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Sea Surface Temperature Variability and Its Influence on Mangroves, Wetlands, and the Green Plant Environment of Coastal Communities of Rivers State, Nigeria

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Abstract

Coastal ecosystems in the Niger Delta are among the most environmentally sensitive and economically important landscapes in West Africa, yet the influence of sea surface temperature (SST) variability on mangrove, wetland, and vegetation systems remains insufficiently documented at the sub-national scale. This study investigates the influence of SST variability on mangroves, wetlands, and vegetation conditions in selected coastal communities of Rivers State, Nigeria, over a thirty-year period (1995–2025). A quantitative geospatial and time-series framework was adopted, integrating satellite-derived SST with vegetation and wetland indicators. SST was analysed from NOAA CDR OISST v2.1 for 1995–2025, while NDVI and NDMI were derived from MODIS products for 2000–2025. The analysis covered Andoni, Bonny, Degema, Okrika, and Opobo/Nkoro local government areas. The study identifies spatial and temporal differences in SST and vegetation conditions and examines their relationships over the common 2000–2025 period. The 2025 MNDWI assessment indicates strong spatial differentiation between water-dominated wetland surfaces and terrestrial or vegetated surfaces. The findings indicate that continued coastal warming, together with anthropogenic pressures, has important implications for mangrove and wetland condition, shoreline stabilisation, flood attenuation, fisheries and carbon sequestration. The study provides an integrated satellite-based framework for monitoring coastal environmental change in Rivers State.

1 Introduction

Sea surface temperature (SST) is one of the most sensitive indicators of global climate change, reflecting the ocean's capacity to absorb and redistribute excess heat generated by greenhouse gas accumulation (IPCC, 2021). As the mean temperature of the upper ocean, SST regulates evaporation rates, precipitation patterns, ocean currents, and the physiological functioning of marine and coastal organisms. Its influence extends beyond open water, shaping estuarine and intertidal ecosystems, including mangrove forests, wetlands, and coastal vegetation.

Mangroves and wetlands occupy a unique position in coastal environments because they are simultaneously highly productive ecological systems and critical buffers against coastal hazards. They stabilise shorelines, attenuate storm surges, provide nursery habitat for fisheries, and sequester substantial quantities of blue carbon in their soils (Alongi, 2008; Rogers et al., 2019). Because these ecosystems occupy the interface between ocean and land, they are exposed to changes in temperature, salinity, tidal inundation, sediment supply and hydrological conditions.

In Nigeria, Rivers State forms part of the Niger Delta, which contains extensive mangrove and wetland environments. The low-lying coastal local government areas of Bonny, Degema, Akuku-Toru, Okrika and Andoni depend heavily on mangrove and wetland ecosystem services for fisheries, shoreline protection and household livelihoods. These ecosystems are already under pressure from oil and gas exploration, dredging and land-use change (UNEP, 2016; Nwankwoala, 2021), while the additional contribution of long-term SST variability requires further spatially explicit assessment.

The relationship between ocean warming and coastal ecosystem condition is well established. Belkin (2009) documented warming across large marine ecosystems, including the Gulf of Guinea, while Alongi (2008) established the importance of temperature, salinity and hydrological inputs in regulating mangrove distribution and productivity. Ellison (2015) highlighted ecological thresholds associated with mangrove vulnerability to sea-level rise, and Rogers et al. (2019) demonstrated the importance of mangroves for blue-carbon storage. These studies provide a basis for investigating long-term thermal variability together with vegetation and wetland indicators at local scales.

This study addresses the need for an integrated spatial and temporal assessment of SST and coastal ecosystem indicators in Rivers State. It uses a thirty-year SST record (1995–2025) and a common 2000–2025 vegetation-analysis period to examine SST variability, vegetation greenness, vegetation moisture and wetland patterns across five coastal local government areas.

1.1 Research objectives

1. To quantify SST variability and long-term trends across selected coastal local government areas of Rivers State from 1995 to 2025.

2. To quantify vegetation greenness and moisture dynamics using NDVI and NDMI from 2000 to 2025.

3. To examine the temporal relationship between SST variability and vegetation conditions during the common 2000–2025 period.

4. To assess the spatial implications of SST variability for mangrove and wetland environments in coastal Rivers State.

1.2 Conceptual framework

The study is informed by the vulnerability-resilience perspective, in which ecological systems are exposed to environmental stress, exhibit varying sensitivities, and possess different capacities to absorb and respond to disturbance (Turner et al., 2003; Adger, 2006; Folke, 2006). In the present context, SST variability represents an environmental exposure, while vegetation and wetland indicators provide observable measures of ecosystem condition. Anthropogenic pressures such as dredging, oil and gas activity and land-use change are treated as potential compounding pressures rather than as effects attributable solely to SST.

