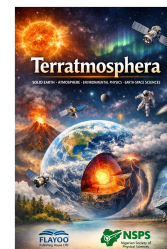


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Spatial variability in nearshore hydrodynamic regimes, morphodynamic zonation, and sediment transport along the southwestern Nigerian barrier–lagoon coastal system

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ABSTRACT

This study examines spatial variability in nearshore hydrodynamics and its implications for sediment transport and coastal evolution along the southwestern Nigerian barrier–lagoon coast. Field measurements (Seme, Yovoyan, Lekki, Okun-Ajah, and Orimedu) reveal pronounced alongshore heterogeneity in wave characteristics, breaker type distribution, and longshore currents. Plunging breakers dominate Seme (60–90%) and Orimedu (70–90%), indicating reflective to intermediate conditions, while Lekki is characterized by spilling breakers (80–90%), consistent with a dissipative morphodynamic state. Okun-Ajah exhibits the highest wave energy (1.3–1.5 m) and steep incidence angles (30–45°), marking it as the most dynamically active and erosion-prone sector. Breaker interval (0.16–0.80 s) and wave inclination (10–45°) show strong spatial variability, reflecting differences in nearshore wave transformation processes. Longshore current velocities (0.17–0.66 m s⁻¹) increase with wave obliquity, confirming wave direction as a key control on alongshore sediment transport. Statistical analyses reveal non-normal distributions and significant zonal differences in wave height, inclination, and breaker interval, with Okun-Ajah emerging with a high-energy anomaly. Strong co-variation between wave height and inclination ($r = 0.94$) coupled with weak correlations with current velocity indicates that sediment transport is governed by interacting hydrodynamic and morphological controls rather than single forcing variables. Three hydrodynamic regimes are identified: dissipative (Lekki), reflective–intermediate (Seme–Yovoyan–Orimedu), and high-energy oblique-attack (Okun-Ajah), defining a morphodynamic gradient driven by spatial variations in wave energy flux and breaker angle. These findings offer a transferable framework for erosion risk assessment and shoreline management in wave-dominated barrier–lagoon environments.

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1. INTRODUCTION

Barrier–lagoon systems typically develop along wave-dominated, microtidal coasts, where shore-parallel sandy barriers enclose lagoons that may be intermittently connected to the open ocean through tidal inlets [1–4]. Their morphology and long-term stability are governed primarily by interactions among wave processes, longshore sediment transport, and sediment-budget equilibrium, making them highly responsive to both natural forcing and human disturbance [1, 3, 5–7].

Within this broader setting, littoral processes, including wave action, tides, and nearshore currents, play fundamental roles in shaping coastal morphology. These processes regulate sediment transport, deposition, erosion, and shoreline reworking [4, 5, 7, 8]. Open-coast beaches are highly dynamic environments in which continuous wave-energy dissipation drives morphodynamic adjustment [8–10]. Wave transformation and breaker dynamics, especially the distinction between plunging and spilling breakers, are widely recognized as indicators of beach state and sediment-transport intensity [5–7, 11, 12]. Longshore sediment transport is controlled largely by wave height and angle of approach, which together determine the magnitude and direction of littoral drift [6].

The interaction between land and ocean systems facilitates continuous sediment redistribution, influencing both short-term beach variability and long-term geomorphic evolution [4, 13]. Accurate characterization of littoral hydrodynamics through parameters such as wave height, breaker interval, breaker type, wave angle, and longshore current velocity is therefore essential for understanding shoreline behaviour and predicting coastal responses to environmental change [14–16]. Such process-based understanding is particularly important in regions undergoing rapid coastal transformation.

The Nigerian coastline along the Gulf of Guinea represents a classic barrier–lagoon system, extending from Badagry through Lagos to Ibeju-Lekki. This coastal stretch is characterized by sandy beaches, beach ridges, tidal inlets, and interconnected lagoons, and it is controlled predominantly by wave-driven littoral processes. Waves approaching obliquely to the shoreline generate persistent longshore currents that redistribute sediment and regulate shoreline configuration. Under sediment-budget equilibrium, the coastline remains relatively stable; however, disruptions caused by natural variability or human interference often result in shoreline retreat or localized accretion [8, 10, 17].

Increasing evidence indicates widespread coastal degradation along the Nigerian shoreline. Recent studies highlight the growing importance of hydrodynamic forcing in controlling shoreline evolution along the Gulf of Guinea. Wave modelling and coastal analyses show that spatial and temporal variability in wave conditions plays a critical role in shaping geomorphic contrasts and coastal response [1, 18, 19], especially along the southwestern Nigerian coast [20, 21]. Long-term shoreline assessments reveal widespread coastal retreat and emphasize the combined influence of wave-driven processes and human interventions on shoreline instability [12, 21]. Multi-decadal shoreline-change analyses further indicate that significant portions of the Lagos barrier–lagoon coast are undergoing persistent erosion, with retreat rates exceeding 2 m year^{-1} in some locations [21]. These changes have been attributed to sea-level rise, reduced sediment supply,

and coastal-engineering structures that disrupt natural sediment-transport pathways [5, 6, 19, 22]. Complementary sedimentological studies also reveal spatial variability in grain-size distribution and sorting, reflecting differences in local hydrodynamic conditions and wave-energy regimes [23–25].

In Nigeria, systematic littoral observations are conducted by the Nigerian Institute for Oceanography and Marine Research (NIOMR), including measurements of wave characteristics, longshore currents, beach profiles, and sediment properties. When analysed over time, these datasets provide valuable insight into shoreline evolution and coastal stability. Complementary peer-reviewed studies demonstrate that integrating field measurements with geospatial shoreline and morphodynamic analyses improves understanding of coastal dynamics and erosion patterns along the Gulf of Guinea [12, 17, 21]. Detailed shoreline assessments along the Lagos barrier–lagoon system reveal persistent erosion and spatial variability in shoreline response linked to both hydrodynamic forcing and coastal-engineering structures [21, 26].

Recent process-based and field-integrated investigations provide deeper insight into the hydrodynamic controls of this system. High-resolution wave modelling along the southwestern Nigerian shelf indicates that the barrier–lagoon coast, including Lekki, is characterized by significant seasonal variability in wave height, period, and energy flux, which directly influences sediment transport and geomorphic contrasts [20]. Site-specific geotechnical and sedimentological investigations within the Lekki Peninsula reveal predominantly sandy, weakly consolidated coastal sediments with variable grain-size distributions, reflecting strong wave reworking and nearshore hydrodynamic forcing [27]. Field-based coastal-engineering studies also show that shoreline evolution along the Lekki coast and other wave-dominated coasts is strongly influenced by longshore sediment transport, wave action, and human interventions such as port development and shoreline-stabilization structures [7, 10, 12].

