IMPACT OF SAND RETENTION STRUCTURES ON SOUTHERN AND CENTRAL CALIFORNIA BEACHES

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EXECUTIVE SUMMARY

Seventy percent of all sandy beaches along the open ocean coast between Morro Bay and the California-Mexico border are retained by structures. They function to maintain a sandy shoreline by changing wave heights and directions and thus the rate at which sand moves along the coast, and/or they alter the sand transport path. Their dimensions, orientation, and location control the configuration and position of the beaches they retain. The great majority of structure-retained beaches owe their existence to rocky headlands, stream and river deltas, reefs, and near-coast submarine canyons. Less numerous artificial structures like groins, jetties, and breakwaters have had mixed success in retaining sandy beaches. Results of a reconnaissance-level investigation of prototype structures help identify conditions favorable to a successful project and flag potential problems. They may also assist in understanding the causes of beach change associated with existing artificial structures. Sandy beach responses in different environments were defined using mapping quality aerial photographs and topographic maps.

Beach retention structures are unevenly distributed. Most are between Morro Bay and Marina del Rey, and between Newport Beach and San Clemente. Not surprisingly, they are especially numerous where mountains or high hills border the coast. In contrast, the comparatively low-lying coast between San Clemente and La Jolla is remarkable for its paucity of these structures. This reach alone accounts for almost half of the 180 km of southern and central California coast not substantially affected by them. Fillet beaches, salients, perimeter beaches, beaches within hook-shaped bays, and beaches in pocket bays, differ in shape, environment, and type of retaining structure. In all cases, however, their sizes tend to be proportional to the dimensions of the structures that retain them.

Fillet beaches are retained on the upcoast side of headlands, groins, shore-connected breakwaters, and a salient in the lee of the Santa Monica breakwater. Fillet shorelines are typically straight and widest against the structure. Fillet beaches are usually triangular in planform. They can only exist where there is a substantial net longshore sand transport rate. In total, they comprise slightly less than 5% of all structure-retained beaches. Half are retained by rocky headlands. The remainder are mostly held by 17 groins that retain over 140 hectares (350 acres) of sandy beach. Fillet width is the best single measure of the size of a fillet beach. Fillet width is the difference between the distance the structure extends beyond the original shoreline and its blocking distance. This distance, between the end of a structure and the fillet shoreline, is therefore a gauge its effectiveness. A small blocking distance implies a relatively short structure will effectively retain a fillet; a large blocking distance indicates a long structure is required to be effective. An empirical relationship between structure blocking distance and the orientation of the local shoreline explains why some groins are effective and others fail to retain a permanent fillet beach. In southern and central California, the most effective structures are located where the coast is oriented between 240 and 310 degrees, and there is a substantial net longshore sand transport rate. In this environment, typified by most of the coast between Point Conception and Santa Monica, the blocking distance is about 35 m referenced to the wetted-bound

shoreline, and near zero if referenced to mean lower low water. All of the more effective groins, including those at Will Rogers State Beach west of Santa Monica, on US Navy property at Point Mugu, and at Ventura, tend to retain substantial fillets because the blocking distance is comparatively small. Wetted-bound blocking distances progressively increase to over 150 m as the shoreline bearing changes from 310 to 360 degrees. Groins have been unsuccessful along the north-south coast of Imperial Beach because the blocking distance exceeds the length of the structures. On the other hand, groins at West Newport and Ocean Beach are ineffective because they were constructed in a near-zero net longshore sand transport environment. In total, 15 southern California groins fail to retain a permanent fillet beach because they are shorter than the needed blocking distance or because the net longshore sand transport rate is low or zero.

Salient beaches are retained in the lee of shore-parallel detached breakwaters. Salients are shoreline bulges that do not extend as far as the offshore structure. Six detached breakwaters have the potential to retain salients, yet the only mature salients are at Venice and Santa Monica. Of the remainder, the Marina del Rey breakwater is not backed by a sandy beach, salients at Channel Islands and Ventura Harbors are systematically dredged, and because a sediment source is lacking, a mature salient has failed to develop in the lee of the long breakwater that protects Los Angeles and Long Beach Harbors. The Venice breakwater has retained its salient for almost a century. When Venice Beach was artificially widened in 1948, the salient lost some of its area due to a reduction in the distance between the breakwater and the shoreline on either side of the salient. The Santa Monica breakwater has retained its salient since 1934. It also lost area when the nearby beach was widened and the breakwater crest was damaged by waves. Salient beaches are retained in all longshore transport environments.

Perimeter beaches are retained in the lee of rocky stream deltas, submerged or partly submerged reefs, and near-coast submarine canyons. Eight shallow submarine canyons retain 36 km of perimeter beach, or 6% of all sandy beaches. Seven of the eight canyons control the position and shape of the adjacent shoreline. Four canyon-retained shorelines are embayments, landward of where they would be if the canyons were not there. Four are shoreline protrusions. Embayments form where the canyon rims are landward of a straight-line projection of the local shoreline. Shorelines protrude where the rims are seaward of that line. Seven of the eight canyons capture littoral sand and thus regulate the supply reaching downcoast beaches. Each of them has a critical infilling volume. The reason they never lose their trapping capacity is that once the critical volume is reached the captured sand is flushed into deeper water, usually during a storm. Canyons with rims landward of the regional trend capture almost all of the net alongshore-moving sand that reaches them; canyons with rims seaward of that line capture very little sand. An understanding of this simple relationship and its implications provides constraints on how a beach might be artificially widened in the lee of a canyon and how its capture rate might be reduced. Water depth at the canyon rim, or the distance from the shoreline to the canyon rim, are not primary factors in the capture rate.

Twenty-two river and stream deltas retain 33 km of perimeter beach, or slightly less than 6% of all sandy beaches. Many of them also transform ordinary waves into desirable peaks

for surf riding. Delta-retained beaches are narrow bands of sand around seaward bulges in the coast. Because deltas project above the surrounding shoreface and extend all the way to the coast, the beaches they retain generally start above mean lower low water and end at +3 or +4 m. The seabed below mllw is typically composed of cobbles and small boulders. Perimeter beaches are retained by deltas in all longshore sediment transport environments. On average, for every meter the delta-retained bulges extend along the coast they project a fifth of a meter seaward.

Thirty-four natural reefs retain 28 km of perimeter beach and 5% of all sandy beaches. Like delta-controlled beaches, reefs retain beaches around bulges in the general trend of the coast, and for every meter those bulges extend along the coast they project a fifth of a meter seaward. Unlike delta-retained beaches, perimeter beaches in the lee of reefs usually extend offshore, often as far as the reef. Sand Point reef just west of Carpinteria is the most effective structure in this category. It retains a 2.3-km long protruding sandy barrier beach that in turn protects the large wetland "El Estero". An interruption in its sand supply occurred after Santa Barbara Harbor was constructed. Although the net longshore flow of sand was later restored with artificial bypassing, the apex of the shoreline never recovered. Apparently when the distance between the reef and the shoreline increased due to erosion, the sand retaining capacity of the reef was lessened. Sea level rise may also be a contributing factor. Reefs retain perimeter beaches in all longshore sediment transport environments.

Fifty-one hook-shaped bays retain 60% of all structure-retained beaches, and 41% of all sandy beaches in central and southern California. Bays bounded by natural structures like rocky headlands, reefs, or stream deltas retain many of the most stable beaches in the area, some over 20-km long. Structures that retain hook-shaped bays are almost always of different size. Those on the north or west ends - the diffraction structures - are largest. They block and diffract waves and are responsible for the curved or hooked portion of the bay. Structures that anchor these bays are responsible for a straight shoreline at their south or east ends. An anchor structure is any feature, including stream deltas, reefs, and rocky headlands, that fixes the position of the downcoast end of a hooked bay. A useful peculiarity of these bays is the fact that alterations in the retaining structures or the sand supply are manifest by a shoreline adjustment throughout the sandy portion of the bay. This means their sand resource can be effectually managed as a unit.

All hook-shaped bays exist in the same environmental context. First, the region downcoast of the diffraction structures is susceptible to erosion. Hook-shaped bays do not form where resistant rock prevents it. Second, the angle between the predominant wave approach direction and a line connecting the diffraction and anchor structures - the control line - is always toward the anchor structure. The alongshore component of energy flux is not so constrained along the shorelines of the bays. Net longshore sand transport is variably toward the diffraction structure, toward the anchor structure, and in both directions away from sand sources like rivers within the bays. Third, diffraction structures are sufficiently high and long that they diffract waves and block a significant portion of the wave energy that approaches from the predominant upcoast direction. Wave blocking and diffraction are responsible for the hook shape. Fourth, anchor structures do not retain a fillet beach,

salient beach, or perimeter beach as far upcoast as the diffraction structures. Spacing is important. If a fillet beach extended to the diffraction structure the bay shoreline would be straight, not hook-shaped.

Sixty-one pocket bays occupy less than 8% of the coast, but like hook-shaped bays they contain some of the most stable beaches south of Point Estero. Laguna Beach typifies a natural pocket bay coast. Bordered by high hills, it is fringed with natural bays retrained between rocky headlands. Its beaches range in shape from nearly straight, but still slightly indented in the center, to notably concave. Crescent Bay was named for the latter planform. Artificial structures retain six popular urban pocket bays; Ocean Beach in San Diego, Big Corona Beach in Newport Beach, East and West Beaches in Seal Beach, Cabrillo Beach in San Pedro, and Redondo Beach. Blocking the alongshore movement of sediment to prevent it from escaping is the primary function of structures that retain pocket bays. Like hooked bays, pocket bays are recognizable by certain attributes. First, the net longshore sand transport rate is zero or very near zero within and adjacent to pocket bays. Second, their shorelines are near symmetrical. If there is a straight segment it will be near the center of the bay. Third, pocket beaches tend to be short – the average is 690 m (versus 4700 m for hook-shaped bays). Fourth, sand contributions and losses tend to be small. In most, the sand resource is conservative, accounting for their stability. Fifth, structures that retain pocket beaches tend to project similar distances seaward of the general trend of the coast. Last, and importantly, adjacent beaches are generally not affected by the bay retaining structures.

While one cannot state absolutely that a structure will only be beneficial, it is obvious that some structures have a greater potential to produce negative impacts than others. One cannot attribute benefits or assign adverse impacts to natural structures because they evolved long before their performance was monitored. This is not the case for artificial structures. Excepting temporary sand denial impacts, adverse impacts were not found for detached breakwaters that retain a salient, and groins, jetties, and shore-connected breakwaters that retain pocket beaches. Based on the function of prototype reefs and stream deltas, it is unlikely an artificial reef would adversely impact a downcoast beach. Detached breakwaters, reefs, and deltas retain shoreline bulges in finite net alongshore sand transport environments. Since the shorelines do not extend to the structure, sand that moves along the coast apparently follows the coastal planform. It is not deflected seaward, nor blocked. Pocket beaches are retained in zero net transport environments where downcoast impacts are minimal.

Three situations have caused most of the erosional impacts associated with artificial structures; sand denial, attachment of some harbor breakwaters to the diffraction headland of a large hook-shaped bay, and the creation of a new hook-shaped bay downcoast of a groin, jetty, or shore-connected breakwater. Sand denial occurs when a structure-retained beach is allowed to develop with sediment from the littoral system. Venice Beach is an example. It was denied sand and it eroded for 25 years as the beach grew in the lee of and upcoast of the Santa Monica breakwater. The problem ended in the 1960's for a combination of reasons. As the beach retained by the Santa Monica breakwater matured and captured less sand, the supply to Venice Beach increased. At the

same time Marina del Rey was completed and its entrance structures functioned to retain sand at Venice Beach. The two entrance jetties and detached breakwater, however, are now creating a new case of sand denial. Sand impoundment at Venice is affecting Playa del Rey. The beginning creation of a new hooked bay has been avoided only by the placement of huge volumes of opportunistic beachfill along that stretch of coast. The sand denial impact is easy to forecast and remedy: Allow no structure-retained beach to accrete with sand from the littoral zone and bypass sand whenever a structure inhibits its downcoast movement.

Sand transport regimes within hook-shaped bays have responded in a consistant way to harbor breakwaters at Dana Point, Point Fermin (the Los Angeles - Long Beach Harbor complex), and Point San Luis, and to the construction of Zuniga Jetty at the entrance to San Diego Harbor. In all four instances sand transport rates increased toward the "new" diffraction structure. Erosion or, at best, no change was the response near the anchor ends of the affected bays. Each of the bays rotated slightly counterclockwise. Beach and harbor impacts have been both beneficial and adverse. The shoreline advance downcoast of Dana Point, for example, was greatest near the harbor. While it progressively declined toward the anchor structure, erosion was not evident even there when shorelines were compared through the 1980's. Sediment transport directions reversed near Port San Luis after its breakwater was built. The harbor is now experiencing sedimentation problems at launch sites and in mooring areas, and some fishing platforms have been rendered useless. Further downcoast, the shoreline in the Pismo Dunes area advanced while it retreated near Mussel Point, the anchor structure.

A more inflexible problem is the initiation of a new hook-shaped bay downcoast of a groin, jetty, or shore-connected breakwater. Natural hooked bays provide huge benefits in the form of comparatively stable beaches. In contrast, when a new hooked bay evolves downcoast of an artificial structure in the same environmental context as hooked bays exist in nature, it is at the expense of the downcoast beach and property behind it. Even though new hooked bays have not been allowed to evolve beyond their very beginnings, some of the most damaging erosion can be attributed to this cause. Responses, for instance, have been the construction of a revetment downcoast of the Navy groins at Point Mugu and sand bypassing on a scheduled basis at Santa Barbara, Ventura, Port Hueneme, and Oceanside. A large artificial beachfill and the construction of a groin created a stable pocket bay and arrested the development of a hooked bay downcoast of King Harbor.

Sea level rise is a natural intervention that is affecting the retention qualities of all low and submerged structures to the detriment of the beaches they retain. As the water depth over river and stream deltas, reefs, and the low breakwater at Santa Monica increases there is a corresponding increase in the amount of wave energy that reaches the coast. Retention effectiveness is thus compromised. Shoreline retreat at south Imperial Beach, for example, is probably caused by the combined effects of sea level rise relative to the surface of the Tijuana River delta, a reduced discharge in the river, and a counterclockwise rotation of the hook-shaped bay to the north. Sand Point reef near Carpinteria may also be losing some of its retention function due to a loss of freeboard in response to a rising sea surface.

Structures along the central and southern California coast clearly affect the beaches. An understanding of how each type of structure functions and in which conditions they thrive and create problems will aid in the evaluation of future beach stabilization schemes.

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IMPACT OF SAND RETENTION STRUCTURES ON SOUTHERN AND CENTRAL CALIFORNIA BEACHES

1.0 INTRODUCTION

A beach retention structure is any feature - natural or artificial - that maintains a sandy shoreline because of the way it affects incident waves and/or the way it alters the path in which sand moves along the coast. The dimensions, orientation, and location of these structures control the configuration and a position of the beaches they retain. Structure-retrained shorelines may be either seaward or landward of where they would be if the structures were not there.

This report describes the findings of reconnaissance-level investigation to quantify the response of sandy beaches to the presence of retention structures in different littoral environments between Morro Bay and the Mexican border in California. Results are based on plan-view measurements made using mapping quality aerial photographs and topographic maps. Shoreline position maps, where available, were used to describe the evolution of beaches retained by artificial structures. Study objectives were to: (1) quantify and catalogue positive impacts of beach retention structures, (2) quantify the geometric characteristics of structure-retained beaches, (3) quantify adverse impacts of beach retention structures, (4) determine where retention-like structures are adversely affecting nearby or distant beaches, (5) determine where retention structures are ineffective because they are not retaining beaches commensurate with their size, (6) develop qualitative relationships that can be used to make project development and policy decisions, and (7) incorporate the measurement data into tables.

The basic study product is the seventh objective: a compilation of structure and beach data, including the size and shape of structure-enlarged and structure-impacted beaches, the dimensions and other characteristics of the retaining structures, and the environmental conditions in their vicinity. These data are presented in the appendix in a series of spreadsheets for different kinds of structure-retained beach, plus a spreadsheet listing all of the artificial structures that affect beaches in the study area. A background section follows this introduction. Next are five sections dealing with the performance of different kinds of structure-retained beaches, a results section that focuses on the pros and cons of artificial beach retention structures, and a summary and conclusions section. Figures are used extensively to illustrate findings.

2.0 BACKGROUND

Natural structures like rocky headlands, offshore reefs, cobble and boulder stream deltas, and submarine canyons, and artificial retention structures like groins, jetties, and breakwaters, retain a majority of sandy beaches in central and southern California. Headland is a general term used to describe shore-normal, shore-connected, naturally occurring features that rise above the sea surface and stick out from the coast. Human interventions have affected the performance of some of the larger headlands. By extending the Port San Luis breakwater out from Point San Luis, for example, its function was changed. Beaches became wider near Pismo Beach, and narrower toward the mouth of the Santa Maria River. Sand began moving in a different direction near Port San Luis too. Some now ends up unwanted in boat launch sites and mooring areas at the port. Beaches have similarly benefited and been adversely impacted when artificial structures were located outside the influence of natural structures.

Negative impacts are of special interest. Wider sandy beaches have been retained on one side of some groins, jetties, and breakwaters, while there was erosion on the other side. Three groins built by the Navy in the 1960's serve to illustrate. These structures functioned well to retain an upcoast fillet beach, but it was necessary to build a revetment downcoast of the last structure to prevent an embayment from forming at the expense of land behind the beach. Upcoast refers to the direction from which the majority of the sand is transported as it moves parallel to the coast; downcoast refers to the direction toward which it is transported. A number of groins, such as those at Imperial Beach and West Newport, have not been successful in retaining a wider beach than would exist in their absence. Due to this mixed achievement public perception of these structures tends to be negative, an opinion not wholly unwarranted. Even today, stated objectives including the goal of no adverse effects are not always attained.

Beaches can be classified according to the type of structure responsible for retaining them, or according to the plan configuration and other characteristics of the retained beach. Substantial crossover, and the fact that no single system serves to isolate all of the significant characteristics of both retaining structure and retained beach, makes classification difficult. Grouping is important, though, to understand cause and response linkages and develop relationships based on statistically significant populations of prototype features. The approach taken in this investigation is to focus on the retained beaches and classify them in the context of their planform characteristics.

2.1 Structure-Retained Beaches

By definition, a beach retention structure retains the adjacent shoreline at a specific location relative to the position, orientation, and dimensions of the structure. As long as the sediment supply, wave climate, mean elevation of the sea surface, and structure dimensions, remain constant, the structure-impacted shoreline will fluctuate about a fixed position. That position, once the shoreline has stabilized, may be seaward or landward of where it would be if the structure were not there. The kinds of beaches retained by structures are summarized in Table 1. Hook-shaped and pocket beaches require a pair of structures to retain them. Fillet beaches, salients, and perimeter beaches, are retained by a single structure. Figures 1-5 illustrate the kinds of structure-retained beach.

Table 1. Kinds of beaches retained by structures.

Kind of beach	Structure type	Beach location	Some California examples
Fillet Beaches (Figure 1)	Sediment-blocking: rocky headlands, groins, jetties, shore-connected breakwaters, tombolos in the lee of detached breakwaters (none in CA)	Upcoast of structure	Point Mugu (headland), Ventura (groins), King Harbor (shore-connected breakwater)
Salients (Figure 2)	Detached wave-blocking and diffraction: two-dimensional reefs, detached breakwaters	In lee of structure	Santa Monica and Venice detached breakwaters)
Perimeter Beaches (Figure 3)	Wave refraction: three-dimensional reefs, rocky stream deltas, submarine canyons, other non-shore-parallel bathymetry	In lee of structure	Malibu, Topanga, and San Mateo Creeks (rocky stream deltas), Sand Point reef, Newport and Scripps Submarine Canyons
Beaches in Hook-shaped Bays (Figure 4)	Diffraction Structure (shore-connected, wave-blocking and diffraction): rocky headlands, groins, jetties, shore-connected breakwaters Anchor Structure (commonly sediment-blocking): rocky headlands, groins, jetties, shore-connected breakwaters, one submarine canyon, reefs	Between structures	Pismo Beach: Santa Maria River Littoral Cell (Point San Luis and Mussel Point), Coronado Beach: Silver Strand (Point Loma and Tijuana River delta), most beaches in Malibu, Mission and Pacific Beaches (False Cape and north jetty at Mission Bay entrance)
Beaches in Pocket Bays (Figure 5)	Both structures commonly sediment-blocking with wave-blocking and diffraction component: rocky headlands, groins, jetties, shore-connected breakwaters	Between structures	Most beaches in Laguna Beach, Redondo Beach, (Topaz St groin and Palos Verdes Peninsula)

Figure 1. Fillet beach upcoast of a groin where Sunset Boulevard ends at the Pacific Ocean (near Santa Monica).

Figure 2. Salient in the lee of a detached breakwater at Venice.

Figure 3. Perimeter beach in the lee of the delta of Malibu Creek.

Figure 4. Beach retained in a hook-shaped bay in Malibu.

Figure 5. Cabrillo Beach, a pocket beach retained between a groin and Point Fermin (San Pedro).

Structures that retain these beaches can be conveniently grouped onto four functional categories (underlined in the second column of Table 1). Functional groupings are used instead of common names to avoid ambiguity, to simplify the discussion of these structures, and to emphasize their common role in retaining a beach. First, are those that primarily block sediment moving in a net direction along the coast. Some of these structures retain a fillet beach upcoast of their location (Fig. 1). The wave climate and sand supply establish the net longshore sediment transport rate, Q_n, and the gross longshore transport rate, Q_g. Their ratio, Q_n/Q_g, is an important determinant of the width of fillet beaches upcoast of rocky headlands, groins, jetties, and shore-connected breakwaters. The same structures also retain pocket beaches (Fig. 5), but in environments where $Q_n = 0$. Second, these same shore-connected structures often block and diffract waves and thus retain a downcoast hook-shaped bay (Fig. 4). Many natural hook-shaped bays are retained by a dominant rocky headland and a subordinate delta or reef. Beaches within them tend to be stable compared to non-structure-retained beaches. On the other hand, hooked bays sometimes develop downcoast of artificial structures at the expense of the downcoast beach and hinterland. The third category is detached wave-blocking and diffraction structures. The only example in the study area is detached breakwaters (Fig. 2) that retain a shoreline bulge or salient in their lee. If properly designed detached breakwaters do not create problems on adjoining beaches. The fourth and last category is submerged or partially submerged wave refraction structures like rocky stream deltas (Fig. 3), reefs, and submarine canyons that retain a perimeter beach in their lee.

We define structure performance by the manner in which beaches evolve adjacent to artificial structures, and by the “final” or mature beach configurations associated with natural structures. Positive and negative impacts are assigned to artificial structures based on the position of the retained beach. A positive beach response is one in which the beach, at maturity, is wider and very likely more stable than it would have been if the structure were absent. A negative response is defined as one in which the downcoast shoreline retreated after the artificial structure was built. Since natural bays matured long before Europeans first arrived in California, rocky shorelines are accepted as a natural state, especially downcoast of the headlands that retain hook-shaped bays. They are not generally considered a negative feature.

2.2 Methodology

Figure 6 is a map showing the study reach between Point Estero north of Morro Bay and the US - Mexico border. The open-coast length of the study reach is approximately 580 kilometers.

Structure and beach characteristics were measured on mapping quality aerial photographs provided by the US Army Corps of Engineers (Los Angeles District) at their photo archives in La Puente, California. Over 2000 individual photos were scanned at that location over the course of about 10 days. Measurements were made on the scanned photos using Autodesk Land Development software. USGS topographic 7.5-minute quadrangles were obtained in digitized form from the National Geographic Society (NGS TOPO! mapping software). Topographic maps were used to locate, scale and orient the aerial photos from which the measurements were made.

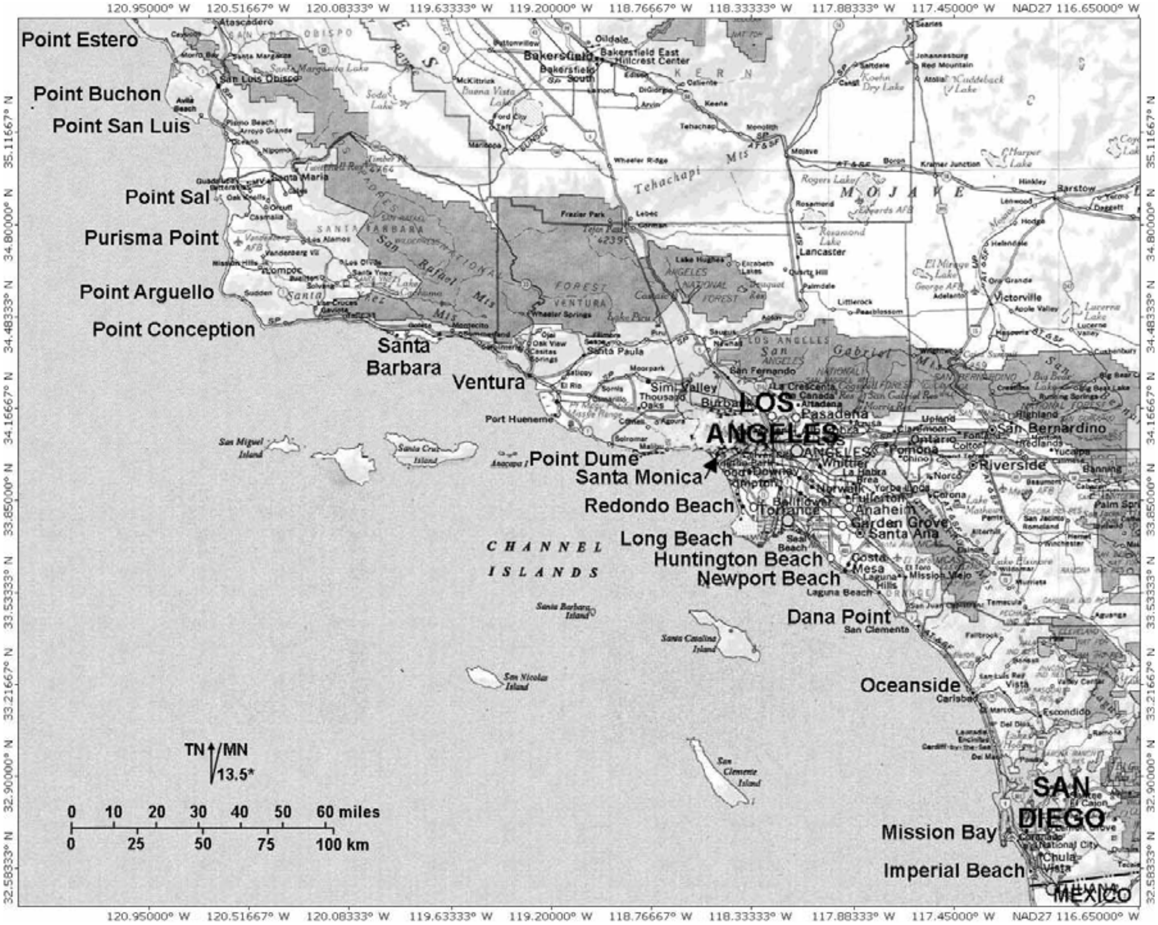


Figure 6. Location map, central and southern California coast.

Photos were selected to best typify end-of-winter and end-of-summer conditions. A selection constraint was that the photo set cover the entire study reach so spatial comparisons could be made. Only two periods of Corps of Engineers aerial photos met these criteria, one that covered the entire coast in the spring of 1987, and the other in late summer 1985.

Intuition and relationships reported in the scientific literature, coupled with a large degree of trial and error, were used to establish parameters that resulted in strong correlations between structures and beaches. In all cases the relationships have recognizable physical meaning. However, they provide only a gross picture of nature. Waves transport sand and are as responsible for the size and configuration of the structure-retained beaches as are the structures. Tidal fluctuations affect the manner in which waves move the sand. In this analysis, wave climate was only considered in a cursory way by defining the net to gross longshore sand transport rate where appropriate. Using wave data alone, the California-specific predictive methodologies included in this report could not have been made. Wave-structure-beach interactions are not yet well enough understood to do that.

In all cases shore-connected structures are located by the NAD 27 latitude and longitude of their tips (in degrees to five decimal places). The Lat/Lon of both ends locates detached breakwaters.

The apex of the shoreline bulge locates perimeter beaches in the lee of river and stream deltas and reefs. Their retaining structures are not identifiable on aerial photos. Submarine canyons are located where the rim of the canyon is closest to shore on charts.

Measurements were made using the Land Development software. In order to make them, the topographic map lat/lon were converted to eastings/northings and the image was spatially imported into Land Development. Locations in Land Development, however, are not ‘spot on’ because Topo does not rescale the image to the precise easting/northing coordinates and rubbersheeting within Land Development did not properly alter the image. Consequently, the images depicted on the topographic map within Land Development were not always geographically accurate. All locations were determined using lat/lon on Topo! so locations were as accurate as it was possible to determine them on magnified topographic maps. The error in location is estimated to be within 20-40 meters of actual. Measurements of structure and beach characteristics within Land Development are accurate to within two and sometimes three significant figures. This translates to measurement accuracy within a few meters when the structure/beach dimension is less than 100 m, and to within 100 m when the measurement is tens of kilometers.

Shorelines are the wetted-bound shorelines. An analysis made using a known depth at the ends of the US Navy groins and the Will Rogers State Beach groins (Moffatt and Nichol, Engineers, 1995) indicates the wetted bound, at least at these locations, is between 18 and 28-m landward of the mean lower low water (mllw) shoreline. The position of the mllw shoreline is probably within 5-10 m of this difference throughout the study area.

The next five chapters deal with the performance of structure-retained beaches. Fillet beaches upcoast of sediment-blocking structures in $Q_n > 0$ environments are addressed first. Salients retained in the lee of detached breakwaters are next. Perimeter beaches retained in the lee of stream deltas, reefs and submarine canyons follow them. Beaches retained by pairs of structures come next with hook-shaped bays and the beaches they retain addressed first. Pocket beaches are last.

