

Compound Coastal Flooding and Climate Change in the Niger Delta: Hydro-Climatic Modelling And Engineering Adaptation A Synthesis and Conceptual Modelling Framework

Sunny O. Asomaku^{1*}, Imiete Godspower², Perri Owunari², Geoffrey Ebe², Benson P. Okwori¹

¹Centre for Disaster Risk Management and Development Studies, University of Port Harcourt, Nigeria

²Department of Environmental Management, Rivers State University, Port Harcourt, Nigeria

*Corresponding Author

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ABSTRACT

The Niger Delta, Africa's largest deltaic and mangrove ecosystem, is increasingly exposed to compound coastal flooding the co-occurrence or successive interaction of fluvial discharge, pluvial runoff, storm surge, tidal elevation, and relative sea-level rise (RSLR) driven by anthropogenic climate change, land subsidence from hydrocarbon extraction, and rapid, unplanned coastal urbanisation. This paper synthesises the peer-reviewed and grey literature on compound flooding processes, hydro-climatic modelling frameworks, and engineering and nature-based adaptation options, and applies that synthesis to the Niger Delta as a regional case study. Evidence reviewed indicates that the Gulf of Guinea coastline is experiencing sea-level rise at approximately 3.9 mm/yr roughly 10% above the global average while localised land subsidence associated with hydrocarbon withdrawal (25–125 mm/yr at active well fields) compounds this signal into a relative sea-level rise of up to ~0.96 m by 2050 in the most affected settlements. Concurrently, regional rainfall intensity increased by an estimated 53% between 2012 and 2017 and a further 12% between 2017 and 2022, while upstream dam operations on the Niger and Benue river systems modulate the timing and magnitude of downstream discharge peaks. A conceptual hydro-climatic modelling framework — coupling rainfall–runoff, river-routing, and storm-surge/tide hydrodynamic components — is proposed for the region, drawing on established compound-inundation modelling practice (e.g., HEC-RAS, MIKE 21, ADCIRC-class coupling). Engineering adaptation options are evaluated along a grey–green–hybrid continuum, with particular attention to mangrove-fronted dike systems, elevated infrastructure, and adaptive, sensor-linked flood defences. The paper concludes that reducing compound flood risk in the Niger Delta requires integrated, basin-to-coast hydro-climatic modelling; regulation of subsidence-inducing extraction; mangrove restoration at scale; and hybrid engineering investment prioritised in the most exposed core states of Bayelsa, Rivers, and Delta.

Keywords: compound flooding; Niger Delta; sea-level rise; land subsidence; hydro-climatic modelling; coastal engineering; nature-based adaptation; climate change

INTRODUCTION

Deltaic coastlines occupy less than one percent of the Earth's land surface yet host a disproportionate share of the global population and economic activity, making them focal points of climate risk (Perilous Future for River Deltas, 2023). The Niger Delta in southern Nigeria the largest delta in Africa and home to the continent's most extensive mangrove forest exemplifies this vulnerability. Spanning approximately 70,000–112,000 km² across nine states and supporting tens of millions of residents, the region combines low-lying topography, a dense distributary river network, extensive hydrocarbon extraction infrastructure, and rapid informal urban growth (Niger Delta area, n.d.; Mangroves of the Niger Delta, 2023).

Flooding in the Niger Delta has historically been understood, and managed, as either a riverine (fluvial) hazard associated with the annual Niger–Benue flood pulse, or a coastal hazard associated with tidal inundation and storm surge. In practice, however, the region's floods are increasingly compound in nature: heavy local rainfall, elevated river discharge (often exacerbated by upstream dam releases from the Kainji, Jebba, and Lagdo reservoirs), high tides, and a rising relative sea level frequently coincide or closely follow one another, producing inundation more severe and longer-lasting than any single driver would produce alone (Eteh et al., 2024; Green et al., 2025). The catastrophic 2012 and 2022 Nigerian floods, both of which inundated large parts of Bayelsa, Rivers, and Delta States, are now widely attributed to this kind of driver interaction rather than to rainfall or river discharge in isolation.

This compounding is amplified by two regionally distinctive stressors. First, the Gulf of Guinea is experiencing sea-level rise at a rate approximately 10% above the global average (Ghomsi et al., 2024). Second, and more acutely, land subsidence associated with more than five decades of oil and gas extraction has locally accelerated relative sea-level rise far beyond the eustatic signal, with subsidence rates at active well fields reported between 25 and 125 mm per year (Musa et al., 2016; Ekwe et al., as cited in Niger Delta land cover map, n.d.). The consequence is a relative sea-level rise trajectory for parts of the delta that is an order of magnitude faster than the global mean — a dynamic with few close analogues outside the Mississippi and Ganges–Brahmaputra deltas (Perilous Future for River Deltas, 2023).

Despite this compounding risk, hydro-climatic modelling of the Niger Delta has, to date, been fragmented: separate studies have addressed river flood susceptibility (Hazzan et al., 2026), sea-level-rise vulnerability (Musa et al., 2014), rainfall–flood relationships (Tosin-Orimolade et al., 2026), and dam-driven flood dynamics (Eteh et al., 2024), but few have integrated these drivers within a single compound-flood modelling framework of the kind now standard in North American and European coastal engineering practice (Santiago-Collazo et al., 2019; Couasnon et al., 2020). This paper addresses that gap in three ways. First, it synthesises the current evidence base on the physical drivers of compound flooding in the Niger Delta. Second, it proposes a conceptual, coupled hydro-climatic modelling framework appropriate to the region's data environment. Third, it evaluates engineering and nature-based adaptation options against that framework, with attention to their feasibility in a resource-constrained, oil-producing deltaic setting.

