Topography and Shoreline Position Are Associated with Hurricane Flood Exposure of Beach-Nesting Birds on an Urban Barrier Island

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Abstract

Beach- and marine-nesting birds are increasingly exposed to coastal flooding as sea-level rise and extreme storms alter nesting habitat. We evaluated associations between local topography, shoreline position, and Hurricane Erin flood exposure at two sectors of the Rockaway Peninsula, New York City: Beach 37th-56th St. and Breezy Point Ocean Side. During 15 weekly surveys from late April to early August 2025, nest locations were recorded and characterized by local beach slope and minimum distance to the high-tide line. Moran's I with permutation tests evaluated spatial autocorrelation across 50-200 m neighborhood thresholds. Hurricane exposure was determined by overlaying nest locations with the observed flood extent. Exposed and unexposed locations at Beach 37th-56th St. were compared using Mann-Whitney U tests and rank-biserial effect sizes. Shoreline distance showed consistent positive spatial autocorrelation at Beach 37th-56th St., but none was detected at Ocean Side. Local beach slope was positively spatially autocorrelated at both sites across all thresholds. Hurricane flooding encompassed 11 of 65 nest locations (16.9%) at Beach 37th-56th St. and all 32 locations (100%) at Ocean Side. Within Beach 37th-56th St., exposed locations occurred closer to the high-tide line than unexposed locations (median: 28.5 vs. 81.5 m; $p < 0.001;\ |r_{rb}| = 1.00$), with no overlap in observed shoreline distances. Local slope also differed (1.23° vs. 3.29°; $p = 0.032;\ |r_{rb}| = 0.394$), although with greater overlap. These results indicate that storm-flood exposure was strongly associated with shoreline position, highlighting fine-scale physical habitat variation as an important consideration for coastal nesting-bird management.

Keywords: beach-nesting birds; coastal flooding; spatial autocorrelation; shoreline position; nest-site topography; Hurricane Erin.

Introduction

Shorebirds are experiencing substantial population declines worldwide, with some of the steepest losses reported among North American bird populations (Smith et al. 2023). Migratory species may be especially vulnerable because they depend on multiple habitats throughout the annual cycle and are exposed to habitat loss, disturbance, and climate-related environmental change across geographically separated regions (Austin and Rehfisch 2003, Koleček et al. 2021). Along coastal breeding areas, these pressures are further compounded by sea-level rise and changing flooding regimes, which can reduce habitat availability before nesting areas are permanently submerged (van de Pol et al. 2024). These concerns are particularly relevant along the Atlantic Coast, where several beach-nesting species of conservation interest -including Piping Plover (*Charadrius melodus*), American Oystercatcher (*Haematopus palliatus*), Least Tern (*Sternula antillarum*), and Common Tern (*Sterna hirundo*)- depend on dynamic beach habitats for reproduction (DEC 2026).

For birds nesting directly on beaches and barrier islands, exposure to coastal flooding is influenced not only by the magnitude of a storm, but also by the physical position of nests within the beach profile. Distance to the shoreline, local slope, berm and dune configuration, and other fine-scale geomorphic features can create marked differences in exposure over relatively short distances. Nesting habitat therefore cannot necessarily be treated as a

uniform sandy surface. At the same time, storms play a dual role in barrier-island systems: extreme flooding can inundate active nesting areas, whereas erosion, overwash, and sediment redistribution can also reorganize coastal morphology and create or remove future nesting habitat. This makes spatial heterogeneity a central component of how nesting areas respond to extreme events and sea-level rise (Austin and Rehfisch 2003, van de Pol et al. 2024).

Despite the recognized importance of coastal morphology, less is known about how simple nest-scale physical variables are spatially structured within individual nesting sectors and whether that structure corresponds to observed exposure during a specific storm event. The Rockaway Peninsula, New York City, provides a useful setting for examining this question within an urban barrier-island system that contains nesting areas with contrasting physical settings. We focused on Beach 37th-56th St., a managed urban sector with recreational use and seasonal protection, and Breezy Point Ocean Side, a less-developed oceanfront sector within the broader Breezy Point landscape. Rather than treating these sectors as replicates of "urban" and "natural" beach types, we used them as contrasting settings within the same barrier-island system.

We evaluated two complementary descriptors of nest-site position: minimum distance to the high-tide line, representing horizontal shoreline position, and local beach slope, representing local topographic configuration. We then asked whether these variables differed and covaried between sectors, whether they exhibited spatial autocorrelation across local neighborhood scales, and whether they were associated with the observed flood extent of Hurricane Erin. Specifically, we asked: (1) how do minimum distance to the high-tide line and local beach slope vary and covary between nesting sectors; (2) are these physical nest-site conditions spatially structured within each sector; and (3) do exposed and unexposed nest locations differ in shoreline position and local slope? We expected nest-site conditions to exhibit fine-scale spatial structures and predicted that, where both exposure states occurred, flooded locations would occur closer to the high-tide line and on lower local slopes.

Study Area

The study was conducted on the Rockaway Peninsula, a barrier-island system along the southern coast of Queens, New York City. The peninsula is characterized by substantial alongshore variability in geology, sediment availability, shoreface morphology, and shoreline behavior. Geophysical studies have shown that sediment thickness and active shoreface characteristics vary over relatively short spatial scales, reflecting differences in underlying geology, historical barrier evolution, natural morphologic features, and human modification (Wei et al. 2021, Wei and Miselis 2022). Coastal engineering has also influenced the peninsula through groins, dredging, and repeated beach-nourishment projects, which have contributed to spatially variable patterns of shoreline accretion and retreat (Janda et al. 2025). These characteristics make Rockaway an appropriate setting for examining fine-scale variation in nesting habitat within a single barrier-island system.

We focused on two ocean-facing nesting sectors with contrasting physical and management settings. Beach 37th-56th St. is in the eastern portion of Rockaway Beach within a densely urbanized and heavily used recreational coastline. Nesting areas in this portion of Rockaway are subject to active seasonal management, including monitoring, symbolic fencing, access restrictions, and protection of areas occupied by breeding Piping Plovers and other beach-nesting birds (Arndtsen 2022). The broader Rockaway Beach shoreline has also experienced repeated nourishment and engineering interventions that contribute to contemporary variation in beach width and shoreline morphology (Wei and Miselis 2022, Janda et al. 2025).

