

Article

Shoreline Behavior at California Groin Fields from Satellite-Based Measurements

Catherine N. Janda ^{1,*}, Teresa Hachey ², Sharon Batiste ³, Mark A. Lundine ¹, Daniel Buscombe ⁴ and Jonathan A. Warrick ¹

¹ U.S. Geological Survey, Santa Cruz, CA 95060, USA; mlundine@usgs.gov (M.A.L.); jwarrick@usgs.gov (J.A.W.)

² Samueli School of Engineering, University of California, Irvine, CA 92697, USA; thachey@uci.edu

³ U.S. Geological Survey (Contractor), Santa Cruz, CA 95060, USA; sbatiste@contractor.usgs.gov

⁴ Washington State Department of Ecology, Applied Coastal Research and Engineering, Olympia, WA 98504, USA; dbus461@ecy.wa.gov

* Correspondence: cjanda@usgs.gov

Highlights

What are the main findings?

- Remote sensing measurements of shoreline positions from Landsat and Sentinel imagery can provide measurements of coastal change dynamics within groin fields.
- The offset of the shoreline positions across groins is a function of wave conditions, groin geometry, and littoral sediment transport, which can be observed from satellite-derived shoreline techniques.

What are the implications of the main findings?

- Satellite-derived shoreline measurements, which have primarily focused on open sandy coasts, can be used to evaluate the effects of coastal structures (such as groins, breakwaters, and jetties) on coastal change dynamics.
- Shoreline dynamics within groin fields can vary significantly from site to site and include patterns from episodic and seasonal effects.

Abstract

Satellite imagery has helped to provide decades of shoreline change data to coastal regions all over the world. Although shorelines around the globe have been armored with different types of coastal structures to try and protect beaches and properties from erosion, there are few studies of shoreline dynamics within structures such as groin fields using satellite images. Here we apply satellite-derived shoreline techniques to three areas of California: Ventura, Santa Monica, and Newport Beach, each site containing groin fields of varying number and length. Shoreline trends during 1984–2022 reveal that the presence of these coastal structures may alter the overall shoreline variability at these locations. Peclet numbers have been calculated for each site to better characterize the variability of longshore transport within and across the study areas and to compare with shoreline change characteristics. The satellite-derived shoreline data reveal offsets or “steps” in the shoreline position across the groins with sediment piling up on one side more than the other due to longshore transport. The magnitudes and dynamics of these shoreline offsets were measured from satellite techniques, and we find that the average offsets are commonly related to groin length. Some shoreline offsets reveal seasonal patterns, with Newport Beach having the largest seasonal patterns of the three sites. We find that these seasonal patterns in shoreline offsets at the Newport Beach groins are related to the seasonal

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variability in wave direction and littoral transport. We conclude that satellite-derived shoreline techniques with Landsat and Sentinel-2 imagery are adequate to characterize shoreline behaviors within the complex coastal settings of groin fields.

Keywords: shoreline; groin; groin field; satellite; littoral cell; longshore transport

1. Introduction

Shorelines are dynamic features that demark the boundary between the land and sea and provide natural resources, coastal habitats, and community benefits including flood protection from storms and recreational spaces [1–4]. With roughly 37% of the world's population living within 100 km of the coast, monitoring these coastal regions is becoming increasingly important [5]. Coastal areas are prone to flooding and property damage from storm erosion, and these vulnerabilities will increase over time with sea-level rise and increased storm damage [6–8], which poses a large risk for coastal communities and properties and may lead to the eventual need for relocation of some areas [6,9]. It is estimated that 75% of the world's shorelines are undergoing some level of erosion [10], with 24% of sandy beaches eroding at rates over 0.5 m/yr [11]. Within the United States, eroding cliffs and bluffs also pose a great risk to the coastlines and communities along these steep landforms [12,13].

Coastal structures, including jetties, sea walls, and groins, line many beaches around the world. These structures are intended to protect the coastline from erosion and reduce the effects of larger waves [12]. While the terms jetties and groins (also referred to as groynes) have been often used interchangeably, they have different definitions. Jetties are designed to stabilize harbors and other marine inlets and are often tens to hundreds of meters long. Groins are generally much shorter (varying between 3 and 200 m long [14]) and are designed to trap sediment in order to stabilize or widen a beach and to prevent the movement of sediment outside the beach area [15–18]. More than one groin along a stretch of shoreline is called a groin field, which are used to stabilize long stretches (kilometers) of beach [19]. Although designed to widen beaches, groins also block the natural rate and direction of sediment transport, which can lead to erosion and unintended sedimentation in other parts of the beach system [15,20].

Coastal management strategies are often based on an action–reaction or a cost–benefit analysis with four overarching options: protection, accommodation, planned retreat, or leave the area in its current state [21–23]. The armoring of the coast, including the construction of groin fields, is considered “protection” because coastal structures are commonly built with the intention of preserving high risk coastal areas and natural resources [24]. Although many countries, including the United States, have discouraged the use of groins for shoreline protection due to poor performance and little guidance on design functionality, these structures continue to be constructed throughout the world [16]. Early groin construction within the United States used logs placed close together, although these often failed due to the inability to retain sand, wood-boring organisms, and propensity to wood rot [25]. Although timber groins are still used in places around the world today because they allow for post construction adjustment if needed [26,27], the majority of groins are made of stone, concrete, or a mixture of the two [28].

Satellite-derived shorelines have been used to map sandy shorelines around the world as an alternative to more traditional methods, including lidar or ground surveys, which can be expensive and time consuming [29,30]. Satellite images also allow for larger observable time scales than these other methods, which results in longer (multiple decade) records of shoreline change. Many studies over the last decade have begun to use satellite

images to observe shoreline change in a variety of different settings [11,30–33], although there remains uncertainty over the effectiveness of these techniques for shorelines with coastal structures, such as groin fields. Here we evaluate the applicability of satellite-derived shorelines to groin fields and examine shoreline change patterns both within and outside of the groins.

Three study sites were selected in California—Ventura, Santa Monica, and Newport Beach—each containing a groin field of varying structure lengths and frequencies for the purpose of testing whether satellite-derived shoreline techniques are able to observe shoreline patterns within and around groin fields (Figure 1). Groin fields in southern California, especially for Ventura, Malibu, Santa Monica, and Newport Beach, are understood to be effective at stabilizing and widening these beaches [17,19]. Additionally, all three study sites are classified as sandy beaches, making them ideal for satellite-derived shoreline algorithms [30].

This study was designed to: (i) evaluate the feasibility of obtaining shoreline data within and adjacent to groin fields with Landsat satellite imagery provided from the collaborative efforts of the National Aeronautics and Space Administration (NASA) and the U.S. Geological Survey (USGS) and Sentinel-2 satellite imagery provided by the European Space Agency (ESA) using the CoastSeg software (version 1.2.16) [34] for shoreline extraction based on the CoastSat algorithms [35] and (ii) describe the shoreline change patterns around these structures from the satellite-derived shoreline data and evaluate the causes of the patterns. As noted, below we use a state-of-the-art satellite-derived shoreline analysis technique (CoastSeg, version 1.2.16) and apply this over a multi-decadal interval of time (1984–2022). Additionally, we compare shoreline change patterns to littoral sediment transport patterns derived from oceanographic estimates, hindcasts, of wave conditions for each site.

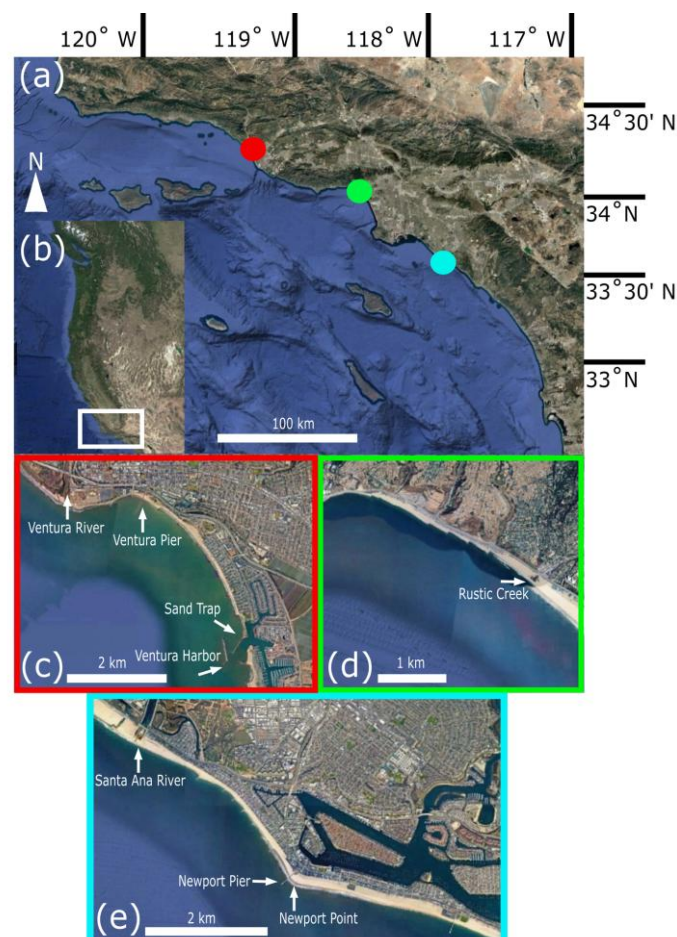


Figure 1. Map of California groin field study sites, including (a) the overall location of the sites with respect to the west coast of the United States corresponding to inset (b), (c) location of Ventura, California (red), (d) Santa Monica, California (green), (e) Newport Beach, California (blue). Places of interest are labeled in white with arrows pointing to their locations, which include: Ventura River, Ventura Pier, Ventura Harbor, Sand Trap in (c), Rustic Creek in (d), and the Santa Ana River, Newport Pier, and Newport Point in (e). Imagery from Google Earth from 30 September 1996 to 15 December 2023. Site coordinates in black are for (a).

2. Materials and Methods

2.1. Study Area

Three of the largest groin fields of southern California were examined in this study, each differing in geographic and oceanographic setting. Sites contain varying shoreline orientations with Ventura more westerly-facing and Santa Monica more southerly-facing (Figure 1). Each site contains groins of varying lengths and spacing, and two sites contain seven groins and one contains eight (Figure 2).

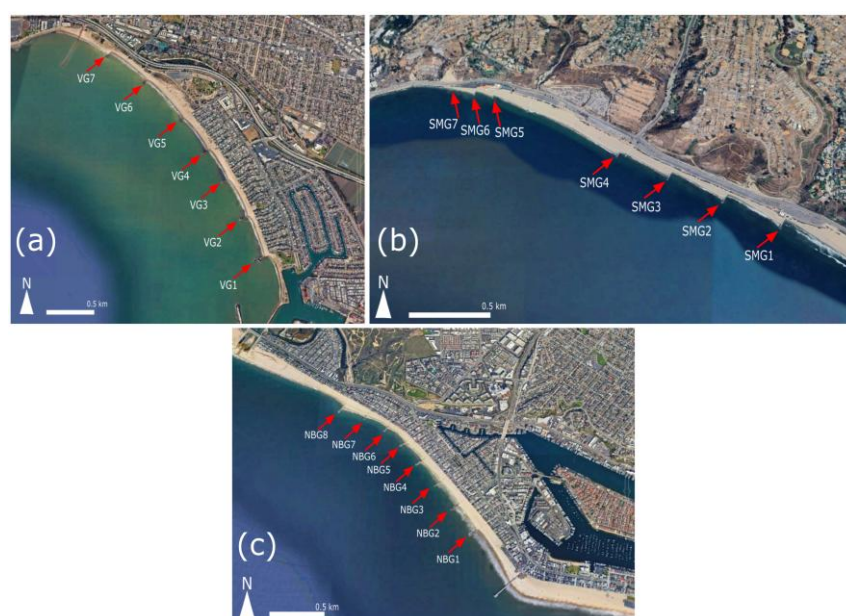


Figure 2. Map of study sites with groins highlighted with red arrows. The naming of these groins follows this convention throughout this study. (a) Ventura, CA. Image from Google Earth from 9 November 2023. (b) Santa Monica, CA. Image from Google Earth from 21 September 2025. (c) Newport Beach, CA. Image from Google Earth from 4 December 2023.