The paper is organised as follows. Section 2 describes the study area. Section 3 reviews the literature on compound flooding drivers, both globally and specific to the Niger Delta. Section 4 sets out the proposed hydro-climatic modelling framework and data requirements. Section 5 synthesises quantitative evidence on flood drivers using tables and figures. Section 6 evaluates engineering and nature-based adaptation strategies. Section 7 discusses limitations and research priorities, and Section 8 concludes.

Study Area

The Niger Delta occupies the Nigerian coastline of the Gulf of Guinea between approximately 4.0°N and 7.0°N and 4.5°E and 8.5°E (Figure 1). The core deltaic plain — defined by the Niger Delta Development Commission to include Abia, Akwa Ibom, Bayelsa, Cross River, Delta, Edo, Imo, Ondo, and Rivers States — covers roughly 70,000 km² of coastal barrier islands, mangrove swamp forest, freshwater swamp forest, and lowland rainforest (Niger Delta area, n.d.). The most flood-exposed core, however, is the low-lying, tidally influenced distributary zone of Bayelsa, Rivers, and Delta States, which sits largely below 40 m elevation and, in many coastal settlements, at or near present mean sea level (Hazzan et al., 2026).

The delta is drained by the combined discharge of the Niger and Benue rivers, which converge at Lokoja before fanning out into a dense network of distributaries — including the Forcados, Escravos, Nun, and Bonny channels — before reaching the Atlantic Ocean. Discharge is strongly seasonal and is further regulated by upstream reservoirs, notably the Kainji and Jebba dams within Nigeria and the Lagdo Dam on the Benue River in neighbouring Cameroon; water releases from Lagdo have been directly implicated in downstream flood peaks in 2012, 2018, and 2022 (Eteh et al., 2024; 2022 Nigeria floods, n.d.).

The delta hosts Africa's largest mangrove ecosystem, historically estimated at 8,000–10,800 km² and concentrated in Bayelsa, Rivers, and Delta States (Mangroves of the Niger Delta, 2023). This mangrove fringe provides natural wave and surge attenuation but has been substantially degraded by oil-industry infrastructure, dredging, and the spread of invasive nipa palm, with one widely cited estimate placing net mangrove loss at approximately 2,536 km² between 1988 and 2023 (Niger River, n.d.). The region is also one of the most intensively developed hydrocarbon provinces in the world, with several hundred onshore oil wells and associated pipeline, flow-station, and dredged-canal infrastructure that has been directly linked to localised land subsidence (Niger Delta land cover map, n.d.).

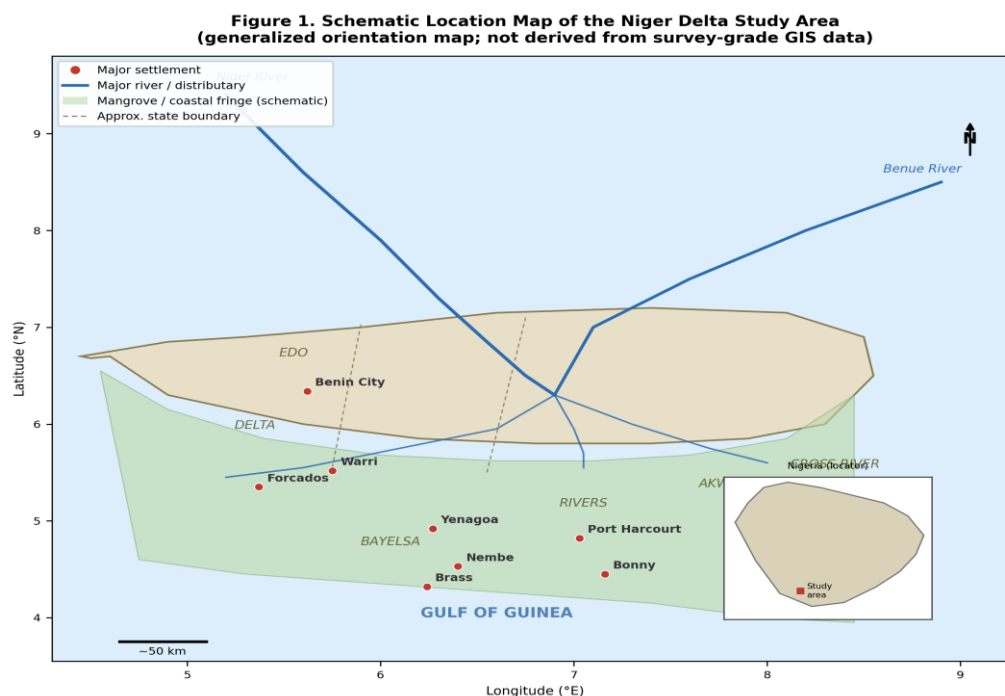


Figure 1. Schematic location map of the Niger Delta study area, showing core coastal states, major settlements, the Niger–Benue distributary network, and the mangrove/coastal fringe zone. The map is a generalized orientation diagram constructed for this paper and is not derived from survey-grade GIS shapefiles; boundary and coastline positions are approximate.

LITERATURE REVIEW

Compound Flooding: Concept and Global Evidence

Compound flooding is defined in the recent literature as the co-occurrence, close succession, or causal interaction of two or more flood drivers — river discharge, surface-water/pluvial runoff, storm surge, astronomical tide, and relative sea-level rise — such that the resulting water level or inundation extent exceeds what any single driver would produce, or exceeds what would be expected from a simple linear superposition of drivers considered independently (Green et al., 2025; Couasnon et al., 2020). Three broad interaction types are recognised: temporally or spatially overlapping hazards sharing a common meteorological trigger (e.g., a storm producing both intense rainfall and storm surge simultaneously); the direct triggering or cascading of one hazard by another (e.g., heavy rainfall arriving on top of an already-elevated, tidally forced river stage); and the incidental co-occurrence of otherwise independent hazards (Green et al., 2025).