Breezy Point Ocean Side is located toward the western end of the Rockaway Peninsula within the broader Breezy Point landscape and Gateway National Recreation Area. This portion of the peninsula is directly exposed to the Atlantic Ocean and forms part of a highly dynamic sandy barrier environment shaped by longshore sediment transport, storm processes, and the historical influence of the Breezy Point jetty (Pendleton et al. 2005). Previous coastal-vulnerability assessments have characterized portions of Breezy Point as low-relief, sandy, and strongly

exposed to oceanic forcing (Hopper and Meixler 2016). Compared with Beach 37th-56th St., the Ocean Side sector represents a less-developed nesting setting, although both sectors occur within a peninsula whose morphology has been influenced by natural processes and human modification.

Methodology

Nest monitoring and spatial data collection

Nest monitoring was conducted once per week for 15 weeks from late April through early August 2025 at Beach 37th-56th St. and Breezy Point Ocean Side. Surveys were designed to document newly detected nests while minimizing disturbance to breeding birds. For each nest, species identity and egg count were recorded at the first observation. Repeated weekly detections of the same nest were not treated as additional records, so each nest contributed a single spatial observation to the dataset.

Nest locations were documented using a Garmin eTrex 10 GPS and a Vortex Fury HD 5000 10×42 rangefinder. When nests could be approached without compromising breeding activity, coordinates were recorded during the nesting season from accessible areas near established protection boundaries. For nests located in areas where direct access could increase disturbance, their positions were reconstructed after the breeding season using field observations, established reference points, rangefinder measurements, and GPS positioning. This procedure allowed nest locations to be incorporated into spatial analysis while reducing the need to approach active nests directly.

High-tide and Hurricane Erin flood mapping

To characterize shoreline position under regular tidal conditions, the high-tide line was mapped on four occasions during the 2025 breeding season using the Garmin eTrex 10 GPS. Surveys were conducted by walking the highest visible water line, primarily during periods associated with high spring tides. For subsequent analyses, the most landward GPS-recorded high-tide position observed during the season was retained as a conservative reference line for regular tidal exposure.

Flood extent associated with Hurricane Erin was mapped separately on August 21, 2025. GPS points were recorded along the observed landward limit of coastal flooding at each study sector and subsequently connected to represent the event-specific flood boundary. Nest locations were then classified according to whether they occurred inside or outside the mapped Hurricane Erin flood extent. This classification represents spatial exposure to the observed flood footprint and was not interpreted as direct evidence of nest failure, mortality, or physical damage.

Local beach slope estimation

Local beach slope was used to characterize topographic conditions associated with each nest location. Measurements were obtained with the rangefinder along cross-shore profiles oriented approximately perpendicular to the shoreline. For each profile, the instrument provided the horizontal distance R and the corresponding vertical elevation difference h between the lower beach reference position and the higher beach profile associated with the nest location. The local slope angle, θ, was expressed in degrees and used as a measure of local beach inclination, rather than absolute nest elevation above a fixed vertical datum. It was calculated as

$$\theta = \tan^{-1}\frac{h}{R}.$$

For each nest location, two physical variables were therefore retained for analysis: minimum distance to the mapped high-tide line (m) and local beach slope (°). Together, these variables describe complementary components of nest-site position: horizontal placement relative to the shoreline and local cross-shore topographic configuration.

Statistical and spatial analyses

Statistical analyses were conducted in *Python* using *SciPy* for descriptive statistics, correlation, linear regression, and nonparametric comparisons (Virtanen et al. 2020). Minimum distance to the high-tide line and local beach slope were first summarized separately for each study sector using measures of central tendency and dispersion

and visualized with histograms and empirical cumulative distribution functions. These descriptive analyses were used to characterize the typical conditions and the range of nest-site environments within each sector, allowing us to determine whether nest locations tended to occupy similar or contrasting shoreline positions and slopes.

The relationship between minimum distance to the high-tide line and local beach slope was evaluated using Pearson's correlation coefficient and simple linear regression. Pearson's r measures the direction and strength of a linear relationship between two variables: positive values indicate that both variables tend to increase together, negative values indicate that one tends to decrease as the other increases, and values near zero indicate little linear association. In this study, r was used to determine whether nest locations farther from the high-tide line tended to occur on steeper or gentler local slopes. Simple linear regression was used to describe the same relationship quantitatively through the regression slope and intercept. The slope indicates the average change in local beach slope associated with a one-meter increase in shoreline distance, providing a direct description of how the physical beach profile changes across nest locations. Calculations were performed using *scipy.stats.pearsonr* and *scipy.stats.linregress* (Virtanen et al. 2020).

Spatial structure in nest-site conditions was evaluated using global Moran's I, calculated separately for minimum distance to the high-tide line and local beach slope within each study sector. Moran's I measures whether nearby locations tend to have similar or dissimilar values. Positive values indicate spatial clustering of similar conditions, values near zero indicate little detectable spatial organization, and negative values indicate that neighboring locations tend to be more different than expected. In this study, Moran's I therefore tested whether nests located near one another also tended to occupy similar shoreline positions or similar local slopes. Binary spatial weights were defined using cumulative neighborhood thresholds of 50, 100, 150, and 200 m. Using several thresholds allowed us to evaluate whether the observed spatial structure persisted across different local spatial scales rather than depending on a single arbitrarily selected distance. Statistical significance was evaluated using 9,999 random permutations, which test whether the observed Moran's I is more extreme than would be expected if the measured values were randomly rearranged among nest locations. Moran's I and permutation-based inference are widely used to quantify spatial autocorrelation in ecological data and are implemented in spatial-analysis frameworks such as *PySAL/ESDA* (Rey et al. 2022).

