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Assessing the Potential of Compound Coastal Flooding from Oceanic Surge and Rainfall Under Climate Change in the Niger Delta Region, Nigeria

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ABSTRACT

Compound coastal flooding, which results from the interaction between oceanic surge and intense rainfall, poses an increasing threat to low-lying coastal regions under a changing climate. However, in many vulnerable areas, including the Niger Delta in Nigeria, flood risk assessments still treat these drivers independently, which may lead to an underestimation of actual hazard exposure. This study investigates the spatiotemporal trends in sea surface elevation and precipitation along the coasts of six Niger Delta states, including Ondo, Delta, Bayelsa, Rivers, Akwa Ibom, and Cross River, to assess the potential for compound flooding. Sea surface elevation data were obtained from the HYbrid Coordinate Ocean Model (HYCOM) for the period 2000–2024, while precipitation data were derived from the Global Precipitation Measurement (GPM) IMERG dataset for 2001–2024. Monthly time series were generated for 10 km buffer zones around each referenced state, and linear trend analyses were conducted to examine changes over time. Results reveal a consistent decline in mean sea surface elevation anomalies across most states, with Akwa Ibom recording the lowest value (–0.0124 m) during 2020–2025. Precipitation trends also show negative slopes across all states, although none were statistically significant at the 0.05 level. Despite these declines, the persistence of coastal flooding in the region suggests that short-term sea-level fluctuations from tidal forcing and storm surges, high-intensity rainfall events, land subsidence from anthropogenic activities, and inadequate drainage infrastructure collectively contribute to flood risk. The findings indicate that reliance on long-term average trends alone is insufficient for understanding flood dynamics. Instead, integrated assessments that account for the interaction of multiple hydro-meteorological and local anthropogenic factors are essential for improving flood resilience and informing adaptation planning in the Niger Delta region.

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INTRODUCTION

Flooding has long been one of the most persistent natural hazards in coastal areas, resulting in loss of lives, displacement, infrastructure damage, and long-term economic setbacks. While individual drivers such as storm surges and heavy rainfall have traditionally been studied and planned for separately, recent events and studies have shown that compound flooding, when multiple drivers such as oceanic surge and rainfall occur together or in close succession, can be significantly more damaging than each hazard acting alone (Green et al., 2024). Coastal zones are particularly vulnerable when storm surges coincide with intense rainfall. Storm surges elevate sea levels and hinder natural drainage, while rainfall increases runoff. When these occur together, water has nowhere to go, leading to deeper and more prolonged flooding inland (Ikuemonisan & Ozebo, 2020; Zhou et al., 2021). The key mechanism behind this interaction lies in hydrodynamic blockage: when storm surge raises sea levels, rivers and drainage systems face increased resistance as they attempt to discharge water into the ocean. If intense rainfall occurs concurrently, as is often the case during cyclonic systems, this inland water becomes trapped; resulting in urban and fluvial flooding that extends further and lasts longer (Gori et al., 2023).

Past events provide clear evidence of the destructive capacity of compound flooding. During Hurricane Harvey in 2017, Houston experienced exceptional rainfall while Galveston Bay was already experiencing elevated water levels due to storm surge. The convergence of these two drivers led to widespread inundation and massive economic damage, with traditional models failing to anticipate the full scope of the flooding because they treated surge and rainfall as isolated hazards (Wahl et al., 2015; Moftakhari et al., 2021). A similar scenario occurred in Mozambique during Cyclone Idai in 2019, where the storm pushed a surge into Beira's coastline while simultaneously releasing intense rainfall over central Mozambique, causing river discharge into the Pungwe and Buzi basins to surge and devastating infrastructure and communities (UNDRR, 2021; Khouakhi & Villarini, 2022). In many cases, flood protection systems designed to handle either storm surge or rainfall were overwhelmed because they were not built to manage their combined impact (Valle-Levinson et al., 2020; Huang et al., 2021; Xu et al., 2024). These events demonstrate how compound flood risks often go underrepresented in planning and disaster preparedness, particularly in regions with weak flood forecasting systems.

