# California coastal sand retention today: Attributes and influence of effective structures

*By*

Nicole Kinsman
*Department of Earth & Planetary Sciences, University of California, Santa Cruz*
*1156 High Street, Santa Cruz, CA 95064*
*nkinsman@ucsc.edu*

*and*

Gary B. Griggs
*Institute of Marine Sciences*
*Department of Earth & Planetary Sciences, University of California, Santa Cruz*
*1156 High Street, Santa Cruz, CA 95064*

## ABSTRACT

One resource for understanding the successful use of retention structures is the record of existing structure performance. We have created a robust catalog of 211 engineered structures that have the potential to retain sandy beaches along California's 1,760-km open-ocean coastline. These structures include those designed in compliment with beach restoration projects, as well as those for which sand retention is auxiliary to the primary intended purpose. We have systematically documented the location of each structure and described its basic form, function, history, and local coastal setting with the assignment of 25 numerical and categorical attributes collected from historic records and aerial imagery. Areas of sandy beach that have accreted in the proximity of coastal engineering structures have been identified by the comparison of pre-structure and modern shoreline positions. The findings suggest that 15 million m$^2$, approximately 18%, of California's total exposed sandy beach area is presently retained in and behind fillet and salient beaches associated with anthropogenic structures. A statistical analysis of numerical attributes in our catalog indicates significant correlations between effective sediment retention and shoreline orientation, blocking distance and structure spacing. Net littoral drift rates are not found to be a significant factor in predicting decadal-scale sand retention effectiveness. This statewide record of structure characteristics is a useful tool for future coastal zone management including the use of engineered structures in combination with beach nourishment along high energy shorelines.

**ADDITIONAL KEYWORDS**: Coastal Protection, Groin, Jetty, Breakwater, Beach Management

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As coastal populations have swelled, construction within the coastal zone has intentionally and inadvertently modified the movement of beach sand. Intentional modification is undertaken with the use of structures designed to control littoral drift by either (1) blocking sediment transport with groins, or (2) reducing incident wave energy with the use of offshore breakwaters. Inadvertent alteration is common when structures designed for other functions act to modify littoral drift in one of the aforementioned ways. These types of structures include, but are not limited to: jetties and breakwaters designed for harbor or inlet protection (e.g. Griggs and Johnson 1976; Johnson 1957; USACE 1994), protruding revetments/seawalls, armored outfall pipes, fences, and piers/wharves (e.g. Weggel and Sorensen 1991; Miller *et al.* 1983). Once a structure is emplaced, retained sand takes the form of a fillet beach (triangular in shape, positioned against a blocking structure) or a salient beach (bulge shaped, in the lee of a structure).

Within California, sandy beaches are popular recreational areas that lie at the heart of an approximately $47 billion annual coastal ocean economy (King 1999; NOEP 2005) and serve as physical buffers to irreversible coastal erosion. It is widely recognized that engineered structures play a large role in the movement of sand on California's beaches (e.g. Herron 1983; Everts and Eldon 2000; Wiegel 1994; Flick 1993). However, the extent to which the shape and total area of California's sandy beaches have been modified by these structures has remained difficult to determine, partially due to a dearth of extended post-construction monitoring studies. The first comprehensive inventory of littoral drift blocking structures along the state's coastline was performed by Shaw in 1980. In this report, 150 structures were classified that altered the natural movement of sediment along that coast. Shaw also suggested that structures are especially effective at widening beaches in areas where regular opportunistic nourishment (a result of the periodic need to maintain harbors and marinas by dredging) is occurring.

More recently, Everts Coastal (2002) performed a reconnaissance level study for the California Coastal Conservancy and found that roughly 1.5 million m$^2$ of sandy beach is retained in fillet beaches by anthropogenic structures in central and southern California (from Pt. Conception to the Mexican border). This study also identified physical factors, such as favorable coastline orientations (240°-310°) and high net longshore transport

## Table 1. List of 11 numerical (*n*) and 14 categorical attributes assigned to each of the 211 cataloged structures named in this study.

| **Attribute** | **Central source(s)** | **Unit** | **Example** |
|---|---|---|---|
| Structure name | USACE design names, Bottin (1988), Everts Coastal (2002) & nearby landmarks | | North Agua Hedionda Lagoon |
| Type | USACE (2008) | | Jetty |
| Latitude [ns] | Shapefile endpoint location | Degrees, WGS 1984 | 33.14564 |
| Longitude [ns] | Shapefile endpoint location | Degrees WGS 1984 | 117.34406 |
| Shape [s] | USACE (2008), Shapefile polygons | | Linear |
| Length [ns] | Pre-structure shoreline Hapke *et al.* (2006) to endpoint | Meters | 212 |
| Width [ns] | Shapefile polygon along length mean | Meters | 20 |
| Bearing [ns] | Shapefile trunk to endpoint | Compass degs. from true north | 243 |
| Shoreline orientation [nsf] | Normal to 1 km pre-structure shoreline Hapke *et al.* (2006) trend | Compass degs. from true north | 234 |
| Blocking distance [nsf] | Pre-structure shoreline Hapke *et al.* (2006) to endpoint along shore normal | Meters | 122 |
| Spacing [nsf] | Along shore distance to nearest adjacent structure | Meters | 80 |
| Trunk | Bottin (1988) & Adelman and Adelman | | Impermeable |
| Construction | Bottin (1988) & Adelman and Adelman | | Rubblemound |
| Year [n] | USACE library, Bottin (1988), Everts Coastal (2002) & Adelman and Adelman | Year | 1954 |
| Intended | USACE library, Bottin (1988) | | Waterway protection |
| Current | Everts Coastal (2002), Adelman and Adelman | | Waterway protection |
| County | California GIS clearinghouse county lines | | San Diego |
| Parks and recreational areas | California State Parks (2008) | | Carlsbad State Beach |
| Buoy | CDIP, NOAA | | Oceanside |
| Littoral cell | Patsch and Griggs (2006) | | Oceanside |
| Drift direction | Patsch and Griggs (2007) | | South |
| Drift rate [nf] | Patsch and Griggs (2007) | Yards$^3$/year | 185,000 |
| Retained area [s] | Shapefile, Hapke *et al.* (2006) | Meters$^3$ & | 13,000 & Moderate |
| Retained length [ns] | Hapke *et al.* (2006) | Meters | 726 |
| Visible fillet salient [s] | After Everts Coastal (2002) | | Yes |
| Historical area [s] | Hapke *et al.* (2006) | | Yes |