Despite these advances, comprehensive statistical evaluation of in situ hydrodynamic parameters and their relationship to shoreline variability remains limited, as most coastal studies in Nigeria rely predominantly on remotely sensed shoreline mapping and proxy indicators rather than field-based hydrodynamic observations [12, 28]. This study addresses that gap by integrating field-based littoral observations with statistical analysis to evaluate hydrodynamic variability across selected monitoring stations within the Nigerian barrier–lagoon system: Seme, Yovoyan, Lekki, Okun-Ajah, and Orimedu. Specifically, the study aims to: (i) characterize littoral hydrodynamics by quantifying wave height, breaker interval, breaker type, and longshore current velocity; (ii) assess spatial variability of littoral forcing along the barrier–lagoon coastline; (iii) examine hydrodynamic conditions in relation to inferred sediment-transport potential; (iv) evaluate spatial patterns in nearshore morphodynamic behaviour; and (v) develop a littoral database to support long-term coastal monitoring and management. By relating hydrodynamic conditions to observed coastal behaviour, the study provides a hydrodynamically informed interpretation of shoreline evolution in southwestern Nigeria and contributes to improved coastal-hazard assessment, infrastructure planning, and sustainable shoreline management [22].

2. THEORETICAL FRAMEWORK

The principal parameters measured were wave type, breaker interval, breaker height, wave inclination, longshore current velocity, and inferred sediment-transport potential.

The dominant breaking-wave type at each station was identified and classified as either spilling or plunging. Breaker interval, T , was determined by selecting a fixed point in the surf zone and recording the time taken for ten successive wave crests to cross that point. The breaker interval was computed as

$$T = \frac{t_{10}}{10}, \quad (1)$$

where t_{10} is the time taken for ten successive wave crests to cross a fixed point (s). If no waves were observed, the value was recorded as a calm condition.

Breaker height, H , was estimated using a levelling staff placed in the surf zone. The vertical difference between the crest and trough of the breaking wave was measured as

$$H = h_c - h_t, \quad (2)$$

where h_c is the elevation of the wave crest (m) and h_t is the elevation of the wave trough (m).

Wave inclination, α , was measured by aligning the 0–180° baseline of a protractor parallel to the shoreline and sighting the angle at which breaking waves approached the shore:

$$\alpha = |\theta_w - \theta_s|, \quad (3)$$

where α is the wave inclination relative to the shoreline (°), θ_w is the direction of wave approach (°), and θ_s is the shoreline orientation (°).

Longshore current velocity, v , was measured by timing the movement of a littoral-drift particle over a known distance along the shoreline:

$$v = \frac{d}{t}, \quad (4)$$

where d is the staked displacement or distance along the shore (m), and t is the travel time of the float (s). For consistency, a fixed distance of $d = 10$ m was staked along the shoreline, giving

$$v = \frac{10}{t}. \quad (5)$$

Although sediment transport was not measured directly, its potential was interpreted using the classical proportional relationship

$$Q \propto H_b^2 \sin(2\alpha), \quad (6)$$

where Q is the longshore sediment-transport rate, H_b is breaker wave height (m), and α is the wave-approach angle (°). This relationship indicates that sediment-transport potential increases with both wave energy and wave obliquity [5]. It is applied here only for qualitative interpretation, not quantitative estimation.

3. STUDY AREA

3.1. LOCATION AND SETTING

The study area comprises a segment of the barrier–lagoon coastal complex along the Atlantic margin of southwestern Nigeria, extending between latitudes 6°22′31.6″ N and 6°25′21″ N and longitudes 2°42′24.6″ E and 3°31′15.3″ E. The investigation was conducted across five selected coastal monitoring stations: Seme Beach at the Nigeria–Benin Republic boundary, Yovoyan Beach in Badagry, Lekki Beach on the Lekki Peninsula, Okun-Ajah Beach in Ajah, and Orimedu Beach in Orimedu (Figure 1). Elevation across the study sites ranges from approximately 4 to 5.6 m above mean sea level. Administratively, the study area spans three local government areas: Badagry, Eti-Osa, and Ibeju-Lekki.

This coastal stretch forms part of the wave-dominated Gulf of Guinea system and is characterized by sandy barrier beaches, low-lying back-barrier lagoons, and dynamic nearshore conditions. Coastal processes in the area are influenced primarily by wind-generated waves and longshore currents, with secondary contributions from tidal variability. Regionally, the barrier–lagoon system extends eastward from the Nigeria–Benin border for more than 180 km along the southwestern Nigerian coastline, although the present study focuses on selected segments within Lagos State.

3.2. GEOLOGY AND GEOMORPHOLOGY OF THE STUDY AREA

The study area lies within the eastern sector of the Dahomey Basin (Figure 2), a coastal sedimentary basin bounded by the Precambrian Basement Complex to the north, the Gulf of Guinea to the south, and the Okitipupa Ridge to the east. The basin comprises Cretaceous to Recent sedimentary sequences, dominated by Quaternary unconsolidated deposits, including fine- to medium-grained sands, silts, clays, and peat formed under marine and lagoonal conditions [29, 30].

Lithologically, the coastal plain is characterized by sandy barrier systems interbedded with clayey and silty units, reflecting alternating depositional environments. The stratigraphic units exhibit limited lateral continuity and commonly thin or pinch out over short distances. Along the coastal transect, near-surface deposits are predominantly sandy and transition downward into clayey and sandy-clay layers. At greater depths, the sequence becomes more heterogeneous and consists of coarse-grained, gravelly to conglomeratic sands interbedded with shale [29–31].

Geomorphologically, the area is defined by barrier islands, beach ridges, coastal dunes, and extensive lagoon systems, including the Lagos Lagoon and Lekki Lagoon. The beaches are generally gently sloping and composed of well-sorted sands, conditions that favour active sediment transport driven by wave action and longshore currents. As a result, the beaches are predominantly erosional, reflecting high wave-energy input and continuous sediment reworking. Shoreline evolution is spatially variable and influenced by natural processes and anthropogenic activities such as sand mining, dredging, and coastal-engineering interventions [9, 18, 19].