The increasing frequency of such interactions is directly associated with ongoing climatic changes. Sea-level rise is a long-term consequence of climate change and plays a direct role in amplifying coastal flood hazards. With higher sea levels, coastal areas begin from an elevated baseline, meaning that smaller storm surges or shorter rainfall events can now breach critical flood thresholds (Vurilj et al., 2025). According to IPCC estimates, global mean sea levels have already risen by more than 20 cm since 1900, with projections indicating continued acceleration under current emissions trajectories (IPCC, 2021). For compound flooding, this means an increasing likelihood of simultaneous inland and coastal inundation, even under relatively moderate weather conditions (Chen et al., 2023). Along with rising seas, climate change is also intensifying rainfall events. A warmer atmosphere can hold more moisture, which translates into heavier precipitation during storms, with extreme rainfall events becoming more frequent and intense, particularly in tropical and subtropical regions (IPCC, 2021; Khouakhi & Villarini, 2022). Storm behaviour is also changing, with growing evidence that tropical cyclones are becoming wetter and slower-moving, prolonging exposure to both surge and rainfall impacts. In regions such as the Gulf of Mexico and the Bay of Bengal, this trend raises serious concerns for compound flood frequency, as longer-lasting storms allow more time for rainfall to accumulate while slow-moving surges give less opportunity for runoff to escape to the sea (Gori et al., 2023). This shifting flood behaviour underlines the urgent need for integrated analysis and planning (Nederhoff et al., 2024).

Despite this growing body of evidence, much of the current flood risk analysis is still based on the assumption that hazards occur independently. As a result, most planning frameworks and infrastructure designs are prepared to handle either storm surge or pluvial flooding, but not their interaction, leading to a systematic underestimation of actual flood risk in coastal cities and settlements. Urban planning codes, flood insurance models, and even early warning systems in many regions remain anchored in single-hazard assumptions (Sun et al., 2024). In developing countries, the problem is even more serious due to lack of long-term data, modeling tools, and resources for comprehensive risk assessments (Ganguli et al., 2022). While studies on compound flooding have grown in recent years, its application in practice remains limited. The growing complexity of coastal flood dynamics, driven by climate change, requires a fundamental shift in how flood risks are evaluated and addressed, especially in areas where sea-level rise and urban expansion intersect (Sun et al., 2024). Relying on outdated models that assume independent hazards can result in design failures and disaster mismanagement (Dong et al., 2022; Chen et al., 2023).

Given the above, understanding how sea level rise and precipitation patterns interact to influence coastal flood dynamics is becoming increasingly essential, especially in highly exposed regions such as the Niger Delta in Nigeria. The region’s low elevation, rapid urbanization, and heavy dependence on natural waterways make it particularly sensitive to both oceanic and atmospheric drivers of flooding (Ikuemonisan et al., 2023). This study is designed to explore how oceanic surge and rainfall interact to amplify coastal flood risk under changing climate conditions. It seeks to provide a deeper understanding of the underlying physical processes that drive compound flooding, as well as to assess the extent to which climate change influences both its frequency and severity. The study evaluates the trend in sea level elevation in the Niger Delta region of Nigeria, examines precipitation patterns across the coastal areas of the region, and investigates the combined influence of sea level changes and rainfall variability on the occurrence and intensity of coastal flooding. A focused investigation into these recent trends is therefore critical to informing long-term resilience planning and adaptation strategies. This study contributes to a growing field of research focused on multi-hazard and compound event analysis, particularly in relation to climate extremes. Focusing on the dual impact of surge and rainfall, this research helps clarify a hazard type that is underrepresented in current planning and risk management frameworks. In practical terms, the findings could be useful for urban planners, civil engineers, and policymakers tasked with protecting lives and infrastructure in vulnerable coastal zones. For societies facing coastal threats, especially in low-lying developing regions, this study reinforces the importance of shifting towards integrated approaches to climate adaptation. A better understanding of compound flooding improves the accuracy of risk forecasting, informs more effective infrastructure design, and helps shape policies that reduce future exposure and losses.

MATERIALS AND METHODS

Study Area

The Niger Delta region of Nigeria is a low-lying, densely populated coastal environment highly exposed to both oceanic and atmospheric drivers of flooding (Daramola et al., 2022). As shown in Figure 1, the terrain is characterized by extensive networks of rivers and creeks, with elevation decreasing toward the Atlantic Ocean.