2 Materials and Methods

2.1 Study area

The study was conducted in selected coastal local government areas of Rivers State in the Niger Delta region of southern Nigeria. The selected local government areas were Andoni, Bonny, Degema, Okrika and Opobo/Nkoro.

The study area contains a complex network of rivers, creeks, tidal channels, estuaries, wetlands and coastal landforms. The environmental setting is characterised by low-lying terrain and strong interaction between marine and terrestrial processes. The selected LGAs represent coastal environments exposed to oceanographic and climate-related environmental changes.

2.2 Research design

The study adopted a quantitative geospatial and time-series research design based primarily on satellite-derived environmental datasets. The methodology combines remote sensing, geographic information systems (GIS), zonal statistics, time-series analysis and correlation analysis. Three principal environmental variables were considered: SST as the ocean thermal variable, NDVI as an indicator of vegetation greenness and vigour, and NDMI as an indicator of vegetation moisture condition.

2.3 Data sources

Dataset	Variable	Period	Spatial/temporal characteristics	Application
NOAA CDR OISST v2.1	SST	1995–2025	Coarse spatial resolution; daily observations	SST variability and trend analysis
MODIS Terra MOD13Q1 v6.1	NDVI	2000–2025	250 m; 16-day product	Vegetation greenness
MODIS Terra MOD09A1 v6.1	NDMI	2000–2025	500 m; 8-day composite	Vegetation moisture
FAO GAUL 2015 Level-2	Administrative boundaries	—	LGA boundaries	Study-area delineation

Table 1 Datasets used in the study.

2.4 Sea surface temperature data processing

SST data were obtained from the NOAA Climate Data Record Optimum Interpolation Sea Surface Temperature Version 2.1 (NOAA CDR OISST v2.1), available in Google Earth Engine as NOAA/CDR/OISST/V2_1. The dataset was used to construct annual SST observations for 1995–2025.

For each year, available SST observations were filtered and aggregated to generate an annual composite. The annual median was used as the representative annual SST value to reduce the influence of short-

term extremes and anomalous individual observations. SST values were converted to degrees Celsius using the dataset scale factor.

Annual SST values were extracted for each selected LGA using zonal statistics. For each LGA and year, the annual SST composite was spatially summarised within the corresponding administrative polygon using the mean SST. The resulting SST dataset contained 5 LGAs × 31 years = 155 observations.

2.5 Treatment of Okrika coarse SST coverage

A spatial coverage problem was encountered for Okrika because the native spatial resolution of OISST is coarse relative to the size and geometry of the Okrika coastal administrative area. Direct extraction at the original LGA boundary produced no valid SST pixels. Diagnostic testing was therefore performed using progressively larger buffers.

Buffer distance	2025 SST
0 km	No value
1 km	No value
5 km	No value
10 km	28.2591 °C
15 km	28.2565 °C
20 km	28.2528 °C
30 km	28.2525 °C

Table 2 Sensitivity of Okrika SST extraction to buffer distance.

Because the SST estimate became available at 10 km and remained relatively stable as the buffer increased, a 10-km buffer was adopted for Okrika SST extraction. The buffer does not increase the spatial resolution of OISST; it provides an adequate spatial sampling area for extracting a representative value from the coarse-resolution product.

2.6 NDVI processing

Vegetation greenness was assessed using the MODIS Terra MOD13Q1 Version 6.1 product (MODIS/061/MOD13Q1). The product provides NDVI at 250-m spatial resolution at a 16-day temporal interval and includes quality-assurance information.

• The image collection was filtered to the study area and grouped by calendar year.

• The DetailedQA band was used to identify acceptable-quality vegetation observations.

• Pixels with MODLAND quality values of 0 or 1 were retained.

• The NDVI band was converted using the MODIS scale factor of 0.0001.

• A median annual composite was produced.

• The annual composite was spatially summarised over each selected LGA using zonal statistics.

• The resulting annual mean NDVI was recorded for each LGA.

The resulting NDVI dataset contained 5 LGAs × 26 years = 130 observations.

2.7 NDMI processing

Vegetation moisture conditions were assessed using the MODIS Terra MOD09A1 Version 6.1 surface-reflectance product (MODIS/061/MOD09A1). MOD09A1 provides atmospherically corrected surface reflectance at 500-m spatial resolution using eight-day composites and contains the NIR and SWIR bands required for NDMI calculation.

NDMI was calculated as: NDMI = (NIR − SWIR) / (NIR + SWIR). Both bands were converted using the MODIS reflectance scale factor of 0.0001. Annual NDMI composites were generated using the median of valid observations for each year from 2000 to 2025, followed by zonal mean statistics for each LGA. Values outside the physically meaningful interval of −1 to +1 were treated as invalid. The resulting NDMI dataset contained 5 LGAs × 26 years = 130 observations.