Hurricane Erin flood exposure was evaluated by overlaying nest locations with the observed event-specific flood extent and classifying each nest location as exposed or unexposed. Because all nest locations at Breezy Point Ocean Side occurred within the mapped flood extent, statistical comparisons between exposure categories were restricted to Beach 37th-56th St. Minimum distance to the high-tide line and local beach slope were compared between exposed and unexposed locations using two-sided Mann-Whitney U tests. The Mann-Whitney test is a nonparametric comparison that evaluates whether values in one group generally tend to be higher or lower than values in another group without requiring normally distributed data. Here, it was used to determine whether exposed nest locations tended to occur closer to the high-tide line or on different local slopes than unexposed locations. Because a p-value indicates evidence for a difference but not its magnitude, rank-biserial correlation was also calculated as an effect-size measure (Kerby 2014). Rank-biserial correlation describes how strongly the two groups are separated, with values approaching an absolute magnitude of 1 indicating increasingly complete separation and values near 0 indicating substantial overlap. Thus, the Mann-Whitney test was used to evaluate whether exposed and unexposed locations differed, whereas the rank-biserial effect size was used to quantify how large that separation was. Statistical results were interpreted together with graphical patterns and effect sizes rather than from statistical significance alone.

Results

Spatial distribution of nest locations and flood extent

A total of 97 nest locations were recorded across the two study sectors during the 2025 breeding season (Table 1). Species composition differed between sectors. Beach 37th-56th St. was characterized by a strong concentration of Least Tern nests together with numerous American Oystercatcher nests, whereas Breezy Point Ocean Side was dominated by American Oystercatcher and contained comparatively few tern nests. Piping Plover occurred at both sectors in similar numbers.

Table 1. Number of nest locations recorded by species and study sector during the 2025 breeding season.

Species	Beach 37th-56th St.	Breezy Point Ocean Side	Total
American Oystercatcher	23	21	44
Common Tern	6	4	10
Least Tern	32	3	35
Piping Plover	4	4	8
Total	65	32	97

Nest locations also showed contrasting spatial distributions between sectors. At Beach 37th-56th St., nests occupied a broader range of shoreline positions, extending from relatively nearshore locations to sites farther inland. The mapped Hurricane Erin flood extent intersected only part of the nesting area, leaving both exposed and unexposed nest locations within the sector (Figure 1). In contrast, nests at Breezy Point Ocean Side were generally concentrated closer to the shoreline, and the observed Hurricane Erin flood extent encompassed all sampled nest locations (Figure 2). This initial comparison indicates greater within-site variation in flood exposure at Beach 37th-56th St., whereas exposure was spatially uniform across the sampled Ocean Side sector.

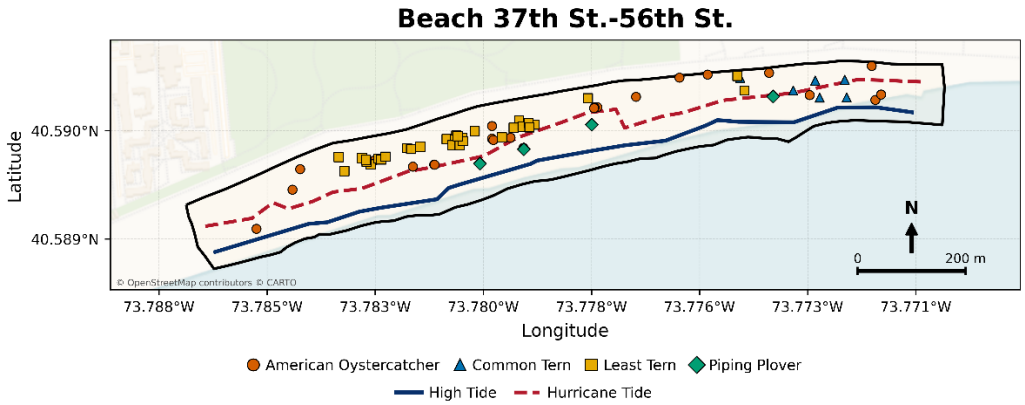

Figure 1. Nest locations and coastal flood lines at Beach 37th-56th St. Nest locations were distributed across a broad range of shoreline positions, and the Hurricane Erin flood extent intersected only part of the sampled nesting area.

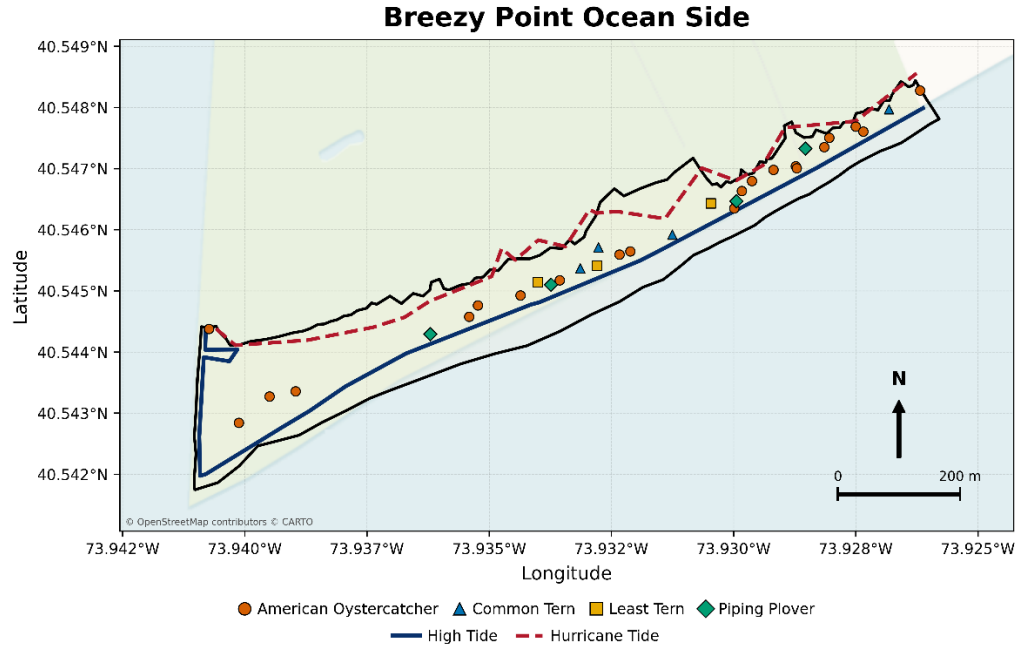

Figure 2. Nest locations and coastal flood lines at Breezy Point Ocean Side. Nest locations were generally concentrated closer to the shoreline, and the Hurricane Erin flood extent encompassed all sampled nest locations.