[n] numerical attribute
[s] collected from measurements made in plan view
[f] shown in Figure 2

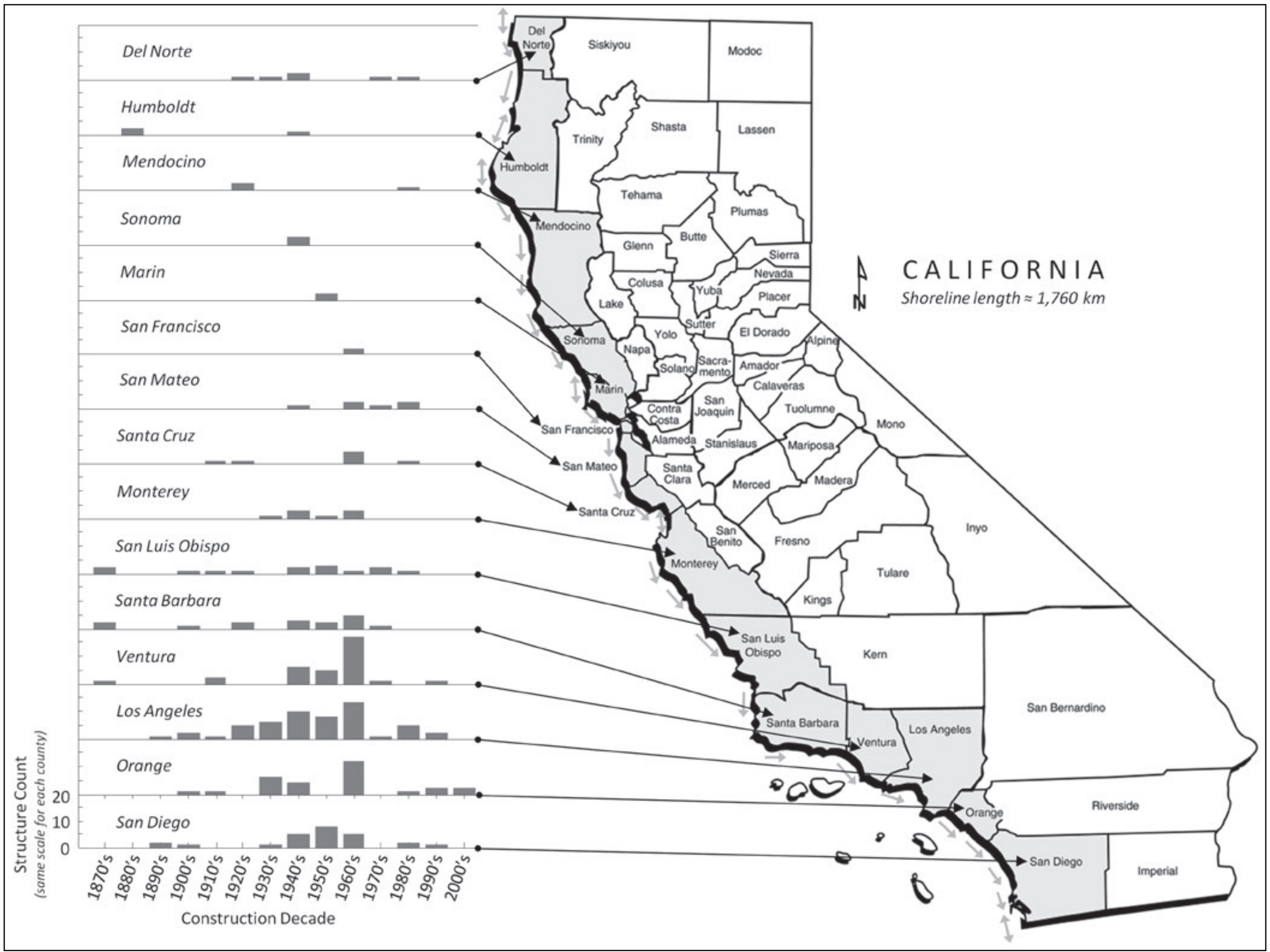

Figure 1. Map shows the spatial and temporal distribution of the 211 structures identified in this study (dominant littoral drift directions shown with gray arrows). The histograms for each coastal California county represent the original construction year or year in which the most recent extensive modification of the structure occurred. Ninety percent of the structures are in excess of 30 years in age.

rates, which correlate to a structure's effectiveness at retaining sand. They found that structures fail to retain visible fillet beaches when they are too short for the calculated blocking distance, or when the net littoral drift rate is low. An update to Everts' work is found in the present issue of *Shore & Beach* (Everts and Eldon 2010). Kraus *et al.* (1994) also report that widely accepted predictors of retention success include high littoral drift rates, longer structure lengths and adequate prefilling. These rules of thumb have been incorporated into the U.S. Army Corps of Engineers 2008 edition of the Coastal Engineering Manual (USACE 2008).

