

Article

Linking Shoreline Change, Environmental Forcings, and Sedimentological Resilience in Nourished Beaches of Cape May and Wildwood, New Jersey, USA: A Multi-Decadal Synthesis

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Abstract

Beach nourishment is a widely used strategy to mitigate coastal erosion, yet its long-term geological impacts remain poorly understood. This study provides a multi-decadal synthesis of shoreline change and sedimentological evolution on the nourished beaches of Cape May and Wildwood, New Jersey, USA. Using shoreline positions from 1991 to 2024, we identify contrasting trajectories: Wildwood exhibits ‘persistent transition’ with severe northern erosion (EPR: -10.0 m/yr) feeding southwards accretion, while Cape May demonstrates a ‘managed equilibrium’ with widespread accretion (mean EPR: $+1.15$ m/yr). Wave energy correlations account for less than 15% of shoreline variability, indicating natural drivers have been superseded by human sediment inputs. Direct sediment comparison shows substantial textural transformation, with median grain sizes increasing from 153 to 435 μm to 467 – 982 μm and sorting degrading from very well to moderately well sorted, reflecting sustained disequilibrium. These findings are synthesized into a conceptual model where nourishment initiates feedback cycles that create human-dependent morphodynamic trajectories. This study concludes that the long-term resilience of developed coasts will depend on a strategic evolution from managing ‘sand as volume’ toward stewarding ‘sediment as a system,’ where textural compatibility is a primary determinant of success.

Keywords: anthropogenic sediment supply; shoreline evolution; sediment texture; coastal resilience; hydrodynamic forcings; nourishment impacts



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1. Introduction

Coastal systems are dynamic environments shaped by the interaction of natural geological processes and human interventions. In the context of accelerating sea-level rise and potentially intensifying storm regimes [1,2], the resilience of these systems is increasingly constrained. On developed coastlines, natural adjustment through landward migration and sediment redistribution is often restricted by infrastructure such as groins, jetties and seawalls, resulting in a reliance on engineering interventions to maintain beach width and protect coastal assets. Among these interventions, beach nourishment has become the dominant soft-engineering strategy worldwide [3–5].

Nourishment is primarily implemented to buffer against storm impacts, mitigate erosion, and counter shoreline retreat [6]. Consequently, much of the existing literature emphasizes engineering-based assessments such as project longevity, sediment retention, and shoreline advance [7–9]. Chronic stressors such as sea-level rise (SLR) and acute storm-induced erosion are also well understood as natural drivers and incorporated into

coastal evolution models [10–12]. Foundational work on New Jersey beach sediment characteristics [13,14] provides valuable context for evaluating how nourishment alters native sediment characteristics.

Despite these advances, a critical aspect remains underexplored: beach nourishment is not simply a volumetric addition but a sedimentological transformation. The placement of externally sourced sediments, often texturally and compositionally distinct from native material can alter sediment budgets, beach face morphology, and long-term grain-size distributions [15–17]. Once placed, this sediment is redistributed by waves, longshore currents, and storms, creating complex evolutionary pathways that remain poorly constrained over decadal timescales. Understanding the sedimentological legacy of repeated nourishment is therefore essential for predicting morphodynamic response and long-term resilience. This knowledge gap is particularly relevant to the New Jersey coastline, a densely developed, meso-tidal system shaped by frequent storms and significant relative sea-level rise [18]. Cape May and Wildwood, in particular, provide an ideal setting to examine these interactions due to their extensive nourishment histories, energetic wave climate, and persistent erosion pressures [19].

The analysis presented here is grounded in established coastal geomorphology and sediment transport theory. Classical shoreline equilibrium models propose that shoreline position reflects a dynamic balance among wave energy, sediment supply, and sea-level rise, and that beaches evolve toward a morphodynamic equilibrium profile governed by hydrodynamic forcing [20,21]. Sediment budget theory further predicts that shoreline advance or retreat is determined by the net gains or losses of sediment within a littoral cell, with human interventions such as nourishment functioning as exogenous additions that reset sediment pathways [22]. Nourishment itself is understood to generate an initial state of morphodynamic disequilibrium, after which profile adjustment, selective winnowing of fine fractions, and textural filtering processes drive its integration into the native system [1,16]. These theoretical frameworks provide the foundation for interpreting how repeated nourishment, interacting with local hydrodynamics, produces divergent evolutionary states such as the Managed Equilibrium in Cape May and the Persistent Transition observed in Wildwood.

This study integrates a comprehensive dataset spanning 1950–2024, incorporating shoreline positions, sea-level trends, wave and storm climatology, nourishment history, and direct sedimentological comparisons between pre-nourishment and modern conditions. The objectives are to: (1) Quantify long-term shoreline-change patterns and evaluate their correlation with chronic (SLR) and acute (storm-energy) environmental drivers. (2) Assess the performance of nourishment projects in mitigating erosion under persistent natural forcings. (3) Evaluate long-term sedimentological impacts by quantifying textural shifts between historical and contemporary sediments. (4) Develop a conceptual model linking nourishment cycles with sedimentological and morphodynamic trajectories.

By explicitly connecting human intervention with natural sediment transport processes, this study offers a holistic assessment of coastal evolution on a managed shoreline. The findings inform broader discussions on the future of nourishment-based management strategies and their long-term geological consequences.

2. Study Area

The study focuses on the oceanic beaches of Cape May and Wildwood, located on the southern barrier island coastline of New Jersey, USA (Figure 1).

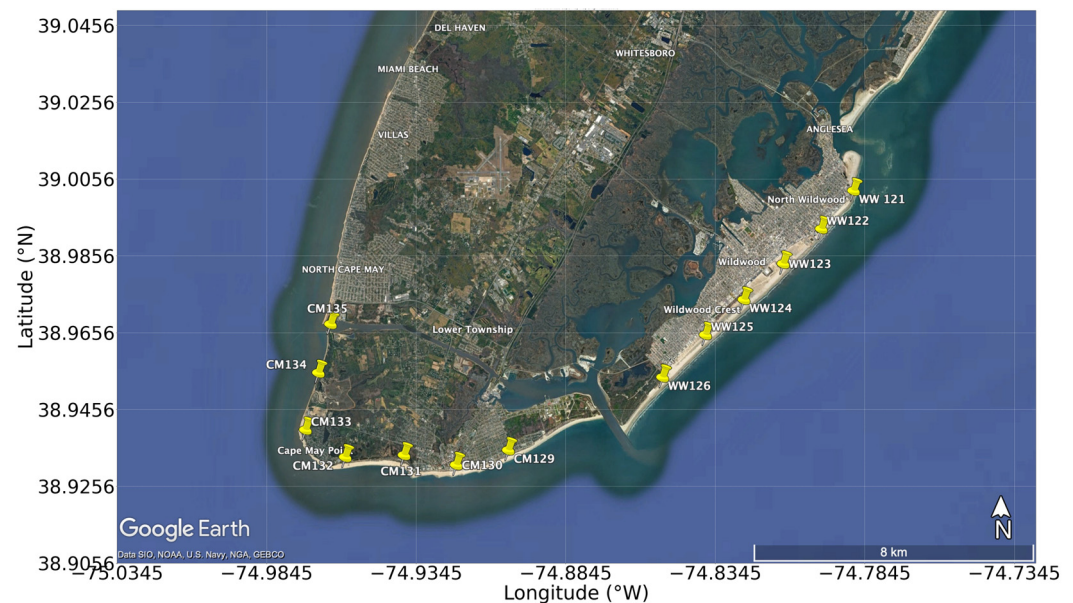


Figure 1. Study area in Cape May and Wildwood, New Jersey and sediment sampling locations.

The oceanic beaches of Cape May and Wildwood, New Jersey, form a critically important and dynamically managed coastal segment. This area is of major economic and ecological importance, supporting a multi-billion-dollar tourism industry [23], providing vital habitat for shorebirds, horseshoe crabs [24] and endangered species such as piping plovers and least terns [25], and serving as the primary natural buffer for coastal infrastructure against storms.

The geological framework is defined by a clear stratigraphy. The basement consists of the Pleistocene Cape May Formation, a unit of unconsolidated sands, silts, and clays of fluvial and marine origin, which also includes early Holocene non-glacial stream deposits [26]. Overlying this basement are the modern beach deposits [26], which are now composed of a hybrid mixture of reworked native sediments and large volumes of sand sourced from the inner continental shelf, emplaced during decades of beach nourishment projects. The surficial beach sands of Cape May and Wildwood are mineralogically typical of the southern New Jersey coast, consisting predominantly of quartz with minor feldspar and trace heavy minerals [13].

Cape May and Wildwood constitute a classic example of a wave-dominated, microtidal coast experiencing long-term transgression [17,27]. The regional coastal dynamics are governed by a dominant southerly longshore drift on the oceanside, driven by wave energy from northeast and east Atlantic storms [28]. Yearly average significant wave height is between 0.8 and 1.6 m, and the tidal range is between 4 and 7 Feet [17].

This natural system has been fundamentally altered by a prolonged history of anthropogenic modification. The construction of the Cape May Inlet jetties in the early 20th century acts as a primary littoral barrier, initiating a downdrift erosion of Cape May beaches [29]. Furthermore, numerous groin fields compartmentalize the shoreline, trapping sediment and creating a complex alongshore pattern of local accretion and erosion [30]. These structures create a sediment-starved regime in their downdrift shadows, establishing the fundamental erosion problem that modern beach management seeks to address [31]. In direct response to these challenges, the beaches of Cape May and Wildwood have been subject to repeated, large-scale beach nourishment projects for over seven decades, constituting one of the most intensively managed coastal segments in the United States [7]. Beach nourishment projects in Cape May and Wildwood primarily use sand dredged from designated offshore borrow areas on the inner continental shelf, as specified by USACE project

plans. The contemporary shoreline is thus a product of this ongoing effort to counteract the erosional trends established in the historical record, with Wildwood undergoing around 10 major nourishments and Cape May a total of 39 nourishment episodes since 1962 [32].