Ventura, California is located within the Santa Barbara littoral cell within the Southern California Bight [19]. The construction of Ventura's groin field was proposed to counter the erosion of the natural beach after sediment input from the Ventura River was restricted by the Matilija and Casitas Dams, built in 1948 and 1959 respectively [36]. There are seven groins constructed at this site as shown in Figure 2a. Ventura Harbor (refer to Figure 1c) is a man-made harbor at the southern end of the groin field that contains two rubble-mound jetties at the entrance, a groin at the southern entrance, and a detached rubble-mound breakwater. Sand is often trapped on the northside of the harbor between the jetty and Ventura groin 1 (VG1; Figure 2a), in an area described as a sand trap, due to the longshore current and the effects of the offshore breakwater. The sand trap has required annual maintenance to pump sand to the southern side of the harbor [37–39]. Sediment is primarily supplied to the area by the Ventura River (refer to Figure 1c) which drains from the Santa Ynez mountains and eastward longshore transport in the Santa

Barbara littoral cell. Roughly 37% of the Ventura River Basin is restricted behind dams which have reduced the sediment supply to the area [36]. The Ventura River has been reported to supply roughly 77,000 m³/yr of sand to the region. Sediment is also supplied to the region via dredging of Santa Barbara Harbor, roughly 40 km to the west, at an average of 245,000 m³/yr [39]. Even with the damming of these rivers, the Ventura River mouth is especially prone to seasonal flooding and erosion during the winter months and during heavy rainfall [36,40].

The Santa Monica groin field is located within the Santa Monica Littoral cell within the Southern California Bight [19]. There are seven groins at the site as shown in Figure 2b, and these groin sizes and spacings are the most variable of the three study area sites. Prior to 1825 the Los Angeles River supplied the majority of sediment to the region, but it altered its course to the south due to heavy flooding [36,41]. Numerous creeks drain the local Santa Monica Mountains and supply roughly 480,000 t/yr of total sediment (mud and sand) to the littoral cell [42]. Malibu Creek is the largest stream that drains from the Santa Monica Mountains and releases roughly 41,000 m³/yr of sediment to the shore. Beaches are backed by steep cliffs and bluffs which are prone to erosion, further contributing to the beach width supplying an average amount of 85,000 m³/yr of material [41]. Since 1926, however, artificial beach nourishments have been the primary source of sand for the littoral cell, with an estimated 440,000 m³/yr of sand added to the beach [41,43].

The Newport Beach groin field is located in the San Pedro Littoral cell within the Southern California Bight [19]. These groins were installed in the 1960s and 1970s which helped to retain sediment and widen the beaches [36]. There are eight groins at the Newport Beach site as shown in Figure 2c. At the western portion of the beach lies the Santa Ana River (refer to Figure 1e) which is heavily regulated by a pair of jetties and supplies the majority of the sediment to the region [36]. This river drains a 4406 km² basin and contains the Prado Dam which has blocked roughly 88% of discharge in the watershed [44]. The Santa Ana River supplies roughly 450,000 t/yr of sediment to the Southern California Bight [42]. Sediment management includes the 2017 dredging project that moved roughly 500,000 m³ of sand from the lower channel of the Santa Ana River to the middle of the Newport Beach groin field [38]. The beach is regularly affected by large waves from Antarctic storms with highest erosion rates reported in the summer [36].

2.2. Groin Field Characteristics

The locations and characteristics of the groin field structures for each site were measured from manual inspection of imagery available in Google Earth from 2022. It should be noted that as we used imagery from 2022 as a baseline, and although there were no identifiable changes to these structures in the Google Earth imagery during our satellite measurements (1984–2022), it is possible some structures were modified over the course of the study. Once groins were identified, the locations and spacing of the structures within the satellite-derived shoreline transects were measured for each study site. Our shoreline-measurement transects were placed ~50 m apart (refer to Section 2.3 below), and the alongshore locations of the groins were calculated based on how far they fell from the nearest transect. In addition to the alongshore locations, we measured groin lengths from where they originated on land to the most seaward point (shown in Table A3 in Appendix A). These lengths were later used to calculate the shoreline offset for each groin (refer to Section 2.4). The naming convention for the groins included a site identifier (V = Ventura, SM = Santa Monica, NB = Newport Beach) and the groin number within each field from south to north (Figure 2).

2.3. Satellite-Derived Shorelines

We used existing satellite-derived shoreline workflows that incorporate nearly four decades of satellite imagery available from the Landsat and Sentinel-2 platforms. Satellite imagery was accessed through Google Earth Engine (GEE) [45], which allows users to access data from image archives of the National Aeronautics and Space Administration's (NASA) Earth Observing Satellites and The European Space Agency's (ESA) Sentinel series. Through the GEE application programming interface (API) [46], five satellites were chosen for this study: Landsat 5, 7, 8, 9, and Sentinel-2. Landsat 5, launched 1984 [47], has a Thematic Mapper sensor and 30 m resolution images for six visible bands [48]. Landsat 7, launched 1999 [47], contained an Enhanced Thematic Mapper sensor with six visible to infrared bands, a 30 m resolution similar to Landsat 5, a 60 m resolution thermal band, and a 15 m resolution panchromatic band [48]. Landsat 8, launched in 2013, has a 30 m Operational Land Imager (OLI) with nine visible to infrared bands and two thermal bands within its Thermal Infrared Sensor (TRIS) [49]. Landsat 9, launched in 2021, has the same sample resolution as Landsat 8 but with an upgraded version of the OLI and TRIS sensors [50]. Sentinel-2 (ESA), has 10–20 m resolutions in visible, near infrared and short-wave infrared bands [30].

CoastSeg [34], which was developed by the U.S. Geological Survey (USGS), is a Python extension for the CoastSat methodology described by Vos et al. [35] and was used to measure shoreline positions in all satellite imagery. The CoastSat algorithms use satellite images to detect the sand and water boundary using a four-stage process, which includes pre-processing of the images by applying cloud masking algorithms, pan-sharpening, and down-sampling. Each image is then divided into red, green, blue, near infrared, and short-wave infrared bands for pixel classification. The sand/water boundary is determined from the Modified Normalized Difference Water Index (*MNDWI*) spectral index, which is computed from a combination of the green (*G*) and short-wave infrared spectral bands (*SWIR1*) shown in Equation (1):

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

The multi-spectral data are used to classify each pixel within an image to one of four classes: sand, water, white water, or other, using a machine learning segmentation classifier trained on hand-classified Landsat and Sentinel-2 imagery [35]. An Otsu threshold is then computed to define the threshold value of *MNDWI* representing the sand–water boundary in each satellite image that maximizes the inter-class variability between the segmented sand and water classes [51].

CoastSeg takes the CoastSat methodology and creates an interactive environment for users to easily visualize the inputs and outputs of their data [34]. The software requires users to define a region of interest (ROI), transects, and a reference shoreline to calculate shoreline positions from the images. CoastSeg will place ROIs within a user defined boundary box with a default size of 20 km². The software will either generate transects and a reference shoreline for the user defined area if none are provided or accept established beach transects from an uploaded GeoJSON file [34].

CoastSeg has a variety of settings that users can alter to optimize the shoreline generation. One major cause for poor extracted shorelines are clouds, which can cause data gaps and inaccurate pixel classifications. CoastSeg contains a “cloud mask” feature which identifies clouds and removes these areas from computations. However, this feature was only turned on for one site, Santa Monica, because sandy beaches can occasionally be misidentified as clouds with the masking feature, leading to unnecessary removal of shoreline data [52]. Santa Monica often had clouds appearing within a stretch of the beach, which led to the decision to turn on the cloud mask to derive data from imagery with these cloud effects. Additional tools in CoastSeg include the minimum shoreline length and minimum

beach area defining the shortest lengths and smallest areas in which shorelines can be found. Also, when extracting shorelines a reference shoreline buffer setting allows the user to define the area around the reference shoreline where CoastSeg will look for shorelines. Table A1 in Appendix A contains the values used for this research for the following CoastSeg settings: cloud mask, allowed distance from clouds, reference shoreline buffer, minimum shoreline length, and minimum beach area.

Each site had predefined transects, a reference shoreline, and ROIs for CoastSeg shoreline extraction. All three sites were also defined by a single 20 km² ROI. Transects for all sites were created orthogonal to the reference shoreline with an average spacing of 50 m using QGIS (version 3.40.2), and we conducted minor manual editing to adjust transect lengths and orientations within the groin fields. Transect spacing is half of the typical CoastSat value of 100 m to ensure highest resolution data could be captured within the groin fields. Ventura contained 96 transects, Santa Monica contained 85 transects, and Newport Beach contained 107 transects. The relative location and orientation of the ROIs, transects, and reference shoreline within CoastSeg are shown in Figure S1 in the Supplemental Materials.

Satellite images from 1 January 1984 to 31 December 2022 were selected for all study sites and were collected from Landsat 5, 7, 8, 9 and Sentinel-2. Images were sorted by usability before running the shoreline extraction process in CoastSeg. Satellite images are inherently noisy due to clouds and image pixel errors, such as a missing visible band [53]. After May 31, 2003, Landsat 7 imagery contains data gaps (roughly 22% of each image) due to a failure of its scan line corrector. This scan line corrector was intended to compensate for the forward motion of the satellite to ensure images were aligned with each other [47]. CoastSeg utilizes an enhanced filtering pipeline that integrates the CoastSat filtering algorithm with additional advanced filters to exclude cloud cover and imagery that insufficiently covers the requested ROI, which include the ROI coverage and download cloud threshold settings [34]. Although these filters remove many images from the download request, images with errors were often left in the dataset.

All satellite imagery were sorted into usable and unusable categories to remove imagery with inadequate data to map shorelines due to fog, haze, and other radiometric conditions using a two-step process. First, the imagery were sorted with a machine learning classifier trained on a dataset [54] containing coastal satellite imagery from around the globe specifically designed to sort out noisy images containing clouds, large data gaps [47], distorted color-spaces, sea-ice, and other environmental artifacts that occlude the water-land boundary. All RGB satellite imagery were compared using a classifier trained to the existing data set [54] and then sorted into “good” and “bad” categories for the purpose of shoreline detection. This process allowed for a more efficient second step, which was the manual inspection and correction of these sorting results. Manual inspection ensured all images were sorted adequately, and we changed several of the sorting results from the classifier. All imagery determined to be usable for shoreline detection after this two-step sorting process were included in the shoreline position analyses detailed below. Table A2 in Appendix A shows an enumeration of the results of this sorting technique for each site.

Extracted shorelines for each transect were then tidally corrected using the FES14 [55] modeled water levels for each image combined with a user defined beach slope. Beach slopes were derived from USGS lidar point clouds using cross-shore profiles that extracted a mean high water (MHW) shoreline position and foreshore points with respect to NAVD88, with the beach slope calculated from linear regression through the foreshore points [56]. The slope data were averaged for all transects for each site and converted from degrees to rise/run (m/m) using the inverse tangent function. The calculated average slopes for the three sites were: 0.083, 0.101, and 0.067 for Ventura, Santa Monica, and Newport Beach, respectively. All shoreline positions at each site were tidally corrected to a

mean sea level (MSL) position. CoastSeg produces tidally correct shorelines based on the CoastSat methodology shown in Equation (2):

$$\Delta x_{tide} = \Delta x + \frac{z_{tide}}{\tan\beta} \quad (2)$$

where Δx_{tide} is the tidally corrected shoreline position, Δx is the raw un-corrected shoreline position, z_{tide} is the tide level extracted from FES14, and $\tan\beta$ is the average beach slope [30]. Although an average beach slope for each site is used, there may be systematic local variations in beach slope throughout the sites due to changing orientation or presence of structures.

There are currently no local field data to compare with the satellite-derived shoreline from our three sites that could be used for accuracy assessments. Shoreline accuracy assessments have been created for Torrey Pines, California to the south of our study areas in Vos et al. [30], which show RMSE for individual shoreline measurements reported at 12.7 m for Landsat and 11.6 m for Landsat and Sentinel images. Accuracy increases with monthly mean values of shoreline positions shown by Vos et al. [57] for Torrey Pines to an RMSE of 9.7 m.

The resulting shoreline position records from the CoastSeg analyses are inherently noisy, even with the filtering algorithm outlined previously in this section. Further filtering of the raw shoreline position data were performed as outlined in Janda et al. [53] to resample the data into monthly mean shoreline positions. Once filtered, we computed time series of the mean monthly shoreline positions across the complete records (1982–2022) to remove additional noise and develop a regular interval shoreline record. Additionally, we evaluated the variability of the shoreline positions at each transect using a standard deviation of the monthly mean values with respect to each transect as well as the average overall shoreline trend from 1984 to 2022. Shoreline change trends for each transect are computed from linear regression and reported in m/yr. MATLAB (version R2025a) was used for shoreline analyses.

