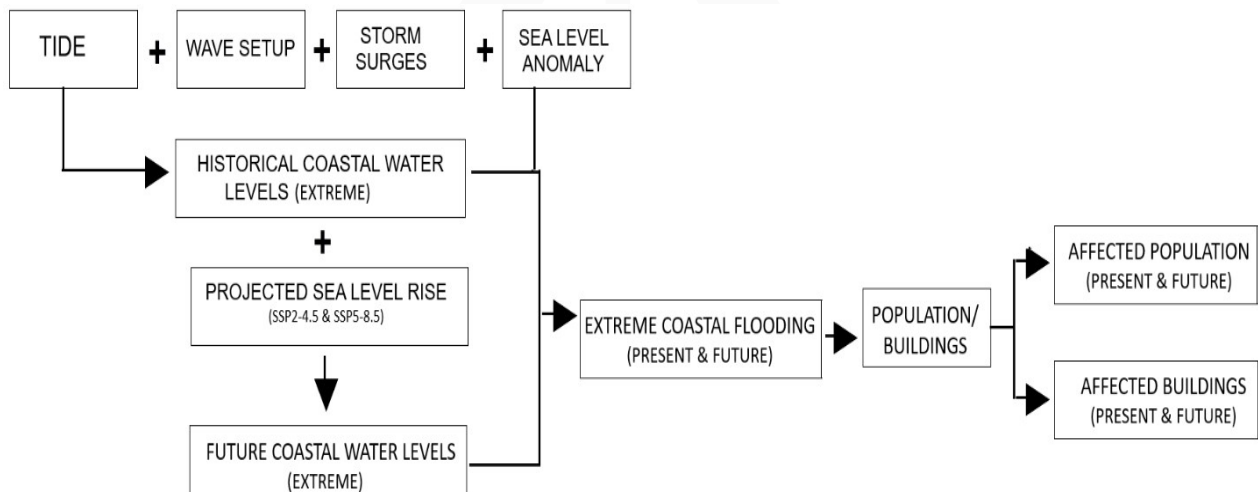


Figure 3. Flowchart of methodology for coastal water levels and flooding estimation.

2. MATERIALS AND METHODS

Using the data and methods described below and as illustrated in Fig. 3, we conducted an elevation-based assessment of coastal inundation vulnerability for the West African coastline. The empirical analysis is based on combining information from geospatial data from different sources, which are analyzed in the Quantum Geographic Information Systems (QGIS 3 v.26) environment.

3.1 Coastal water levels

Coastal water levels (CWLs) were obtained from Dada et al. (2023). They were quantified based on the formula of Almar et al. (2021) (Eq. 1):

$$CWL = SLA + DAC + T + R \quad (1)$$

The model integrated the sea level anomaly (SLA), the height of the storm surge or dynamic atmospheric correction (DAC) caused by atmospheric pressure and winds, the level of the astronomical tide (T), and the height of wave breaking to produce extreme levels (R). The CWL estimations have been validated against several tide gauge data (see Almar et al. (2021) and Dada et al. (2023) for further information on data acquisitions and analyses). The extreme coastal water levels (ECWLs) were designated as the highest 2%, or the 98th percentile, to physically assess the effects of ECWLs on the study area (following a common definition of extreme storms). ECWLs were then used as forcing for coastal flooding extent and estimates.

3.2 Coastal topographical data

Coastal topography was from the SRTM15+V2.5.5 digital elevation model (DEM), a global bathymetry and topography grid at 15 arcsecs (0.5 x 0.5 km at the Equator). This latest SRTM+DEM includes ocean bathymetry, over 33.6 million multibeam and single beam measurements, altimetry data from Cryosat-2, SARAL/AltiKa, and Jason-2, and onshore topography data from SRTM-CGIAR V4.1 (Tozer et al., 2019). Further, a high-resolution (~0.2 km) coastline dataset of global self-consistent hierarchical high-resolution geography (GSHHG) was used to define the Nigerian Mahin mud coastline for calculations of flooding extent.