Nest-site physical conditions and shoreline-slope relationships

Nest locations at Beach 37th-56th St. occupied a substantially broader range of physical conditions than those at Breezy Point Ocean Side. At Beach 37th-56th St., minimum distance to the high-tide line extended from approximately 15 to 110 m, with a mean near 71 m (Figure 3). The distribution was concentrated toward the middle and upper portion of this range, although a smaller group of nests occurred relatively close to the high-tide line. Local beach slope was also highly variable, ranging from approximately 0.7° to 5.9°. Most nest locations occurred at intermediate slopes, particularly around 3-3.5°, while smaller groups occurred on both very gentle (<2°) and relatively steep (>5°) portions of the beach. Together, these distributions indicate that nest locations at Beach 37th-56th St. occurred across a heterogeneous set of shoreline positions and local topographic conditions rather than within a single narrow physical profile.

Breezy Point Ocean Side showed a markedly different distribution. Nest locations were considerably closer to the high-tide line, with a mean distance of approximately 25 m and most observations concentrated around 20-30 m. Local beach slopes also occupied a much narrower range than at Beach 37th-56th St., with most nests occurring between approximately 2.0° and 2.6°. A small number of observations occurred at lower slopes, producing an asymmetric distribution and suggesting that the sampled nesting area included a dominant intermediate-slope setting together with a smaller group of gentler-slope locations. Thus, although both sectors contained local variation, Ocean Side nest locations occupied a more restricted combination of shoreline distance and slope conditions.

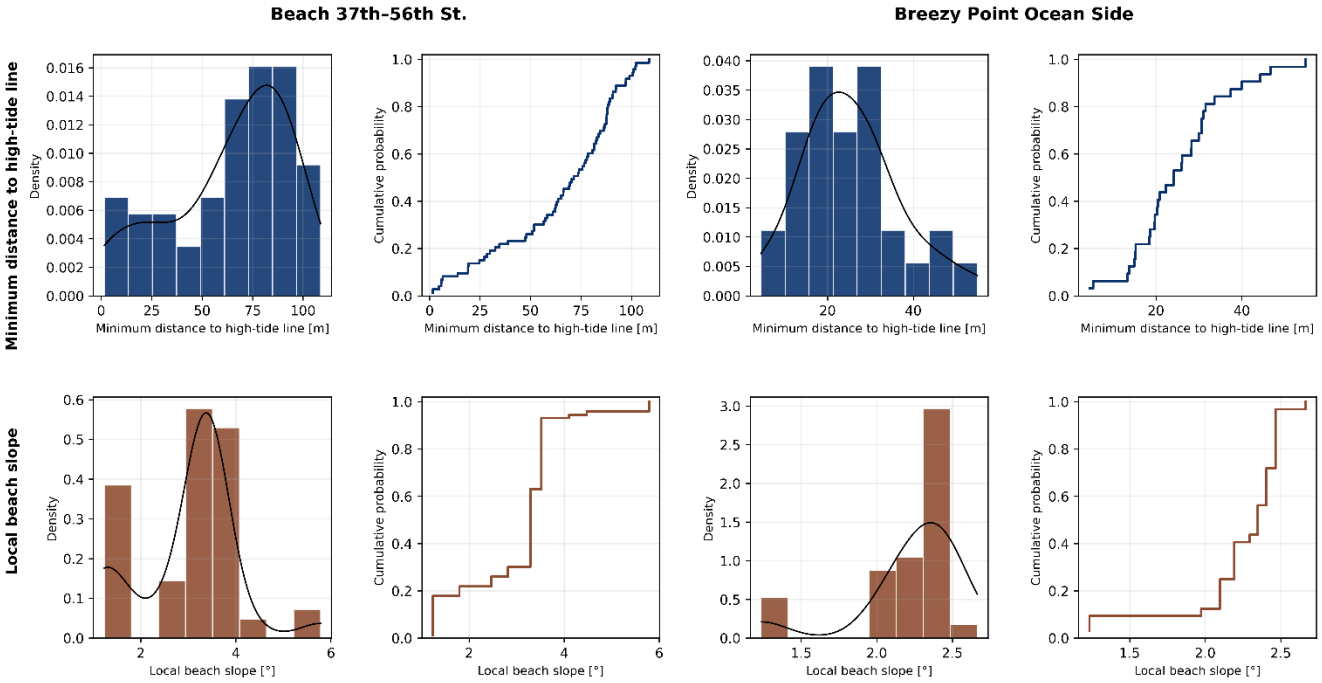

Figure 3. Distribution of nest-site physical conditions between study sectors. Beach 37th-56th St. showed a broader range of minimum distances to the high-tide line and local beach slopes, whereas Breezy Point Ocean Side was more concentrated near the shoreline and within a narrower range of slope values.

The relationship between these two physical variables further distinguished the sectors (Figure 4). At Beach 37th-56th St., the slope was moderately positively correlated ($r = 0.373$). The fitted regression slope of +0.016°/m indicated that locations farther from the high-tide line tended, on average, to occur on steeper local beach slopes. However, the scatterplot also showed substantial variation around the fitted line, including groups of nests occurring at similar shoreline distances but on markedly different slopes. The positive relationship therefore describes a general site-level tendency rather than a uniform cross-shore gradient across all nest locations.

In contrast, Breezy Point Ocean Side showed a moderate negative relationship between shoreline distance and local beach slope ($r = -0.590$), with a regression slope of -0.019°/m. Nest locations closer to the high-tide line generally occurred on steeper local slopes, whereas locations farther inland tended to occur on gentler slopes. The scatterplot also suggests that this negative relationship was influenced by the coexistence of a relatively dense group of nests at slopes near 2.2-2.5° and a smaller set of low-slope observations at greater shoreline distances. Consequently, the linear relationship should be interpreted as a summary of the overall spatial configuration rather than evidence of a single continuous beach profile.