This study was undertaken to update and expand existing inventories of coastal structures within California. Further goals include an estimation of the total beach area that these structures have a role in retaining, and to use the existing knowledge of structure performance in California to identify conditions and structure characteristics that favor successful sediment retention.

## CATALOG OF SEDIMENT RETENTION STRUCTURES IN CALIFORNIA

### Temporal and Spatial Distribution

The groins, jetties, breakwaters and other coastal structures that are described in this study are unevenly distributed along California's diverse coastline (see Figure 1), which includes highly urbanized areas, coastal lowlands, and extensive sea cliffs of varying relief. California's mesotidal coast experiences increased wave and storm activity on a seasonal timescale, with a predominant wave approach from the northwest. This wave climate results in net longshore sediment transport to the south along much of the coast, with localized and seasonal drift reversals at some locations. The great majority of beach sand along the state's shoreline is supplied by river and stream runoff, with a smaller contribution from actively eroding sea cliffs (Griggs 2005). As shown in Figure 1, the majority of artificial coastal structures are located in southern California, with 75% located in the five southernmost counties; this translates to a density of one structure for every 2.5 km of coastline from Santa Barbara to the Mexican border.

The structures included in this catalog have initial construction dates as far back as 1872. The oldest structures are historically industrial piers and wharves that have been maintained in situ since the early 1870s (e.g. Stearn's Wharf in Santa Barbara or the Ventura Pier). The earliest rubblemound structures in California date to the 1890s and include the Humboldt Bay jetties, Zuniga Point jetty and the San Pedro Breakwater in Los Angeles. As of 2010, the average shore-normal coastal structure in California is 55 years in age and the median year of initial construction or extensive modification is 1963.

Large population growth following World War II led to the extensive construction of harbors and marinas, coastal recreational areas and water treatment/power facilities along the state's coastline from the 1940s to 1960s. In addition to the emplacement of many coastal structures, this development boom triggered three important changes in the coastal sediment budget: (1) an increase in volumes of opportunistic beach nourishment as large quantities of sand were dredged to open new harbors and marinas; (2) large volumes of sand added to the shoreline from coastal construction projects in former dune areas (Wiegel 1994; Flick 1993); and (3) the initiation of a long-term reduction in the sediment supply from rivers due to damming (Herron 1983; Willis and Griggs 2003; Sherman *et al.* 2002).

## Inventory Methods

To assemble a robust and up-to-date catalog of man-made coastal engineering structures in California we conducted multiple visual inspections of the state's entire coastline using three image collections: (1) USGS digital orthophoto quadrangles (DOQs); (2) Quickbird satellite imagery; and (3) oblique historic aerial images from the California Coastal Records Project. When possible, the most recent DOQ available was used to create a digitized GIS polygon shapefile of structure outlines. The satellite imagery was used to verify structure locations and temporal persistence. Oblique aerial images were used to validate construction histories, construction materials and to confirm current structure functions. In total, 211 structures with the potential to retain sediment have been identified and included in this updated inventory.

Each inventoried structure is characterized by 25 attributes (after Kraus *et al.* 1994), which describe the structure's form, function, local vicinity and retained beach area (see Table 1). Some of these are numerical attributes and are illustrated in Figure 2. For additional information about the included measurements and how numerical values were assigned on non-linear structures or in complex coastal areas, please refer to the metadata associated with the catalog's published shapefile.

Nonnumeric attributes are also assigned to each structure. Structure type is based on the original intended function. Trunk permeability is simplified to be bicategorical: structures highly permeable to sand (e.g. pilings), or structures largely impermeable to sand, including most rubblemound structures. Intended and current uses illustrate how the primary purpose of some structures has changed through time. Littoral cell, dominant littoral drift direction and estimated local net littoral drift rates are taken from Patsch and Griggs (2006; 2007) and are not available at every structure location. Where drift directions are not available, dominant drift direction is inferred from the fillet position.