4. MATERIALS AND METHODS

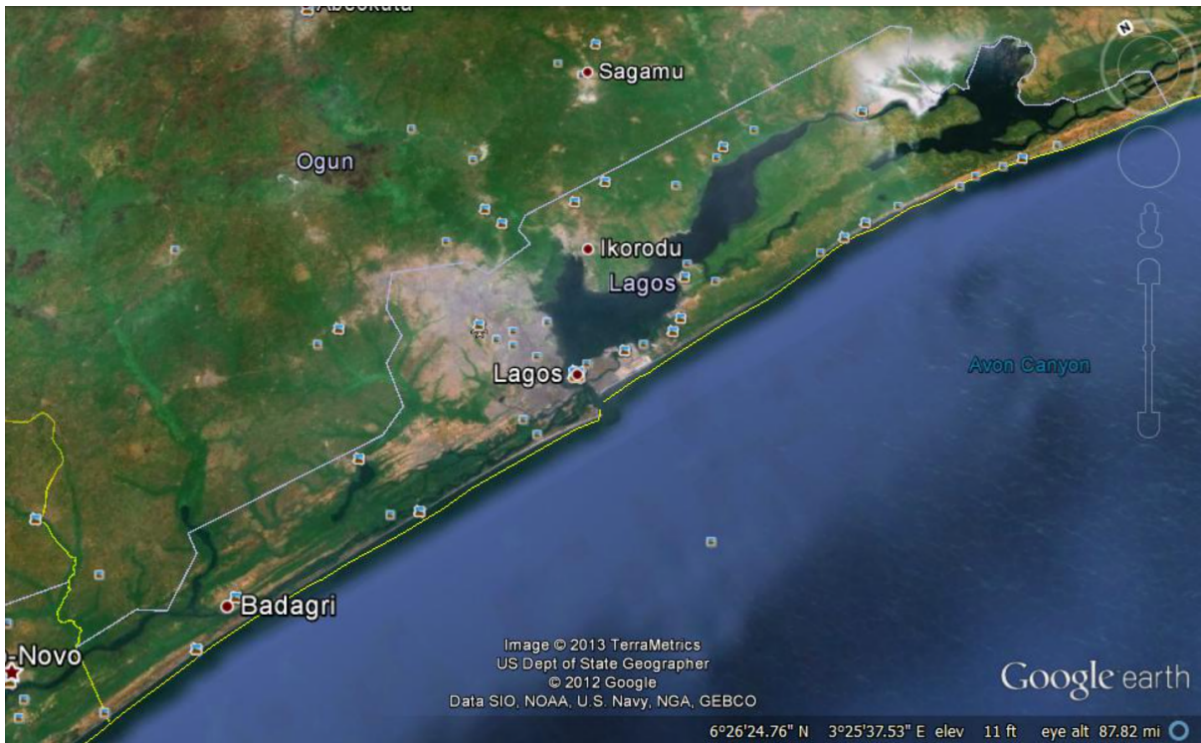


Figure 1. Satellite imagery of the study area showing the barrier–lagoon system and spatial continuity of the shoreline (modified from Titocan *et al.*, [32]). The linear coastal geometry and lagoon-ocean interface highlight the dominance of longshore sediment transport and support the morphodynamic zonation identified in this study.

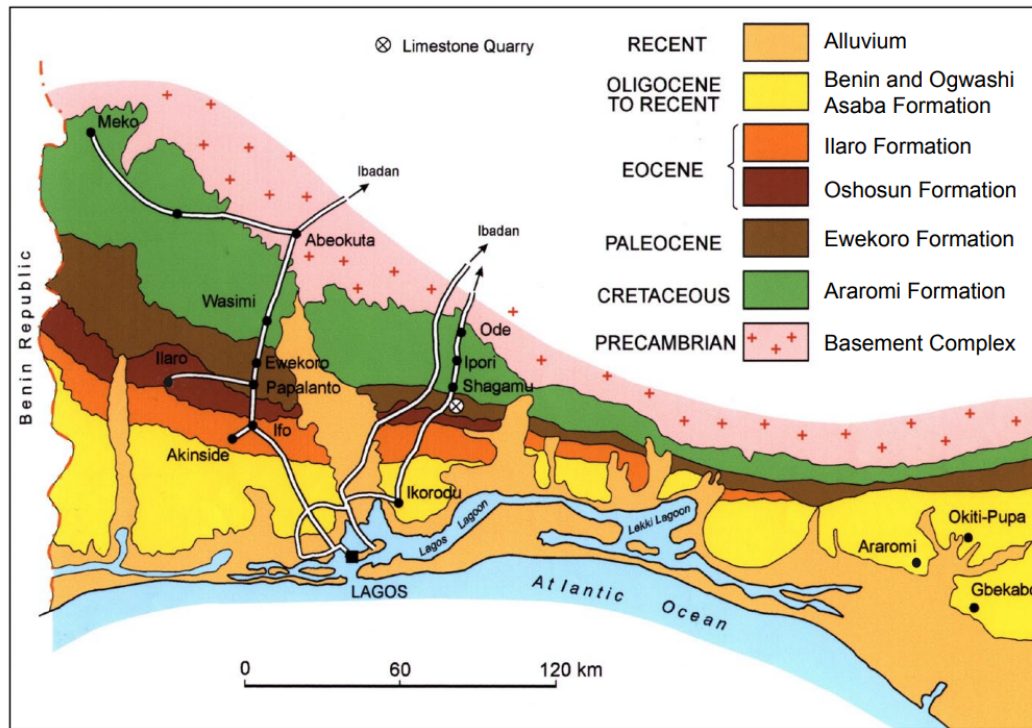


Figure 2. Geological map of the Dahomey Embayment, Nigerian sector, and location of the study area, after Obaje [29] and Aizebeokhai and Oyeyemi [33].

4.1. MATERIALS

The materials used for field data collection included a theodolite, tripod, Garmin 76S GPS receiver, measuring tape, stopwatch,

protractor, levelling staff, and littoral-drift particles (floats).

4.2. FIELD DATA COLLECTION

Field measurements were conducted during a sampling campaign between 19 and 25 March 2015 to assess nearshore hydrodynamic conditions and shoreline dynamics. A network of monitoring stations was established along each beach at 500 m intervals, with each station demarcated using backshore and foreshore stakes. Such systematic spatial sampling frameworks are widely adopted in coastal morphodynamic studies to capture alongshore variability in beach processes [4, 7, 34].

Topographic beach profiling was carried out using a theodolite at the following stations: SM1–SM5 (Seme Beach), YV1–YV5 (Yovoyan Beach), LK1–LK5 (Lekki Beach), OA1–OA4 (Okun-Ajah Beach), and OM1–OM5 (Orimedu Beach). The dataset used in this study is part of the NIOMR monitoring programme, which comprises repeated field measurements collected over multiple observation periods. Littoral observations followed established coastal field procedures for measuring wave characteristics, breaker types, and longshore currents, thereby ensuring consistency in hydrodynamic data acquisition [4, 15, 16]. Observations were made under normal astronomical tidal forcing conditions, modulated by spring–neap variability and prevailing meteorological conditions at the time of measurement.

4.3. DATA ANALYSES

Descriptive and inferential statistical analyses were conducted to quantify spatial variability in nearshore hydrodynamic parameters across the five coastal sectors: Seme, Yovoyan, Lekki, Okun-Ajah, and Orimedu. Measured variables included breaker interval (s), wave height (m), wave inclination ($^{\circ}$), longshore velocity (m s^{-1}), and breaker-type proportions (plunging and spilling).