Global assessments demonstrate that failing to account for these interactions systematically underestimates flood hazard. Using a global river-discharge and storm-surge model, Couasnon et al. (2020) showed that the statistical dependence between discharge and surge extremes varies markedly by coastline and that ignoring this dependence understates the probability, and therefore the design return period, of compound events at many river mouths worldwide. Case studies of specific storms reinforce this point: coupled hydrodynamic

modelling of Hurricane Harvey (2017) and Hurricane Matthew (2016) found that river–surge and tide–river interactions produced non-linear increases in upstream flood extent relative to single-driver simulations, with compound modelling reducing water-level prediction error by up to 69–79% relative to single-process models in some cases (Frontiers, 2020; ScienceDirect, 2025).

Flood Drivers Specific to the Niger Delta

The dominant flood driver identified across recent Niger Delta studies is rainfall intensity, reinforced by the region's dense drainage network and low relief. Using a frequency-ratio (FR) statistical model applied across the unified Niger Delta for the first time, Hazzan et al. (2026) found that 71.8% of the region's land area (approximately 26,297 km²) falls within moderate-to-very-high flood susceptibility, with rainfall, proximity to rivers, and drainage density the strongest explanatory factors, and Bayelsa, Rivers, and Delta States identified as the most at-risk. A companion land-use/land-cover study reported a 53.1% increase in areal rainfall between 2012 and 2017 and a further 11.5% increase between 2017 and 2022 across the region, directly implicating rainfall intensification in both the 2012 and 2022 Nigerian flood disasters (Tosin-Orimolade et al., 2026).

Superimposed on this rainfall signal is the effect of upstream dam operation. Using Sentinel-1 synthetic aperture radar (SAR) imagery for 2018–2022, Eteh et al. (2024) documented a delayed downstream flood response at Obiafu following water releases from the Kainji, Jebba, and Lagdo dams, with peak inundation in October 2020 and October 2022 coinciding with the combination of high local rainfall and upstream releases. The 2022 Nigeria floods — which killed over 600 people nationally and included a boat disaster on the Niger River that killed 76 — were attributed jointly to unusually heavy rainfall, climate change, and the release of water from the Lagdo Dam beginning in September 2022 (2022 Nigeria floods, n.d.).

On the coastal side, tidal and storm-surge dynamics interact with a subsiding, low-gradient shoreline. Musa et al. (2014), applying a 17-indicator coastal vulnerability index using GIS-based exposure, susceptibility, and resilience metrics, found that 42.6% of the Niger Delta coastline is highly vulnerable to sea-level rise, with the most exposed segments characterised by low slope, low topography, high mean wave height, and unconfined aquifers vulnerable to saline intrusion. A related analysis using a GIS 'bathtub' inundation approach estimated relative sea-level rise of 0.14–0.96 m by 2030–2050 once local subsidence is added to the eustatic signal (Musa et al., 2016) — a range further contextualised in Section 3.3 below.

Land Subsidence and Relative Sea-Level Rise

Relative sea-level rise (RSLR) — the change in sea level relative to the local land surface — is the operative hazard metric for coastal deltas, because it combines the eustatic (global-average) sea-level signal with local vertical land motion (Musa et al., 2014). In the Niger Delta, vertical land motion is dominated by subsidence associated with hydrocarbon and groundwater withdrawal, compounding a natural deltaic subsidence process driven by sediment compaction and reduced upstream sediment supply following river regulation. Reported subsidence rates range from approximately 7–9 mm/yr in settlement areas such as Bonny to 25–125 mm/yr at active oil-extraction sites (Musa et al., 2016), with one time-lapse levelling study in the south-east Niger Delta basin estimating an average subsidence rate of 86 mm/yr directly attributable to hydrocarbon production (Niger Delta land cover map, n.d.).

At the regional scale, the Gulf of Guinea's eustatic sea level is rising at approximately 3.89–4.5 mm/yr — roughly 10% above the global average of 3.5 mm/yr — with satellite altimetry indicating an acceleration of approximately 0.09 mm/yr² since 1993 (Ghomsi et al., 2024). Under CMIP6 climate model ensembles, Ghomsi et al. (2024) project a likely (5th–95th percentile) Gulf of Guinea sea-level rise of 0.20–1.38 m by 2100, with up to 4,332 km² of coastal land potentially subject to permanent inundation under high-emission scenarios, and up to 2 million people at risk of displacement region-wide. When local subsidence is superimposed on this eustatic trend, the Niger Delta's RSLR trajectory substantially exceeds the Gulf of Guinea regional average, placing the delta among the most rapidly subsiding, and therefore most rapidly

flooding, deltaic coastlines globally — alongside the Mississippi and Ganges–Brahmaputra deltas (Perilous Future for River Deltas, 2023).

Mangrove Degradation and Loss of Natural Buffering

Mangrove forests attenuate wave energy and storm surge, and their loss removes a substantial natural buffer against compound coastal flooding (Engineering With Nature, n.d.). Niger Delta mangrove extent has been estimated at 10,515 km² in 2010, declining to 8,240 km² by 2020 — a loss of roughly 22% in a single decade — driven by oil-industry infrastructure, dredging, urbanisation, and encroachment by the invasive nipa palm (Ogoni women restore mangroves, 2025). Over the longer term, 1988–2023, net mangrove loss across the delta has been estimated at approximately 2,536 km² (Niger River, n.d.). Because mangrove loss and land subsidence are frequently co-located — both concentrated around oil-industry infrastructure — the region faces a reinforcing cycle in which the same activities that accelerate relative sea-level rise also degrade the natural systems best placed to buffer its effects.