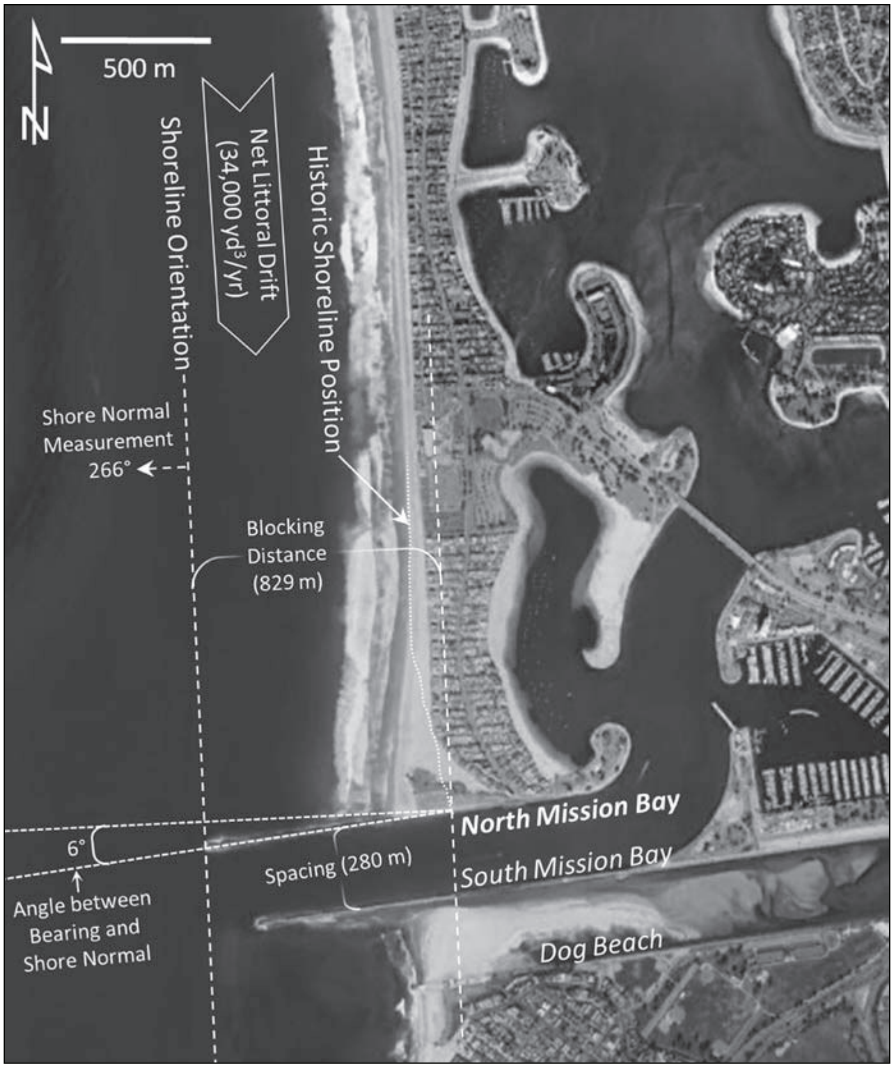

**Figure 2. Image depicting the measurements used in the statistical analysis of structures, shown for the North Mission Bay Jetty. The inland extent of the structure is defined as the position where the historic shoreline intersects with the structure. The shoreline orientation is measured along the shore normal in compass degrees from true north. The net littoral drift rate is obtained from Patsch and Griggs (2007).**

Error in the assignment of these attributes is minimized by cross referencing multiple sources of information, including previously published inventories. Only a limited number of shoreline positions are available from historical aerial images, so some error in numerical measurements may have arisen around structures that lack a pre-structure shoreline position close to the time of construction. For information on the calculation and accuracy of these shoreline positions, see Hapke *et al.* (2006) and Pajak and Leatherman (2002). All direct measurements are accurate within one meter, the maximum resolution of the lowest resolution images used.

## Catalog Results

The 211 structures cataloged in this study are comprised of 61 groins, 50 piers/wharves, 49 jetties, 36 breakwaters, and 15 other types of structures. There

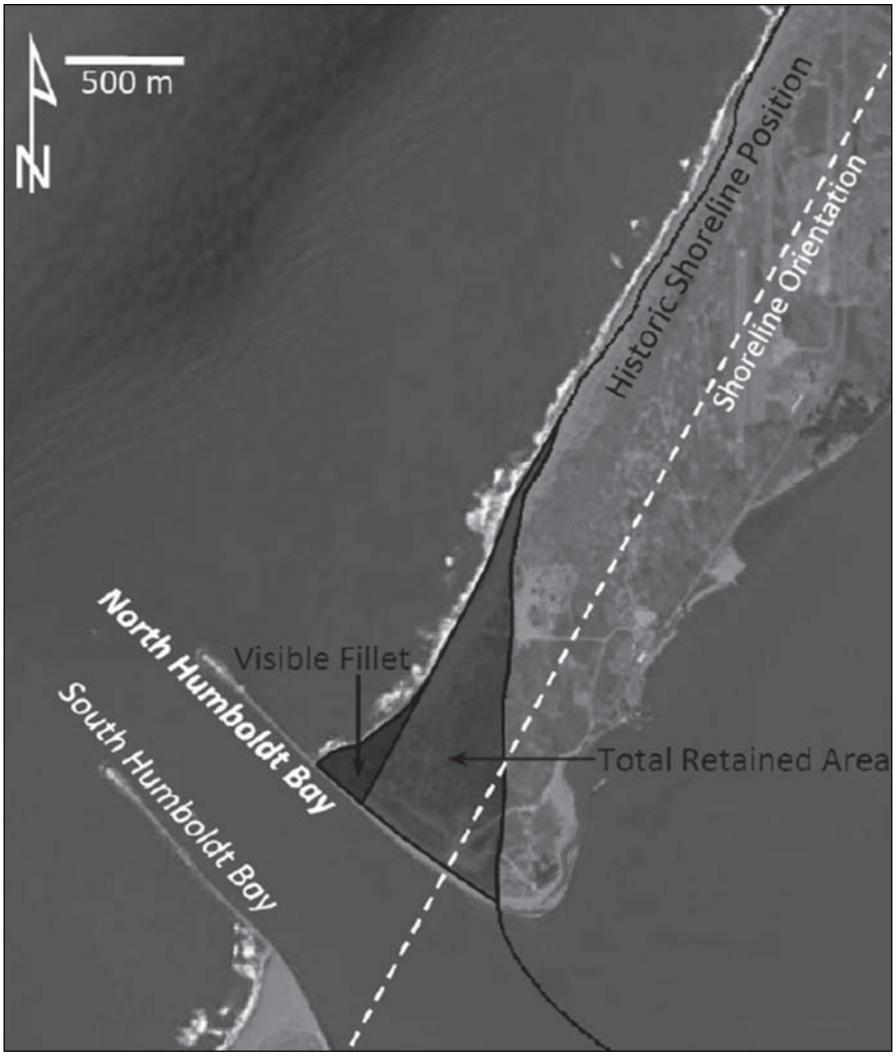

**Figure 3. Aerial image of North Humboldt jetty in northern California showing both the visible fillet area (40,400 m$^2$) and the total retained area (665,100 m$^2$) based on the pre-structure shoreline position.**