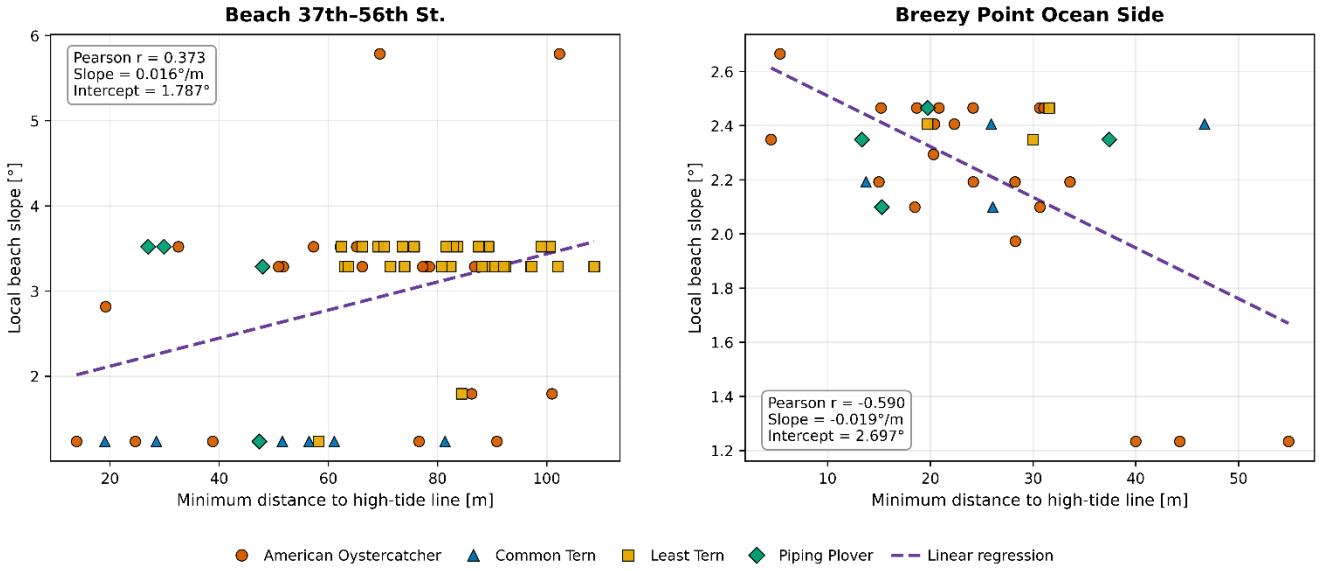

Figure 4. Relationship between shoreline distance and local beach slope. Beach 37th-56th St. showed a moderate positive relationship between minimum distance to the high-tide line and local beach slope, whereas Breezy Point Ocean Side showed a moderate negative relationship, indicating contrasting spatial organization of these physical variables between sectors.

Taken together, the descriptive distributions and shoreline-slope relationships reveal two distinct forms of nest-site physical organization. Beach 37th-56th St. supported nests across a wider range of shoreline positions and local slopes and exhibited a weak-to-moderate tendency toward steeper slopes farther from the high-tide line. Ocean Side, by comparison, contained nests within a narrower range of physical conditions and exhibited the opposite relationship, with local slope generally decreasing as distance from the high-tide line increased. These contrasting patterns provide the physical context for the subsequent spatial-autocorrelation and Hurricane Erin exposure analyses.

Spatial autocorrelation of nest-site conditions

Spatial autocorrelation analyses revealed clear differences in how shoreline position and local beach slope were organized within the two study sectors (Figure 5). At Beach 37th-56th St., minimum distance to the high-tide line showed consistent positive spatial autocorrelation across all evaluated neighborhood thresholds. Moran's *I* decreased from approximately 0.34 at 50 m to 0.17 at 200 m, while remaining statistically significant throughout the 50-200 m range. This pattern indicates that nest locations situated near one another tended to occupy similar positions relative to the high-tide line, with the strength of this spatial similarity gradually weakening as the neighborhood radius increased. The persistence of positive autocorrelation across multiple distances suggests that shoreline position at Beach 37th-56th St. was spatially organized over more than one local scale rather than being randomly distributed among nest locations.

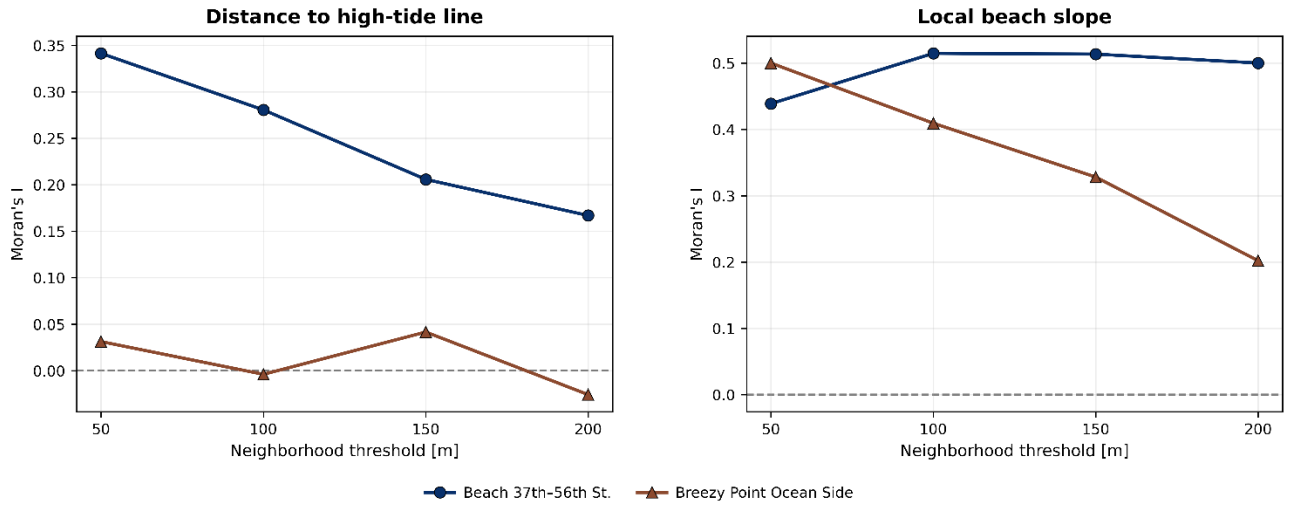

Figure 5. Spatial autocorrelation of nest-site conditions across neighborhood thresholds. Moran's *I* was evaluated using cumulative neighborhood thresholds of 50-200 m with permutation tests. Distance to the high-tide line showed consistent positive spatial autocorrelation at Beach 37th-56th St., whereas no significant spatial autocorrelation was detected at Breezy Point Ocean Side. Local beach slope was positively spatially autocorrelated at both sites across all evaluated thresholds.