Hydro-Climatic Modelling Framework

This paper does not report the output of a newly executed, site-calibrated numerical simulation; rather, it synthesises published field, remote-sensing, and modelling evidence (Sections 3 and 5) and proposes a conceptual, coupled hydro-climatic modelling framework appropriate to the Niger Delta's data environment, following established international compound-flood modelling practice. This framing is made explicit so that the quantitative figures and tables that follow are read as an evidence synthesis and illustrative scenario framework rather than as new primary simulation results.

Data Sources

A hydro-climatic compound-flood model for the Niger Delta would draw on five broad data streams: (i) meteorological forcing — satellite and gauge-based rainfall (e.g., CHRS/PERSIANN, TRMM/GPM), reanalysis wind and pressure fields, and downscaled CMIP6 projections under SSP2-4.5/SSP5-8.5 scenarios; (ii) hydrological forcing discharge records and reservoir-release schedules for the Kainji, Jebba, and Lagdo dams; (iii) coastal/oceanographic forcing tide-gauge and satellite-altimetry sea-surface height, and storm/swell wave climatology for the Gulf of Guinea; (iv) topographic and bathymetric data SRTM or LiDAR-derived digital elevation models, channel bathymetry, and land-use/land-cover classification; and (v) subsidence data InSAR or repeat-levelling estimates of vertical land motion at oil-field and settlement locations (Eteh et al., 2024; Niger Delta land cover map, n.d.).

Coupled Model Architecture

Consistent with recent reviews of compound-inundation modelling (Santiago-Collazo et al., 2019; Green et al., 2025), a Niger Delta framework would couple three model classes. A rainfall–runoff/hydrologic model (e.g., HEC-HMS or an equivalent distributed model) would convert basin rainfall into inflow hydrographs for the Niger–Benue system, explicitly incorporating upstream reservoir operating rules. A river-routing and floodplain hydraulic model (e.g., HEC-RAS 2D or MIKE 21/MIKE Hydro River) would propagate these hydrographs through the distributary network, resolving overbank flooding across the low-gradient delta plain; comparative studies indicate that HEC-RAS and MIKE 21 produce broadly comparable stage and inundation-extent predictions at matched grid resolutions, with reported Nash–Sutcliffe efficiencies above 0.9 in well-calibrated applications elsewhere (Understanding Suitability of MIKE 21 and HEC-RAS, n.d.). A coastal hydrodynamic/storm-surge model (e.g., an ADCIRC-class unstructured-mesh model) would simulate tide- and wind-driven surge propagation from the Gulf of Guinea into the distributary mouths, coupled to the river model through time-variant discharge boundary conditions at the freshwater–tidal interface (Frontiers, 2020).

Because deterministic coupling of all three components is data- and compute-intensive, a statistical dependence layer — following the copula-based approach of Couasnon et al. (2020) — is proposed as a

complementary, lower-data-burden approach for a first-pass compound-flood hazard screening across the delta's many ungauged distributaries, prior to targeted deterministic modelling at priority sites (e.g., Port Harcourt, Warri, Yenagoa, Bonny).

Compound Flood Hazard Classification

Following Bilskie and Hagen's (2018) zonation concept as summarised in recent reviews, the delta's floodplain can be conceptually divided into a fluvial-dominated zone (upper distributary reaches, where river discharge and dam releases dominate), a coastal-dominated zone (open coastline and outer estuary, where tide and storm surge dominate), and a compound transition zone in between — corresponding closely to the densely settled mid-delta around Yenagoa, Warri, and inland Port Harcourt — where fluvial and coastal drivers interact most strongly and where compound-flood risk is therefore greatest (Santiago-Collazo et al., 2019).

Results: Synthesis of Compound Flood Drivers

This section brings together the quantitative evidence reviewed in Section 3 in tabular and graphical form, organised around the four principal drivers of compound coastal flooding in the Niger Delta: historical flood chronology, sea-level rise and subsidence, rainfall intensification, and mangrove-buffer loss.

Historical Flood Chronology

Table 1 summarises the major flood events affecting the Niger Delta and its wider Niger–Benue catchment since 2012, highlighting the recurring combination of intense rainfall and upstream dam release as the dominant compounding pathway, alongside the persistent coastal exposure of Bayelsa, Rivers, and Delta States.

Table 1 Major Flood Events Affecting the Niger Delta and Niger–Benue Catchment, 2012–2025

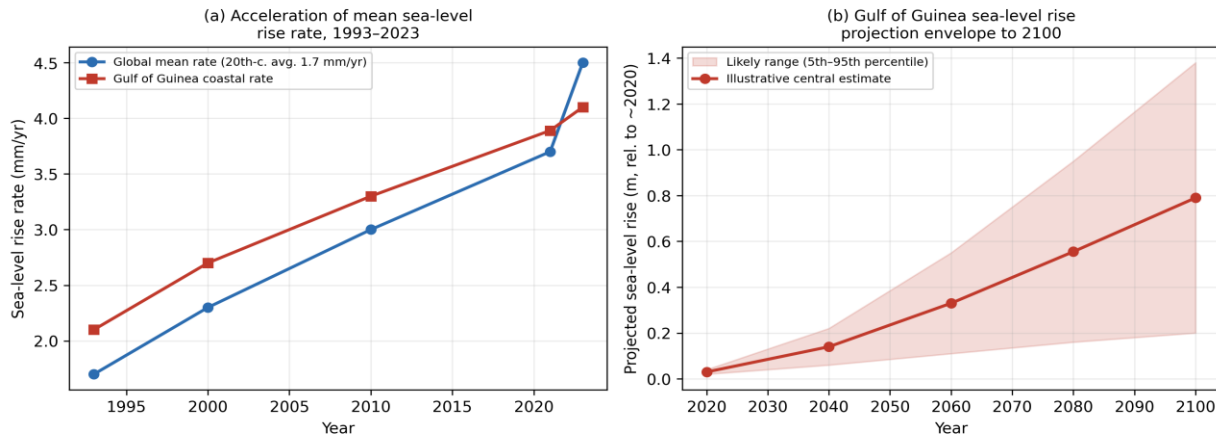
Year	Primary affected area(s)	Principal drivers	Reported impact
2012	Bayelsa, Rivers, Delta, Kogi, Anambra	Extreme rainfall; Niger–Benue peak discharge; coastal tidal backwater	Widespread displacement, farmland loss, and food-production decline (New research: flooding displacement and conflict, n.d.)
2017–2018	Benue/Kogi corridor; Niger Delta	Lagdo Dam release + extreme rainfall	90+ deaths (2017); 108+ deaths and >441,000 affected (2018) (Flooding in Nigeria: A Comprehensive Review, n.d.)
2020	Niger–Benue corridor, incl. Obiafu (Niger Delta)	Dam operations + seasonal flooding; peak SAR-detected inundation in October	68 deaths; ~436,000 affected nationally (Eteh et al., 2024; Flooding in Nigeria: A Comprehensive Review, n.d.)
2022	Bayelsa, Rivers, Anambra, Delta, Kogi, Benue (32 states)	Extreme rainfall + climate change + Lagdo Dam release (from 13 Sept.)	600+ deaths nationally, incl. 76 in the Ogbaru boat disaster; peak Niger Delta inundation October 2022 (2022 Nigeria floods, n.d.; Eteh et al., 2024)
2025	Niger State, Rivers State, Kwara State (incl. Mokwa)	Extreme rainfall; dam/embankment failure	538 deaths nationally; >3,000 houses submerged; 15M+ affected (2025 Nigeria floods, n.d.)