This configuration enhances land–sea connectivity and increases vulnerability to coastal and compound flooding driven by surge–rainfall interactions. The study area spans six coastal states, Ondo, Delta, Bayelsa, Rivers, Akwa Ibom, and Cross River, and is characterised by an extensive network of rivers, creeks, estuaries, and mangrove swamps that are strongly influenced by tidal dynamics. Its proximity to the Atlantic Ocean makes it vulnerable to oceanic surge, while its tropical climate is marked by intense and prolonged rainfall events, particularly during the wet season (Musa et al., 2016). These two drivers frequently interact, especially when heavy rainfall coincides with elevated sea levels, restricting river discharge and increasing the likelihood of inundation. In addition, ongoing land subsidence, rapid urban expansion, and alterations to natural drainage systems further intensify flood susceptibility across the region. Under climate change, projected sea level rise and changes in precipitation patterns are expected to exacerbate these existing vulnerabilities, making the Niger Delta a critical hotspot for studying compound coastal flooding processes (Adeyeri et al., 2017).

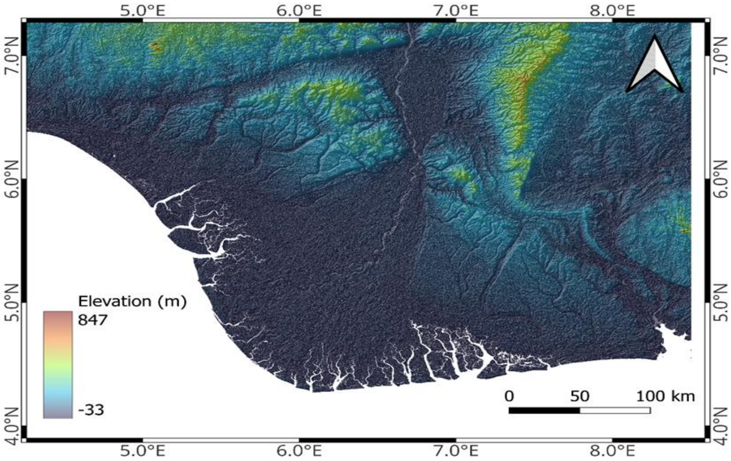

Figure 1: Shuttle Radar Topography Mission (STRM) Digital Elevation Model of the Niger Delta Showing Spatial Variations in Topography Across the Coastal and Inland Areas. Elevation Ranges from Approximately −33m to 847m Above Mean Sea Level, with Low-Lying Coastal Plains and dense River Networks Clearly Delineated [Source: Authors, 2026]

The study focused on six locations, which represents key coastal states within the Niger Delta region of Nigeria: Ondo, Delta, Bayelsa, Rivers, Akwa Ibom, and Cross River. Representative offshore sea surface points were defined using their geographic coordinates (Figure 2), based on verified offshore positions for each state. Around each point, a buffer of 10 km radius was created to represent the spatial extent for data extraction, ensuring adequate coverage of local variability in sea surface elevation.

Dataset Description and Processing

Sea Surface Elevation

Sea surface elevation data were obtained from the HYCOM (Hybrid Coordinate Ocean Model) Image Collection hosted on the Google Earth Engine platform. This dataset provides gridded daily global ocean surface elevation, available from January 1, 2000, to December 31, 2024. The elevation values are derived from hydrodynamic simulations, representing sea surface topography influenced by currents, tides, and thermal expansion.

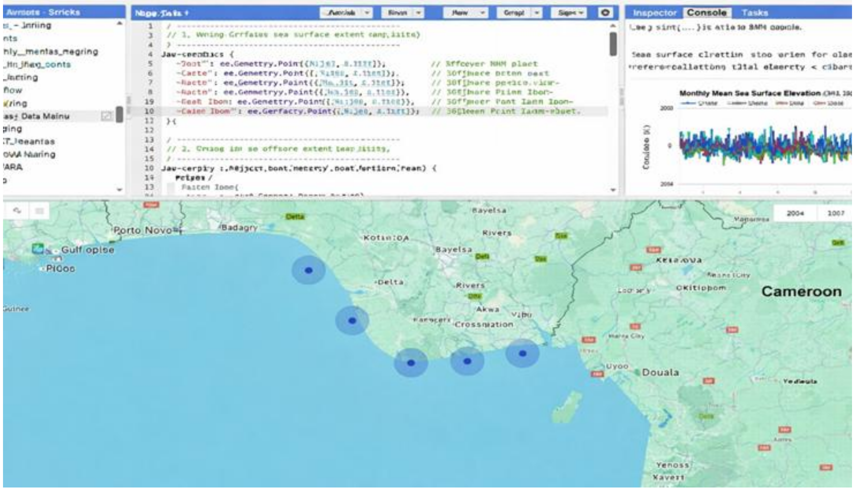

Figure 1: Map View from Google Earth Engine Showing Six Offshore Reference Points (Ondo, Delta, Bayelsa, Rivers, Akwa Ibom, and Cross River) Along the Niger Delta Coastline, Represented in Blue. Each Point was Buffered by a 10 km Radius and Used as a Referenced Location for Extracting Monthly Total Precipitation and Sea Surface Elevation Data