2.8 MNDWI and wetland mapping

MNDWI and wetland mapping: the supplied manuscript reports a 2025 MNDWI assessment with approximately 0.64 for water-dominated wetland surfaces and approximately −0.91 for terrestrial/vegetated surfaces. The supplied source package does not document the sensor/product, band specification, cloud masking, compositing, threshold, or validation steps sufficiently to reproduce the MNDWI map; these details have therefore not been invented.

The current manuscript reports a 2025 MNDWI assessment in which water-dominated wetland surfaces have values of approximately 0.64 and terrestrial or vegetated surfaces approximately −0.91. These results are retained in Section 3, but the processing details must be supplied from the actual analysis before submission.

2.9 Temporal harmonisation

Because the SST record begins in 1995 while the MODIS vegetation records begin in 2000, two temporal analysis periods were established. Period 1 (1995–2025) was used for long-term SST variability and trend analysis. Period 2 (2000–2025) was used for integrated SST–NDVI–NDMI analysis because it represents the common temporal period of the datasets.

2.10 Statistical analysis

Statistical analysis: SST trend significance is represented in the supplied SST trend figure using the Hamed–Rao modified Mann–Kendall test at $p < 0.05$, with Sen's slope used to quantify the direction and rate of change. The numerical Sen's slope values reported in Table 3 are retained from the verified project analysis. Complete test statistics and software details are not reproduced where they are not documented in the supplied manuscript.

The final statistical section should report the exact test statistic, p-value, effect/trend estimate and significance criterion for every inferential result presented in the Results.

3 Results

Reported class/area	MNDWI value or location	Source-reported interpretation
Water-dominated wetland surfaces	≈ 0.64	High positive MNDWI signature
Terrestrial/vegetated surfaces	≈ −0.91	Low negative MNDWI signature
Reported coastal concentrations	Bonny, Degema, Okrika, Andoni	Extensive wetland/mangrove-associated environments

Table 3. MNDWI evidence reported in the supplied manuscript.

3.1 Spatial distribution of wetlands and mangroves

The 2025 MNDWI map of Rivers State reveals spatial differentiation between water-dominated wetlands (MNDWI ≈ 0.64) and terrestrial or vegetated surfaces (MNDWI ≈ −0.91). Coastal local government areas including Bonny, Degema, Akuku-Toru, Okrika and Andoni are characterised by higher MNDWI signatures, indicating extensive wetland and mangrove-associated environments, whereas inland areas such as Ikwerre, Etche and Emohua show lower MNDWI values.

3.2 SST variability and spatial patterns

The manuscript reports a defined thermal gradient in the 1995 SST baseline, with the western estuarine axis around Degema–Akuku-Toru acting as a relatively cooler zone, while the central corridor around Port Harcourt, Obio/Akpor and Eleme exhibited higher thermal values. By 2020–2025, higher-temperature zones were reported across parts of the central and eastern coastal belt, including Okrika, Ogu/Bolo, Gokana, Khana, Opobo/Nkoro and Andoni.

LGA	Sen's slope (°C/year)	Trend direction	Significance
Andoni	0.027863	Increasing	$p < 0.05$
Bonny	0.027493	Increasing	$p < 0.05$
Degema	0.025845	Increasing	$p < 0.05$
Okrika	0.027287	Increasing	$p < 0.05$
Opobo/Nkoro	0.028303	Increasing	$p < 0.05$

Table 4. Hamed–Rao modified Mann–Kendall/Sen trend summary for SST, 1995–2025.

Note: The supplied SST trend map reports Hamed–Rao modified Mann–Kendall significance at $p < 0.05$.

3.3 NDVI dynamics

The manuscript reports vegetation decline in parts of the eastern coastal corridor, including Khana, Gokana, Oyigbo and Opobo/Nkoro, with reported NDVI changes ranging from −1.06 to −0.21 in the relevant change-map analysis.

LGA	Mean NDVI (reported)
Opobo/Nkoro	≈ 0.195
Andoni	≈ 0.180
Bonny	≈ 0.171
Degema	≈ 0.164
Okrika	≈ 0.158

Table 5. Reported mean NDVI by selected coastal LGA, 2000–2025.

3.4 NDMI dynamics

NDMI was used to represent vegetation moisture condition during 2000–2025. The manuscript establishes the data-processing procedure and the 130-observation dataset but does not provide the numerical NDMI trend results in the current Results section.

3.5 SST–vegetation relationships

The integrated analysis was designed to examine the relationship between SST variability and vegetation condition over the common 2000–2025 period. The current manuscript does not provide a complete numerical table of the SST–NDVI and SST–NDMI coefficients for all five LGAs.

