

Article

Shoreline Change of Western Long Island, New York, from Satellite-Derived Shorelines

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Abstract: Shoreline measurement techniques using satellite-derived imagery can provide decades of observations of shoreline change. Here we apply these techniques to the western south shore of Long Island, New York, which has three distinct beaches, Rockaway Peninsula, Long Beach, and Jones Beach Island, which are 18, 15, and 24 km in length, respectively. These beaches are recreation areas for millions of regional residents and include several groin fields, sediment dredging and nourishment operations, and a coastal wave climate that includes winter northeasterly storms and summer hurricanes. The shorelines along the western ends of these three beaches have been accreting at ~4 m/yr during the observation record (1984–2022) resulting from net westward longshore drift. The central 10–12 km of the beaches have lower shoreline change rates, and these rates are generally lowest within the groin fields (0.5–1.5 m/yr). Shoreline change observations also provide evidence for westward propagating accretion and erosion sediment waves that have durations of several years. Beach nourishment projects are shown to significantly influence rates of shoreline accretion, and this is commonly followed by significant shoreline retreat during the subsequent years.

Keywords: shoreline; littoral cell; satellite; sediment



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1. Introduction

Sandy shorelines are rapidly changing boundaries between terrestrial and marine environments. As sea levels continue to rise, coastal communities along these shorelines are becoming more at risk of flooding, property damage, and the need for landward relocation [1–3]. Beach erosion is therefore often a concern to coastal communities, and is caused by wave action, changes in land use, as well as changes to littoral budgets caused by sediment transport mass balances and processes [4,5]. Many of the existing shoreline mapping techniques such as surveys with global navigation satellite system receivers (GNSS), lidar, and coastal video imaging are often time consuming and expensive [6,7]. With shoreline change measurements from satellite imagery data, we are better able to monitor changes of shoreline positions over decadal periods of time and at relatively low cost [8–10].

Barrier islands, which are unconsolidated and elongated bodies of sand or gravel lying above the high-tide level and separated from the mainland by a lagoon or marsh, are important to monitor as they protect the mainland from storm surges and extreme tides while also providing a unique habitat for a variety of plant and animal species [11–14]. Atlantic Coast barrier islands formed thousands of years ago due to a slowdown of sea level rise, longshore distribution of sediment and the energy and direction of nearshore waves [15,16]. Generally, barrier islands will migrate landward over time due to sea-level

rise, through a process called rollover migration. Increasing future sea levels are expected to accelerate migration for some barrier islands, especially where sediment supplies are sufficient [17,18], whereas others are at higher risk of being permanently breached or inundated particularly after extreme surges from large storms such as hurricanes [13,19,20].

Long Island, New York, lies just east of New York City extending nearly 191 km in length [21], with a maximum width of only 32 km (20 miles) [22]. The island ranges from being moderately to densely developed to undeveloped wilderness areas [21]. On the southern shore of Long Island, there are several barrier islands separating the core of Long Island from the sea. This study focuses on two barrier islands (Long Beach and Jones Beach Island) as well as one barrier spit [23] (Rockaway Peninsula) that protects and separates the Atlantic Ocean from Jamaica Bay (Figure 1). This coastal region is composed of sand-size particles transported by westward-directed littoral currents [24]. These areas also have a long history of storm damage and economic loss from coastal flooding and erosion events, which has led to an increase in the use of sand nourishment projects to widen the beaches and the building and replacement of groins and jetties along the more urbanized regions and the barrier inlets. In the future, there is an expectation that new ways will be needed to protect these coasts from impacts due to sea-level rise, persistent flooding, and increased erosion [25].

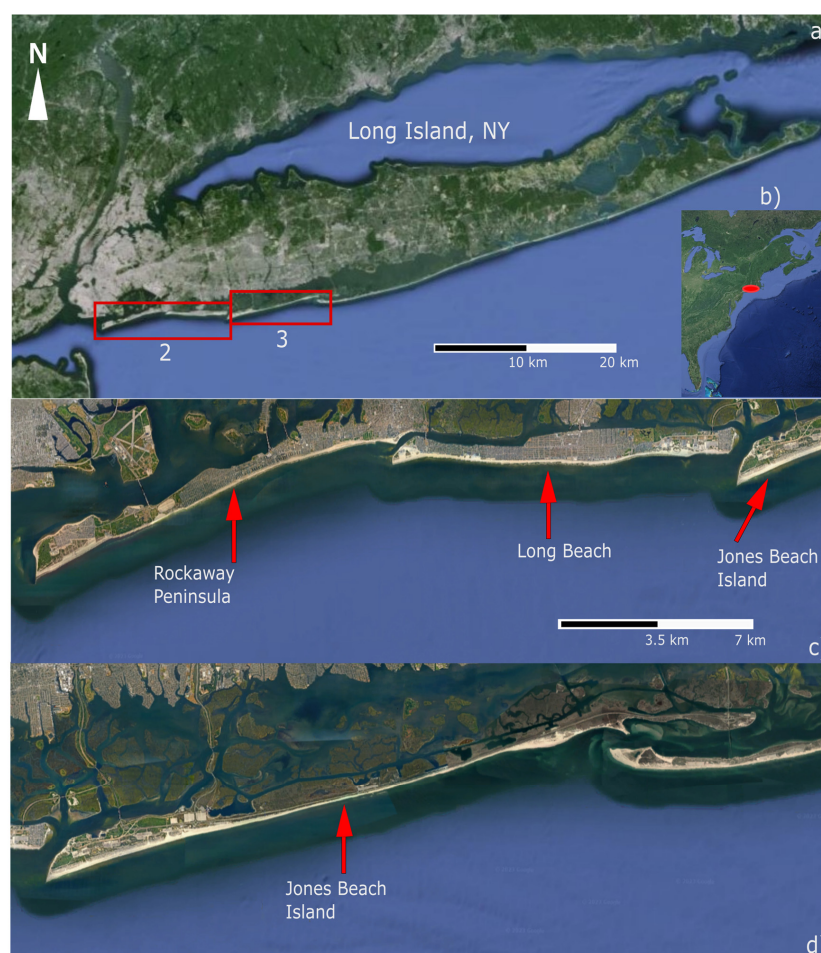


Figure 1. The Long Island study area, including (a,b) the overall location of Long Island with respect to New York and the greater U.S. East Coast with inset 2 corresponding to (c) and inset 3 corresponding to (d), (c) the location of Rockaway Peninsula and Long Beach, and the western end of Jones Beach Island, (d) Jones Beach Island. (c,d) have the same scale. Imagery from Google Earth from 14 December 2015, to 1 January 2021.

Much of southern Long Island was created from two terminal moraines during the last glacial advance (Harbor Hill and Ronkonkoma) [26]. Thousands of years later, westward littoral drift helped create a series of barrier islands and a barrier spit, Rockaway Peninsula, on the southern shore of Long Island [26]. According to the U.S. Army Corps of Engineers [27], Jones Beach Island experienced erosion, especially from 1962–1974, due to a reduction in its eastern sediment source, Fire Island, resulting from an installment of a jetty that reduced the westward littoral drift. The U.S. Army Corps of Engineers surveys also showed that the western end of Jones Beach Island was steadily accreting while the rest of the island was eroding [27].

The two more densely developed sites, Rockaway Peninsula and Long Beach, have several engineered structures along the shoreline including groin fields and jetties. Groins are dam-like structures extending into the littoral zone to restrict longshore sediment movement [28]. Armored jetties are used throughout the south shore of Long Island to stabilize several inlets, including Shinnecock, Moriches, Fire Island, Jones Beach, East Rockaway, and Rockaway [21]. Rockaway Peninsula contains 61 structures, Long Beach contains 47 structures, and Jones Beach Island has one large, armored jetty at its western end. Many of the groins at these sites are seen in the earliest satellite images from Landsat 5 in 1984. To provide better context to the recent coastal changes of the south shore of Long Island, we have developed a 38-year record of shoreline change from satellite imagery. Throughout the study period, however, some groins have been rebuilt or destroyed, and other new groins that range from roughly 50 m to 150 m in length have been added. The new groin projects have been done to meet public needs to slow beach erosion and to repair older structures that have become compromised [29].

Climate change and increasing temperatures give rise to more frequent storms in the area. Most notably, Hurricane Sandy caused major flooding and damage to the Long Island coastal region in October 2012. Figure 2 is composed of oblique aerial images of the study area after the effects of Hurricane Sandy as captured by a flight conducted by the U.S. Geological Survey (USGS) [30]. These images provide an insight into the physical differences between the three study areas with Rockaway Peninsula and Long Beach containing houses and other buildings close to shore while Jones Beach Island is mostly undeveloped.

The goals of this work are to evaluate the shoreline change trends and variations with time along the study area coast and to characterize the processes responsible for these changes. Possible reasons for change, investigated in this study, include beach nourishments, the effects of waves, and the presence of groin fields. Another possible reason, which was not investigated in detail in this study, is submerged bars that may exist offshore which may have their own storm-related dynamics that are not seen in the satellite imagery. Sandy beaches around the world often contain submerged bars which can contribute to sediment transport [31]. CoastSeg (version 1.1.35), developed by the USGS using the shoreline mapping algorithms of the more-established CoastSat software [32], was used to extract shorelines from imagery provided by several U.S. (Landsat) and European (Sentinel) satellites [33]. CoastSat has been used to map many of the coasts along the Pacific Ocean and some of the eastern coast of the United States [32,34]. The CoastSat shoreline extraction technique uses spectral characteristics of the imagery to define shoreline positions for each cloud-free image.



Figure 2. Study site imagery from a USGS oblique aerial photography mission on 5 November 2012, following the passage of Hurricane Sandy [30]. These photos are derived from Area 5 of the aerial survey, and photo numbers are provided in the descriptions: (a) Rockaway Peninsula (photo: 2012_1105_150843d), (b) Sediment build up behind groin on Rockaway Peninsula (photo: 2012_1105_150551d), (c) Developed area on Rockaway Peninsula (photo: 2012_1105_150445d), (d) Long Beach (photo: 2012_1105_150206d), (e) Jones Beach Island (photo: 2012_1105_145700d), (f) Jones Beach Island (photo: 2012_1105_144711d2).

As described in the Materials and Methods section below, a time series of shoreline positions was obtained to evaluate how the barrier islands have been changing over time. There are relatively few satellite derived shoreline change analyses in literature over regional scales despite their demonstrative utility for sediment management issues over regional scales [35,36]. Our study is also somewhat unique in that it uses satellite-derived shoreline time-series to better understand the dynamics of the shoreline region undergoing complex changes due to the interplay of both natural and anthropogenic activities [35,37].

2. Materials and Methods

2.1. Satellite-Derived Shorelines

The imagery from both the Landsat satellites (United States) and Sentinel 2A-2B (European) are available for public use through Google Earth Engine (GEE). GEE is a cloud-based geospatial processing platform tied to the archive of images from The National Aeronautics and Space Administration's (NASA) Earth Observing Satellites and The European Space Agency's (ESA) Sentinel series [38]. The major attraction of GEE is that users are able to access and analyze data from a public catalog through a library of operators provided by the API [39].