Descriptive statistics, including mean, standard deviation, and coefficient of variation, were computed to evaluate central tendency and relative dispersion for each parameter. Higher-order distribution characteristics, including skewness and kurtosis, were assessed to examine deviations from normality [35]. Prior to inferential analysis, the data were assessed for normality and homogeneity of variance using the Shapiro–Wilk test and Levene’s test, respectively. The results indicated deviations from normality and unequal variances among groups for several parameters. Spatial differences among coastal sectors were evaluated using the Kruskal–Wallis test [36], which compares median values across multiple independent groups without assuming normality. Statistical significance was evaluated at the 95% confidence level ($p < 0.05$).

Pearson correlation analysis was performed to quantify relationships among hydrodynamic variables and to identify dominant process linkages controlling nearshore dynamics. Correlation strength was interpreted as weak ($|r| < 0.3$), moderate ($0.3 \leq |r| < 0.7$), and strong ($|r| \geq 0.7$) [37]. Effect-size estimates, η^2 (eta squared), were computed for breaker interval, longshore velocity, wave height, and wave inclination using

$$\eta^2 = \frac{SSB}{SSB + SSW}, \quad (7)$$

where SSB is the sum of squares between groups and SSW is the sum of squares within groups. All statistical analyses were conducted using standard scientific computing procedures, and results are presented in tables and graphical formats. Although

nearshore bathymetry was not measured directly, its influence is inferred from observed wave-transformation patterns and established coastal morphodynamic relationships [4, 7, 8, 10, 16].

4.4. MEASUREMENT UNCERTAINTY AND ERROR ESTIMATION

Measurement uncertainties were evaluated based on instrument precision and field-observation limitations. Wave-height measurements were obtained visually using graduated staff references, with an estimated uncertainty of ± 0.05 – 0.10 m, consistent with standard nearshore observational techniques and associated visual-estimation errors. Breaker interval was measured using a stopwatch, with an uncertainty of approximately ± 0.02 – 0.05 s due to stopwatch timing limitations and human reaction time, which are well documented in field-based wave observations.

Longshore current velocity was estimated using float tracking over measured distances, with an uncertainty of ± 0.03 – 0.08 m s^{-1} , reflecting cumulative timing and distance-measurement errors inherent in tracer-based approaches. Wave-inclination angles were determined visually relative to shoreline orientation, with an estimated uncertainty of ± 2 – 5° , consistent with field-based angular-estimation techniques used in coastal-process studies. These uncertainty ranges are consistent with standard field-based coastal measurements and fall within acceptable limits reported in coastal-engineering and geomorphological studies; therefore, they are considered insufficient to alter significantly the observed spatial patterns of hydrodynamic variability [4, 7, 15, 16].

5. RESULTS AND DISCUSSION

5.1. SPATIAL VARIABILITY OF NEARSHORE HYDRODYNAMIC PARAMETERS

Marked spatial variability in nearshore hydrodynamics is evident across the 24 stations distributed within the five coastal sectors, as reflected in contrasting distributions of breaker types, wave energy, and longshore current velocities (Table 1). Plunging breakers predominate at Seme and Orimedu, where values generally range from 60% to 90%, indicating relatively steeper beach faces and more energetic wave-shoaling conditions. In contrast, Lekki is consistently characterized by spilling breakers (80–90%), suggesting a more gently sloping, dissipative nearshore profile that promotes progressive wave-energy dissipation. Yovoyan exhibits intermediate behaviour, with nearly balanced plunging and spilling wave proportions, indicative of transitional morphodynamic conditions. Okun-Ajah records the highest wave heights (1.3–1.5 m) and displays mixed breaker types (20–60% plunging), reflecting enhanced wave energy and dynamic instability within the surf zone. The observed alongshore variations in breaker regimes and hydrodynamic parameters are interpreted as being controlled by spatial differences in beach morphology and nearshore bathymetry. This interpretation aligns with established beach-morphodynamic frameworks, in which reflective beaches are typically associated with plunging breakers and dissipative systems with spilling breakers [8, 10, 12]. Consequently, the observed zonal contrasts underscore the role of local geomorphic controls in modulating wave-transformation processes and sediment-transport dynamics along the coastline.

Breaker arrival intervals measured within the surf zone range from 0.16 to 0.80 s, with an overall mean of approximately 0.34

Table 1. Summary of nearshore hydrodynamic conditions and wave characteristics across the study beaches.

Zone	Plunging wave (%)			Spilling wave (%)			Breaker interval (s)			Longshore velocity (m s^{-1})			Wave height (m)			Inclination ($^{\circ}$)		
	Mean	Min.	Max.	Mean	Min.	Max.	Mean	Min.	Max.	Mean	Min.	Max.	Mean	Min.	Max.	Mean	Min.	Max.
Lekki	12.0	10	20	88.0	80	90	0.700	0.50	0.80	0.366	0.20	0.60	0.92	0.80	1.00	16.0	10	20
Okun-Ajah	32.5	20	60	67.5	40	80	0.400	0.30	0.50	0.393	0.17	0.55	1.45	1.30	1.50	40.0	30	45
Orimedu	78.0	70	90	22.0	10	30	0.236	0.18	0.32	0.426	0.33	0.55	0.74	0.60	0.80	13.0	10	15
Seme	76.0	60	90	24.0	10	40	0.186	0.16	0.22	0.432	0.26	0.58	0.92	0.80	1.00	14.6	10	18
Yovoyan	62.0	50	70	38.0	30	50	0.198	0.16	0.22	0.464	0.29	0.66	0.78	0.70	0.90	10.4	10	12

s. These values represent the time between successive breaking bores at a fixed nearshore observation point, rather than offshore breaker intervals. Such short intervals are characteristic of turbulent bore-arrival frequencies generated during wave breaking and transformation within the surf zone, particularly under dissipative and intermediate morphodynamic conditions, where wave merging and reformation produce rapid bore succession [4, 7, 8]. Empirical and theoretical studies of surf-zone hydrodynamics further demonstrate that bore-driven processes dominate energy dissipation and momentum transfer in shallow-water environments, leading to shortened apparent breaker-arrival time relative to offshore conditions [38, 39]. Lekki records relatively longer periods (approximately 0.50–0.80 s), whereas Seme (approximately 0.19 s) and Yovoyan (approximately 0.20 s) are characterized by shorter-period waves, indicating spatial variability in wave-transformation processes across the zone. Despite these differences, all sites are dominated by short-period waves, suggesting predominantly locally generated sea states rather than fully developed swell conditions.

Wave heights average approximately 0.93 m, with maximum values observed at Okun-Ajah (1.3–1.5 m), identifying this sector as the most energetic along the coast. Longshore current velocities range from 0.17 to 0.66 m s^{-1} , with a mean of approximately 0.43 m s^{-1} , and higher velocities are generally associated with increased wave obliquity. This relationship is consistent with established coastal-engineering formulations, in which longshore current magnitude is strongly controlled by breaker angle and wave-energy flux [15, 16].