In contrast, minimum distance to the high-tide line at Breezy Point Ocean Side showed Moran's *I* values close to zero across all thresholds, ranging from slightly positive to slightly negative values. None of these values was statistically significant. Thus, although Ocean Side nests occupied a comparatively narrow range of shoreline distances overall, nearby nest locations were not consistently more similar in shoreline position than would be expected under a random spatial arrangement. This result distinguishes restricted variability from spatial autocorrelation: a variable may occupy a narrow numerical range without necessarily forming spatial clusters of similar values.

Local beach slope exhibited a different pattern. Positive spatial autocorrelation was detected at both study sectors across all evaluated neighborhood thresholds. At Beach 37th-56th St., Moran's *I* remained relatively stable and strong, increasing from approximately 0.44 at 50 m to values near 0.51 at 100-150 m and remaining close to 0.50 at 200 m. This persistence indicates that neighboring nest locations tended to share similar local slope conditions across the full range of spatial scales examined. The result is consistent with the broader slope heterogeneity observed in Figure 3 but shows that this heterogeneity was not spatially random; instead, similar slope conditions occurred in localized portions of the beach.

At Breezy Point Ocean Side, local slope was also positively spatially autocorrelated, but the strength of the pattern declined progressively with increasing neighborhood distance. Moran's *I* decreased from approximately 0.50 at 50 m to 0.41 at 100 m, 0.33 at 150 m, and 0.20 at 200 m, while remaining statistically significant at all thresholds. This decline suggests that slope similarity was strongest among nearby nest locations and became less pronounced as increasingly distant locations were included in the same neighborhood. In other words, Ocean Side exhibited relatively localized patches of similar slope conditions rather than the more persistent spatial structure observed at Beach 37th-56th St.

In sum, these results show that the two physical variables were structured differently across the nesting landscape. At Beach 37th-56th St., both shoreline position and local beach slope exhibited spatial organization, whereas at Ocean Side only local slope showed significant spatial autocorrelation. The analyses therefore indicate that fine-scale physical conditions around nest locations were not uniformly or randomly distributed, and that the spatial organization of these conditions differed between sectors. These patterns provide important spatial context for evaluating whether Hurricane Erin flood exposure was concentrated within portions of the nesting landscape.

Hurricane Erin flood exposure and nest-site conditions

Hurricane Erin flood exposure differed markedly between the two study sectors (Figure 6). At Beach 37th-56th St., 11 of 65 nest locations (16.9%) occurred within the mapped flood extent, whereas the remaining 54 locations were outside the observed inundation area. In contrast, all 32 nest locations at Breezy Point Ocean Side occurred within the mapped flood footprint. Because Ocean Side contained no unexposed locations, within-site statistical comparisons between exposure categories were restricted to Beach 37th-56th St.

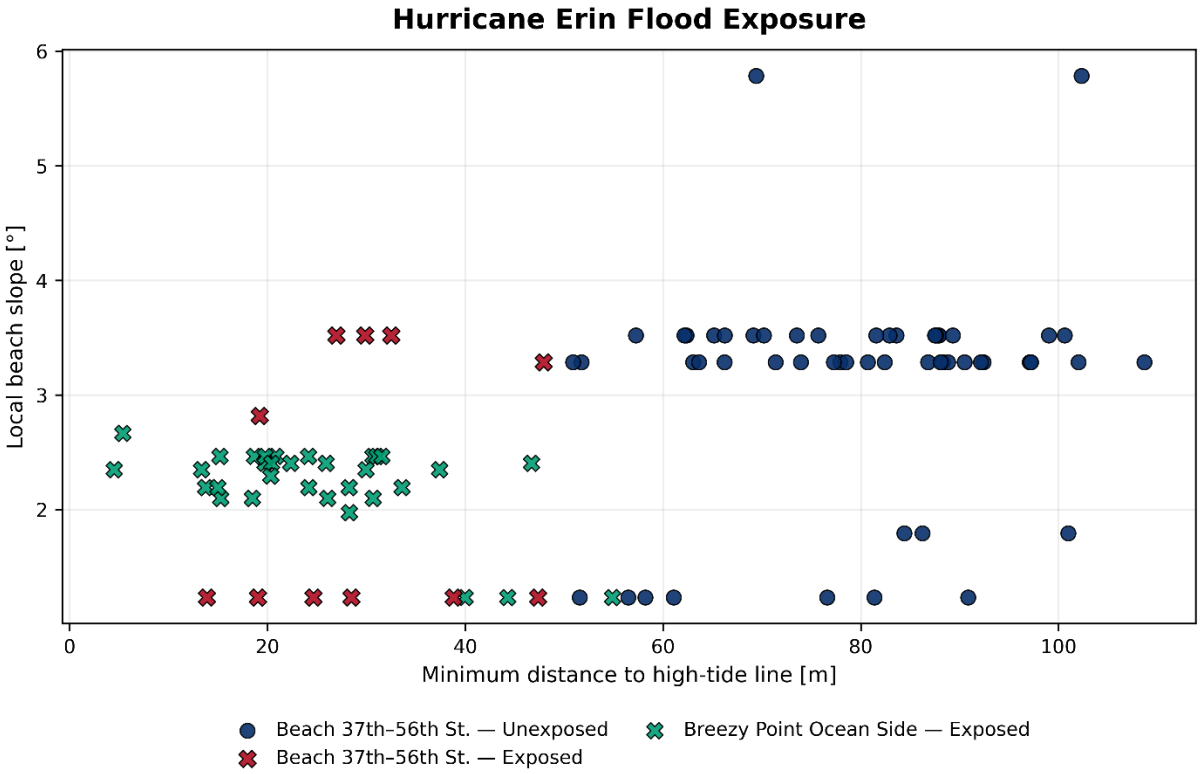

Figure 6. Hurricane Erin flood exposure in relation to nest-site conditions. Nest locations are shown according to minimum distance to the high-tide line and local beach slope. Hurricane Erin flood exposure encompassed 11 of 65 nest locations (16.9%) at Beach 37th-56th St. and all 32 nest locations (100%) at Breezy Point Ocean Side. Within Beach 37th-56th St., exposed locations occurred closer to the high-tide line than unexposed locations, whereas local beach slope showed greater overlap between exposure groups.