A series of satellite platforms are available in the GEE catalog and useful for shoreline mapping. Landsat 5, which carried a Thematic Mapper sensor, provided 30-m resolution

images for six visible to infrared bands and 120-m resolution for its thermal band. Landsat 7 included an Enhanced Thematic Mapper sensor with six visible to infrared bands with 30-m resolution, a thermal band at 60-m resolution, and a 15-m resolution panchromatic band [40]. Landsat 8, launched in 2013, has a 30-m Operational Land Imager (OLI) with nine visible to infrared bands and two thermal bands in its Thermal Infrared Sensor (TIRS) [41]. Landsat 9, launched in 2015, has upgraded versions of the OLI (OLI-2) and TIRS (TIRS-2) sensors with the same sample distances as its predecessor, Landsat 8 [42]. In this study, Sentinel 2A and 2B are referred to as just ‘Sentinel 2’. Sentinel 2 provides 10–20-meter resolution imagery in visible, near infrared and short-wave infrared bands [43].

The CoastSat shoreline detection method, as accessed through the CoastSeg platform, has four main stages in order to create a shoreline time series for predefined cross-shore transects. It starts with retrieving the desired satellite images for the region of interest from the GEE archive. Then, pre-processing of the multispectral images occurs, which includes cloud masking, pan-sharpening, and down-sampling. For each scene, five multispectral bands are used in the pixel classifications: red, green, blue, near infrared, and short-wave infrared. CoastSat determines the location of the sand and water boundary from the Modified Normalized Difference Water Index (MNDWI) spectral index, which is computed from a combination of the green (*Green*) and shortwave infrared (*SWIR1*) spectral bands which is defined by Equation (1) [32].

$$MNDWI = \frac{(Green - SWIR1)}{(Green + SWIR1)} \quad (1)$$

To determine the *MNDWI* value defining the shoreline uniquely in each image, a Neural Network classifier, called Multilayer Perceptron in scikit-learn, classifies pixels into four classes: sand, water, white water, and other land features (vegetation, buildings, etc.). If the classification is successful, the shoreline interface is then defined to be the *MNDWI* value differentiating sand and whitewater pixels using Otsu thresholding [32]. The Otsu methodology uses an iterative process to calculate pixel classification within an image [44]. In CoastSat, this Otsu threshold is defined as the threshold that maximizes the inter-class variance between the sand and water classes [32]. If the classifier fails, it defaults to a non-guided Otsu thresholding procedure, more common to generic land/water masking from remotely sensed imagery of non-coastal imagery.

CoastSeg provides a more user-friendly environment to conduct shoreline mapping, with an interactive space to visualize inputs and outputs, among other advantages mostly concerning the speed and reproducibility of workflows [33]. CoastSeg requires the user to define regions of interest (ROIs), transects, and a reference shoreline vector to calculate shoreline positions [33]. ROIs capture the areas of interest by defining rectangular areas from which the imagery will be downloaded. CoastSeg will place ROIs within a user-defined boundary box with a default size of 20 km² [33]. These automatically generated ROIs were used for the Long Beach and Jones Beach Island locations, resulting in 4 ROIs to capture Long Beach and six ROIs to capture Jones Beach Island (Table A1). The default ROIs for Rockaway Peninsula were oriented at an angle and did not cover the shoreline well, so revised ROIs were generated by hand using QGIS. Transects for all ROIs were created in QGIS and were spaced every 50 m along and perpendicular to the reference shorelines, with a cross-shore length of 400 m. The default ROI and transect orientations were established to optimize the shoreline extraction and to remove effects from back barrier shorelines, persistent ponding landward of the beaches, and some large parking lots that were spectrally similar to water and therefore caused erroneous shoreline estimates in the study areas. Overall, Rockaway Peninsula contained 361 transects covering 18.1 km of coast, Long Beach contained 299 transects covering 15 km of coast, and Jones Beach Island contained

469 transects covering 23.5 km of coast. The placement and orientation of these ROIs, reference shoreline, and transects are shown in Figure S1 in the Supplemental Materials.

Imagery was obtained for the study area between 1 January 1984, and 31 December 2022, and the images were classified according to perceived usability for the purposes of shoreline extraction. This involves a consideration of noise in the shoreline region of each image. By this process, roughly one third of downloaded images were removed from the study due to clouds, spots, or image errors, such as missing an RGB band. Landsat 7 imagery is degraded after 2003, following a failure of its scan line corrector, leaving images with large data gaps [45]. Tables A1 and A2 show the result of this classification. The number of images available for analyses varied between 1984 and 2022 depending on the ROI. The majority of the images came from Sentinel 2, but most of them were scrapped due to errors mentioned previously. The largest difference between downloaded images compared to usable images from GEE was from Sentinel 2, with 85% of images needing to be removed for Rockaway Peninsula ROI 2 (Table A2).

Despite the automated nature of the shoreline mapping algorithms, some manual work is required to determine the optimal settings for particular environments and imagery. Choices made can significantly affect the quality of resulting data, so CoastSeg implements several settings to optimize shoreline mapping for the coastal environment of interest and limiting errors from features such as cloudy skies (Table A3), in such a way that is easy to keep track of. A cloud mask is ordinarily used to automatically “black out” clouds in images; however, due to sandy beaches being mistaken as clouds in the Long Island imagery, this feature was turned off. The cloud threshold parameter controls the maximum portion of the imagery that clouds can inhabit before the image is removed from the analysis. The minimum beach area and minimum shoreline length define the smallest/shortest area in which shorelines will be found. One of the most important settings is the reference shoreline buffer, which can vary depending on the ROI, and defines the area from which shorelines will be extracted by dilating the reference shoreline vector [33]. These buffer areas are shown in Figure 3 (middle panels) as a purple region around the reference shoreline. Most ROIs were given reference shoreline buffers of 100–250 m, although the eastern portion of Jones Beach Island (ROI 10) required a much larger buffer (>300 m) owing to the exceptional shoreline accretion that occurred over our interval of study. Values for all CoastSeg settings used in this study are provided in Table A3.

To transfer mapped waterline positions to vertical datum-based shoreline positions for tidal corrections [43], horizontal corrections were implemented for each transect using FES14 [46] modeled water levels for the time of each image and beach slope. Beach slopes were assessed by the USGS using lidar collected in 2000 and were calculated from a cross-shore profile that encompassed a 40-meter swath of the topographic lidar data [47]. This profile method was used to extract a mean high water shoreline position and while doing so it also computes a beach slope between roughly −1 to 1-m elevations with respect to NAVD88. Notably only half of Jones Beach Island was surveyed by lidar [47], so an average slope was calculated for the entire island and applied to the unsampled region. The slopes were converted from degrees to rise/run (m/m) using the inverse tangent function. The average slope for the three main study areas were found to be: 0.054, 0.070, and 0.129 for Rockaway Peninsula, Long Beach, and Jones Beach Island, respectively. For simplification, these average slopes were used for each study area, consistent with previous applications of CoastSat [43]. All shoreline positions were referenced to mean sea level (MSL) following [33].

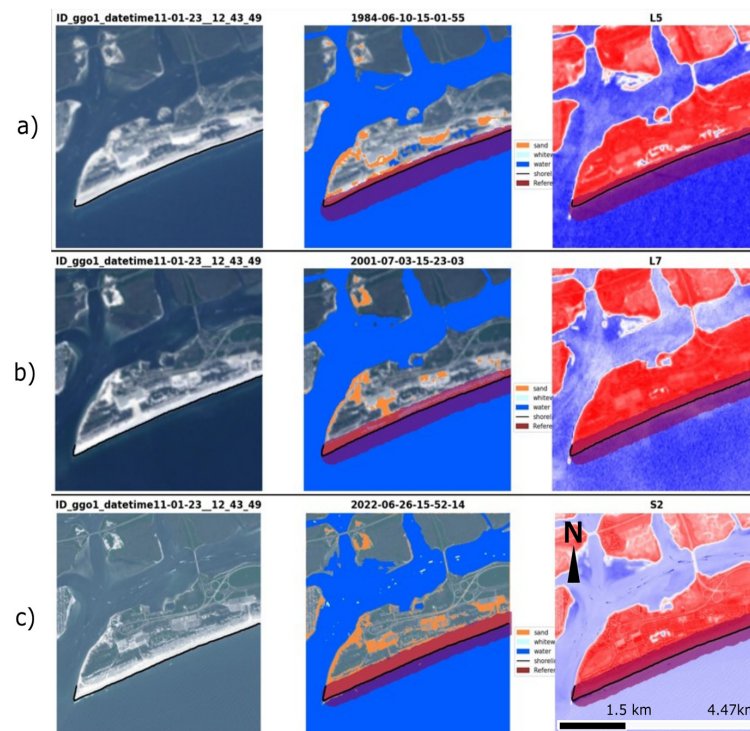


Figure 3. CoastSeg shoreline mapping outputs for the western end of Jones Beach Island during summer conditions (June–July) of (a) 1984, (b) 2001, and (c) 2024. CoastSeg outputs include the raw visible imagery from Google Earth Engine [38] with the mapped shoreline (**left column**), Neural-Network-mapped land cover classes (colors) and the shoreline buffer area (red; **middle column**), and MNDWI output with shoreline position mapped along the Otsu-defined threshold value (black line; **right column**).

Examples of the analysis results for three different dates and satellite sensors are shown for the western end of Jones Beach Island, also referred to as Jones Beach Island ROI 1, in Figure 3. The leftmost images are the RGB band image which have been modified for better contrast with the resulting shoreline position, the middle images are the pixel classification placed on top of the true-color image, and the rightmost images are the MNDWI with the shoreline mapped at the threshold value. The reference shoreline buffer, as mentioned previously, is shown on the middle and rightmost images to highlight the spatial search limits for CoastSeg to determine the shoreline boundary.

Shoreline positions along each transect were extracted from all useable imagery, and these raw position data were examined for transects that were sparse with data. This could happen due to transects landing directly on water areas, jetties, persistent Landsat 7 stripe errors causing missing data [45], or persistent clouds. In total 4 transects were dropped from Rockaway Peninsula, 3 transects from Long Beach, and 21 from Jones Beach Island.

The tidally corrected shoreline positions were then analyzed for patterns and trends. To create island wide datasets, the ROI outputs were to be combined into larger arrays (cf. Tables A1 and A2). As the shoreline position data were inherently noisy [43], they were resampled into monthly averages across the 38 years. Blank or NaN values in the monthly data were linearly interpolated over, irrespective of the size of the data gap, to create a complete time-series dataset. These blank values represented between 6.3 and 19.7% of the monthly records for the transects.

To further reduce noise from event, seasonal and/or other variations in the shoreline positions, the monthly data were also smoothed with the non-parametric locally estimated scatterplot smoothing (LOESS) low-pass filter [48]. Here we use the approach of the seasonal-trend decomposition with LOESS (STL) of Cleveland et al. (1990), which eliminates

all seasonal patterns in the data to produce multi-year non-linear trends. LOESS is based on a series of local regressions and uses traditional least-square methods for data analysis relying on a 2-D scatterplot as its building block [49].

Time-dependent rates of change were computed from month-to-month gradients in the monthly LOESS-filtered shoreline position data. The use of the LOESS-filtered data produced more continuous shoreline change data, relatively free from the effects of outliers and the noisiness of our satellite-derived shoreline data. As noted below, the shoreline change rates from the LOESS-filtered data allowed for detection and measurement of propagating longshore sediment waves (both accretionary and erosional) and the multi-year effects of beach nourishment projects. Lastly, we computed linear trends for each transect by fitting least-squares linear regressions through the raw monthly data.