3.0 FILLET BEACHES

Fillet beaches are retained upcoast of rocky headlands, groins, jetties, and shore-connected breakwaters where the net longshore sediment transport rate is greater than zero. Pocket beaches, dealt with in a later section, may be retained between a pair of the same kinds of sediment-blocking structures where the net rate is zero or near zero. Fillet beaches are typically triangular in shape and widest against the structure. Lechusa Point, shown in Figure 7, is an example of a natural headland that retains a noticeable fillet beach. Artificial sediment-blocking structures are groins, jetties, and shore-connected breakwaters like those illustrated in Figures 1, 5, 8 and 9. The salient that formed in the lee the Santa Monica breakwater shown in Figure 10 is also a sediment-blocking structure. The beach upcoast of it is the most notable fillet in southern California.

Figure 7. Lechusa Point, a rocky headland that retains a fillet beach in Malibu.

Figure 8. Groins and groin-retained fillets at Will Rogers State Beach west of Santa Monica (1960's or 1970's photo).

Figure 9. Shore-connected breakwater and the upcoast fillet beach at the north side of Oceanside Harbor (1990's photo).

Figure 10. Fillet beach upcoast of the salient that formed in the lee of the Santa Monica breakwater; fillets within the Will Rogers State Beach groins at left (1970's photo).

3.1 Beach-Structure Relationships

Fillet beaches are retained where the alongshore component of wave energy flux is finite and there is a source of sand available for downcoast transport. In addition, if the structure is to retain a wider upcoast beach than would exist in its absence, it must be sufficiently impermeable, high, and long, that it is capable of blocking or impeding the movement of some or all of the sand that is transported parallel to shore.

In southern and central California, approximately 21 km of sandy beach is retained in fillets upcoast of 45 rocky headlands, groins, jetties, shore-connected breakwaters, plus the salient at Santa Monica. Table A2, a spreadsheet in Appendix A, summarizes the characteristics of these structures and the fillets they retain.

Two parameters that help define fillet-structure interactions can always be gotten – unambiguously - from aerial photographs (Fig. 11), the bearing of the fillet shoreline, α , and the structure blocking distance, Y_{bf} . The structure blocking distance is the length of wetted structure between its tip and the place where the fillet shoreline intersects it. Empirical relationships between Y_{bf} and the effective length of the structure, y_s , can be used to predict the size of the fillet beach. The effective length of an artificial structure is the shore-normal distance from the pre-project shoreline to the tip of the structure. The most important environmental variable is the known or estimated ratio of the net to gross longshore sediment transport rate. Two of three parameters define the most important geometric characteristics of the retained beach: (1) the fillet projection distance alongside the structure, Y_f , (2) the fillet angle, α_f , which is the difference in the bearing of the fillet shoreline, α , and the bearing of the shoreline as it would be if the structure were absent, and (3) the length of the fillet, X_f .

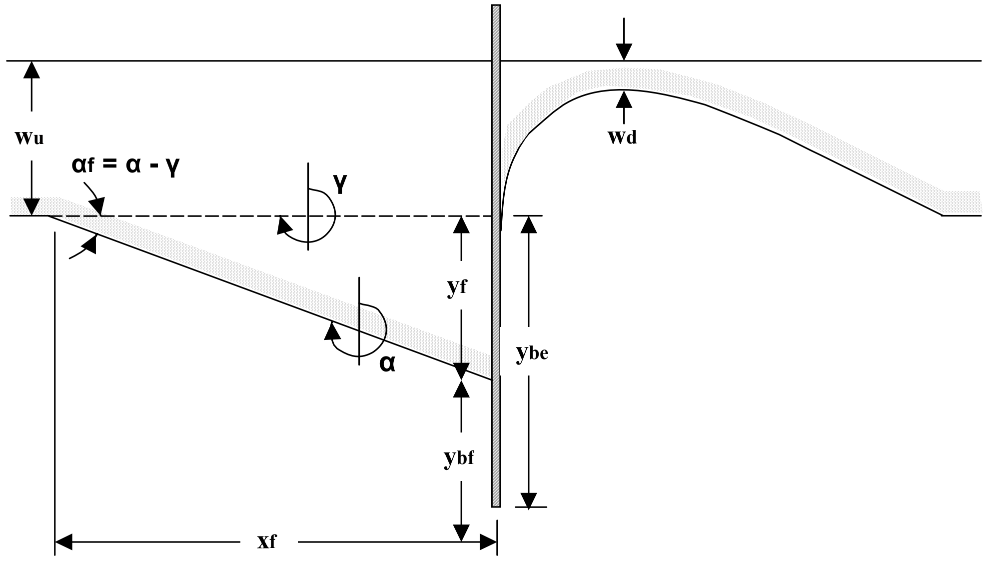
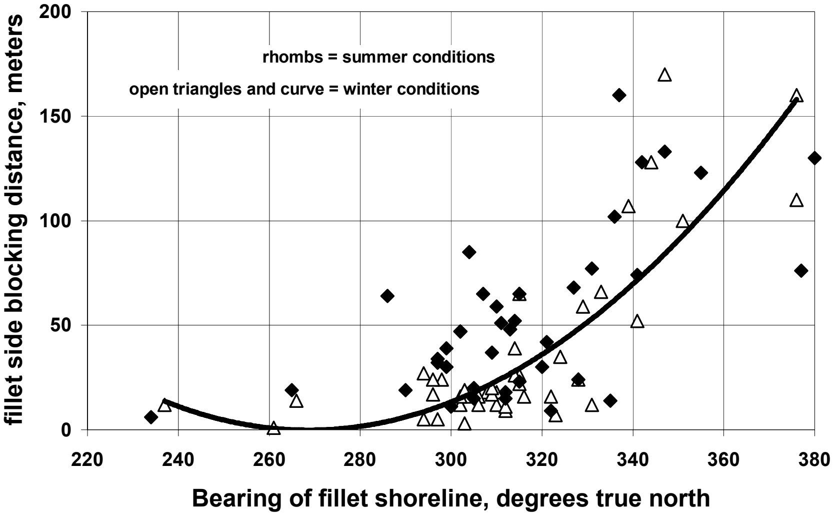


Figure 11. Definition sketch: fillet beach.

The structure blocking distance and the bearing of the fillet shoreline are related as shown in Figure 12. The correlation coefficient for the curve is 0.70. Triangles are winter blocking distances; rhombs are summer distances. The correlation between the blocking distance and the net longshore sand transport rate is 0.21, but when the blocking distance is plotted against the net to gross longshore sand transport ratio, as shown in Figure 13, it improves to 0.61. In contrast, there is more scatter in the Figure 14 plot of the fillet shoreline bearing and the net to gross ratio where the correlation coefficient is 0.43. This indicates the net to gross transport ratio is a more important control on the blocking distance than the orientation of the fillet shoreline. Although poor, the relationship between the net longshore sand transport rate and the blocking distance is also better. The wide scatter in all of these parameters, however, suggests the relationships are much more complex than those shown in Figures 12-14. Net transport rates are more accurate than net to gross ratios. The process of elimination that works well to define the net rate using sediment budget analytical techniques cannot be used to determine the net to gross ratio. We found more insight could be gained by inspecting the performance of specific artificial structures.



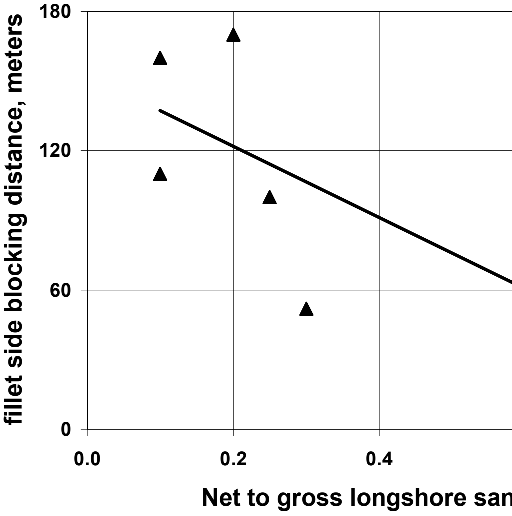


Figure 12. Structure blocking distance versus the bearing of the fillet shoreline.

Figure 13. Structure blocking distance versus the net to gross longshore sand transport ratio.

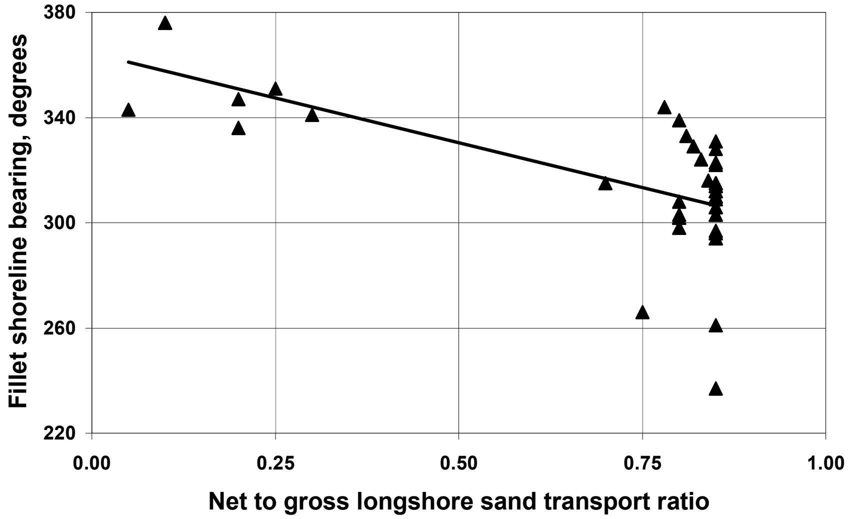


Figure 14. Bearing of the fillet shoreline versus the net to gross longshore sand transport ratio.

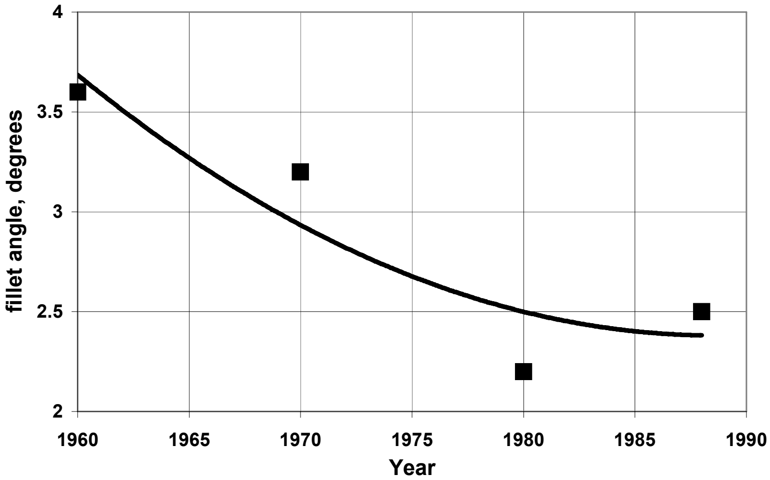
3.2 Examples of Human Interventions

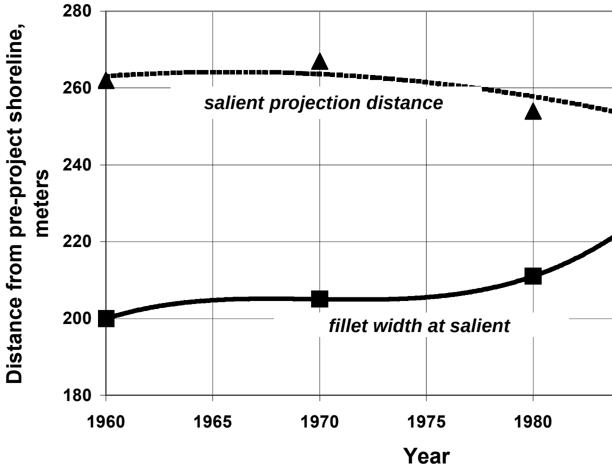
Examples illustrate the relationship between the structure blocking distance and the bearing of the fillet shoreline. They define the way in which fillets evolve to maturity (Santa Monica fillet), the way mature fillets respond to winter storms (Oceanside Harbor fillet), and an advancing upcoast shoreline (King Harbor fillet), how blocking distances and fillet shoreline bearings change with the orientation of the coast (Santa Monica Bay), and how blocking distances and fillet shoreline bearings change within groin fields (Will Rogers State Beach, US Navy at Point Mugu, and Ventura groins).

3.2.1 Fillet Evolution at Santa Monica

Insight into the relationship between blocking distance and fillet angle can be gotten by an inspection of the evolutionary history of a prototype fillet. The time it takes a fillet to evolve to maturity is inversely proportional to the net longshore sediment transport rate and directly proportional to the dynamic equilibrium size of the fillet. In most places in California fillets formed so rapidly that multiple surveys are unavailable to quantify their evolution. However, because of its size, the fillet upcoast of the Santa Monica salient evolved slow enough that its sequence is detectable in shoreline positions obtained from Corps of Engineers maps. The longshore sand transport regime is nearly steady at this site, which means the fillet was nourished at a near constant rate. The net to gross longshore sediment transport ratio is an estimated 0.8.

Santa Monica breakwater was constructed in 1934 and a salient began developing almost immediately. Soon thereafter, a fillet beach began forming northwest of the salient (Fig. 10). Position maps document the evolution of this fillet from 1960 until 1988, by which time it had probably reached a state of near dynamic equilibrium. As it evolved, the fillet angle and blocking distance progressively declined as shown in Figures 15 and 16. Although the distance between the pre-project shoreline and the apex of the salient declined slightly, the width of the fillet against the salient (the sediment-blocking structure) increased until 1988 when it was near the apex (Fig. 17). The fillet angle declined from about 3.6 degrees in 1960 to 2.5 degrees in 1988. An overview of these changes is summarized in Figure 18, which indicates the fillet began expanding near the salient then advanced upcoast.





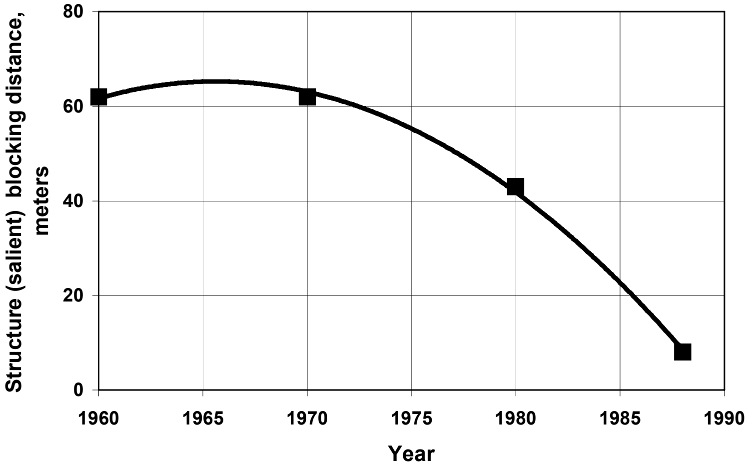


Figure 15. Evolution of fillet angle, Santa Monica breakwater salient.

Figure 16. Evolution of structure blocking distance,

Santa Monica breakwater salient.

Figure 17. Evolution of structure length (salient projection distance) and fillet width, Santa Monica breakwater.

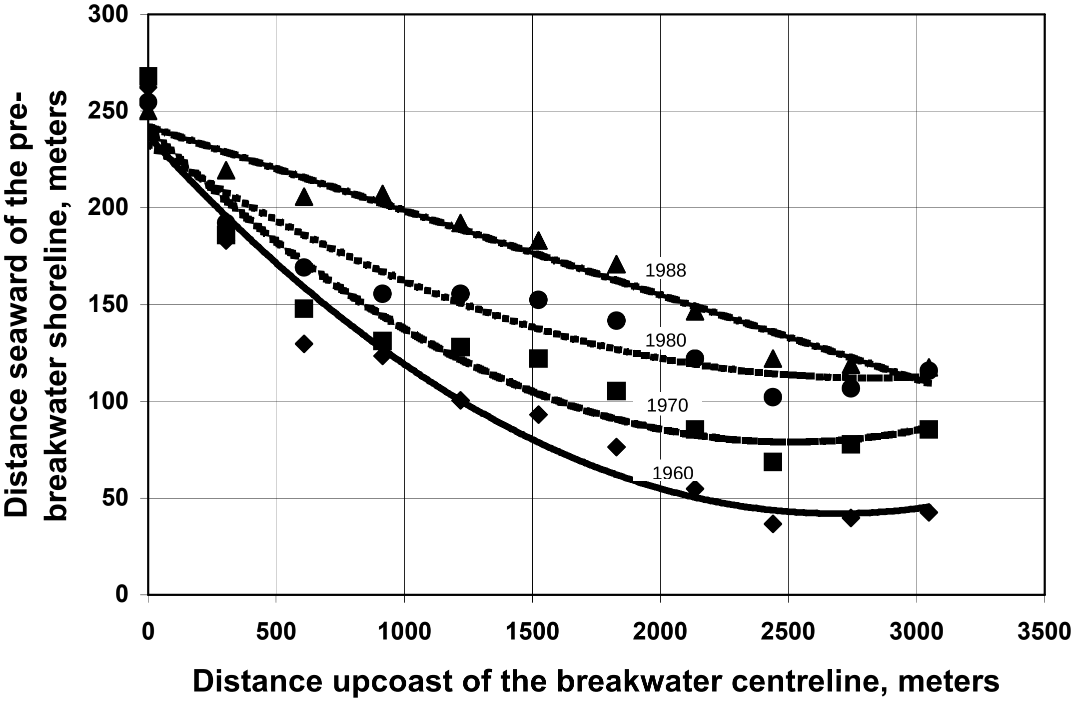


Figure 18. Evolution of the fillet shoreline upcoast of the salient, Santa Monica breakwater.

3.2.2 Fillet North of the Oceanside Harbor Breakwater

Construction began on the north Oceanside (Camp Pendleton) Harbor breakwater in 1941, at which time it began impounding sand**.** The fillet reached a dynamic equilibrium state around 1970 when the blocking distance stabilized at about 130 m in the winter. Figure 9 shows the breakwater and the fillet in the mid-1980's. The blocking distance of the Oceanside breakwater is the shore-normal distance between the break in orientation of the structure and the shoreline.

Everts Coastal (2001) compared shoreline positions before and after the breakwater was constructed to establish the blocking distance. They located the upcoast limit of the fillet by measuring the orientation of the upcoast shoreline in segments to determine where it deviated from its regional alignment. They determined a fillet length of 1200 to 1400 m with a plan area of 55,000 to 70,000 square meters (sm). The fillet angle averages 6 degrees in the winter. During ENSO storm events the shoreline retreated uniformly, i.e., the fillet angle remained nearly constant while the blocking distance increased. Recovery occurred as the shoreline advanced with a near constant fillet angle.

3.2.3 Fillet Change during a Period of Shoreline Advance at King Harbor

Construction began on the north breakwater at King Harbor in 1938. Prior to that time, sand that moved south in Santa Monica Bay was lost in Redondo Submarine Canyon. The natural head of the canyon lies just off the horseshoe-shaped pier in the center of Figure 19. Its position regulated the width of the downcoast beach. When the shoreline advanced, more sand was lost to the canyon; when it retreated less sand was lost. Canyon losses ceased or were greatly reduced when the north breakwater began intercepting sand in 1938 (Dunham, 1965). Almost immediately a fillet began forming on the Hermosa Beach side of the harbor and the south beach (Redondo Beach) began eroding.

Figure 19. King Harbor: the north breakwater is at the upper center in the photo and Redondo Beach is out of the photo in the foreground.

A simple sediment budget analysis suggests the net longshore sediment transport rate near King Harbor and the quantity of sand lost in Redondo Submarine Canyon have both increased in recent years. Table 2 shows the budget upcoast of the harbor for two intervals of fillet development, with the 1935-1953 budget being the least well defined. Data in this table were extracted from shoreline maps prepared by Coastal Frontiers (1992). Two large opportunistic beachfills on Dockweiler Beach, one in 1947 when coarse dune sand was made available during the construction of the Hyperion Sewage Treatment plant, and the other between 1960 and 1963, when Marina del Rey was excavated (Leidersdorf et al., 1993), are responsible for maintaining the past 50-years of wide beach near the marina entrance. We assume no sand reached the canyon in the early period, and all of the beachfill remained in the littoral zone. An examination of Table 2 indicates the net longshore sediment transport rate from the upcoast (north) to the downcoast (south) reach was perhaps 60,000 cmy between 1935 and 1953, and about four times that value between 1953 and 1990. In the latter period there was a large shift in sand volume from Dockweiler Beach to Manhattan Beach and Hermosa Beach, and all the way to King Harbor. There was also an apparent loss of 6.2 million cubic meters (cm) of sand that cannot be discounted as an aberration related to seasonal variations in shoreline positions or other factors. It is difficult to attribute it to any sink other than Redondo Submarine Canyon.

Table 2. Approximate sediment budget between Marina del Rey and King Harbor, (1935-1953 data in bold type, 1953-1990 data in parentheses; all data extracted from Coastal Frontiers, 1992).

Reach	**Length, meters**	**Beach area change, square meters**	**Artificial beachfill, cubic meters**	**Net change in sand volume, cubic meters****
Upcoast: Marina del Rey to LA-El Segundo groin	5500	**+920,000** (-85,000)	**9,300,000*** (8,100,000)	**8,300,000** (-8,900,000)
Downcoast: LA-El Segundo groin to King Harbor	7300	**+110,000** (+430,000)	**0** (+1,200,000)	**+990,000** (+2,700,000)
Summation	12,800	**+1,030,000** (+345,000)	**+9,900,000** (+9,300,000)	**0** (-6,200,000)

* 7.7 million of the 10.5 million cm Hyperion 1947 fill is assumed to have been placed on the upcoast beach; this volume is equal to the volume change in the upcoast reach plus the volume change in the downcoast reach

** One square meter of beach area is assumed to be sustained with 9 cubic meters of sand

The large increase in the capture rate in Redondo Canyon must be the amount of sand that passed the north King Harbor breakwater. Figure 20 indicates its blocking distance progressively declined from the time it was constructed until the last survey in 1990. Shoreline positions shown in this figure end about 220 m from the breakwater due to survey limitations, but the trends clearly indicate a decline in the blocking distance. The figure also shows a corresponding increase in the width of the beach upcoast of the fillet. The reason for the large increase in net transport rate in the 1953-1990 period may a loss of effectiveness in a groin at the boundary between El Segundo and Los Angeles. Coastal Frontiers (1992) refers to this structure as the El Segundo-LA groin.

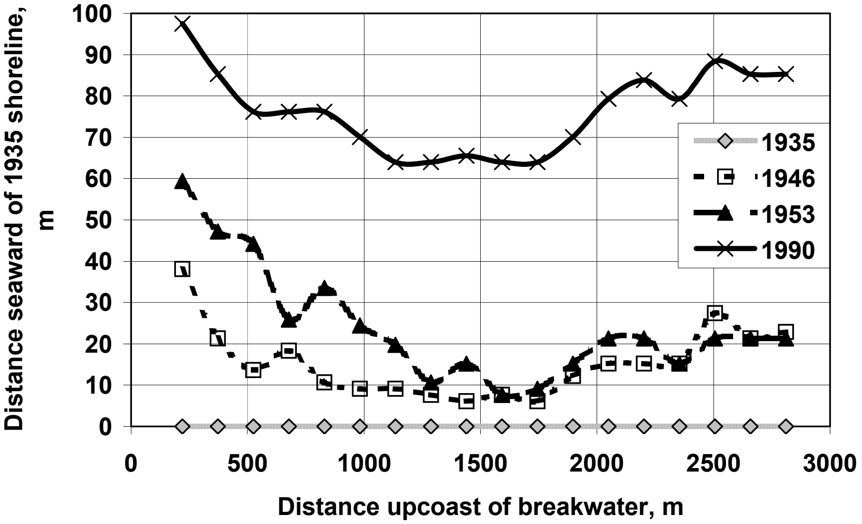


Figure 20. Shoreline response to the north breakwater at King Harbor, 1935-1990 (data from Coastal Frontiers, 1992).

Figure 20 indicates the King Harbor fillet evolved in stages and that it was probably controlled by the width of the upcoast beach. From 1938 to sometime between 1946 and 1953, the fillet evolved to a width of about 65 meters while the shoreline 1500-m upcoast of the structure remained within 10 m of its 1935 position. In this period the effective length of the structure was 197 m. The blocking distance is from the fillet shoreline to where the breakwater curves from nearly shore-normal to shore-parallel (Figure 19). By1990, the upcoast shoreline had advanced 55 m and the fillet had reached a second mature state. But the fillet width declined to about 45 m. The effective length of the structure was reduced to 142 m. Further inspection of Figure 20 indicates that while the blocking distance and effective length of the structure declined, and the fillet advanced, the fillet angle remained nearly constant.

3.2.4 Gradient in Fillet Characteristics in Santa Monica Bay

Structure blocking distances, the bearings of fillet shorelines, and the net to gross longshore sand transport ratio, all change in a consistent and like way between Las Tunas, at the east end of Malibu, and King Harbor. In this reach the shoreline changes orientation by about 80 degrees as evident in Figure 21. The net to gross longshore sand transport ratio exhibits a sharp drop as the shoreline shifts from a west-east to a nearly north-south orientation as shown in Figure 22. Figures 23 and 24 show the structure blocking distance and fillet shoreline bearing follow the transport ratio trend of Figure 22.

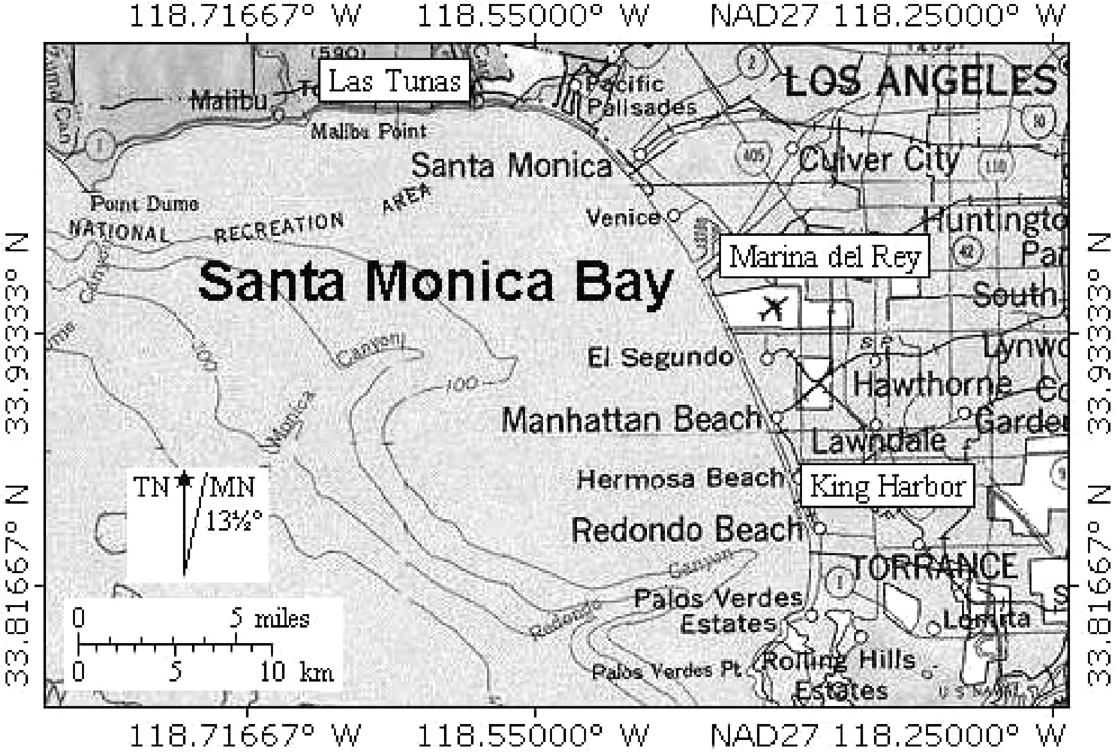
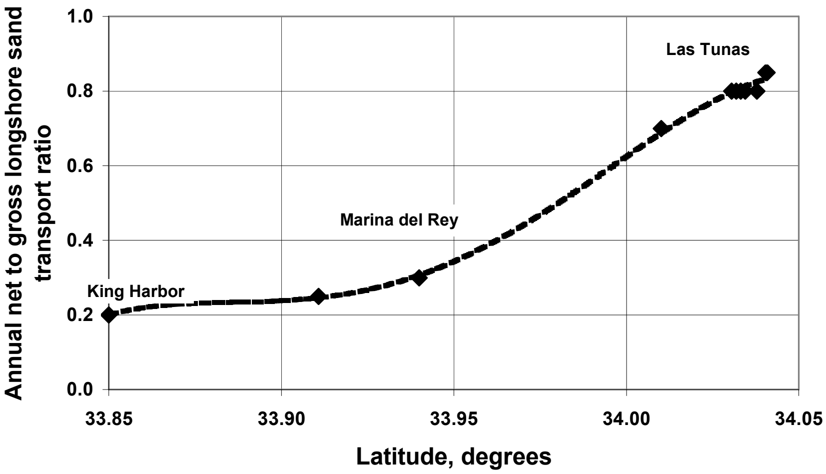
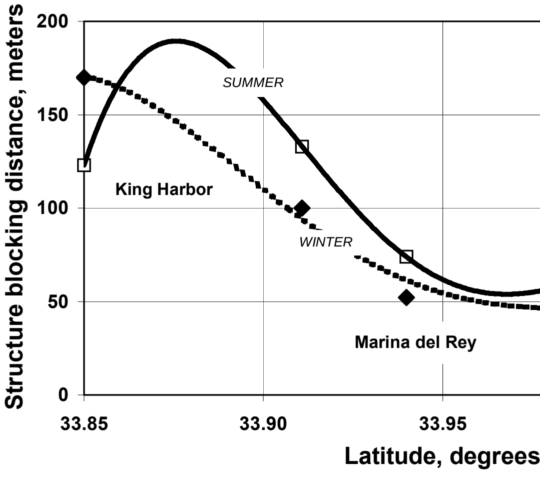


Figure 21. Location map, Santa Monica Bay (from NGS Topo!).