3.3 Historical and projected sea level rise

Based on the linear assumption (Eq. 1), the present time series of ECWLs in the study area (1993-2015) was estimated. To determine projections until 2100, two SLR scenarios based on the IPCC Sixth Assessment Report Sea Level projections, which incorporate global land movement, were employed. These were SSP2-4.5 and SSP5-8.5, for moderate and very high future greenhouse gas emissions (IPCC, 2021). The datasets for the study area were obtained from the National Aeronautics and Space Administration's Sea Level Projection (<https://sealevel.nasa.gov>). The IPCC Sea level projection

values were obtained from the nearest point to the study area. The extreme value estimates of ECWL were combined with selected RSLR projections (Dada et al., 2023). The resulting projected ECWLs were then combined with topography data to determine the potential extent of extreme coastal flooding at the Nigerian Mahin mud coastline in 2050 and 2100.

3.4 Coastal inundation modelling

Coastal flooding was examined using the bathtub method, which followed the same approach as Kirezci et al. (2021). According to the bathtub inundation model, a place with an elevation less than the projected flood level will be inundated like a "bathtub" (Dada et al., 2023). In the GIS environment, the elevation of each cell of a DEM is compared to a projected sea level, and any cells with values lower than the predicted sea level are considered to be in floodplains (Yunus et al., 2016). Using the static (bathtub) flood modelling technique (Breilh et al., 2013; Poulter and Halpin, 2007), areas hydraulically connected to the ocean were determined for each averaged value of CWLs throughout the entire coastline (Dada et al., 2023; Hinkel et al., 2014). A flood-fill algorithm based on nearest neighbours selects which grid cells are flooded at each projected flood height (Prahl et al., 2018). The process was conducted thrice for each projected flood height (1993-2015, 2050, and 2100). The bathtub model's application for flood risk assessment may be limited due to the vertical uncertainty of DEMs in the order of metres, resulting in an underestimation of coastal flood risk, particularly in low-lying coastal zones. However, other studies have used it to map coastal flood inundations all over the world (e.g., Gallien et al., 2018; Melet et al., 2018; Strauss et al., 2012; Titus and Richman, 2001; Vaan de Sante et al., 2012).

3.5. Buildings and population exposure

The NASA Socioeconomic Data and Applications Centre (SEDAC) 1-km resolution GPWv4 Rev. 11 population counts dataset, which can be found at (<https://sedac.ciesin.columbia.edu/data/set/gpw-v4-population-count-rev11>), was used to determine the number of persons that were flooded in 2015. To calculate future flood exposure, the SEDAC's 1-km resolution global population projection grids based on the Shared Socioeconomic Pathways (SSP) dataset which can be found at (<https://sedac.ciesin.columbia.edu/data/set/popdynamics-1-km-downscaled-pop-base-year-projection-ssp-2000-2100-rev01/data-download>) were used for 2050 and 2100. To estimate the buildings affected, the ECWF polygon was used to estimate buildings affected by the flood, with buildings selected based on their location within the flood risk zone. The attribute table of affected structures was exported to count the number of buildings affected. Based on the current information, the estimate for the buildings applies to all periods. This suggests that the number of exposed buildings may rise as development progresses in the future. The year 2015 was used as the reference year, with subsequent time steps of 2050 and 2100. For each point in time, the potential exposure was estimated for the

given return period and grid cell under baseline and future climate conditions.

4. RESULTS

4.1 Extreme coastal water levels

As climate change, the mean ECWLs in the area were projected to increase from 1.6 m in 1993-2015 (present) to 2.1 and 2.25 m (under both SSP2-4.5 and SSP5-8.5) by 2050 (Fig. 4). Further, the mean ECWL was projected to accelerate during the present century under these scenarios, reaching 2.4 m (under SSP2-4.5) and 2.85 m (under SSP5-8.5) by the year 2100. Due to these increasing ECWLs, an increase in flooding was observed around Mahin Lake by 2050 under the SSP2-4.5 and SSP5-8.5 scenario (Figs 5 - 7) and in addition at the upper part of the lake by 2100 under the SSP2-4.5 and SSP5-8.5 scenario (Fig. 7) as compared to the present (Fig. 5).