## Table 2.

**Definition of categorical area sizes for retained beaches in this catalog. These thresholds are used to differentiate between effective and ineffective sediment retention by structures in the statistical analysis.**

| Categorical retainer area | Equivalent numerical area (m$^2$) | Approximate area | Number of structures in category |
|---|---|---|---|
| None/negligible | 0, or seasonally smaller than study resolution | 0 | 68 |
| Small | $\leq 10^{3.2}$ | <½ American football field | 19 |
| Medium | $\leq 10^{4.3}$ | < 4 American football fields | 17 |
| Large | $\leq 10^{5.3}$ | < 40 American football fields | 57 |
| Very large | $\leq 10^{6.4}$ | < 570 American football fields | 50 |

is strong agreement found between the artificial structures identified in this study and those identified by Shaw (1980) and Everts Coastal (2002) in southern California. Additional structures in central and northern California have not previously been included in such inventories.

The cataloged structures include 155 structures that are impermeable to sand at the trunk, and 56 permeable structures. The majority (116) are linear in shape; 31 have a dogleg or are bent in some way, and 10 are curved. The mean length of structures is 403 meters and the mean width of the structures is 15 meters. Only 14% of the structures are oriented at an angle of less than 60 degrees to the shoreline; most structures are perpendicular to the coast. Structure clustering is common, with 76% of structures being located within at least one km of an adjacent structure. Rubble-mound construction is the most common type of design, accounting for 67% of the structures within the state.

The majority of these structures are still being used for their original intended purpose, with 22% serving a different primary purpose today. Most changes in use are attributed to piers and wharves that have gone from being commercial/industrial to recreational. Some structures have been modified to serve dual functions, such as Seal Beach Pier, which had an impermeable groin added to the base in 1959 (see Figure 5A) (Wiegel 1994). Seventy-nine different national, state, and local parks are identified as lying inshore of these structures, potentially in areas that may be shaped by their influence.

The full content of the catalog, with extended descriptions of each attribute, is available for use online in the California Department of Boating and Waterway's geodatabase.

### ESTIMATE OF ARTIFICIALLY RETAINED BEACH AREA

Sandy beaches are highly dynamic geomorphic features, making it difficult to quantify the component of human induced change due to engineered retention structures. Fillet beach dimensions and blocking distances have traditionally been used to estimate the retention abilities of individual littoral drift blocking structures. Everts Coastal (2002) estimated the beach retention effectiveness of structures in southern California using visual assessments of fillet beach shape from aerial photos. This method accurately identifies the fillet area and is a good measure for evaluating the degree to which structures are effective at capturing sand.

Our preliminary investigation of beaches in the proximity of California coastal structures revealed that merely reporting the area of a salient or fillet beach will not fully account for the total change in beach area. The fillet or salient is the result of a structure's ability to "detain" sand moving alongshore. The amount of "retained" sand, however, is a combination of the sand in the fillet or salient *and* the buffered sandy beach area behind these trapped accumulations. Because the construction of many structures in California coincided with extensive artificial beach widening throughout the state, very large areas of beach have been retained with the shoreline position stabilized well seaward of where it was historically. An example of the discrepancy between the fillet area and the total retained area based on historic shoreline position is shown in Figure 3.

To quantitatively evaluate total sand retention in the state, we first independently replicated the visible fillet measurements for structures along the entire state's shoreline and found 1.65 million $m^2$ of sandy beach; a total area in strong agreement with the 1.5 million $m^2$ of retained sand in southern California that was reported by Everts Coastal in 2002. In order to take into account total changes in beach area that are not visibly apparent as fillets and salients in modern aerial photos, we used historic shoreline positions obtained from work by Hapke *et al.* (2006), as shown in Figure 3. Retained area is reported as both a numerical and categorical value within the catalog (see Table 1). Categorical values are assigned to enable easy comparison between structures. The five categorical values are exponential in size, as seen in Table 2, and account for the full range of retained beach areas observed throughout California.

The final revised estimate of retained sand in California based on historical shoreline positions is 15±1 million $m^2$. That translates to 18% of the total exposed sandy beach area in California today (USDA 2008). These results suggest that significant portions of California's sandy beaches are currently in their present form due to the effects of various types of engineered structures, whether or not this was the initial intended purpose of each structure.