2.4. Shoreline Offset from Groins

Adjacent to groins, there is often a visible “step” in the shoreline where sand piles on one side of the groin more than the other, commonly a result of the groin blocking the natural longshore littoral transport [58]. To quantify the size and dynamics of these shoreline steps (herein referred to as ‘offsets’), we measured shoreline offsets at each groin from the monthly mean shoreline position records. A schematic of the shoreline offset due to the presence of groins is shown below in Figure 3, which shows that the change in shoreline position from a reference point (Δy) may be calculated for each of the groin-adjacent transects and summed to compute the shoreline offset distance across the groin structure. Using this framework, we used the two transects directly surrounding each groin to compute shoreline offsets. In cases where transects were either directly on top of groins or intersected these features, the next closest transect was chosen for the analysis. This occurred at the groin structures VG1, VG6, VG7, SMG3, and SMG7.

Due to transects not having the same origin point distance from a groin because of the coastline and reference shoreline, a new reference line, called D2 is created in reference to D1 which is created along the length of the groin (refer to Figure 3). As mentioned previously, transects were created in QGIS relative to the reference shoreline. The reference shoreline was created as an approximation of where shorelines would occur if offsets were not present. For every groin in the study, offsets were computed from the groin mid-point drawn from D1, where D2 intersected the transects (Figure 3). Table A3 contains the specifics of each groin as well as the coordinate of the location where D1 and D2 intersect.

Once the shoreline offset values were computed from the mean monthly shoreline time series, the data were passed through a Hampel filter to remove the effects of extreme outliers in the data. Hampel filters compute the median of a window composed of a sample input vector and surrounding data points to remove outliers [59]. Parameters used for the Hampel filter include a window size of 0.05 (equivalent to increments of 5% of the shoreline observations of each transect), an outlier extend of 3, which looked for outliers past 3 standard deviations, and a total of 5 iterations. Resulting values of Δy were defined to be positive in the seaward direction (negative in the landward direction), and shoreline offset values were defined to be positive if the beach was broader on the south side of the groin and negative under the opposite condition (i.e., the diagram in Figure 3 shows a negative shoreline offset condition).

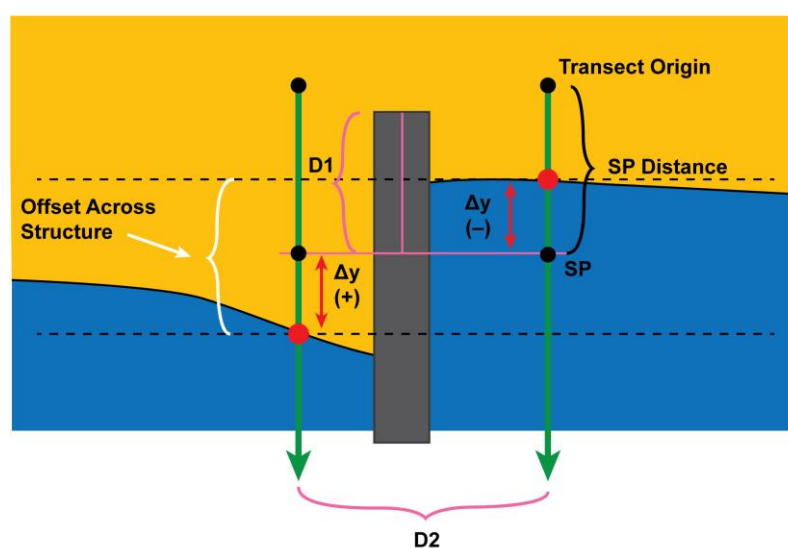


Figure 3. Schematic of Δy and offset workflow where transects surrounding structure are shown in green. Structure points (SP) are calculated from the midpoint of the groin denoted as D1. A perpendicular line, D2, is drawn to better calculate the exact location of the structure points. Structure point distance (SP distance) is computed from the transect origin point to the structure point. Δy 's, shown in red, are computed as the difference between the structure point distance and the shoreline cross distances computed by CoastSeg. The offset is then computed from the difference between the Δy 's on either side of the groin.

In an ideal situation, shoreline positions in areas without groins would be highly coherent from transect to transect, resulting in very little difference between the shoreline positions of adjacent transects over time. However, transect-to-transect variability in our shoreline position measurements exist because of geomorphic phenomena such as time-varying shoreline curvature (e.g., shoreline cusped features) and remote sensing uncertainties in the shoreline position measurements. In this way, the transect-to-transect variability in shoreline position in areas outside of the groin fields can be used to evaluate our detection limits for our measurements of shoreline offsets at the groins. To compute shoreline offset detection limits, we compared all adjacent transects outside of the three groin fields. This resulted in dozens of transect pairs per site. Time series of the difference in the shoreline positions for each transect pair were calculated, and the mean and standard deviation of these differences were computed to evaluate the bias and variability of these differences. Offset detection limits were assessed at the 2-sigma level by doubling the computed standard deviations of the differences for all transect pairs from each site. A compilation of the mean and median values of these 2-sigma values is provided in Table 1,

which indicate that our remote sensing techniques were able to detect shoreline offsets at the groins at levels of 5-to-8 m depending on the site.

Table 1. Results of comparing shoreline variability for adjacent transects outside of the influence of groins. Mean and median values of shoreline differences at the 2-sigma level are shown.

Site	Mean (m)	Median (m)
Ventura	8.5	8.4
Santa Monica	6.2	5.1
Newport Beach	7.7	7.3

We hypothesized that the shoreline offsets at the groins varied depending on the time of year and wave direction. To evaluate this hypothesis, we examined both time series of the monthly offset values and computed average shoreline offsets for each month of the year from the 1984–2022 records.

2.5. Wave Data, Littoral Transport, and Peclet Numbers

We use measurements and hindcasts of wave conditions to evaluate the potential for littoral sediment transport in the vicinity of the groin fields over a range of spatial and temporal scales. Wave data from the CDIP-MOP (Coastal Data Information Program Monitoring and Prediction System) hindcast models [60] were obtained to characterize the general seasonal wave changes at each site. These data provide wave condition information on the inner shelf at the 10 m isobath. Daily hourly data were downloaded for 2000–2022 for every available day for these three sites for all CDIP-MOP transects in the defined study area, providing a time series of significant wave height (m) and bulk wave direction (degrees relative to north). Daily averages were computed from the hourly data to create wave roses for each site to observe general wave conditions over the winter and summer seasons (Figure 4).

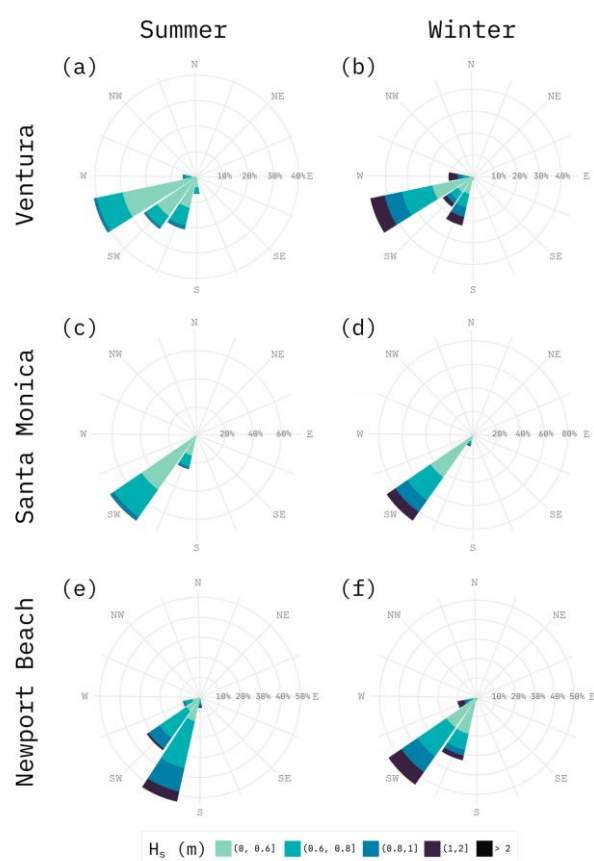


Figure 4. Wave roses derived from CDIP-MOP wave data (2000–2022) with summer corresponding to June, July, August, September and winter corresponding to December, January, February, March. (a) Ventura summer. (b) Ventura winter. (c) Santa Monica summer. (d) Santa Monica winter. (e) Newport Beach summer. (f) Newport Beach winter.

In addition to these general offshore wave conditions, we estimated littoral sediment transport potential for each site using the CDIP-MOP wave hindcast data [60], assuming that sand is available for transport at the sites, using the CERC equation [61], shown in Equation (3):

$$Q = K\gamma\sqrt{g}H^{\frac{5}{2}}\sin(2\theta_b) \quad (3)$$

where Q is the transport potential in m^3/s , K is an empirical coefficient defined as $K = 0.39$, g is the acceleration due to gravity in m/s^2 , H is the significant wave height at breaking in meters, θ_b is the relative angle of the waves in relation to the coast at breaking and γ is defined as the sediment and fluid characteristics shown in Equation (4):

$$\gamma = \frac{\sqrt{2}\rho_w}{16(\rho_s - \rho_w)\phi} \quad (4)$$

where ρ_w is the density of water in kg/m^3 , ρ_s is the density of the sediment in kg/m^3 , and ϕ is the sediment porosity.

We used the CERC formulas to estimate the direction and magnitude of sediment transport using the CDIP-MOP wave hindcast data on an hourly basis along its 100 m spaced transects to observe the spatial extent of the variability of longshore transport along the three study areas [60]. Some data gaps exist in the spatial availability of the CDIP-MOP data, for example near the Ventura and Newport Piers, which seem to be related to data removal owing to these structures. CDIP-MOP data were downloaded from the CDIP THREDDS (Thematic Real-time Environmental Distributed Data Services) server [60] for 2000–2022, with 2000 being the beginning of the data record available. We also used the hourly estimates of littoral transport to calculate mean transport, mean monthly transport, and Peclet numbers as summarized below.

Littoral Peclet (Pe) numbers, as introduced by Kahl et al. were calculated using the CDIP-MOP-based estimates of littoral transport to characterize the direction and variability of littoral drift [61]. Broadly, the Pe number is a dimensionless number that measures the ratio of advective to diffusive transport and is often applied in mass or heat transfer problems [62,63]. Within the context of coastal morphology, advective transport can be conceptualized by waves moving sediment primarily in one direction (upcoast or downcoast) with a relatively steady littoral current (alongshore transport [64]). Diffusion can be defined by waves coming in from multiple angles, carrying sediment in multiple directions, leading to a combination of upcoast and downcoast transport, although a dominant direction may prevail [65]. Pe numbers were computed using Equation (5):

$$Pe = \frac{Mean(Q)}{STD(Q)} \quad (5)$$

where Mean and STD are the average and standard deviation of the complete records of littoral transport (Q), representing advective and diffusive components of alongshore transport respectively [61]. To assess the seasonal variability in transport, average Pe values were computed for each month from the complete Q records. Following the interpretation framework proposed in Warrick et al. [66], $Pe = 0.5$ is used as the threshold between advection and diffusion dominated transport. This value was empirically derived from the distribution of Pe numbers for several littoral cells (>1000 CDIP-MOP transects) and used to identify zones of littoral convergence and divergence and explain shoreline change patterns in Warrick et al. [66]. This established framework is used to interpret alongshore transport patterns, although we acknowledge alternative thresholds may be

re-computed or modified in the future as justified by different locations or applications. When $|Pe| > 0.5$, the transport is defined as advection-dominant, meaning littoral sediment is carried primarily by a unidirectional alongshore transport current, while a $|Pe| < 0.5$ can be considered diffusion-dominant and sediment is spread bi-directionally both upcoast and downcoast. The sign of the Pe indicates the dominant transport direction, with positive values indicating upcoast (northward) transport and negative values reporting downcoast (southward).