3. Materials and Methods

3.1. Data Sources and Pre-Processing

To evaluate the multi-decadal evolution of the Cape May and Wildwood beach systems, this study integrates four primary data categories: (1) shoreline position, (2) environmental forcings (sea-level rise and wave climate), (3) human intervention through beach nourishment, and (4) sedimentological characteristics. The sedimentary analytical period extends from 1950 to 2024, enabling direct comparison between a pre-nourishment sedimentological baseline [13] and contemporary beach conditions. These datasets collectively provide the resolution needed to quantify long-term shoreline dynamics and associated sedimentological shifts.

3.1.1. Shoreline Change Analysis

Shoreline change was quantified using the Digital Shoreline Analysis System (DSAS) [33]. Annual shoreline positions from 1991 to 2024 were manually digitized from high-resolution Google Earth Pro (Version 7.3.6.10441) imagery and imported into ArcGIS Pro (Version 3.5) for processing. The shoreline was delineated as the instantaneous water line or, where visible, the wet/dry boundary, which provides a consistent and commonly used proxy for shoreline position in the absence of tide-referenced imagery [34].

A baseline was established parallel to the general coastal orientation and transects were generated at 100 m spacing across both Cape May and Wildwood. Transects were extended sufficiently offshore to ensure intersection with all digitized shorelines and were cast in a single seaward direction from the baseline for consistency. DSAS version 6.0.170 was used to compute End Point Rates (EPR), defined as the distance between the earliest available (1991) and most recent (2024) shoreline positions divided by elapsed time [35,36]. This metric provides a robust, cumulative measure of net erosion or accretion over the 33-year study period, integrating both natural processes and management interventions.

Positional Accuracy and Image Consistency: To ensure digitization reliability, shorelines were extracted using the highest-resolution imagery available for each year. Google Earth typically provides horizontal positional accuracy of $\pm 2\text{--}5$ m, consistent with published benchmarks [36]. To quantify operator precision, a representative subset of shoreline segments was digitized three times, yielding a mean internal deviation of ± 3.2 m. Imagery from comparable tidal stages and, where possible, similar seasonal windows was selected to minimize horizontal offsets associated with tidal variation and seasonal beach-width fluctuation. Because uncertainties $< \pm 3.2$ m over the 33-year analysis window equate to ~ 0.1 m/yr, shoreline change rates below this threshold were interpreted as indicative of stable or insignificant change. These procedures collectively ensured consistency in shoreline extraction and minimized geolocation uncertainty.

3.1.2. Relative Sea-Level Rise (SLR)

Relative sea-level data were obtained from the NOAA tide-gauge record at Atlantic City, New Jersey (Station ID: 8534720), spanning 1965–2024 [37]. Monthly mean sea-level records were analyzed using an ordinary least-squares linear regression to calculate long-term SLR rates (mm/yr). The regression was evaluated with 95% confidence intervals to quantify uncertainty in the trend estimate. This tide gauge record is the closest long-term reference for the study area and is widely used as the regional indicator of relative SLR along the southern New Jersey coast.

3.1.3. Wave Climate and Storm Identification

Significant wave height (H_s) data were obtained from the Wave Information Studies (WIS) hindcast dataset for station ST63152, located offshore of the study area and covering 1980–2024 [38,39]. The long-term H_s record was used to calculate the 95th percentile storm threshold, against which all hourly wave data were evaluated. Storm events were defined as periods when H_s exceeded this threshold for at least 12 consecutive hours, following commonly applied coastal storm-detection criteria [40]. Each identified event was cross-referenced with the NOAA Storm Events Database to ensure consistency in classification and to distinguish true ocean-forcing events from short-lived wave anomalies. This approach provides a robust basis for evaluating storm-driven wave energy across the study period.

3.1.4. Beach Nourishment Data

A comprehensive nourishment history for Cape May and Wildwood was compiled using publicly accessible datasets from the U.S. Army Corps of Engineers (USACE) and the National Beach Nourishment Database (2025) [32]. For each nourishment event, information on project year, placement length, and total sand volume (cubic yards) was extracted. When multiple sources reported differing volumes or partial emergency fills, values were cross-checked against USACE project documents to ensure consistency. Nourishment data were then aligned temporally with shoreline change trends to evaluate the timing, magnitude, and geomorphic impact of major sediment addition episodes across the study period.

3.2. Sedimentological Analysis

3.2.1. Field Sampling

Sediment samples were collected along the high tide line (HTL) at predetermined locations shown in Figure 1. The sampling methodology followed McMaster's method [13] to ensure full comparability with the pre-nourishment 1950 dataset. Sampling at the HTL provides a consistent proxy for active swash-zone processes, where sediments are continuously reworked and sorted by waves, making this position the most sensitive indicator of nourishment-driven textural change. Although HTL sampling does not capture full cross-shore variability across the foreshore, berm, or dune, it ensures methodological consistency and allows direct comparison with the 1950 pre-nourishment dataset. Accordingly, the interpretations in this study focus on alongshore and temporal textural patterns rather than detailed cross-shore facies variability.

All sediment samples were collected in August 2024 to ensure consistent seasonal conditions across all stations. Summer represents the most stable morphological state of these beaches, when sediment reworking is dominated by fair-weather wave processes rather than storm-driven winter conditions. Collecting samples during a single season reduces temporal variability and allows the results to be compared directly with the pre-nourishment dataset, which was also collected during summer months.

At each site, a 30 cm downspout core was inserted approximately 15 cm into the beach surface and extracted (Figure 2a). This coring method reduces lateral contamination and ensures consistent sampling depth across all stations. To quantify small-scale spatial variability, four replicate samples were collected within 4.5 m (15 ft) of each primary location (Figure 2b). Each replicate was processed and analyzed separately as an independent sample to characterize intra-site heterogeneity and enhance dataset robustness. Table 1 lists the geographic coordinates of all sampling and monitoring stations corresponding to Figure 1.

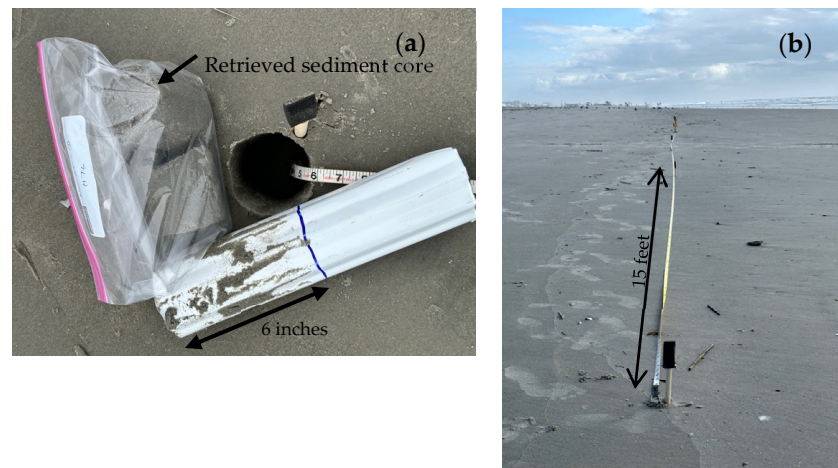


Figure 2. (a) Downspout pipe used to retrieve the sediment core along the HTL. (b) Four sampling points at a major sampling site within 15 feet of distance. The image shows the WW 126 location.

Table 1. Coordinates of sediment-sampling and monitoring stations in Cape May and Wildwood, New Jersey.

Cape May	Coordinates		Wildwood	Coordinates	
	Lat (N)	Long (W)		Lat (N)	Long (W)
CM 129	38°55′57.62″	74°54′13.77″	WW 121	38°59′58.83″	74°47′18.27″
CM 130	38°55′44.01″	74°55′15.63″	WW 122	38°59′26.00″	74°47′56.90″
CM 131	38°55′52.97″	74°56′17.87″	WW 123	38°58′50.37″	74°48′44.10″
CM 132	38°55′51.10″	74°57′27.90″	WW 124	38°58′16.84″	74°49′31.67″
CM 133	38°56′19.60″	74°58′12.20″	WW 125	38°57′44.13″	74°50′18.08″
CM 134	38°57′8.89″	74°58′1.12″	WW 126	38°57′4.83″	74°51′9.72″
CM 135	38°57′53.99″	74°57′47.30″			

3.2.2. Laboratory Processing

All samples were oven-dried at 80 °C for 24 h to ensure consistent moisture removal. Grain-size analysis was performed by dry sieving 500 g of each sample through a standard U.S. sieve series (mesh sizes 6.680–0.053 mm) using a Ro-Tap[®] mechanical shaker (W.S. Tyler, Mentor, OH, USA) for 10 min, following McMaster [13]. Weight percentages retained on each sieve were used to compute granulometric statistics in GRADISTAT v8.0, including mean grain size, sorting, skewness, and kurtosis, using the Folk and Ward method [41].