## STATISTICAL ANALYSIS

### Two-Sample Bootstrapping

To isolate patterns in the characteristics of engineered structures that favor the retention of large areas of sandy beach, we conducted a statistical analysis of the numerical structure attributes in our catalog. Our approach was to examine the collective pool of 211 existing structures within California, and to identify statistically significant differences between structures that are successful at retaining sandy beaches and those that are not. In order to accomplish this, structures which act as full littoral barriers (impermeable) had to be separated from those that act to reduce incident wave energy (permeable) because the mechanics of how they retain sand are fundamentally different (see Everts Coastal 2002). To simplify the analysis, detached breakwaters and structures within harbors were removed. For paired jetty structures, only the numerical characteristics of the jetty that retained a larger volume of sand were included

While previous studies have defined a metric of retention success based on the size of the visible fillet, this study used the total retained area based on pre-structure shoreline positions to split the structures into two groups; effective and ineffective. Full littoral barriers tend to retain more sand, so a higher threshold was used to define successful retention for these types of structures. For this study, effective sediment retention for impermeable structures is the presence of a retained area "Large" or greater (see Table 2); 59 structures are effective by this measure and 112 are ineffective. For permeable structures, success is defined as those that have a retained "Medium" or greater; totals for these groups were 13 effective and 29 ineffective.

Bootstrapping is a resampling strategy, underlain by the assumption that a population is independent and identically distributed and that your sample is representative of the total population. This type of analysis is commonly used when sampling design does not allow for use of traditional parametric techniques (Chernick 2008). As a nonparametric technique, the criteria that must be met to perform more traditional hypothesis testing can be relaxed in regard to the need for large sample sizes and normally distributed data (Davison 1997). This type of analysis is ideal for this data set because we are limited in sampling a full range of possible structures by the number, extent, and configuration of existing structures along the state's coastline.

A two-sample bootstrap approach compares the means of two populations, to test if they are significantly different from one another. A statistically significant difference between the effective ($x_1$) and ineffective ($x_2$) structure populations for any given numerical parameter reveals an attribute that can be correlated to the sand retention capacity of these structures in California. A two-sample bootstrap test was performed on each set of numerical attributes for both the impermeable and permeable structures, after the methods described by Splitstone and Ginevan (2004). The steps involved in each of these analyses are shown below:

1. $x_1$ & $x_2$ are independently resampled 10,000 times, with replacement.

2. For each resample, a mean value is calculated yielding a bootstrapped sample mean for both populations: $\bar{x}_1b$ & $\bar{x}_2b$.

3. The difference in calculated means ($\bar{x}_1b$ - $\bar{x}_2b$), or $\bar{x}_{diff}$,) is a bootstrapped distribution for $\mu_1 - \mu_2$, the difference in the underlying population means.

4. If zero is NOT within the 95% confidence interval on the histogram of the 10,000 $\bar{x}_{diff}$ values, then the actual difference between $\mu_1$ & $\mu_2$ is significantly different than zero.

The null hypothesis for this test is that the attribute being tested is not correlated to the retention effectiveness. If this null hypothesis is true then the resulting histogram group should be centered on zero. If the null hypothesis is false, the center of the histogram will be offset or significantly different than zero. In this latter case we can say with 95% confidence that, for the range of structures currently present within California, there is a significant difference in the measured attribute between structures that are successful in retaining beach sand and those that are not.

### Statistical Results

The resulting histograms from the two-sample bootstrapping analysis are presented in Figure 4 for five of the numerical structure attributes. Statistically significant differences between the effective and ineffective retention structures were found in impermeable blocking distances (subplot a), impermeable shoreline