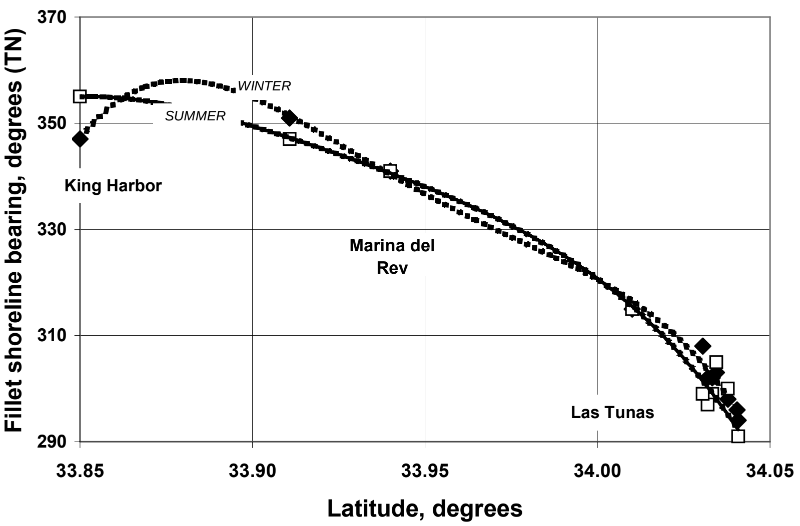


Figure 23. Relationship between the structure blocking distance and latitude in Santa Monica Bay.

Figure 24. Relationship between the bearing of the fillet shoreline and latitude in Santa Monica Bay.

Figure 22. Relationship between the net to gross longshore sand transport ratio and latitude in Santa Monica Bay.

3.2.5 Fillets in Groin Fields

Three groin fields have been effective in retaining a wider beach upcoast of the first groin and a wider beach within the groin compartments. Their locations are at Figure 25. The structure blocking distances are related to the bearing of the fillet shorelines as Figure 26 illustrates. Rhombs are Will Rogers State Beach groins, squares are US Navy groins, and triangles are Ventura groins. The end-of-winter curve is the dashed line; the summer curve is solid. A question of some importance in the use of multiple structures is whether the blocking distance changes in a groin field because the bearing of the fillet shoreline changes or because it increases with successive structures in a downcoast direction. Figure 26 suggests it is controlled by the orientation of the fillet shoreline. In the Ventura groin field, the blocking distance progressively increases in a downcoast direction as the shoreline bearing changes. However, in the other two groin fields the coast is approximately straight and the blocking distance does not indicate a change downcoast of the first structure. The best fit to the winter data shown in Figure 26 is

$$y_{bf}\,(winter) = 7.23x10^{-2}\alpha^{2} - 4.41x10^{1}\alpha + 6.73x10^{3} \qquad (1)$$

with a correlation coefficient of 0.97. The best fit to the summer data is

$$y_{bf}\,(summer) = 4.91x10^{-2}\alpha^{2} - 2.94x10^{1}\alpha + 4.44x10^{3} \qquad (2)$$

with a correlation coefficient of 0.88. An inspection of Figure 27 indicates only a slight tendency for the fillet angle to decline with the bearing of the fillet shoreline. In most cases the fillet angle is seven degrees or less, meaning the bearing of the pre-project shoreline is close to the bearing of the fillet shoreline in Figure 26. When the fillet shoreline bearing is greater than about 310 degrees, changes in the blocking distance are mostly due to the shoreline bearing and not the fillet angle.

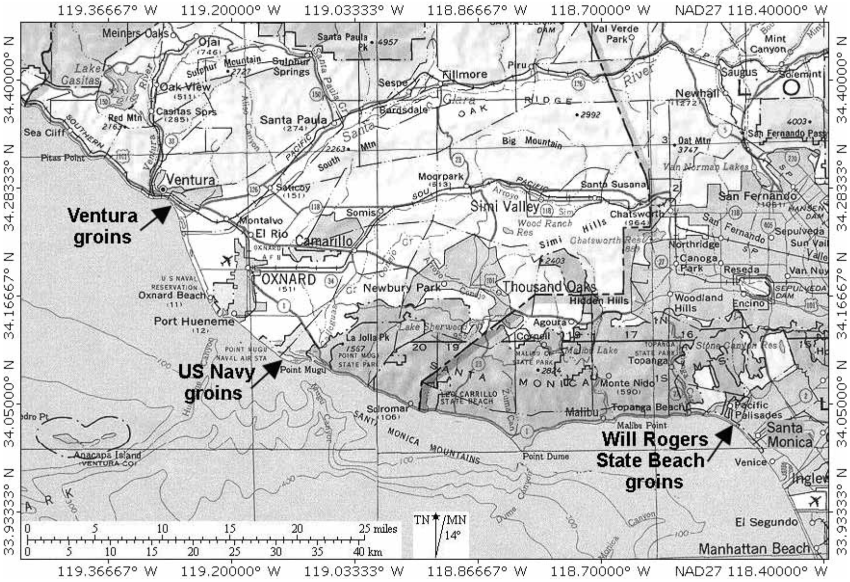


Figure 25. Location map: effective groin fields in southern California.

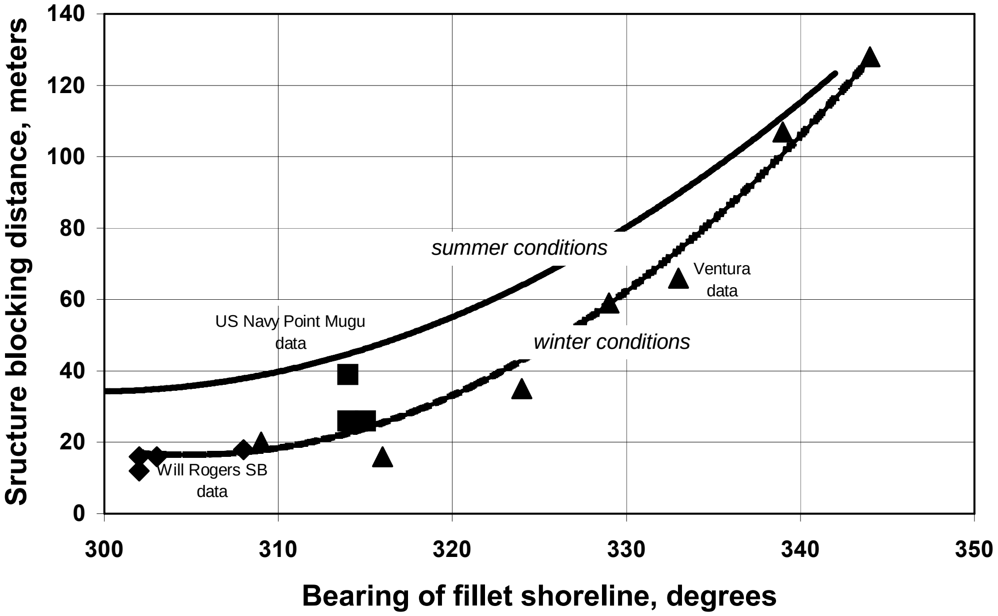


Figure 26. Structure blocking distance versus the bearing of the fillet shoreline in southern California groin fields.

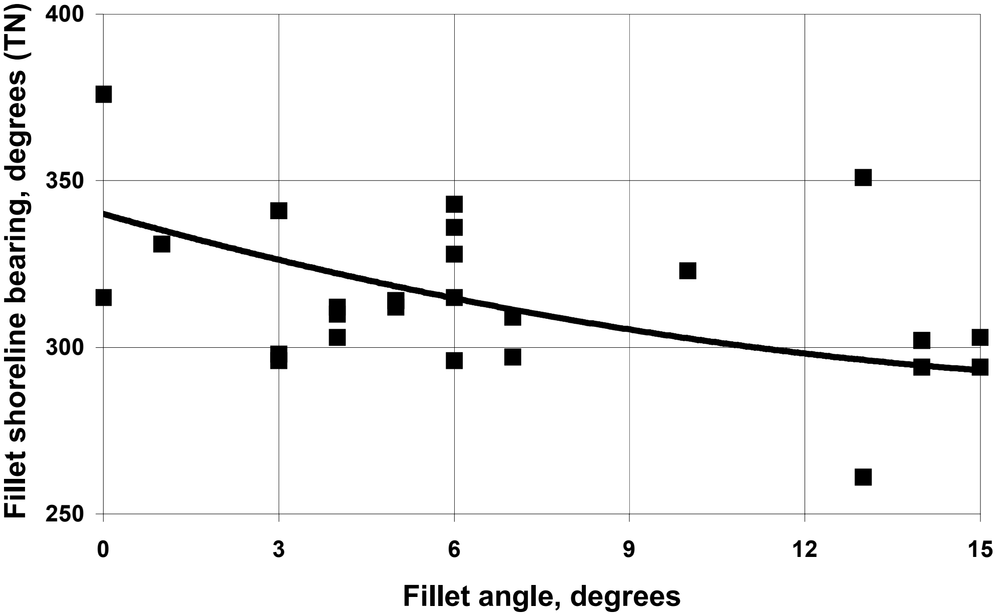


Figure 27. Fillet angle versus the bearing of the fillet shoreline in southern California groin fields.

3.2.6 Groins at Point Mugu NAWS: Downcoast Shore Retreat.

Downcoast erosion followed the construction of the three groins on US Navy property near Point Mugu in 1967. The Navy response to this problem was to construct a revetment downcoast of the last groin. The groins, shown in Figure 28, were built following a severe retreat of the shoreline downcoast of Port Hueneme. According to Herron and Harris (1966), this coast was “extremely stable” from at least1852 until 1938 when jetties were constructed to protect the entrance to Port Hueneme. The west jetty channeled sand into Hueneme Submarine Canyon and deprived the downcoast of much of its sand supply. By 1948, the shoreline had retreated over 200 meters near the port. Over time the retreat zone expanded to the east. By the mid-1950’s it had reached the Navy facility 13-km downcoast. The erosional sequence illustrated in Figure 29 is classic evidence for the incipient formation of a hook-shaped bay. Even though an average 160,000 cmy was artificially bypassed between 1938 and 1960, the deficit averaged over 650,000 cmy (Moffatt and Nichol, Engineers, 1995).

Figure 28. US Navy groins downcoast of Port Hueneme (1992 photo).

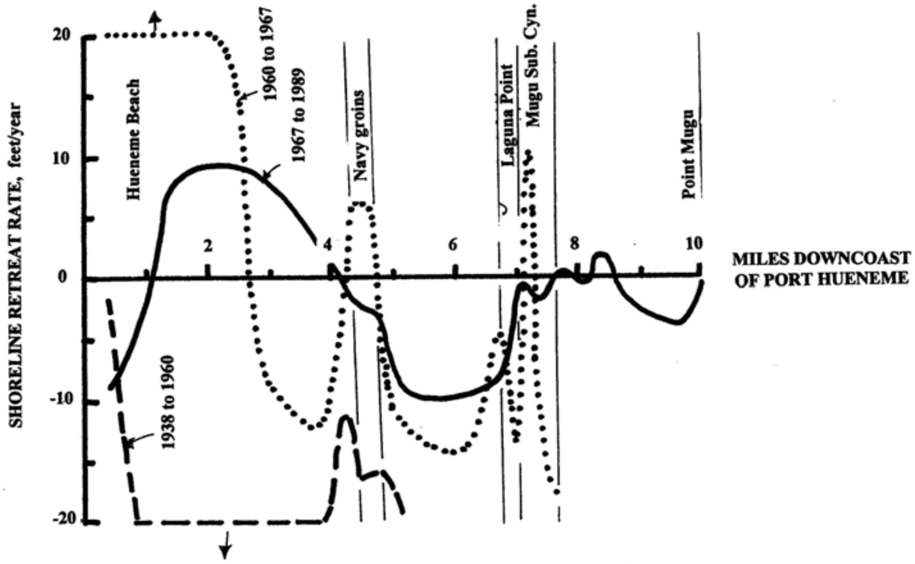


Figure 29. Shoreline change rates, Port Hueneme to Laguna Point, Ventura County; 1852-1938, 1938-1960, 1960-1967, 1967-1989 (from Moffatt and Nichol, Engineers, 1995).

Channel Islands Harbor was constructed in 1960, partly to provide a mechanism to bypass sand on a routine basis to Hueneme Beach. During its construction, about 4.7 million cm of sand were placed downcoast of the entrance to Port Hueneme. On a 2-yr schedule since then, an average of over one million cmy has been artificially bypassed from the lee of a detached breakwater just north of the harbor entrance. This practice produced dramatic results. In the reach to 6 km downcoast of Port Hueneme there was a net accumulation between 1960 and 1989 (Fig. 29).

While the Navy groins stabilized the coast to the west, the last groin began blocking and diffracting waves. This initiated the creation of erosional hook-shaped bay. The anchor structure is Laguna Point which was reasonably stable between 1967 and 1989 (Fig. 29). But between the last groin and Laguna Point shoreline retreat averaged almost 2.5-m per year (my). Further to the east the shoreline change rate was about equal to its pre-1967 rate, indicating sand was passing the groins and Laguna Point, and the wave blocking and diffraction effect of the last groin was responsible for the retreat. In addition, all three groins deflect sand seaward in order so that it can pass around them. This sand is not transported directly shoreward after passing the last structure. Rather it moves alongshore with a net shoreward component and reaches the shoreline some distance downcoast, adding to the development of the hooked bay. To arrest its expansion, the Navy constructed a revetment east of the last groin as shown in Figure 30.

Figure 30. Revetment downcoast of the east or last groin along the US Navy coast between Hueneme Beach and Point Mugu; Laguna Point at upper right (1992 photo).

4.0 SALIENTS

Offshore breakwaters and narrow, shore-parallel reefs function as detached wave-blocking and diffraction structures. If they retain a wider beach in their lee it is evident as a bulge in the shoreline. When the bulge connects to the structure it is referred to as a tombolo. A tombolo will only form if the structure is exposed above the sea surface at all tide levels, if it is long, and if it is close to shore. In contrast, if the structure is a greater distance offshore, or is shorter, or if waves pass over it, such that the bulge only projects partway to the structure, the retained beach is called a salient. Natural two-dimensional reefs have yet to be identified in southern and central California, but they may exist submerged.

4.1 Distribution

Six artificial structures in southern California clearly function such that they might retain a salient or tombolo. As shown in Table 3, though, only the Venice and Santa Monica breakwaters retain a mature salient and none retains a tombolo. The impacts of the Venice and Santa Monica breakwaters are discussed in detail in Everts Coastal (2002). Reasons a mature salient or tombolo is lacking in the lee of the other breakwaters are given in the table. Figure 31 is an oblique photo looking north over the Silver Stand beach (Ventura County) toward an immature salient in the lee of the detached breakwater at Channel Islands Harbor in Ventura County.

Table 3. Salients in the lee of detached breakwaters in southern California.

Breakwater location	Salient	Remarks
Los Angeles – Long Beach Harbor breakwater	NA	Due to its length and high crest elevation this breakwater dissipates most of the wave energy that reaches it. Two navigation gaps allow some penetration, but oil islands, harbor facilities, and a marina complex makes it very difficult to sort out the breakwater's impact on the artificially enhanced beach at Long Beach. The lack of a sediment source prevents the build up of a salient in the lee of this breakwater.
Marina del Rey	NA	This breakwater was constructed to reduce surge in the marina; its impact on adjacent beaches is not well defined because it is located adjacent to the marina entrance. Harbor entrance jetties and the detached breakwater affect nearby beach behavior in a complex way.
Venice	Salient	This salient was well developed before the beach was artificially widened in 1948 and before a groin connected the center of the structure to the shore in the early 1960's. (Note: most references incorrectly show this salient as a tombolo)
Santa Monica	Salient	This salient has changed its size as the depth over the crest of the breakwater declined due to wave-caused damages and as the nearby shoreline advanced.
Channel Islands	Salient never matures	This breakwater was constructed to create a trap from which sand could be artificially bypassed to Hueneme Beach. Frequent bypassing precludes the development of a mature salient.
Ventura Harbor	Salient never matures	This breakwater is employed to create a sand trap in order to keep it out of the harbor entrance. Frequent bypassing precludes the development of a mature salient.

Figure 31. Detached breakwater and salient at Channel Islands Harbor (background); every two years over 2 million cubic meters of sand are artificially bypassed from the salient to Hueneme Beach (out of the picture to the right of the entrance to Port Hueneme in the foreground).

4.2 Structure-Beach Response

Everts Coastal (2002) recently evaluated the effectiveness of high and low detached breakwaters in southern California. Based on the prototype performance of these structures in the local wave climate they developed relationships to estimate salient area, A_r, as a function of the shore-parallel length of the structure, x_s, the distance between the structure and the pre-project shoreline, y_s, and the crest elevation of the structure with respect to mean sea level (the structure freeboard), F_b. Salient area is proportional to the distance the salient projects seaward of the pre-project shoreline, Y_r. Figure 32 is a definition sketch for detached breakwaters (and shore-parallel, two-dimensional reefs).

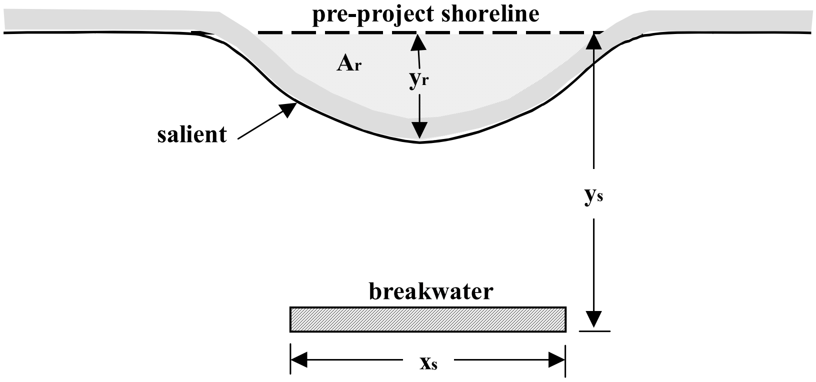


Figure 32. Definition sketch: detached breakwaters.

Governing variables for high, impermeable structures are the length of the structure and its distance from shore. The salient projection distance is directly proportional to x_s, and inversely proportional to y_s. The salient projection distance is controlled solely by wave action at the ends of these structures. Wave energy does not pass over or through them. Diffracted wave energy in the lee of a breakwater increases with wave height, wave period, and water depth at the diffraction point.

When some of the incident energy passes over or through a low or submerged structure, the effect of wave transmission must also be considered. Wave transmission is destructive to a salient. As the portion of the incident energy increases (wave transmission coefficient increases) the salient projection distance declines. Wave transmission increases with a decline in structure freeboard and with structure permeability. A structure freeboard that exceeds about 1.2 times the means significant wave height precludes most overtopping wave energy. The transmission coefficient varies continuously as the sea surface rises and falls with respect to the fixed position of the breakwater crest.

4.3 Beach Performance

Detached breakwaters at Venice and Santa Monica are located away from jetties and their salients have not been systematically mined. Both of them have been remarkably effective in retaining large salients for decades. Salient characteristics adjusted through time, however, because the distance between the structures and the shoreline y_s (Fig. 32) declined due to artificial beach enhancement and natural accretion. At the Santa Monica breakwater, the salient also adjusted because of a reduction in freeboard.

4.3.1 Venice Breakwater

Venice breakwater is 180-m long and sufficiently high that very little wave energy passes over it, even at high stages of the tide. This breakwater was constructed in 1905 and has retained a salient continuously for almost 100 years. At the time it was built it was about 325 m from the shoreline. In 1948, a huge opportunistic beachfill advanced the shoreline about 120 meters in the vicinity of the breakwater. Between 1965 and 1988 the nearby shoreline advanced further at an average 0.6 my. In the 1960’s a groin was constructed out to the structure and as shown in Figure 33 the shoreline sometimes intersects the structure. At most other times, though, the shoreline does not reach it (Fig. 2).

Figure 33. Venice salient and breakwater: note the groin that retains sand mostly on its upcoast side.

Changes in the position of the apex and the shape of the salient caused by the advance of the shoreline and the groin are evident in Figure 34. The salient projection distance was about 90 m in 1935. After accounting for the elongation impact of the groin it averaged about 60 m between 1965 and 1988. The salient would not be as pointed as it appears in Figure 35 if the groin were absent. In 1935 the salient area was about 33,000 square meters (sm) while in the later period it averaged about 25,000 sm.

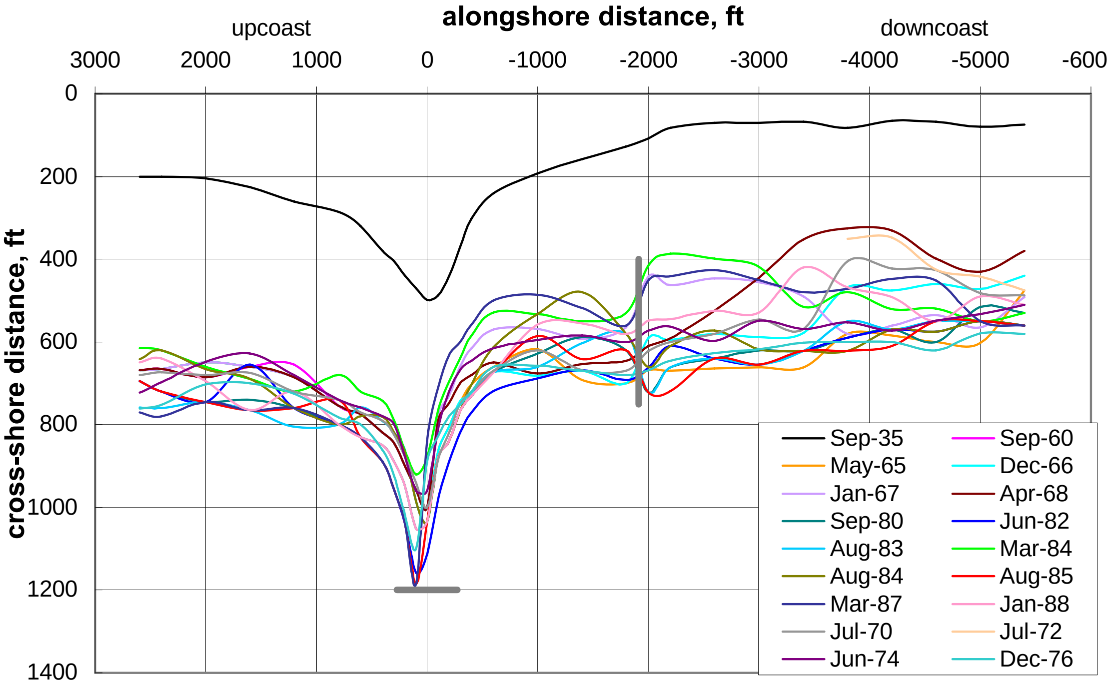


Figure 34. Shorelines in the vicinity of the Venice breakwater (data from Corps of Engineers shoreline maps).

4.3.2 Santa Monica Breakwater

Santa Monica breakwater was completed in 1934. In the long run it has not been as successful in its design objective of creating a safe and quiescent haven and mooring area for small craft as it is in retaining a wide salient (Fig. 35) and upcoast fillet beach (Fig. 18). This structure is about 610-m long. At the time it was built its crest was about 3 m above mean lower low water (mllw) and it had a width of 3 m. It was constructed in a water depth of 8 m (mllw), 600-m from shore. Settlement and wave damage reduced its crest elevation until after the 1982-83 ENSO it was barely awash at low tide.

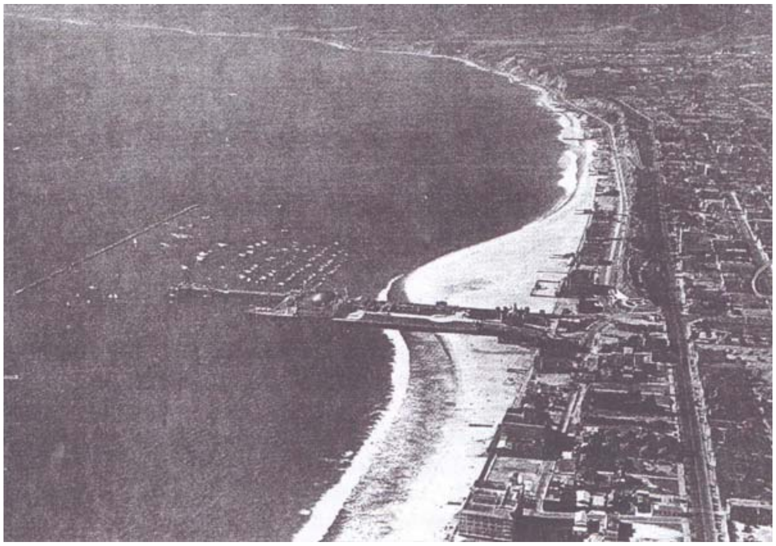


Figure 35. Salient in the lee of Santa Monica breakwater around 1940 (compare with Figure 10, photo from USACE-LAD archive).

Immediately following construction a salient began forming in the lee of the breakwater. This response is shown by the 1935 shoreline in Figure 36. By the early 1940's, or earlier (Fig. 35), the salient reached its most seaward position. From there it declined slightly until 1988 when the last survey shown in Figure 36 was made. The small decline in the salient projection distance between the 1940's and 1988 (Fig. 37) is due to a near balance in the positive effect imposed by an advance in the shoreline on both sides of the salient, i.e., a reduction in the distance between the structure and the shoreline, and the negative effect due to a loss of crest elevation. The response as referenced by the area of the salient was a small decline as shown in Figure 38. Figure 39 illustrates the relationship between the salient area and the projection distance at Santa Monica.

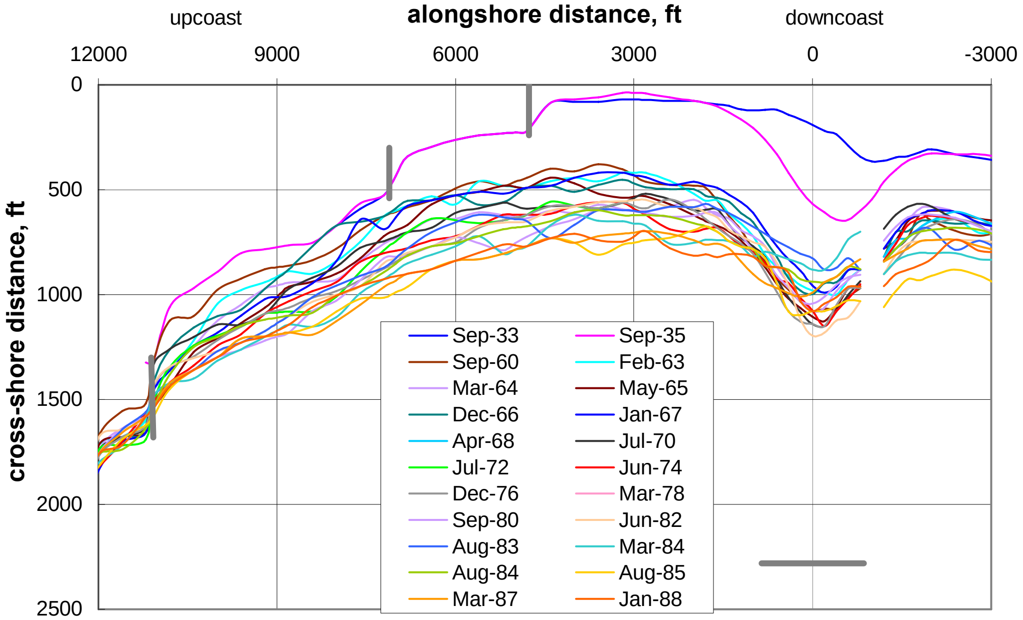


Figure 36. Shoreline positions in the lee of and upcoast (to the right) of the Santa Monica breakwater (from Everts Coastal, 2002).

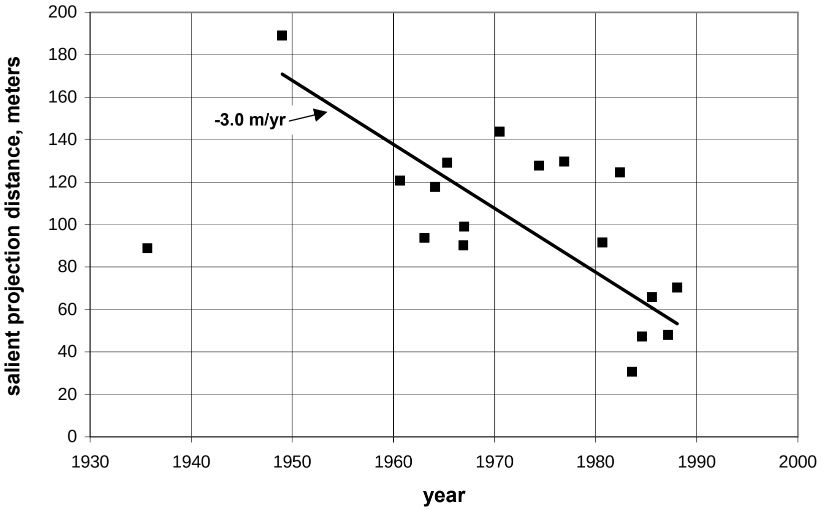


Figure 37. Salient projection distance as a function of time: Santa Monica breakwater (from Everts Coastal, 2002).

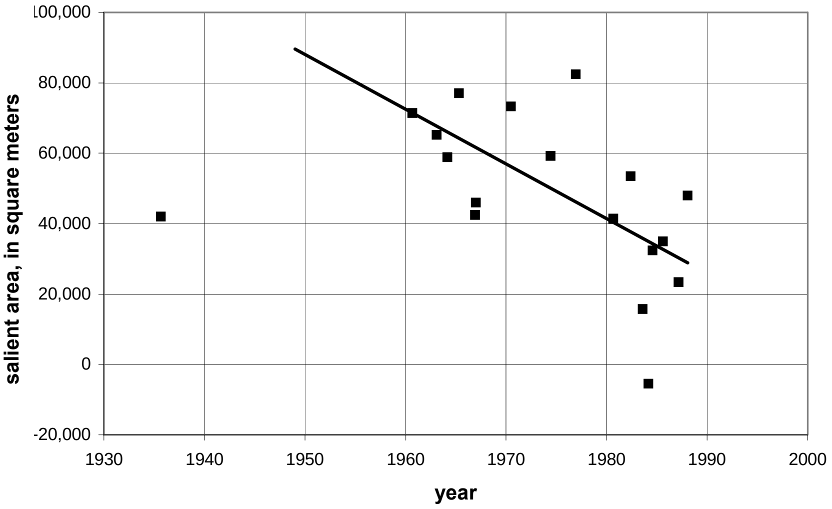


Figure 38. Salient area as a function of time: Santa Monica breakwater (from Everts Coastal, 2002).