To ensure analytical reliability, all sieving procedures were standardized across samples. Replicate HTL samples from each station were processed independently to evaluate intra-site textural variability. GRADISTAT outputs were manually cross-checked for a subset of samples to verify correct statistical calculations and to identify potential outliers associated with micro-scale sediment heterogeneity. These quality-control steps optimized data processing and improved the robustness of the sedimentological dataset.

4. Results

4.1. Multi-Decadal Shoreline Change and Environmental Forcings

4.1.1. Quantitative Shoreline Change Rates (1991–2024)

DSAS analysis for 1991–2024 reveals distinct evolutionary trajectories for Wildwood and Cape May; two adjacent systems experiencing similar environmental forcings but displaying markedly different responses. Wildwood exhibits a strongly bipolar pattern of extreme erosion in the north and pronounced accretion southwards, indicating a system in persistent sedimentary transition. In contrast, Cape May demonstrates a predominantly

accretional trend consistent with a stable, managed equilibrium, aside from localized bayside erosion. A summary of EPR statistics is presented in Table 2.

Table 2. Summary of End Point Rate (EPR) Statistics for Wildwood and Cape May (1991–2024).

Location/Station	Trend	EPR Range (m/yr)	Average EPR (m/yr)
WILDWOOD (Overall)	Near-Zero Net	−11.70 to +5.67	
WW 121	Severe Erosion	−7.91 to −11.70	~−10.0
WW 122	Erosion	−4.05 to −4.90	~−4.6
WW 123	Accretion	+2.06 to +3.73	~+3.3
WW 124	Accretion	+4.62 to +4.91	~+4.7
WW 125	Accretion	+3.23 to +3.60	~+3.4
WW 126	Accretion	+1.08 to +1.41	~+1.2
CAPE MAY (Overall)	Net Accretional	−0.88 to +3.99	
CM 129	Accretion	+2.35 to +3.99	~+3.0
CM 130	Accretion	+1.12 to +1.58	~+1.3
CM 131	Accretion	+1.20 to +2.33	~+1.8
CM 132	Accretion	+2.88 to +3.12	~+3.0
CM 133	Accretion	+1.41 to +2.00	~+1.7
CM 134	Erosion	−0.88 to −0.60	~−0.7
CM 135	Erosion	−0.40 to −0.30	~−0.3

Wildwood Shoreline Trends

In Wildwood, erosion is concentrated in the northern sector, where 31.25% of transects (30 transects) register statistically significant retreat (linear regression p value < 0.05). Average EPR values reach −6.50 m/yr, with WW 121 showing the most severe erosion (−7.91 to −11.70 m/yr). Starting WW 123, accretion dominates and 68.75% of transects (66 transects) exhibit positive EPR values averaging +2.88 m/yr, with WW 124 and WW 125 showing the highest accretion rates (+4.62 to +4.91 m/yr and +3.23 to +3.60 m/yr, respectively). These spatially contrasting trends reflect strong alongshore sediment redistribution driven by persistent southerly longshore transport. Figure 3a shows the shoreline change (accretion/erosion) rates obtained from DSAS and Figure 3b shows the annual shoreline change in Wildwood.

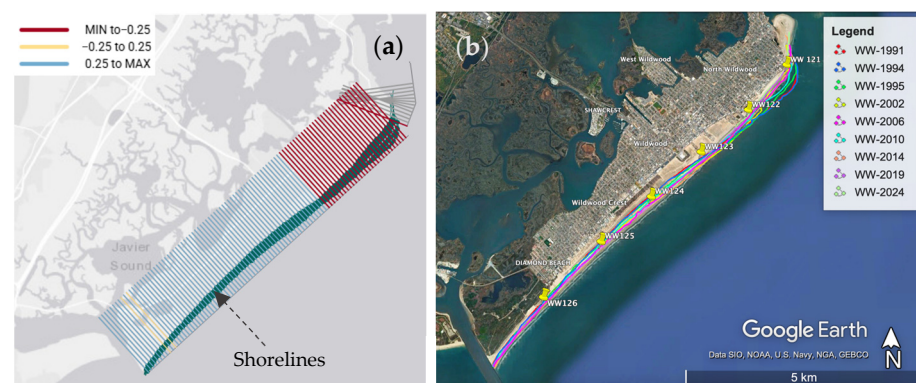


Figure 3. (a) Shoreline change rates for each transect obtained from DSAS. Northern Wildwood shows erosional patterns while central and southern show accretional values. (b) Annual shoreline change from 1991 to 2024 (Google Earth Pro Version 7.3.6.10441).

Cape May Shoreline Trends

In Cape May, DSAS results show that 79% of transects (105 of 133) experienced net accretion, with an average oceanside EPR of +1.15 m/yr and corresponding average Net Shoreline Movement (NSM) of +38.01 m on average. Most accretional transects (76%) were

statistically significant (linear regression p value < 0.05). Erosional trends were confined to the bayside, where transects averaged -0.50 m/yr. The most significant erosion was focused on the CM 134 of the bayside, with EPRs ranging from -0.88 to -0.60 m/yr. Oceanside accretion was strongest at CM 132 ($+2.88$ to $+3.12$ m/yr) and CM 129 ($+2.35$ to $+3.99$ m/yr). CM 130, CM 131, and CM 133, exhibited strong but more moderate accretional rates, ranging from $+1.12$ to $+2.33$ m/yr. The presence of nodal points of sediment accumulation, likely influenced by the interaction of nourishment placements and the complex wave field around coastal structures [30,42,43]. Additional shoreline-change statistics from Linear Regression Rate (LRR) and Weighted Linear Regression (WLR) corroborate these findings.

Figure 4a shows the DSAS analysis results of shorelines from 1991 to 2024 and the dominant accretional/erosional trends along the shoreline and Figure 4b shows annual shoreline changes in Cape May for the same period. Figure 5 shows the highest eroded and accreted locations in Cape May with the yearly change in shorelines.

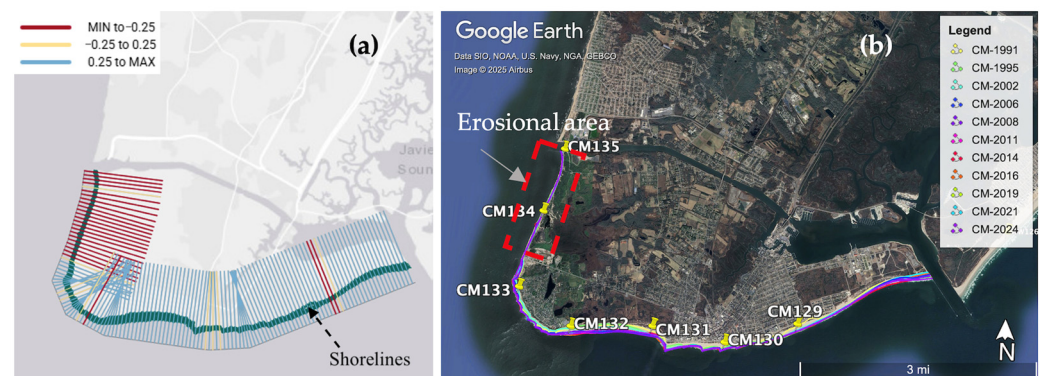


Figure 4. (a) Calculated Shoreline change rate using DSAS. This shows accretion/erosion trends of shorelines in Cape May (1991 to 2024). (b) Annual shorelines in Cape May from 1991 to 2024 (Google Earth Pro V.7.3.6.10441).



Figure 5. (a) Highest eroded location CM 134. Annual shorelines indicate a landward movement (b) Accretion in CM 132 (c) Accretion in CM 129. Annual shorelines indicate a seaward movement of the shoreline.

High Tide Line (HTL) Movement

Temporal variation in the HTL positioning trends measured using Google earth pro (version 7.3.6.10441), support the DSAS findings. Figure 6 shows the total HTL change compared to 1991. In Wildwood, WW 121 experienced the most extreme retreat (-272.2 m), whereas WW 124 recorded substantial shoreline advance ($+184.5$ m). Cape May's oceanside transects advanced by more than 100 m at several locations, while bayside transects showed statistically consistent retreat. Higher R^2 values for erosional and accretional sectors indicate persistent, long-term trends rather than short-term fluctuations. Table 3 shows the annual net landward/seaward movement of the High Tide Line (HTL) of each sampling station, 1991 (earliest available), as the baseline.

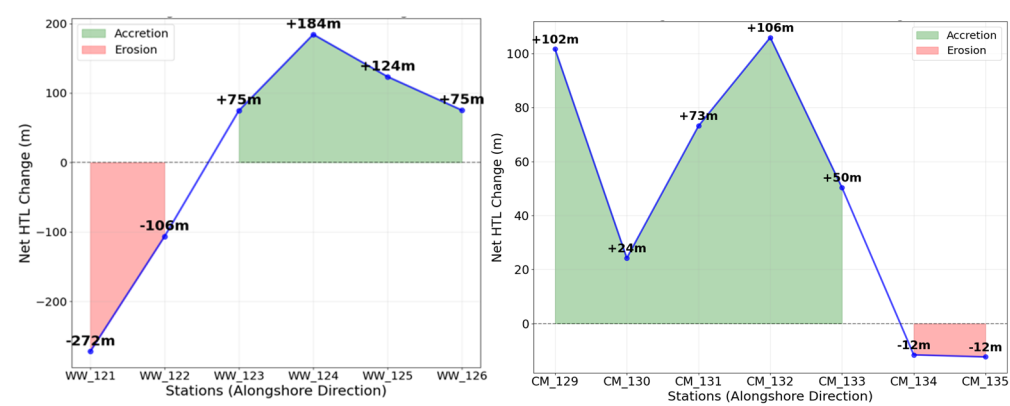


Figure 6. Net change in HTL from 1991 to 2023, Wildwood and Cape May (measured in m).