2.6. Statistical Analyses

To evaluate patterns and relationships between the shoreline offsets at the groins and the wave and transport conditions that may be influencing these shorelines, we conducted a series of correlation analyses. For these analyses, we calculated groin length, median shoreline offset magnitude, monthly median shoreline offsets for all months, seasonal shoreline excursion distance defined by Warrick et al. [31], mean overall Pe , mean summer Pe , mean winter Pe , mean monthly Pe for each month, wave power seasonality, and wave power ratio. Only transects surrounding groins were used for these correlation analyses. Following the methods of Warrick et al. 2025 [31], monthly mean values of wave power (P) and dominant wave direction (Dir) were downloaded from CDIP-MOP, and the monthly minimum (P_{min}) and maximum (P_{max}) values were used to evaluate the wave power seasonality, defined here as the wave power ratio (P_{ratio}). Wave power ratio is defined to be [31]:

$$P_{ratio} = \frac{P_{max} - P_{min}}{P_{max}} \quad (6)$$

Combinations of variables were tested (e.g., median shoreline offset and mean overall Pe) and correlation analyses were conducted to determine if any combinations were statistically significant. Correlations (R^2) and p -values were computed and considered statistically significant for R^2 above 0.35 and p -values less than 0.05. Further comparisons were made between mean overall Pe and median shoreline offset magnitude by creating lag matrices to look for any delay response between the two variables. Mean overall Pe was lagged 12 times, for each month, and then cross-correlated to the median shoreline offset magnitude. Cross-correlations were examined within the monthly data records to evaluate potential phase lagging in shoreline responses to wave conditions.

We have also conducted analyses comparing the overall shoreline variability for transects within groin fields to those outside of the groin field. These comparisons allow us to assess whether the three groin fields significantly alter shoreline variability. Comparisons of shoreline variability between these two differing sections of beach were done using shoreline standard deviations and a two-sample t -test with $p = 0.05$. Data at extremely variable locations, such as the Ventura Pier, Rustic Creek at Santa Monica, and transects that were within the Santa Ana River mouth at Newport Beach, were removed from this analysis to limit the potential high variability bias that these features added to the regions outside of the groin fields.

3. Results

3.1. Overall Shoreline Change Patterns

Spatial-temporal patterns in the shoreline positions for each site are provided in plots of the demeaned monthly shoreline positions for each site, with shoreline positions for each transect plotted relative to the mean of each transect (Figure 5). For these plots, the northern extent of the study area is shown on the lefthand side, and the location of groins are shown with black dots on the x-axes.

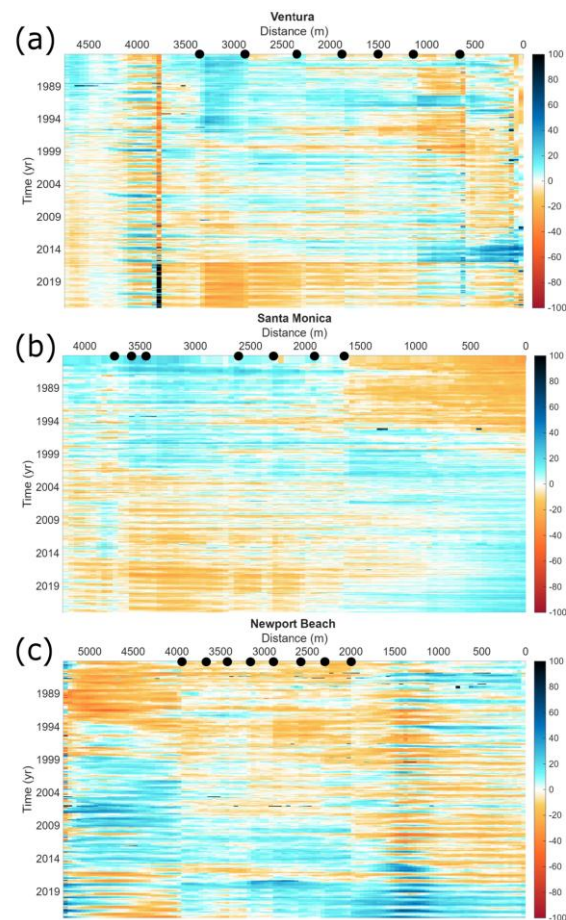


Figure 5. Spatial-temporal plots for resampled mean monthly data at all three study sites. (a) Ventura, (b) Santa Monica, (c) Newport Beach. Distance on x-axis is in meters which corresponds to each respective site. Time in years on y-axis. Color bar denoting the change with respect to each transects' mean, with red corresponding to more erosional and blue corresponding to more accretional. Black dots along the x-axis correspond to the approximate location of the groins at each site which were calculated from Google Earth imagery (24 June 2022—Ventura, 17 February 2022—Santa Monica, 24 April 2022—Newport Beach).

Ventura contains a long pier at approximately 3750 m alongshore distance, which is associated with a highly variable stripe in the shoreline position data. The high variability of shoreline positions at this transect was due to the transect being directly on the pier and the occasional characterization of the pier as a shoreline by the CoastSeg algorithms. Although this pier is clearly disrupting the local shoreline position data, these effects are not shown to extend into adjacent transects, and these highly variable shoreline positions are not observed for any of the other groin sites (Figure 5). The effects of the Ventura Pier (refer to Figure 1c) may be a function of its shape (roughly 480 m long and 9 m wide), which is approximately five times longer than the average groin at the site (96 m long and 10 m wide). This pier transect at Ventura was kept within the study as an example of how data may be influenced by large coastal structures. Newport Beach also contains a pier within the study area, at roughly 1350 m along this shoreline distance (Figure 5c), but this pier did not alter the data like the pier at Ventura. The pier at Newport Beach differs from the one at Ventura because it is shorter at roughly 310 m long and has no transects that intersect it.

Other sources of local shoreline variability include the Santa Ana River at the western end of the Newport Beach study site with the last three transects falling within this outlet region (longshore distances of 5300 to 5200 m) where higher shoreline variability occurs.

Although the Santa Ana River mouth is often closed with sediment, it also can be open allowing the flow of water, and the system is periodically dredged resulting in extraction of sediment from the river mouth according to the American Shore and Beach Preservation Association (ASBPA) National Beach Nourishment Database [38]. Overall, this results in higher shoreline position variability at the Santa Ana River mouth (Figure 5c). In addition, a few transects of the study were directly on groins as mentioned previously (i.e., VG1, VG6, VG7, SMG3 and SMG7), but there does not seem to be higher shoreline variability at these structures (Figure 5).

All three sites exhibited patterns of erosion and accretion over the observed study interval. Ventura primarily experienced erosional patterns after 2015, while Newport Beach experienced overall accretional patterns during the same interval of time (Figure 5a,c). Santa Monica experienced erosional patterns from the locations 0–1500 m and accretion from 1500–4200 m during 1984–1995, and there seems to be transitions in most of the Santa Monica shoreline change patterns during 1995–2000 (Figure 5b). We suspect that the Santa Monica groins play a role in these coastal change patterns because the southern limit of this groin field is located at 1500 m.

The location of the groins for each site coincides with distinctive lighter stripes in the shoreline position data, indicative of lower variability in the shoreline positions near these structures (Figure 5). Shoreline standard deviations and average shoreline trends from 1984 to 2022 were calculated for each transect in the three study areas and are shown along with groin locations in Figure 6. In general, shoreline positions have somewhat lower variability within the groin fields, especially at the Ventura and Newport Beach sites, whereas the highest values of shoreline standard deviation occur at features such as the Ventura Pier and the mouth of the Santa Ana River (Figure 6a,c). Mean standard deviations for each site in its entirety were calculated to be 10.92 m, 11.25 m, and 13.63 m for Ventura, Santa Monica, and Newport Beach, respectively. Newport Beach contained the highest mean standard deviation, which may be due to the higher variability around the Newport Pier and the Santa Ana River. Ventura has the highest standard deviation of 45 m at the Ventura Pier, which increased the overall mean standard deviation of Ventura by 0.74 m (standard deviation is 10.18 m without the pier). Although mean standard deviations within the groin fields are lower across all three sites (10.31 m, 9.95 m, and 10.44 m for Ventura, Santa Monica, Newport Beach, respectively), than outside the groin fields (12.43 m, 11.06 m, 15.79 m), only these differences at Newport Beach were found to be statistically significant using a two-sample t-test with 95% confidence intervals comparing transects within the groin field to transects outside the groin field. Results of this two-sample t-test are shown in Table 2 for each study area. Even though the comparisons did not yield statistically significant differences at all three sites, Ventura exhibits lower standard deviation in the middle of the groin field with a mean of 8.48 m, which are lower than the ends of the groin field with a mean of 12.68 m. This pattern within the Ventura groins may indicate that the groins still have an effect on shoreline variation.

Table 2. Results from the two-sample t-test for shoreline standard deviations at each site with *p*-values, 95% confidence interval ranges, and the standard deviations reported. Areas of high variability such as the Ventura Pier, Rustic Creek, and transects within the Santa Ana River mouth are excluded from the analyses. Asterisk (*) denotes significant values.

Site	<i>p</i> -Value	Confidence Intervals	Standard Deviation (m)
Ventura	0.25	[−0.59–2.24]	3.45
Santa Monica	0.12	[−0.27–2.23]	2.67
Newport Beach *	5.00×10^{-10}	[3.25–5.88]	3.29

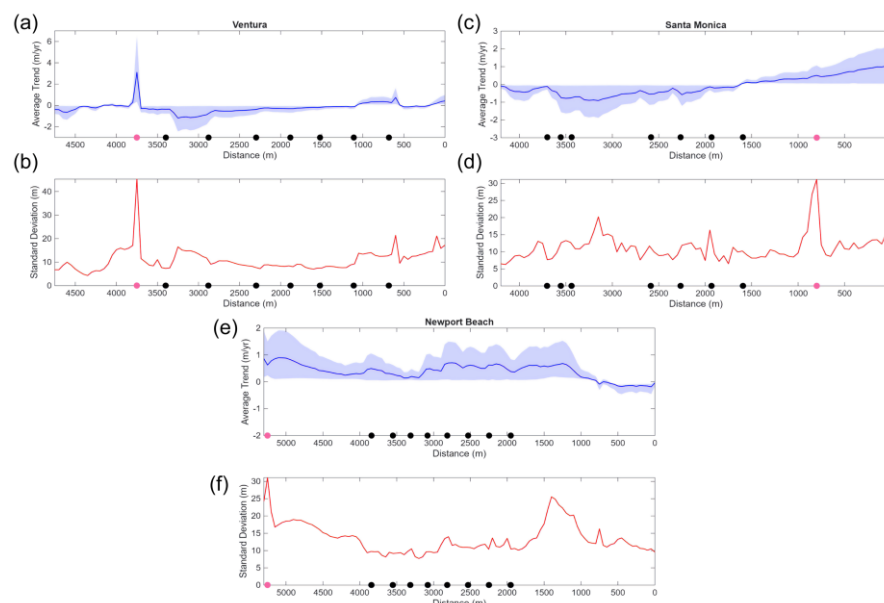


Figure 6. Standard deviations in meters (red) and average shoreline trend in m/yr (blue) of each site, computed along each transect using the raw monthly resampled data. The 95% confidence intervals are shown in a light blue behind the average trends. Distance in meters. Approximate groin locations are shown as black dots along the x-axis which were calculated from Google Earth imagery (24 June 2022—Ventura, 17 February 2022—Santa Monica, 24 April 2022—Newport Beach). (a) Ventura average trend, (b) Ventura standard deviation, (c) Santa Monica average trend, (d) Santa Monica standard deviation, (e) Newport Beach average trend, (f) Newport Beach standard deviation. Areas of high variability are shown with pink dots along the x-axis.

Santa Monica has somewhat different patterns in shoreline variability compared to the other two sites with the largest standard deviation values located at roughly 900 m and 3200 m (Figure 6b). The spike at 900 m corresponds to Rustic Creek (refer to Figure 1d), which has a very small outlet to the Pacific Ocean that is ephemerally open to the sea and is ponded when closed. When this creek mouth is sealed, it is likely that CoastSeg misidentified the ponded water as the shoreline positions, which resulted in shorelines extracted at more inland locations and, thus, higher overall variability. The 3200 m location is right between the two distinct groin fields at Santa Monica. Without the presence of groins, the shoreline seems to be more variable because it is no longer constricted by the structures.

Shoreline trend rates from linear regression vary considerably across the sites. Similarly to findings of Warrick et al. [66], shoreline trends for Newport Beach are increasing on average, and Santa Monica has a negative shoreline trend until 1500 m where it switches to a positive trend, similarly to what was observed in Figure 5. Shoreline trends seem to remain stable for Ventura which was also observed in Warrick et al. [66] except for the erosional trend within the northern two groins. Negative trend rates in Ventura are related to the dramatic shoreline erosion that occurred in the 2015–2016 winter (cf. Figure 5). Average trends inside the groin fields are -0.32 m/yr, -0.45 m/yr, and 0.45 m/yr for Ventura, Santa Monica, and Newport Beach, respectively.