4.2 Flood extent and flood-prone areas

Figures 4-7 show the flooding extent in the present (1993-2015), by the years 2050 and 2100 under different climate projections in the study area because of the ECWLs. The results revealed that the study area is potentially vulnerable to ECWLs. As shown in Figures 4-7, about 19 km² of land is submerged in the present (Fig. 5) while between 55 (about a 189% increase from the present flooding extent) and 68 (about a 258% increase from the present flooding extent) km² area will be submerged by 2050 under SSP2-4.5 and SSP5-8.5, respectively (Fig. 6). By 2100, about 125 km² (about a 558% increase from the present flooding extent or 194% increase from the SSP2-4.5 climate scenario by 2050) and 170 km² (about a 795% increase from the present flooding extent or 208% from the SSP5-8.5 climate scenario by 2050) will be submerged under SSP2-4.5 and SSP5-8.5, respectively (Fig. 7). This means that people and assets will be potentially endangered if no protection is deployed.

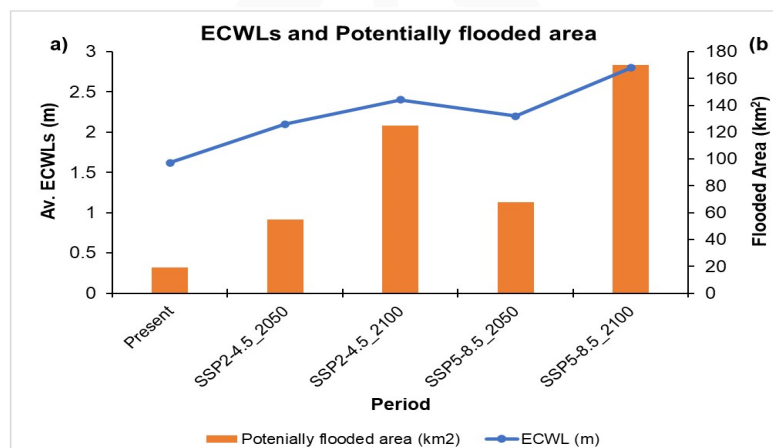


Figure 4. a) The mean present and projected ECWLs at the study section of the mud coast. b) The potentially flooded areas in the present and future at the study section of the mud coast.

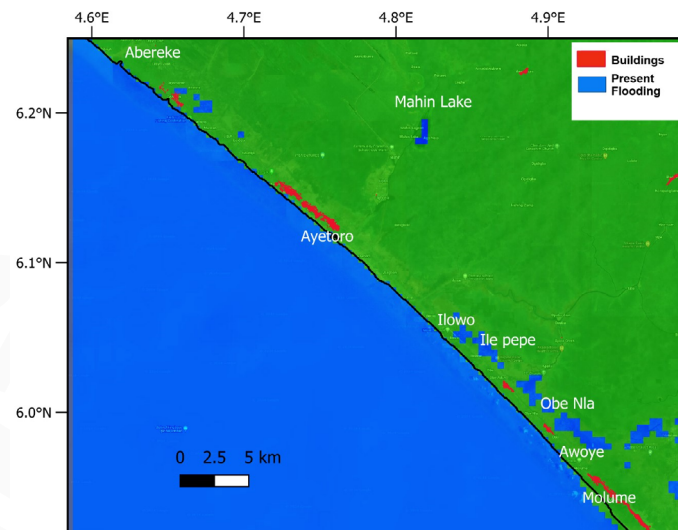


Figure 5. ECWF for historical (averaged 1993-2015) 98th percentile ECWL. The blue colour on land signifies a potentially flooded area under the 98th ECWL percentile.