Time Series Generation

To analyze temporal trends in sea surface elevation, a monthly mean time series was computed for each buffered region. The HYCOM dataset was filtered for each month within the study period (2000–2024), and the average surface elevation over each region was computed using a mean reducer at a spatial scale of 10 km. Monthly data were extracted only when valid elevation measurements were available.

Precipitation Data Extraction and Analysis

To complement the sea surface elevation analysis and understand potential hydrometeorological influences on coastal dynamics, monthly precipitation data were extracted from the Global Precipitation Measurement (GPM) Integrated Multi-satellite Retrievals for GPM (IMERG) Final Run dataset (Version 6). This dataset provides global precipitation estimates with monthly temporal resolution, spanning from January 2001 to December 2024. It integrates observations from satellite-based microwave and infrared sensors, offering consistent and spatially extensive rainfall measurements. The same six offshore coastal points previously used for sea surface elevation analysis, Ondo, Delta, Bayelsa, Rivers, Akwa Ibom, and Cross River, were retained to ensure spatial consistency. Each point was buffered with a radius of 10 km to define a circular sampling area. This buffer ensured that precipitation measurements represented a broader offshore region rather than a single pixel. For each monthly timestep, the total precipitation volume over each buffered area was computed. This was achieved by first obtaining the average precipitation depth (in millimeters) within the area for that month, then converting it to meters and multiplying it by the total area (in square meters) of the buffer. The resulting value, expressed in cubic meters (m^3), represents the total volume of rainfall received each month within the 10 km buffer zone for each coastal location.

RESULTS AND DISCUSSION

Sea-Surface Elevation

Figure 3 shows the time series of sea surface elevation for the selected locations from 2000 and 2025. The sea surface elevation data for the six coastal states across four time periods, 2000 – 2004, 2005 – 2009, 2010 – 2019, and 2020 – 2025m reveals a consistent downward trend in mean sea surface height anomalies for most states, especially from 2010 onward. This observation is notable and potentially significant in understanding localized sea level dynamics in the Gulf of Guinea region. As shown in Table 1, in the earliest period (2000 – 2004), all six states recorded positive sea surface elevations, with Bayelsa (0.0090 m) and Delta (0.0081 m) showing the highest values. This period likely reflects relatively stable oceanic conditions, possibly under the influence of long-term decadal oscillations or neutral climate phases. During 2005–2009, there is a noticeable decline in values in most locations, particularly in Ondo (0.0011 m) and Delta (0.0030 m), while Cross River and Akwa Ibom experienced slight increases. The generally lower values could reflect transitional oceanographic processes, possibly linked to regional wind patterns or changes in ocean currents.

The most significant drop occurs between 2010 and 2019. Ondo and Delta exhibit negative anomalies (–0.0004 m and –0.0014 m respectively), with Bayelsa and Akwa Ibom showing even more pronounced decreases (–0.0058 m and –0.0082 m). This sharp decline could be attributed to enhanced vertical ocean mixing, increased evaporation, or local subsidence effects, and may reflect a combination of climate variability and localized geophysical processes such as tectonic adjustments. In the most recent period (2020–2025), the negative trend continues across most locations. Akwa Ibom records the lowest value (–0.0124 m), suggesting a persistent and deepening sea level anomaly. Ondo and Delta follow similar patterns with values of –0.0065 m and –0.0094 m respectively. Cross River, however, deviates from this regional pattern, showing a positive elevation anomaly (0.0004 m), which may indicate localized oceanic or atmospheric dynamics influencing this particular stretch of the coastline.