Relationship	LGA	Coefficient	p-value	n	Evidence
SST–NDVI	Andoni	r = 0.0773	p = 0.7075	26	Coefficient and p-value previously verified in project analysis
SST–NDMI	Bonny	r = −0.2652	p = 0.1904	26	Coefficient and p-value previously verified in project analysis
SST–NDVI	Degema	r = -0.2867	p = 0.2502	26	Coefficient and p-value previously verified in project analysis
SST–NDMI	Okrika	r = -0.2890	p = 0.2624	26	Coefficient and p-value previously verified in project analysis

Table 6. Correlation-analysis reporting status for the common 2000–2025 period.

3.6 Integrated SST, vegetation and wetland patterns

The manuscript reports that the southern coastal fringe, including Bonny, Andoni and Okrika, together with the western Degema–Akuku-Toru axis, retains extensive wetland and mangrove cover, while transitional areas around Obio/Akpor, Eleme and Oyigbo show wetland fragmentation. Field observations and key-informant accounts reported in the original manuscript describe mangrove dieback and increased dry-season salinity intrusion in some locations.

Integrated spatial assessment: the supplied source package does not contain a separate embedded integrated SST–vegetation–wetland map. The interpretation is therefore retained in text and supported by Figs. 1–6.

4 Discussion

4.1 Long-term SST variability and coastal environmental change

The observed spatial and temporal SST patterns indicate substantial variability across the coastal study area. The interpretation should be based on the verified trend statistics and should distinguish measured SST trends from broader climate mechanisms.

4.2 SST and mangrove/wetland condition

The study framework suggests several pathways through which ocean thermal variability may interact with coastal ecosystems, including effects on evaporation, salinity, sea-level-related inundation and sediment dynamics. However, observed spatial correspondence should be interpreted as association unless the statistical design demonstrates causality.

4.3 SST and vegetation response

NDVI and NDMI provide complementary indicators of vegetation greenness and moisture condition. Differences among LGAs may reflect the interaction of oceanographic exposure with freshwater influence, hydrological connectivity, land-use change and other anthropogenic pressures.

4.4 Spatial heterogeneity among coastal LGAs

The retention of extensive wetland and mangrove cover in several coastal LGAs alongside reported fragmentation in transitional areas indicates that ecosystem response is spatially heterogeneous. This supports the vulnerability-resilience perspective used in the study.

4.5 Implications for environmental monitoring

The combined use of SST, NDVI, NDMI and MNDWI provides a practical remote-sensing framework for tracking coastal environmental change. Repeated monitoring can help identify areas where thermal variability coincides with vegetation stress or wetland change.

4.6 Study limitations

The principal limitations include the coarse spatial resolution of the OISST product, the need for a 10-km sampling buffer for Okrika, the indirect nature of satellite indicators of ecosystem condition, and the influence of confounding factors such as dredging, oil and gas activities, land-use change, sediment supply and hydrological modification. Correlation or spatial correspondence alone should not be interpreted as proof of direct SST causation.

5 Conclusions

This study investigated SST variability and its relationship with mangrove, wetland and vegetation conditions across five coastal local government areas of Rivers State, Nigeria. The analysis used a 1995–2025 SST record and a common 2000–2025 vegetation period. The results indicate pronounced spatial differentiation in coastal environmental conditions and provide evidence that SST variability occurs alongside changes in vegetation and wetland indicators. The findings support continued integrated satellite-based monitoring of coastal ecosystems in Rivers State.

6 Environmental Management Implications

• Establish routine SST-linked monitoring of mangrove and wetland condition using MNDWI and complementary vegetation indicators.

• Support community-based mangrove restoration and protection in areas where field observations confirm dieback or degradation.

• Strengthen monitoring and regulation of dredging and canal-cutting activities that may alter sediment supply and tidal hydrology.

• Integrate mangrove and wetland condition indicators into coastal climate adaptation and disaster-risk-management planning.

Declarations

Competing Interests

The authors declare that they have no competing interests.

Author Contributions

Chijioke Christian Agu and Dr. Mohammad J Yusuf: Conceptualization, methodology, data curation, formal analysis, investigation, visualization, writing—original draft, and writing—review and editing. Prof. Tanko Ogah: Supervision, conceptualization, methodology, validation, and writing—review and editing. Dr. Mohammad Alkali: Supervision, methodology, validation, and writing—review and editing.