Note. Compiled from the sources cited in each row; figures are as reported in the original sources and were not independently re-verified against primary government disaster statistics.

Relative Sea-Level Rise Trajectory

Figure 2 situates the Niger Delta within the wider Gulf of Guinea sea-level trend, showing the observed acceleration in the rate of rise since 1993 and the projected 21st-century envelope reported by Ghomsi et al. (2024). Figure 3 then decomposes the delta-specific relative sea-level rise signal into its eustatic and subsidence components, following Musa et al. (2016), illustrating why locations near active oil-field infrastructure face RSLR roughly an order of magnitude greater than locations experiencing the eustatic signal alone.

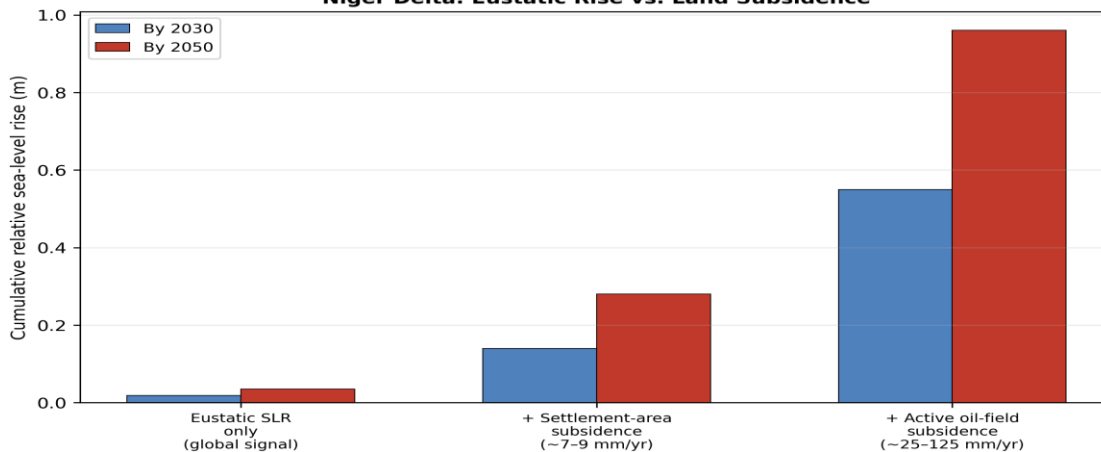
Figure 2. Observed Acceleration and Projected Envelope of Sea-Level Rise in the Gulf of Guinea



Note. Reconstructed from reported endpoints in Ghomsi et al. (2024); intermediate points are illustrative interpolations, not independently modeled.

Figure 2. (a) Observed acceleration in the mean sea-level rise rate, global vs. Gulf of Guinea coastal, 1993–2023; (b) projected Gulf of Guinea sea-level rise envelope to 2100. Reconstructed from reported endpoints in Ghomsi et al. (2024); intermediate points are illustrative interpolations.

Figure 3. Composition of Relative Sea-Level Rise (RSLR) in the Niger Delta: Eustatic Rise vs. Land Subsidence



Note. Eustatic component (19 mm by 2030; 35 mm by 2050) and subsidence bands (7–9 mm/yr settlements; 25–125 mm/yr active oil-extraction sites) as reported in Musa et al. (2016); bars show illustrative summed RSLR bounds, not site-specific measurements.