4.3 Exposed buildings and population to ECWF

Table 1 shows the exposed buildings and population to ECWF for the present (2015) and future (2050 and 2100) under different climate change scenarios. For instance, the total number of buildings exposed to ECWF increased from 2181 at present to 2312 buildings in 2050 and 3003 buildings in 2100 under SSP2-4.5. Under SSP5-8.5, it increased from 2450 buildings in 2050 and 3839 buildings in 2100. However, it is noteworthy that the estimate for the buildings is based on the current information and applies to all periods. This suggests that the number of exposed buildings may rise as infrastructural development progresses in the study area in the future. The study area was potentially exposed to ECWF and increased from 24,856 in the present to 80,023 people in 2050 and 97,594 people in 2100 under SSP2-4.5. Under SSP5-8.5, it increased from 91,994 people in 2050 to 128,083 people in 2100. These results underscore the high vulnerability of the study area to sea level rise.

Table 1. Buildings and population exposed to present and future coastal flooding

Period	*Buildings (numbers)	Population (persons)
Present	2,181	24,856
SSP2-4.5_2050	2,312	80,023
SSP5-8.5_2050	2,450	91,994
SSP2-4.5_2100	3,003	97,594
SSP5-8.5_2100	3,839	128,083

* Based on the current information, the estimate applies to all periods. This suggests that the number of exposed buildings may rise as development progresses in the future.

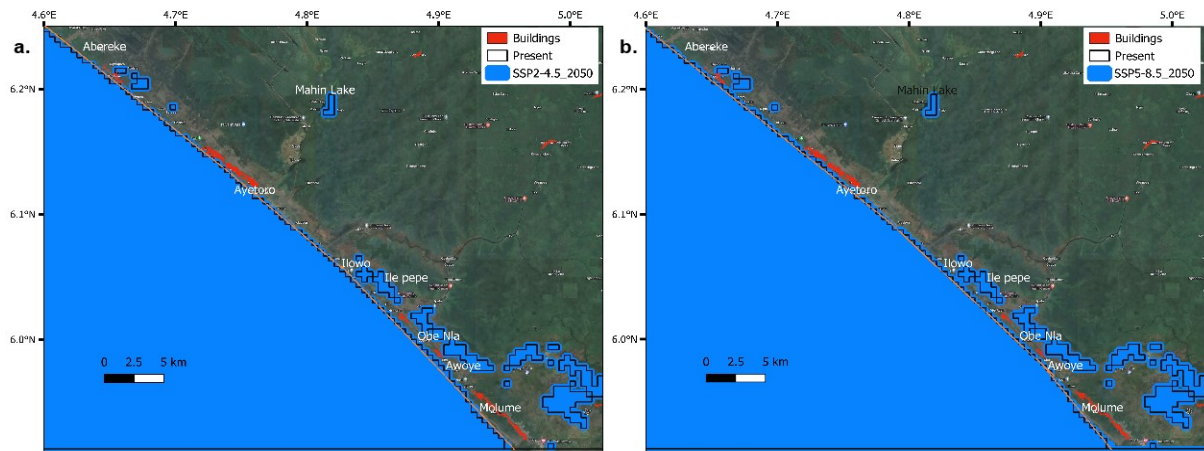


Figure 6. a-b) Extreme coastal water flooding for 98th percentile ECWL under SSP2-4.5 and SSP5-8.5, by 2050. The blue colour on land signifies a potentially flooded area under the 98th ECWL percentile.