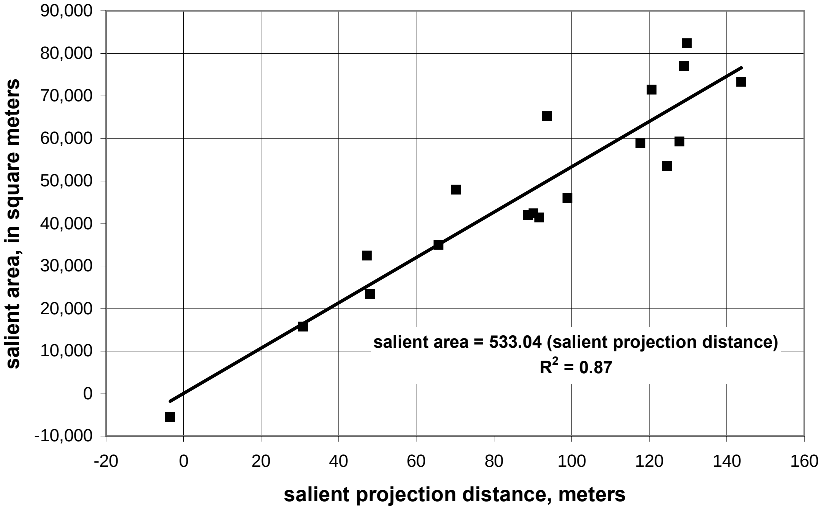


Figure 39. Salient area versus salient projection distance at Santa Monica (from Everts Coastal, 2002).

5.0 PERIMETER BEACHES

Any irregular, three-dimensional bottom configuration that is responsible for retaining a beach by bending waves is herein considered to be a wave refraction structure. These features change the approach direction and height when the waves break. As a consequence, only along a curved shoreline is it possible for the net alongshore component of wave energy flux to be uniform on an annual basis, i.e., it is possible for a beach to be retained in dynamic equilibrium.

In comparison to the nearby seafloor, wave refraction structures are either anomalously deep or anomalously shallow. Near-coast submarine canyons best typify deep, or negative, wave refraction structures. Underwater canyons cause waves to diverge over them and wave heights to decline in their lee. Depending on the location of the structure the result is either a shoreline bulge or a shoreline depression (or embayment). Rocky stream deltas and submerged reefs are good examples of positive refraction structures that stick up above the nearby seabed. Waves converge over them and the result is always a shoreline bulge in their lee. Depending on the amount of energy that is dissipated in breaking and bottom friction, wave energy may or may not be concentrated at the time the waves break.

A perimeter beach is the name given to beaches that form adjacent to wave refraction structures identified in this investigation. Perimeter beach is a catchall descriptor for beaches retained along the landward margins of rocky stream deltas, and in the lee of wide submerged reefs and near-coast submarine canyons. Other kinds of wave refraction structure, no doubt, retain beaches. However, detailed shallow water bathymetry is not currently available along most of the study coast to identify the link between them and beaches they retain. The characteristics of beaches retained by deltas and reefs were measured. But because the structures are partially or totally submerged their characteristic geometric parameters could not be determined on aerial photos and topographic maps. Existing bathymetry is also inadequate for the task. As with low anc submerged detached breakwaters, wave-energy transmission determines the extent to which the structure will retain a beach. Water depth over the crest is the key variable. Adequate bathymetry would be crest elevations to plus or minus no more than 0.15 m, and horizontal control to plus or minus 3 m (Everts Coastal, 2002). This accuracy can only be obtained by detailed, structure-specific, shallow-water surveys. Until such seabed data are obtained it will not be possible to develop beach-structure relationships for deltas and reefs.

5.1 Near-Coast Submarine Canyons

Shallow submarine canyons affect the southern California coast in two important ways. First, they control the position and shape of the adjacent shoreline, most importantly whether that shoreline protrudes seaward or is indented shoreward of the general trend of the coast. Second, these seafloor depressions capture sand and thus regulate the supply reaching downcoast beaches. Each of the eight near-coast submarine canyons in the study area has a critical infilling volume. When that volume is exceeded the sand deposit in the head of the canyon becomes unstable and is flushed downslope into water often thousands of meters deep. Flushing usually occurs during a high-energy wave event. Thanks to this mechanism the canyon heads never fill, and thus never lose their capacity to permanently capture littoral sand.

Because of their large size, and the number of investigations that have been conducted in them, it is possible to define the sand capture rate and larger bathymetric characteristics of the canyons. Figure 40 illustrates these characteristics and the attributes of the perimeter beaches they retain. Figure 41 is a map showing the locations of southern California near-coast submarine canyons. Table 3A in Appendix A is the spreadsheet listing of the submarine canyon data. Dume Canyon was deleted from the analysis because the nearby coast is Point Dume. This rocky point is responsible for controlling the configuration of the shoreline in the lee of this canyon, not the refraction effects of waves passing over it.

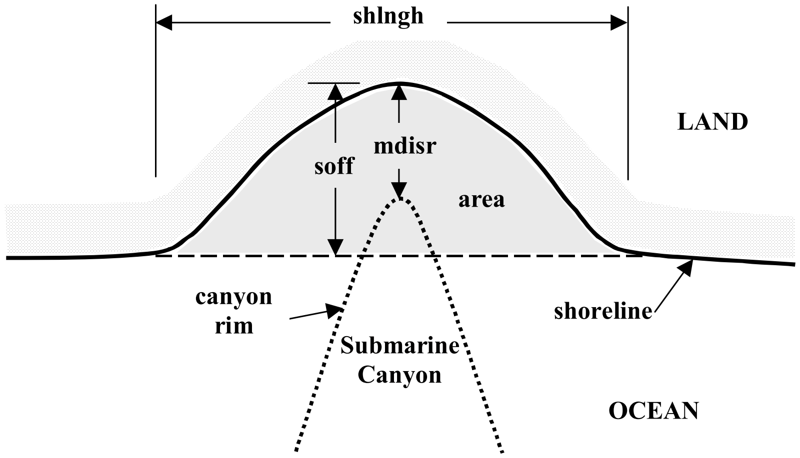


Figure 40. Definition sketch: near-coast submarine canyons (negative refraction structures).

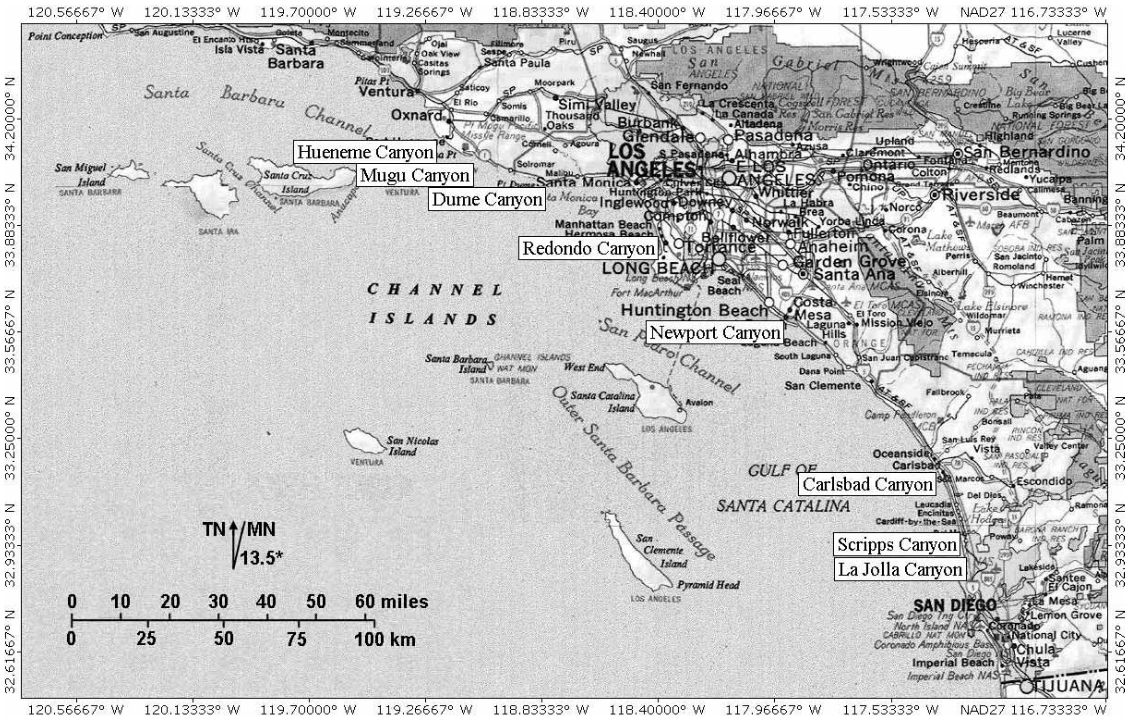


Figure 41. Location of submarine canyons that affect the littoral zone in southern and central California.

Although the canyon population is rather small, the results of a simple analysis of the structure-beach linkage indicates a single fundamental relationship that governs the way shallow water, southern California submarine canyons affect the coast. This key factor is the shore-normal distance between a projection of the regional trend of the shoreline and the most shoreward position of the canyon head rim – the canyon offset distance. This simple parameter provides constraints on how a beach in the lee of a canyon might be artificially enhanced and how the canyon sand capture rate reduced.

Unremarkably, the canyon offset distance was positive for the four perimeter beaches that are seaward of the general trend of the coast, and negative for those that appear as embayments with respect to the general coastal trend. Newport Submarine Canyon shown in Figure 42 retains the largest seaward projecting perimeter beach. Balboa Peninsula, West Newport, and Newport Harbor owe their existence to this canyon. In its absence, the shoreline would be against the cliffs on the inland side of Pacific Coast Highway. La Jolla Shores shown in Figure 43 is the shoreline embayment associated with the negative offset distance in the lee of La Jolla Submarine Canyon. In total, submarine canyons retain about 36 km of perimeter beach between Port Hueneme and La Jolla.

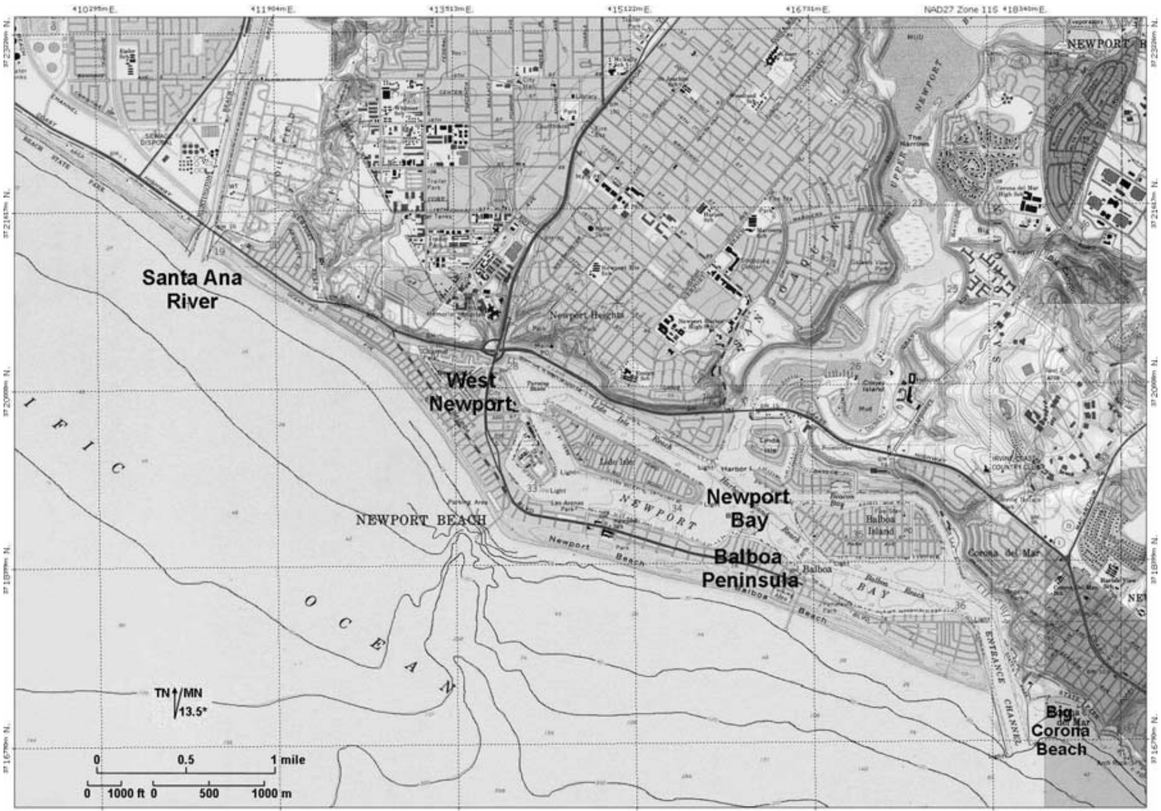


Figure 42. Newport Submarine Canyon retains the shoreline projection from the mouth of the Santa Ana River to Corona del Mar.

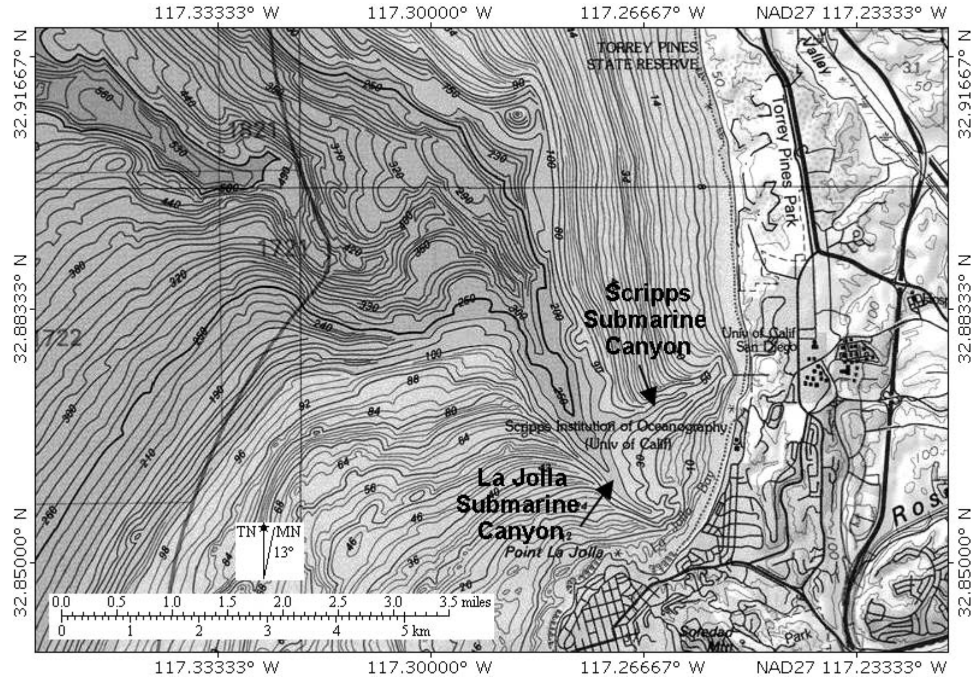


Figure 43. The La Jolla – Scripps Submarine Canyon Complex retains the shoreline embayment at the south end of the Oceanside Littoral Cell.

More surprising is the relationship between the sand capture ratio and the canyon offset distance shown in Figure 44. The sand capture ratio is the rate at which sand is trapped in a canyon (and thus permanently lost to the littoral system) divided by the net longshore sediment transport rate in the vicinity of the canyon. When the canyon-offset distance is negative, meaning the canyon is landward of the general trend of the shoreline; canyons in the study area capture almost all of the sand moving downcoast. In contrast, when the canyon offset is positive, the canyon captures very little sand. Downcoast beaches are affected to a much lesser degree.

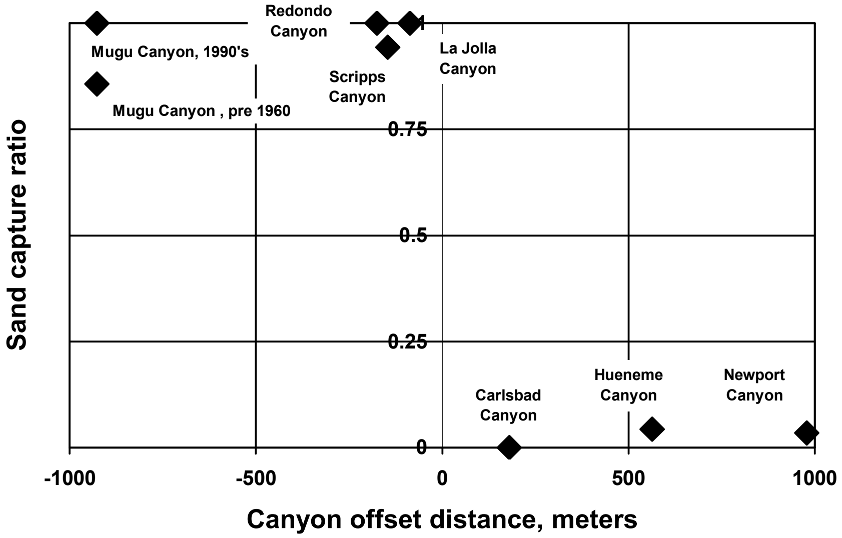


Figure 44. Sand capture ratio versus canyon offset distance.

Previous canyon studies, such as those by USACE-LAD (1988) in Scripps and La Jolla Canyons, Moffatt and Nichol, Engineers (1995), in Mugu and Hueneme Canyons, and Everts Coastal (1996) in Newport Canyon, focused on the relationship between the distance from the shoreline to the canyon rim or the water depth at the canyon rim as primary controls on the sand capture rate. Figure 45 indicates this relationship, as a general rule, is not clear-cut for California canyons. It does show that the capture rate in an individual canyon changes when the distance to the canyon rim is altered. Between the pre-1966 era and the 1990's the distance between the shoreline and canyon rim declined in Mugu Canyon and the capture ratio increased. Mugu Canyon is the only canyon with a negative offset that is not at the end of its littoral cell. Sand that passes it reaches beaches as far downcoast as Marina del Rey. In the pre-1966 period, perhaps 120,000 cubic meters per year was transported alongshore on a 50-m wide shallow platform between the rim and the shoreline (Moffatt and Nichol, Enginners, 1995). By the 1990's the canyon rim had retreated to within 20 meters or so of a revetment. The fixed location of the revetment prevented the transport platform from retreating as the canyon rim retreated. Rather the platform narrowed so the amount of sand that passed the canyon declined. Other canyons with negative offsets are at or very near the ends of their respective littoral cells. If they did not trap all of the sand that reached them the adjacent shorelines would have progressively advanced out against the natural sediment-blocking structures. This did not happen just upcoast of Point La Jolla (downcoast of Scripps and La Jolla Canyons), and upcoast of Palos Verdes Peninsula (downcoast of Redondo Canyon), attesting to the fact the canyons captured the net transport rate.

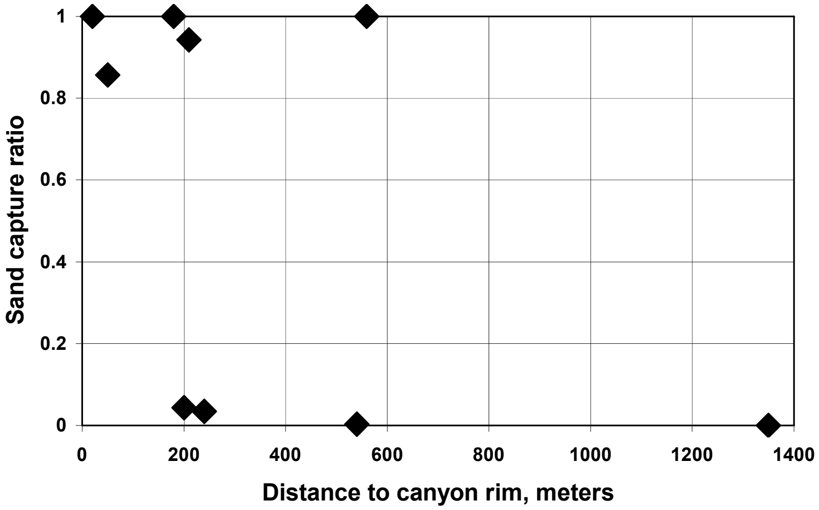


Figure 45. Sand capture ratio versus the distance to canyon rim.

5.2 Rocky Stream Deltas

River and especially stream deltas are common shallow water features in southern California. They are notable because they retain shallow sandy beaches around the perimeters of seaward-bulging shorelines that in other circumstances would be rocky. In addition, some of them transform ordinary waves into desirable peaks for surf riding. Because they project above the surrounding shoreface and extend all the way to the coast, the sandy perimeter beaches they retain are just narrow bands. Most begin above mllw. The seabed is typically composed of deltaic cobbles and small boulders seaward of the beach. For many people this surface affects inwater recreational pursuits, especially those that involve walking. Figures 46 through 49 and Figure 3 are scenes of typical perimeter beaches in the lee of rocky deltas in southern California.

Figure 46. Perimeter beach at the mouth of Topanga Creek (east end of Malibu).

Figure 47. Cobble surface of the Topanga Creek delta at low tide.

Figure 48. Perimeter beach at the mouth of San Mateo Creek near San Clemente.

Figure 49. Revetment protecting homes on the sand spit in the lee of the rocky delta of the Tijuana River at Imperial Beach.

Perimeter beaches in the lee of stream and river deltas fringe about 33 km of the study coast. They are most common between Point Conception and Santa Monica where near-coast mountains and high—gradient streams provide the ideal environment for the transport of cobbles and boulders during freshets. Perimeter beaches, however, are found in other places as well as illustrated in Figures 48 and 49.

Delta-retained beach parameters provide useful information on their characteristics. These data are listed in the spreadsheet in Table 4A in the Appendix. The 22 perimeter beaches on this list are those in which a ribbon of sand was present in all seasons around the landward periphery of a delta. Perimeter beach length is the straight-line, shore-parallel distance between the junctions of the curved (approximately parabolic) segment of the delta-retained beach with the adjacent shoreline. The projection distance is the distance between the apex of the shoreline projection and the line connecting the landward limits of the shoreline bulge. The area between shoreline and the landward line is usually not all sand. In most places, like at San Mateo Creek shown in Figure 48, it includes uplands. Figure 50 clearly shows the relationship between the length and projection distance of delta-retained perimeter beaches in southern California. For every meter these bulges extend along the coast they project a fifth of a meter seaward. Perimeter beaches are retained by deltas in all longshore sediment transport environments.

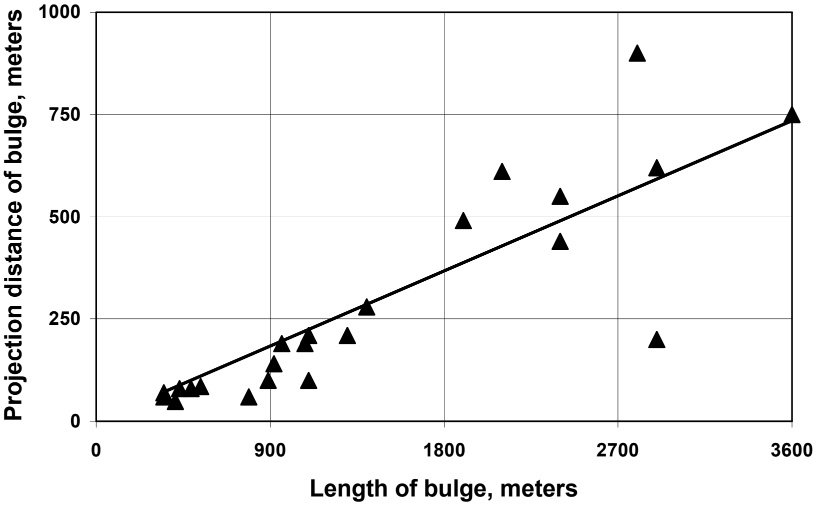


Figure 50. Relationship between the distance the shoreline bulges seaward and the alongshore length of perimeter beaches retained by river and stream deltas.

5.3 Reefs

Natural reefs that retain a sandy shoreline bulge in all seasons are most common in the same locations that rocky stream deltas retain perimeter beaches. Only six of 34 reef-retained perimeter beaches were not located between Point Conception and Topanga Point in Malibu. Most reefs are fully submerged. All retain shoreline projections over 20 meters, but average 170 m (spreadsheet at Table 5A in Appendix A). In total they retain about 28 km of sandy beach. Submerged reefs are inferred to exist because there is a perimeter beach around a bulge in the coast remote from a stream discharge point. Figure 51 shows the relationship between the projection distance and the straightline length of the delta-retained perimeter beaches. Very similar to delta-retained beaches, for every meter a reef-retained perimeter beach extends along the coast it projects a fifth of a meter seaward. By far the largest perimeter beach is retained by Sand Point reef.

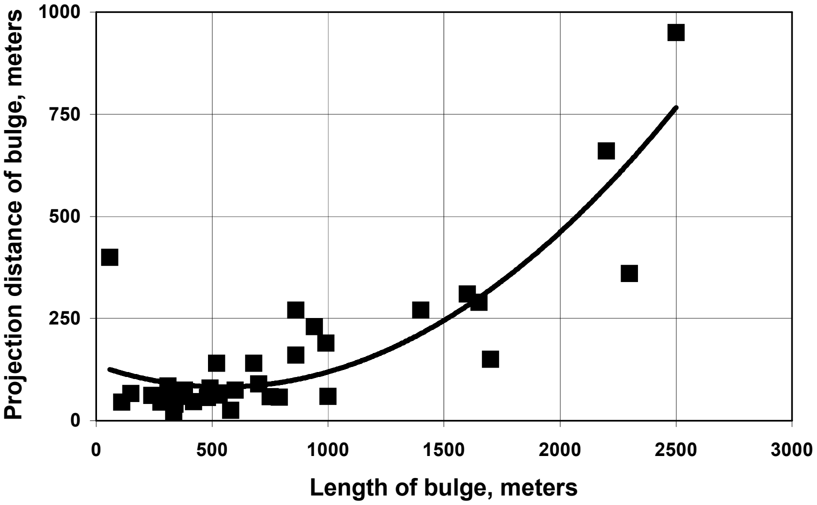


Figure 51. Relationship between the distance the shoreline bulges seaward and the alongshore length of perimeter beaches retained reefs.

Sand Point reef retains a huge projecting sand spit in its lee (Fig. 52). Bathymetry is not definitive in this area, but due to the large size of the reef it is possible to draw some conclusions. That portion of the reef above mllw on the most recent chart is about 200-m parallel to, and 60-m normal to the coast. The rocky tips are apparently bare at mllw. The area above a depth of 2 m (mllw) is approximately 700-m long parallel to and 450-m long normal to the coast. The perimeter beach is a narrow sand spit about 2300-m long. It projects out about 360-m from the line connecting its alongshore ends. The Sand Point spit protects a large wetland (The Estero) in the same way West Newport and Balboa Peninsula protect Newport Bay (Fig. 42).

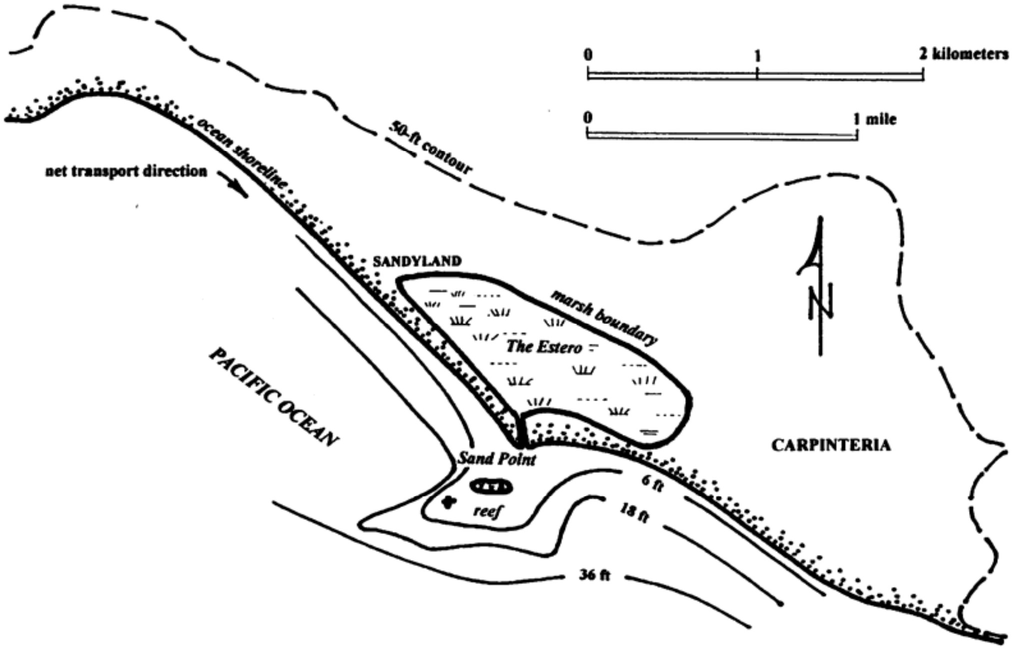


Figure 52. Barrier beach (perimeter beach) retained in the lee of Sand Point reef near Carpinteria.

An interruption of the sand stream reaching Sand Point occurred when about 1.35 million cubic meters (cm) accumulated around Santa Barbara Harbor between 1927 and 1933. The zone of sand deficit probably reached Sand Point in 1937 or 1938 when the apex of the perimeter beach in the lee of the reef began retreating. In 1969 the point was about 150-m landward of its 1938 position. The approximately 240,000 cubic meters per year (cmy) easterly net transport rate was artificially reestablished at Santa Barbara Harbor in 1933, but the amount deposited near the harbor was never replaced. Beaches up and downcoast of Sand Point experienced less permanent retreat than the beach closest to the reef. Quite possibly, shoreline retreat at the point reduced the effectiveness of the reef, thus causing its further retreat.