Table 3. Summary table of HTL change compared to 1991 in Wildwood and Cape May (1991 to 2024). The full dataset is in Table S1.

Station	Net Change (m)	Rate (m/yr)	R ²	Trend
WW 121	−272.2	−7.36	0.737	Severe Erosion
WW 122	−106.4	−3.61	0.614	Severe Erosion
WW 123	+74.8	+1.69	0.180	Accretion
WW 124	+184.5	+5.83	0.901	Accretion
WW 125	+123.5	+4.47	0.637	Accretion
WW 126	+75.2	+1.68	0.459	Accretion
CM 129	+101.6	+1.87	0.459	Accretion
CM 130	+24.3	+0.54	0.232	Accretion
CM 131	+73.2	+1.03	0.129	Accretion
CM 132	+105.9	+4.62	0.841	Accretion
CM 133	+50.3	+2.47	0.786	Accretion
CM 134	−11.6	−0.53	0.781	Erosion
CM 135	−12.3	−0.34	0.692	Erosion

4.1.2. Role of Chronic and Acute Forcings

Sea-Level Rise as a Chronic Stressor

Relative sea-level data from the Atlantic City tide gauge (1966–2024) show a significant upward trend (0.42 mm/yr; $p < 0.001$), resulting in a cumulative rise of ~0.30 m (Figure 7). This rising baseline enhances wave run-up, increases inundation frequency, and intensifies erosion pressures across the study area.

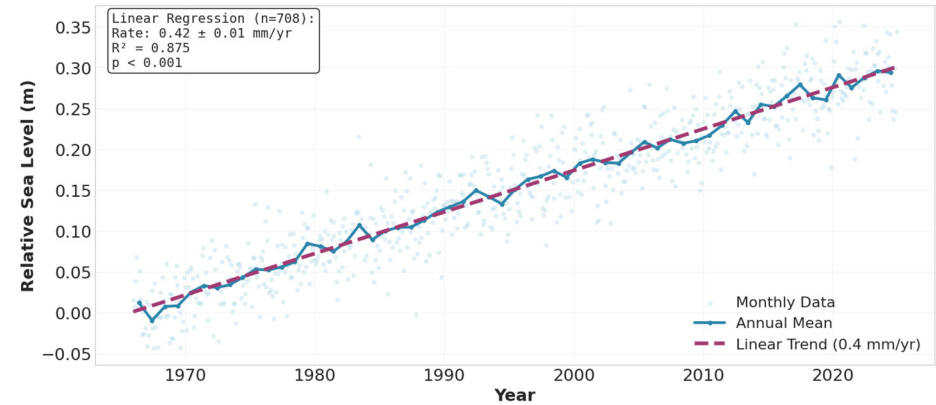


Figure 7. Relative Sea level change 1966–2024 (WIS 8536110 station).

Storm Frequency and Event Characteristics

Storm-event analysis for the Cape May region (1996–2025) identifies a total of 187 high-energy events (Figure 8). Coastal floods constitute the majority of events (140; 75%). Additional drivers include storm surge/tide events (32; 17%), winter storms (34; 18%), and tropical storms (15; 8%). The 2003–2005 cluster accounts for nearly one-quarter of all surge- and flood-related events, emphasizing the episodic nature of acute coastal forcing.

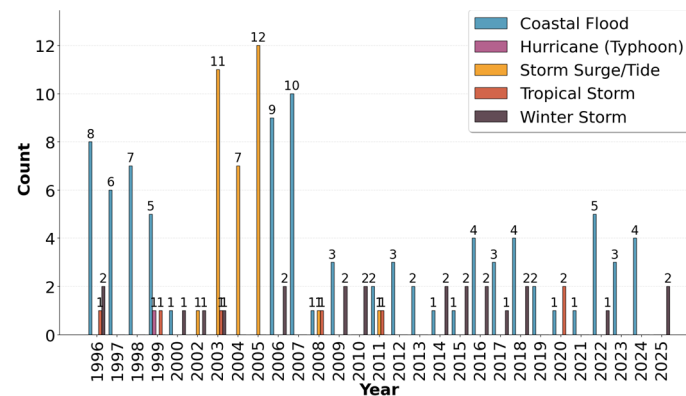


Figure 8. Major events occurred in the Cape May region from 1996 to 2025. Coastal flooding events are prominent throughout the period.

Wave Climate and Storm-Level Wave Conditions

The offshore wave record from WIS ST63152 wave record (1980–2024) shows a mesotidal regime with a mean H_s of 0.85 ± 0.15 m (Figure 9). Full dataset is in Table S2.

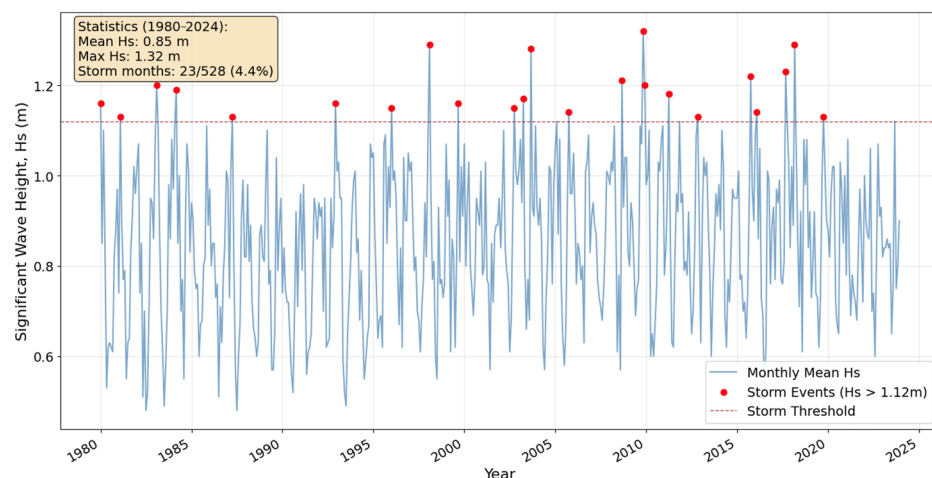


Figure 9. Temporal variation in the significant wave height (H_s) (m), data from WIS station 63152, 1980–2024.

Storm-level waves (>95th percentile; $H_s > 1.25$ m for ≥ 12 h [44]) occurred 8–12 times annually. Wave conditions were most energetic in winter (H_s is 40% higher than in the summer), consistent with prior regional analyses [18].

Wind–wave coupling (Figure 10) shows a moderate correlation ($r = 0.72$, $R^2 = 0.63$), indicating local wind-driven wave generation has some control of the wave climate to some extent [45]. Waves predominantly approach from the northeast, reinforcing the strong southerly longshore transport.

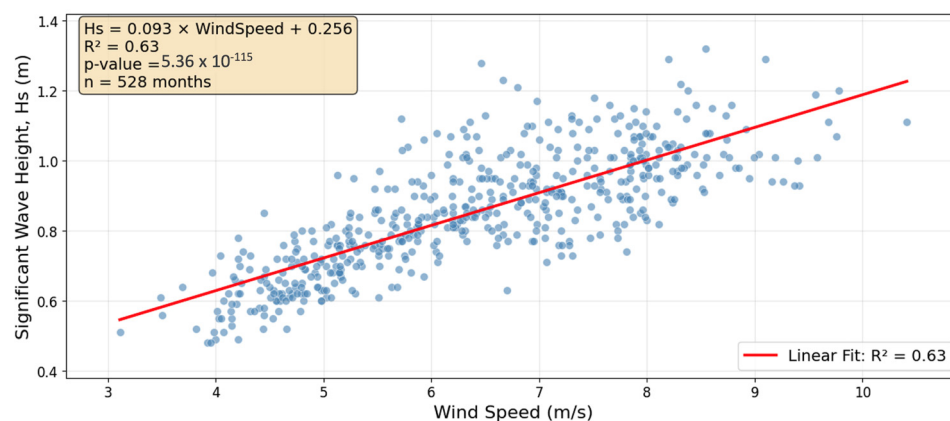


Figure 10. Correlation Between Wind Speed (m/s) and Significant Wave Height (Hs) (m), WIS Station 63152 Cape May (1980–2024).

Correlation Between Forcings and Shoreline Change

Despite this energetic climate, correlations between annual H_s and shoreline change (HTL variation) were weak and statistically insignificant at both sites (Wildwood: $r = 0.44$, $R^2 = 0.195$; Cape May: $r = -0.20$, $R^2 = 0.05$) (Figure 11). Although cumulative wave-energy metrics (e.g., annual sums of H_s^2 or wave power) can provide insight into broader energetic conditions, correlating these with shoreline position requires high-frequency shoreline measurements. Because shoreline positions in this study are available only as annual snapshots, cumulative wave-energy indices could not be meaningfully linked to shoreline change. Preliminary inspection of high-energy years (e.g., 2003–2005) showed no consistent shoreline response, further supporting the limited influence of wave climate relative to nourishment-driven sediment supply.