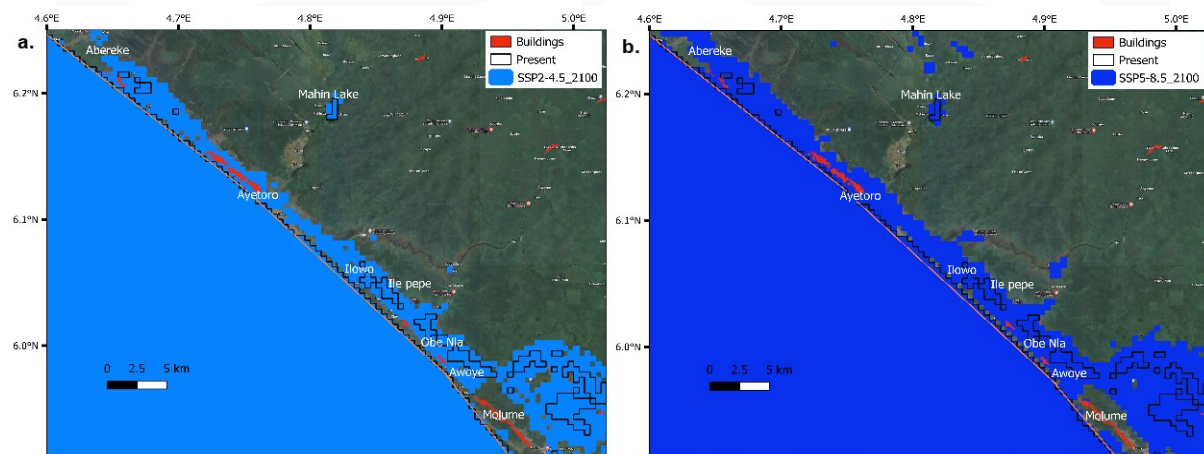


Figure 7. a-b) Extreme coastal water flooding for 98th percentile ECWL under SSP2-4.5 and SSP5-8.5, respectively by 2100. The blue colour on land signifies a potentially flooded area under the 98th ECWL percentile.

5. DISCUSSION

Climate change is causing a rise in global sea levels through melting ice and the expansion of seawater due to warming. The climate change-induced sea-level rise directly threatens lives and livelihoods in the coastal regions around the world. The present study is carried out to determine the degree to which a section of the Nigerian Mahin mud coast is susceptible to potential ECWF. Going by the results, the Mahin section of the Nigerian coastline is extremely vulnerable to ECWLs and this will increase towards the end of 2100 (Fig. 4). The present study shows that more people and buildings

will be exposed to ECWF events towards the end of the 21st century in the study area (Table 1). The people and buildings exposed to the ECWF events will experience the lowest impacts under SSP2-4.5 and the highest impacts under SSP5-8.5 (Table 1). These results are similar to the findings of Dada et al. (2023, 2024). As suggested by Dada et al. (2023), the results of the present study should be regarded as a caution to regulate future coastal developments effectively in the study area and along the Nigerian coast.

It is important to also note that the ECWF that occurred under the SSP2-4.5 and SSP5-8.5 scenarios in 2050 mostly occurred through the estuary's inlets as the coastal water levels were lower compared to the elevation of most of the beaches in the study area. This situation will change under these scenarios by 2100, as most of the beaches will be submerged. In addition, an increase in flooding is observed around Mahin Lake by 2050 under the SSP2-4.5 and SSP5-8.5 scenarios (Fig. 6) and in addition at the upper part of the lake by 2100 under the SSP2-4.5 and SSP5-8.5 scenarios (Fig. 7) as compared to the present (Fig. 5). This shows that the deeper estuary channel facilitates the passage of water into the lake via the estuary inlets. This phenomenon is most likely driven by two processes: a decrease in frictional barrier to water movement and an increase in channel cross-sectional area. A deeper channel allows more water to flow beyond the channel and into the lake, whereas a shallower channel stops the flow, causing water to accumulate inside the channel and flood the immediate environment (Mansur et al., 2023). An increase in estuary channel depth increases the channel's cross-sectional area, which increases the volume of water travelling through it (Hughes, 2002; Mansur et al., 2023).

This finding is consistent with previous studies that indicate that channel deepening enhances inland floodwater propagation and raises flood risk (Cai et al. 2012; Lopes et al. 2013; Orton et al. 2015). For example, a study found that deepening the major channels of Portugal's Ria de Aveiro lagoon increases the lagoon flood extent area (Lopes et al. 2013).