2.2. Sediment Nourishment Observations and Comparisons with Shoreline Change

Beach nourishment projects are carried out occasionally to help increase beach width and the overall sand volume of beaches. Sediment sources include sedimentation within the inlets, which may be a navigational hazard, or offshore sand sources of the inner continental shelf. To assess the effects of sediment contributions from inlet dredging and beach nourishment activities on shoreline positions in the study area, we used the observations provided by the American Shore and Beach Preservation Association's (ASBPA) National Beach Nourishment Database [50], which covers projects in the study area during 1927–2019. The nourishment projects captured in this database as noted by Elko et al. (2021) vary by geographically distinct placement locations, the project year, and the volume of sediment moved [50].

We organized the nourishment observations for the three study area beaches (Rockaway Peninsula, Long Beach and Jones Beach Island) and summed all project sediment volumes within each calendar year. The ASBPA data for Long Beach included two different placement locations, one in the central portion of the island and the other at Point Lookout at the eastern end of the island, see Figure S2 for Point Lookout location in the Supplemental Material. We evaluate these two placement areas separately and distinguish them with the terms 'mid' and 'east' to denote the middle and eastern portions of the island, respectively.

For the comparison with shoreline positions, ASBPA nourishment data from 1980 to 2019 were considered, and this resulted in total volumes of beach nourishment of 13.6, 3.7, 2.0 and 11.2 million m³ for Rockaway Peninsula, Long Beach (mid), Long Beach (east), and Jones Beach Island, respectively. Some of the largest nourishment projects occurred during or after 2013 following the impacts of Hurricane Sandy and other subsequent storms, including a 2.2 million m³ project at Rockaway Peninsula in 2014, a 3.7 million m³ at Long Beach (mid) in 2019, and a 1.6 and a 1.4 million m³ at Jones Beach Island in 2014 and 2018. The total number of years in which one or more nourishment projects were carried out, enumerated over the 38-yr time series ranged from 1 for Long Beach (mid) to 21 for Rockaway Beach on Rockaway Peninsula.

Annual beach nourishment volumes were compared with annual shoreline change by computing the mean shoreline positions within the three primary regions of each beach of the study area: the accreting western tip, the more stable middle beach section, and the highly dynamic eastern ends. These three regions were delineated by the distinct patterns of shoreline change highlighted in the Results below, and the boundaries between these regions were set at 3.5 and 16.0 km for Rockaway Peninsula, 1.3 and 11.0 km for Long Beach, and 8.0 and 18.8 km for Jones Beach Island (cf. Figure 5). The effects of nourishment on shoreline change were assessed with annual shoreline change measured in the LOESS filtered data, and linear correlation coefficients (r) between the time series of nourishment volume and shoreline change were used to characterize relationships. The time history of the nourishment (both

before and after projects) was evaluated with a simple cross correlation analysis of time-lagged correlations by shifting the mean shoreline change by annual increments.

Examination of the monthly and LOESS-filtered shoreline position data suggested that several of the nourishment projects occurred over multiple calendar years and that the project year in the ASBPA database captured the end of the project rather than the timing of the maximum sediment placement. Therefore, for projects that clearly had the majority of shoreline change during a different year than the reported ASBPA project year, we shifted the year used in the data presented and analyzed here. This only occurred for three projects, the 2019 Long Beach (mid) project, the 2014 Long Beach (east) project, and the 2014 Jones Beach Island project; the years for these projects were shifted one year earlier owing to massive beach growth during the second half of the previous year. As noted below, the greatest statistical significance was found between nourishment volumes and the shoreline regions that directly received the sediment, and these results are highlighted in the Results below.

2.3. Wave Observations and Comparisons with Shoreline Change

To assess the influence of ocean waves on coastal change, we collected wave information from the ERA5 hindcast models [51]. ERA5 provides hourly-daily estimates for numerous atmospheric, ocean-wave and land-surface quantities [51]. Daily average data were collected for the same interval of time as the satellite imagery (1984–2022) resulting in time series of the date of data collection (noon of every available day), significant wave height (m), mean wave direction (degrees relative to North), peak wave period (s), mean wave period (s), wave power (kW/m), and wave setup (m). Wave data were generated from a point oceanward of the study area and in adequately deep enough water to use the wave power formulations detailed below (40.47 latitude, −73.07 longitude, water depth ~55 m).

The wave data from the ERA5 hindcast were used to create a directional wave rose and time series of wave power (P) and significant wave heights (H ; Figure 4). The majority of waves observed in the study area come from the southeast and the south with heights of 0.5 to 2 m. Wave energy (E), wave group velocity (C_g), and wave power (P) were computed using the deep-water approximations, shown in Equations (2) to (4) [15]:

$$E = \frac{1}{8} \rho g H^2 \quad (2)$$

$$C_g = \frac{1}{2} \frac{gT}{2\pi} \quad (3)$$

$$P = EC_g \quad (4)$$

where ρ is the density of seawater (1025 kg/m³), g is the acceleration of gravity (9.81 m/s²), and T is the wave period (s).

We were unable to make comparisons between the estimated wave power and shoreline change according to the approach of Yates et al., who reported a direct correlation between the wave energy, shoreline change rate, and the relative shoreline position for Torrey Pines, California [52]. This is owing to the substantial time dependence in the relative shoreline positions from long-term accretion, the effects of beach nourishment and wave-like propagation of shoreline change patterns. Thus, we made comparisons between magnitudes of monthly shoreline change and monthly wave power for broad coastal sections by means of linear correlation analyses, and significance in these relationships was tested with p -values. These coastal sections were the same as defined above for the beach nourishment analyses, and captured the integrated western, middle and eastern regions of each of the three beaches. Owing to the marked shoreline changes observed from beach nourishment, we focused on the shoreline sections that had no direct nourishment: the western portions of each beach and the middle section of Long Beach during the interval 1984–2016.

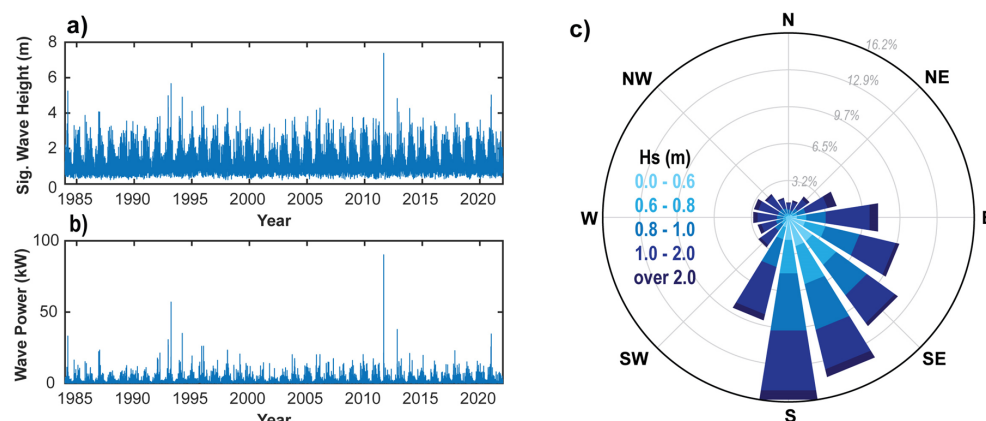


Figure 4. Wave data for southern Long Island from the ERA5 hindcasts from 1984–2022. Time series of the significant wave height (a) and wave power (b) show seasonal variations and large events such as the Nor’easter of March 1993 and Hurricane Sandy of October 2012. A directional wave rose is shown in (c). The exact location of data collected from ERA5 is shown as Figure S3 in the Supplemental Materials.

Shoreline change was measured from the raw monthly and the LOESS-filtered shoreline position data. We considered several metrics of the monthly wave power, and the mean monthly values were found to have the highest correlation values between the wave power and shoreline position and are presented below in the results section. Additionally, we report the median shoreline change rates for both the greatest and smallest wave powers, using the 10th percentile to define these wave conditions that represented the variations in shoreline changes, and mean shoreline positions for each section were used in comparisons with wave power estimates. These segments were created before and after groin fields as well as before any major landscape changes (Jones Beach Island ROI 10). Rockaway Peninsula was broken into 6 sections at the following increments in the alongshore distance: 0–3550, 3600–7250, 7300–12,050, 12,100–14,250, 14,300–17,550, and 17,600–18,300 m. Long Beach was broken into 4 sections from 0–1300 m, 1350–4800 m, 4850–10,900 m, and 10,950–14,900 m. Zero is defined to be the western most edge of each respective location. Jones Beach Island was broken into 3 sections from 0–7300 m, 7350–18,750 m, and 18,800–23,350 m.

3. Results

3.1. Shoreline Trends and Variability

Demeaned monthly shoreline positions for all study area transects were assembled to present the spatial and temporal patterns in the shorelines (Figure 5). The total number of generated shorelines ranged from 881 to 1646 depending on the ROI before the monthly resample was applied. Table A4 in the Appendix A shows the values at all 13 ROIs. All three beaches appear to be accreting sediment overall over the 38-yr time span, although with distinct spatial patterns in these changes and some punctuated intervals or events of erosion and accretion. High rates of accretion occur on the western ends of all three beaches, where roughly 150-m of accretion occurred over the 38-yr record (Figure 5). For Rockaway Peninsula and Long Beach, there are distinct geographical breaks that divide the western region of accretion and a middle region with less shoreline change. These abrupt transitions in accretion rates occur over ~200-m longshore distances and they are coincidental with the ends of the westernmost groin fields of each beach (Figure 5a,b). Jones Beach Island, in contrast, has a broader ~2-km stretch of shoreline where the rates of accretion decrease gradually, and this beach is unique for the study area in that it does not have any groins (Figure 5c).