Table 1: Mean Sea Surface Elevation Anomalies (in Meters) for Selected Coastal States in Southern Nigeria Across Four Time Periods (2000–2025), Illustrating Temporal Variations in Local Sea Level Behaviour

Period	Ondo	Delta	Bayelsa	Rivers	Akwa Ibom	Cross River
2000 – 2004	0.0068	0.0081	0.0090	0.0083	0.0069	0.0060
2005 – 2009	0.0011	0.0030	0.0085	0.0078	0.0087	0.0092
2010 – 2019	–0.0004	–0.0014	–0.0058	–0.0046	–0.0082	0.0069
2020 – 2025	–0.0065	–0.0094	–0.0087	–0.0054	–0.0124	0.0004

Precipitation Trends

Figure 4 shows the monthly total precipitation volume. The figure indicates a generally decreasing trend in annual precipitation across all six coastal states, although the strength and statistical significance of these trends vary. In Ondo State, the slope of -0.0066 mm/year is very small, with a low correlation (r = -0.0635) and a high p-value (0.7846), indicating no meaningful trend. The variation in rainfall is likely random or due to short-term fluctuations. Delta State shows a steeper slope of -0.0345 mm/year. The correlation coefficient (r = -0.4089) suggests a moderate negative relationship, and the p-value (0.0657) is close to the 0.05 threshold, indicating a potentially emerging trend that may become more apparent over a longer period.

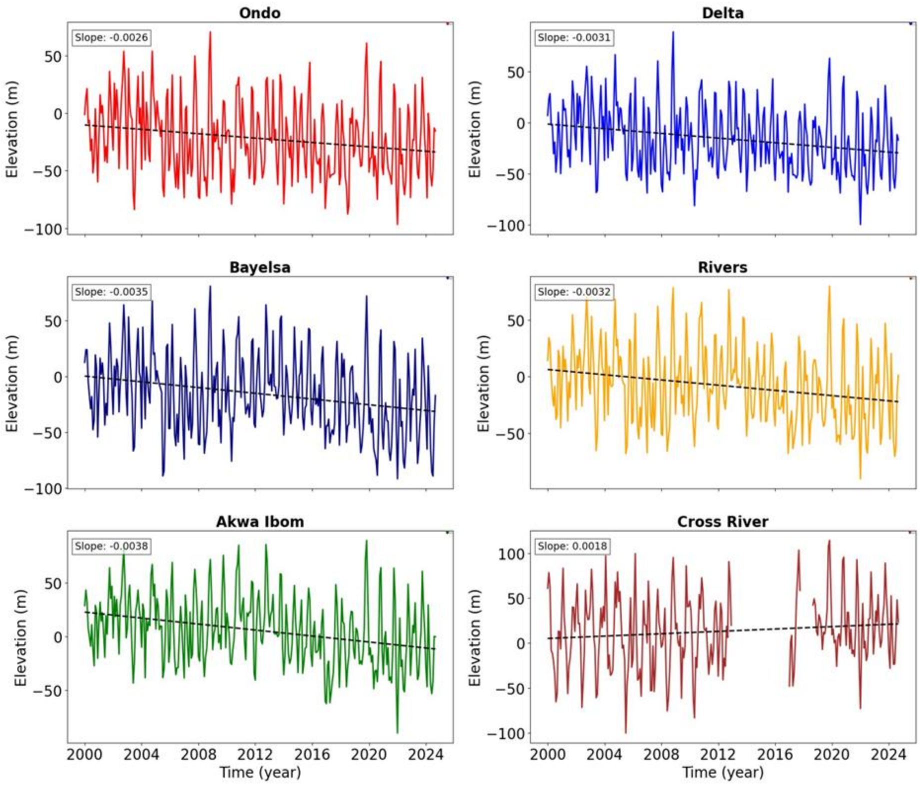

Figure 3: Time Series of Sea Surface Elevation for the Selected Locations from 2000 and 2025