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Figures

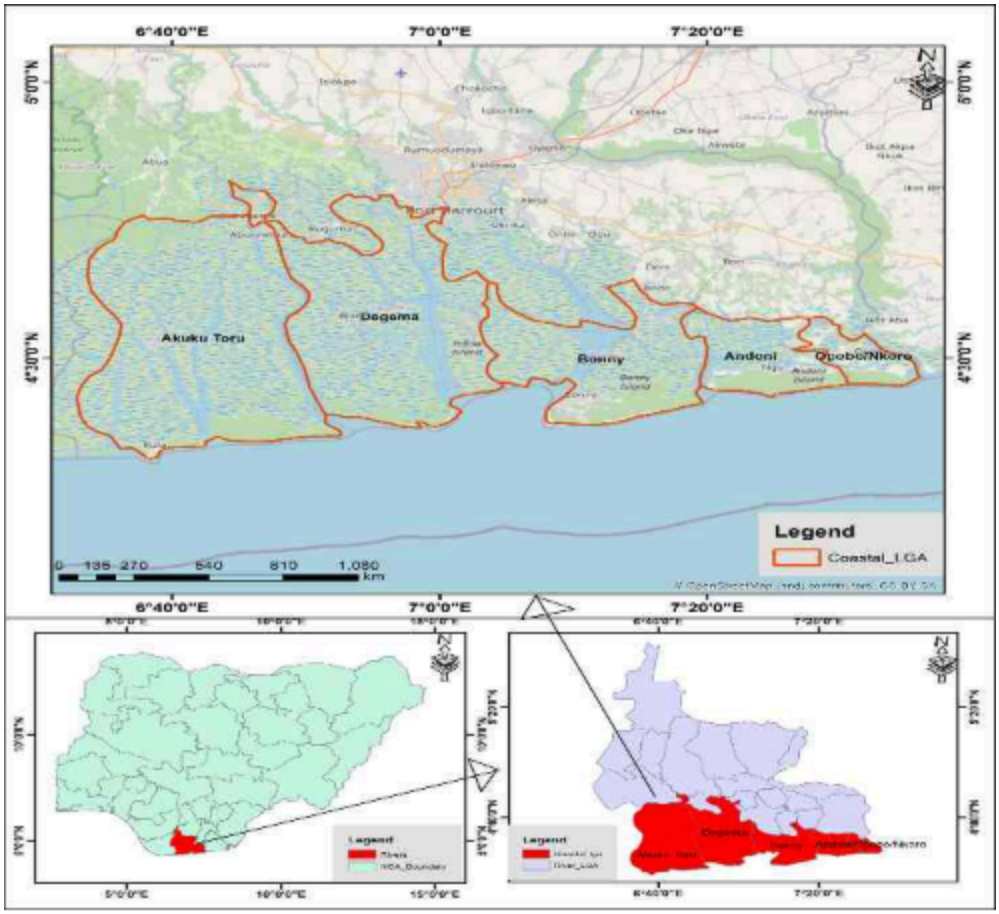

Figure 1

Location of the study area showing the selected coastal local government areas of Rivers State, Nigeria.

Source: Supplied project GIS analysis.