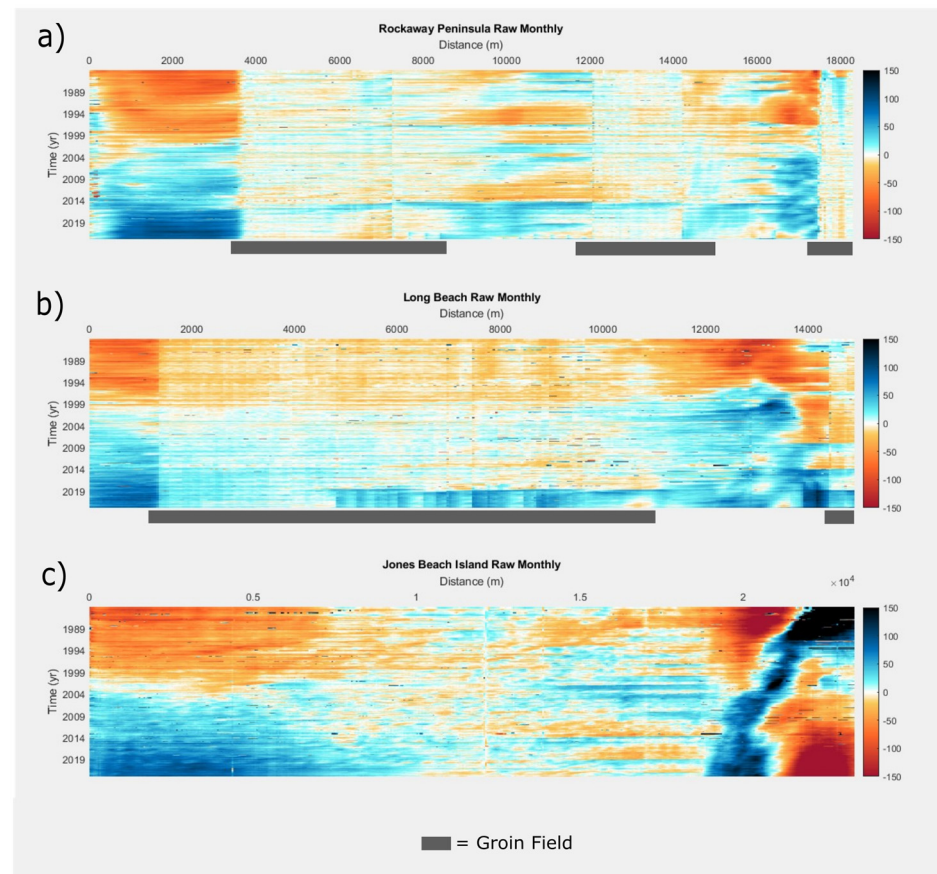


Figure 5. Raw monthly resampled shoreline positions for the three regions of the study area (a) Rockaway Peninsula, (b) Long Beach, and (c) Jones Beach Island. Shoreline positions are shown with respect to the mean position of each transect (shown as zero). Color bar ranges from 150 (accretion in blue) to -150 (erosion in orange). Groin fields are shown as a gray bar underneath the corresponding locations, which occur only on Rockaway Peninsula and Long Beach.

Example shoreline positions from the 38-yr record were mapped to assist with the visualization of the accretion patterns of the western ends of the study area beaches (Figure 6). The steady seaward expansion of the shoreline positions near the western beach ends are evident at each site, and the shoreline accretion is observed to be bound by the westernmost beach-terminating jetties of each beach (Figure 6).

Overall, the monthly shoreline position data provide evidence of both coherent and non-coherent patterns of shoreline change across the three beaches based on our analysis (Figure 7), which suggests that shoreline change may result from several factors that vary in time and space across the beaches. Closer examination of the time series of shoreline positions reveals temporal patterns in the shoreline change and how these patterns vary along the study area beaches (Figure 7). One overriding pattern in all the monthly time-series data is the high-frequency (i.e., less than a year) variability in the shoreline positions, which is likely a result of shoreline seasonality, the effects of storms, and noise in the data (Figure 7). Over intervals of several years, however, shoreline positions commonly exhibit multi-year oscillations, and these oscillations are not always in phase between the transects. For example, shoreline positions for the two highlighted Rockaway Peninsula transects with accretion trends (lighter colored lines; Figure 7a) show opposing patterns of accretion and erosion centered during 1993, 1997, and 2014 even though they are only 2.2 km apart.



Figure 6. Western ends of each site showing the overall accretion using QGIS. See legend for color corresponding dates. The first continuous shoreline for each respective year was used for the visualization. (a) Rockaway Peninsula, (b) Long Beach, (c) Jones Beach Island. Images are from Google Earth within QGIS.

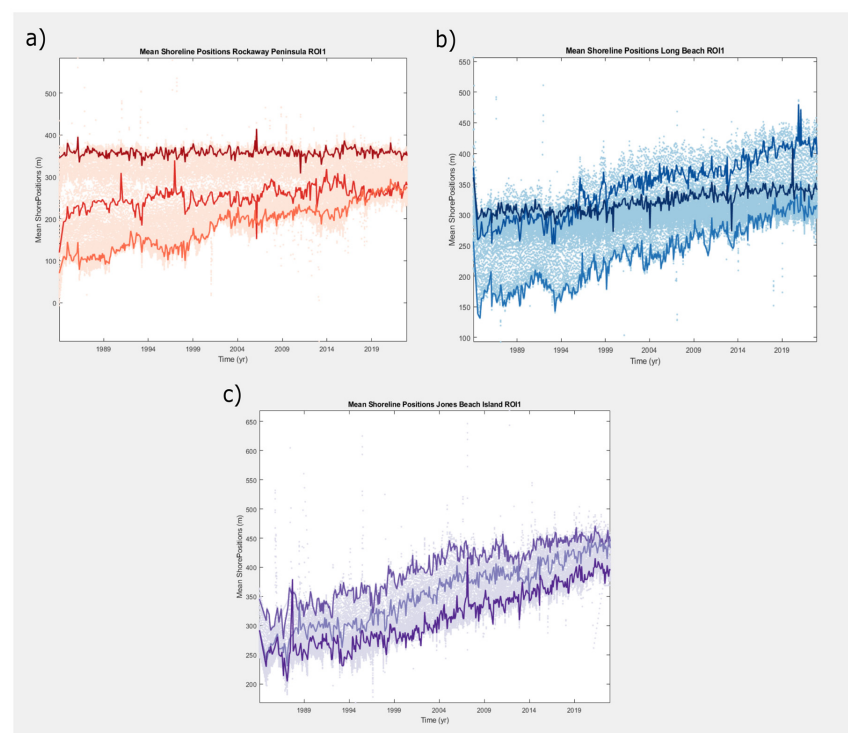


Figure 7. Mean raw monthly shoreline positions (dots) for the western sides of each beach site highlighting temporal trends (lines) and variability. (a) Rockaway Peninsula highlighting transects

6, 50, 100, which are at 300, 2500, and 5000 m from the western end of the beach. **(b)** Long Beach highlighting transects 6, 24, 40, which are at 300, 1200, and 2000 m from the western end of the beach. **(c)** Jones Beach Island highlighting transects 4, 20, 85, which are at 200, 1000, and 4250 m from the western end of the beach. Unique transects were selected to represent different regions of each ROI corresponding to the beginning, middle, and end of the region shown.

To reduce noise and eliminate outliers in the sub-annual variations in the shoreline positions, the monthly data were smoothed with the non-parametric LOESS filter (as detailed in Section 2.1), and examples of this filtering are shown in Figure 8. The transects shown in this figure were obtained from the accreting western ends of each beach and are outside of the influence of groin fields (Figure 8). Overall, the LOESS filter removed noise, annual-scale oscillations, and events while preserving multi-annual trends in the data. As shown in the example data, all three beaches include outlier data that have little consequence on the LOESS smoothed results, which is one of the strengths of using LOESS over other techniques such as local averaging (Figure 8). The LOESS filtered shoreline positions capture the multi-year patterns of change, such as the interval of erosion at the Long Beach transect during 1992–1993 and intervals of elevated rates of accretion such as during 1998 and 2014 at Jones Beach transect (Figure 8).

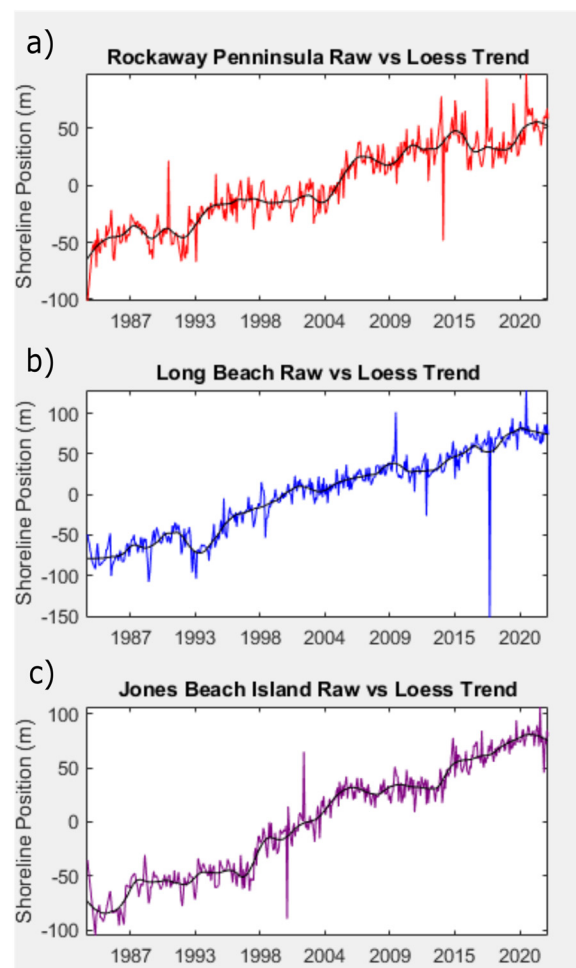


Figure 8. Comparison of raw monthly mean shoreline positions (red, blue, purple lines) and the LOESS filtered positions (black lines) for an example transect from each of the three study area beaches. Transect 12, which is 600 m from the western ends, is shown for each of the study areas to highlight patterns in the data, including time-dependent trends, events, and noise.

A compilation of the LOESS filtered shoreline positions provides a comprehensive picture of the coastal changes along the three study area beaches (Figure 9). One of the prominent patterns in these shoreline changes is the lower rates of change with the groin fields of both the Rockaway Peninsula and Long Beach, which are shown by “whiter” areas within these plots (Figure 9a,b). Beyond these groin fields, there are higher rates of shoreline change, which is shown by brighter colors. Other prominent patterns include the broad scale accretion that occurred in the centers of Rockaway Peninsula and Long Beach during 2014 and 2018, respectively, and the 200–300 m of shoreline change at the eastern end of Jones Beach Island (Figure 9). This latter phenomenon, along with other propagating waves of accretion and erosion, are examined in greater detail below in Section 3.2.

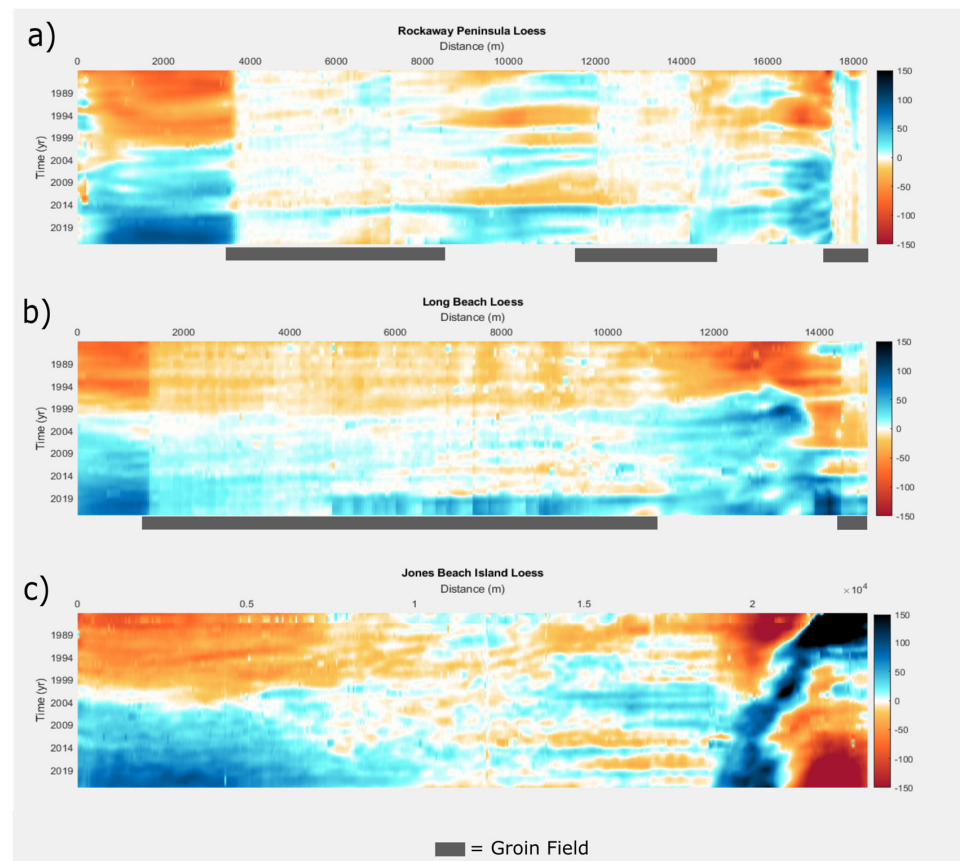


Figure 9. Low-pass shoreline positions of the three study area beaches from LOESS filtering of the mean monthly shoreline data: (a) Rockaway Peninsula, (b) Long Beach, (c) Jones Beach Island. Groin fields are shown as a gray bar underneath the corresponding locations, occurring only on Rockaway Peninsula and Long Beach.