Wave-inclination angles vary significantly, from relatively low values at Yovoyan (approximately 10°) to markedly higher values at Okun-Ajah (approximately $30\text{--}45^{\circ}$), consistent with enhanced alongshore sediment-transport potential under oblique wave incidence [5–7, 40]. Wind patterns further support these hydrodynamic trends, with southwesterly winds dominating Seme, Yovoyan, Lekki, and Orimedu, whereas southeasterly winds prevail at Okun-Ajah, reinforcing the observed wave–current interactions and their influence on nearshore sediment dynamics [41].

The pronounced spatial variability in wave characteristics and longshore currents indicates the presence of distinct morphodynamic compartments along the coastline, likely controlled by differences in nearshore bathymetry, shoreline orientation, and wind forcing. Such spatial compartmentalization of coastal processes is widely documented in morphodynamic studies, where local controls govern wave transformation and sediment-transport pathways [7, 10, 18, 26, 42]. Okun-Ajah, characterized by high wave heights (1.3–1.5 m), large incidence angles ($30\text{--}45^{\circ}$), and moderate-to-high longshore velocities (0.17–0.55 m s^{-1}), emerges as a zone of intensified hydrodynamic activity and enhanced sediment-mobility potential. This behaviour is consis-

tent with established formulations linking wave energy and obliquity to increased alongshore sediment-transport rates [10, 43]. Orimedu also exhibits relatively energetic conditions, suggesting increased susceptibility to shoreline change. Although measurement uncertainties are inherent in field-based observations, the magnitude of spatial differences observed across the study area exceeds the estimated error ranges, indicating that the identified hydrodynamic patterns are robust.

5.2. SPATIAL VARIABILITY IN WAVE EXPOSURE AND WIND FORCING

The observed distribution of wave opening and wind direction indicates a broadly consistent hydrodynamic regime along the southwestern Nigerian barrier–lagoon coast, with localized variability linked to shoreline orientation and site-specific exposure. The predominance of easterly wave opening across Seme, Yovoyan, Okun-Ajah, and most of Orimedu suggests that these segments are largely exposed to waves approaching from the eastern sector. This pattern is consistent with the regional wave climate of the Gulf of Guinea, where Atlantic swell waves commonly approach the coast at oblique angles [5, 18]. In contrast, westerly wave opening at the Lekki stations and at one Orimedu location reflects localized shoreline curvature and orientation, which can modify wave approach through refraction and nearshore transformation [4, 15, 16].

Wind direction across the study area is predominantly southwesterly, aligning with the dominant maritime airflow associated with the West African monsoon system [44]. This prevailing wind regime reinforces the oblique nature of wave incidence along much of the coastline. The presence of southeasterly winds at Okun-Ajah and one Lekki station indicates minor spatial variability, likely influenced by short-term atmospheric fluctuations or localized coastal geometry.

The combined pattern of easterly wave opening and dominant southwesterly winds suggests conditions favourable for the generation of longshore currents along most segments of the coast. Oblique wave approach is a primary driver of alongshore flow and sediment redistribution in sandy coastal environments [15, 16]. Although direct measurements of sediment transport were not undertaken, the observed hydrodynamic configuration indicates the potential for sustained alongshore sediment movement, particularly in the more uniform sectors such as Seme and Yovoyan. In contrast, the variability observed at Lekki and Okun-Ajah may reflect localized modifications in current patterns, which could influence spatial differences in coastal response [4, 7].

Table 2. Descriptive statistics and variability of nearshore hydrodynamic parameters across the study area.

Parameter	Mean	Standard deviation	CV (%)
Breaker interval (s)	0.34	0.21	62.0
Wave inclination (°)	17.92	10.86	60.6
Wave height (m)	0.94	0.26	27.6
Longshore velocity (m s ⁻¹)	0.42	0.13	32.0

Table 3. Skewness and kurtosis statistics for hydrodynamic parameters ($n = 24$).

Parameter	Skewness	Kurtosis	Distribution shape
Breaker interval (s)	1.23	0.19	Moderately positively skewed, near-normal tails
Wave inclination (°)	1.77	2.12	Strongly positively skewed, leptokurtic
Wave height (m)	1.24	0.69	Positively skewed, moderately heavy-tailed
Longshore velocity (m s ⁻¹)	-0.07	-0.85	Approximately symmetric, slightly platykurtic

5.3. NON-NORMALITY AND VARIABILITY IN NEARSHORE HYDRODYNAMIC PARAMETERS

Coefficient-of-variation values confirm strong spatial heterogeneity, with breaker interval and wave inclination exhibiting the greatest variability (Table 2). This underscores wave transformation and directional forcing as primary controls on nearshore dynamics. Wave height shows moderate variability, while longshore velocity is comparatively less variable. Skewness–kurtosis analysis (Table 3) reveals distinctly non-normal distributions in key hydrodynamic parameters, highlighting the importance of episodic forcing within the nearshore system.

Wave inclination exhibits strong positive skewness (1.77) and pronounced leptokurtosis (2.12), indicating intermittent high-angle wave events that substantially exceed mean conditions. Given the nonlinear dependence of longshore sediment transport on wave-approach angle, proportional to $\sin(2\alpha)$, such episodic events are likely to enhance alongshore transport potential and influence shoreline adjustment [10, 16]. Wave height is also positively skewed (1.24) with moderate kurtosis (0.69), reflecting sporadic high-energy wave pulses superimposed on generally moderate conditions, a pattern typical of wave-dominated coasts influenced by variable wind forcing [4, 7, 45]. Breaker interval shows moderate skewness (1.23) with near-normal kurtosis (0.19), indicating a mixed wave climate dominated by short-period sea states with limited swell influence, consistent with observations from fetch-limited coastal environments [4, 45].

Spatially, these statistical extremes are most pronounced at Okun-Ajah, where elevated wave heights (1.3–1.5 m) and high incidence angles (30–45°) indicate episodic high-energy, high-obliquity forcing conducive to increased hydrodynamic energy and potential shoreline reconfiguration. In contrast, Lekki is characterized by lower-energy spilling breakers (80–90%) and reduced wave heights (0.80–1.0 m), consistent with more dissipative morphodynamic behaviour [4, 7, 10, 12].

Longshore velocity is approximately symmetric (skewness = -0.07; kurtosis = -0.85), indicating a relative absence of extreme current-driven events compared with wave forcing. Previous studies have demonstrated that spatial variability in wave angle and transformation processes across the surf zone strongly

Table 4. Kruskal–Wallis H -values and p -values.