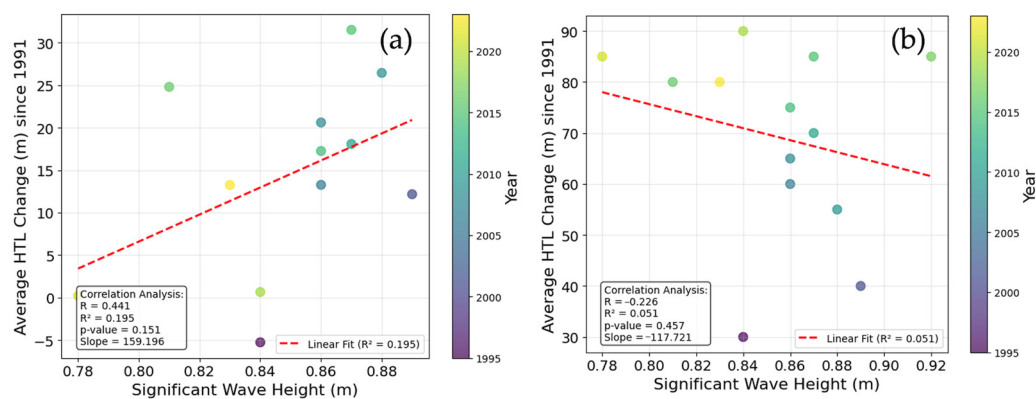


Figure 11. The correlation between the average significant wave height (H_s) and the average HTL change for (a) Wildwood, (b) Cape May beaches. Both show statistically insignificant correlation.

This disconnection between wave forcing and shoreline response underscores that both study areas have transitioned to human-dominated systems where the sedimentological legacy of nourishment and engineered structures overrides natural hydrodynamic controls.

4.2. Human Intervention: Nourishment Efficacy in a Dynamic System

Nourishment and Shoreline Response

Cape May has received ~11.1 million cubic yards of sediment since 1962, while Wildwood has received ~2.15 million cubic yards. Major nourishment events are summarized in Table 4. Beach nourishment episodes, including nourished beach length (ft) and volume (cubic yards) are given in Table S3.

Table 4. Beach Nourishment Summary (1962–2025).

Location	Total Volume (cy)	Major Events	Correlation with Shoreline Trends
Cape May	~11,115,545	1991: 1.37M cy 2005: 1.08M cy 2011–2023: Sustained program (>3.5M cy)	Strong: Direct correlation with accretion dominance (Oceanside EPR: +1.3 to +3.0 m/yr)
Wildwood	~2,150,000	2011–2024: Intensive program (>1.8M cy) 2024: 0.79M cy 1989–1991: 0.29M cy	Complex: Subsidizes natural transport; severe erosion persists in the north (EPR: −10.0 m/yr) while feeding southern accretion (EPR: +1.2 to +4.7 m/yr)

Wildwood nourishment has been episodic and insufficient to counter strong longshore transport. Northern stations continue to undergo severe retreat (e.g., WW 121, ~10 m/yr) while southwards accretion (EPR ~+4.7 m/yr) remains high due to sediment redistribution and nourishment pulses (Figure 12). Less frequent, larger-scale nourishments in Wildwood are mismatched with its high-energy, alongshore-dominated system, resulting in a “sediment conveyor belt” effect [46,47].

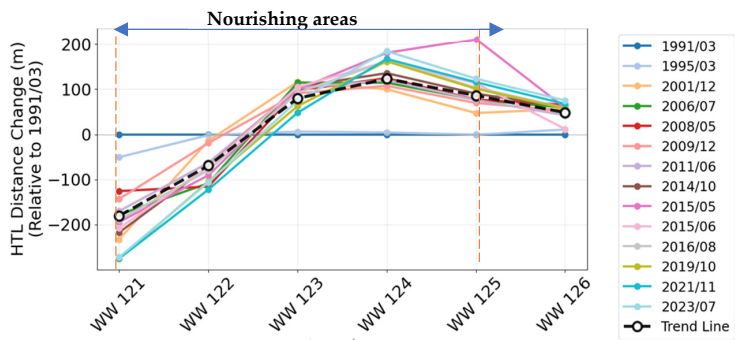


Figure 12. Annual HTL variation (as a shoreline movement indicator) indicates the continuous retreat in the North Wildwood and advance in central and southern Wildwood.

Nourishment acts as a transient subsidy rather than a stabilizing mechanism, maintaining Wildwood in a state of persistent transition. Cape May’s sustained, high-volume, strategically timed nourishment has produced a stable accretional regime. Stations CM 132 and CM 133, once erosion-prone, now show strong, consistent progradation (Figure 13). The alignment of nourishment with local hydrodynamics supports a managed equilibrium.

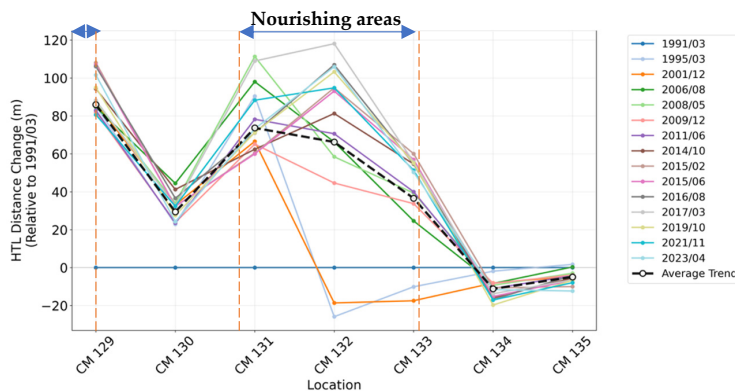


Figure 13. Annual variation in HTL compared to 1991, in Cape May. Nourishment has successfully caused the accretion of historically retreating locations, such as CM 132 and CM 133. Bayside shows temporal erosion while CM 134 shows the highest shoreline retreat.

4.3. Sedimentological Transformation

4.3.1. Sediment Characteristics: 1950 vs. 2024

A direct comparison of beach sediments from the pre-nourishment era (1950) and the contemporary managed era (2024) reveals a fundamental and universal sedimentological transformation driven by decades of beach nourishment. The summary of grain size analysis results of Wildwood and Cape May 2024 (after multiple nourishment episodes) is shown in Table 5.

Table 5. The summary of the 2024 HTL grain size analysis results of Wildwood and Cape May.

Transect	Modality	Mean Grain Size (μm)	Median Grain Size (μm)	Sorting (Folk & Ward, ϕ)	Skewness (ϕ)	% Gravel	% Sand	Sediment Description
WW 121	Unimodal	445–463	483.8	0.37–0.64	0.36 to 0.72	0%	>99.9%	Well Sorted to Moderately Well Sorted Medium Sand
WW 122	Unimodal/Bimodal	449–464	482.6	0.36–0.58	0.36 to 0.69	0%	100%	Well Sorted to Moderately Well Sorted Medium Sand
WW 123	Bimodal	411–461	467.2	0.45–0.65	0.59 to 0.66	0%	100%	Moderately Well-Sorted Medium Sand
WW 124	Bimodal	438–456	475.0	0.47–0.62	0.59 to 0.69	0%	100%	Moderately Well Sorted to Well Sorted Medium Sand
WW 125	Bimodal	447–458	474.5	0.46–0.50	0.58 to 0.59	0%	100%	Well Sorted Medium Sand
WW 126	Bimodal	451–468	478.1	0.30–0.46	0.30 to 0.59	0%	100%	Well Sorted to Very Well Sorted Medium Sand
CM 129	Unimodal	498–505	501.1	0.16–0.17	0.00 to −0.16	0%	100%	Very Well Sorted Coarse-Medium Sand
CM 130	Unimodal	497–503	499.1	0.16–0.20	0.00 to −0.14	0%	100%	Very Well Sorted Medium-Coarse Sand
CM 131	Unimodal	500–512	505.2	0.16–0.23	−0.19 to 0.00	0%	100%	Very Well Sorted Coarse Sand
CM 132	Unimodal	500–521	507.0	0.16–0.29	−0.32 to 0.00	0%	100%	Very Well Sorted Coarse Sand
CM 133	Unimodal	497–498	497.3	0.15–0.16	0.00	0%	100%	Very Well Sorted Medium Sand
CM 134	Trimodal	938–1142	982.3	0.91–1.11	−0.28 to −0.05	14–26%	74–86%	Poorly Moderately Sorted Gravelly Sand
CM 135	Unimodal	524–543	515.0	0.44–0.48	−0.09 to 0.06	0–1%	99–100%	Well Sorted Coarse Sand

Wildwood sediments are predominantly well- to moderately well-sorted medium sands with unimodal to bimodal distributions, reflecting mixing between nourishment sediment and native material [48,49]. The consistent positive skewness (very fine skewed) across all Wildwood transects (0.30 to 0.72 ϕ) indicates a fine-tailed distribution.

Cape May oceanside sediments are very well-sorted coarse-to-medium sands (mean grain size: 497–533 μm), whereas bayside sediments contain significant gravel fractions (14–26%) and multimodal textures. The skewness on the oceanside ranges from near-symmetrical to coarse-skewed (0.00 to −0.32 ϕ), a signature of a winnowing environment where finer fractions have been efficiently removed, leaving a lag of coarser material [17,48]. This contrast reflects different energy regimes, with ocean-side sediments experiencing consistent wave reworking that produces well-sorted sands [50], while bayside areas receive mixed sediment inputs from both marine and terrestrial sources, resulting in poorer sorting and higher gravel content [13,48,49].

Pre-nourishment (1950) sediment data are shown in Table 6. The 1950 dataset reveals two distinct sediment populations: (1) Wildwood and northern Cape May (CM 129–130), composed of homogeneous, very well-sorted fine sand, and (2) central to southern Cape May (CM 131–135) composed of coarse, more heterogeneous sands and gravel.