6.0 BEACHES IN HOOK-SHAPED BAYS

Sixty percent of all structure-retained beaches in central and southern California are located within hook-shaped bays. Occupying over 40% of the entire ocean coast south of Point Estero, these bays are bounded by two structures - the vast majority of which are natural. Hooked bays retain some of the most stable and some of the longest sandy beaches in the region. On the other hand, some of the most damaging erosion has occurred in places where these bays began forming following the construction of artificial structures. Substantial shoreline adjustments, both beneficial and adverse, also occurred the where the beach-retaining function of natural structures was altered by artificial ones.

The importance of hook-shaped bays has been recognized for nearly a century (Johnson, 1919). In the past 30 years Silvester (i.e., 1970, 1976) and his colleagues (i.e., Hsu et al., 1989) at the University of Western Australia have studied and quantified these bays. They refer to them as headland controlled bays. We use a somewhat different nomenclature to incorporate the unlike ways in which the structures function as a pair to retain a single beach between them. This approach also allows us to include both natural and artificial structures in our analyses. We refer to the larger of the two structures (Fig. 53) as the diffraction structure since it functions to block and diffract waves. Examples are rocky headlands (most common), stream and river deltas, reefs, groins, jetties, and shore-connected breakwaters. Diffraction structures are responsible for the curved portion of the bay and in the study region they are always at their north or west end. We call the smaller structure at the south or east end the anchor structure because it functions to fix that boundary. A characteristic feature of a hook-shaped bay is a straight segment of shoreline adjacent to the anchor structure. Most anchor structures are headlands, stream and river deltas, and near-coast shore-connected reefs.

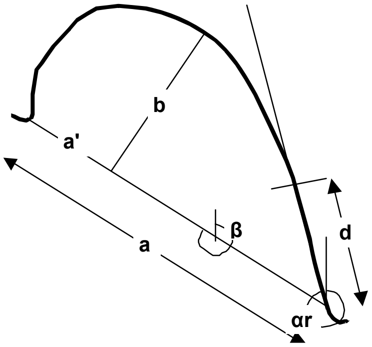


Figure 53. Definition sketch, hook-shaped bays and beaches.

In a fully developed bay, the sandy beach is continuous from the diffraction structure to the anchor structure. This is most likely where the diffraction structure is a delta or reef. It is almost never the case where the diffraction structure is a massive rocky headland. In many locations the evolution of the shoreline was halted against a headland. The Santa Maria River hook-shaped bay is an example. Figure 54 shows the central portion of the 22-km long, wide, and continuous sandy beach with Mussel Point, the anchor structure, in the distant background. Figure 55 shows the rocky north quarter of the bay near Point San Luis. This part of the bay contains pockets of sandy beach. Avila and Olde Port Beaches are two of them. Shell Beach is a rocky segment without substantial sandy beach. Point San Luis was the natural diffraction structure, but the Port

San Luis Breakwater moved the diffraction point toward Mussel Point and usurped its role a century ago. An example of smaller hooked bays is at Figure 4.

Figure 54. Wide sandy beach in the central portion of the Santa Maria River hook-shaped bay; Mussel Point the anchor structure is in the far upper center (San Luis Obispo County).

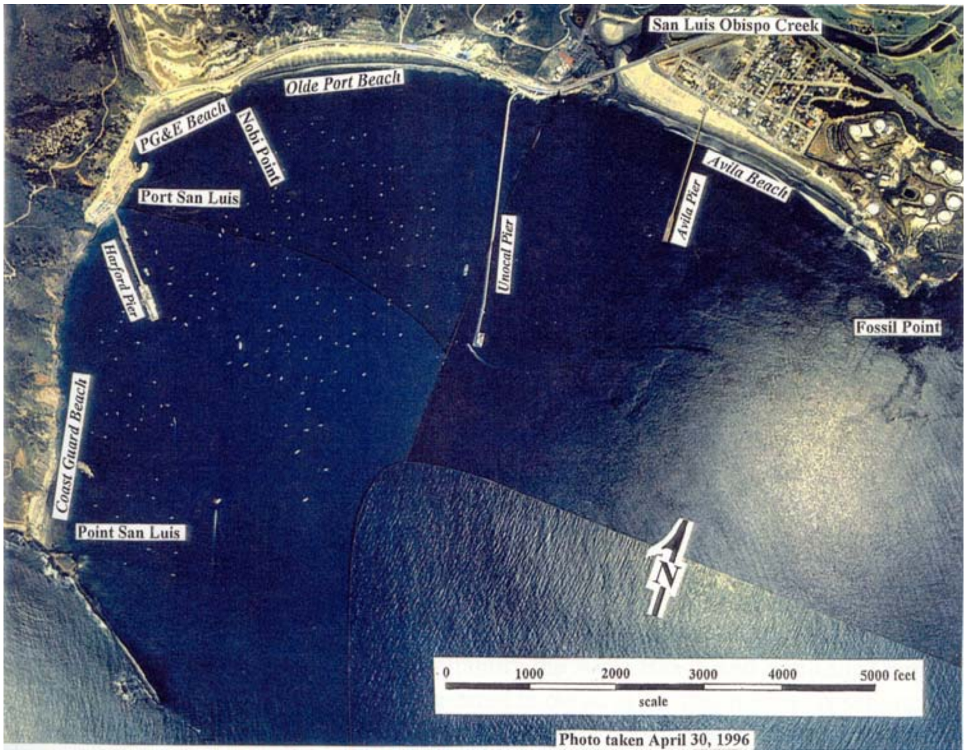


Photo taken April 30, 1996

Figure 55. Rocky coast with small sandy beaches in the north part of the Santa Maria River hook-shaped bay; Point San Luis the diffraction structure is at the lower left (San Luis Obispo County).

6.1 Benefits and Adverse Impacts

As shown in Figure 56, almost all beaches along the central California coast from Point Estero (north of Morro Bay) to Point Conception are retained within mature, natural hook-shaped bays. The same is true for most of the beaches in Malibu and many of the south-facing beaches between Point Conception and Ventura. The Silver Strand Littoral Cell in San Diego is a hook-shaped bay retained in the lee of Point Loma. Prior to the construction of a breakwater that protects Los Angeles and Long Beach Harbors, a natural hooked bay retained beaches between Point Fermin and the seacliffs at Huntington Beach. Hook-shaped bays occupy 240 km of the central and southern California coast.

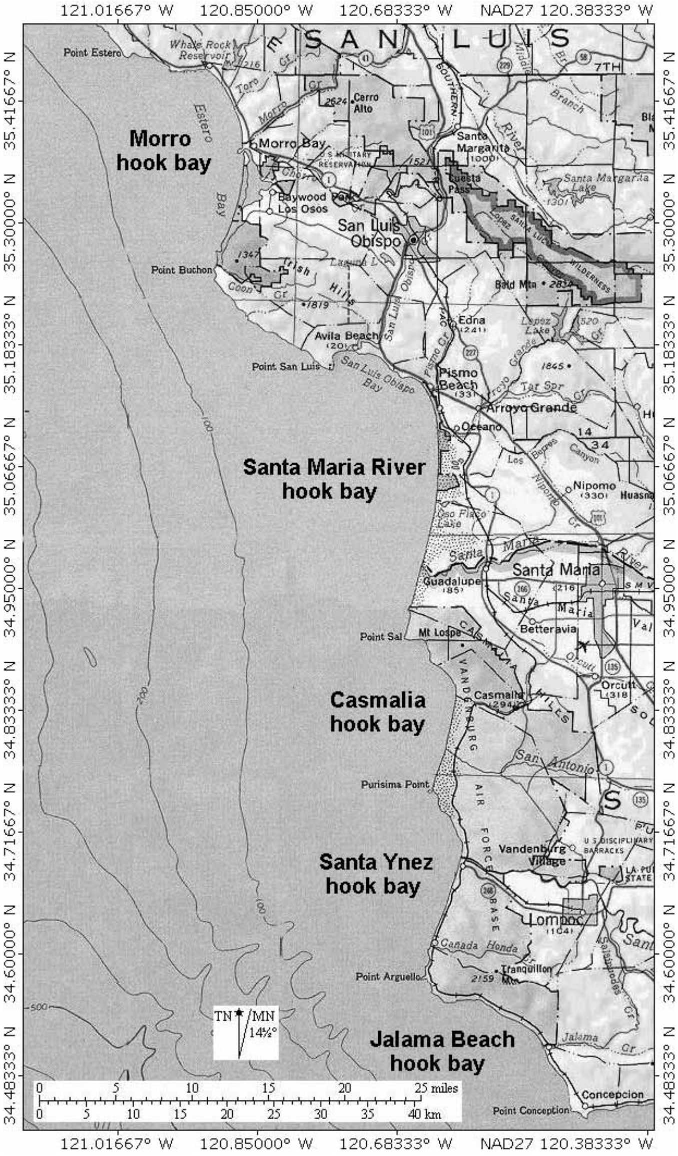


Figure 56. Hook-shaped bays north of Point Conception.

The most serious potential adverse impact of any groin, jetty, or shore-connected breakwater in southern and central California is the development of a hook-shaped bay downcoast of the structure. Its evolution will most likely be at the expense of the sandy beach and property behind it. That is, it will be created by erosion rather than accretion processes. This is in contrast to the accretional formation of a fillet, salient or perimeter beach, if allowed to develop naturally. To date there have been three human reactions to even the beginning of an evolutionary sequence that would create a hook-shaped bay. The first is to revet the shoreline, as the US Navy has done downcoast of the last of three groins at Point Mugu (Fig. 30). A more common response has been to bypass sand to arrest the progressive erosion that produces a hook-shaped bay. Programs for this purpose are currently in operation at Santa Barbara, Ventura, Channel Islands, and Oceanside Harbors. A third, but similar response is to periodically replenish the downcoast beach to prevent a hooked bay from forming. This is the present Corps of Engineers tactic at Surfside Colony in northern Orange County.

6.2 Structure - Beach Responses

Two structure parameters and four shoreline shape and orientation parameters define the first order configuration of a hook-shaped bay. Structure parameters, as shown in Figure 53**,** are: (1) the distance between the diffraction and anchor structures, a, and (2) the bearing of a line – the control line - between the diffraction and anchor structures, B. Four geometric parameters define the bay shoreline: (1) the perpendicular distance between the control line and the shoreline where the bay is most indented, b, (2) the distance along the control line between the diffraction structure and the maximum indentation line, a', (3) the bearing of the straight shoreline at the anchor end of the bay, α, and (4) the length of the straight shoreline, d. The wave obliquity angle, $\gamma = \alpha - \mathrm{B}$, is the angle between the bearing of the control line and the bearing of the straight shoreline adjacent to the anchor structure.

Five conditions serve as guides to determine whether a hook-shaped bay is likely to begin forming downcoast of an artificial structure. These conditions were found to be attributes of all hook-shaped bays in southern and central California. First, the region downcoast of the structure must be susceptible to erosion. Hook-shaped bays do not form where resistant rock prevents it. And, as shown in Figures 3 and 55**,** they do not fully develop if resistant rock prevents it. Second, the alongshore component of wave energy flux must be substantially greater than zero along the control line and directed toward the anchor structure. That is, the angle between the predominant wave approach direction at the control line (but not necessarily along the straight segment of shoreline near the anchor structure) must open toward the anchor structure. Third, the diffraction structure must be sufficiently high and long that it blocks a significant portion of the wave energy that approaches from the predominant upcoast direction. Fourth, the diffraction structure must diffract waves at its tip. And fifth, the anchor structure must not retain a straight beach as far upcoast as the diffraction structure.

These conditions define the functions of the two retaining structures in maintaining the hook shape. They also identify differences between hook-shaped and pocket beaches. A specific net longshore sediment transport rate is not a condition for a hook-shaped bay. The net rate entering and leaving natural hooked bays in the study area range from near zero to over 200,000 cmy. The net rate also varies within some of the large hooked bays. Sand is delivered at point sources such as river mouths, and lost at other places such line sinks at dune fields. In many it is also transported out around the anchor structure. The Santa Maria River hook-shaped bay is an example of this complex longshore transport situation.

Wave blocking and diffraction control the amplitude of wave energy and the wave approach direction downcoast of a diffraction structure. Hence these functions define the alongshore component of wave energy flux and the amount of sand that is transported parallel to shore. Waves that approach from upcoast are blocked, reducing the amount of wave energy that reaches the downcoast shoreline in comparison to what it would be if the structure were absent. Wave diffraction also affects wave amplitude and direction. Diffraction refers to wave transformation from the tip of the structure to the beach as incident energy is spread sideways along the structure and outward in an arc. Wave amplitude declines with distance away from the truncation point. The amount of diffracted energy increases with wave height, period, and water depth.

The anchor structure is equally as important as the diffraction structure in defining the shape and size of a hook-shaped bay. It regulates the amount of sand that is carried around it, and if it is a sediment-blocking structure, it is partially responsible for the bearing of the straight shoreline, α (Fig. 53). The position and separation distance between the two structures define the length of the bay and the bearing of the control line. Bay length, a, is the most important factor in forecasting the indentation distance, b, the indentation position, a', and the length of the straight shoreline, d.

6.3 Beach Performance

Measurements were made of 51 hook-shaped bays to quantify the shoreline parameters shown in Figure 53. Results are in the Table 6A spreadsheet in Appendix A. Most bays lack proper names so the name of a prominent feature, such as a beach, headland, river, or town, is used to identify them for easy reference. These bays provide a substantial population to develop empirical relationships to define their shoreline configuration as a function of the two structure parameters, a and B. When these parameters are given, the shape of the bay as defined by the shoreline parameters can be forecast to the extent relationships between the structure and shoreline parameters are quantified.

6.3.1 Indentation Distance

Figure 57 is a scatter plot showing the relationship between the ratio of the indentation distance to the length of the control line, b/a, and the obliquity angle, γ. Southern and central California hook-shaped bay data are shown as squares**.** Also included are data compiled by Bishop (1982). His data (rhombs) are from personal measurements in Lake Erie and Lake Ontario plus data selected from literature sources in which the sites are Japan, a few in California (north part), South Africa, and Australia. The best second-order polynomial curves to both data sets fall nearly atop one another. Further, the scatter is similar for both data sets as evidenced by the r^2 = 0.79 correlation for Bishop's data and r^2 = 0.79 for the more numerous California data acquired in this study. Bishop's data were included to illustrate how close the California data follow the empirical indentation distance versus obliquity angle relationship from other locations. Both the Bishop and California curves were constrained to pass through the origin, a necessary boundary condition. The equation for the California data is

$$\frac{b}{a} = -5.28x10^{-5}\gamma^2 + 9.86x10^{-3}\gamma \qquad (3)$$

in which $\gamma = \mathrm{B} - \alpha$. Equation 3 is applicable within the range 210< B <360 degrees and 5< γ <46 degrees.

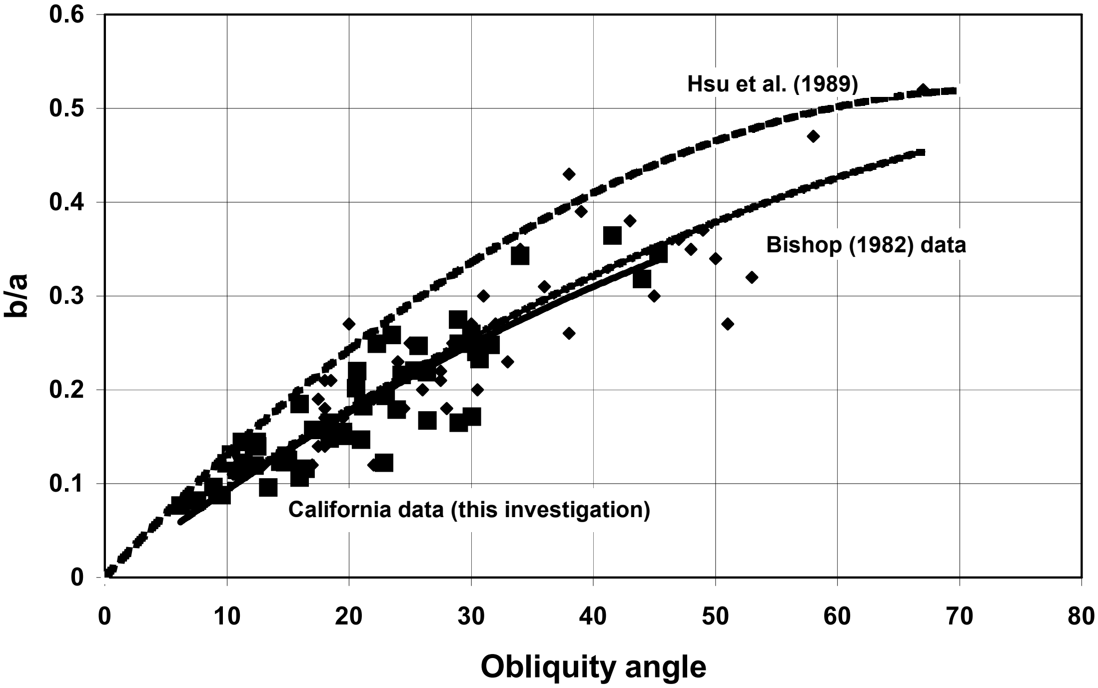


Figure 57. Relationship between b/a and γ.

More investigations of hook-shaped bays have been made to define the Equation 3 relationship than any other. Silvester (1970) was the first and the ratio shown for Hsu et al. (1989) in Figure 57 is a direct resultant of his early work. The hook-shaped bays used in Hsu et al's analysis are reported to be in static equilibrium. Static equilibrium refers to a state where there is no sediment entering or leaving the bay, sediment losses are negligible, and the net longshore sediment transport rate is zero. The version of the indentation ratio published by Hsu et al., (1989) is

$$\frac{b}{a} = -9.4x10^{-5}\gamma^2 + 1.4x10^{-3}\gamma . \qquad (4)$$

An inspection of Figure 57 indicates the southern and central California data and Bishop's (1982) data generally fall well below Hsu et al's (1989) curve. This deviation increases as the obliquity angle increases. Indeed, the Hsu et al. curve forms a nice upper limit for the California and Bishop data. An explanation for the discrepancy might be the difference between static equilibrium bays used to define Equation 4, and the non-static bays used to develop the California and Bishop data sets. The curve for bays in static equilibrium would fall above the curve for bays with sediment inputs. Paradoxically though, the California datum points near the Equation 4 curve are in net longshore transport environments where the rate is large, not in static bays. It is therefore not easy to explain the 4 to 17 degree difference in obliquity angles for the same indentation ratios. It would, however, be difficult to accept any relationship other than empirically derived Equation 3 to forecast hook-shaped bay characteristics in the study area.

The indentation distance is also a clear function of the bay length as shown in Figure 58. This figure indicates the relationship is not linear and is best fit by a second-order polynomial of the form

$$b = 7.26x10^{-6}a^2 + 0.159a \qquad (5)$$

which is dimensional in meters with $r^2 = 0.98$.

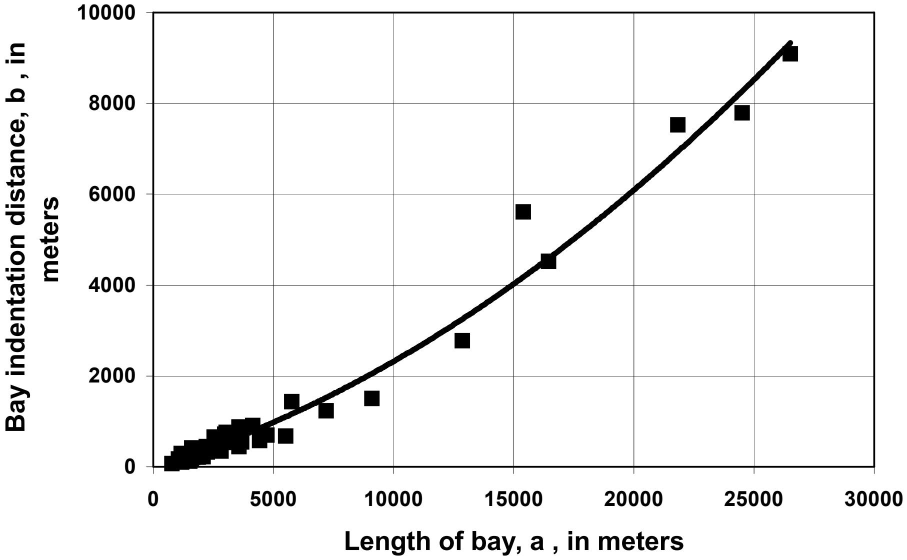


Figure 58. Relationship between b and a for hook-shaped bays.

6.3.2 Indentation Location

Bay size dictates the location of maximum indentation, a', as shown in Figure 59. This location on the control line referenced to the diffraction headland (Fig. 53) progressively declines from about 0.5 a for the largest hooked bays to about 0.25 a for the smaller ones. The location of maximum indentation is best represented by the second-order polynomial fit to a, such that

$$a' = 2.15x10^{-6}a^2 + 0.396a \qquad (6)$$

which is dimensional with units in meters with $r^2 = 0.95$. Silvester and Hsu (1997) suggest the location of the maximum indentation distance is a function of the distance between headlands and the obliquity angle, but we found scant evidence of that relationship in the California data as shown in Figure 60. The correlation coefficient for the curve in this figure is 0.22.

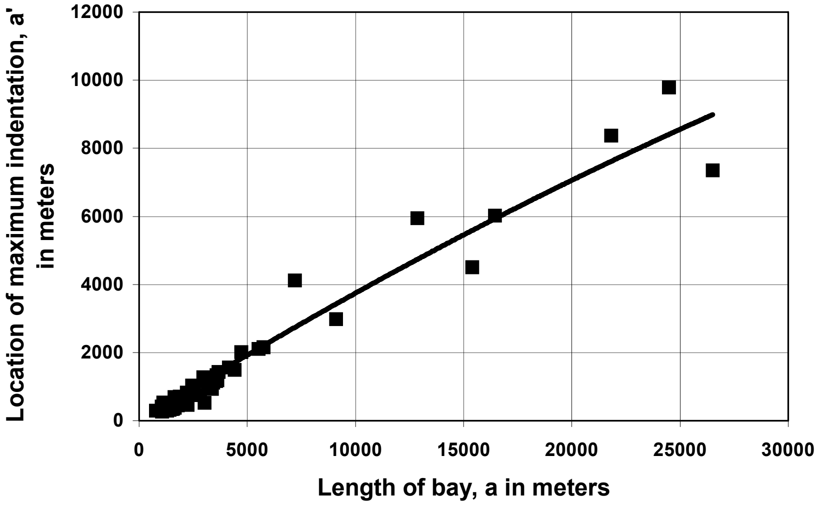


Figure 59. Relationship between $a^{'}$ and a for hook-shaped bays.

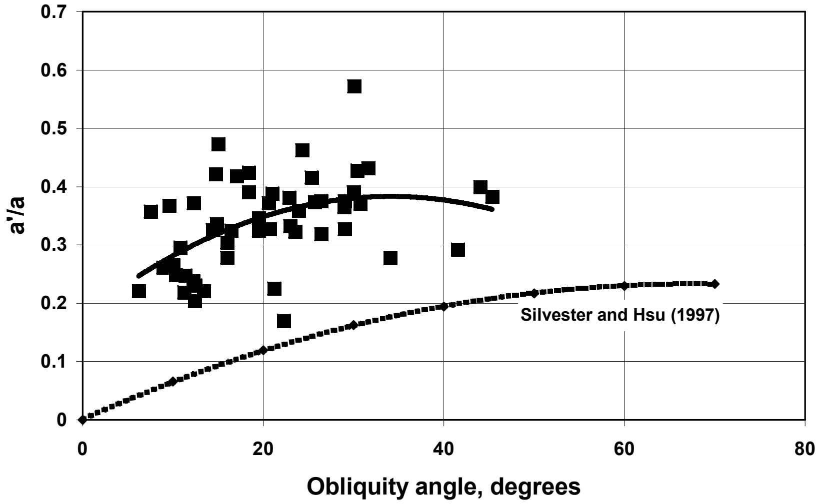


Figure 60. Relationship between $a^{'}/a$, and γ for hook-shaped bays.

6.3.3 Orientation of the Straight Shoreline

The orientation of the straight shoreline (Fig. 53) is equal to the bearing of the control line plus the obliquity angle. An inspection of the curve that best describes the obliquity angle of southern and central California bays, shown in Figure 61, indicates

$$\alpha = 1.0728\mathrm{B} \qquad (7)$$

with a correlation coefficient of 0.94. Both bearings are in degrees true north and applicable in the range $210 < \mathrm{B} < 360$. Thus, the obliquity angle increases from about 17 degrees when the control line bearing is 230 degrees (close to southeast-northwest) to about 26 degrees when the control line bearing is 360 degrees (north-south).

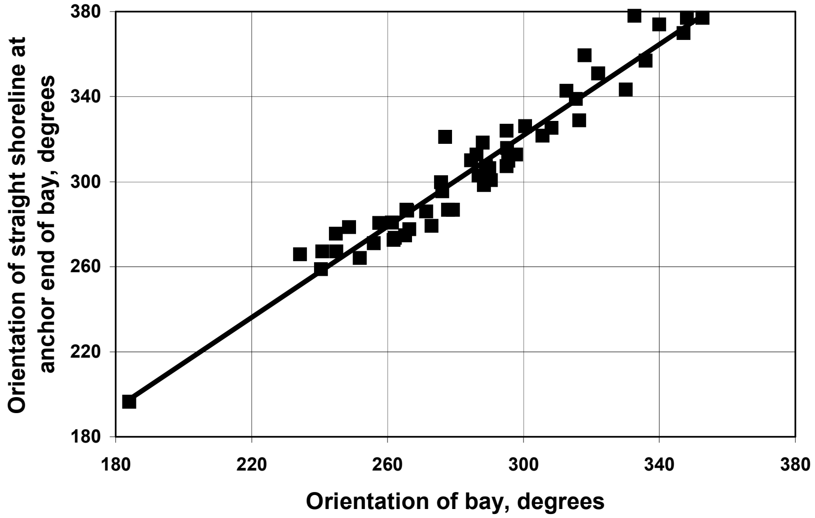


Figure 61. Relationship between α and B for hook-shaped bays.

The rather surprising Equation 7 finding was tested and no correlation was found between the bearing of the straight shoreline and its latitude, counter to what one might expect for a latitude-dependent wave climate. It is especially interesting since the coastal wave climates vary north to south of Point Conception. Offshore islands south and east of the point shadow the region while the coast to the north is exposed to deepwater waves from a full 180-degree arc of the Pacific Ocean.

The expansion of the obliquity angle with control line bearing is either due to the more north-south orientation of the more westerly-facing bays or because those are the largest bays. The best correlation we found incorporated the obliquity angle as a function of the ratio of the indentation distance to the bay length in Equation 3. This yielded the relationship containing both the control line bearing and length, shown in Figure 62

$$\alpha = \mathrm{B} + 8.42x10^{-4} a + 18.4 \qquad (8)$$

in which $r^2 = 0.97$.

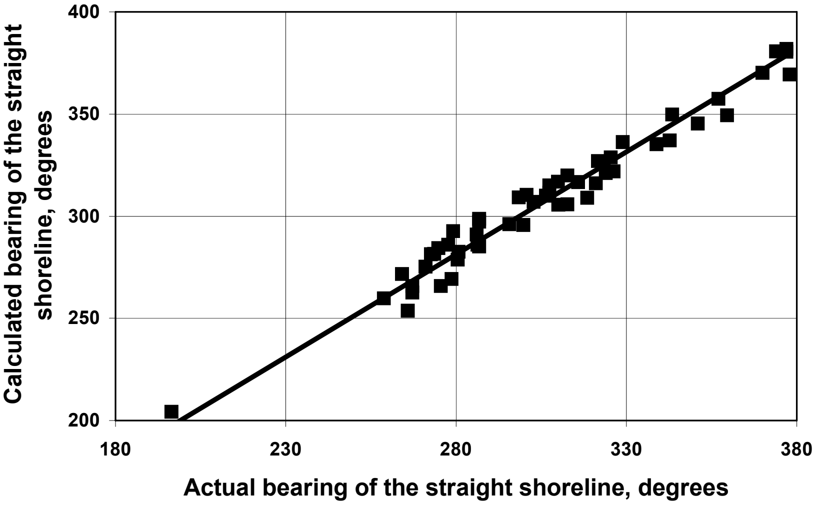


Figure 62. Relationship between calculated α (Eq. 8) and the actual α for hook-shaped bays.

6.3.4 Length of Straight Shoreline

The length, d, of the straight shoreline that abuts the anchor headland is proportional to the length of the control line as shown in Figure 63. The best-fit to the curve is

$$d = 8.68x10^{-10} - 2.97x10^{-5}a^2 + 0.438a \qquad (9)$$

where the extensive scatter results in a correlation coefficient of 0.77 and a near-constant ratio of $d \approx 0.23a$. This relationship suggests the straight shoreline is controlled primarily by the bearing between the two headlands, and not solely by the anchor headland. A discernable relationship was also found between the ratio, d/a, and the obliquity angle as illustrated in Figure 64, in which

$$\frac{d}{a} = 4.17x10^{-4}a^2 - 3.34x10^{-2}a + 0.852. \qquad (10)$$

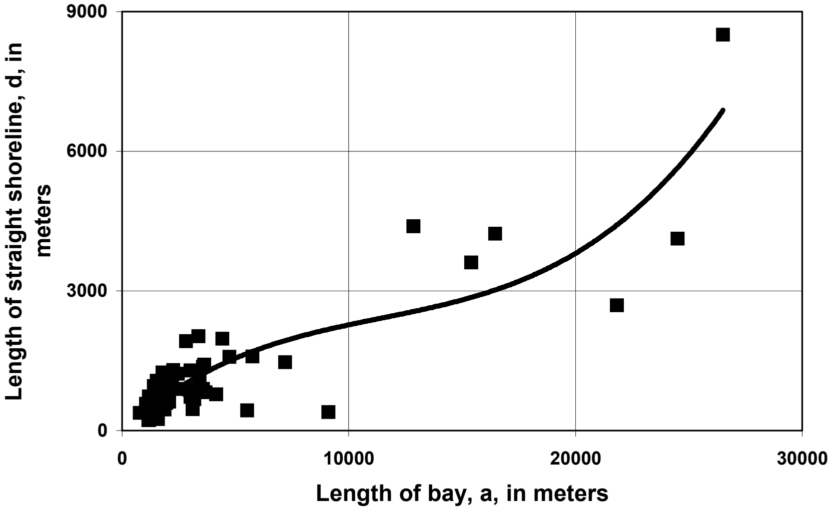


Figure 63. Relationship between d and a.