Variable	H -statistic	p -value	Interpretation
Breaker interval (s)	18.29	0.0011	Strong zonal variability
Longshore velocity (m s ⁻¹)	1.26	0.8683	No zonal difference
Wave height (m)	16.02	0.0030	Strong zonal variability
Wave inclination (°)	15.09	0.0045	Strong zonal variability

influences energy-dissipation patterns and nearshore hydrodynamics, with implications for sediment-transport dynamics [7, 16, 39, 45]. Collectively, the results demonstrate a wave-angle-dominated morphodynamic system in which episodic directional wave events, rather than current variability alone, are likely to exert a dominant influence on sediment-transport potential and shoreline response. This behaviour aligns with process-response models of coastal morphodynamics, which emphasize the dominant role of wave-energy flux and breaker angle in controlling sediment-transport pathways and shoreline evolution [10, 15, 16].

5.4. NON-PARAMETRIC ANALYSIS OF SPATIAL VARIABILITY

Given deviations from normality and homogeneity of variance, the Kruskal–Wallis test was applied to evaluate spatial differences in hydrodynamic parameters across the five coastal sectors. This test is appropriate for comparing multiple independent groups when parametric assumptions are violated [36]. The results indicate statistically significant zonal differences in breaker interval ($H = 18.29$, $p = 0.001$), wave height ($H = 16.02$, $p = 0.003$), and wave inclination ($H = 15.09$, $p = 0.005$), confirming pronounced spatial variability in wave characteristics across the study area (Table 4). These differences are driven primarily by the Okun-Ajah sector, which exhibits consistently higher wave heights (1.3–1.5 m) and markedly larger inclination angles (30–45°), reflecting a distinct high-energy, obliquely forced hydrodynamic regime.

Breaker interval also shows significant variation among zones, with relatively higher values observed at Lekki than at Seme and Yovoyan, indicating spatial differences in nearshore wave-transformation processes. Such variability is consistent with established coastal morphodynamic frameworks that emphasize the role of wave transformation and nearshore bathymetry in controlling spatial hydrodynamic patterns [4, 7]. In contrast, longshore velocity does not exhibit statistically significant differences among zones ($H = 1.26$, $p = 0.868$), indicating substantial overlap in current magnitude across the study area. This supports the interpretation that longshore currents are not structured solely by zonal wave conditions but are influenced by multiple interacting controls, including wave-breaking processes, shoreline geometry, and local bathymetry [15, 16].

5.5. NONLINEAR COUPLING IN NEARSHORE HYDRODYNAMICS AND IMPLICATIONS FOR SEDIMENT-TRANSPORT POTENTIAL

Pearson correlation analysis reveals a structured but generally weak-to-strongly coupled nearshore hydrodynamic system, in which wave-related parameters exhibit stronger interdependence than their relationships with current responses (Table 5). To ensure consistency in interpretation, correlation strength is classi-

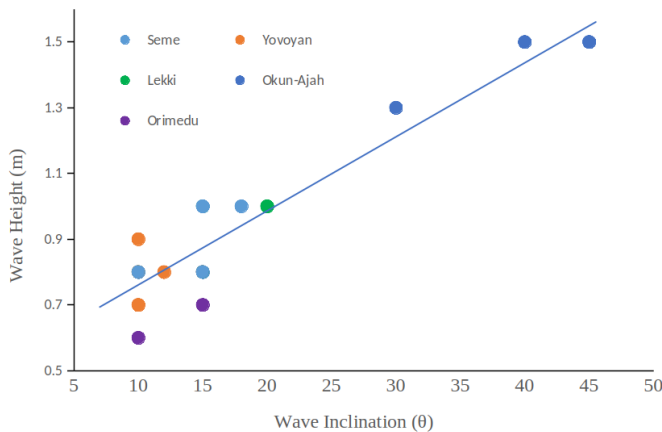


Figure 3. Relationship between wave height and wave inclination across the study beaches.

fied as weak ($|r| < 0.3$), moderate ($0.3 \leq |r| < 0.7$), and strong ($|r| \geq 0.7$).

The strongest relationship is observed between wave inclination and wave height ($r \approx 0.94$, $p < 0.001$), indicating robust covariation between wave energy and directional forcing across the study area (Figure 3). This suggests that higher-energy wave conditions tend to be associated with more oblique wave-approach angles, reflecting coupled wave-transformation processes in the nearshore zone. The strong statistical association indicates that wave-energy state and wave directionality behave as a linked forcing system in the study domain.

In contrast, relationships between wave parameters and longshore velocity are generally weak ($|r| < 0.3$). Wave inclination shows a weak negative correlation with longshore velocity ($r = -0.15$, $p > 0.05$), while wave height also exhibits a weak negative relationship ($r = -0.11$, $p > 0.05$). These results indicate that, within the limits of linear correlation, longshore current magnitude is not directly controlled by individual wave parameters alone. Instead, current response is likely influenced by a combination of factors, including nearshore bathymetry, shoreline orientation, wave-breaking processes, and frictional dissipation within the surf zone.

Breaker interval also shows weak associations with other hydrodynamic variables, including wave height ($r = 0.28$, $p > 0.05$) and wave inclination ($r = 0.25$, $p > 0.05$), suggesting partial independence between wave temporal characteristics and both energy and directional forcing within the study area. This reflects a mixed nearshore wave climate in which wave-transformation processes reduce simple linear coupling among parameters.

Breaker-type distributions show a structurally constrained inverse relationship between plunging and spilling breakers ($r = -1.00$, $p < 0.001$), reflecting their compositional dependence rather than independent physical behaviour. Nevertheless, the spatial transition between breaker types provides a useful indicator of changing nearshore energy conditions, from steeper, more energetic environments dominated by plunging breakers to more dissipative settings characterized by spilling breakers.

From a sediment-transport perspective, the correlation structure suggests that alongshore sediment dynamics are not gov-

erned by a single dominant hydrodynamic variable but rather by the combined and spatially variable interaction of wave energy, wave direction, and nearshore morphology. The strong coupling between wave height and wave inclination indicates that energetic and directional forcing may act jointly to enhance alongshore sediment-transport potential, consistent with theoretical formulations in which transport is proportional to wave-energy flux and a function of wave-approach angle [7, 10, 43]. However, the weak linear relationships between wave parameters and longshore velocity suggest that sediment-transport efficiency is likely modulated by additional local controls, including seabed morphology, breaker-dissipation patterns, and nearshore hydrodynamic complexity.

5.6. NEARSHORE HYDRODYNAMIC REGIMES AND MORPHODYNAMIC ZONATION

Statistical and process-based analyses identify three distinct nearshore hydrodynamic regimes across the study coastline, reflecting spatial variations in wave energy, breaker type, and longshore forcing (Figure 4). The first is a plunging-dominated reflective-intermediate regime, represented by Seme, Yovoyan, and Orimedu. These sectors are characterized by high proportions of plunging breakers (70–90%), relatively short breaker intervals (0.16–0.25 s), and moderate longshore current velocities (0.3–0.5 m s^{-1}). These conditions indicate relatively steeper beach profiles where wave breaking is concentrated within narrow surf zones, resulting in rapid energy dissipation and enhanced cross-shore sediment exchange. The coexistence of moderate longshore currents and strong cross-shore forcing suggests a transitional morphodynamic state in which erosional and depositional processes may alternate depending on prevailing wave conditions [4, 10].