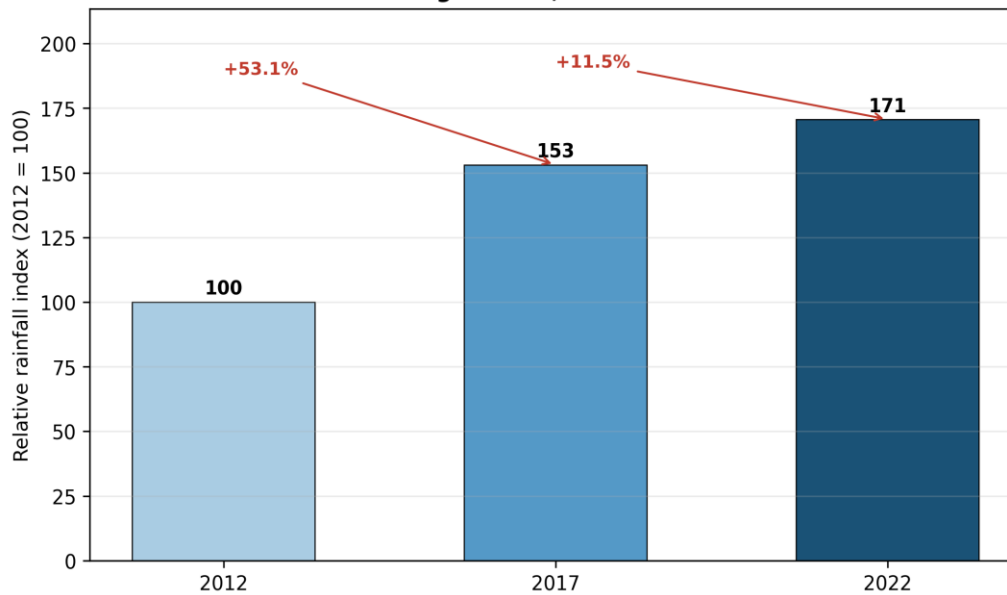
Figure 3. Composition of relative sea-level rise (RSLR) in the Niger Delta, comparing the eustatic signal alone with eustatic rise plus settlement-area and active oil-field subsidence, by 2030 and 2050. Constructed from ranges reported in Musa et al. (2016).

Rainfall Intensification and Compounding Potential

Figure 4 illustrates the relative increase in areal rainfall across the Niger Delta between 2012 and 2022, based on the percentage changes reported by Tosin-Orimolade et al. (2026). The sharp 2012–2017 increase coincides with the run-up to the catastrophic 2012 flood event, while the continued (albeit slower) increase

through 2022 coincides with the second major flood disaster of the decade, consistent with a compounding relationship between rainfall intensification and downstream/coastal inundation severity.

Figure 4. Relative Increase in Regional Rainfall Across the Niger Delta, 2012–2022



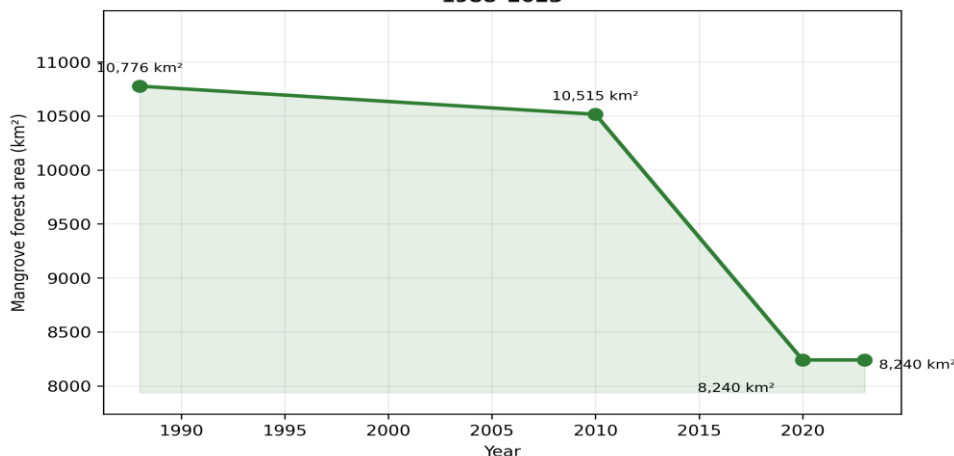
Note. Index constructed from the percentage increases in areal rainfall reported by Tosin-Orimolade et al. (2026): +53.1% (2012–2017) and +11.5% (2017–2022); absolute mm values were not re-derived.

Figure 4. Relative increase in regional rainfall across the Niger Delta, 2012–2022 (index, 2012 = 100). Constructed from percentage changes reported in Tosin-Orimolade et al. (2026).

Loss of Natural Coastal Buffering

Figure 5 shows the decline in Niger Delta mangrove extent since 1988. The accelerated loss after 2010 — coincident with expanding oil-and-gas infrastructure and dredging activity — represents a parallel and reinforcing driver of compound flood risk, since mangrove loss both increases wave and surge penetration inland and is frequently co-located with the same oil-extraction activity responsible for the region's most severe subsidence.

Figure 5. Decline in Niger Delta Mangrove Forest Extent, 1988–2023



Note. 2010 and 2020 values (10,515 km² and 8,240 km²) reported in Mongabay (2025), citing a 2023 mangrove-extent study; 1988 baseline back-calculated from the reported ~2,536 km² net loss over 1988–2023 (EBSCO Research Starters, n.d.). The 2023 value is held at the 2020 level pending finer-resolution data.

Figure 5. Decline in Niger Delta mangrove forest extent, 1988–2023. 2010 and 2020 values from Mongabay (2025); 1988 baseline back-calculated from the reported 1988–2023 net loss (Niger River, n.d.).

Compound Flood Driver Matrix

Table 2 synthesises the physical drivers reviewed above into a compound-flood driver matrix appropriate to the Niger Delta, following the driver taxonomy of Green et al. (2025) and Couasnon et al. (2020).

Table 2 Compound Flood Driver Matrix for the Niger Delta

Driver class	Physical process	Niger Delta manifestation	Key evidence
Fluvial	River discharge from Niger–Benue system, modulated by reservoir operation	Delayed downstream flood peaks at Obiafu following Kainji/Jebba/Lagdo releases	Eteh et al. (2024)
Pluvial	Direct rainfall and local surface runoff	53.1% rainfall increase 2012–2017; 11.5% further increase 2017–2022	Tosin-Orimolade et al. (2026)
Coastal – tidal/surge	Astronomical tide and wind/pressure-driven storm surge	Tidal backwater into distributaries during peak river discharge; king tides reaching further inland	Musa et al. (2014); President Tinubu Reaffirms Commitment (2026)
Relative sea-level rise	Eustatic rise + land subsidence	RSLR of ~0.14–0.96 m by 2030–2050 near oil-field infrastructure	Musa et al. (2016); Ghoms et al. (2024)
Buffer loss	Mangrove/wetland degradation reducing wave and surge attenuation	~22% mangrove loss 2010–2020; ~2,536 km ² net loss 1988–2023	Ogoni women restore mangroves (2025); Niger River (n.d.)