The consistently positive skewness across all samples indicates these deposits are fine-skewed. This division suggests fundamentally different sediment sources or wave energy conditions between these two areas at the time [48,51].

Table 6. Grain size analysis data from 1950 McMaster’s data [13].

Location	Median Grain Size (μm)	Sorting (φ)	Skewness	Sediment Description
WW 121	175	0.18	1.01	Very Well Sorted Fine Sand
WW 122	159	0.24	0.99	Very Well Sorted Fine Sand
WW 123	160	0.14	0.99	Very Well Sorted Fine Sand
WW 124	166	0.20	0.99	Very Well Sorted Fine Sand
WW 125	153	0.17	1.03	Very Well Sorted Fine Sand
WW 126	177	0.23	0.99	Very Well Sorted Fine Sand
CM 129	157	0.18	1.07	Very Well Sorted Fine Sand
CM 130	182	0.23	1.00	Very Well Sorted Fine Sand
CM 131	351	0.91	1.53	Poorly Sorted Medium Sand
CM 132	326	0.41	0.97	Well Sorted Medium Sand
CM 133	335	0.33	1.03	Well Sorted Medium Sand
CM 134	760	0.37	1.00	Well Sorted Coarse Sand
CM 135	435	0.78	1.70	Moderately Sorted Medium Sand

4.3.2. Differentiation Between Pre and Post-Nourishment Sediment Characteristics

All sites exhibit significant coarsening from 1950 to 2024 (Figure 14a). Wildwood shows an average increase of 312 μm, while Cape May increases by ~209 μm. The most extreme coarsening occurs at CM 134 (+222 μm), consistent with high-energy reworking and mixed sediment inputs. Sorting has universally degraded (Figure 14b). Wildwood transitioned from very well-sorted fine sands to moderately well-sorted sands, indicating incomplete textural equilibration following nourishment. Cape May’s sorting responses vary, reflecting multiple sediment sources, reworking processes, and intervention history. Together, these patterns highlight divergent sedimentological pathways: Wildwood remains in transition due to episodic nourishment and strong longshore transport, while Cape May exhibits multiple equilibrium states shaped by sustained sediment inputs and complex hydrodynamics.

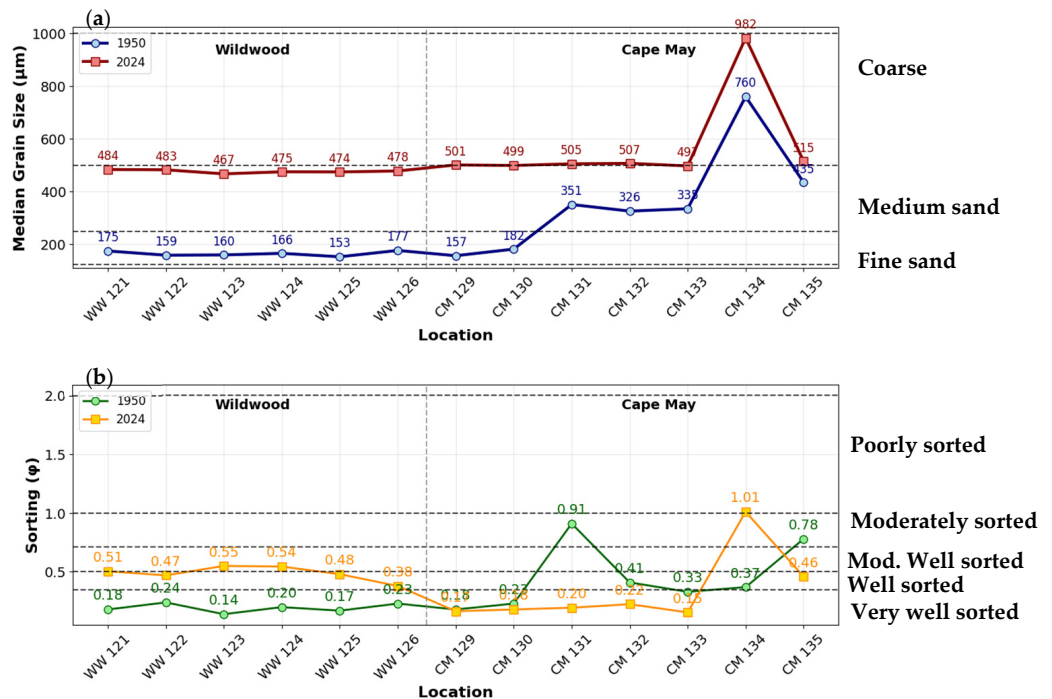


Figure 14. (a) Median grain size (D₅₀) in Wildwood and Cape May 1950 and 2024 (b) Sorting values of Wildwood and Cape May sampling stations in 1950 and 2024.

5. Discussion

5.1. Anthropogenic Sediment Supply as the New Dominant Control on Shoreline Dynamics

The multi-decadal dataset compels a fundamental reinterpretation of the primary drivers of shoreline change on these managed coasts. The findings demonstrate that the classical model of coastal evolution, where shoreline position is principally a function of wave energy and sea level rise [52–55] has been superseded. This divergence from expected wave-driven shoreline behavior indicates a breakdown of classical shoreline equilibrium assumptions, highlighting nourishment as the dominant forcing mechanism [16,20,21]. In its place, a new model emerges where the massive, cyclic input of anthropogenic sediment from beach nourishment is the dominant control on shoreline behavior, effectively decoupling the system from its natural forcings [56].

This is most strongly illustrated by the contrast between Wildwood and Cape May. The catastrophic erosion at WW 121 (EPR ~ -10.0 m/yr; Net HTL Change -272.2 m) contrasted with the dramatic accretion at WW 124 (EPR $\sim +4.7$ m/yr; Net HTL Change $+184.5$ m) is not a failure of nourishment but rather a direct manifestation of its localized impact within a high-energy transport system. The sediment introduced during episodic nourishments does not stabilize the northern shoreline. Instead, it is rapidly mobilized, effectively subsidizing the natural southerly longshore drift and fueling accretion downdrift. In Wildwood, nourishment has become the primary sediment source for a pre-existing natural process, creating a sediment conveyor belt that perpetuates a state of ‘Persistent Transition’ [46].

Conversely, Cape May’s widespread oceanside accretion with 79% of transects advancing at an average rate of $+1.15$ m/yr is a direct testament to the scale and frequency of its nourishment program. The placement of over 11 million cubic yards of sand has fundamentally altered the sediment budget, saturating the local transport system. This massive anthropogenic supply has effectively buffered the shoreline against erosional pressures from sea level rise and storm impacts [57,58], creating a sediment-rich system that can prograde despite ongoing natural forcings. The transition of historically erosional areas like CM 132 into accretion hotspots (EPR $\sim +3.0$ m/yr) signifies the achievement of a human-maintained ‘Managed Equilibrium’.

The statistically insignificant correlation between significant wave height and shoreline change at both sites ($R^2 < 0.20$) provides quantitative proof of this model shift. If natural wave energy were the primary control, the energetic winter months and storm events would reveal a clear, correlative signal on shoreline position [53]. The absence of a statistically significant correlation indicates that the influence of short-term wave forcing is masked by the dominant influence of episodic sediment inputs from nourishment [53]. This decoupling highlights that for intensively managed coastlines like these, understanding the nourishment cycle is more critical for predicting future shoreline position than analyzing the wave climate alone.

5.2. The Anthropogenic Imprint on Beach Sedimentology

Analysis of the seven-decade sedimentological record yields definitive stratigraphic and textural evidence that beach nourishment constitutes a sustained geological alteration, not a transient geomorphic adjustment, fundamentally resetting the inherent sedimentological character of the coastal zone. The universal and pronounced coarsening observed across both study areas with median grain sizes shifting from fine sand ($153\text{--}435\text{ }\mu\text{m}$) to medium and coarse sand ($467\text{--}982\text{ }\mu\text{m}$) serves as a direct sedimentological fingerprint of the nourishment practice. This shift is primarily the result of sourcing sand from offshore borrow sites, which typically contain coarser sediments compared to the well-sorted native beach sands [16,17,48].

Beyond coarsening, the degradation in sediment sorting from the Very Well Sorted condition of the pre-nourishment era [13] to predominantly Moderately Well Sorted modern sediments is a critical indicator of a system in a prolonged state of textural disequilibrium [59]. These patterns are consistent with selective transport theory, whereby hydrodynamic winnowing preferentially removes fine sediments while retaining coarser fractions, generating the coarse-skewed, bimodal, and poorly sorted textures documented in this study [22]. This textural immaturity directly affects coastal processes by modifying infiltration rates, altering beach-face hydrodynamics, and influencing erosional thresholds during storms, thereby reshaping the resilience of the coastline [16,48,49,59].

This phenomenon is particularly evident in Wildwood, where widespread bimodality reflects an active, hybrid sediment body in which native and nourishment sands remain incompletely mixed. The consistently positive skewness further confirms the persistence of the fine native fraction amid the newer, coarser material, highlighting ongoing sedimentary adjustment. In contrast, Cape May's oceanside has achieved near-symmetrical to coarse-skewed, well-sorted sediment distributions, suggesting that a longer history of frequent reworking has led to a new, human-maintained textural equilibrium. The sedimentology of the un-nourished bayside reflects natural erosional processes. Although coarsening is also observed there, the extreme shift at CM 134 to a very coarse, poorly sorted, gravelly sand with coarse skewness represents a classical lag deposit, where wave action selectively removes finer fractions in an erosional setting [59,60]. This signature indicates sediment starvation and selective erosion rather than purposeful sediment addition [13,59,61].