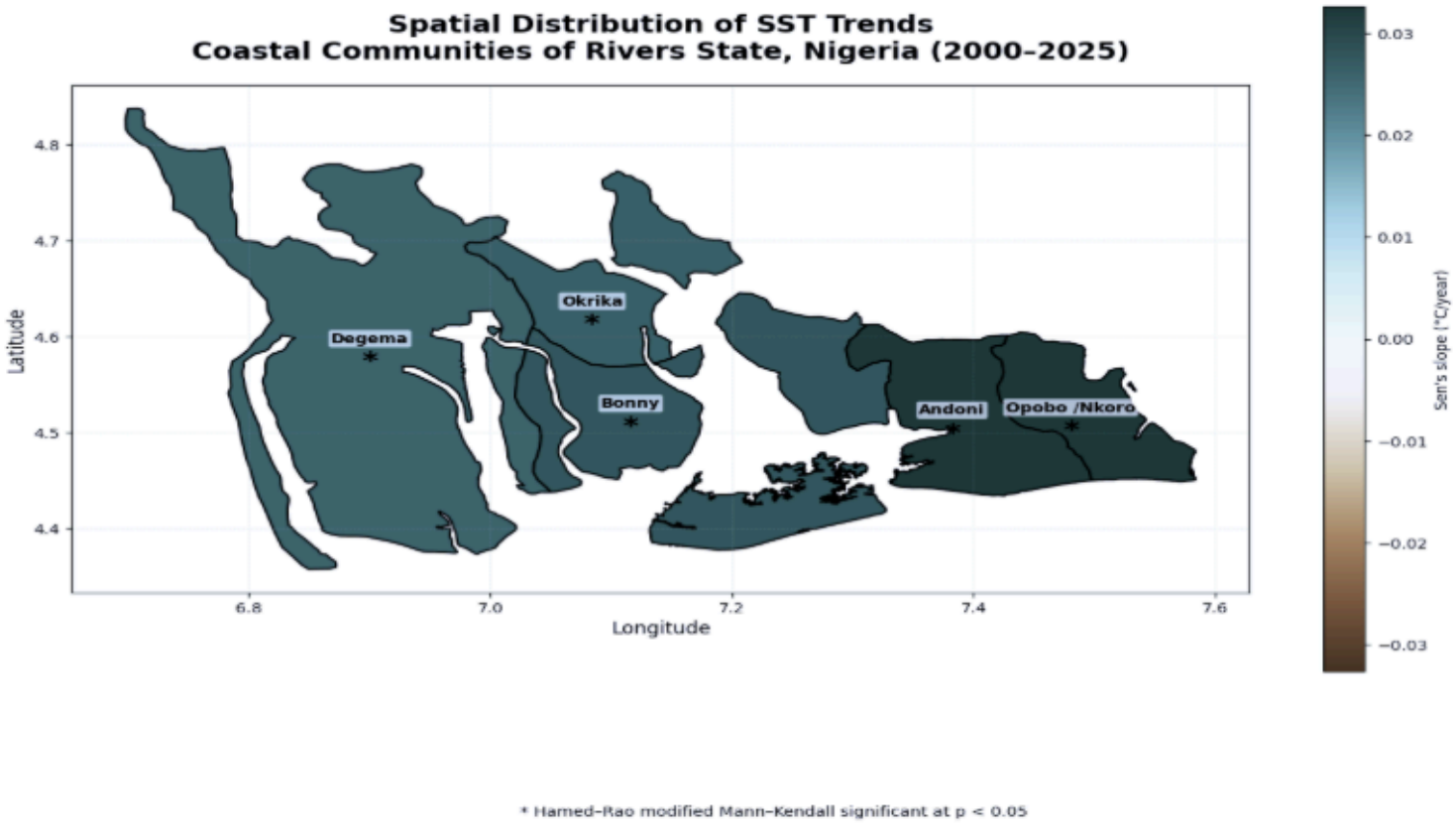

Figure 2

Spatial distribution of SST trends across the five selected coastal local government areas of Rivers State, Nigeria (2000–2025).

Source: Supplied project SST trend analysis.