5.1 The variability and trends of the CWL and its components

Previously, Dada et al. (2020) identified that the CWL components exhibit clear seasonal cycles with more coastal flooding events in the study area. According to them, extreme events during intra- and inter-annual CWL are caused by the combination of large swell-waves run-up and high tides. The R that makes the most contribution to coastal flooding has a seasonal cycle that is more energetic during the wet season when the wind forcing is stronger in the Southern Hemisphere. They also pointed out that altimetry-derived SLA is the main component that accounts for the CWL trend in the study area. However, its contribution to the periodic total coastal water level variability is small and may have a less significant impact on the coastal flooding events in the study area. Notwithstanding, while the SLA is likely responsible for the subtle increase in the trend of CWL, the R is largely responsible for its variability as well as the extreme/coastal flooding events (Dada et al., 2020).

5.2 Implications of coastal flooding hazards in the study area

Coastal flooding could deteriorate under future SLR consequences in the study area (Figs 5–6). The mean ECWLs in the study area are projected to increase from 1.6 m in 1993–2015 to 1.9 and 1.93 m by 2050 under SSP2-4.5 and SSP5-8.5, respectively, with further acceleration to 2.38 and 2.82 m by 2100 following the same climate scenarios (Fig. 4). These rises imply increasing coastal flooding in the study area. The study area is at risk of extreme coastal water levels, with 19 km² of land currently submerged (Fig. 5). By 2050, 21–21.8 km² of land will be submerged under SSP2-4.5 and SSP5-8.5, respectively (Fig. 6). By 2100, 125 km² and 128 km² will be submerged (Fig. 7), posing potential threats to people and assets. This implies that in the presence of 1.9 and 1.93 m at the deep estuary inlets channel, the area of fresh flooding will increase by approximately 11% and 15% for the moderate and high SLR scenarios by 2050, respectively, compared to the present. With 2.38 and 2.83 m ECWLs for medium and high scenarios by 2100, flooding will increase by about 556% and 574%, respectively.

Being a low-lying area, this coastal area is highly exposed to coastal flooding. The potential extreme flood events are likely to affect the socioeconomic of the area. As indicated in the previous studies in the study area, flooding causes a wide range of impacts (Badru et al., 2017; Dada et al., 2019, 2020; Daramola et al., 2022a, b; Ebisemiju, 1987; Komolafe et al., 2021; Ogunrayi et al., 2024; Olorunlana, 2013; Popoola, 2022), with greater consequences on the population as well as the socio-economic activities, particularly fishing, which is the dominant source of livelihood in the study area. This degree of vulnerability should propel decision-makers and coastal managers to consider the protection of this section of the Nigerian coastline.

Most parts of the study area are low-lying with varying elevations that range between < 0.5 and 3 m above mean sea level (Dada et al., 2019, 2020). The geomorphology - low relief/ elevation- and geology (sediment composition) of the study area play a major role in determining the main factor governing the accelerated coastline retreat as well as flooding in the area (Adesina et al., 2020, 2022, 2023, 2024; Dada et al., 2020; Ebisemiju, 1987; Olorunlana, 2013). Due to elevations, most parts of the area are overtopped during extreme events thereby subjecting the area to instantaneous rates of surface lowering and coastline retrogradation. The frequency of overtopping by waves and tidal currents is determined by the low relief/ elevation (Dada et al., 2020), which in turn has caused spatial variations in the rate of coastline retrogradation rate in the study area (e.g., Badru et al., 2017; Dada et al., 2019, 2020; Daramola et al., 2022; Ebisemiju, 1987; Komolafe et al., 2021; Ogunrayi et al., 2024; Olorunlana, 2013; Popoola, 2022). This assertion is consistent with the present findings.