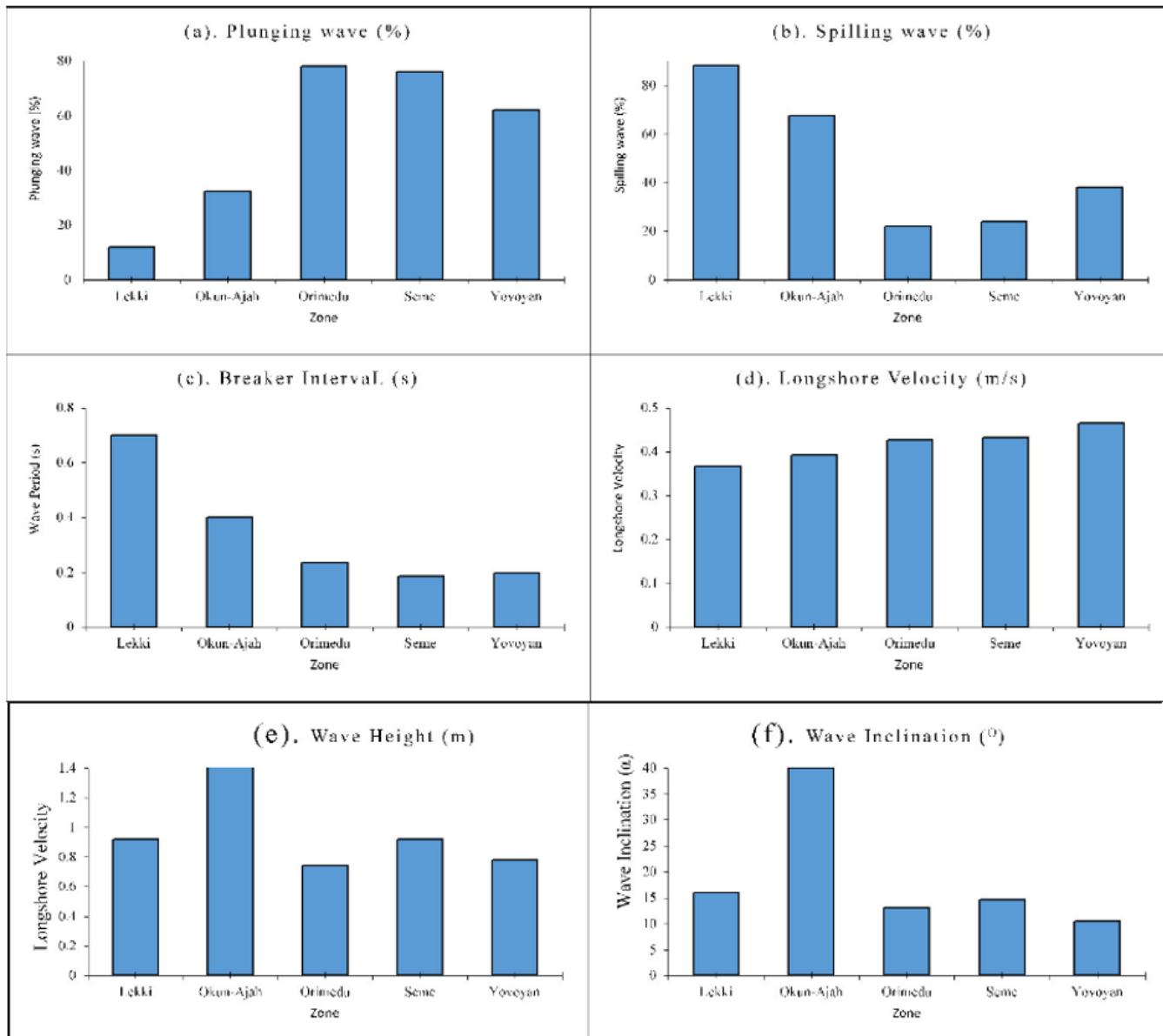
The second regime is a dissipative regime represented by Lekki. Lekki is dominated by spilling breakers (80–90%) and relatively high breaker intervals (0.50–0.80 s), consistent with a more dissipative nearshore morphology. Although wave heights remain moderate (0.8–1.0 m), energy is dissipated progressively across a wider surf zone due to gentler beach slopes. This promotes more uniform sediment suspension and reduced localized erosion, in agreement with dissipative beach behaviour described in previous studies [10, 12].

The third regime is a high-energy oblique-attack regime represented by Okun-Ajah. Okun-Ajah is distinguished by the highest wave heights (1.3–1.5 m), largest wave-inclination angles (30–45°), and elevated longshore velocities (0.17–0.55 m s^{-1}). These conditions indicate a high-energy, obliquely forced coastal sector where wave momentum is efficiently partitioned into alongshore transport, enhancing sediment redistribution and shoreline adjustment. This sector is therefore the most morphodynamically active and potentially erosion-prone within the study area [4, 7].

Higher wave heights are generally associated with increased wave inclination, reinforcing the role of combined energy-direction forcing in regulating longshore sediment transport. Conversely, breaker-type distribution reflects spatial differences in energy dissipation: plunging breakers dominate steeper, higher-energy sectors, while spilling breakers are associated with more dissipative conditions. Collectively, these patterns define a clear morphodynamic gradient along the coastline, tran-

Table 5. Pearson correlation matrix among key hydrodynamic and breaker variables. Values represent correlation coefficients (r); statistical significance is indicated as * $p < 0.05$, ** $p < 0.01$, and * $p < 0.001$.**

Variables	Wave height (m)	Wave inclination ($^{\circ}$)	Breaker interval (s)	Longshore velocity ($m s^{-1}$)	Plunging breaker (%)	Spilling breaker (%)
Wave height (m)	1.00	0.94***	0.28	-0.11	-0.42*	0.42*
Wave inclination ($^{\circ}$)	0.94***	1.00	0.25	-0.15	-0.43*	0.43*
Breaker interval (s)	0.28	0.25	1.00	-0.16	-0.42*	0.42*
Longshore velocity ($m s^{-1}$)	-0.11	-0.15	-0.16	1.00	0.28	-0.28
Plunging breaker (%)	-0.42*	-0.43*	-0.42*	0.28	1.00	-1.00***
Spilling breaker (%)	0.42*	0.43*	0.42*	-0.28	-1.00***	1.00

**Figure 4. Spatial variability of hydrodynamic parameters across coastal zones: (a) plunging wave percentage; (b) spilling wave percentage; (c) breaker interval; (d) longshore velocity; (e) wave height; and (f) wave inclination.**

sitioning from dissipative conditions at Lekki to more reflective–intermediate and high-energy oblique regimes toward Orimedu, Seme, and Okun-Ajah.