Linear regression of each LOESS-filtered shoreline versus time provides estimates of the linear rates of shoreline change (difference between initial and final positions relative to the mean) over the 38-yr records, and computed shoreline change rates are accretionary (positive) for most of the study area (Figure 10). As noted above, high rates of accretion were observed at the western ends of each beach segment, where shoreline trends averaged ~ 4 m/yr, which is equivalent to ~ 150 m of shoreline change over the 38-yr time series (Figure 10). Another region with high rates of shoreline change was the eastern end of Jones Beach Island, where a portion of the shoreline accreted at ~ 8 m/yr and an adjacent portion of shoreline eroded at over -14 m/yr (Figure 10c). This significant systematic shift in the shoreline is described more fully in Section 3.2 below. Linear shoreline change rates were much smaller in the areas containing groin fields on Rockaway Peninsula and Long

Beach, where mean rates were roughly 0.5 and 1.5 m/yr, respectively. This is equivalent to ~20 m of accretion within the groin fields of Rockaway Peninsula and ~60 m of accretion for the groin field on Long Beach during the 38-yr records.

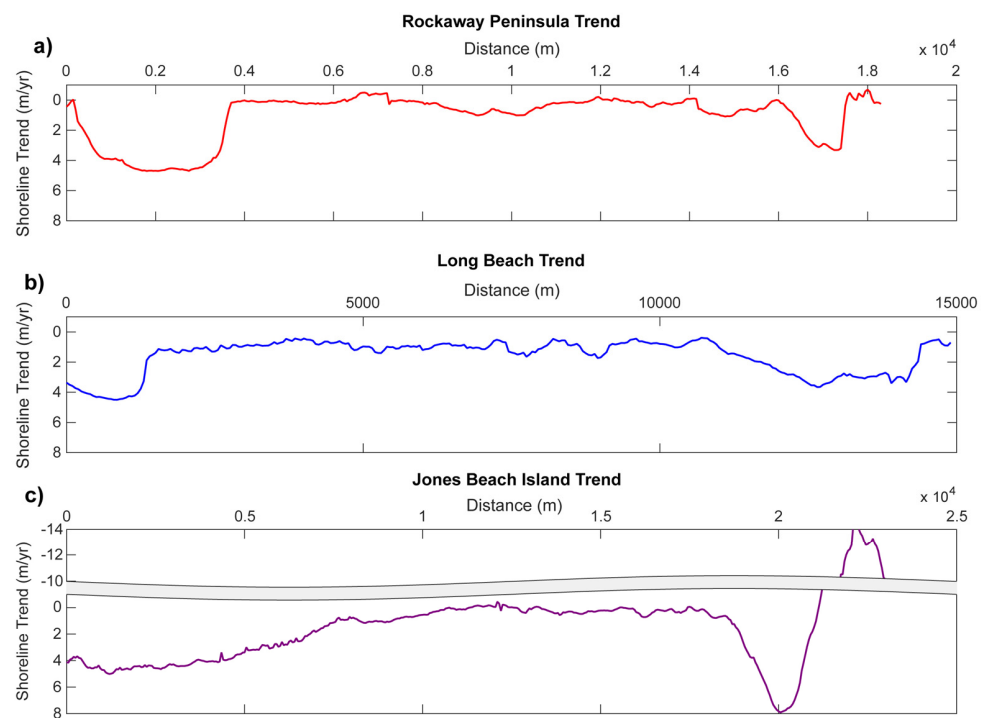


Figure 10. Trends in the shoreline positions for the three study area beaches computed from linear regression of the LOESS-filtered monthly shoreline data. (a) Rockaway Peninsula, (b) Long Beach, (c) Jones Beach Island. Note the break in values in (c) to highlight the higher rates of erosion near the eastern end of Jones Beach Island. A version of (c) without the y -axis break is provided in the Supplemental Materials as Figure S4.

The amount of variation about the mean shoreline position at each transect was evaluated with measurements of the standard deviation of the raw monthly shoreline position time series (Figure 11). This was not done on the trend data as shown in Figure 10, but only on the raw monthly shoreline positions to better observe the amount of shoreline position variation. Rockaway Peninsula and Long Beach have similar patterns of shoreline variance with a peak in the standard deviation of about 50-m near the western ends, and standard deviations of 10–20 m within the groin fields (Figure 11a,b). The shoreline variation is higher on the remaining beaches without groins, including the eastern ends of these two beaches and shoreline region between the Rockaway Peninsula groin fields. Along Jones Beach Island, which contains no groin fields, the shoreline standard deviation hovers around 10–30 m for the majority of the island, with values of 40–60 m near the westernmost end of the beach and values of almost 200 m eastward of the 20 km on Jones Beach Island. The exceptional high values on the eastern end of Jones Beach Island results from an eroded spit that has slowly moved down the island, as discussed in detail in Section 3.2.

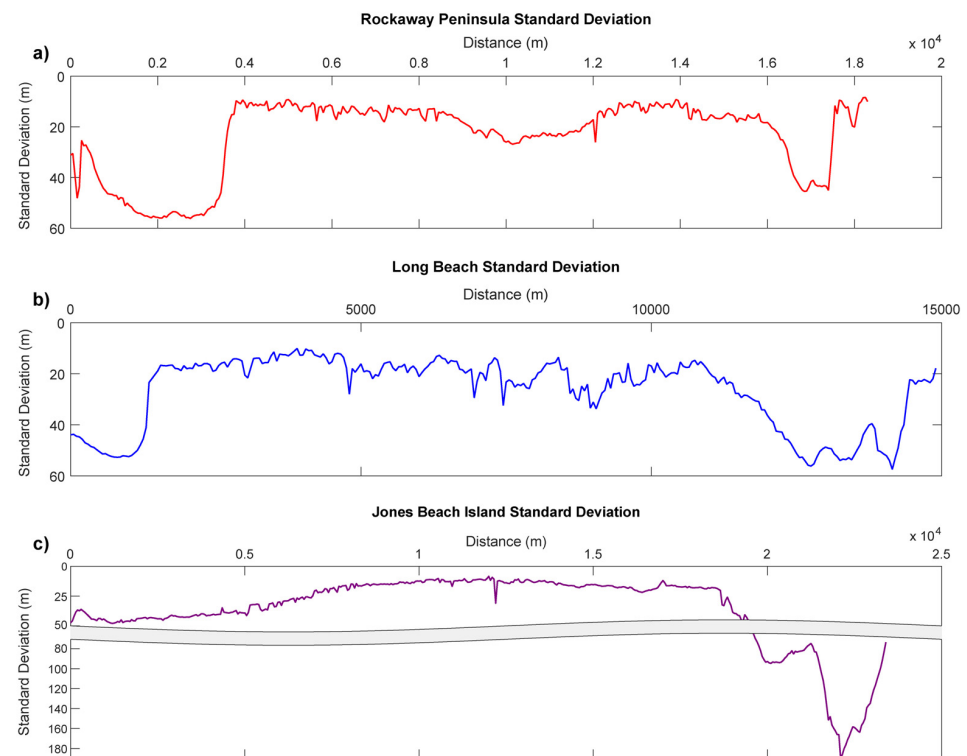


Figure 11. Standard deviation of each site: (a) Rockaway Peninsula, (b) Long Beach, (c) Jones Beach Island. Standard deviation in meters and distance in meters. A version of (c) without the y-axis break is provided in the Supplemental Materials as Figure S5.

3.2. Erosion and Accretion Waves

To identify the timing and patterns of accretion and erosion along each of the three study area beaches, time series of monthly shoreline changes between each LOESS filtered shoreline were calculated. These calculations reveal that these low-pass monthly shoreline changes ranged between -8 and 8 m/mo, with most concentrated between -2 to 2 m/mo, and oscillated between erosive and accretive phases through the time series (Figure 12). In order to create Figure 12, each successive monthly shoreline was compared to the previous shoreline position to create a better snapshot of smaller shoreline patterns not captured by the broader analysis previously (Figures 5 and 9). Additionally, several of the broad accretion and erosion events highlighted by these analyses were observed to propagate in a westward alongshore direction, suggesting that some of the accretion and erosion events exhibited wave-like behavior along the shore (Figure 12). Prominent wave-like behaviors were found on all three of the study area beaches, and they were observed to move along at least several kilometers of beach and extended over at least several years of time (Table 1). The mean duration of these coastal waves was over 4.5-yr and the mean alongshore speed was 1.28 m/d, although these parameters varied substantially between each event (Table 1). These values were determined through visual interpretation of the figure by determining the start and end date as well as the distance between the two points. All of the wave-like behaviors in the shoreline—both erosion and accretion—moved westward, which is the general direction of littoral drift at these sites [53].

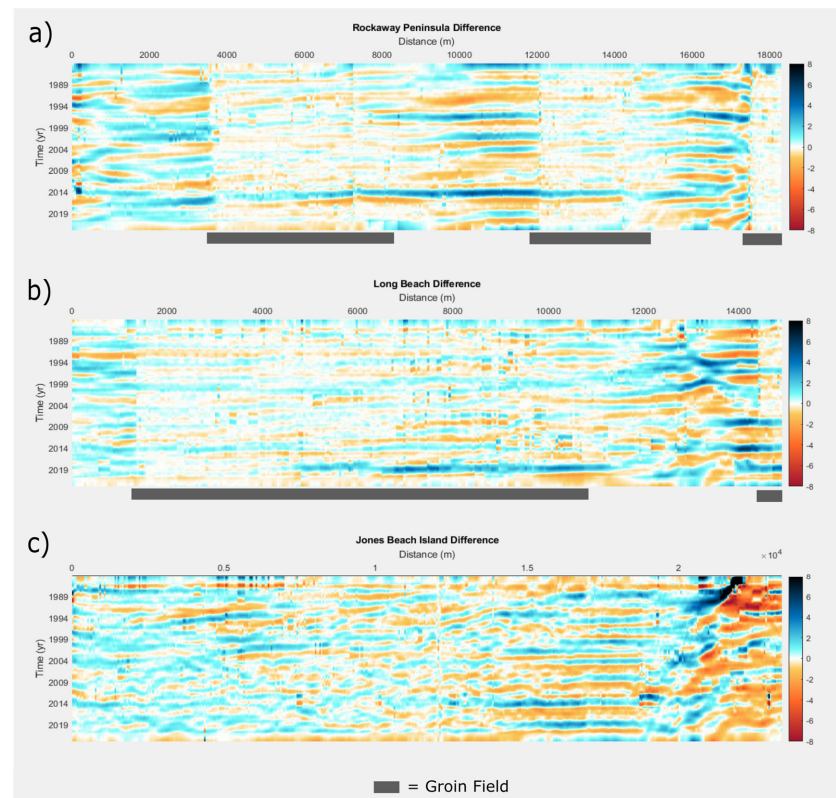


Figure 12. Site wide difference from the previous data point, resamples LOESS monthly data. (a) Rockaway Peninsula, (b) Long Beach, (c) Jones Beach Island. Color bar ranging from 8 (accretion in blue) to -8 (erosion in orange). Groin fields are shown as a gray bar underneath the corresponding location, only occur on Rockaway Peninsula and Long Beach.