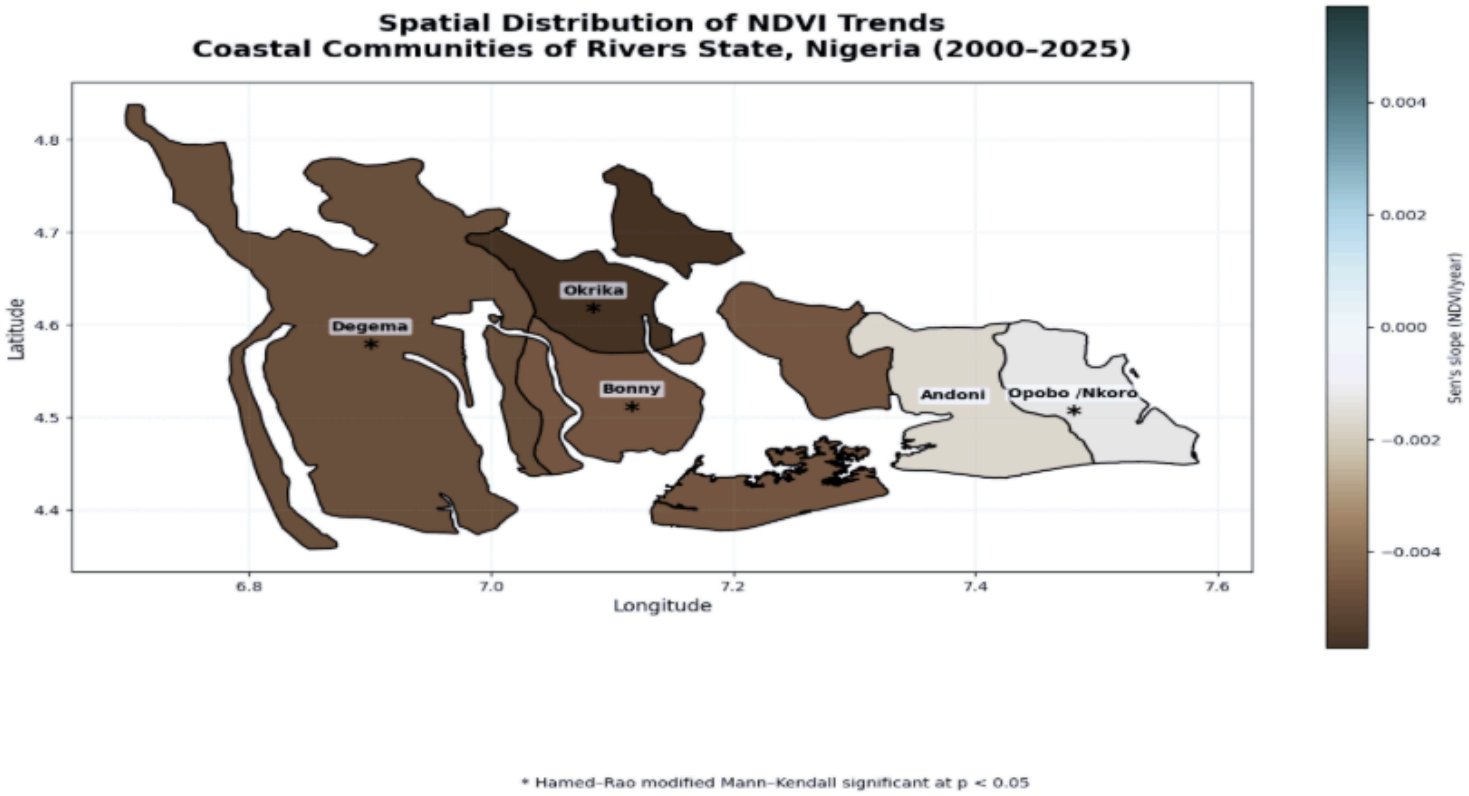

Figure 3

Annual NDVI trends for the five selected coastal local government areas, 2000–2025.

Source: Supplied project NDVI trend analysis.

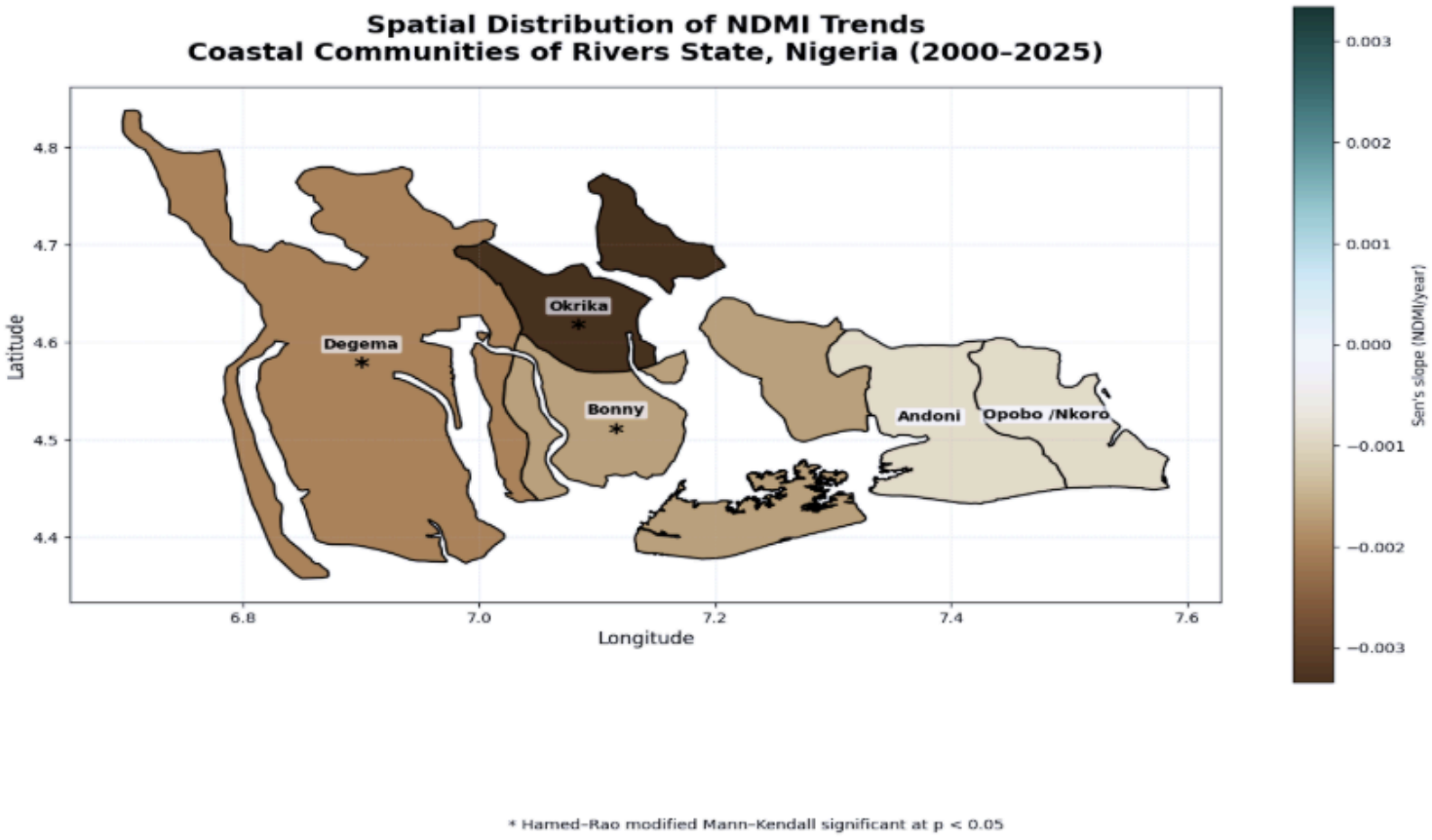

Figure 4

Fig. 5 Annual NDMI trends for the five selected coastal local government areas, 2000–2025.