Note. Compound events arise where two or more of these driver classes coincide temporally (e.g., peak rainfall during high tide) or spatially (e.g., subsidence hotspots within the coastal-surge zone).

Engineering and Nature-Based Adaptation

Coastal engineering practice increasingly frames adaptation along a grey (engineered), green (nature-based), and hybrid continuum, with growing evidence that hybrid approaches offer the most cost-effective long-term risk reduction in low-income, rapidly urbanising deltaic settings (Tiggeloven et al., 2026). This section evaluates adaptation options for the Niger Delta against that continuum.

Grey (Engineered) Infrastructure

Conventional grey infrastructure — dikes, seawalls, revetments, tidal barriers, and elevated causeways — provides high, predictable protection levels but at substantial capital and maintenance cost, and can create a false sense of security that encourages further development in exposed areas (An engineer's guide to the future of flood defense, n.d.). For the Niger Delta's distributary geometry, ring-dike protection of priority settlements (Port Harcourt, Warri, Yenagoa, Bonny) combined with tidal/surge gates at key distributary mouths represents the most direct analogue to established deltaic flood-defence practice elsewhere (e.g., the Netherlands' Delta Works). However, because much of the delta's subsidence is itself driven by continued hydrocarbon extraction, grey infrastructure alone cannot address the underlying cause of relative sea-level rise and would require periodic re-elevation as subsidence continues (Niger Delta land cover map, n.d.). Modern grey-infrastructure practice increasingly embeds sensors and automated control (SCADA) systems into barriers and floodgates, enabling dynamic operation of pumps and sluices during storm events and generating performance data that can refine future design (An engineer's guide to the future of flood defense,

n.d.). Given the Niger Delta's data-sparse hydrometric network, instrumented flood-defence infrastructure would additionally serve a valuable environmental-monitoring function.

Nature-Based and Hybrid Solutions

Mangrove restoration, particularly when combined with a foreshore dike ('hybrid') configuration, is among the most extensively evidenced nature-based coastal defences globally. A recent global assessment found that mangrove restoration fronting engineered dikes substantially reduces expected annual flood damage relative to dikes alone, with benefits disproportionately accruing to low-income coastal communities — a finding of direct relevance to the Niger Delta, where flood-exposed populations are frequently among the region's poorest (Tiggeloven et al., 2026). Mangroves attenuate wave energy and reduce dike overtopping, potentially allowing lower and less costly engineered defences than a grey-infrastructure-only approach, while simultaneously restoring fisheries habitat and carbon storage co-benefits (Engineering With Nature, n.d.). Successful mangrove-based adaptation, however, requires accommodation space for landward migration as sea levels rise; rigid dikes placed too close to the shoreline can themselves undermine long-term mangrove persistence even while temporarily protecting them from wave stress (Frontiers, 2021, as cited in Section 3.4). This implies that hybrid designs for the Niger Delta should incorporate deliberate setback distances and adaptive management review points rather than fixed, one-time infrastructure specifications. Community-based mangrove restoration is already underway in parts of the delta — for example, women-led replanting initiatives in Ogoniland — offering an institutional entry point for scaling hybrid designs (Ogoni women restore mangroves, 2025).

Local and Institutional Adaptation Practices

Field assessment of existing community coping practices in the lower Niger Delta identified a mix of sustainable and unsustainable local responses to flooding, erosion, and inundation: constructive practices include the digging of runoff-retention pits, planting of bamboo and banana stands to control erosion, and raising of building floor levels or sandbagging ahead of the flood season; less sustainable practices include the dumping of refuse in eroded gullies and construction of hand-dug wells or boreholes in already-contaminated areas (Musa et al., 2016). A formal engineering-adaptation strategy for the delta should therefore build on, rather than displace, the constructive elements of existing local practice, while addressing the drivers of the unsustainable practices (principally inadequate solid-waste management and safe water access) through parallel investment.

Early Warning and Governance

Because compound flood severity in the Niger Delta depends on the coincidence of independently forecastable drivers — rainfall, dam release schedules, and tidal/surge conditions — a coordinated early-warning system integrating meteorological forecasts, upstream reservoir-release notifications, and tide/surge predictions offers a comparatively low-cost, high-leverage adaptation option. Existing evidence points to a specific institutional gap here: Eteh et al. (2024) found a measurable delay between upstream dam releases and downstream flood peaks at Obiafu, implying that coordinated release scheduling and advance downstream warning could materially reduce compound flood severity even without new physical infrastructure. Regional coordination between Nigerian authorities and Cameroon's Lagdo Dam operators — repeatedly identified as a contributing factor in the 2012, 2018, and 2022 floods — is a particular governance priority (2022 Nigeria floods, n.d.).