Within Beach 37th-56th St., shoreline position showed the clearest separation between exposed and unexposed nest locations. Exposed locations occurred substantially closer to the high-tide line, with a median distance of 28.5 m compared with 81.5 m for unexposed locations (Table 2). The Mann-Whitney comparison was significant, and the absolute rank-biserial correlation was 1, indicating complete separation between exposure groups in the observed sample. This pattern was also evident graphically: exposed nest locations occupied the nearshore portion of the sector, whereas unexposed locations were concentrated farther inland. In the observed data, the most inland exposed location remained closer to the high-tide line than the nearest unexposed location, reinforcing the strong association between shoreline position and flood exposure during this event.

Local beach slope also differed between exposure groups, but the pattern was weaker. Exposed locations had a median local slope of 1.23°, compared with 3.29° for unexposed locations ($p = 0.032$; $|r_{rb}| = 0.394$). Unlike shoreline distance, however, slope values showed substantial overlap between groups (Figure 6). Thus, gentler local slopes were more common among exposed locations, but slope alone did not provide the same degree of separation observed for distance to the high-tide line.

Table 2. Nest-site conditions by Hurricane Erin flood exposure at Beach 37th-56th St. Values are medians. Exposed and unexposed nest locations were compared using two-sided Mann-Whitney U tests; $|r_{rb}|$ represents the absolute rank-biserial effect size. Breezy Point Ocean Side was not tested because all nest locations were exposed.

Variable	Exposed	Unexposed	p-value	$\|r_{rb}\|$
Shoreline distance	28.5 m	81.5 m	<0.001	1.000
Local beach slope	1.23°	3.29°	0.032	0.394

The combined pattern suggests that, within Beach 37th-56th St., shoreline position was more strongly associated with Hurricane Erin flood exposure than local beach slope. The complete exposure observed at Ocean Side further indicates that this sector occupied a substantially different physical and hydrodynamic setting during the event. These results should be interpreted as associations with the mapped flood footprint rather than as evidence of nest failure or direct storm damage.

Discussion

Contrasting physical organization of nesting habitat

Nest locations occupied markedly different physical settings at Beach 37th-56th St. and Breezy Point Ocean Side. Beach 37th-56th St. encompassed a much broader range of shoreline distances and local beach slopes, whereas Ocean Side nests were concentrated closer to the high-tide line and within a narrower slope range. The opposite shoreline distance-slope relationships observed between sectors further indicate that these variables cannot be interpreted independently of local beach configuration. At Beach 37th-56th St., locations farther from the high-tide line tended to occur on steeper local slopes, whereas Ocean Side showed the reverse tendency. These contrasts are consistent with the broader geomorphic complexity documented along the Rockaway Peninsula, where sediment availability, shoreface morphology, engineering structures, and nourishment history vary substantially alongshore rather than forming a uniform barrier profile (Wei and Miselis 2022, Janda et al. 2025).

This result supports the interpretation of beach-nesting habitat as a heterogeneous physical mosaic rather than an interchangeable sandy surface. Recent work on Least Terns and Snowy Plovers similarly shows that beachface morphology can influence where birds place nests and can be related to breeding outcomes, including flooding failure (Ruiz de Alegría-Arzaburu et al. 2025). Landscape-scale habitat characteristics are also known to constrain the distribution of Piping Plovers, reinforcing the importance of examining physical structure at more than one spatial scale (Anteau et al. 2014).

However, our results do not demonstrate that the physical differences between the two sectors were caused by management. Beach 37th-56th St. occurs within a highly modified portion of Rockaway, but the peninsula reflects interactions among natural sediment dynamics, geological framework, storms, and historical engineering. The appropriate interpretation is therefore that the sectors represent contrasting contemporary physical settings, not experimental replicates of "urban" and "natural" beach types. This distinction is important because attributing the observed nesting patterns directly to nourishment or other interventions would require replicated sites or explicit before-after information.

Spatial structure of nest-site conditions

The Moran's *I* analyses showed that variation in nest-site conditions was not simply numerical variation among individual nests; some of that variation was spatially organized. At Beach 37th-56th St., both distance to the high-tide line and local beach slope showed positive spatial autocorrelation. Nearby nest locations therefore tended to share similar physical conditions, indicating spatial patches within the nesting landscape. Shoreline-distance autocorrelation weakened as the neighborhood threshold increased from 50 to 200 m, whereas slope

autocorrelation remained comparatively persistent. These patterns suggest that different components of beach morphology may operate over different spatial scales.

Ocean Side showed an informative contrast. Local beach slope was positively autocorrelated at all evaluated thresholds, but the strength of this structure declined with increasing neighborhood distance. This pattern is consistent with relatively localized areas of similar slope conditions. In contrast, shoreline distance showed no detectable spatial autocorrelation despite its relatively narrow overall distribution. This distinction illustrates why descriptive variability and spatial autocorrelation are not equivalent: nest locations may occupy a restricted range of conditions without those conditions forming spatially clustered patches.

The spatial structure found here is ecologically relevant because birds experience nesting habitat locally rather than as a site-wide average. Habitat studies of Piping Plovers have similarly emphasized that the distribution of suitable breeding habitat is spatially uneven and linked to landscape features rather than total beach area alone (Anteau et al. 2014). More broadly, the geomorphic heterogeneity documented for Rockaway provides a plausible physical context for the spatial clustering observed in our nest-site variables (Wei and Miselis 2022).

Importantly, the Moran analysis does not demonstrate that birds selected slope or shoreline clusters. It shows that the physical conditions measured at nest locations were spatially structured. Demonstrating habitat selection would require comparison with available but unused locations. This distinction should remain explicit because our sampling design describes nesting locations rather than selection relative to habitat availability.