Source: Supplied project NDMI trend analysis.

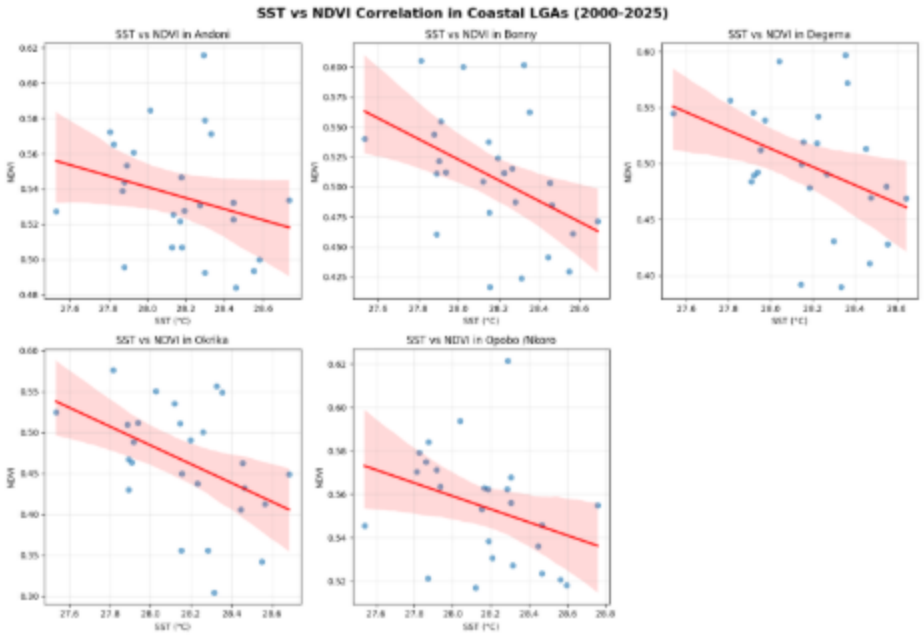

Figure 5

SST–NDVI relationships for the selected coastal LGAs.

Source: Supplied project SST–NDVI correlation analysis.

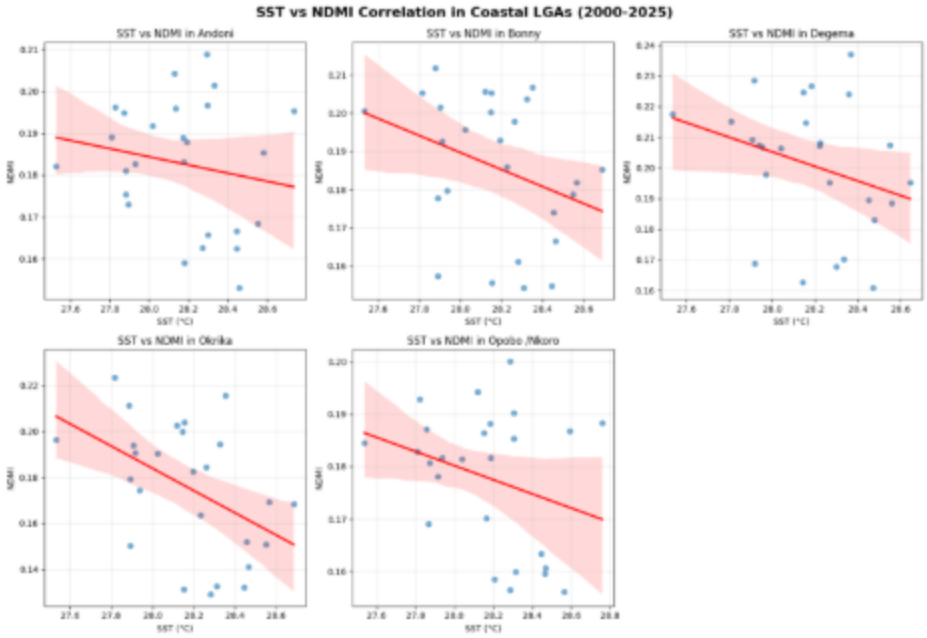

Figure 6

SST–NDMI relationships for the selected coastal LGAs.

Source: Supplied project SST–NDMI correlation analysis.