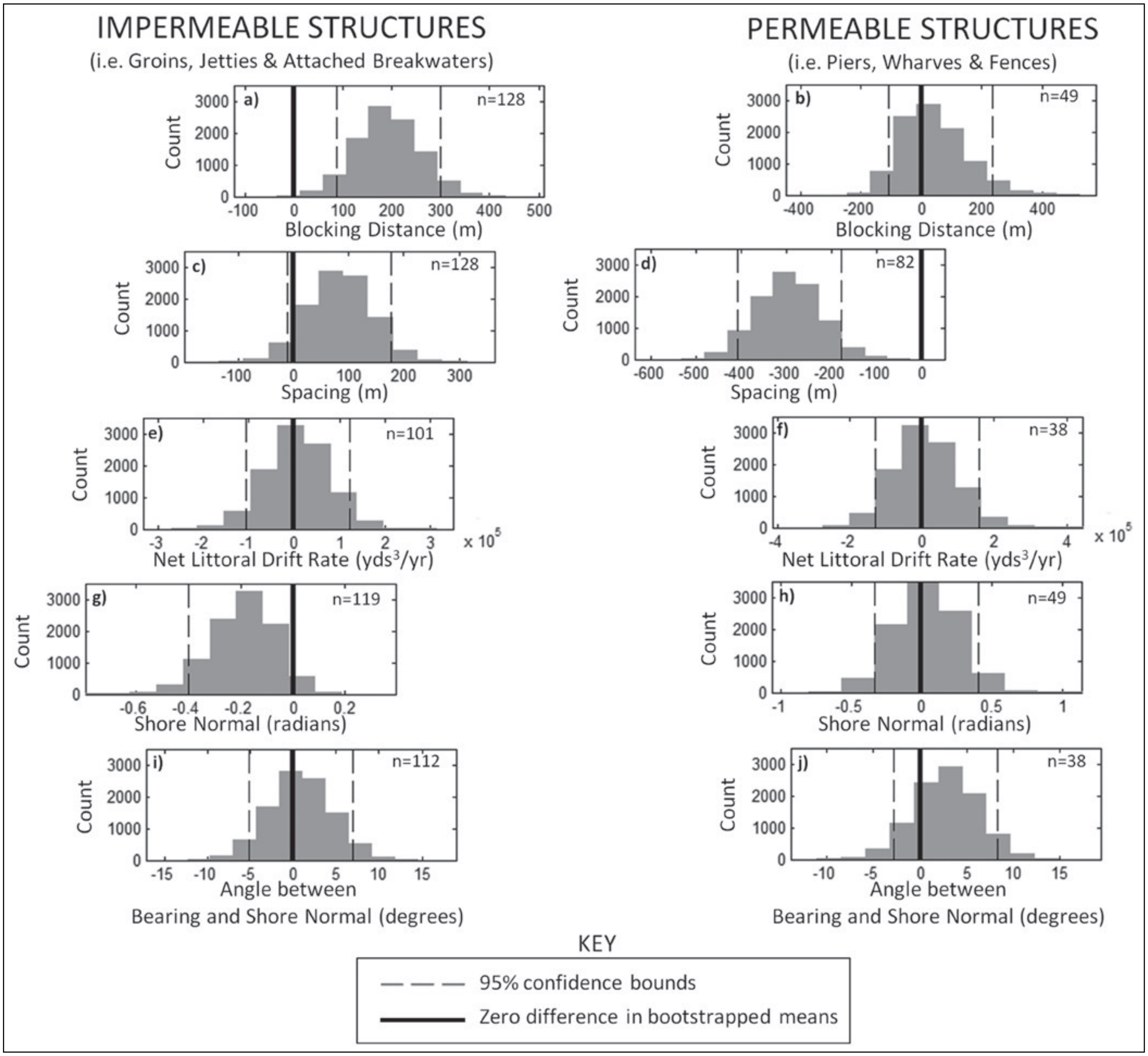

**Figure 4. Each graph is a bootstrapped distribution of mean differences between effective and ineffective retention structures for six different numerical attributes. The measured attribute is statistically similar between the effective structure population and ineffective structure population when the zero difference line falls within the confidence interval.**

orientations (subplot g) and the spacing between permeable structures and the nearest adjacent structure (subplot d). Of all the numerical attributes tested, the only attribute found to be significant for permeable structures is the structure spacing. Subplot d illustrates that permeable structures in California that retain salient beaches are, on average, 300 meters closer to adjacent structures than those that are ineffective at retaining an artificial beach.

For impermeable structures, the results of the two-sample bootstrapping test reveal two attributes that correlate to the ability of structures to retain large, seasonally persistent beaches. The first is the blocking distance of the structure, shown in subplot a. Impermeable structures that retain fillet beaches in California have a blocking distance approximately 200 meters greater than the average blocking distance of structures that do not retain a fillet beach. The second observed parameter that correlates with structure success is the average shoreline orientation, as measured by the shore normal. Impermeable structures that retain a large beach are more likely to be positioned on shorelines that face more southerly directions (by 11 compass degrees, on average).

Contrary to expected results and previous studies, mean net littoral drift rates are not observed to be higher at structures that successfully retain beaches (see subplots e & f). The angle between the shoreline and the structure bearing is also not shown to be significantly correlated to the retentive success of structures in this analysis (see subplots i & j).

## DISCUSSION

### Influence of Retention Structures

As California undergoes a long-term reduction in sand supply from rivers, an increase in coastal armoring, and an increase in the severity and frequency of winter storms (Storlazzi and Griggs

2000), one would expect a corresponding reduction in the size of coastal beaches. Contrary to this hypothesis, numerous shoreline change studies report that a majority of California's shorelines are either accretionary or stable (e.g. Kandib and Ryan 1989; Orme *et al.* 2010). Based on the findings of this study, the widespread use of coastal retention structures, especially in southern California, may serve as a partial explanation for this discrepancy. The historic addition of large volumes of sand from a variety of sources throughout southern California's littoral cells is another significant factor in this trend (Patsch and Griggs 2007; Grandy and Griggs 2009).

The historical context in which most of the structures in California were built is characterized by artificially widened beaches and inflated coastal sand budgets fed by the dredging of existing harbors and the development of new marinas and coastal waterways. This history of California's beaches is well explained by Wiegel (1994) and others and the role that retention structures have had in stabilizing these wide beaches has been alluded to (Griggs 2004). We were able to use historic shoreline positions to quantify beach retention at locations where structures have maintained shorelines seaward of their historic position. The idea that these structures, and the small fillet and salient beaches associated with them, are capable of anchoring and buffering larger areas of the backbeach from erosion is not new (Kraus *et al.* 1994), but the extent to which this is occurring on California's beaches may be a unique result of the timing of structure construction.

This calls into question whether or not retention structures in California can be judged by the same metrics of long-term success as structures in other locations. Typically, once groins and other erosion control structures are built and backfilled, their success is judged by their ability to continue trapping additional sand to maintain a large fillet or salient beach. This is a logical metric when a structure is built on a retreating shoreline. However, the structures built in California around the 1960s were commonly built on artificially widened beaches. Few of these structures are truly successful at trapping large amounts of littoral drift year-round or at substantially widening beaches post-construction, but they have been very effective at anchoring and stabilizing the widened beaches that they were constructed on, even amidst a continued decline in passive beach nourishment since the 1960s (Flick 1993).