5.2.1 The case of the Ayetoro community

Ayetoro Town is one of the communities in the study area which has been facing coastal flooding due to ocean surges for many years. The surges have destroyed schools, health centres, and other critical

infrastructures, and left more than 5,000 people homeless (<https://learningenglish.voanews.com/a/nigeria-s-happy-city-is-helpless-against-rising-sea-/7668276.html>). Residents have also reported losing millions of Naira worth of property (<https://www.africanews.com/2024/06/23/ayetoro-the-nigerian-coastal-town-drowning-under-seawater//>; PM News, 2024; Premium Times, 2024; Punch Nigeria, 2023). The community has expressed concern about the impact of the ocean surge on vulnerable residents living in makeshift structures and who have shifted their houses severally, especially the elderly, as well as the loss of economic livelihoods for many whose primary source of income is fish processing (<https://cappaafrica.org/2024/06/03/residents-of-ayetoro-protest-against-ocean-surge-in-ondo-demand-govts-urgent-intervention/>). Additionally, community schools have been relocated several times due to the challenges posed by often unexpected ocean surges, disrupting learning processes and academic calendars and causing many students to drop out (PM News, 2024; Premium Times, 2024; Punch Nigeria, 2023). The Federal government previously awarded coastline defensive wall project contracts costing billions of Naira to safeguard the community from persistent ocean surges, but none of them worked due to an alleged contractors' lack of technical know-how (PM News, 2024; Premium Times, 2024; Punch Nigeria, 2023). However, an extensive purpose-built barrier along the shoreline based on recommendations of the community, environmental experts and previous scientific findings may be necessary.

5.3 Solutions and Shore Protection Measures

In light of the potential future rise in coastal water levels in the study area, it is crucial to implement urgent measures such as coastal engineering structures. However, the cost of constructing hard/grey coastal engineering structures with deep foundations, especially in muddy coastal environments like those in the study area (Adesina et al., 2020, 2022, 2023), raises concerns. In this context, exploring nature-based techniques seems to be a promising option for the long-term restoration of the vulnerable, yet degraded Nigerian Mahin mud coast (Adesina et al., 2020, 2022, 2023). The present study shows that sea-level rise may accelerate in the future. It's important to design flexible coastal protection to adapt to these changes. However, the traditional methods of protecting coastal areas from floods, like dikes, seawalls, and embankments, are facing increasing challenges and undergoing significant change due to rising sea levels (Shariot-Ullah, 2024). The maintenance and stability of these structures are not always feasible (Smith and Aalst, 2003), especially in areas where land subsidence is a problem. Additionally, these structures can disrupt natural processes and threaten the environment (Temmerman et al., 2013). The importance of preserving nature is often disregarded in these conventional approaches.

There is significant potential in combining nature-based and traditional engineering approaches. For example, flood protection could involve ecosystem buffers before resorting to artificial defenses. This approach can help reduce the necessary defense size and overall risk. One example of this is the uti-

lization of wetlands in the Rhine-Meuse-Scheldt Delta, which function as a natural defense against increasing sea levels, providing flood protection in the Netherlands and Belgium (Temmerman and Kirwan, 2015). The adaptive pathways approach involves planning coastal protection measures that can be adjusted based on short-term changes, rather than being committed to a single uncertain long-term scenario until the end of the 2100s (Nicholls, 2018). This approach can help us keep up with rising water levels. Coastal adaptation can be classified in different ways. One commonly used approach is the IPCC typology, which includes retreat, accommodation, and protection (Dronkers et al., 1990; Bijlsma et al., 1996). Also, an "attack" adaptation strategy has been proposed to address sea level rise (e.g., RIBA and ICE, 2010). Sea level rise and flood management and adaptation planning can be developed by combining one or more approaches that include resist, accommodate, avoid or retreat, and advance.

Resist: The "resist" approach involves structural measures to keep tidal and flood inundation out of developed areas. This includes traditional hard-engineered solutions like sea dikes, seawalls, storm surge barriers, and nature-based measures such as mudflats and marsh buildings (Siders, 2019; Siders and Keenan, 2019; Koslov, 2016; Klein et al., 2001). However, rising sea levels can make this approach costly and inflexible without careful planning. The resist approach has several advantages, such as the ability to implement large-scale projects and pursue development opportunities. However, it also has disadvantages, including complex implementation and potential environmental impacts. It may also lead to an overall increase in flood risk and limit waterfront access or views for existing properties (Siders, 2019; Koslov, 2016; Klein et al., 2001).