5.3. The Management Paradox: Divergent Outcomes from Nourishment Strategies

The synthesis of multi-decadal shoreline change, nourishment history, and sedimentological data reveals that the contrasting states of Cape May and Wildwood are not coincidental; they are the predictable outcomes of the interaction between management strategy and local hydrodynamics. These interactions have pushed each coastal system onto a distinct evolutionary pathway; *Managed Equilibrium* in Cape May and *Persistent Transition* in Wildwood. The contrasting behaviors align with sediment-budget theory: Cape May functions as a sediment-rich cell capable of maintaining equilibrium, while Wildwood remains sediment-deficient and therefore highly sensitive to longshore transport gradients [22].

Cape May's strongly accretional trend reflects the establishment of a new, human-defined equilibrium state. This *Managed Equilibrium* is not analogous to a natural steady state; rather, it is maintained through strategic, high-frequency nourishment that continually replenishes the sediment budget and pre-emptively offsets erosional forces [55]. The consistent shoreline advance across 79% of transects is therefore not simply a cumulative response to discrete nourishment events but an indication that the baseline sediment budget has been fundamentally reset to a human-maintained, sediment-rich state. This management predictability allows the beach morphology and sedimentological characteristics to mature into a stable, though anthropogenic, configuration [16,48,62].

In contrast, the episodic nourishment strategy employed in Wildwood North is unable to overcome the dominant natural process that shapes the system: a strong, persistent southerly longshore current. High-volume sediment placements, such as the 2024 project, are insufficient to saturate the transport system. As a result, nourishment does not stabilize the shoreline but instead acts as a temporary sediment subsidy that is rapidly redistributed alongshore. This dynamic perpetuates a continual cycle of adjustment, trapping Wildwood in a state of *Persistent Transition*. In this regime, the northern reaches experience repeated, catastrophic erosion as new sediment is immediately mobilized, while the southern sectors accrete from the redistributed nourishment sand.

This behavior is mirrored in the sedimentology. Wildwood's sediments exhibit persistent bimodality, positive skewness, and only moderate sorting. These are signs of a hybrid sediment assemblage that is continually mixed but never afforded sufficient time or stability to achieve textural maturity [63,64]. Each new nourishment pulse reintroduces textural disequilibrium, resetting the adjustment process before the system can reach stabilization. Therefore, while Cape May has been engineered into a stable anthropogenic state, Wildwood remains locked in a cycle driven by a mismatch between nourishment strategy and inherent sediment transport dynamics.

5.4. An Integrated Conceptual Model of Managed Beach Evolution

Figure 15 illustrates a four-phase conceptual model of managed beach evolution under repeated human intervention. The model integrates shoreline-change trends, hydrodynamic forcings, nourishment history, and sedimentological transformations observed in Cape May and Wildwood, situating them within the broader context of the Anthropocene, in which human actions function as primary geological drivers. Each phase represents a distinct combination of anthropogenic forcing, sedimentary state, and morphodynamic adjustment, and each corresponds directly to the empirical patterns documented in this study. In this framework, beach nourishment operates not merely as an engineering activity but as an Anthropocene process that alters sediment budgets, resets equilibrium conditions, and establishes new, human-maintained evolutionary trajectories, ranging from the Managed Equilibrium seen in Cape May to the Persistent Transition characterizing Wildwood.

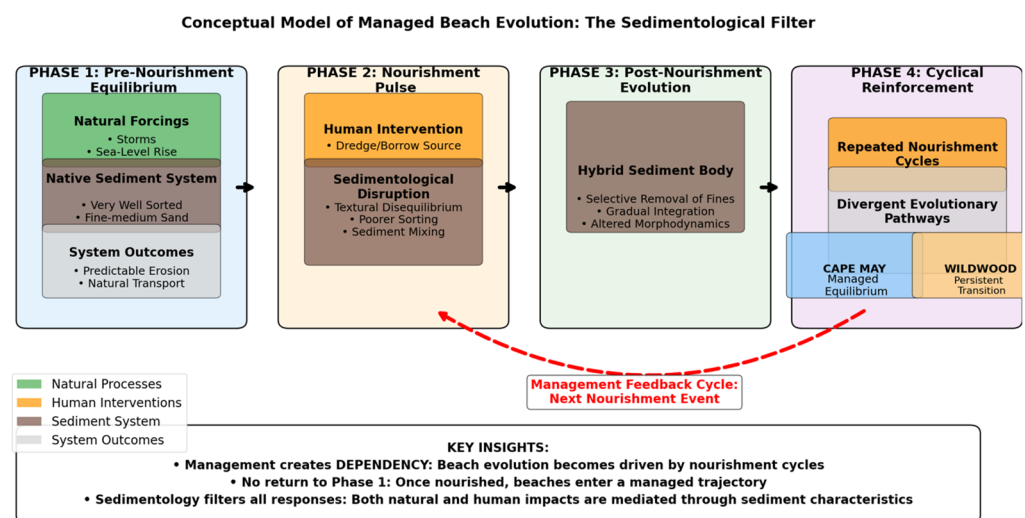


Figure 15. The four-phase conceptual model of managed beach evolution, from Pre-Nourishment Equilibrium through the Nourishment Pulse to Post-Nourishment Evolution, culminating in divergent management pathways.

This model consists of four sequential phases, each representing a transformation in the sediment system:

Phase 1: Pre-Nourishment Equilibrium.

Phase 1 represents the pre-Anthropocene coastal state in which shoreline behavior and sediment characteristics were governed entirely by natural forcings. Prior to human intervention, the beaches of Cape May and Wildwood functioned as naturally regulated systems shaped by the balance among wave climate, sediment supply, storms, and relative sea-level rise. The well-sorted fine-to-medium sands documented in the 1950 dataset reflect a stable native sediment system operating within this natural morphodynamic equilibrium. In this phase, shoreline change followed predictable responses to hydrodynamic forcing, and

sediment budgets were controlled solely by natural sources and sinks. This state serves as the reference baseline against which all subsequent, human-altered phases must be interpreted.

Phase 2: The Nourishment Pulse.

Phase 2 marks the point at which anthropogenic forcing enters the coastal sediment system. The first nourishment event introduces a large-volume pulse of sediment typically coarser, more poorly sorted, and compositionally distinct, sourced from offshore borrow areas. This abrupt external input disrupts the natural equilibrium described in Phase 1 and shifts the system into a state of pronounced textural and morphodynamic disequilibrium. In the context of the Anthropocene, this phase represents a fundamental transition in which human activity overtakes natural sediment supply as the dominant geological process. Empirically, this shift is reflected in the documented grain-size jump from fine native sands (153–435 μm) to medium–coarse nourishment sands (467–982 μm) and the corresponding decline in sorting quality. This disruption sets the path for all later beach evolution, affecting both the possibility and pace of system re-equilibration.

Phase 3: Post-Nourishment Evolution.

Phase 3 marks the beginning of the beach's adjustment to the anthropogenic disturbance introduced in Phase 2. After placement, the nourishment sand enters an extended period of reorganization in which natural processes, including selective winnowing, cross-shore sediment exchanges, bar migration, and longshore transport act as sedimentological filters. Finer fractions are preferentially removed, while coarser particles accumulate, gradually integrating the nourishment material into the native sediment system. The pace and direction of this adjustment depend strongly on local hydrodynamics, shoreline orientation, and the intensity of longshore transport. During this stage, the beach no longer behaves as a natural system but as an Anthropocene hybrid whose morphodynamic trajectory is controlled by the interaction between natural processes and engineered sediment supply. The hybrid sediment body begins to develop new textural and morphological signatures, such as coarsening, bimodality, or improved sorting, depending on the balance between sediment inputs and transport capacity.

The contrasting results from this study illustrate the divergence of outcomes within this phase. Cape May, with frequent nourishment and moderate transport gradients, shows evidence of progressive sorting and stabilization. This indicates movement toward a human-maintained equilibrium. Wildwood, dominated by strong southerly longshore drift, remains in a state of perpetual readjustment. Nourishment material is rapidly redistributed, preventing the hybrid sediment body from maturing. In this sense, Phase 3 represents the crucial inflection point where nourished coasts either evolve toward stability or remain trapped in continued adjustment.

Phase 4: Cyclical Reinforcement and Divergent Pathways.

Phase 4 represents the long-term, cumulative consequences of repeated nourishment in an Anthropocene coastal system. Once nourishment becomes a recurring management intervention, its effects are no longer episodic but structural: each sediment pulse feeds back into the evolving morphodynamic system, reinforcing or destabilizing the trajectory set during earlier phases.

Two dominant pathways emerge:

(a) Managed Equilibrium (e.g., Cape May).

In settings where nourishment frequency and volume are sufficient to saturate local sediment transport, the system accumulates a sustained sediment surplus. Over successive nourishment cycles, selective winnowing, frequent reworking, and cross-shore exchanges gradually refine the hybrid sediment body, improving sorting and producing a stable beach morphology. This repeated anthropogenic input creates a human-maintained equilibrium, which is a predictable shoreline position, reduced erosional variability, and long-term

sedimentological maturity. Cape May exemplifies this pathway: decades of regular nourishment have produced consistent accretion, well-sorted sands, and morphodynamic stability despite ongoing natural forcing.

(b) Persistent Transition (e.g., Wildwood).