Table 1. Major wave-like behaviors in the study area shorelines as observed in the shoreline change time series computed by LOESS-filtered data and presented in Figure 12. Events are listed chronologically by study area.

Date	Number of Days	Speed (m/Day)	Location of Midpoint	Accretion/Erosion
7 June 1984– 16 July 1988	1500	1.27	Rockaway Peninsula at 16.3 km	Erosion
7 March 2013– 2 December 2015	1000	0.60	Rockaway Peninsula at 17.1 km	Erosion
23 September 2013– 15 April 2017	1301	3.34	Rockaway Peninsula at 5.1 km	Accretion
6 November 1997– 29 May 2001	1300	1.19	Long Beach at 12.6 km	Accretion
7 May 2009– 24 October 2011	900	1.17	Long Beach at 9.1 km	Erosion
16 May 2015– 6 December 2018	1300	0.89	Long Beach at 13.0 km	Erosion
24 December 1984– 2 December 1992	2900	0.43	Jones Beach Island at 21.0 km	Accretion
28 January 1986– 2 October 1996	3900	0.40	Jones Beach Island at 23.0 km	Erosion
16 June 1990– 25 July 1994	1500	2.23	Jones Beach Island at 3.7 km	Erosion

Table 1. Cont.

Date	Number of Days	Speed (m/Day)	Location of Midpoint	Accretion/Erosion
21 July 1991– 10 February 1995	1300	1.31	Jones Beach Island at 13.0 km	Erosion
24 August 1992– 10 January 1997	1600	1.22	Jones Beach Island at 13.3 km	Accretion
Mean $\pm$ St. Dev. (Min–Max)	1680 $\pm$ 900 (900–3900)	1.28 $\pm$ 0.86 (0.40–3.34)		

The most prominent wave-like behaviors were observed to occur on Jones Beach Island near the eastern end of the beach (roughly between the 20 and 23-km alongshore position) and moved at ~ 0.4 m/d, which were the slowest speeds of the observed waves (Table 1). Arguably, there are several recurring accretion and erosion wave-like phenomena in this region of the study area during the duration of the study (1984–2022; Figure 12c). These phenomena were related to the large-scale shoreline changes that occurred along the eastern portion of Jones Beach Island and highlighted above (Figures 5c, 9c, 10c and 11c). Examination of the satellite imagery for this region of coast that were used in this study provides evidence that these shoreline changes were part of broad scale planform changes in the coastal landforms (Figure 13). These changes include the welding of a spit, observable in 1984 (Figure 13a) to the coast, which resulted in back-beach ponds (Figure 13b) that experienced sedimentation with time (Figure 13c–f). Another geomorphic process occurring in this region was the westward translation of the Fire Island inlet, which lies between Jones Beach Island and Fire Island to the east. Evidence for this translation can be seen in the propagation of the western tip of Fire Island into the imagery between 2000 and 2022 (Figure 13d–g). Coincidental with the westward translation of this inlet, the Jones Beach Island shoreline is observed to erode in an arcuate pattern near the point opposite of the tip of Fire Island (Figure 13g). Overall, these observations suggest that multiple factors have influenced the shoreline evolution of the eastern end of Jones Beach Island, and that these changes have resulted in the largest measured changes in shoreline position (Figures 9 and 10) and a series of wave-like accretion and erosion features propagating westward along this portion of the study area (Figure 12; Table 1)

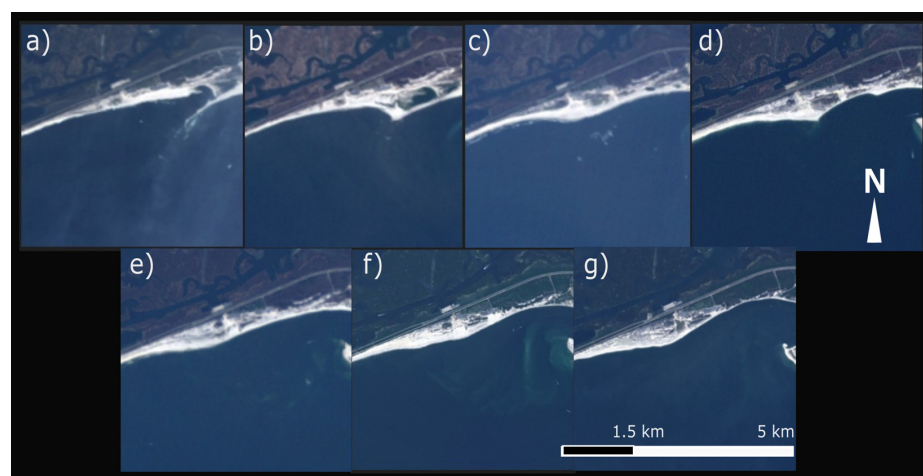


Figure 13. Images of Jones Beach Island from ROI 10 show the geomorphic changes to the coastal landforms time. (a) September 30, 1984 (Landsat 5), (b) March 17, 1988 (Landsat 5), (c) October 25, 1993 (Landsat 5), (d) October 20, 2000 (Landsat 7), (e) November 11, 2008 (Landsat 7), (f) August 19, 2015 (Landsat 8), (g) September 15, 2022 (Landsat 9).

3.3. Shoreline Change—The Effects of Beach Nourishment

Time series of beach nourishment volumes and regionally averaged shoreline positions at these nourishment sites are shown in Figure 14. In general, there are coherent patterns between the nourishment projects and accretion of the shoreline. For example, most of the largest nourishment projects result in tens of meters of shoreline accretion, such as observed in 1996 and 2014 at Rockaway Peninsula, 2018 in the middle of Long Beach, 1994–1995, 2008 and 2013 at the eastern end of Long Beach (Point Lookout), and 2013 and 2018 at Jones Beach Island (Figure 14). The 1994–1995 nourishment project at the eastern end of Long Beach, which resulted in ~50-m of beach accretion in this region, may have influenced the subsequent ~20-m of accretion of the middle of Long Beach during 1997–2002 (Figure 14b,c), as this pattern is consistent with westward propagating accretion patterns during this time (see Section 3.2 above).

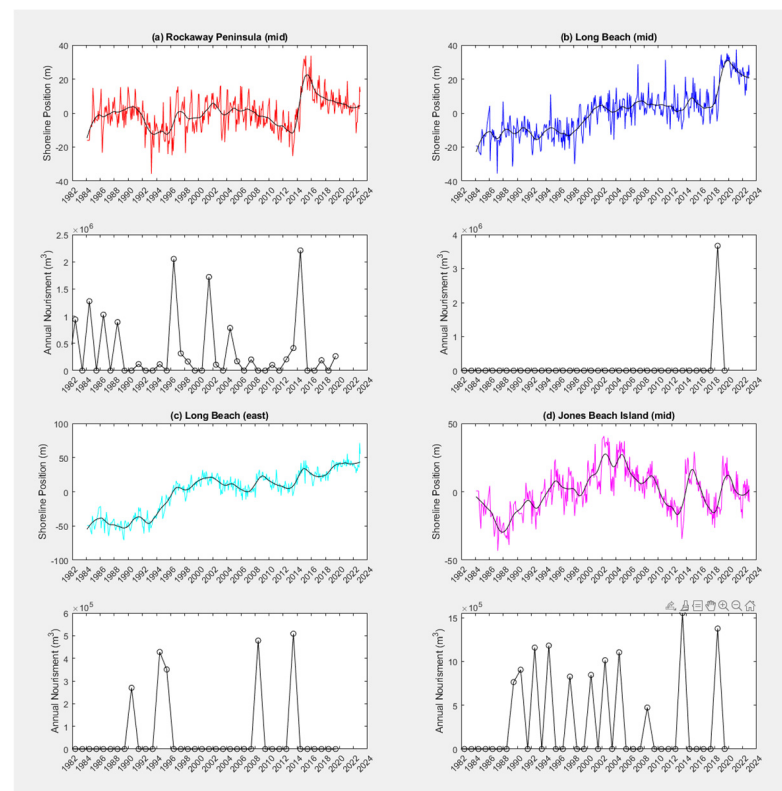


Figure 14. Mean regional shoreline positions (colors = monthly raw positions, black = LOESS-filtered positions) and sediment nourishment volumes from the ASBPA National Beach Nourishment Database for four nourishment sites in the study area: (a) the middle of Rockaway Peninsula, located between 3.5 and 16.0 km on this peninsula/barrier spit [23], (b) the middle of Long Beach, located between 1.3 and 11.0 km on this island, (c) the eastern end of Long Beach, located between 11.0 and 14.0 km on this island, and (d) the middle of Jones Beach Island, located between 8.0 and 18.8 km on this island.

The spatial scales of these nourishment-related accretion events can be observed in the shoreline change plots for the entire study area (Figures 5, 9 and 12). For example, the 2013 nourishment project on Rockaway Beach is observed to influence shoreline positions over the majority of the peninsula's beach (Figures 5a and 12a), which is consistent with the 10-km alongshore project length reported by ASBPA [50]. Similar multi-kilometer accretion patterns resulted from the 2018 nourishment project on Long Beach (Figures 5b and 12b). Nourishment to Jones Beach Island is generally constrained to the eastern portion of the island, near Gilgo Beach, between the 14 and 19 km locations on this

island (Figures 5c and 12b). The location of these more specific nourishment locations is shown in Figure S2 of the Supplemental Materials.

Cross-correlation analyses between the annual time series of nourishment and shoreline change rates in these four regions each reveal consistent associations (Figure 15). All four of the nourishment regions have significant accretion events during the year of the nourishment projects, with correlation coefficients ranging from 0.52 to 0.72 ($p < 0.002$ for all; Figure 15). The strongest correlation is shown for Rockaway Beach, and the weakest is shown for Jones Beach Island, where the nourishment projects have been more persistent (cf. Figure 14). Within a year of the nourishment projects, correlations are generally positive, which is likely a result of the use of the low-pass LOESS filtering on the shoreline positions (Figure 15). Two-to-three years following the nourishment projects, correlations are consistently negative, which suggests the onset of net erosion during that timescale (Figure 15). Evidence of the subsequent retreat of the shoreline positions during the years following nourishment is observed in the time series of all the investigated sites, such as shown for all nourishment events conducted since 2010 (Figure 14). Thus, there are significant relations between beach nourishment and the time-dependent patterns in the shoreline positions for all the three main study area beaches.