Accommodate: The accommodate approach allows continued occupation of the coastal floodplain while managing risk by reducing the consequences of exposure (Das Neves et al., 2023; Siders and Keenan, 2019; Klein et al., 2001). This is achieved through floodproofing of buildings and infrastructure, and economic and social measures to increase community resilience. An example measure is dry floodproofing of buildings, which involves raising habitable spaces using fill, structure, or piles (Das Neves et al., 2023; Siders and Keenan, 2019; Klein et al., 2001). The accommodate approach is currently the status quo for most coastal flood risk management in the study area, where communities use different formal and informal tools to regulate development on the coastal floodplain without implementing major structural flood protection works (resist).

Avoid / Retreat: The avoid/retreat approach focuses on limiting new development in flood-prone areas (avoid) and gradually moving existing structures away from high-risk areas (retreat). It is effective in reducing risk over the long term but faces challenges due to land use pressures. Managed retreat is gaining acceptance but has implementation challenges, particularly in terms of equity and financial compensation. While it offers opportunities for habitat, culture, and recreation, it may lead to the loss of development potential and could raise equity concerns (Siders, 2019; Siders and Keenan, 2019; Koslov, 2016; Klein et al., 2001).

Advance: This approach involves various scales of land reclamation to create space for implementing resist and accommodate approach measures. This can include constructing engineered or nature-based shoreline wave attenuation works, dikes, and new developments on raised lands. The advanced approach for shoreline erosion or flood protection works requires less land (Siders, 2019; Siders and Keenan, 2019; Koslov, 2016; Klein et al., 2001). It offers potential habitat, cultural, and recreational benefits but may impact intertidal and marine habitats, increase floodplain development risks, and limit waterfront access or views. It also involves complex regulations, and high costs, and may require rebuilding over time. Examples of this approach on a large scale can be seen in Hong Kong, Singapore, and the Netherlands, all of which have high population densities and small land bases (Arkema et al., 2024; Hernández-Delgado, 2024; Wolff et al., 2023; Guerry et al., 2022). A large-scale Nigerian example is the development of the Nigerian Eko Atlantic City in Lagos which involves the reclamation of land from the Atlantic Ocean to create a peninsula for development (<https://www.royalhaskoningdhv.com/en/projects/a-new-coastal-city-built-on-reclaimed-land-from-the-sea>).

5.4 Study's limitations

It is important to note that uncertainty and limitations may exist in the procedure used in the present study, starting from digital elevation model-derived topography, and coastal water level estimation to coastal water projections. Other sources of uncertainty may occur during the wave run-up estimation. The wave run-up estimation depends on the composite beach slope of the study (smaller at the lower tide mark and steeper at the high tide mark), which may introduce some uncertainties (Almar et al., 2021; Dada et al., 2023). Likewise, uncertainties may arise while translating the offshore wave heights into wave run-ups at the shore (Almar et al., 2021; Dada et al., 2023). In addition, although we assumed that the amplitude of the AT is deterministic, this may change with an increase in sea level (Serafin et al., 2017).

CONCLUSIONS

This study investigates the vulnerability of a section of the Nigerian mud coastline to the potential risk of extreme coastal flooding, by combining DEM with reanalyzes and sea level components. Results show that the study area is highly susceptible to extreme flooding and this will increase by the end of the century. This highlights the need for coastal development schemes and protection, particularly in the face of climate change and increasing anthropic pressure. Further, it implies that coastal dwellers in the study area are most likely to relocate inland many times before the end of the twenty-first century. To address this, policymakers and coastal planners must strike a balance between major quality-of-life needs for the people, while avoiding continuous displacement. Climate mitigation and adaptation methods such as green infrastructure and housing redevelopment are one way to handle these concerns collaboratively (Melix et al., 2023). However, without appropriate policies and in-



creased support, a continuous wave of relocations may be unavoidable.

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