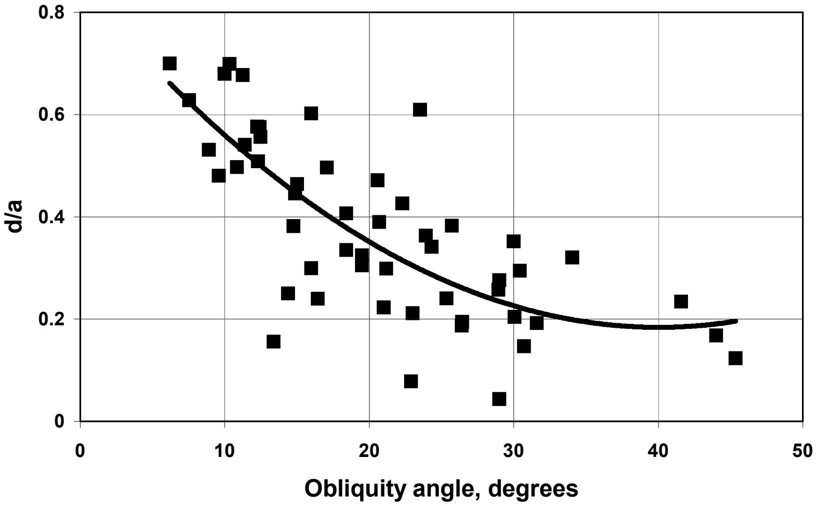


Figure 64. Relationship between d/a and γ.

7.0 BEACHES IN POCKET BAYS

Pocket bays occupy only about 8% of the coast south of Point Estero, but they contain some of the most stable and popular beaches in southern California. Like beaches in hooked bays, those in pocket bays are retained by two structures. Unlike hooked bays quite a few pockets are retained by artificial structures. Examples where one of the two structures is artificial include Ocean Beach (San Diego) shown in Figure 5, Big Corona Beach (Newport Beach) shown in Figure 65, and Redondo Beach. Two artificial structures retain East and West Beaches at Seal Beach. Natural headlands retain the multitude of pocket beaches in Laguna Beach, such as Emerald Bay shown in Figure 66.

Figure 65. Big Corona Beach retained by a natural headland and the east jetty at the entrance to Newport Bay.

Figure 66. Emerald Bay, a pocket beach at Laguna Beach.

A pocket bay might be considered a special case of a hook-shaped bay, but substantial differences in the way beaches perform in them warrant their separate consideration. This is especially true when one is dealing with proposed artificial retaining structures. In contrast to the diffraction and anchor structures that retain hook-shaped bays, pocket bay structures function in similar ways to contain a sandy beach between them. The net longshore sediment transport rate within pocket bays is always negligible. It is worth noting, though, that a hook-shaped bay rather than a pocket bay may develop if the bounding headlands project different distances from the coast even in places where the regional net rate is zero. An example is the shallow hooked bay that retains Mission and Pacific Beaches. False Point projects much further to the west than the jetty at the entrance to Mission Bay. Just across the entrance to Mission Bay, a natural headland and a jetty that are of similar length retain the pocket at Ocean Beach. While in certain situations hook-shaped bays develop as erosional features downcoast of groins, jetties, and shore-connected breakwaters, adverse impacts associated with artificial structures that retain pocket bays are negligible.

Pocket beaches range in shape from nearly straight, but still slightly indented in the center, to notably concave seaward. Crescent Bay in Laguna Beach (Fig. 67) was named for this characteristic planform. Wave blocking and diffraction are the functions that control the shape of the shoreline near the structures in a pocket bay. Sediment blocking is what retains the sand within them. A definition sketch for pocket bays with the symbols used in this report is at Figure 68.

Figure 67. Crescent Bay, a pocket beach in Laguna Beach.

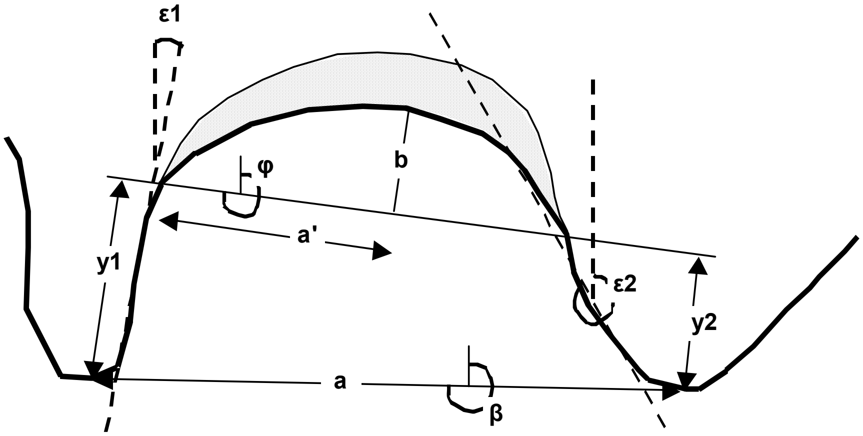


Figure 68. Definition sketch: pocket bay and beach.

As just noted, the primary function of structures that retain pocket beaches is to block sediment and prevent it from passing out of the pocket. Most, but not all, pocket beaches are retained between sediment-blocking structures. One exception is the prominent shoreline bulge that retains a near-zero net transport environment on Balboa Peninsula. This feature, retained by Newport Submarine Canyon, restricts the movement of sand between the peninsula and West Newport (Fig. 69). The west jetty at Newport Harbor is the other structure that retains the beach along Balboa Peninsula. Pocket bays are essentially closed systems. In most of them, sand contributions tend to be small and losses are likewise small. This is not universally the case though. In a few places there is a substantial seaward-directed loss across the shorebase, but it is balanced by contributions from land sources and shoreline stability is thus maintained.

Figure 69. Shoreline projection between Balboa Peninsula and West Newport.

7.1 Distribution

Sixty-one pocket bays occupy 44 km of the southern and central California coast. These bays are most prevalent as natural features between the entrance to Newport Bay and Dana Point. Natural sandy pockets are also found along the west-facing borders of many of the massive, rugged headlands that function as diffraction structures to retain hook-shaped bays. This includes those north of Point Conception, Palos Verdes Peninsula, and the wide, projecting headlands at La Jolla and Point Loma. Pocket beaches are also found nested in the rocky portion of some hook-shaped bays near the diffraction headlands.

Table 4 is a list of artificially retained pocket beaches in the study area. Each of these bays exhibits symmetry. Each lacks preferential straight beach at one end. The net longshore sediment transport rate is low to negligible along all of them. Each is nearly stable. None require a substantial amount of beachfill to maintain it. And all are located south of King Harbor.

Table 4. Artificially retained pocket beaches in southern California.

Pocket beach	North or west retention structure	South or east retention structure	Remarks
Ocean Beach	Jetty at the entrance to Mission Bay	Headland at Naragansett Avenue	Wide and stable pocket beach
Big Corona Beach	East jetty at the entrance to Newport Bay	Small headland in Corona del Mar	Wide and very stable pocket beach
East Beach (Seal Beach)	Groin at Seal Beach Pier	West jetty at Anaheim Bay	East Beach loses sand to West Beach
West Beach (Seal Beach)	Jetty at the outlet of the San Gabriel River	Groin at Seal Beach Pier	Sand the moves from east to west around the groin is bypassed
Cabrillo Beach	Palos Verdes headland (Point Fermin)	Groin	Artificially created pocket along the Los Angeles – Long Beach breakwater
Redondo Beach	Groin	Palos Verdes headland	Very stable artificially enhanced pocket

7.2 Structure-Beach Response

A pocket bay has certain characteristics that identify and distinguish it from hook-shaped bays. The six attributes summarized in Table 5 must also pertain if a pocket bay is to be artificially created. They are common to all natural and artificial pocket bays in southern and central California.

Table 5. Characteristics of pocket bays in southern and central California.

Condition	Characteristic
1	The net longshore sand transport rate is zero or very near zero in a pocket bay
2	Pocket bay shorelines are near symmetrical; If there is a straight segment it will be near the center of the bay (rather than against the south or east anchor structure as it is in all hook-shaped bays); typically the shoreline is curved adjacent to each retaining structure in a pocket bay

Condition	Characteristic
3	Pocket bays tend to be short; none in southern or central California is more than 4-km long
4	Pocket bays tend to be very stable; sand contributions are usually small and losses are similarly small
5	The two structures that retain pocket bays tend to project similar distances seaward of the general trend of the coast
6	Beaches adjacent to pocket bays are not substantially affected by the retaining structures

7.3 Beach Performance

Using the 61 sets of pocket bay data in Table 7A (Appendix A) it was possible to develop a set of empirical relationships. The most useful is the relationship between the shoreline bearing of a pocket beach and a small number of structure parameters. As with hook-shaped bays, the structure variables are a, the distance between the tips of the structures, and B, the bearing of the control line between the structures (Fig. 68). A third environmental variable, δ, is the bearing of the 10-m isobath as measured on the seabed offshore of and on either side of the bay. Other structure variables were tested: $y_1 - y_2$, the difference in the lengths of the structures, which is not independent of B, and $\varepsilon_1, \varepsilon_2$, the bearing directions of the headlands.

Shoreline variables are φ, the orientation of the shoreline between the headlands, b, the maximum shoreline indentation with respect the locations where the shoreline joins the structures, and a', the location of maximum shoreline indentation from the north or west retaining structure along a straight line connecting the shoreline to the structures. The bay indentation distance (Fig. 68) equal to $((y1+y2)/2)+b$, cannot be determined using an empirical approach because the landward position of the shoreline with respect to the ends of the structures is not primarily structure controlled. Rather it is dependent upon the slope of the shoreface and the balance between the sand input to the bay by stream discharge, seacliff erosion, and artificial beach enhancement, and the volume lost around the headland, over their submerged extensions, and in an offshore direction.

7.3.1 Shoreline Indentation Distance

As with hook-shaped bays, the shoreline indentation distance, b, is primarily controlled by the width of the bay between the retaining structures, i.e., the length of the control line, a, as illustrated in Figure 68. The best fit to the curve shown Figure 70 is

$$b = -4.13x10^{-6} a^2 + 0.112a \qquad (11)$$

in which r^2 = 0.65. The relationship between the indentation distance and the length of the sandy shoreline of the bay is similar. Reflecting the preponderance of natural pockets in the data set, the ratio of the length of the sandy beach to the distance between headlands is 0.85.The indentation ratio does not vary greatly with the difference in the orientations of the shoreline and the control line between headlands, $\varphi - \mathrm{B}$.

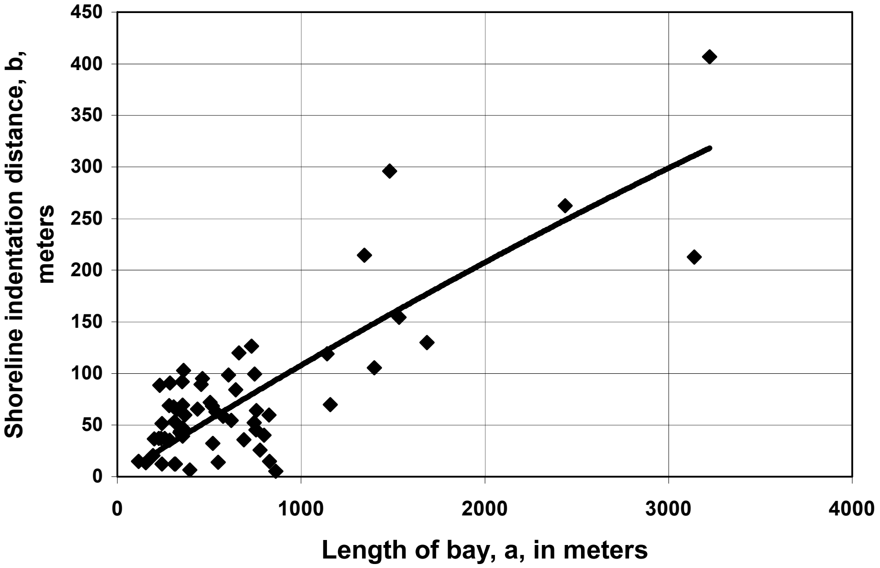


Figure 70. Relationship between b and a for pocket bays.

7.3.2 Indentation Location

Not surprisingly, the location of maximum indentation is, on average, very near the center of the pocket bays as shown in Figure 71. The best fit to the relationship between the indentation location and the length of these bays is the second-order polynomial

$$a' = 3.12x10^{-5}a^2 + 0.397a \qquad (12)$$

with $r^2 = 0.95$. The linear relationship is $a' = 0.505a$, with nearly as good a correlation coefficient of $r^2 = 0.90$.

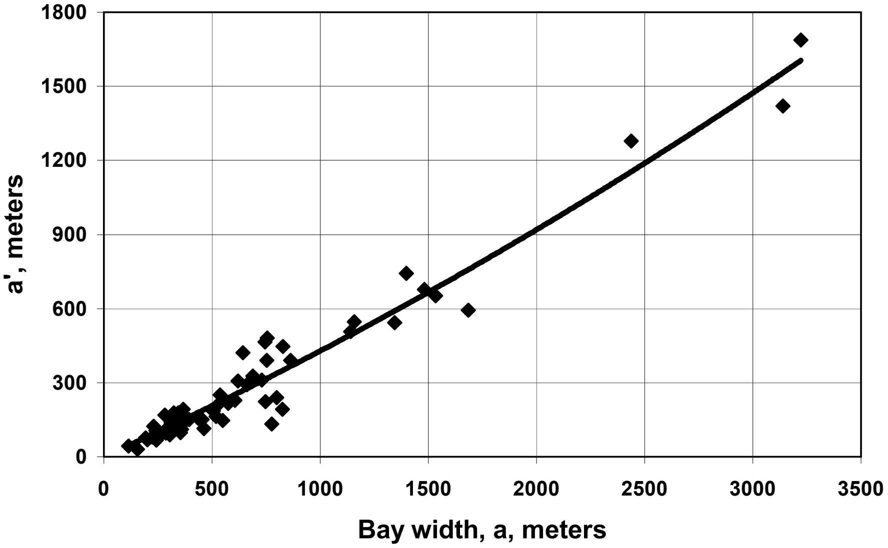


Figure 71. Relationship between a and a' for pocket bays.

7.3.3 Bearing of the Sandy Shoreline

The relationship between the bearing of the pocket shoreline relative to the bearing of the control line is shown in Figure 72. The linear fit to the curve is

$$\varphi = 0.892\mathrm{B} + 35.7 \tag{13}$$

with a correlation coefficient of 0.91. The relationship in Figure 73 between the bearing of the pocket shoreline and the bearing of the 10-m isobath is

$$\varphi = 1.0002\gamma\,. \tag{14}$$

Scatter reduces this correlation coefficient to 0.88. Equation 14 indicates that, on average, pocket shorelines are parallel to the 10-m isobath. A combination of the control line bearing and the bearing of the 10-m isobath improves the correlation. This relationship to estimate the bearing of the shoreline in a pocket bay is

$$\varphi = 0.451\mathrm{B} + 0.500\gamma + 17.8 \tag{15}$$

in which $r^2 = 0.95$. The Equation 15 relationship is plotted in Figure 74.

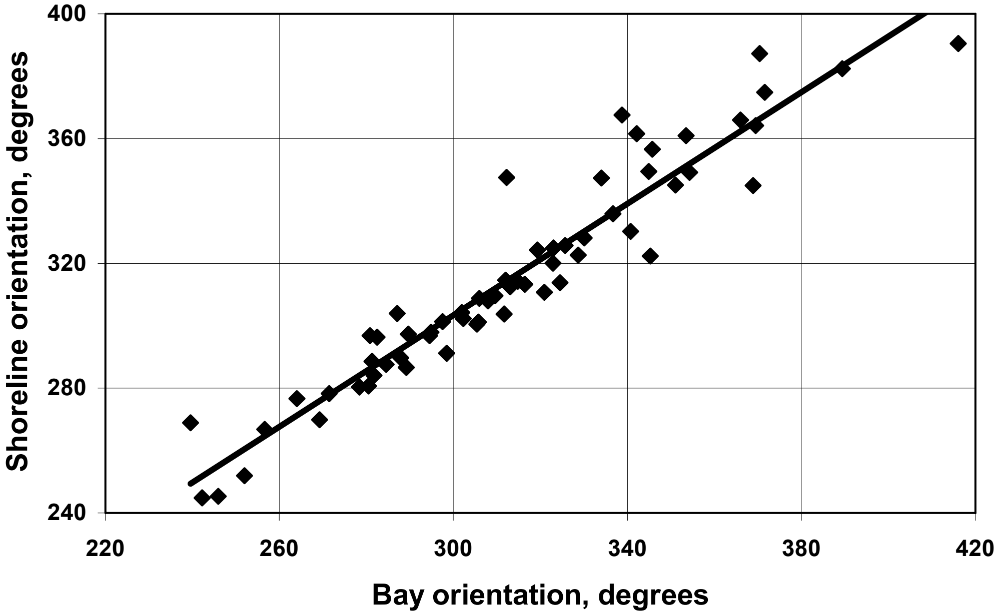


Figure 72. Relationship between φ and B for pocket bays.

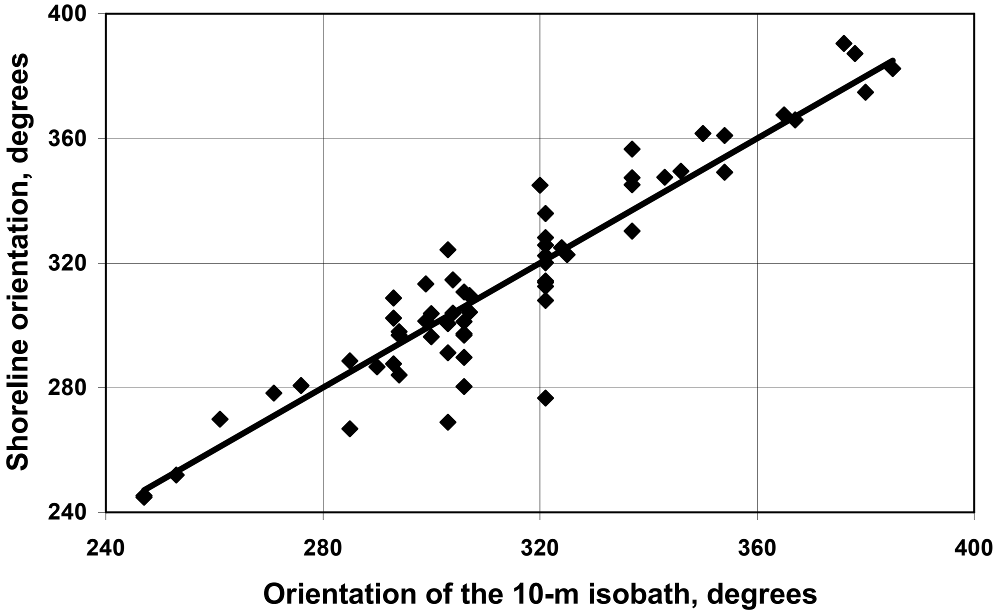


Figure 73. Relationship between φ and γ for pocket bays.

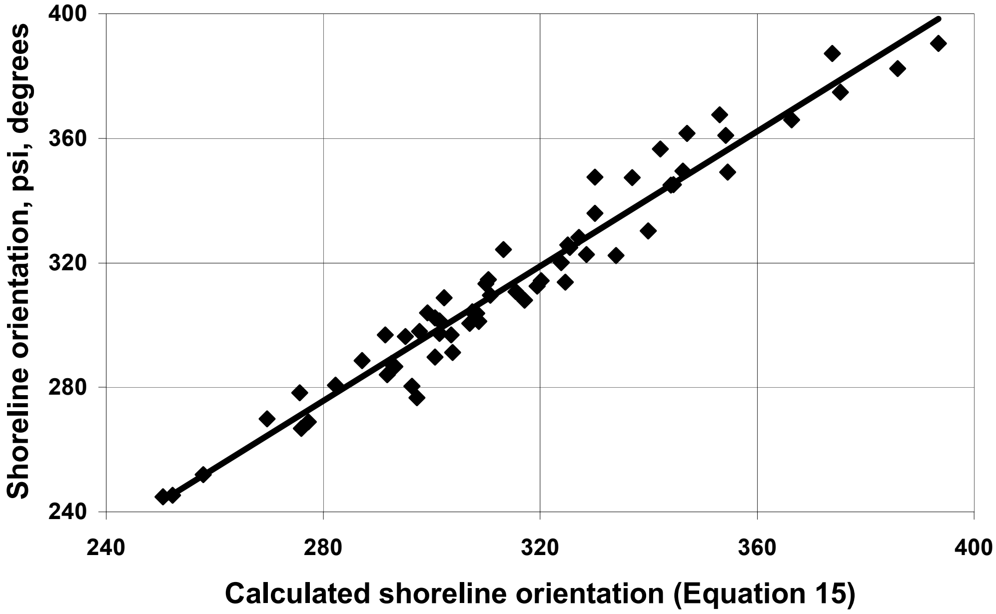


Figure 74. Equation 15 relationship for pocket bays.

The zero net longshore sediment transport rate in a pocket bay requires the predominant wave approach direction be normal to the pocket shoreline. The small to non-existent mean difference between the bearings of the 10-m isobath and the pocket shoreline therefore suggests the refraction effect between a depth of 10 m and these pocket beaches is statistically rather small. The approximately ± 35-degree maximum scatter about the mean in Figure 73, however, indicates there are other factors involved. Three were evaluated: (1) the impact of different bay indentation distances, (2) the impact of headlands that project different distances from the coast, and (3) the impact of headlands that are non-parallel and that are not oriented parallel to the approach direction of the predominant waves. Bay indentation alone seems to have little impact on the orientation of the sandy shoreline. A difference in headland lengths was already considered in Equation 13 in the control line bearing term. Headland orientations, at least in the range ± 30 degrees from a line normal to the general coastal trend, were also found to have little or no impact on the orientation of the bay shoreline. This is probably because most of the headlands flair outward and away from the pocket beaches.

A combination of the hooked bay and pocket bay data produced little improvement in the relationship between the indentation distance, b, and the length of the control line, a. It produces a poorer correlation between the bearing of the sandy shoreline, α or φ, and the bearing of the control line, B, and no improvement in the relationship between the indentation location, a', and a.

8.0 RESULTS: PROS AND CONS OF ARTIFICIAL BEACH RETENTION STRUCTURES

Natural structures retain beaches where they would not otherwise exist. They retain wider beaches where, in the absence of the rocky headland, river or stream delta, reef, or near-coast submarine canyon, they would be narrower. Natural retention structures were here before cities, roads, railroads, harbors, and all the other belongings of a modern society. They are scenic background that sets the rugged, attractive central and southern California coast apart. Many beaches retained by natural structures are in a state of near dynamic equilibrium. Because they have not evolved in recent time, it would for be difficult to develop a set of criteria to evaluate their performance. A baseline from which to make comparisons is lacking. If there have been changes, it was usually because of some human intervention. Artificial structures are a different proposition. Their performance is known. The evolution of beaches they retained and shorelines they adversely impacted have been documented, at least qualitatively. California is living with the effects.

Accordingly, the assignment of negative impacts must focus exclusively on groins, jetties, and breakwaters – artificial sand retention structures. A description of the uneven distribution of the different kinds of structure-retained beach provides an introduction to a discussion of the benefits and adverse impacts of artificial structures. Separate sections address the effectiveness of groins, adverse impacts of sand denial by groins, jetties, and breakwaters, adverse impacts of hook-shaped bays that form downcoast of these structures, and impacts that occur when natural hook-shaped bays are altered when some harbor breakwaters are constructed. Explanations of how the empirical results might be used to assist in making technically rational policy and project development decisions are included.

8.1 Distribution of Structure-Retained Beaches

Structure retained beaches comprise about 70%, or 400-km, of the open ocean coast between Morro Bay and the Mexican border. A breakdown by beach type is at Table 6. Sixty percent of all structure-retained beaches, and 41% of the 580-km long coast, lies within hook-shaped bays. Of the remaining structure-retained beaches, 24% are naturally maintained perimeter beaches in the lee of deltas, reefs, and submarine canyons. Pocket bays bounded by both natural and artificial structures comprise another 11% of the structure-retained beaches and eight percent of all beaches. Four percent of all beaches are fillet beaches. Salients in the lee of artificial detached breakwaters comprise less than one percent of all beaches.

Structure-retained beaches are noteworthy for their uneven distribution. Most are between Morro Bay and Marina del Rey, and between Newport Beach and San Clemente. In contrast, most beaches between Surfside Colony (Orange County) and the Santa Ana River mouth, and between San Clemente and La Jolla (San Diego County), lack significant structure control. The San Clemente to La Jolla reach is worth mentioning since it alone accounts for almost half of the study coast that is not substantially affected by retention structures. In most locations between Point Conception and Santa Barbara that are not described as structure-controlled a thin sandy beach lays atop a rather high and resistant, seacliff-connected, rocky shore platform. This raised

Table 6. Distribution of structure-retained beaches in southern and central California.

Kind of structure retained beach	Kilometers of retained beach	Percent of coast
Fillet beaches	21	4
Salients	1	<1
Perimeter beaches		
In lee of deltas	33	6
In lee of reefs	28	5
In lee of submarine canyons	36	6
In hook-shaped bays	240	41
In pocket bays	44	8
TOTALS	**403 of a total 580**	**70**

area functions as a non-moving wave energy dissipator during storms, much like a three-dimensional reef or stream delta. In this sense it also retains a perimeter beach.

Groins, shore-connected breakwaters, jetties, and some protruding revetments, retain slightly over half of the fillet beaches. Detached breakwaters are responsible for two mature salients. Groins and jetties retain about 2% of the pocket beaches. Lengthwise, fillet beaches, pocket beaches, and salients, represent less than 5% of all structure-retained beaches. In comparison over 20% of all beaches retained by natural structures have been affected by artificial structures. Most are natural hook-shaped bays that were altered when large breakwaters were connected to rocky headlands.

8.2 Effective and Ineffective Groins

Groins are the only structures that have been built in southern and central California with the principal objective of retaining a sandy beach. Accordingly, they alone can be evaluated with respect to meeting that objective. Their performance has been a mixed bag. Some have performed admirably. Others have not done well at all. Some have produced detectable adverse impacts on downcoast beaches. Others have been ineffective in permanently retaining wider beaches. Table 7 summarizes the performance of existing groins. Other groins have been constructed in the past, but they are now either buried as are some at Sunset Beach in Orange County, or they have deteriorated or been removed as have a series of steel sheet pile structures at Las Tunas Beach in Malibu. Effective and ineffective groins, and groins that adversely impact downcoast beaches provide information that can be used to better define and predict groin performance in southern and central California. Groins that are ineffective in retaining an upcoast fillet beach do not adversely affect downcoast beaches.

The 17 fully effective groins are all located in high net to gross longshore sand transport environments. Figure 1 is an example of a single structure that was successfully retaining a fillet when the photo was taken. Figure 28 shows groins retaining an upcoast fillet at the US Navy facility at Point Mugu. In total, effective groins retain about 140 hectares (350 acres) of sandy beach that would not be there if the groins were absent. Beaches within the groin compartments and upcoast of the groins have not been surveyed on the frequency needed to compare fillet

Table 7. Summary of upcoast beach performance for existing groins in southern California.

Groin Location	Number of structures	Effectiveness in retaining a fillet beach	Reason
Imperial Beach	2	Ineffective	Too short
Coronado (Hotel del Coronado)	1 (curved structure)	Effective before 1946; relatively ineffective after 1946 **(no downcoast impact at present)**	1946 beach enhancement reduced effective groin length; structure now functions more like an offshore breakwater
Ocean Beach	1	Ineffective	Zero Q_n environment
San Luis Rey River, Oceanside	1	Possibly effective **(downcoast impact not defined)**	Q_n controlled by Oceanside Harbor breakwater and sand bypassing
San Juan Creek, Dana Point	1	Moderately effective **(downcoast impact not defined)**	Q_n controlled by Dana Point Harbor breakwater
West Newport, Newport Beach	8	Ineffective	Too short for near zero net longshore sediment transport environment
El Segundo, Chevron Groin	1	Effective **(downcoast impact required a revetment)**	Moderate Q_n environment
Playa del Rey	2	Ineffective in 1985-87	Too short
"LA Groin", Playa del Rey	1	Effective in the past; probably ineffective today **(downcoast impact not defined)**	Moderate Q_n environment
Venice	2	Ineffective	Too short
Will Rogers State Beach, Santa Monica	4	Effective **(downcoast impact mitigated by fillet retained upcoast of the Santa Monica salient)**	High Q_n environment
Sunset Blvd., west Santa Monica	1	Effective **(downcoast impact mitigated by revetment that protects a restaurant parking lot)**	High Q_n environment
US Navy, Point Mugu	3	Effective **(adverse downcoast impact required a revetment)**	High Q_n environment
Ventura	7	Effective (**downcoast impact partly mitigated by Ventura Harbor breakwater and salient)**	High Q_n environment

stability with the performance of nearby beaches. However, none of the effective groins have required artificial nourishment to retain their fillets in recent years, although BEACON (Noble Consultants, 1989) reports shore retreat in Pierpont Bay (Ventura groins).