Where natural transport processes exceed the capacity of nourishment additions, repeated interventions do not move the system toward stability but continually reset it. Episodic, high-volume placements reintroduce coarse, poorly sorted sediment that is rapidly redistributed alongshore before it can equilibrate. Each nourishment cycle thus reinforces a state of perpetual adjustment, preventing the hybrid sediment body from maturing. Wildwood illustrates this condition: strong southerly longshore drift mobilizes nourishment sand almost immediately, producing chronic erosion in the north and transient accretion in the south. The system remains locked in an Anthropocene disequilibrium where management inputs cannot keep pace with natural transport gradients.

This conceptual model highlights two critical principles for coastal management. (a) Management Creates Dependency. The first nourishment event irreversibly shifts the beach onto a managed trajectory. Natural resilience is replaced by dependence on the timing, volume, and frequency of future nourishment cycles. Once this trajectory begins, returning to a pre-nourishment state is no longer possible. (b) The Primacy of the Sedimentological Filter. Sediment characteristics such as grain size, sorting, and modality, are not passive descriptors but active controls governing coastal evolution. These properties dictate thresholds for erosion, transport efficiency, ecological compatibility, and the long-term cost and sustainability of management strategies. Ultimately, it is the sedimentological signature of nourishment, not simply the added volume, that determines the system's future directions.

5.5. Broader Implications and Future Expectations

The multi-decadal evolution of Cape May and Wildwood demonstrates that beach nourishment is not simply an engineering intervention but a transformative geological force. The divergent evolutionary pathways of these adjacent coastlines reveal insights with wide-reaching implications for coastal geomorphology, management policy, ecology, and climate adaptation.

First, the results show that human intervention can surpass natural hydrodynamic controls, producing new anthropogenic landforms that diverge fundamentally from natural equilibrium states [15,64]. The shift from a natural, sediment-limited system to either a *Managed Equilibrium* (Cape May) or *Persistent Transition* (Wildwood) marks a paradigm shift in coastal geomorphic theory. The finding that wave energy accounts for less than 15% of shoreline variability in the study area, confirms that the sedimentological legacy of nourishment, together with engineered structures, overwhelmingly dictates shoreline behavior. This challenges traditional coastal evolution models and demands a new framework where coastal systems are understood as hybrid natural-human landscapes.

The sedimentological transformations documented in this study have direct and far-reaching socioeconomic consequences for tourism-dependent coastal communities. Coarsening of beach sediment steepens the beach face, causing waves to break closer to shore and creating less safe swimming conditions, which in turn elevates lifeguard intervention rates and reduces recreational quality [65–67]. These physical changes diminish visitor satisfaction and can undermine the economic reliability of destinations such as North Wildwood, where severe erosion and frequent emergency nourishment cycles reduce both esthetic appeal and functional beach width during peak tourism months. The financial implications for municipalities are substantial: repeated emergency nourishments require multimillion-dollar expenditures, temporary beach closures, and increased operational

costs associated with dredging and equipment mobilization. Property values and local investment confidence are also affected as rapidly retreating shorelines elevate insurance premiums and long-term risk exposure for oceanfront infrastructure. In contrast, Cape May's Managed Equilibrium, achieved through consistent, strategically timed nourishment supports more predictable beach conditions, stabilizes recreational use, and reduces the need for costly emergency interventions. These divergent outcomes demonstrate that sedimentological characteristics are not merely geological descriptors but central determinants of fiscal sustainability, tourism resilience, and long-term coastal management costs.

Thirdly, the ecological consequences of nourishment-driven sediment coarsening are substantial. Historically, the native, well-sorted fine sands along Cape May and Wildwood supported diverse invertebrate communities such as the Atlantic mole crab (*Emerita talpoida*), surf clams (*Donax variabilis*), and sand fiddler crabs (*Uca pugilator*), all of which rely on fine, mobile, easily borrowable substrates for feeding, respiration, refuge, and reproductive success [68,69]. Studies show that increases in grain size and decreases in sorting significantly reduce burrowing efficiency, elevate predation risk, disrupt feeding behaviors, and lower recruitment success [70,71]. Because these benthic organisms form the primary prey base for many shorebirds, sediment coarsening has cascading effects on higher trophic levels [72]. Shorebirds, including the piping plover and red knot, as well as sea turtles require specific sediment textures to maintain nest stability, thermal conditions, and substrate workability [73,74]. Shorebirds such as Piping plovers and Least Terns prefer coarse sand for nesting [75]. Coarser, poorly sorted sands diminish habitat suitability for intertidal macroinvertebrates by altering moisture regimes, increasing compaction, and reducing the availability of burrowable substrate [72,76]. Collectively, these habitat modifications demonstrate that nourishment-induced changes to sediment texture are not merely geomorphic transformations but represent ecological shifts that can affect biodiversity, trophic interactions, and long-term habitat resilience. These findings underscore the need for sedimentologically compatible nourishment strategies that preserve ecological function alongside geomorphic performance.

Finally, the resilience of managed coastlines under accelerating climate change will hinge on their sedimentological and morphological states [77]. A beach in *Managed Equilibrium* with a mature, integrated sediment body may be more capable of accommodating sea-level rise through gradual landward migration or vertical accretion. Conversely, a beach locked in *Persistent Transition* faces higher vulnerability. Its continual textural disequilibrium and rapid sediment loss rates will demand ever-increasing nourishment volumes to maintain position against rising seas. Thus, the future of coastal defense depends on sedimentologically intelligent management, emphasizing long-term textural stability rather than short-term volumetric gain. Ultimately, the characteristics of the sand placed today will determine the cost, sustainability, and feasibility of protection decades into the future.

5.6. Limitations

While this study presents a comprehensive, multi-decadal assessment of managed beach evolution, several limitations must be acknowledged. The shoreline change analysis, although spanning 33 years, is derived from discrete shoreline positions that may not fully capture the rapid erosion–recovery cycles occurring between image timestamps. Consequently, some high-frequency variability associated with individual storms or nourishment events may be smoothed out. Moreover, the DSAS- and HTL-based analyses emphasize planform shoreline position, which, although widely used and highly informative, do not account for three-dimensional morphological adjustments such as beach profile volume changes, dune evolution, or offshore bar dynamics. These processes play an important role in determining sediment budgets and coastal resilience.

Similarly, while the grain-size analysis reveals robust sedimentological trends, it is based on point sampling conducted exclusively at the high tide line. Sediment characteristics across the full active coastal profile, from the dune system to the surf zone are likely more variable than captured here, and our approach may not fully represent cross-shore sorting complexities. This limitation means that the interpretations presented here focus on alongshore and temporal textural trends rather than detailed cross-shore facies variability. Additionally, although the correlation analysis demonstrated a weak direct relationship between significant wave height and shoreline change, it could not isolate the relative influence of other interacting controls, such as nourishment-derived sediment supply, gradients in longshore transport, and the localized effects of coastal structures. While cumulative storm-wave energy could be calculated from WIS data, the annual temporal resolution of shoreline imagery prevents quantitative assessment of how cumulative or lagged energy affects shoreline movement.

Despite these limitations, the strong and internally consistent signals observed across both study sites, two adjacent but morphodynamically divergent systems, provide high confidence in the central conclusions. The evidence robustly supports the existence of distinct evolutionary pathways and underscores the dominant role of sedimentology in shaping the long-term trajectories of managed beaches.

6. Conclusions

This multi-decadal synthesis has linked shoreline change, environmental forcings, and sedimentological resilience to reveal the fundamental principles governing nourished beach evolution in Wildwood and Cape May, New Jersey. The findings demonstrate that on heavily managed coastlines, the classic model of coastal change, driven primarily by wave climate and sea-level rise, has been superseded by an anthropogenic paradigm.

Our analysis shows that while chronic sea-level rise and episodic storms shape the environmental background, their ability to explain shoreline variability is secondary to the strongest influence of human sediment supply. The effectiveness of nourishment is governed not only by the volume of sediment added but also by its texture. The system-wide coarsening and deterioration in sorting documented since the pre-nourishment era is the clearest sedimentological signature of human intervention. This ‘sedimentological filter’ determines the system’s resilience, influencing whether nourishment drives the shoreline toward a stable Managed Equilibrium or an unstable Persistent Transition. These results underscore that nourishment must be understood within the theoretical context of sediment budgets and morphodynamic equilibrium, as its sedimentological signature governs long-term coastal behavior.

The conceptual model developed here provides a framework applicable to managed coastlines worldwide. It demonstrates that nourishment functions as a geological forcing agent, setting the system on a new evolutionary trajectory in which the natural equilibrium state is effectively lost. Long-term coastal resilience, therefore, depends on shifting from reactive volumetric nourishment to proactive sedimentological management. Ensuring textural compatibility between nourishment sand and native sediments is not a minor engineering consideration but the most critical factor for achieving ecological sustainability, economic viability, and geomorphic stability in an era of accelerating sea-level rise.

Supplementary Materials: The following supporting information can be downloaded at: <https://www.mdpi.com/article/10.3390/jmse13122408/s1>, Table S1: Change of HTL in meters (1991 as baseline) in Wildwood and Cape May. Negative values show HTL retreat, and positive values show HTL advancement. Measured using Google Earth Pro (v.7.3.6.10441) Satellite images; Table S2: Average wave climate data (Significant wave Height H_s , Wave period T_p , Wind speed, Wind direction,

wave direction). Data from WIS station 631652 [39]; Table S3: Beach nourishment history of Wildwood and Cape May beaches [7,32].

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