Adaptation Option Matrix

Table 3 Engineering and Nature-Based Adaptation Options for the Niger Delta

Category	Option	Primary function	Niger Delta consideration
Grey	Ring dikes / seawalls	Direct water-level	High cost; requires periodic re-

	around settlements	priority exclusion	elevation as subsidence continues
Grey	Tidal/storm-surge gates at distributary mouths	Regulate tidal and surge ingress	Complex distributary geometry increases design and maintenance cost
Grey (smart)	Sensor-linked (SCADA) flood-defence infrastructure	Dynamic, monitored operation of pumps/sluices	Adds environmental-monitoring value in a data-sparse basin
Green	Mangrove restoration	Wave/surge attenuation; habitat and carbon co-benefits	Requires landward setback space; aligns with existing community restoration efforts
Hybrid	Mangrove-fronted dikes	Reduced dike design requirements; long-term cost efficiency	Evidence indicates disproportionate benefit to low-income coastal communities
Soft / institutional	Coordinated dam-release early warning	Reduce compound coincidence of rainfall + dam release + high tide	Requires Nigeria–Cameroon coordination on Lagdo Dam operations
Soft / community	Runoff-retention pits; erosion-control planting; elevated floors	Localised risk reduction using existing practice	Build on documented constructive local practices; address unsustainable practices via parallel investment

Note. Categories follow the grey–green–hybrid–soft adaptation continuum discussed in Tiggeloven et al. (2026) and An engineer's guide to the future of flood defense (n.d.).

DISCUSSION

The evidence synthesised in Sections 3 and 5 supports three integrated conclusions. First, the Niger Delta's flood risk cannot be fully characterised, nor cost-effectively managed, through single-driver assessment. Fluvial flood-susceptibility mapping (Hazzan et al., 2026), sea-level-rise vulnerability indices (Musa et al., 2014), and dam-driven SAR flood monitoring (Eteh et al., 2024) each capture part of the picture, but the underlying physical processes — rainfall, discharge, tide, surge, and subsidence — interact, particularly in the mid-delta transition zone around Yenagoa and Warri. This reinforces the case, made in Section 4, for an integrated hydro-climatic modelling framework rather than continued reliance on single-hazard studies.

Second, land subsidence associated with hydrocarbon extraction is, at present, the single largest controllable driver of relative sea-level rise in the delta's most exposed communities — an order of magnitude larger than the eustatic climate-change signal at active well fields (25–125 mm/yr subsidence versus ~3.9–4.5 mm/yr eustatic rise; Musa et al., 2016; Ghomsi et al., 2024). This has an important, if politically difficult, implication: near-term reduction of relative sea-level rise in the most affected settlements depends as much on the regulation of groundwater and hydrocarbon withdrawal practices as on global greenhouse-gas mitigation, even though the latter remains essential for the region's longer-term (post-2050) risk trajectory.

Third, the paper's engineering-adaptation review indicates that grey infrastructure alone is unlikely to be either affordable or durable at delta-wide scale, given continuing subsidence and the sheer length of exposed distributary shoreline. The strongest available evidence favours hybrid, mangrove-fronted designs at priority sites, combined with coordinated early-warning governance addressing the specific, evidenced gap in upstream dam-release coordination (Tiggeloven et al., 2026; Eteh et al., 2024).

LIMITATIONS

This paper is a literature synthesis and conceptual modelling framework rather than a report of newly executed, site-calibrated numerical simulation. The figures presented in Section 5 reconstruct and interpolate published summary statistics (e.g., reported percentage rainfall changes, reported sea-level-rise endpoints) for illustrative purposes and should not be read as independently derived model output; readers requiring calibrated, grid-resolved flood hazard maps should consult primary hydrodynamic modelling studies once these are conducted for the specific reaches and settlements of interest. Several quantities used in this synthesis — the 1988 mangrove-extent baseline in Figure 5, and the intermediate years in the sea-level projection envelope in Figure 2 — were back-calculated or interpolated from reported endpoints in the absence of finer-resolution published data, as noted in each figure's caption. In addition, much of the underlying evidence base itself derives from remote-sensing and statistical (frequency-ratio, GIS-index) studies rather than fully coupled physical simulations, reflecting genuine, still-unresolved data constraints in the region rather than a limitation specific to this synthesis.

Priorities for Future Research

Four research priorities follow directly from the gaps identified above: (a) deployment of InSAR-based subsidence monitoring across the full distribution of onshore oil-field infrastructure, to replace the currently sparse point-based subsidence estimates with a spatially continuous dataset; (b) development and calibration of a coupled rainfall-runoff/river-routing/storm-surge model for at least one priority reach (the Bonny–Port Harcourt corridor is the strongest candidate given its population density and existing SAR flood-monitoring baseline); (c) formal statistical dependence analysis, following Couasnon et al. (2020), between Niger–Benue discharge extremes and Gulf of Guinea storm-surge/high-tide extremes, to quantify compound-event return periods specific to the delta; and (d) life-cycle cost-benefit analysis comparing grey, green, and hybrid adaptation portfolios under the RSLR scenarios presented in Figure 3, following the assessment methodology of Tiggeoven et al. (2026).

CONCLUSION

Compound coastal flooding — the interaction of intensifying rainfall, dam-regulated river discharge, tidal and storm-surge dynamics, and an accelerating relative sea-level rise driven jointly by climate change and hydrocarbon-extraction-induced subsidence — represents the central, and still under-modelled, flood-risk challenge facing the Niger Delta. The evidence reviewed in this paper indicates that no single driver adequately explains the region's flood history; the catastrophic 2012 and 2022 events, in particular, reflect the coincidence of extreme rainfall, upstream dam release, and elevated coastal water levels. A regionally appropriate hydro-climatic modelling framework, coupling rainfall–runoff, river-routing, and coastal hydrodynamic components with a statistical compound-dependence layer, would substantially improve the delta's flood-risk evidence base relative to the current fragmented, single-hazard literature. On the adaptation side, the evidence favours a hybrid, mangrove-fronted engineering approach at priority settlements, integrated with coordinated trans-boundary early-warning governance and continued support for constructive community-level adaptation practices, rather than reliance on grey infrastructure alone. Given that localised land subsidence currently exceeds the global climate-change sea-level signal by an order of magnitude in the delta's most exposed communities, regulation of subsidence-inducing extraction practices should be treated as a first-order, near-term adaptation priority alongside — not subordinate to — longer-term climate mitigation.

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