Groins or groin systems labeled ineffective in Table 7 have failed to stabilize a shoreline that had previously been recessional. Nor have they retained a permanently wider beach on one side than the other. The lack of success is due to either a structure that is too short, or to a location in a zero or near zero net longshore sand transport environment. Groins are sediment-blocking structures that do not retain a wider beach on one side when $Q_n = 0$. A series of photos serves to illustrate the lack of a fillet beach on the upcoast side of ineffective groins. Figure 75 shows this situation at Imperial Beach. According to USACE-LAD (1987), longshore sediment transport is in a net south to north direction (from the background to the foreground in the photo) at this site. The lack of a fillet on either side of the groins in a $Q_n > 0$ environment thus suggests their ineffectiveness is because they are too short. On average the distance between the tip of the north groin and the shoreline is about 100 m while it is about 60 m at the south groin. The orientation of the shoreline is north-south (360 degrees). Figure 76 shows a groin in the pocket beach at Ocean Beach. Again there is no fillet beach on either side of this structure. Although it is rather short, the fact the groin is located in a $Q_n = 0$ environment (USACE-LAD, 1988) would preclude the development of a permanent fillet. Figure 77 is a photo of another ineffective groin at Venice. Figure 34 shows the shoreline advances and retreats out of phase on either side of this structure, indicating it is too short. The net transport rate at the Venice site is perhaps 15,000 cmy to the south and the shoreline orientation is about 330 degrees.

Figure 75. Lack of a fillet beach on either side of groins at Imperial Beach.

Figure 76. Ineffective groin at Ocean Beach, San Diego.

Figure 77. Ineffective groin at Venice, Los Angeles County.

The eight groins shown pictured in Figure 78 have similarly been ineffective in stabilizing the shoreline at West Newport. They were constructed at every fourth street ending between 1968 and 1973 to counter a persistent retreat of the shoreline. In the 20th century West Newport lost an annual average 30,000 cm of sand. Losses were essentially the same before and after the groins were constructed, before and after the beach was artificially enhanced, and before and after Prado Dam on the Santa Ana River reduced the peak flood flows (Everts Coastal, 1996). The Santa Ana River discharges just to the west of this groin field. Daily field measurements indicated the net longshore component of wave energy fluxes at West Newport in 1992-93 (Everts Coastal, 1996) and along Balboa Peninsula in 1993-94 (Everts Coastal, 1995) were very near zero. Like groins that are too short, natural headlands, like the one illustrated in Figure 79 may also fail to retain a permanent fillet.

Figure 78. Ineffective groins at West Newport, Newport Beach.

Figure 79. Small headland that fails to retain a permanent fillet at Torrey Pines State Beach (San Diego County).

8.3 Guide to Predict the Effectiveness of Groins, Jetties, and Shore-Connected Breakwaters

The width of the fillet at a groin, jetty, or shore-connected breakwater, is a measure its size. Hence it is a gauge of its effectiveness. Fillet width is equal to the difference in effective structure length and structure blocking distance (Fig. 11). Effective length is the distance between the pre-project shoreline and the end of the structure. It is thus a proxy for the cost of the structure, its visual intrusiveness, and possibly its potential to harm swimmers and surfers and interfere with navigation. Blocking distances can be forecast by applying an empirical relationship developed with central and southern California prototype data.

The most effective structure groin is the one with the smallest blocking distance that retains the desired width of fillet. When the blocking distance is small, structures with relatively short effective lengths will retain a fillet as shown in Figures 1, 8 and 28. When the blocking distance is large, a long structure is required to retain a fillet, such as that shown in Figure 9. If the blocking distance is equal to or greater than the effective length of the structure, a fillet will not be retained. This is the reason some groins, such as the two at Imperial Beach (Fig. 75) and one at Venice (Fig. 77) are ineffective.

In southern California, the most effective sediment-blocking structures are located where the bearing of the open coast shoreline is between 240 and 310-320 degrees and there is a substantial net longshore sand transport rate. As shown in Figures 12 and 26, the blocking distance progressively increases from a bearing of near 310 degrees to 360 degrees. At 360 degrees it is five times larger than it is between 240 and 310 degrees. In most cases the fillet angle is seven degrees or less (Fig. 27) so the bearing of the pre-project shoreline is close to the bearing of the fillet shorelines in Figures 12 and 26. Figure 12 was developed using all of the sediment-blocking structures, both natural and artificial, that retained a fillet. Figure 26 was derived from groins in groin systems. Figure 26 is probably more useful for evaluating the effectiveness of artificial structures although the fillet bearing range is more limited. Both figures show winter and summer blocking distances are different. If a structure is being evaluated with respect to its retention of a permanent upcoast beach, the summer blocking distance illustrated in Figure 26 must be used.

Figures 12 and 26 clearly indicate groins and other sediment blocking structures are not as effective on north-south coasts as they are on east-west coasts. Before there is any retention capacity, for example, a structure on a north-south coast must project at least 150-m past the pre-project shoreline. This is the reason the 100-m and 60-m long groins along the north-south coast of Imperial Beach are ineffective (Fig. 75). On a coast with a bearing of 270 degrees the summer blocking distance is on the order of 30 or 35 m. Even there, however, before there is any permanent retention of a fillet beach the effective length of the structure would have to exceed that minimum blocking distance. It is instructive to apply Figures 12 and 26 to the coast with the fewest beach retention structures in the study area – San Clemente to La Jolla. The coastal bearing at Oceanside and Carlsbad is about 326 degrees (TN) while it averages 348 degrees in the Solana Beach - Del Mar area. These locations are not optimum for a groin, but the minimum blocking distance approaches 150 m at Solana Beach and Del Mar. It is only about half as much at Oceanside and Carlsbad.

Straight groins oriented normal to shore are the most effective. The actual lengths of the curved groin at Coronado (Hotel del Coronado), and the curved shore-connected breakwaters at Oceanside and King Harbors, are greater than their effective lengths would be if the structures were straight.

A planning-level methodology to predict the size of a salient that will be retained in the lee of a detached breakwater or artificial reef at Encinitas, as given in Everts Coastal (2002), can be applied with limitations elsewhere in southern California. Their approach is based, in part, on empirical data obtained from the salients at Venice and Santa Monica.

8.4 Adverse Impacts of Sand Denial

An adverse impact due to sand denial will occur in two circumstances. First, if a beach retained by a groin, jetty, or breakwater, is allowed to develop naturally in a $Q_n > 0$ environment, or if the longshore sand transport stream is permanently interrupted, downcoast beaches will likely erode. Second, if a beach in a $Q_n = 0$ environment is retained by a detached breakwater (or a yet-to-be-built artificial reef), and it is allowed to develop naturally, sandy beaches on either side are likely to be adversely impacted. The reason is simple; sand retained on one beach is sand denied other beaches. Sand denial was once the rule rather than the exception in southern California. It is still affecting at least one popular recreational beach.

Artificially induced sand denial caused beaches to deteriorate downcoast of Santa Barbara Harbor, Ventura Harbor, Port Hueneme, King Harbor, and Oceanside Harbor. Each of these harbors is in a $Q_n > 0$ environment and none is at the end of its littoral cell. Frequent and costly artificial sand bypassing has restored the longshore sand flow at all but King Harbor. Sand that accumulated there was sand denied Torrance Beach at Redondo Beach, causing serious erosion. The problem was subsequently mitigated through the artificial addition of over one million cubic meters of sand dredged from an offshore source and, importantly, the construction of the Topaz

Street groin. That groin prevented the beachfill from being lost in Redondo Submarine Canyon. Thirty years later, the artificially created pocket beach between the groin and Palos Verdes Peninsula remains stable.

Non-shore connected structures may also create sand denial problems. In the first decades after the Santa Monica breakwater was constructed the salient that formed in its lee, and the fillet that formed upcoast of the salient, denied sand to Venice Beach. The erosion problem became so acute that on three occasions large quantities of sand were mined from the salient and bypassed to Venice. After the salient and its fillet beach matured, as illustrated in Figure 18**,** sand again passed downcoast in sufficient quantity to maintain Venice Beach. The north jetty at the entrance to Marina del Rey is also responsible for the progressive shoreline advance. In turn, though, the jetty and other harbor structures are denying it to Playa del Rey. Even with about 8 million cm of sand excavated from Marina del Rey and placed on the beach in the early 1960's (Leidersdorf et al., 1994), the three miles of shoreline downcoast of the marina entrance retreated over 50-ft between 1953 and 1990 (Coastal Frontiers, 1992). This is the current and ongoing example of sand denial caused by a retention structure.

The prescriptions for sand denial are simple. Require artificial filling of all beaches that are to be retained by artificial structures. Refrain from interrupting the longshore movement of sand to downcoast beaches, or if that is not possible, artificially bypass the sand to maintain its longshore flow. These are standard practices in most places and should be a part of all projects unless a good reason is given for their omission. The problem at Playa del Rey is not only sand denial, but the tendency of that beach to attain a hook shape in the lee of the south jetty and detached breakwater at the entrance to Marina del Rey.

8.5 New Artificially Created Hook-Shaped Bays

Longshore transport reversals and the shoreline erosion that sometime occur downcoast of groins, jetties, and some breakwaters, are more difficult to deal with than sand denial. These unwanted responses come about as a new hook-shaped bay begins forming. No instance was found of an artificially induced bay forming by accretion outside the confines of a natural bay. Mitigation to arrest the development of hooked bays includes sand bypassing, artificial beach nourishment, revetment construction, and the placement of other retention structures. Mitigation efforts and costs are ongoing and will continue as long as the structures are there.

This impact is has not been uncommon in southern California. A revetment (Fig. 30) constructed downcoast of the last US Navy groin was built to prevent the further evolution of a hooked bay. A detached breakwater at the harbor and the periodically dredged salient it retains prevents a hooked bay from expanding much beyond the last groin at Ventura. The fillet that formed upcoast of the salient in the lee of Santa Monica breakwater extends all the way to the last groin at Will Rogers State Beach, thereby preventing a hooked bay from forming there. Harbor bypassing arrested the deterioration of downcoast beaches that lie outside natural hook-shaped bays at Santa Barbara, Ventura, Port Hueneme, and Oceanside. In contrast, Dana Point Harbor and the coast downcoast of it are within a natural hooked bay. When the Dana Point breakwater extended the diffraction point 2-km downcoast, the shoreline near the harbor responded by advancing.

8.5.1 Where Will a New Hook-Shaped Bay Form?

Findings of this study indicate a new hooked bay will begin forming downcoast of groins, jetties, and shore-connected breakwaters that are not connected to large natural headlands when five conditions are met. Listed below, these conditions were found to be attributes of all hook-shaped bays in southern and central California.

First, the region downcoast of the structure must be susceptible to erosion. Hook-shaped bays do not form where resistant rock prevents it. As shown in Figures 4 and 55, the extent to which even natural bays indent into the existing coastal landmass depends on the susceptibility of the hinterland to wave-caused scour. The revetment is why a hooked bay has not developed to any extent downcoast of the US Navy groins west of Point Mugu (Fig. 30).

Second, the alongshore component of wave energy flux must be substantially greater than zero along the control line between the artificial structure (the diffraction structure) and the next structure downcoast (the anchor structure). It must be directed toward the anchor structure. That is, the angle between the predominant wave approach direction at the control line must open toward the anchor structure. If the predominant wave approaches normal to the control line a pocket beach will be retained.

Third, the artificial diffraction structure must be sufficiently high and long that it blocks a significant portion of the wave energy that approaches from the predominant upcoast direction.

Fourth, the diffraction structure must also diffract waves at its tip. To effectively block and diffract waves a groin, jetty, or shore-connected breakwater must stick out from the pre-project shoreline.

Fifth, the anchor structure must not retain a straight beach as far upcoast as the artificial diffraction structure. Structure spacing is critical. The distance between structures determines whether downcoast erosion will occur. When the beach retained by one structure extends upcoast to the next structure, the beach between them will usually not be adversely impacted. This is what happens between properly spaced groins like those at Will Rogers State Beach (Fig. 8). Each of these groins retains the shoreline in an advanced position to the next groin. The spacing between the last groin and the next anchoring structure becomes the critical distance. It regulates the amount of downcoast beach and hinterland that is eroded and the length and depth of the hooked bay that forms.

8.5.2 Guide to Predict the Configuration of a New Hook-Shaped Bay

If the five conditions pertain, the configuration of a hooked bay, if it is allowed to evolve to maturity, can be estimated. Since this has not been allowed to happen, we illustrate the method with a bay that developed downcoast of a groin at Fernald Point (east of Santa Barbara) within a larger natural hooked bay. There was only a modest if any adverse impact on the downcoast shoreline.

The bay and the control line that defines it are shown in Figure 80. Shoreline parameters for the bay were calculated using Equations 5 (indentation distance), 6 (location of maximum indentation), 8 (bearing of straight shoreline) and 9 (length of straight shoreline), which were obtained from Figures 58, 59, 62 and 63. Results are at Table 8. Measured parameter values are in the second column. Column 3 is a list of the calculated values obtained using the measured length and bearing of the control line between the tip of the groin and the anchor structure. The fourth column shows the percent difference in the calculated and measured values. Only the calculated and measured bearing of the straight shoreline is the same. Calculated shoreline values are all larger than measured values for the remaining parameters. The difference ranges to140% suggesting this approach is at best semi-quantitative. However, it provides a realistic way to estimate the shape and general size of the hook-shaped bay that is likely to form downcoast of an artificial structure if it meets the five conditions specified in the previous section.

Figure 80. Small hook-shaped bay that formed downcoast of a groin in the natural hooked bay east of Fernald Point.

Table 8. Characteristics of the groin-controlled hook-shaped bay east of Point Fernald.

Parameter	Measured value	Calculated value	Percent difference*
Length of bay, a	1180 m		
Bearing of control line, Β	269 deg		
Indentation distance, b	159 m	198 m	124
Location of maximum indentation, a'	354 m	467 m	132
Bearing of straight shoreline, α	288 deg	288 deg	0
Length of straight shoreline, d	340 m	477 m	140

* (calculated value/measured value) times 100

8.6 Impacts of Altering a Natural Hook-Shaped Bay

Massive rocky headlands that functioned as diffraction structures to retain large natural hook-shaped bays have been altered by the construction of Dana Point Harbor, Los Angeles-Long Beach Harbor, and Port San Luis. Even before these harbors were built conditions in the lee of the headlands made them sought-after anchorages. Headland-connected breakwaters took advantage of this feature and reduced costs. They also shortened the length and modified the orientation of the natural control lines. In some cases the result was an overall benefit; in others the impact was adverse. Zuniga Jetty, constructed to keep sand out of the entrance to Sand Diego Bay has affected the configuration of the Silver Strand hook-shaped bay. Although not connected to a headland, Zuniga Jetty also created a new diffraction point at its tip, shifting it partially from Point Loma.

Examples show how outcomes could have been predicted in general terms prior to the construction of the breakwaters and jetty. At Port San Luis, the movement of sand discharged from San Luis Obispo Creek reversed and is now transported to and being deposited in the harbor. The shoreline just downcoast of Dana Point Harbor advanced seaward. Zuniga Jetty is blocking and diffracting waves such that the north end of the hooked bay has advanced while the anchor end at Imperial Beach retreated in recent years.

In all three instances, outcomes were the same. Sand transport toward the diffraction end of the bays increased (Zuniga Jetty), or it reversed and is now directed toward the diffraction end (Dana Point Harbor and Port San Luis). Shorelines advanced in portions of the bays closer to the new diffraction points; shorelines retreated or failed to advance near the anchor structures. Structure controls all were affected the same way. Control line lengths all declined: control line bearings all increased.

8.6.1 Port San Luis

In pre-harbor times Point San Luis, the rocky diffraction headland, and Mussel Point, the smaller anchor headland 26-km to the south, retained the Santa Maria River hook-shaped bay shown in Figure 81. Sand entered the littoral zone in the north end of the bay through San Luis Obispo Creek (Fig. 55) and moved slowly toward Mussel Point (Fig. 54) or offshore. But, with the completion of the Port San Luis breakwater in 1913, sand began moving in the opposite direction. According to Everts Coastal (1996) the average annual transport of creek-source sand to the harbor today averages about 2300 cmy. The transport reversal is responsible for the continual clogging of the launch areas, the redundancy of some fishing platforms, and the infilling of mooring sites, especially those nearest the breakwater.

A second breakwater impact was an altered sediment transport regime south of Shell Beach. Between 1900 and 1976 perhaps 1 million cm of sand was shifted to the north. The shoreline advanced a maximum 100 m as shown in Figure 82. Rocky headlands prevented northward moving sand from passing Shell Beach. Everts Coastal (1995) found the shoreline in the vicinity of the Santa Maria River mouth retreated about 75 meters with most of the retreat occurring between 1935 and 1970. This retreat is probably due to a combination of the altered bearing of

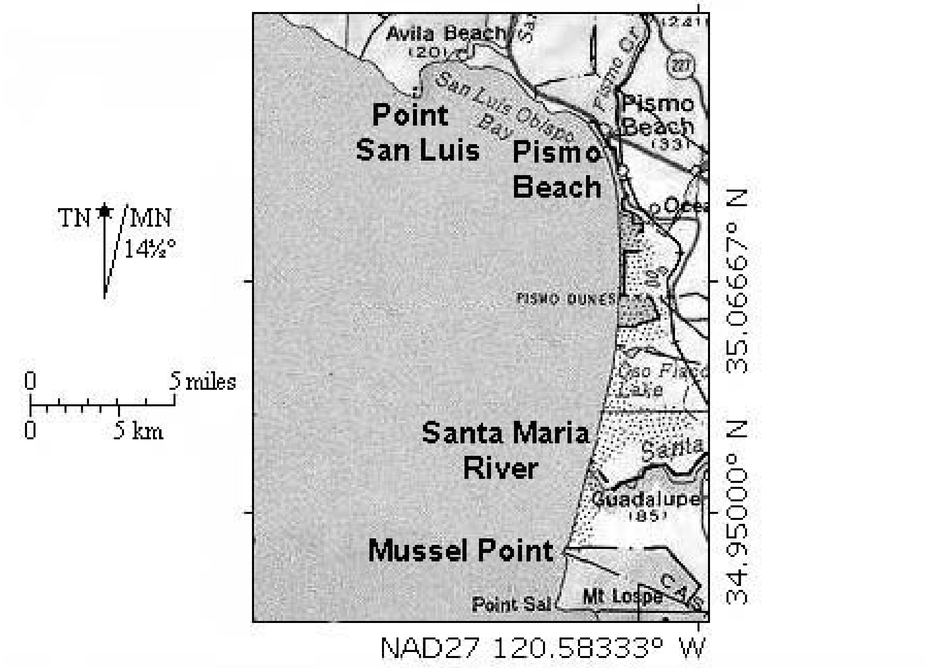


Figure 81. Location map, Santa Maria River hook-shaped bay.

the control line and a reduced sand contribution since Twichell Dam was built in 1958. Moffatt and Nichol, Engineers reckon the post-dam discharge has averaged between 40,000 and 175,000 cmy while the pre-dam discharge was on the order of 300,000 cmy. They also suggest little or no sediment is passing out of the bay in an alongshore direction around Mussel Point.

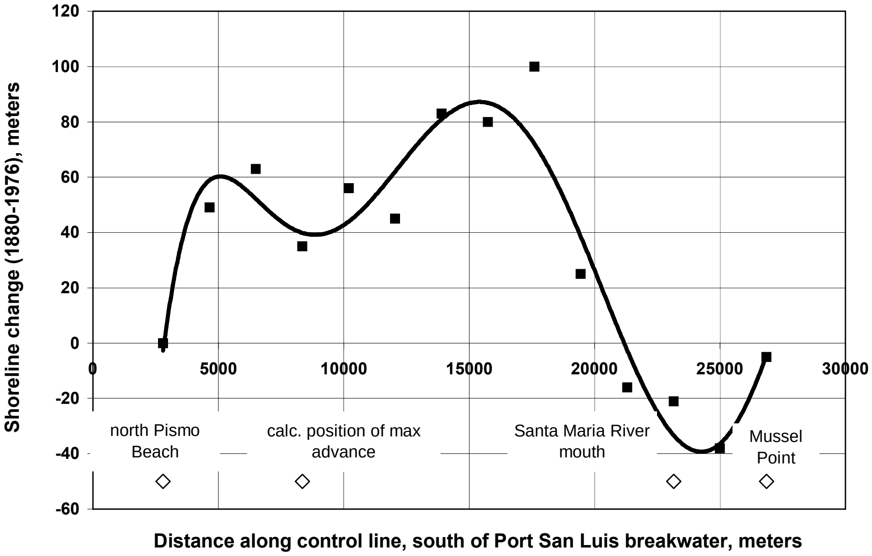


Figure 82. Shoreline changes in the Santa Maria River hook-shaped bay: 1880-1976 (value extracted from shoreline changes measured on historic NOS T-sheets and supplied by S. Tonkin, Moffatt and Nichol, Engineers, 2002).

The breakwater shifted the position of the diffraction structure 660-m closer to Mussel Point and increased the bearing of the control line from 340.5 degrees to 342 degrees. Wave blocking created the wave "shadow" region where sand from San Luis Obispo Creek is now accumulating. Diffraction at the end of the breakwater changed the longshore component of energy flux so it is now directed toward the port. Intuition would have predicted the depositional site but the source of sand might not have been as obvious.

8.6.2 Dana Point Harbor

Prior to 1968, the Dana Point headland was the diffraction structure at the northwest end of a 9-km long natural hook-shaped bay (Fig. 83). The anchor structure was and remains a subtle shoreline bulge where the beach narrows at Avenida Mariposa in San Clemente. Under natural conditions the bay was in near dynamic equilibrium when averaged over periods of decades. Year to year fluctuations were large, however, depending on the discharge of sand from San Juan Creek. Recent discharges of note were in 1938 and 1969. Sand also reached the bay from north to south around Dana Point. USACE-LAD (1997) estimated that flux at perhaps 11,000 cmy in an average year. In the late 1960's, about 650,000 cm beachfill sand taken from a land source (USACE-LAD, 1990) was placed to counter an erosion problem that threatened buildings near the creek mouth. In late 1968, the south harbor breakwater was connected to Dana Point, extending the diffraction point almost 2-km to the east (Fig. 82) thereby diminishing the length of the hooked bay to about 7 km.

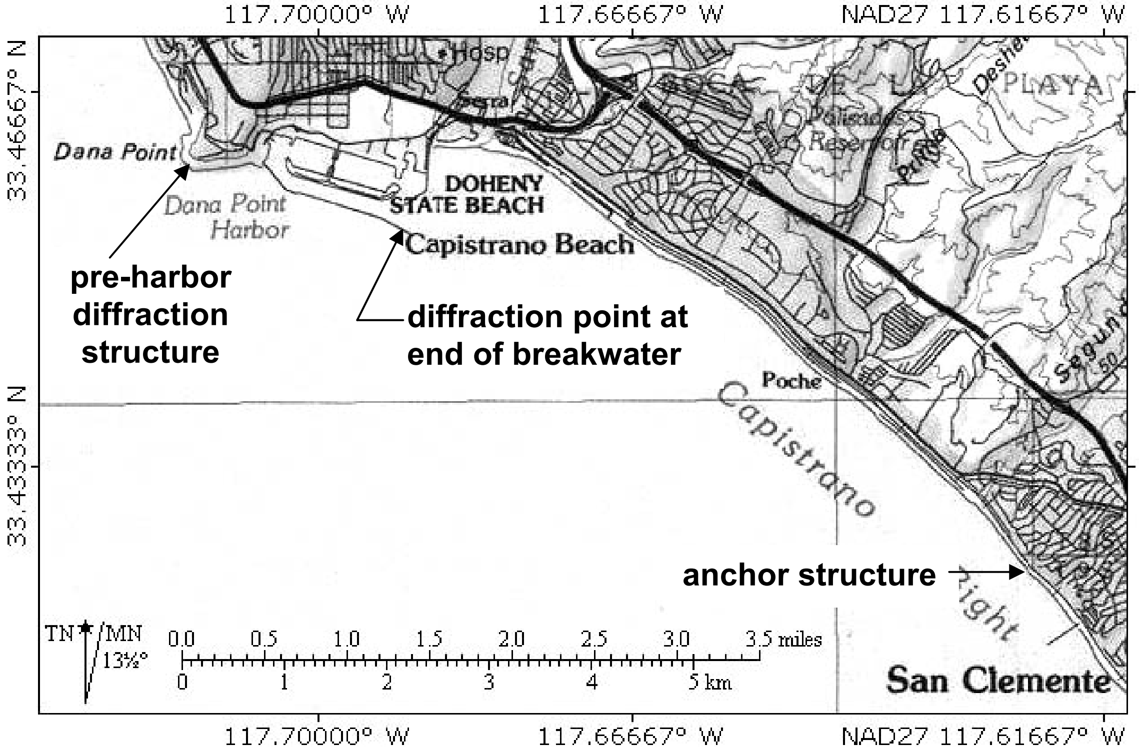


Figure 83. Dana Point hook-shaped bay.

The shoreline response was almost immediate. From the east breakwater to about 4-km to the southeast it advanced with the largest advance adjacent to the harbor (Fig. 84). In 13 years it shifted seaward a maximum 80 m about 4800-m southeast of Dana Point. Closer to the creek it probably advanced a greater distance. In the same time period, the shoreline at the anchor structure remained nearly stable. Construction reduced the length of this hook-shaped bay from 9110 m to 6910 m and increased the bearing of the control line from 295 to 297 degrees. Like at Port San Luis, the new position of the diffraction point created a reduced or even possibly a net-zero longshore movement of sand to the southeast and a consequent accumulation of creek-source sand near the new diffraction structure.

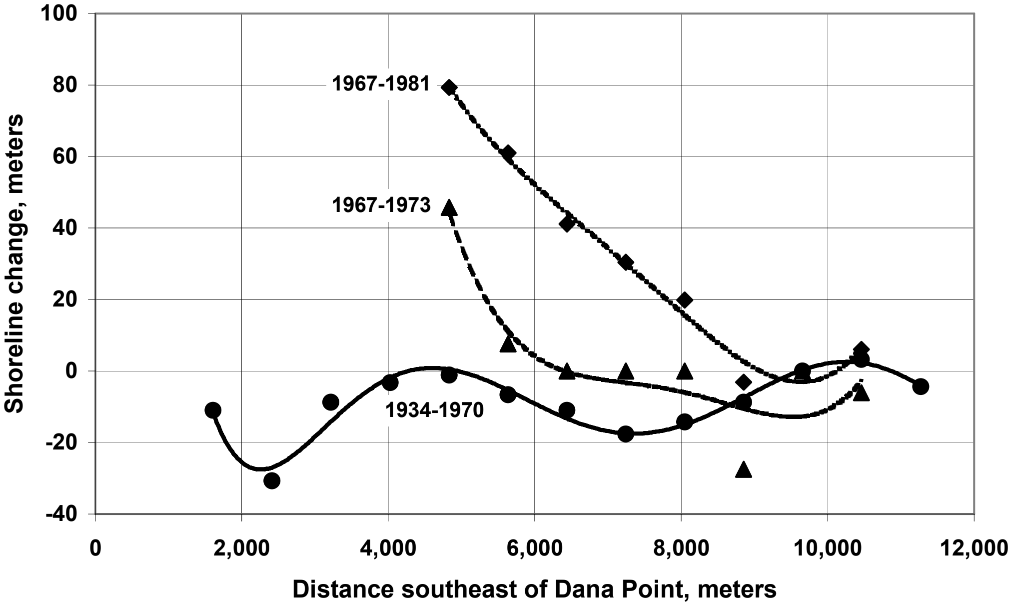


Figure 84. Shoreline positions before and after the 1968 construction of Dana Point Harbor.

8.6.3 Zuniga Jetty

In its natural state, the Silver Strand hooked bay shown in Figure 85 was retained between Point Loma and a shoreline protrusion in the lee of the rocky Tijuana River delta (Fig. 49). Two human interventions have altered the configuration of this bay. The first was the construction of Zuniga jetty between 1893 and 1904. By 1933 the shoreline had advanced over 250 m at the jetty. The advance progressively declining to 30-m about 2500-m to the southeast, thence remained at approximately 30-m to the anchor structure (1887-1933 distribution in Fig. 86). Sand moves in a net south to north direction in this bay. The sand source was the Tijuana River and in this time period the annual discharge rate is estimated to have been between 100,000 and 150,000 cm (USACE-LAD, 1987). By 1938, a dam in Mexico and two smaller dams in the US controlled 70 percent of the watershed, and the river’s sand contribution dropped accordingly (Everts Coastal, 2001).

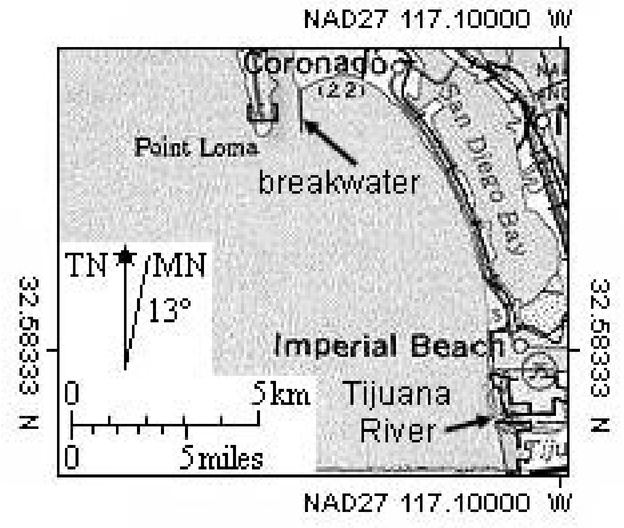


Figure 85. Location map, Silver Strand hook-shaped bay.