3.2. Shoreline Offset of Groins

Shoreline offsets and Δy s were computed for each site, and Figure 7 below shows a time series of Δy for transects surrounding two groins for each site. In this figure, blue lines correspond to the southern transect of each groin, whereas red lines correspond to the northern transect.

For the situation for which the northern transect has a more positive Δy value than the southern transect (i.e., Figure 7a–c,e), there is a clear and persistent shoreline offset across the groin, for which the shoreline on the northern side of the groin is further seaward than the southern side. These offsets are shown to be greatest for the two Ventura groins (roughly -45 m and -30 m for VG1 and VG6 respectively; Figure 7a,b) and for SMG1 in Santa Monica (roughly -28 m; Figure 7c). Groin SMG6, in contrast, shows little difference in the Δy values across this groin, indicating that the shoreline offset is commonly near zero at this site (Figure 7d).

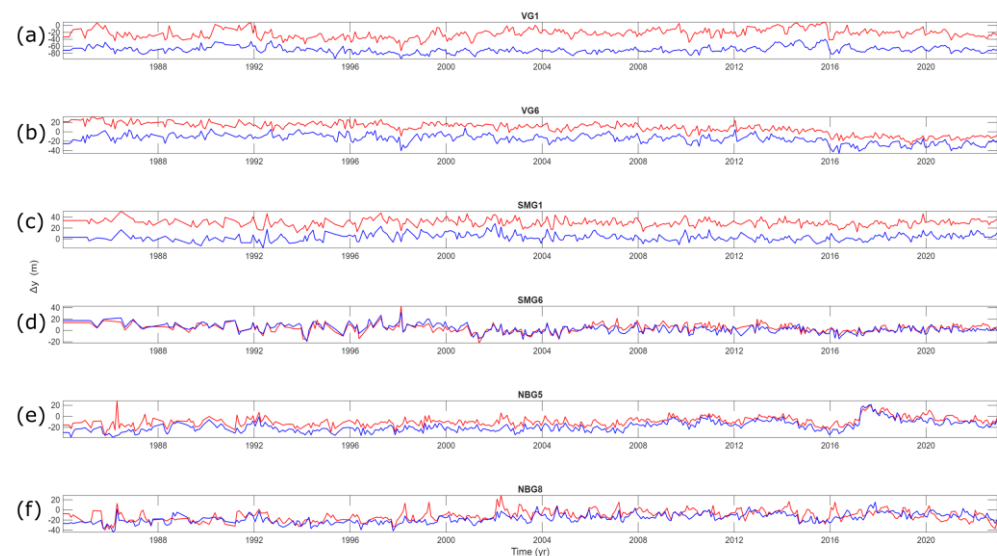


Figure 7. Δy time series for six highlighted groins. (a) VG1 and (b) VG6 from Ventura, (c) SMG1 and (d) SMG6 from Santa Monica, and (e) NBG5 and (f) NBG8 from Newport Beach. Red lines are the northern transect surrounding a groin and blue lines are the southern transect surrounding a groin. Δy in meters along y-axis and time in years along x-axis. Refer to Table S1 in the supplemental materials for exact transect numbers used.

We note that the differences of the Santa Monica groins are representative of the two distinct subsets of groins within this field. SMG1, which is within the southernmost field of longer groins (SMG1 to SMG4), seems to behave similarly to the groins at Ventura, where there is a steady, near constant shoreline offset across each structure. SMG6, in contrast, is in the middle of the northern section of shorter groins (SMG5 to SMG7), and these groins do not have much difference in Δy between the southern and northern transects, suggesting much smaller to negligible shoreline offsets.

Other patterns are shown in Newport Beach. For example, NBG5, which is in the middle of Newport Beach's groin field, has a steady increase in both values of Δy after 2017 (Figure 7e), which corresponds to a nourishment project that took place after the 2015–2016 El Nino [38]. This sand was placed largely between NBG6 and NBG5, explaining why other groins such as NBG7 and NBG8 do not show this distinct widening pattern. The northern Newport Beach groin, NBG8, is closest to the Santa Ana River and seems to have regular oscillations between the two Δy values. Oscillations in the Δy values, are likely indicative of the seasonal changes in the shoreline offset condition across the groin, which is something we examine in more detail in Section 3.3.

3.3. Seasonality of Shoreline Positions and Offsets

The seasonality of the shoreline offsets across the groins was evaluated with computations of median monthly Δy and offset values to better understand how groins behaved

over changing seasonal wave climates. Median monthly offsets were computed for each groin structure for each month to observe whether the offset magnitude and direction changed on a seasonal basis. These monthly offset time series were computed for each site and presented a figure for each site (Figure 8: Ventura, Figure 9: Santa Monica, Figure 10: Newport Beach) and 25th, 50th, and 75th percentile metrics of the data are presented in Table 3.

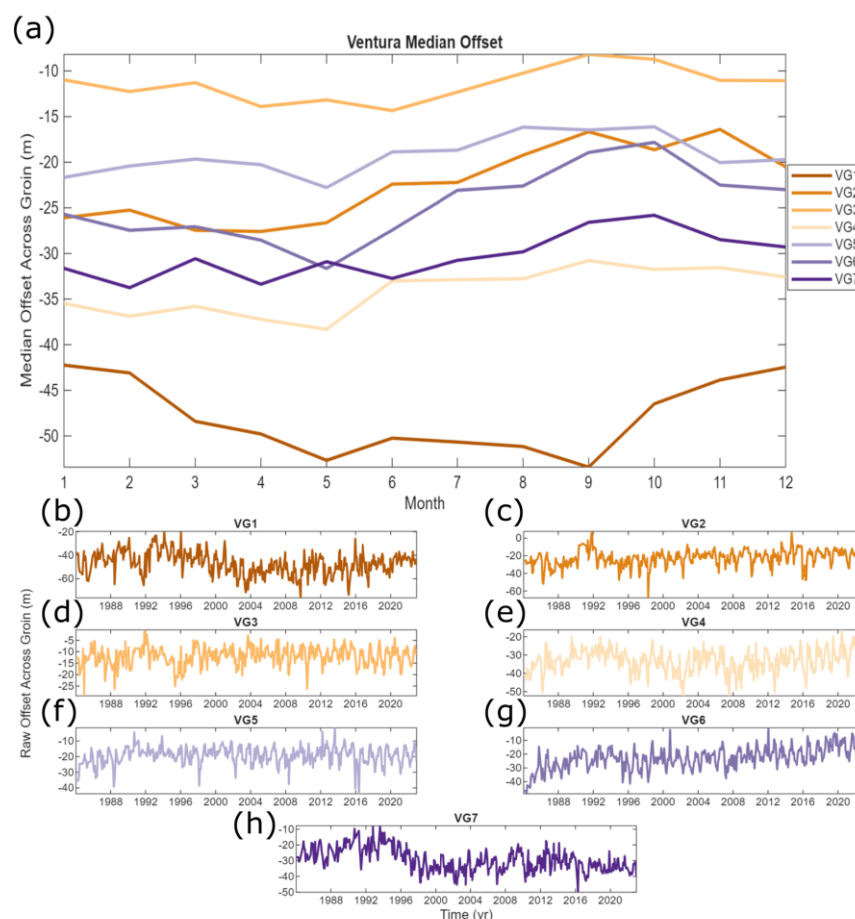


Figure 8. Monthly median shoreline offset (a), with raw monthly time series of respective groins underneath for Ventura (b–h). Raw shoreline offset across groin on y-axis in meters and time on x-axis in years.

Table 3. Shoreline offset statistics showing the 25th, 50th (median), and 75th percentiles for each groin. Median values are shown on top of the interquartile range (IQR) which is defined as the 75th–25th percentiles of the data. Shoreline offsets are in meters.

Groin	Shoreline Offset (m)	
	Median	[IQR]
VG1	−46.6	[−40.8–53.6]
VG2	−21.7	[−17.1–27.9]
VG3	−11.7	[−9.1–14.3]
VG4	−35.6	[−29.1–37.3]

VG5	−19.0 [−15.6—22.5]
VG6	−22.7 [−17.8—27.3]
VG7	−30.1 [−24.2—35.0]
SMG1	−27.4 [−22.8—30.7]
SMG2	−25.5 [−28.2—22.2]
SMG3	−24.2 [−20.7—27.2]
SMG4	−15.8 [−12.4—1.6]
SMG5	2.7 [6.2—1.7]
SMG6	0.4 [3.5—3.9]
SMG7	−6.6 [−2.7—11.8]
NBG1	−12.2 [−7.6—17.0]
NBG2	−2.9 [−0.5—5.5]
NBG3	−0.3 [2.7—3.2]
NBG4	0.4 [4.3—2.3]
NBG5	−9.1 [−6.3—11.7]
NBG6	−2.4 [0.7—5.5]
NBG7	−7.5 [−5.5—9.8]
NBG8	−4.4 [0.1—10.7]

Groins VG2–VG7 at Ventura contain similar median monthly offset patterns with the lowest magnitudes in September–October and largest magnitudes in May–June (Figure 8). VG1 has a distinctly different monthly pattern than the other groins of this site, which may be due to shoreline orientation or the annual dredging operations that occur immediately south of VG1 [38]. These operations are done to remove excess sand build up and move the sediment south of the Ventura Harbor to protect the harbor inlet. VG1 also has the largest offset magnitude of the study, having commonly 45–55 m of shoreline offset.

Santa Monica, in contrast, has two distinct groups in the shoreline offset values, the northern groins (SMG5–SMG7), which have offset magnitudes of roughly less than 5 m throughout the year, and the southern groins (SMG1–SMG4), which have offset magnitudes of 15–30 m (Figure 9). These offset magnitudes correspond to the lengths of the groins, whereas the smaller groins (SMG5–SMG7) have some of the smallest offsets in the entire study, and the larger groins (SM1–SMG4) have larger shoreline offsets (Figure 9). As noted in the Methods Section, our 95% confidence intervals of uncertainty for measuring these offsets are 5–6 m for the Santa Monica site (Table 1), which suggests that many

of the observed offsets and monthly median values for the northern set of Santa Monica groins (SM5–SM7) were below these thresholds and not significant (Figure 9).

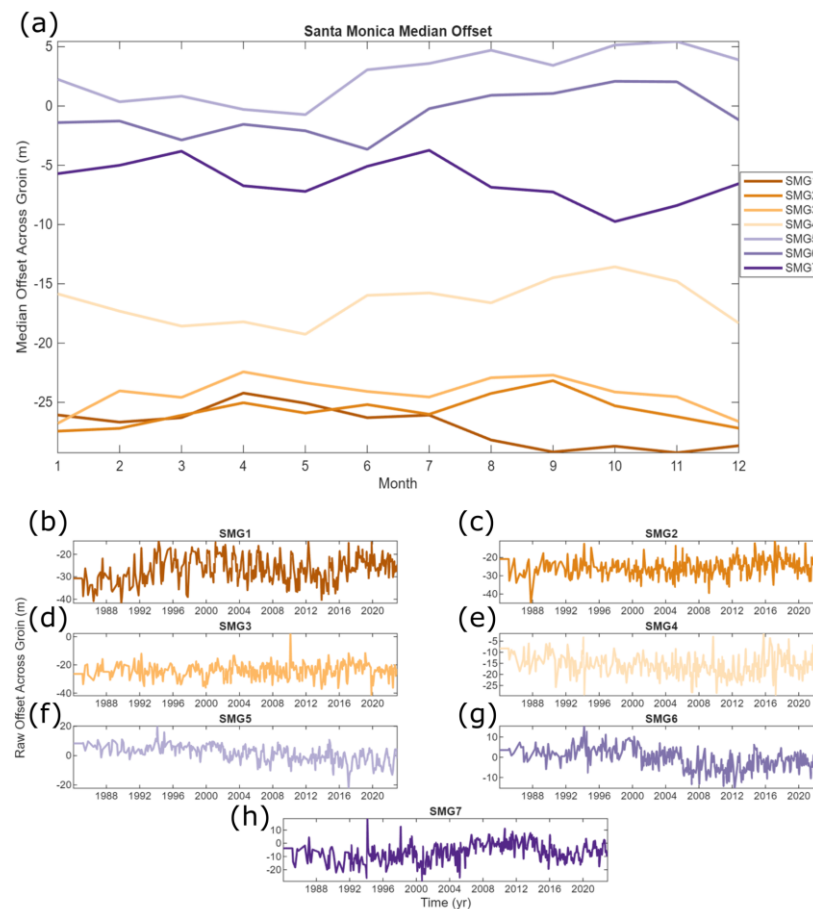


Figure 9. Monthly median shoreline offset (a), with raw monthly time series of respective groins underneath for Santa Monica (b–h). Raw shoreline offset across groin on y-axis in meters and time on x-axis in years.