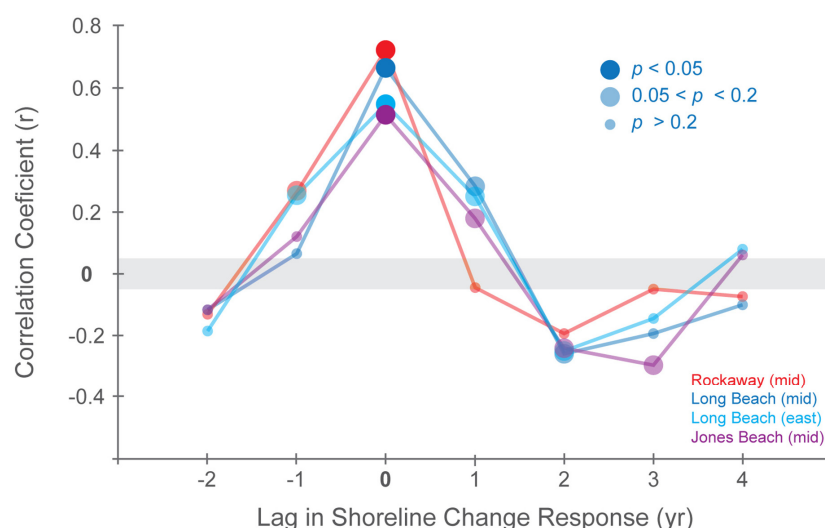


Figure 15. Correlation coefficients between annual rates of sediment nourishment and LOESS-filtered shoreline change shown for the four coastal regions presented in Figure 15. Positive correlations represent shoreline accretion (positive change) from nourishment, and negative correlations represent shoreline erosion (negative change) from nourishment. Significance in the correlation coefficients shown with symbol size and color. Cross-correlation analyses conducted for lags of -2 to 4 years.

3.4. Shoreline Change—The Effects of Waves

To evaluate the influence of waves on shoreline changes over the study area, we compared wave power from the hindcast data of ERA5 with monthly shoreline change rates averaged over broad multi-kilometer scales of the three beaches. As mentioned previously, these data were taken at a point off the coast of Jones Beach Island (40.47 latitude, -73.07 longitude) shown in Figure S3 of the Supplemental Materials. These comparisons were limited to four beach sections without regular direct beach nourishment, which as shown in Section 3.3 can have large effects on shoreline positions. Data used in these comparisons are shown in Figure 16 and include three of the accreting western ends of the study area beaches and the middle region of Long Beach. Waves are observed to have regular seasonal patterns with larger wave power during the winter and smaller wave power during the summer (Figure 16a). Seasonal patterns are expressed somewhat weakly in the monthly shoreline positions with periodic erosion events during the winter

(Figure 16b–e). For example, intervals with the greatest wave power, such as the 1993 and 1998 winters, were observed to correspond to tens of meters of erosion on the western ends of Rockaway Peninsula and Long Beach (Figure 16b,c), but lower to negligible erosion in the other beach sections (Figure 16d,e).

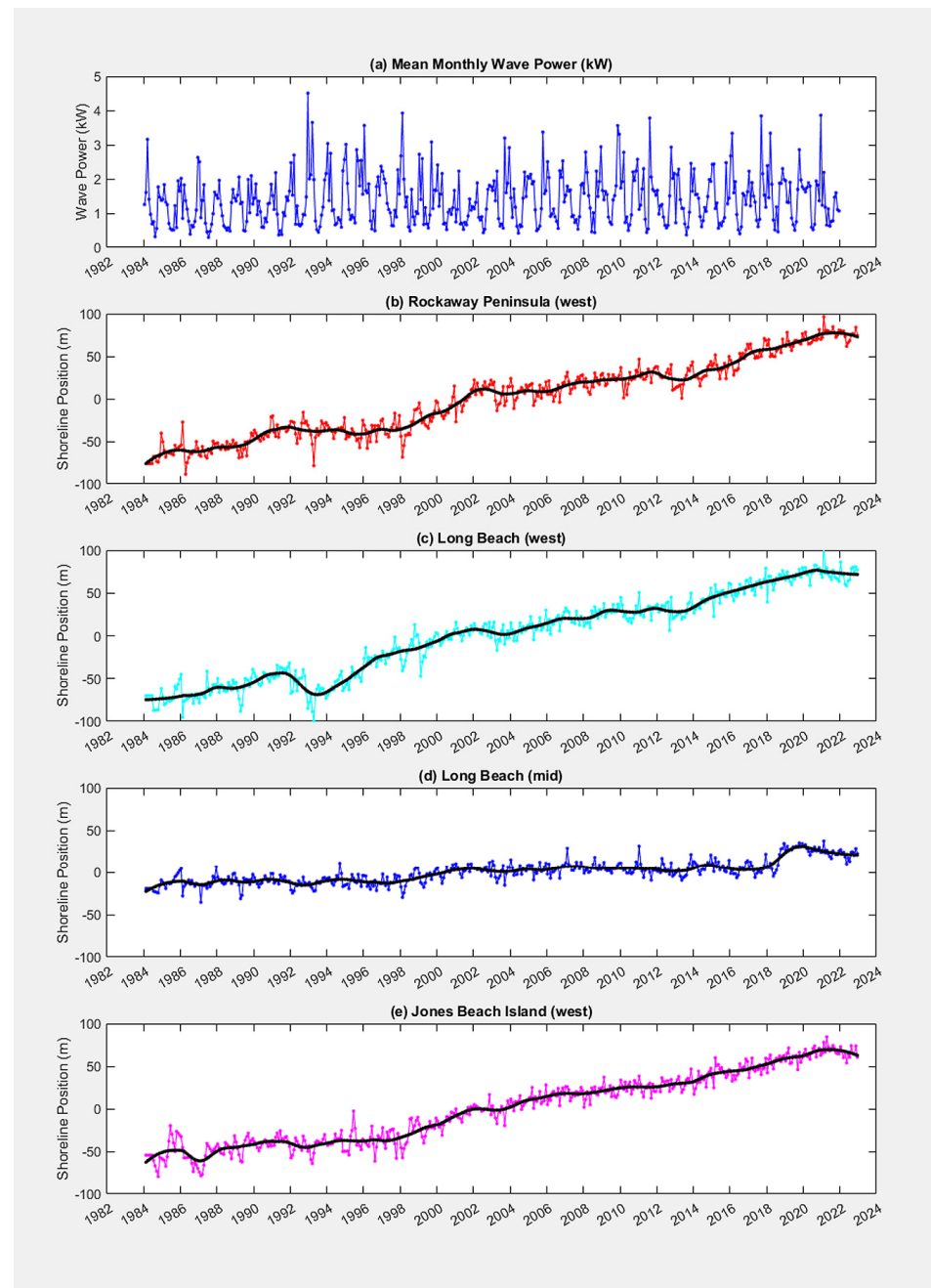


Figure 16. Time series of offshore wave power and shoreline change from beach sections that have limited to no direct beach nourishment effects. (a) Monthly mean wave power computed from the offshore ERA5 hindcast site. (b–e) Mean shoreline positions for broad beach sections of the western regions of (b) Rockaway Peninsula, (c) Long Beach, (d) the middle region of Long Beach, and (e) Jones Beach Island. In each shoreline position plot, the monthly mean position is shown with colored symbols and lines and the LOESS-filtered positions are shown with black symbols and lines. Shoreline change measurements were computed from differences in the monthly shoreline position data.

Correlation coefficients (r) between mean wave power and mean shoreline change were computed for the raw monthly and LOESS-filtered data as shown in Table 2. For these analyses, we only considered the 1984–2016 records for the middle section of Long Beach to eliminate the potential effects of the 2018 nourishment project. All correlations for the raw monthly shoreline data were negative, which suggests that shoreline erosion generally occurs during larger wave power and accretion generally occurs with smaller wave power, and all these relationships were significant at $p < 0.0001$ (Table 2). However, these coefficients ranged between -0.21 and -0.23 , which suggests that only ~5% of the variance in mean shoreline positions could be explained by wave power. These correlation coefficients become insignificant ($p > 0.05$) for the LOESS-filtered shoreline data, which suggests that variations in monthly wave power have little effects on the longer-term (multi-year) rates of shoreline change (Table 2). The weak, but significant, associations in the raw monthly shoreline change rates are also observed in median shoreline change values, which are net negative for the largest wave power values and net positive for the smallest wave power values, even though the distribution of these values (as shown with the interquartile ranges) overlap substantially (Table 2). This overlap signifies that the signal within the data is noisy leading to the weak associations between the wave power and the median shoreline change as the wave power is assumed to be the same at the three locations based on the coordinate the data was obtained from (Figure S3).

Table 2. Correlation coefficients between mean shoreline and mean wave power.

Study Area Beach Section	r (Raw Monthly)	r (LOESS)	Shoreline Change, Largest 10% Wave Power * (m/mo)	Shoreline Change, Smallest 10% Wave Power * (m/mo)
Rockaway Peninsula, western	-0.21 ($p < 0.0001$)	-0.08 ($p = 0.07$)	-0.5 [-4.0 – 3.2]	3.2 [-0.7 – 5.7]
Long Beach, western	-0.23 ($p < 0.0001$)	-0.01 ($p = 0.83$)	-1.2 [-5.8 – 2.6]	2.3 [0.2 – 5.7]
Long Beach, middle	-0.22 ($p < 0.0001$)	-0.05 ($p = 0.29$)	-1.0 [-4.4 – 1.9]	1.5 [-0.4 – 3.9]
Jones Beach Island, western	-0.22 ($p < 0.0001$)	-0.04 ($p = 0.45$)	-2.9 [-6.3 – 0.8]	2.0 [0.1 – 5.6]

Notes: * The median and interquartile range (in parentheses) of shoreline change from the raw monthly data are shown for the largest and smallest 10th percentile of monthly wave power observations.

4. Discussion

Satellite-derived shoreline measurements were made for three multi-kilometer long beaches of Long Island, New York, and these measurements revealed significant effects from coastal structures such as groins, westward transport and accretion at the ends of these beaches, westward movement of littoral sediment in wave-like accretion and erosion events, a significant response of the interannual shorelines to beach nourishment projects, and a minor, but significant, role of wave power on shoreline changes.

Overall, the three study area beaches showed net accretion over the 1984–2022 record interval. The accretionary growth of the western ends of each beach outpaced the shoreline change rates of the middle and eastern ends of Rockaway Peninsula and Long Beaches (Figures 9 and 10). This quick growth suggests that the shoreline offset across these study area inlets have grown over the 38-yr record (cf. Figure 1), which is consistent with the findings of Thevenot and Kraus (1995) [54]. The shoreline change patterns of Jones Beach Island are much more complicated, owing to the dynamics of a beach-welding spit and the migration of the eastern inlet (Figure 13).