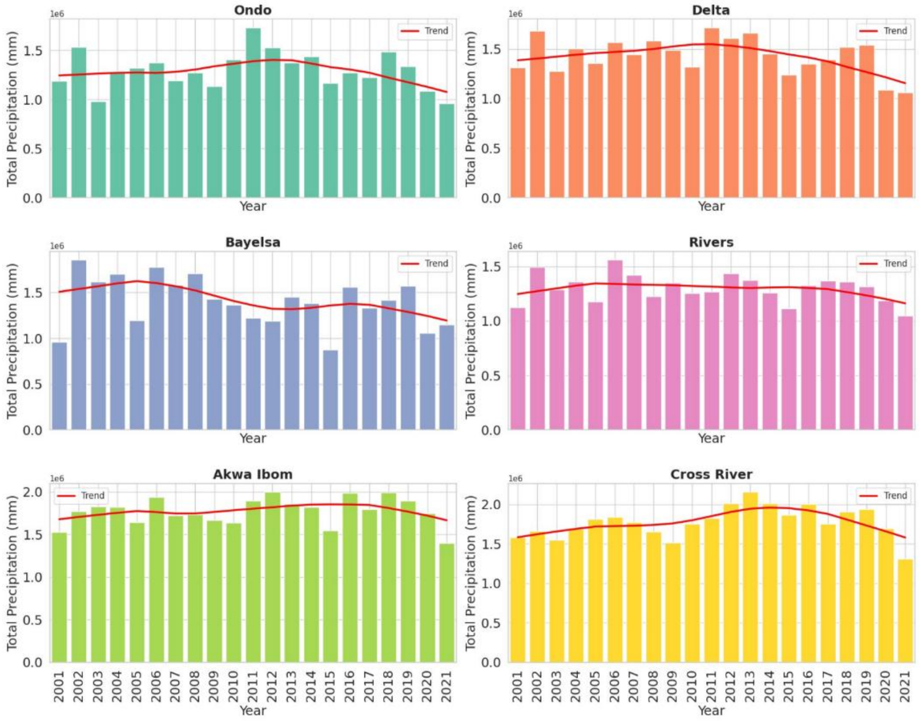

Figure 4: Monthly Total Precipitation Volume (m³) - GPM IMERG (2001–2021)

Table 2: Linear Trends and Statistical Parameters of Annual Total Precipitation for Selected Coastal States in Southern Nigeria Based on Long-Term Time Series Analysis

State	Slope (mm/year)	r-value	p-value	Std. Error
Ondo	-0.0066	-0.0635	0.7846	0.0238
Delta	-0.0345	-0.4089	0.0657	0.0176
Bayelsa	-0.0234	-0.2547	0.2653	0.0204
Rivers	-0.0302	-0.4083	0.0661	0.0155

State	Slope (mm/year)	r-value	p-value	Std. Error
Akwa Ibom	-0.0238	-0.3563	0.1129	0.0143
Cross River	-0.0295	-0.3787	0.0904	0.0165

Bayelsa records a slope of -0.0234 mm/year, with weak correlation (r = -0.2547) and a nonsignificant p-value (0.2653). This suggests some reduction in precipitation, but it is not statistically significant. Rivers State has a slope of -0.0302 mm/year, similar in magnitude to Delta. The correlation is moderate (r = -0.4083), and the p-value (0.0661) is just above the threshold. Like Delta State, this may point to a downward trend that is not yet strong enough to be conclusive. In Akwa Ibom, the slope is -0.0238 mm/year. The correlation (r = -0.3563) is moderate, and the p-value (0.1129) does not support statistical significance. The trend is present but weak. Cross River shows a similar pattern, with a slope of -0.0295 mm/year, moderate correlation (r = -0.3787), and a p-value of 0.0904. Although not statistically significant, the trend is consistent with the other states.

Discussion

The temporal patterns in sea surface elevation anomalies and annual precipitation across the coastal states of southern Nigeria provide an important basis for evaluating potential contributors to coastal flooding in the region. Analysis of sea surface elevation anomalies between 2000 and 2025 shows a general transition from positive to negative values over time. During 2000 to 2004, all coastal states recorded slightly positive anomalies, indicating relatively higher-than-average sea levels. This pattern gradually reversed in subsequent years, and by 2020–2025 most states, including Ondo, Delta, Bayelsa, Rivers, and Akwa Ibom, recorded negative anomalies. Cross River remained an exception, with values fluctuating around zero or slightly positive. Although the magnitudes of these anomalies are small, even subtle variations in sea level can be important in low-lying coastal environments where elevation is minimal and drainage capacity is limited. Precipitation records over the same coastal states indicate a general decline in annual rainfall over the past two decades. All states show negative linear trends in total precipitation (Figure 5), with Delta and Rivers exhibiting the strongest decreases. However, none of the trends are statistically significant at the five percent level, indicating that the observed reductions may not represent a consistent long-term shift in rainfall totals. It is also important to note that annual precipitation totals do not fully represent flood hazard, since short-duration, high-intensity rainfall events, often more influential in triggering urban and coastal flooding, can still occur even when overall annual rainfall is decreasing.