Newport Beach has the most distinct seasonal patterns in the shoreline offsets, and two different seasonal patterns are shown for this groin field. The most southern groin, NBG1, has its largest offset in September, while the most northern groin, NBG8, has its largest offset in February (Figure 10). These two groins are at the ends of the groin fields, and their seasonal shoreline offset patterns seem to be 180° out of phase with each other. Groin NBG8 reaches a shoreline offset of zero during the late summer to autumn, while having a pronounced negative offset in the winter. However, this seasonality pattern at NBG8 seems to change after 2016, when the summer-to-autumn offsets are more positive (Figure 10i). We then compared the median offset for before and after 2016 (1984–2015 and 2016–2022) with results shown in Table 4 below. Median offsets between these two time periods were compared for all months, summer months, and winter months to observe the changes. After 2016, all eight groins at Newport Beach experience an overall increase in shoreline offset, with some varying seasonal offset change. Besides NBG1, all groins also experience a larger summer median offset change, with NBG8 experiencing the largest change of 15.5 m between the two periods. Throughout the study period, NBG1 has the largest offset magnitude, averaging around 15 m, and ranging from 10 m in the winter to spring to 20 m in the summer to autumn (Figure 10). This result implies that the 2016 nourishment project may have altered the shoreline dynamics throughout the groin field.

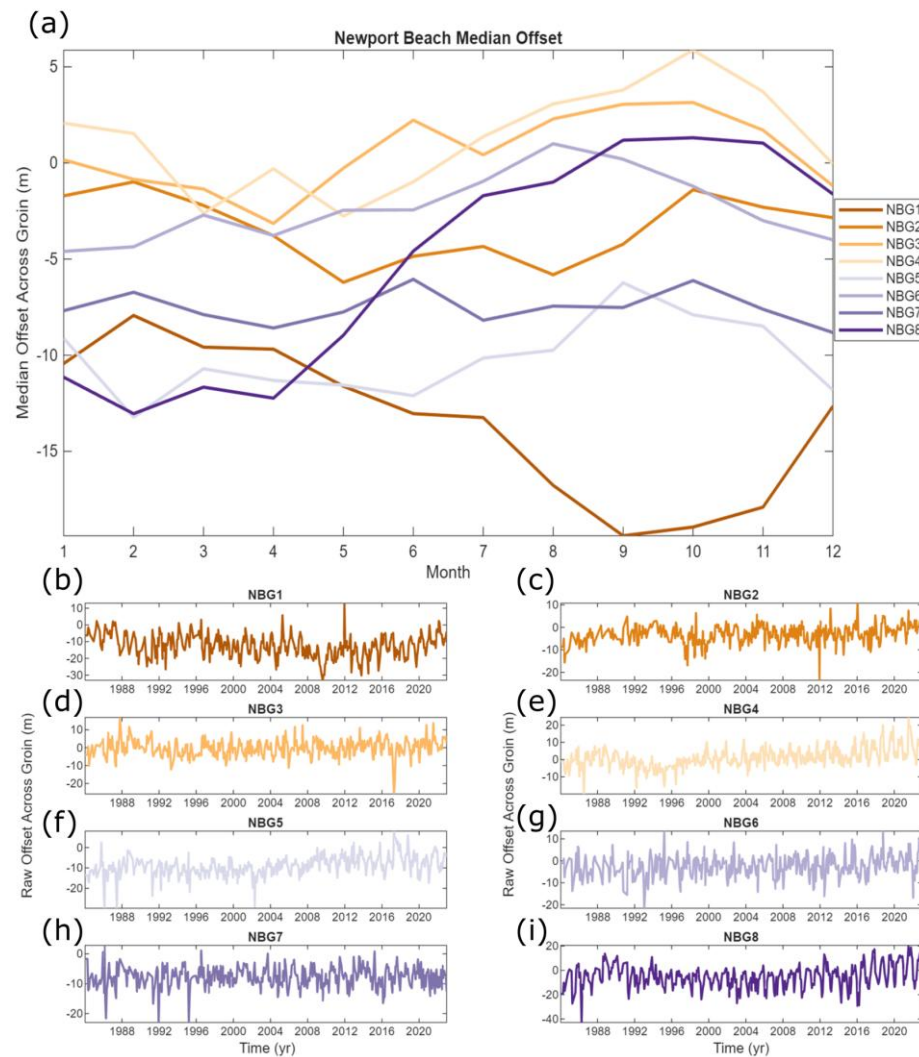


Figure 10. Monthly median shoreline offset (a), with raw monthly time series of respective groins underneath for Newport Beach (b–i). Raw shoreline offset across groin on y-axis in meters and time on x-axis in years.

Table 4. Overall, summer, and winter median shoreline offset change for Newport Beach comparing 1984–2015 and 2016–2022. Summer is defined as June, July, August, and September. Winter is defined as December, January, February, and March. Shoreline offsets are in meters.

Groin	Overall Median Change	Summer Median Change	Winter Median Change
NBG1	0.5	−2.7	2.5
NBG2	2.8	3.9	2.3
NBG3	1.8	3.3	−2.4
NBG4	7.4	13.0	5.1
NBG5	4.9	7.9	0.5
NBG6	1.5	4.5	−2.1
NBG7	0.7	0.3	−3.2
NBG8	8.3	15.5	−2.5

3.4. Littoral Transport and Peclet Numbers

Mean monthly Peclet numbers (Pe) and mean monthly potential longshore transport ($Q_{\text{potential}}$) are shown in Figure 11 to illuminate how the values change throughout the year. Pe and $Q_{\text{potential}}$ were computed at each CDIP transect and mapped onto the nearest CoastSeg transect to compare with the shoreline change results. Both the CDIP transect

numbers and the CoastSeg transect numbers are shown in Figure 11. Ventura and Santa Monica are dominated by southward diffusion ($-0.5 < Pe < 0$) for the majority of the years, but both experience periods of southward advection ($Pe < -0.5$), around the spring and summer months. Exceptions to this pattern occur near VG1, which exhibits northward transport for all months ($Pe > 0$), and at several transects south of the groin field in Santa Monica, which experience northward diffusion ($0 < Pe < 0.5$) during the summer months. The spatiotemporal distribution of $Q_{\text{potential}}$ is also similar for Santa Monica and Ventura, where $Q_{\text{potential}}$ is strongest during the summer months. Santa Monica experiences its strongest monthly mean $Q_{\text{potential}}$ in March at $-0.65 \text{ Mm}^3/\text{yr}$ and weakest in August at $-0.15 \text{ Mm}^3/\text{yr}$, while Ventura's strongest monthly mean occurs in January at $-1.2 \text{ Mm}^3/\text{yr}$ and weakest in August at $-0.17 \text{ Mm}^3/\text{yr}$.

Newport Beach experiences a very different pattern in littoral transport, with oscillations in longshore transport direction within its groin field as well as a section with northward transport ($Pe > 0$) throughout the year. Newport Beach is primarily southward diffusive ($-0.5 < Pe < 0.5$) for winter and spring (November–May) between the westernmost end of the study to NBG5. The site becomes primarily northward diffusive until after Newport Point (past CDIP transect 426) where the pattern becomes a mix of southward diffusion and advection. Within this northward diffusive band $Q_{\text{potential}}$ ranges from $1.2 \text{ Mm}^3/\text{yr}$ to $960 \text{ m}^3/\text{yr}$. Outside of this region, $Q_{\text{potential}}$ has similar magnitudes, although in the negative direction, denoting a southward direction.

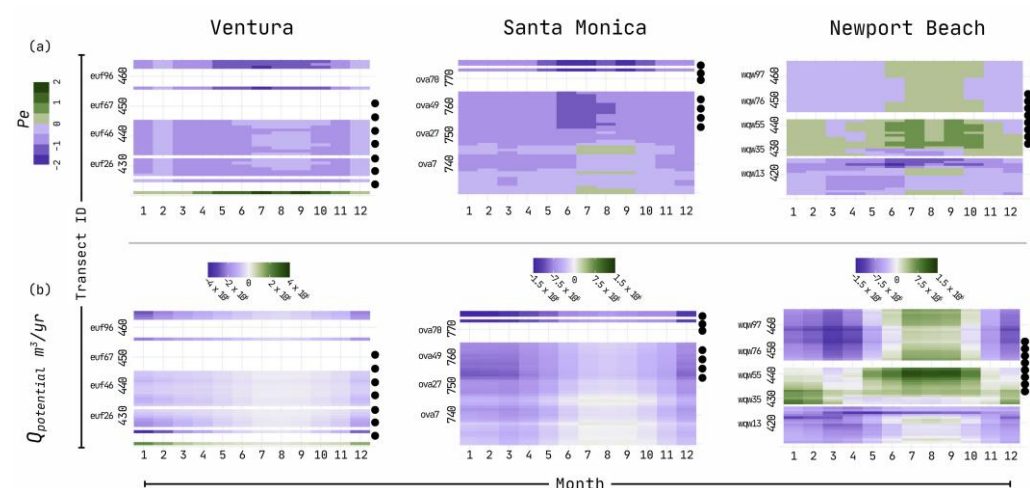


Figure 11. (a) Mean monthly Pe number for each CDIP-MOP Transect. Color bar is the same for all three sites ranging from -2 to 2 . (b) Mean monthly potential longshore transport ($Q_{\text{potential}}$) for each CDIP-MOP Transect in m^3/yr . Black dots to the right of each plot correspond to the approximate locations of groins at each site. Color bar for Ventura ranges from -4×10^6 to $4 \times 10^6 \text{ m}^3/\text{yr}$. Color bars for Santa Monica and Newport Beach are the same, ranging from -1.5×10^6 to $1.5 \times 10^6 \text{ m}^3/\text{yr}$. CDIP-MOP transect numbers are vertical to plots and CoastSeg transect names are horizontal to plots for both (a) and (b).

Figure 12 shows the annual mean Peclet numbers on transects of the site maps to visualize the patterns around the study areas. Data gaps that occur at Ventura and Santa Monica result from gaps in the CDIP-MOP source data. In general, Ventura and Santa Monica have primarily southward transport ($Pe < 0$) during the 2000–2022 record, with the exception south of VG1 where sediment begins to pile on an angled jetty protecting Ventura Harbor (refer to Figure 12a) where $Pe = 0.522$. Ventura has a mix of diffusive and advective patterns within its groin field. Santa Monica has a diffusive pattern throughout the site but becomes advective as Pe becomes more negative within the groin field as shown by the darker purple shade in Figures 11a and 12b. The maximum negative Pe

within the Santa Monica groin field is -0.836 and -0.571 outside its groin field. Newport Beach has a primarily southward diffusive pattern for 2000–2022 up until NBG5 where the pattern switches to northward diffusive ($0 < Pe < 1$) with a maximum Pe at 0.462 , which suggests net convergence of sediment transport. Once around Newport Point south of NBG1, the pattern returns to a southward direction and Pe ranges between -0.020 and -0.992 along the easternmost stretch.

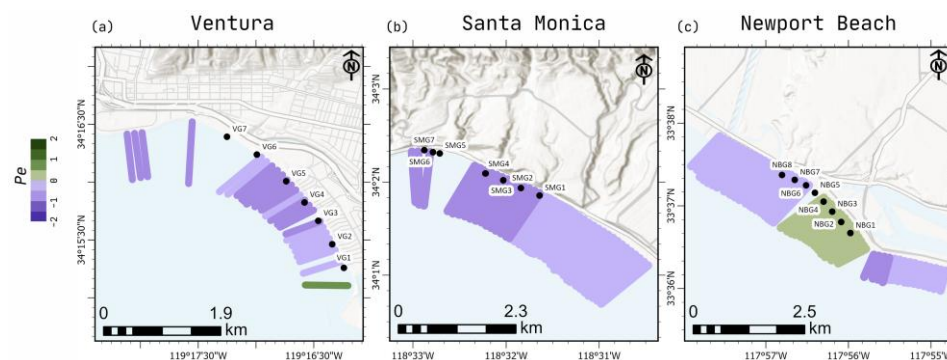


Figure 12. Maps of regions of interest with CDIP-MOP transects colored by mean (2000–2022) Pe number. (a) Ventura, (b) Santa Monica, (c) Newport Beach. Peclet number scale denoted in left color bar denoting northern longshore transport in green and southern longshore transport in purple. Values closer to zero are more diffusive while values with magnitudes closer to one are more advective. Figure created in ArcGIS Pro (version 3.4.2) by ESRI with World Terrain Basemap (Esri, TomTom, Garmin, FAO, NOAA, USGS, © OpenStreetMap contributors, and the GIS User Community).