The net accretionary patterns of the study area beaches require sources of littoral sediment. There has been over 30 million m³ of beach nourishment to the study area between 1980 and 2019, as detailed by ASBPA [50] and presented here in Section 2.2 and Figure 14. While much of this sediment has originated from dredging of the inlets separating these beaches, the net effect of these nourishment projects has been shoreline accretion on the order of tens of meters per project (Figure 14). Although there is net erosion during the years following these nourishment projects (Figure 15), the timing and magnitude of these projects, especially the large projects in the final decade of the measurements shown here contribute substantially to the net accretion patterns of these beaches (Figure 14). Other sources of littoral sediment may include offshore sediment from the inner continental shelf [55]. For example, Wei et al. [26] provided estimates of the Holocene sediment thickness for Rockaway Peninsula, which range between 0 and 11 m, with the largest thicknesses near the western end of the peninsula. These sandy shelf deposits have the potential to move inshore toward the beach and supply the littoral cell with new sediment, as suggested for other coastal areas including other parts of Long Island [55,56].

Our observations of net shoreline accretion contrasts with the 1962–1974 findings by the U.S. Army Corps of Engineers [27] in which Jones Beach Island was experiencing net erosion. This recorded historical erosional event was due to the removal of one of Jones Beach Island's eastern sediment sources, Fire Island. Fire Island had inlet jetties installed which reduced westward littoral drift to Jones Beach Island [27]. The regular dredging of this inlet since the 1970s and use of this sediment for nourishment clearly has had a positive effect on the Jones Beach Island shoreline position (cf. Figures 14d and 15), which suggests that regular maintenance of this sediment supply is a likely cause of this transition from net erosion to net accretion.

The overall westward littoral drift for the Long Island study area has been detailed by several previous studies [20,27], and it is supported by the observation of accretion of the western ends of the study area beaches (Figures 5 and 6). Our observations of westward-advection, wave-like behavior in shoreline erosion and accretion are additional evidence of westward littoral drift (Figure 12; Table 1). Our observations of these wave-like patterns are consistent with the measurements of similar measurements of longshore sand waves along South Hampton Beach of Long Island, New York, by Thevenot and Kraus [54]. They measured sand waves with cross-shore amplitudes of ~40 m, longshore wavelengths of ~1 km, and annualized speeds of ~0.4 km/yr. These observations are consistent with our measurements, which had annualized mean speeds of 0.5 km/yr (Table 1) without the use of fieldwork. Thus, the westward movement of littoral sediment along Long Island persistently results in the development of accretion and erosion waves that persist for years as they transition along several kilometers of the region's shoreline, slowing down in groin fields then speeding up again outside of those fields.

Shoreline position changes at the study area beaches were related to a combination of several factors, and occasionally several of these factors were observed to work in concert. For example, some large-scale nourishment projects during 2013–2018 both broadened beaches and initiated accretion sediment waves along these beaches. An example of a nourishment-related sediment wave can be seen near the western end of Rockaway Beach on Rockaway Peninsula following the 2014 nourishment project (Figure 5). As documented in Table 1, this sediment wave persisted for over 3.5 yr and was fast moving of the documented waves (3.34 m/d or 1.2 km/yr).

One factor that was shown to have relatively negligible effects on the shoreline position was the offshore wave conditions, as shown by time-series comparisons and correlation analyses (Table 2). This is in stark contrast to some other beaches whose multi-decadal

dynamics have been reported in the literature, such as the beach at Torrey Pines, California, where seasonal variations in wave energy directly relate to variations in shoreline positions [52]. And yet, Pianca et al. noted that beaches of the U.S. East Coast generally have large discrepancies between wave forcing and response time scales and often have mismatched shoreline response to wave conditions [57]. We find similar conditions, whereas waves can explain a limited amount of the shoreline change variations (Table 2). While there is some evidence for erosion during large events, such as the 1993 winter storms, and during higher wave power conditions (Table 2), these relationships are exceptionally weak suggesting that other factors play more important roles in the time-dependent shoreline positions.

Shoreline data tell a lot about a beaches dynamic, but don't encapsulate the whole picture of what may be happening below the waves. Submerged sandy bars are among one of the features that may have a role in shaping the shoreline at these sites. Evidence of offshore sediment supplies are seen at a neighboring island, Fire Island east of Jones Beach Island [20,58], which may extend throughout the region. Surveys at this adjacent island confirm that offshore ridges are connected to the shoreface and are persistent, which in turn influence the morphodynamics between the beach and bar [58]. Spielmann et al. aimed at understanding the role of bars on beach nourishment placement which could also be at play here [59]. Due to the lack of bathymetry data, we were unable to conclude if submerged bars are a reason for the movement of sediment. More work in this location, using remote sensing techniques for submerged bars to determine the exact presence and dynamics of these features, would improve overall understanding, as satellites are limited due to accuracy and frequency of images.

5. Conclusions

Satellite-based techniques provide effective methods to generate decadal scale time series of shorelines. Although these techniques commonly include uncertainties in excess of 10-m for each measurement, the potential to document changes, such as those shown here for western Long Island, New York, owing to the large amount—hundreds to over a thousand—of satellite images available to build shoreline time series. Additionally, shoreline changes, such as those shown here for western Long Island, may exceed the shoreline uncertainty values such that long-term patterns and responses to events can be clearly documented. No fieldwork was conducted during this study to reach the results. For the beaches of western Long Island, we show that the satellite-derived shoreline measurements provide new information about the geographic and time-dependent variations in shoreline change. These results should assist with further understanding of the history of these beaches and how coastal management from nourishment and structures such as jetties and groins and natural processes, such as coastal sediment waves, influence these highly populated and utilized coasts.

Supplementary Materials: The following supporting information can be downloaded at: <https://www.mdpi.com/article/10.3390/coasts5010002/s1>, Figure S1: Orientation and numbering of each site location directly from CoastSeg. Rockaway Peninsula (top) contains 3 ROIs, 1, 2, 3. Long Beach (middle) contains 4 ROIs, 1, 2, 4, 6. Jones Beach Island (bottom) contains 6 ROIs, 1, 2, 5, 6, 8, 10. ROI numbering is from west to east. Figure S2: Locations of more specific beach nourishment projects. (a) shows the location of Rockaway Beach (red) on Rockaway Peninsula and the location of Point Lookout (cyan) on Long Beach. (b) shows the location of Gilgo Beach (purple) on Jones Beach Island. (a) and (b) have the same scale. Imagery from Google Earth from 14 December 2015, to 1 January 2021. Figure S3: Exact location of ERA5 wave data downloads at 40.47 latitude, −73.07 longitude, water depth ~55 m. Figure created using data from ERA5. Data taken from 1 January 1984, to 31 December 2022. Figure S4: Trends in the shoreline positions for the three study area beaches computed from

linear regression of the LOESS-filtered monthly shoreline data. (a) Rockaway Peninsula, (b) Long Beach, (c) Jones Beach Island. Shown without the use of the break-axis function. Figure S5: Standard deviation of each site: Top (red) Rockaway Peninsula, Middle (blue) Long Beach, Bottom (purple) Jones Beach Island. Standard deviation in meters and distance in meters. Shown without the use of the break-axis function.

Author Contributions: Conceptualization, C.N.J. and J.A.W.; methodology, C.N.J., J.A.W., D.B. and S.B.; software, S.B. and D.B.; validation, C.N.J. and J.A.W.; formal analysis, C.N.J. and J.A.W.; data curation, C.N.J.; writing—original draft preparation, C.N.J.; writing—review and editing, C.N.J., J.A.W., D.B. and S.B.; visualization, C.N.J. and J.A.W. All authors have read and agreed to the published version of the manuscript.

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Data Availability Statement: All shoreline position data are available in a USGS Data Publication (Janda, C.N., Warrick, J.A., Buscombe, D., and Batiste, S. 2025, Shoreline Change of Western Long Island, New York from Satellite Derived Shorelines data release, <https://doi.org/10.5066/P14VFGZ> (accessed on 10 December 2024).

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Conflicts of Interest: The authors declare no conflicts of interest.

Appendix A

Details of the available satellite imagery and CoastSeg settings used to map shorelines in the imagery are provided in this appendix. Table A1 provides the total counts of satellite imagery available for each ROI in the study area. Table A2 provides the imagery counts for the final number of images used for each ROI in the study area. Table A3 includes the final settings used within CoastSeg for shoreline detection and shoreline extraction. Table A4 provides the number of extracted shorelines for each ROI from CoastSeg.

Table A1. Total number of images downloaded from Google Earth Engine before image removal.

ROI Name	L5	L7	L8	L9	S2
Rockaway Peninsula ROI1	825	792	336	38	990
Rockaway Peninsula ROI2	626	737	336	37	1691
Rockaway Peninsula ROI3	817	785	336	37	1972
Long Beach ROI1	868	850	359	39	1022
Long Beach ROI2	740	771	360	37	577
Long Beach ROI4	636	617	344	30	577
Long Beach ROI6	514	478	178	21	577
Jones Beach Island ROI1	485	467	177	21	577
Jones Beach Island ROI2	459	464	177	21	577
Jones Beach Island ROI5	459	462	177	21	577
Jones Beach Island ROI6	459	462	177	21	577
Jones Beach Island ROI8	459	462	186	21	577
Jones Beach Island ROI10	459	466	194	21	577

Table A2. Final number of images used in the shoreline mapping analyses following removal of unusable images.

ROI Name	L5	L7	L8	L9	S2
Rockaway Peninsula ROI1	570	534	227	27	197
Rockaway Peninsula ROI2	366	474	236	28	242
Rockaway Peninsula ROI3	512	509	233	24	731
Long Beach ROI1	512	349	243	28	716
Long Beach ROI2	410	268	235	25	421
Long Beach ROI4	327	281	120	17	406
Long Beach ROI6	310	314	125	17	412
Jones Beach Island ROI1	316	298	120	16	415
Jones Beach Island ROI2	309	296	114	15	419
Jones Beach Island ROI5	302	285	112	15	406
Jones Beach Island ROI6	286	264	102	14	382
Jones Beach Island ROI8	311	287	107	14	407
Jones Beach Island ROI10	304	291	107	13	399

Table A3. Final CoastSeg settings used for shoreline detection and extraction.

Variable	Value
Dates	Start: 1/1/1984 End: 12/31/2022
Satellites	L5, L7, L8, L9, S2
Reference Shoreline Buffer	Jones Beach Island & Long Beach: 233 Jones Beach Island ROI 8: 100 Jones Beach Island ROI10: 356 Rockaway Peninsula: 194
Minimum Shoreline Length	147 m
Minimum Beach Area	140 m ²
Allowed Distance from Clouds	218 m
Apply Cloud Mask	False
Cloud Threshold	0.5
Image Size Filter	On
Percentage Bad Pixels	50%
Sand Color	Default
Alongshore Distance	25 m
Max STD	15 m
Max Range	−100 m

Table A4. Number of extracted shorelines for each ROI from CoastSeg.

ROI Name	Number of Shorelines
Rockaway Peninsula ROI1	1646
Rockaway Peninsula ROI2	1442
Rockaway Peninsula ROI3	1578
Long Beach ROI1	1137
Long Beach ROI2	1167

Table A4. Cont.

ROI Name	Number of Shorelines
Long Beach ROI4	976
Long Beach ROI6	969
Jones Beach Island ROI1	986
Jones Beach Island ROI2	966
Jones Beach Island ROI5	943
Jones Beach Island ROI6	881
Jones Beach Island ROI8	943
Jones Beach Island ROI10	929

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