Key to a full understanding of the importance of these stabilized beaches is recognition that 18% of the total beach area in California is currently stabilized by the presence of manmade structures. Without these structures, many economically important beaches in southern California could be much narrower than they are presently. Figure 5B illustrates what Seal Beach would look like today if the shoreline position was rolled back to where it was prior to artificial nourishment and the subsequent construction of the groin under the pier in 1959. While this dramatic depiction cannot be proven as an alternative outcome for the beach, there is little explanation other than the presence of the groin for why small-scale nourishment projects in a declining overall sediment budget would be able to maintain a beach so much wider than the beach was historically.

Anthropogenic structures have stabilized extensive stretches of sandy beach in California, but this coastal protection approach is not without drawbacks. The most common negative effects of structures that we observed were downdrift erosion, waterway sedimentation/infilling (see Figure 2, south of Mission Bay) and effects on recreation. Downdrift erosion is more commonly observed in historic images taken before fillet accumulation and prior to shoreline equilibration. Downdrift erosion can be easily mitigated if appropriate back-filling is incorporated in the construction phase. Equilibration is not able to occur if barriers protect a maintained waterway where sand must be regularly dredged/bypassed around the waterway to avoid infilling and sediment starvation downcoast. Due to local sediment budgets or the nearshore wave climate, there are many structures that are not effective at retaining sand at all.

For all of these reasons, retention structures are not the answer everywhere. With careful consideration of the local physical setting, by employing regional sediment management, and by considering the long-term costs of maintenance and necessary sediment bypassing, the prudent use of these structures could be beneficial in many areas.

## Attributes of Effective Retention Structures

Accompanying the possible use of sand retention options to compliment sediment nourishment projects are numerous questions about site selection and appropriate structure design. To help answer some of these questions we point to the statistical analysis of existing structures within the state.

Overall, very few of the numerical attributes showed any statistically significant correlation to retention effectiveness. This is partially due to how the line between effective and less effective structures was drawn, but it also highlights the wide range of structure shapes and settings that are present along the state's coastline. Greater blocking distances have been experimentally shown to trap larger beaches when positioned in the same conditions as shorter structures (Kraus *et al.* 1994) and this relationship holds true for the population of impermeable retention structures in California. The relationship between a structure's bearing relative to the coast and the retention effectiveness is also well documented, but this relationship did not manifest itself as significant in the presented data. This is likely a result of the vast majority of structures in California being constructed about 90° to the shoreline and not evidence that this angle is not important.

The lack of significant statistical correlation between net littoral drift rate and sediment retention is unexpected, but it builds on arguments presented previously that structures along the state's coast have entered into equilibrium with littoral drift rates and that sediment retention in California is not directly linked to a structure's ability to trap large quantities of new sand from littoral drift. On a decadal timescale, structures included within this study retained sandy beaches in a wide range of net longshore sediment transport rates. The significance of shoreline orientation has been highlighted by other California based studies of sand retention, and the observation that structures on more southerly oriented beaches are more prone to retain large volumes of sand could be a useful consideration in the initial planning of future nourishment projects.

A significant finding of this study was that impermeable structures were

**Figure 5. (A) Oblique aerial image of Seal Beach in Orange County, California (Adelman and Adelman 2009). (B) Seal Beach today, shown with the 1932 shoreline position prior to artificial nourishment and the later construction of the groin under the pier in 1959 (Wiegel 1994). This area is characterized by net littoral drift to the north (Patsch and Griggs 2007). The site was regularly nourished with ~250,000 yd$^3$ of sand every 1-2 years from 1950-1970, and again several times in the 1980s (Coyne 2000). This is an example of how existing structures such as wharves and piers could be modified to play a larger role in future nourishment efforts.**

more likely to retain sand when they are located near an adjacent structure. This is probably a result of compounded changes in nearshore wave climate on coastal stretches that have multiple structures present. Future work needs to be done to address the effects of wave climate in regards to the behavior of both permeable and impermeable retention structures on California beaches because shoreline orientation alone does not serve as a complete proxy for these effects.

## CONCLUSIONS

We have assembled the first California-wide inventory of coastal structures that have the potential to retain sandy beaches, including nontraditional structures that are present in the littoral zone such as piers, fences and outfall pipes. This inventory includes 211 structures and contains useful information about each structure's form, function and setting that can be used by coastal planners to recognize permutations that have shown historic success in retaining the wide sandy beaches that are so important to the state's economy and identity. This full catalog is freely available online from the California Department of Boating and Waterways. During the creation and analysis of this structure catalog several findings about the behavior of these structures have been revealed:

1) Numerous structures play a role in the retention of sand on California's beaches; these include both structures designed to retain sand and those that do so as a secondary effect. Additionally, structures designed to perform one function have the potential to be re-engineered and reexamined for incorporation into regional sediment management plans.

2) When the construction history of structures that alter littoral transport is viewed within the context of changes in the California coastal sediment regime, it appears that many of these structures were constructed along beaches that had already been widened as a result of opportunistic nourishment activity.

3) While visible fillet and salient beaches may serve as useful indicators of a structure's ability to retain sand, they do not provide the best estimate of total retained beach area. Based on modern and pre-structure shoreline positions, we found that 15 million $m^2$ of sandy beach, 18% of California's total beach area, is presently retained by structures along the coast. This area is an order of magnitude higher than when it is estimated from visibly retained areas alone.

Shoreline orientation and blocking distance are the most important factors contributing to sand retention success based on the impermeable structures present along California's shoreline today. Permeable structures that are located closer to adjacent structures are more effective at retaining salient beaches. The commonly reported guideline that high net littoral drift rates are required for sediment retention structures to succeed may be misleading in areas where the structures have equilibrated with the coast.

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