3.5. Correlations Between Shoreline Change and Littoral Processes

Correlations between shoreline change and various littoral process variables were conducted to investigate potential relationships in statistical significance between these parameters. For example, we hypothesized that the shoreline offset may relate to wave directions and Pe values, which may influence longshore transport.

First, correlations between the shoreline positions on northern and southern transects of each groin were computed to examine the shoreline change relationships across the groins. All structures contained R^2 values above 0.35 and p -values less than 0.05 (Table 5). Although there is generally good correlation between the shorelines on either side of groins, notable patterns exist in the data. For example, the two end groins in Newport Beach (NBG1 and NBG8) have the lowest correlations of that study site, which is consistent with the observation that these two groins had regular seasonal variability in the shoreline offset across the groin (cf. Figure 10).

Table 5. R^2 for monthly resampled raw Δy s for transects on either side of groins, exact transect names used are within Table S1.

Groin	R^2
VG1 *	0.47
VG2 *	0.55
VG3 *	0.72
VG4 *	0.59
VG5 *	0.63
VG6 *	0.58
VG7 *	0.40
SMG1 *	0.40
SMG2 *	0.61

SMG3 *	0.68
SMG4 *	0.68
SMG5 *	0.78
SMG6 *	0.60
SMG7 *	0.47
NBG1 *	0.55
NBG2 *	0.81
NBG3 *	0.78
NBG4 *	0.72
NBG5 *	0.70
NBG6 *	0.63
NBG7 *	0.81
NBG8 *	0.32

* Groins have p -values less than 1.5×10^{-8} .

Shoreline offset values were compared to various metrics to determine whether statistical relationships existed. Monthly shoreline offset magnitudes, Pe numbers, and groin lengths were parameters evaluated in these tests. Results of comparing monthly offset and monthly Pe data are provided within Appendix B; Tables A4–A6 for Ventura, Santa Monica, and Newport Beach, respectively. Overall, the monthly comparisons of these values for Ventura and Newport Beach were not statistically significant except during the late summer and fall months (August to November; Tables A4 and A6). Santa Monica, however, had statistically significant results for 10 of the 12 months (March through December; Table A5). Evaluation of the complete datasets revealed several significant relationships (Table 6). For example, we found that the overall shoreline offsets at Ventura and Newport Beach were not significantly related to Pe (both $p > 0.22$), whereas the offsets at Santa Monica were significantly related to Pe ($R^2 = 0.78$, $p = 2.85 \times 10^{-4}$; Table 6). However, after graphing the Santa Monica data, it was observed that the two distinct groin fields at this site (the shorter northern groins and longer southern groins) persistently occurred in two groupings of the data, which may imply that these strong relationships were spurious correlations related to these groups. To test this hypothesis, the two groin fields at Santa Monica were examined separately. The Santa Monica southern groins (SMG1, SMG2, SMG3, and SMG4) had very weak relationships in all tested comparisons (Table 6). The Santa Monica northern groins (SMG5, SMG6, and SMG7), however, showed a strong relationship between groin length and offset magnitude with R^2 averaging 0.87 and a p -value of 0.03. Overall, offset magnitudes had a stronger relationship with groin length than Pe numbers based on R^2 and p -values, although Newport Beach had a weak relationship which may be due to the seasonal cycles present at this site. Summer and winter offsets were also compared to groin length for Newport Beach due to the weak overall signal. R^2 values were higher for summer than winter, but both relationships were not statistically significant (Table 6).

Table 6. Coefficients of determination (R^2) and p -values for various shoreline offset, wave parameters, and Pe. Wave ratio is defined from Equation (6). Ventura = V, Santa Monica = SM, and Newport Beach = NB. Asterisk (*) denoting significant values ($p < 0.05$).

Comparison	R^2	p -Value
V Offset Magnitude vs. Mean Monthly Peclet Number	0.21	0.22
SM Offset Magnitude vs. Mean Monthly Peclet Number *	0.78	2.85×10^{-4}
SM Southern Groins Offset Magnitude vs. Mean Monthly Peclet Number	0.19	0.28
SM Northern Groins Offset Magnitude vs. Mean Monthly Peclet Number	0.25	0.67
NB Offset Magnitude vs. Mean Monthly Peclet Number	0.02	0.67

V Offset Magnitude vs. Groin Length *	0.45	0.009
SM Offset Magnitude vs. Groin Length *	0.80	1.6×10^{-5}
SM Southern Groins Offset Magnitude vs. Groin Length	0.21	0.25
SM Northern Groins Offset Magnitude vs. Groin Length *	0.87	0.03
NB Overall Offset Magnitude vs. Groin Length	0.04	0.45
NB Summer Offset Magnitude vs. Groin Length	0.11	0.21
NB Winter Offset Magnitude vs. Groin Length	0.01	0.68

To evaluate for further time-dependent Pe relationships, the median monthly offset magnitudes were compared to lagged Pe values. These were computed for each groin of the study area. Pe values were placed into a lag matrix where values were lagged 12 times for each month. Month lag corresponds to how many months ahead (positive) or behind (negative) a correlation was observed. Very few structures had statistically significant results, with only nine of the 22 total structures across all three sites having an R^2 above 0.35 (Table 7). Of note, NBG1 and NBG8, which behaved out of phase with each other, both contained a two-month positive lag with their corresponding Pe resulting in R^2 of 0.49 and 0.56, respectively. This two-month positive lag suggests that shoreline offsets respond with a two-month delay to Pe at these two groins.

Table 7. List of significant lagged mean monthly Peclet number and offset magnitude correlations. Only values containing R^2 of 0.35 or greater are reported. Transect name is derived from CoastSeg which assigns a three-letter code to a region. Ventura = euf, Santa Monica = ova, Newport Beach = wqw.

Structure and Transect	R^2	Month Lag
VG1 euf 14	0.40	−1
VG3 euf 30	0.58	−4
VG5 euf 46	0.57	+6
SMG1 ova 33	0.45	−2
SMG3 ova 47	0.38	+5
NBG1 wqw 40	0.49	+2
NBG3 wqw 52	0.43	+1
NBG6 wqw 68	0.37	−3
NBG8 wqw 79	0.56	+2

4. Discussion

The effects of groin structures on shoreline positions was observed at all three sites of the study area, and similarities and differences were found in the shoreline change patterns. All three sites showed time-dependent shoreline variations which may be explained by the movement of littoral sediment through the groin fields. As shown in Figure 5, groins seemed to “mute” the shoreline change patterns, showing up as lighter bands in the data. Although the shoreline change signal was reduced, the overall shoreline change patterns showed similar accretion and erosion signals within the groin fields to areas where groins were absent. Ventura experienced several accretionary and erosional waves that seemed to step through the groin field (roughly in 1998, 2005, 2008, 2011, 2013, 2015, and 2020). Ventura also had a period of erosion starting in 2016, especially in the region of the groins (1000–3500 m). Notably in Santa Monica around the year 2000, an accretionary wave was observed moving through the groin field which took a few years to fully move past the 1500 m mark at the end of the groin field. Newport Beach also experienced similar patterns through its groin field, notably an erosional wave in 2015–2016 which aligned with the strong 2015–2016 El Nino season [67]. This wave is followed by an accretionary event centered near NBG5 which corresponds to a nourishment project in which

roughly 500,000 m³ of sediment was dredged from the Santa Ana River and was placed onto the beach [38].

There were distinct differences in the seasonal patterns of shoreline change and shoreline offsets across the groins, and we have summarized these patterns in the conceptual model figure provided as Figure 13. Ventura and Santa Monica had a relatively consistent pattern in shoreline offsets around groins; Newport Beach, in contrast, had a strong seasonal cycle, especially around NBG1 and NBG8 which had median offsets behaving 180° out of phase with each other (Figure 13). After 2016–2017, Newport Beach began to have a slightly different pattern that was originally not observed within the median data, shown in Figure 13i,j. Sediment began to pile significantly on the right side of NBG8 during the fall-winter season. Beginning in 2017, according to the ASBPA National Beach Nourishment Database [38], regular dredging of the Santa Ana River began on a yearly basis, with the last one currently recorded in 2021 [38]. Sand was dredged from the Santa Ana River ocean outlet and placed back onto the beach, occurring near NBG6 and NBG5, altering the shoreline pattern. This dredging may have disrupted the natural flow of sediment to the region and altered the shoreline pattern.

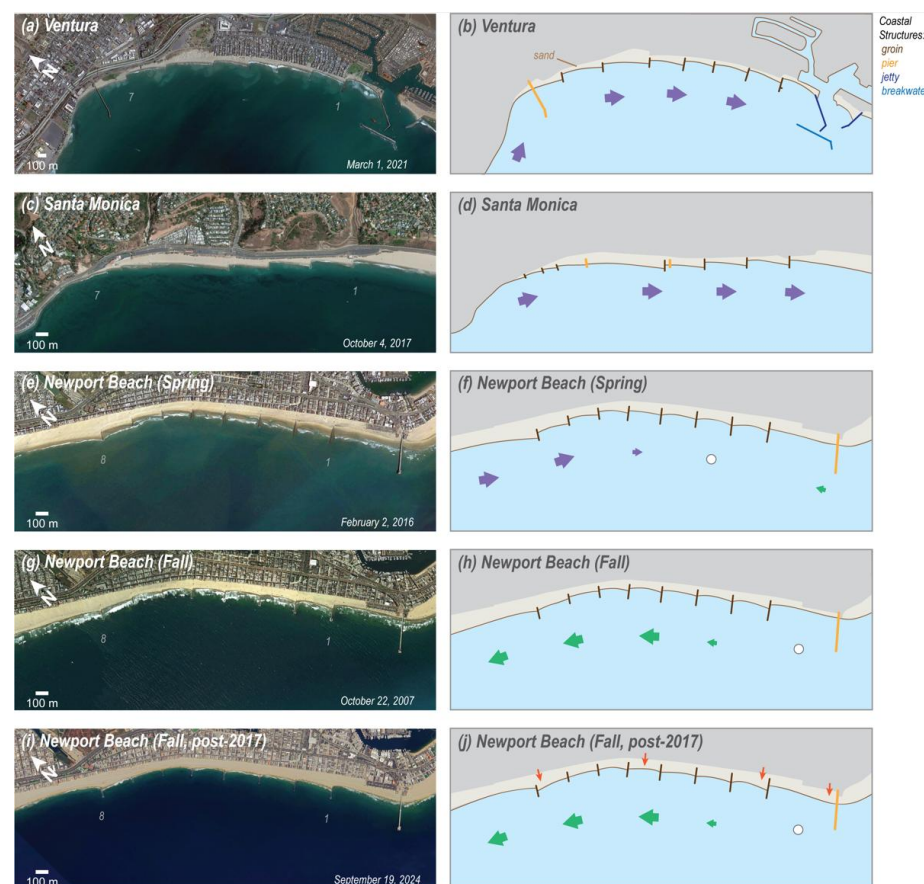


Figure 13. Conceptualization of observed longshore transport and shoreline patterns around groin fields at each site. Left panels (a,c,e,g,i) show satellite images from Google Earth for each site with the date of each image shown in the bottom right corner. Right panels (b,d,f,h,j) show drawings of each site with longshore transport shown as arrows. Purple arrows denote southerly transport while green arrows denote northerly transport similarly to Figure 12. Arrow size is relative to the magnitude of the longshore transport and is not to scale. White dots correspond to areas of transitional directions. Red arrows shown in panel (j) highlight the new pattern Newport Beach obtained after 2016–2017 (refer to Discussion Section for more information).

Groin length was observed to be an important parameter for the shoreline offset magnitude. Santa Monica's two distinct groin fields have shown that groins under 42 m behave very differently than larger groins even within the same region of interest (Figures 9 and 13). These shorter groins were still able to trap sediment but on a smaller scale than the other structures. If the groins were even smaller, shoreline offset effects may not have been measurable in the satellite-derived data. NBG7 at Newport Beach is also among the shortest groins in the study at 48 m long. Although not as small as the groins in Santa Monica, NBG7 has roughly 3 m of total shoreline offset annually which is the smallest offset reported at Newport Beach. NBG7 is also nested within the natural curve of the shoreline with NBG8, one of the longest groins at Newport Beach at almost 100 m, blocking southward fluxes of sediment, especially in the spring season, before it reaches NBG7 (Figure 13). From the results in Table 1 and Figure 8, we observed that all groins at Ventura had significant monthly median offset values greater than the measurement uncertainty values. Santa Monica's first four longer groins also had significant monthly median offsets, but the three northernmost and smallest groins had such small offsets that they were not significantly different than transect-to-transect offset measurement uncertainty (Table 1 and Figure 9). Newport Beach had a mix of significant monthly median offsets which may be due to varying groin length and a stronger seasonal signal than the other two sites (Table 1 and Figure 10).