5.7. INTEGRATED MORPHODYNAMIC INTERPRETATION AND COASTAL-MANAGEMENT IMPLICATIONS

The integrated analysis of hydrodynamic parameters reveals a predominantly wave-dominated littoral system in which spatial variability is governed by the combined influence of breaker-type distribution, wave height, wave-approach angle, and longshore current velocity. The observed dominance of eastward wave ap-

proach and southwest wind forcing suggests a consistent regional directional regime that influences alongshore sediment-transport pathways across the study coastline.

Distinct morphodynamic zones can be identified. Okun-Ajah represents the most energetic and dynamically active sector, characterized by the highest wave heights (1.3–1.5 m), large wave-inclination angles (30–45°), and elevated longshore current velocities, indicating enhanced sediment-transport potential and increased susceptibility to shoreline adjustment. Orimedu also exhibits relatively energetic conditions and may function as a secondary zone of morphodynamic activity. In contrast, Lekki is characterized by spilling-dominated breakers and lower-energy wave conditions, indicating a more dissipative coastal environment with reduced morphodynamic intensity.

These spatial variations have important implications for coastal management. High-energy sectors such as Okun-Ajah and parts of Orimedu may require prioritization for erosion monitoring and mitigation planning, while lower-energy sectors such as Lekki may be more suitable for infrastructure development due to reduced wave forcing. However, all sectors remain dynamically active and subject to seasonal and event-scale variability, underscoring the need for site-specific management strategies rather than uniform regional approaches.

The observed patterns are consistent with classical coastal formulations that relate longshore sediment transport to wave-energy flux and the sine of twice the breaker angle [4, 7, 8, 10, 12, 15, 16, 43]. However, the results also suggest that the translation of wave energy into sediment transport is spatially modulated by local controls such as nearshore bathymetry, shoreline orientation, and sediment characteristics. Consequently, while wave obliquity and energy act as primary forcing mechanisms, their geomorphic expression varies across the coastline, reinforcing the importance of site-specific morphodynamic assessment.

5.8. COASTAL-EVOLUTION PATHWAYS AND ASSOCIATED MANAGEMENT IMPLICATIONS

Barrier-lagoon systems along the southwestern Nigerian coast are predominantly wave dominated, with longshore sediment transport serving as the primary mechanism controlling shoreline evolution [15, 16]. Within such systems, spatial variability in wave energy and direction governs the balance among sediment redistribution, shoreline progradation, and erosion. Coastal evolution is therefore best understood as a function of gradients in alongshore sediment flux rather than uniform shoreline behaviour.

The hydrodynamic patterns identified in this study suggest that zones of elevated wave energy and oblique wave approach are likely to function as sediment-redistribution nodes, where enhanced longshore transport promotes shoreline reworking and potential downdrift impacts. In contrast, lower-energy sectors tend to favour more gradual sediment exchange and relative morphological stability under average conditions, although they may still respond dynamically to episodic forcing events. This spatial variability implies that shoreline change along the study coast is inherently non-uniform, with localized erosion or accretion arising from imbalances in sediment supply and transport efficiency.

From a management perspective, these dynamics introduce significant risks when interventions disrupt natural sediment

pathways. Hard engineering structures, such as groynes, seawalls, and breakwaters, constructed without adequate consideration of prevailing longshore transport can induce sediment trapping, leading to updrift accretion and downdrift erosion hotspots. Similarly, shoreline-stabilization efforts in high-energy sectors may require continuous maintenance due to persistent wave forcing and sediment mobility. These risks highlight the need to align coastal-protection strategies with the underlying hydrodynamic regime and sediment-transport gradients.

More broadly, the findings reinforce established morphodynamic models that link shoreline response to wave-energy flux and breaker angle, while also demonstrating that the translation of hydrodynamic forcing into geomorphic change is strongly modulated by local controls such as bathymetry, shoreline orientation, and sediment characteristics [7, 8, 10, 12]. This underscores the limitation of applying uniform management approaches across spatially heterogeneous coastlines.

The insights derived from this study extend beyond the immediate study area. Many barrier-lagoon coasts in West Africa and similar low-gradient, wave-dominated environments globally exhibit comparable hydrodynamic forcing and sediment-transport behaviour. The observed relationships between wave conditions, sediment mobility, and shoreline response therefore provide a transferable framework for anticipating coastal evolution and informing adaptive management in analogous settings.

It should be noted that the present analysis reflects hydrodynamic conditions during the sampling period. Given the influence of seasonal variability, extreme events, and tidal modulation on coastal processes, future studies incorporating multi-seasonal and event-scale observations are recommended to refine these interpretations and improve predictive capability.

6. CONCLUSION

This study provides a comprehensive geophysical assessment of nearshore hydrodynamics and morphodynamic behaviour along the wave-dominated barrier-lagoon coast of southwestern Nigeria. The results demonstrate pronounced spatial variability in wave characteristics, breaker types, and longshore currents across the five coastal sectors (Seme, Yovoyan, Lekki, Okun-Ajah, and Orimedu), reflecting strong control by local morphology, nearshore bathymetry, and shoreline orientation.

The coastal system is dominated by spatially distinct hydrodynamic regimes: a dissipative environment at Lekki, characterized by spilling breakers and reduced energy-dissipation variability; a reflective-intermediate regime across Seme, Yovoyan, and Orimedu, dominated by plunging breakers and moderate longshore currents; and a high-energy, obliquely forced regime at Okun-Ajah, marked by elevated wave heights, steep wave-incidence angles, and enhanced sediment-transport potential. These regimes collectively define a clear alongshore morphodynamic gradient driven primarily by wave-energy flux and wave-approach angle.

Statistical analyses further reveal strong coupling between wave height and wave inclination, while longshore current responses exhibit weaker direct dependence on individual wave parameters. This indicates that sediment-transport processes are governed by nonlinear interactions among wave forcing, coastal geometry, and nearshore morphological controls rather than sin-

gle dominant variables. Episodic high-angle wave events and spatial variability in wave-transformation processes further reinforce the importance of directional forcing in shaping shoreline dynamics.

From a coastal-evolution perspective, the study shows that shoreline change along the coast is non-uniform and strongly modulated by gradients in alongshore sediment transport. High-energy sectors function as sediment-redistribution nodes with elevated susceptibility to erosion and shoreline adjustment, while lower-energy sectors exhibit comparatively stable morphodynamic behaviour under average conditions.

Overall, the findings emphasize that coastal evolution in this system is wave driven, spatially heterogeneous, and governed by interacting geophysical processes. The results highlight the need for site-specific coastal-management strategies and provide a transferable framework for understanding and managing similar barrier-lagoon systems in other wave-dominated coastal environments.

DATA AVAILABILITY

The data are available on request from the corresponding author.

DECLARATION OF COMPETING INTEREST

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this manuscript.

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