Shoreline position and Hurricane Erin flood exposure

The strongest event-specific result was the association between shoreline position and observed Hurricane Erin flood exposure. All 32 nest locations at Ocean Side occurred within the mapped flood footprint, whereas only 11 of 65 locations at Beach 37th-56th St. were exposed. Within Beach 37th-56th St., exposed locations occurred much closer to the high-tide line than unexposed locations, with medians of 28.5 and 81.5 m, respectively. The rank-biserial effect size of 1 indicates complete separation between groups in the observed sample. Local beach slopes also differed, but its smaller effect size and substantial overlap between groups indicate that slope was a weaker discriminator of exposure during this event.

This finding is consistent with the general expectation that nest flooding risk depends strongly on position within the coastal profile. Recent work has shown that rising water levels can reduce shorebird habitat quality through increased nest flooding well before the habitat itself is permanently submerged (van de Pol et al. 2024). Likewise, studies of beach morphology have documented links among supratidal configuration, nest placement, and flooding-related reproductive failure in beach-nesting birds (Ruiz de Alegría-Arzaburu et al. 2025).

The approximately 48-51 m separation between exposed and unexposed observations at Beach 37th-56th St. should not, however, be interpreted as a universal biological or geomorphic flood threshold. It represents the separation observed for one sector during one event. Flood penetration depends on storm characteristics, waves, water levels, beach morphology, antecedent conditions, and local barriers, all of which can change between events. The more defensible conclusion is that relative shoreline position strongly differentiated Hurricane Erin exposure within this nesting sector.

The weaker slope effect is also informative. Local inclination may contribute to water movement and beach morphology, but a single slope measurement cannot capture the full hydrodynamic pathway of storm flooding. Dunes, berms, depressions, overwash channels, beach width, and alongshore morphology may alter exposure even among locations having similar local slopes. This is likely to help explain why slopes differ statistically between groups but showed considerably more overlap than shoreline distance.

Conservation and Management Implications

The strong short-term exposure observed during Hurricane Erin should not be interpreted to mean that storm disturbance is uniformly detrimental to beach-nesting birds. Barrier-island storms can simultaneously inundate active nests and create habitat that becomes valuable in subsequent breeding seasons. Following Hurricane Sandy in New York, overwash and associated landscape disturbance created extensive open habitat used by Piping Plovers, and birds subsequently selected sites in or near storm-created overwash areas (Walker et al. 2019). Later work in the same barrier-island system found that the disturbed landscape provided favorable chick habitat and contributed to high reproductive output after the storm (Robinson et al. 2023).

This apparent contradiction highlights an important temporal distinction. Immediate nest exposure and long-term habitat value are different ecological responses. A storm may flood nests during the breeding season while simultaneously creating sparsely vegetated, low-elevation, early successional habitat that becomes suitable for nesting or chick foraging later. For example, it was documented that Hurricane Sandy removed vegetation and altered barrier morphology in ways that subsequently increased suitable Piping Plover habitat (Walker et al. 2019). Therefore, our Hurricane Erin analysis should be interpreted specifically as an assessment of event-scale spatial exposure, not as an assessment of the storm's overall ecological effect on the Rockaway nesting system.

From a management perspective, the most relevant implication is therefore not that one beach type is inherently safer, but that flood exposure can vary substantially over short spatial distances within coastal nesting habitat. Maintaining information on shoreline position, local topography, and storm-flood boundaries could help identify areas with contrasting exposure and guide post-storm monitoring. At the same time, management should retain the dynamic habitat features produced by natural disturbance where they provide suitable nesting or foraging conditions. Evidence from Hurricane Sandy shows that protecting storm-created habitat can be important because suitable habitat may otherwise remain unused when recreational disturbance or stabilization restricts access (Walker et al. 2019).

Limitations and future research

Several limitations should be considered when interpreting these results. First, the Hurricane Erin analysis represents a single storm event and therefore captures event-specific flood exposure rather than a general or universal measure of nest vulnerability. The spatial extent of flooding can vary among storms depending on water level, wave conditions, storm trajectory, antecedent beach morphology, and local barriers. Consequently, the observed separation between exposed and unexposed nest locations at Beach 37th-56th St. should not be interpreted as a fixed shoreline-distance threshold applicable to other events or sites.

Second, the study compared two contrasting nesting sectors within the Rockaway Peninsula, but each sector represents only one local setting. Although Beach 37th-56th St. and Breezy Point Ocean Side differ in management context and physical configuration, the design does not allow these differences to be attributed causally to urbanization, nourishment, or management. Broader inference would require replication across multiple managed and less-developed sectors, ideally over several breeding seasons and storm events.

Third, the spatial analyses were based on conditions measured at nest locations. Moran's I therefore identifies spatial structure in the physical environments occupied by nests, but it does not demonstrate habitat selection because unused or available habitat was not sampled for comparison. Future work could address this limitation using availability-based designs, such as used-versus-available habitat models, to determine whether birds select shoreline positions or slope conditions beyond what is simply available within each sector.

Finally, flood exposure was defined from the mapped Hurricane Erin inundation footprint and should be interpreted as spatial exposure rather than confirmed nest loss, reproductive failure, or mortality. Future studies should link

event-specific flood mapping with nest fate, repeated topographic surveys, and hydrodynamic or elevation data referenced to a common vertical datum. Extending the study across multiple years would also allow evaluation of whether spatial patterns in shoreline position, slope, and exposure remain stable or shift as the barrier island changes. Together, these approaches would help distinguish short-term storm exposure from longer-term habitat change and improve understanding of how dynamic coastal morphology influences nesting success and habitat persistence.

Conclusion

Our results indicate that nest-site flood exposure on the Rockaway Peninsula occurred within a spatially heterogeneous physical landscape. Beach 37th-56th St. contained a wider range and stronger spatial structuring of nest-site conditions, whereas Ocean Side was characterized by nests closer to the shoreline and complete exposure to the observed Hurricane Erin flood footprint. Within the partially exposed Beach 37th-56th St. sector, shoreline distance provided substantially stronger separation between exposed and unexposed locations than local beach slope. These findings support the broader view that coastal nesting habitat should be evaluated as a spatially structured and dynamic landscape, rather than solely through site-wide averages or simple categories such as urban versus natural beach.

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