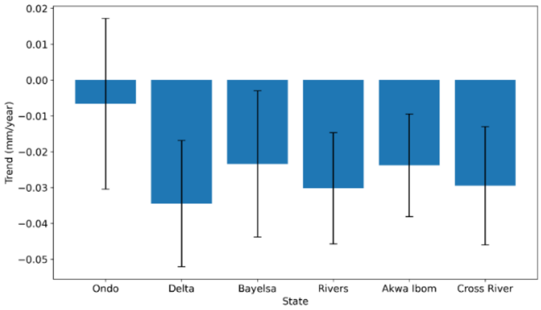

Figure 5: Linear Trends in Annual Total Precipitation

In examining possible drivers of coastal flooding within the study area, multiple interacting processes must be considered. Although average sea surface elevation exhibited a declining trend across most locations, temporary increases associated with tidal fluctuations and storm surges remain important drivers of coastal inundation. Previous studies have demonstrated that short-term sea-level extremes often contribute more directly to flood occurrence than long-term mean sea-level changes, particularly in low-lying coastal environments where even modest water-level increases can result in extensive inundation (Nicholls & Cazenave, 2010; Oppenheimer et al., 2019). Consequently, flood hazards may persist despite observed reductions in average sea surface elevation. Similarly, the observed decrease in annual rainfall does not necessarily imply a reduction in flood risk. Several studies have shown that rainfall intensity, duration, and temporal concentration exert stronger controls on urban flooding than annual rainfall totals (Wasko & Sharma, 2017; Berndtsson, 2010). Intense rainfall events can rapidly exceed the capacity of drainage systems, generating surface runoff and localized flooding even in years characterized by lower cumulative precipitation. This phenomenon is particularly relevant in rapidly urbanizing regions of coastal Nigeria, where drainage infrastructure often remains inadequate relative to increasing runoff volumes.

Land subsidence represents another critical factor influencing flood susceptibility. In the Niger Delta, natural sediment compaction and anthropogenic activities such as groundwater withdrawal and hydrocarbon extraction have been identified as major causes of land-surface lowering (Ikuemonisan et al., 2023; Higgins et al., 2014). Subsidence increases relative sea level by reducing land elevation relative to the ocean surface, thereby enhancing flood exposure even where absolute sea levels remain stable or decline. Similar relationships between subsidence and increasing coastal flood risk have been documented in other deltaic regions worldwide, including the Mississippi Delta and Jakarta coastal plain (Chaussard et al., 2013; Erkens & Sutanudjaja, 2015). Furthermore, rapid urban expansion contributes to increased flood vulnerability through the replacement of permeable surfaces with impervious materials, thereby reducing infiltration and increasing surface runoff. Studies conducted in coastal Nigerian cities have reported that unplanned urban growth and inadequate stormwater infrastructure significantly exacerbate flood occurrence and impacts (Adelekan, 2010; Ayanlade & Radeny, 2020). Therefore, the flooding patterns observed within the study area are likely the result of the combined influence of coastal processes, land subsidence, extreme rainfall events, and anthropogenic alterations to the urban landscape.

CONCLUSION

The study assessed the potential for compound coastal flooding in the Niger Delta by examining trends in sea surface elevation and precipitation. Although both variables showed generally declining trends, these did not correspond to a reduction in observed flood risk. This indicates that flooding in the region is not controlled by long-term averages alone, but by short-term interactions between oceanic and atmospheric processes. Episodic storm surges, tidal influences, and high-intensity rainfall events remain critical drivers of flooding, particularly when they occur simultaneously and restrict drainage. In addition, land subsidence, rapid urbanization, and inadequate drainage infrastructure continue to amplify flood vulnerability across the region. The findings demonstrate that reliance on single-driver or trend-based assessments is insufficient for representing the complexity of coastal flooding. Instead, integrated approaches that consider the interaction of multiple drivers are essential for accurate risk evaluation. This study is, however, subject to some limitations. The analysis relied on gridded datasets, which may not fully resolve local-scale variability, particularly in highly heterogeneous coastal environments. The use of offshore buffer zones may also not fully represent inland flood dynamics. In addition, the study focused on long-term monthly trends and did not explicitly analyse extreme events or the timing of co-occurring surge and rainfall episodes, which are central to compound flooding processes. Furthermore, other important drivers such as land subsidence, drainage capacity, and river discharge were not quantitatively incorporated into the analysis. The study therefore emphasizes the need for improved flood management strategies that incorporate compound flooding dynamics to enhance resilience and reduce future risk in the Niger Delta.

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