Observed shoreline patterns were generally consistent with the wave conditions and computed littoral transport directions for the study area. Ventura had fairly constant southward transport, which is evidenced by the waves of sand moving through the system (Figure 5a). Some of the more pronounced sediment waves shown in Figure 5a (darker blue bands) occurring from 4200–3500 m were likely derived from sediment pulses from the Ventura River just west of the study region. Three of largest sediment pulses along the shoreline occurred in 1998, 2005, and 2011, and these events corresponded to the highest river discharges according to the USGS stream gage discharge data for the Ventura River (USGS gauging station 11118500: Ventura River near Ventura) [68]. The mean annual discharges for 1998, 2005, and 2011 are reported to be 364.2 ft³/s, 309.5 ft³/s, and 62.4 ft³/s respectively over the calendar year (defined as January 1 to December 31), which are 543.1%, 446.5%, and 10.3% greater than the annual average of 56.6 ft³/sec over the 1984–2022 records respectively. Although there are other considerable accretion events, especially in 2013, 2015, and 2020, these events do not correspond as well to increased river discharge, possibly because of sediment pulses from other sand sources further west of the Ventura River or inherent variability of alongshore and cross-shore sediment transport.

Within the groin field at Ventura, there were mixes of diffusive and advective southerly patterns, possibly from longshore currents hitting the groin structures as shown in Figure 12a. Ventura VG1 also contained a consistent northward transport direction (Figure 12a), which may be attributed to site orientation as well as the region being a highly managed section of coast. Near yearly dredging of Ventura Harbor and the sand trap on the harbor jetty at this site (Figure 1c) may have further altered the transport direction at VG1 [37–39]. Santa Monica also had a consistent southward transport (Figure 13d), although there was a transition from advective to diffusive once past SMG1 (Figure 12b). During the summer at Ventura and Santa Monica, there was a weaker $Q_{\text{potential}}$ downcoast than in the winter months (Figure 11b). This likely resulted from the weaker wave climate in the summer months than in the winter and seasonal changes in the wave directions. Santa Monica and Ventura also remained in a southerly advective/diffusive direction throughout the year, while Newport Beach was more seasonal (Figure 11).

In contrast to the Ventura and Santa Monica groin fields, Newport Beach had the largest seasonal patterns in longshore transport as shown by an alternating Pe pattern

within its groin field (Figure 11). The effects of these alternating littoral transport directions are highlighted in the shoreline offsets across each groin shown in Figure 10, where NBG1 and NBG8 have monthly median shoreline offsets out of phase with each other. Beyond the southern end of the groin field near Newport Point the longshore transport and Pe patterns returned to a southward direction as mentioned previously. It is suggested that these changes in transport direction may be due to Newport Beach's shoreline curvature and its undersea canyon that alters wave directions and heights in the region [69,70]. Newport Beach also had the largest change in wave direction between summer and winter (refer to Figure 4) going from primarily southern in the summer to southwestern in the winter, which also had a strong effect on Pe values. Newport Beach had almost a full reversal in transport directions over each annual cycle for almost all observed transects, alternating between southward to northward during some point in the year (Figure 11). This reversal in transport directions also supports the large seasonal cycles in shoreline offsets, especially on the groins on the northern and southern ends of the groin field (NBG1 and NBG8; Figures 10 and 13). Although several statistical comparisons were performed throughout the study, there was no significant relationship between Pe numbers and shoreline offset magnitudes. This result may suggest that while longshore transport is a primary cause of the shoreline offsets across the groins, the variations of this offset are more a function of groin geometry and spacing than sediment transport variations, as shown by the shorter groins in Santa Monica with negligible shoreline offsets.

5. Conclusions

Satellite-derived shorelines were extracted to observe the effects of groins at three sites within the state of California: Ventura, Santa Monica, and Newport Beach. Satellite data are inherently noisy and even with smoothing and filtering may still contain uncertainties of approximately 10 m depending on the resolution of the satellite image. Even with these potential uncertainties, we created a data set with hundreds of shoreline measurements spanning almost 40 years and were able to identify unique shoreline change patterns and trends within groin fields. Groins may reduce shoreline variability depending on site characteristics as well as create distinct shoreline offsets at the groin, both of which were quantified from the satellite-derived shoreline data. Data from transects on either side of a groin helped determine the magnitude of the shoreline offset, and these offsets were observed to differ significantly over time and across the study area, correlations with variables such as groin length and change in longshore transport direction indicate possible causes for many of these differences. The results presented here could assist with furthering the understanding of how groins affect shoreline variability and how to better manage developed coastlines. Furthermore, the results provide examples of how these complex shoreline change phenomena within groin fields can be measured with standard satellite-derived shoreline techniques.

Supplementary Materials: The following supporting information can be downloaded at: <https://www.mdpi.com/article/10.3390/rs18152608/s1>, Supplemental Figure S1. Site orientations (region of interest (ROI), reference shoreline, and transects) within the CoastSeg software. (a) Ventura (red), (b) Santa Monica (green), (c) Newport Beach (blue). Site color borders correspond to Figure 1. North arrow is the same for all three sites. Supplemental Table S1. List of transect names surrounding each groin. Transect names are given by CoastSeg software, defined by a three-letter code and a number. Numbers are in ascending order from south to north.

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editing, C.N.J., J.A.W., S.B., T.H., M.A.L., and D.B.; visualization, C.N.J., J.A.W., and T.H. All authors have read and agreed to the published version of the manuscript.

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Appendix A

Details pertaining to methodology: settings used for shoreline extraction in CoastSeg [34], number of usable satellite images at each site after applied filters, and setup done to create the structure points for computing Δy and shoreline offsets. Table A1 contains the extracted shoreline settings used within CoastSeg [34] to create the satellite-derived shorelines. Table A2 contains the number of usable satellite images after applying the filtering methodology. Table A3 contains the calculations of D1, D2, groin length, and the coordinate point of each groin midpoint.

Table A1. Settings used within CoastSeg [34] to create satellite-derived shoreline data.

Variable	Ventura	Santa Monica	Newport Beach
Cloud Mask	False	True	False
Allowed Distance from Clouds	N/A	50	N/A
Reference Shoreline Buffer	100	100	150
Minimum Shoreline Length	147	147	147
Minimum Beach Area	139	139	139

N/A values indicate that the cloud mask was not used at these sites

Table A2. Number of usable images downloaded from Google Earth Engine [46] after applying image filters.

Satellite	Ventura	Santa Monica	Newport Beach
L5	623	327	559
L7	647	339	632
L8	290	290	288
L9	31	44	34
S2	1026	296	310

Table A3. Parameters used in order to calculate Δy and shoreline offsets for each structure including groin length (m), D1 length (m), D2 length (m), and coordinates of the intersection point between D1 and D2. Coordinates in WGS84.

Groin	Length (m)	D1 (m)	Longitude	Latitude	D2 (m)
VG1	158.0	79.0	−119.2709055	34.25423940	120.0
VG2	115.0	57.5	−119.2725271	34.25775865	100.0
VG3	106.0	53.0	−119.2744588	34.26109168	100.0
VG4	104.0	52.0	−119.276531	34.26381318	100.0
VG5	74.0	37.0	−119.2791032	34.26683327	100.0
VG6	91.0	45.5	−119.2833031	34.27055252	120.0
VG7	88.0	44.0	−119.2874728	34.27332247	100.0
SM G1	68.0	34.0	−118.5273478	34.03101841	100.0
SM G2	66.0	33.0	−118.5306116	34.03238253	100.0

SM G3	72.0	36.0	−118.5338724	34.03369814	140.0
SM G4	65.0	32.5	−118.5370026	34.03494806	100.0
SM G5	32.0	16.0	−118.5451639	34.0385344	100.0
SM G6	41.0	20.5	−118.5463879	34.03877078	100.0
SM G7	28.0	14.0	−118.5479877	34.03907859	140.0
NBG1	120.0	60.0	−117.9330445	33.61119319	100.0
NBG2	99.0	49.5	−117.9348925	33.61336445	100.0
NBG3	82.0	41.0	−117.9365972	33.61548099	100.0
NBG4	90.0	45.0	−117.9384452	33.61747742	100.0
NBG5	78.0	39.0	−117.9401797	33.6192513	100.0
NBG6	67.0	33.5	−117.9419959	33.62074076	100.0
NBG7	48.0	24.0	−117.9442429	33.62185224	100.0
NBG8	99.0	49.5	−117.9468391	33.6227868	100.0

Appendix B

Details pertaining to monthly correlations between monthly mean Peclet number and monthly median offset magnitude. Table A4 shows the results for Ventura. Table A5 shows the results for Santa Monica. Table A6 shows the results for Newport Beach.

Table A4. Monthly correlations between monthly mean Peclet number and monthly median shore-line offset magnitude for Ventura.

Ventura Monthly Comparison	R ²	p-Value
January Offset Magnitude vs. January Mean Peclet Number	0.16	0.29
February Offset Magnitude vs. February Mean Peclet Number	0.17	0.28
March Offset Magnitude vs. March Mean Peclet Number	0.26	0.16
April Offset Magnitude vs. April Mean Peclet Number	0.05	0.56
May Offset Magnitude vs. May Mean Peclet Number	0.07	0.49
June Offset Magnitude vs. June Mean Peclet Number	0.16	0.28
July Offset Magnitude vs. July Mean Peclet Number	0.42	0.06
August Offset Magnitude vs. August Mean Peclet Number	0.44	0.05
September Offset Magnitude vs. September Mean Peclet Number	0.50	0.03
October Offset Magnitude vs. October Mean Peclet Number	0.37	0.08
November Offset Magnitude vs. November Mean Peclet Number	0.02	0.73
December Offset Magnitude vs. December Mean Peclet Number	0.01	0.86

Table A5. Monthly correlations between monthly mean Peclet number and monthly median shore-line offset magnitude for Santa Monica.

Santa Monica Monthly Comparison	R ²	p-Value
January Offset Magnitude vs. January Mean Peclet Number	0.15	0.24
February Offset Magnitude vs. February Mean Peclet Number	0.28	0.10
March Offset Magnitude vs. March Mean Peclet Number	0.77	3.98×10^{-4}
April Offset Magnitude vs. April Mean Peclet Number	0.83	1.06×10^{-4}
May Offset Magnitude vs. May Mean Peclet Number	0.84	7.11×10^{-5}
June Offset Magnitude vs. June Mean Peclet Number	0.83	1.01×10^{-4}
July Offset Magnitude vs. July Mean Peclet Number	0.80	2.12×10^{-4}
August Offset Magnitude vs. August Mean Peclet Number	0.79	2.37×10^{-4}
September Offset Magnitude vs. September Mean Peclet Number	0.79	2.56×10^{-4}
October Offset Magnitude vs. October Mean Peclet Number	0.67	2.20×10^{-3}
November Offset Magnitude vs. November Mean Peclet Number	0.70	1.30×10^{-3}

December Offset Magnitude vs. December Mean Peclet Number	0.69	1.60×10^{-3}
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Table A6. Monthly correlations between monthly mean Peclet number and monthly median shore-line offset magnitude for Newport Beach.

Newport Beach Monthly Comparison	R ²	p-Value
January Offset Magnitude vs. January Mean Peclet Number	0.06	0.42
February Offset Magnitude vs. February Mean Peclet Number	0.18	0.13
March Offset Magnitude vs. March Mean Peclet Number	0.02	0.65
April Offset Magnitude vs. April Mean Peclet Number	0.02	0.64
May Offset Magnitude vs. May Mean Peclet Number	0.01	0.81
June Offset Magnitude vs. June Mean Peclet Number	0.05	0.43
July Offset Magnitude vs. July Mean Peclet Number	0.05	0.44
August Offset Magnitude vs. August Mean Peclet Number	0.37	0.02
September Offset Magnitude vs. September Mean Peclet Number	0.24	0.07
October Offset Magnitude vs. October Mean Peclet Number	0.33	0.03
November Offset Magnitude vs. November Mean Peclet Number	0.39	0.02
December Offset Magnitude vs. December Mean Peclet Number	0.16	0.16

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