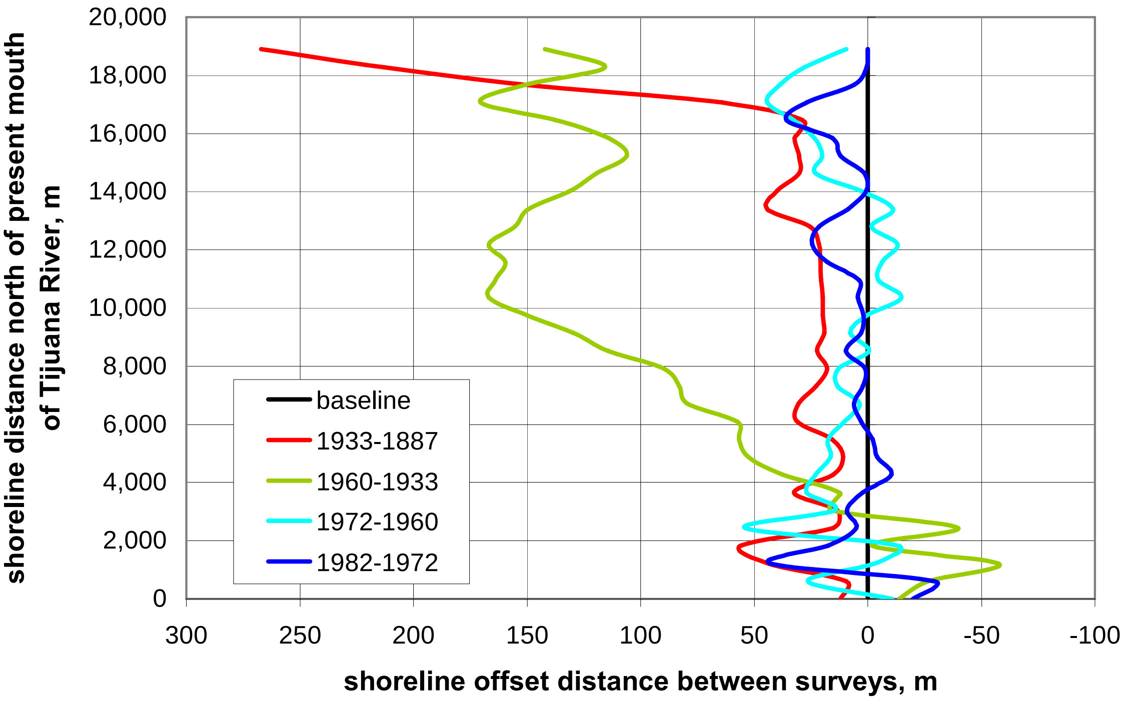


Figure 86. Shoreline offset distance between surveys (data from USACE-LAD, 1987).

The second intervention was a series of beachfills that by 1982 totaled 25 million cm. Eighty percent of it was placed at the south end of Coronado in 1946. This opportunistic enhancement remains the largest ever in California. By 1960, the beachfill had shifted to the 1933-1960 distribution shown in Figure 86. Between 1960 and 1972 there was a slight loss in the fill region and accretion toward the jetty. Accretion in the south part of the bay was probably due to sand discharged from the channel below Rodriguez Dam in the 1969 flood. Between 1972 and 1982, the northward movement of sand from the fill site continued, and it may be continuing today (Everts Coastal, 2001).

Results of the two human interventions are summarized in Figure 87, which shows the total change in the position of the shoreline in the bay from just before Zuniga Jetty was constructed until 1982. Almost 3 million square meters of new beach were added (about a square mile). The only place that did not benefit was the region in the vicinity of the river mouth, i.e., at the anchor structure. The progressively increasing pattern of shoreline advance in Figure 86 is altered by an "indent" near the jetty. Everts Coastal (2001) posits it is due to an erosion wave that moves ahead of the accretion wave created by the large beachfill and in the direction of the net flux.

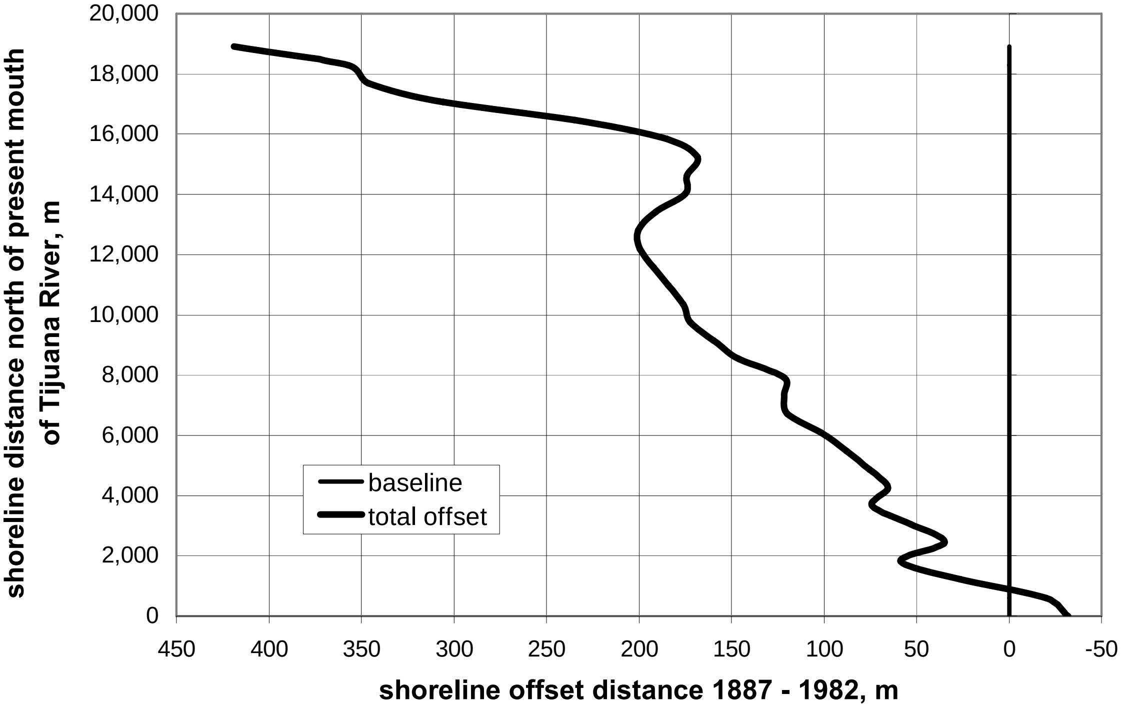


Figure 87. Cumulative change in the position of the shoreline in the Silver Strand hook-shaped bay between 1887 and 1982 (from Everts Coastal, 2001).

Most of the accreted sand was artificially placed. The natural retention structures, Point Loma and the Tijuana River delta, and Zuniga Jetty, are retaining it. The jetty is mainly responsible. Before it was constructed, and before the Tijuana River sand source was degraded by human interventions, much of the sand that reached the bay was carried north and thence offshore onto Zuniga shoal. Wave blocking by the jetty and diffraction at its end is responsible for the huge and predictable progressive advance of the shoreline toward the north in this hook-shaped bay. This counterclockwise rotation of the entire bay shoreline cannot be attributed solely to the beachfills and a reduced discharge in the Tijuana River near the anchor end.

9.0 SUMMARY AND CONCLUSIONS

Rocky headlands, stream and river deltas, reefs, near-coast submarine canyons, and artificial structures retain seventy percent of all sandy beaches in southern and central California. Beaches newly retained by groins, jetties and shore-connected breakwaters comprise only a few percent of the total. On the other hand, almost 25% of the beaches retained by natural structures were modified by artificial structures in the past 130 years. Most of those alterations were in bays held between pairs of headlands, deltas and reefs.

Project development and policy decisions, beach management tactics, planning level evaluations, and engineering design, all benefit greatly by familiarity with other decisions, tactics, evaluations, and designs. Existing structures often yield valuable information when efforts are made to duplicate their function. This was the starting point for the early design of groins, jetties and breakwaters. When the objective was sand retention, it was usually met. Often, though, the benefit was cancelled by unanticipated impacts elsewhere. The California coast it is an ideal laboratory to improve empirical methodologies due to the large number of both natural and artificial prototypes. This reconnaissance-level investigation focused on the response of sandy beaches to the presence of retention structures between Morro Bay and the Mexican border. The goal was to better identify conditions and predict outcomes where structures benefit and harm beaches. Structure and beach characteristics were defined using mapping quality aerial photographs and topographic maps.

Artificial structures have had mixed success in retaining beaches in southern California. Knowledge of the conditions that produce favorable and unfavorable results serves to identify likely successful projects and flag potential problems. It may also be useful in understanding the causes of beach change associated with existing structures. Empirical relationships provide guides to predict: (1) the way in which beaches in hook-shaped bays are likely to change if one or both of the end structures are altered, (2) the development of new hook-shaped bays downcoast of groins, jetties, and shore-connected breakwaters, and (3) the width of fillet beaches retained upcoast of these structures. This capability might assist in defining setback distances and be used to determine where artificial beach enhancement will be most effective. Another application might be to evaluate the vulnerability of wetlands to anticipated beach change and help develop lagoon outlet maintenance procedures. The guides are not meant to serve as the final decision-making criterion, but to draw attention to conditions under which the probability of favorable and unfavorable results is heightened. Scatter in the data, perhaps due to differing sand supplies or differences in local wave climates, imply the relationships are best used to define changed sand transport directions and trends in shoreline change.

9.1 Beaches Retained in Bays

Beaches retained in bays – meaning between two structures - are more common than perimeter beaches retained in the lee of deltas, reefs, and submarine canyons; salients retained in the lee of detached breakwaters; and fillet beaches retained upcoast of groins, jetties, and shore-connected breakwaters. Sixty percent of retained sandy beaches are in hook-shaped bays and 11% are in pocket bays. Together bay beaches comprise almost 50% of all beaches in central and southern

California. A notable characteristic of bay beaches is that the entire bay shoreline adjusts in a predictable way to a human alteration of the retaining structures. The performance of structures built within the bays is similarly governed by the overall control imposed by the retaining structures. Beach response to an intervention that can be predicted everywhere means the bay sand resource can be managed as a unit, an obvious advantage. The orientation and length of a line that connects the retaining structures – the control line - are the paramount controls on the beach response. Shoaling in the launch and mooring areas at Port San Luis, the displacement of over a million cm of sand from near the mouth of the Santa Maria River toward Pismo Beach, and beach widening downcoast of Dana Point, are some responses that could have been predicted before harbor breakwaters were constructed.

9.2 Fillet Beaches

Fillet beaches are accretional features retained upcoast of headlands, groins, jetties, and shore-connected breakwaters. Groins are the only artificial structures designed with sand retention as their principal objective. Fillet width is a measure their effectiveness. Fillet width is equal to the difference between structure length and structure blocking distance. Blocking distance refers to the length of structure between its tip and where the fillet shoreline intersects it. An empirical relationship based on the orientation of the shoreline provides a means to predict blocking distances. It explains why some groins are effective and some are failures as beach retention structures. In southern California, seventeen groins retain over 140 hectares of permanent fillet beach. An equal number, though, are ineffective. When the blocking distance is small, relatively short structures retain a fillet. When it is large, a long structure is required. A fillet will not be retained if the blocking distance is equal to or greater than the length of the structure. This is the reason some groins, such as the two at Imperial Beach are ineffective. Groins at West Newport are ineffective because of a near-zero net longshore sand transport rate. In central and southern California, the structures that most effectively retain a fillet are located: (1) where the coast is oriented between 240 and 310-320 degrees (between southwest and northwest), and (2) the net longshore sand transport rate is substantial. Sediment-blocking structures are much less effective on west facing parts of the coast.

9.3 Adverse Impacts of Groins, Jetties, and Breakwaters

Sand denial is the cause of an adverse impact when a structure-retained beach is allowed to develop with sand from the littoral system. Venice Beach is an example. It was denied sand when the salient and later fillet began forming near the Santa Monica breakwater. The problem continued into the 1960’s at which time the upcoast retained beach had matured enough that the natural sand flow was partially restored and entrance structures at Marina del Rey retained it. These structures, however, are now responsible for creating another sand denial response. The initiation of a hook-shaped bay at Playa del Rey has been avoided only by the placement of huge volumes of opportunistic beachfill. The sand denial impact is easy to forecast and remedy: Allow no structure-retained beach to accrete with sand from the littoral zone.

A more inflexible problem is the initiation of an erosional hook-shaped bay. Groins, jetties, and breakwaters have adversely impacted some beaches for this reason. New bays that form downcoast of these structures should be differentiated from existing natural bays where rocky headlands have been altered by breakwaters. New bays usually evolve as erosional features. The response in existing bays is variously erosion or accretion.

New hook-shaped bays develop in specific circumstances, found to be attributes of all hooked bays in southern and central California. First, the downcoast region must be susceptible to erosion. Hook-shaped bays do not form where resistant rock prevents it. Second, the alongshore component of wave energy flux must be substantially greater than zero along a line connecting the artificial structure and an anchoring structure. That is, the angle between the predominant wave approach direction and this line must open toward the anchoring structure. The anchoring structure is any feature further downcoast that fixes the position of the shoreline. Third, the artificial structure must be sufficiently high and long that it diffracts waves and blocks a significant portion of the wave energy that approaches from the predominant upcoast direction. Fourth, the anchoring structure must not retain a beach as far upcoast as the artificial structure. The distance between the structure and the anchoring structure determines whether downcoast erosion will occur. When the beach retained by the anchoring structure extends upcoast to the groin, jetty or shore-connected breakwater, the beach between them will generally experience little of no adverse impact. This is the situation within groin fields like those at Will Rogers State Beach near Santa Monica, US Navy groins east of Point Mugu, and at seven groins at Ventura. Empirical relationships between structure and shoreline parameters provides a means to predict the dimensions and mature configuration of a hook-shaped bay that is likely to form downcoast of a groin, jetty or shore-connected breakwater.

9.4 Artificial Structures Without Measurable Adverse Impacts

While one cannot state absolutely that a structure will only be beneficial, it is obvious that some structures have a greater potential to produce negative impacts than others. Excepting temporary sand denial impacts, adverse impacts were not found for (1) detached breakwaters that retain a salient, (2) positive wave refraction structures, including reefs and stream deltas, and (3) structures that retained pocket beaches. Most structures in the first two groups retained shoreline bulges in $Q_n > 0$ environments. Since the shorelines did not extend to the structure, sand that moved along the coast apparently followed the coastal planform. It was not deflected seaward, nor was it blocked. Pocket beaches are retained in $Q_n = 0$ environments where downcoast impacts are minimal. Some of the most stable beaches in southern and central California are pocket beaches retained by one artificial structure and a natural headland, or two headlands.

9.5 Impact of Sea Level Rise

To the detriment of the beaches they retain, sea level rise impacts are affecting the retention qualities of river and stream deltas, reefs, and the low breakwater at Santa Monica. The size of beaches retained in the lee of low and submerged structures is inversely proportional to the amount of energy reaching them (and directly proportional to the length of the structure). As the water depth over the structure increases there is a corresponding increase in the amount of energy that reaches the coast. Structure effectiveness thus declines as the sea surface rises. If sea level continues rising in the future – it rose 0.2 m in the last century – the effectiveness of these structures will continue to be compromised. Everts Coastal (2002) illustrates the sea level rise impact for a 200-m long and 100-m wide reef with a freeboard now at mllw. They estimate a rise in sea level twice the 20th century rise would reduce the size of the salient about 60%, or from about 18,000 sm to 7000 sm by 2100. The sea level rise effect is occurring today and it is not associated with factors that respond to local control. The retreat of the shoreline at south Imperial Beach, for example, is probably a function of the combined effects of sea level rise with respect to the freeboard of the Tijuana River delta, a reduced discharge in the river, and a counterclockwise rotation of the hooked shoreline that occurred after Zuniga Jetty was constructed.

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APPENDIX A

SPREADSHEETS

This appendix contains the following spreadsheets (tables):

- **A1 ARTIFICIAL STRUCTURES BETWEEN POINT ESTERO AND MEXICO**
- **A2 FILLET BEACHES RETAINED BY ROCKY HEADLANDS, GROINS, JETTIES, AND SHORE-CONNECTED BREAKWATERS**
- **A3 PERIMETER BEACHES RETAINED BY NEAR-COAST SUBMARINE CANYONS**
- **A4 PERIMETER BEACHES RETAINED BY RIVER AND STREAM DELTAS**
- **A5 PERIMETER BEACHES RETAINED BY REEFS**
- **A6 BEACHES RETAINED WITHIN HOOK-SHAPED BAYS**
- **A7 BEACHES RETAINED WITHIN POCKET BAYS**

Spreadsheets contain structure dimensions, related beach data, and environmental data collected from aerial photographs, topographic maps, charts, and published reports. These data pertain to the open ocean coast between Point Estero near Morro Bay and the US – Mexico border. Bays, lagoons, and protected reaches like the coast of Long Beach are excluded. When not obvious, definitions are given at the bottom of the spreadsheets. Aerial photographs were scanned at the US Army Corps of Engineers (Los Angeles District) facility in La Puente. Vertical mapping quality photos from late summer 1985 and winter or spring 1987 provided continuous coverage for the entire coastline and were used in all analyses.

A1 ARTIFICIAL STRUCTURES BETWEEN POINT ESTERO AND MEXICO

ARTIFICIAL STRUCTURES WITH THE POTENTIAL TO RETAIN SANDY BEACHES (n = 98)

Structure location	latitude	longitude	type of structure	structure setting	structure impact on beaches
Imperial Beach	32.58384	117.13282	groin	south structure of two	none
Imperial Beach	32.58757	117.13312	groin	north structure of two	none
Coronado	32.67863	117.1792	curved groin	hook is to the north	modestly effective; constructed to provide a launch site for small boats
Zuniga Jetty	32.66636	117.22214	jetty	entrance to San Diego Bay	long structure that blocks sand from entering the entrance to San Diego Bay
Ocean Beach	32.75129	117.25243	groin	near mouth of San Diego River	not effective
Mission Bay	32.75585	117.25807	jetty	south structure	retains sand in Ocean Beach pocket
Mission Bay	32.75827	117.25925	jetty	north structure	retains sand in Mission-Pacific Beach pocket
Batiquitos Lagoon	33.08693	117.31273	jetty	south structure	unknown, but may function to create a hook-shaped bay to the south
Batiquitos Lagoon	33.08744	117.31286	jetty	north structure	unknown, but will probably function to retain an upcoast fillet
South Carlsbad	33.13816	117.33893	outfall jetty at power plant	south structure	slight impact
South Carlsbad	33.13827	117.33893	outfall jetty at power plant	north structure	slight impact
Agua Hedionda Lagoon	33.14489	117.34336	jetty	south structure	functions to create a small hook-shaped bay to the south
Agua Hedionda Lagoon	33.14528	117.3438	jetty	north structure	functions to create a small non-permanent fillet, often with some fraction of cobbles
San Luis Rey River	33.20249	117.39141	groin	north side of river mouth	fillet shifts sides depending on season; sand bypassing and the influence of the Oceanside Harbor breakwaters affect the function of this structure
Oceanside Harbor	33.20681	117.39852	breakwater	south structure	not determined
Oceanside Harbor	33.20624	117.40189	breakwater	north structure	retains an upcoast fillet
San Juan Creek	33.46174	117.68314	groin	north side of river mouth	retains a beach to the northwest; other structure is east harbor breakwater

Structure location	latitude	longitude	type of structure	structure setting	structure impact on beaches
Dana Point Harbor	33.4566	117.69111	breakwater	east structure	retains the beach between the harbor and the groin
Dana Point Harbor	33.45406	117.69047	breakwater	south structure	functions as a diffraction structure, creating a hook-shaped bay to the southeast
Newport Harbor	33.58957	117.87654	breakwater	east structure	retains the pocket at Big Corona Beach
Newport Harbor	33.58829	117.87864	breakwater	west structure	retains the beach on Balboa Peninsula
West Newport Beach	33.61255	117.93246	groin	no. 1 from the east	ineffective
West Newport Beach	33.61365	117.93337	groin	no. 2 from the east	ineffective
West Newport Beach	33.61462	117.93422	groin	no. 3 from the east	ineffective
West Newport Beach	33.61565	117.93512	groin	no. 4 from the east	ineffective
West Newport Beach	33.6166	117.93608	groin	no. 5 from the east	ineffective
West Newport Beach	33.61758	117.93702	groin	no. 6 from the east	ineffective
West Newport Beach	33.61855	117.93787	groin	no. 7 from the east	ineffective
West Newport Beach	33.61836	117.93883	groin	no. 8 from the east	ineffective
Santa Ana River	33.62847	117.95658	jetty	east structure	may retain sand on West Newport Beach
Santa Ana River	33.6292	117.95837	jetty	west structure	may retain sand on the beach in south Huntington Beach
Talbert Channel	33.63176	117.96158	jetty	east structure	very little if any impact
Talbert Channel	33.63193	117.96196	jetty	west structure	very little if any impact
Huntington Beach	33.65307	118.0051	pier	long structure	long structure, apparently dissipates wave energy and retains a salient centered on the base of the pier
Anaheim Bay	33.72651	118.0992	jetty	east structure	prevents sand transport to the east; probably functions as a diffraction structure, but frequent artificial beach enhancements prevent a hook-shaped bay from forming
Anaheim Bay	33.72734	118.10101	jetty	west structure	retains East Beach at Seal Beach
Seal Beach	33.7377	118.10685	groin	next to Seal Beach Pier	retains sand on East Beach
San Gabriel River	33.7397	118.11497	jetty	east structure	retains sand on West Beach, Seal Beach
Alamitos Bay	33.73642	118.11941	jetty	east structure	long structure possibly functions as a diffraction point
Alamitos Bay	33.73725	118.12116	jetty	west structure	retains sand on Long Beach
Los Angeles-Long Beach Harbor Complex	33.72309	118.136	breakwater	east end	functions as a diffraction structure, responsible for the incipient development of a hook-shaped bay to the southeast
Los Angeles-Long Beach Harbor Complex	33.71001	118.28378	breakwater	west end	structure creates quiescent conditions to the north, thereby retaining Long Beach

Structure location	latitude	longitude	type of structure	structure setting	structure impact on beaches
Cabrillo Beach	33.70561	118.27817	groin	east end of Cabrillo Beach	retains sand in the Cabrillo Beach pocket
Redondo Beach	33.83198	118.38994	groin	end of Topaz Street	effectively retains sand in the Redondo Beach pocket
King Harbor	33.84092	118.39433	breakwater	at south tip of structure	retains an upcoast fillet
El Segundo	33.91077	118.42617	groin	near power plant	long groin is retaining a fillet to the north, but is responsible for the erosional development of a hook-shaped bay to the south that has been arrested by a revetment
Imperial Hwy	33.92786	118.43507	groin	just south of highway junction with PCH	not effective at all times of year
Playa del Rey	33.94993	118.44812	groin	Dockweiler Beach	not effective at all times of year
Los Angeles Airport	33.93997	118.44250	groin	Dockweiler Beach	groin was effective in 1985 and 1987
Ballona Creek	33.96064	118.45666	jetty	southeast side of stream mouth	in lee of Marina del Rey breakwater
Marina del Rey	33.96035	118.45929	jetty	southeast side of navigation channel	in lee of Marina del Rey breakwater
Marina del Rey	33.96274	118.46093	jetty	northwest side of navigation channel	in lee of Marina del Rey breakwater
Marina del Rey	33.9583	118.45959	detached breakwater	southeast end	with south jetty retains a small salient-like feature on the south side, but also functions as a diffraction point and if sand was not periodically placed on Dockweiler Beach, a erosional hook-shaped bay will form
Marina del Rey	33.96367	118.46351	detached breakwater	northwest end	with north jetty retains a fillet-salient on the Venice side
Venice	33.98179	118.47089	groin	south of Venice breakwater	not effective at all times of year
Venice	33.98452	118.47551	detached breakwater	southeast end	effective in retaining a salient; groin connects the center of the breakwater to shore
Venice	33.98564	118.47656	detached breakwater	northwest end	effective in retaining a salient; groin connects the center of the breakwater to shore
Venice	33.99705	118.48415	groin	between detached breakwaters	not effective at all times of year
Santa Monica	34.00599	118.50003	detached breakwater	southeast end	effective in retaining a salient
Santa Monica	34.0096	118.50431	detached breakwater	northwest end	effective in retaining a salient; salient retains a fillet to the northwest
Will Rogers Beach SP	34.03443	118.53644	groin	east structure	very effective in retaining a fillet
Will Rogers Beach SP	34.03321	118.53324	groin	east-central structure	very effective in retaining a fillet

Structure location	latitude	longitude	type of structure	structure setting	structure impact on beaches
Will Rogers Beach SP	34.03189	118.52996	groin	west-central structure	very effective in retaining a fillet
Will Rogers Beach SP	34.03052	118.52679	groin	west structure	very effective in retaining a fillet
Sunset Blvd.	34.03778	118.55499	groin	at Gladstone's Restaurant	very effective in retaining a fillet
west of Sunset Blvd.	34.04049	118.56341	groin	structure may no longer be there	very effective in retaining a fillet
west of Sunset Blvd.	34.04075	118.56402	groin	structure may no longer be there	very effective in retaining a fillet
Las Tunas	34.03880	118.60006	groin	structure has been removed	the function of this structure is influenced by wave refraction over the delta of Topanga Creek
US Navy, Point Mugu	34.10714	119.14191	groin	east structure	retains sandy fillet; revetment to east prevents the further development of an erosional hook-shaped bay
US Navy, Point Mugu	34.10856	119.14355	groin	central structure	retains sandy fillet
US Navy, Point Mugu	34.10997	119.14561	groin	west structure	retains sandy fillet
Port Hueneme	34.14286	119.21116	harbor jetty	east side of channel	primary impact is small; may function as a wave-blocking and diffraction structure to create a hook-shaped bay at Hueneme Beach in the absence of frequent sand bypassing from Channel Islands Harbor
Port Hueneme	34.14386	119.21527	harbor jetty	west side of channel	retains sand on Silver Strand Beach
Port Hueneme	34.14474	119.21585	spur on the north jetty	pointed toward Silver Strand Beach	functions to retard the flow of sand into Hueneme Submarine Canyon
Channel Islands Harbor	34.15402	119.22918	detached breakwater	south end of structure	diffraction structure functions to create a hooked bay at Silver Strand Beach, but frequent bypassing prevents its development
Channel Islands Harbor	34.15958	119.23349	detached breakwater	north end of structure	indeterminate due to frequent bypassing from salient
Channel Islands Harbor	34.15585	119.22659	jetty	south structure	indeterminate
Channel Islands Harbor	34.15707	119.22744	jetty	north structure	impact muted by effects of detached breakwater and routine bypassing from salient,
Mandalay Beach	34.2058	119.25207	power plant outfall jetty	south structure	no noticable impact
Mandalay Beach	34.20607	119.25225	power plant outfall jetty	north structure	no noticable impact
Ventura Harbor	34.2466	119.27277	detached breakwater	south end of structure	indeterminate due to frequent bypassing from salient
Ventura Harbor	34.2507	119.27304	detached breakwater	north end of structure	indeterminate impact due to frequent bypassing
Ventura Harbor	34.24616	119.26944	shore-connected breakwater	south structure	indeterminate impact

Structure location	latitude	longitude	type of structure	structure setting	structure impact on beaches
Ventura Harbor	34.24782	119.27082	shore-connected breakwater	north structure	impact muted by effects of detached breakwater, routine bypassing from salient, and Pierpont groin no. 7
Ventura	34.25427	119.27059	groin	no. 7, southeasternmost structure	retains a sandy fillet
Ventura	34.25749	119.27205	groin	no. 6	retains a sandy fillet
Ventura	34.26076	119.27381	groin	no. 5	retains a sandy fillet
Ventura	34.26339	119.27605	groin	no. 4	retains a sandy fillet
Ventura	34.26652	119.27846	groin	no. 3	retains a sandy fillet
Ventura	34.27013	119.28258	groin	no. 2	retains a sandy fillet
Ventura	34.27296	119.28670	groin	no. 1 northwesternmost structure	retains a sandy fillet
west of Ventura	34.29352	119.33940	revetment	protects highway	retains a sandy fillet
Seacliff	34.35006	119.42348	revetment	at pier	retains a sandy fillet
Punta Gorda (canyon)	34.35539	119.44186	groin	at pier	retains a sandy fillet
Carpinteria State Beach	34.38903	119.51741	small reef/headland	east end of beach	retains a sandy fillet upcoast of a tar-sand outcrop
Sandyland	34.40398	119.54519	revetment	protects homes	retains a straight shoreline upcoast to the next revetment
Serena	34.40969	119.55268	revetment	protects homes	revetment retains a small fillet beach
Fernald Point	34.41918	119.61883	groin	east side of point	this groin retains a small upcoast beach and functions as a wave-blocking and diffraction structure to retain a downcoast hooked bay
Santa Barbara Harbor	34.40307	119.69080	breakwater	west end of harbor	retains upcoast Ledbetter Beach, without artificial bypassing an erosional hook-shaped bay would evolve to the east

A2 FILLET BEACHES RETAINED BY ROCKY HEADLANDS, GROINS, JETTIES, AND SHORE-CONNECTED BREAKWATERS

FILLET BEACHES RETAINED BY ROCKY HEADLANDS, GROINS, JETTIES, SHORE CONNECTED BREAKWATERS, AND A SALIENT (n =46)

Name of structure	**Latitude**	**Longitude**	**kind**	**gamma**	**alpha** summer	**alpha** winter	**fang** summer	**fang** winter	**fpdist** winter	**fldist** winter	**bdistf** summer	**bdistf** winter	**bdistd** summer	**bdistd** winter	**wu**	**wd**	**ngtr**	**ntr**
Coronado groin (pre-1946)	32.67857	117.17926	groin															
Oceanside Harbor	33.21390	117.40471	breakwater	326	337	336	11	10	110	680	160	130	500	500	160	0	0.20	25000
Dana Point	33.46258	117.71483	rocky headland	337	337	343	0	6	43	330	231	166	500	500	40	0	0.05	11000
King Harbor	33.84996	118.39988	breakwater	340	355	347				370	123	170		600	30	0	0.20	200000
El Segundo-power plant	33.91077	118.42617	groin	338	347	351		13		190	133	100	227	220	30	12	0.25	200000
LAX	33.93997	118.44250	groin	338	341	341	3	3		550	74	52	123	139	30	30	0.30	200000
Santa Monica breakwater fillet	34.01005	118.49850	salient	315	315	315					65	65	65	65	30	30	0.70	87000
Will Rogers Beach SP	34.03443	118.53644	groin	288	305	303	17	15		350	15	16	60	31	30	28	0.80	175000
Will Rogers Beach SP	34.03321	118.53324	groin	288	299	302	11	14		300	30	12	54	39	30	30	0.80	175000
Will Rogers Beach SP	34.03189	118.52996	groin	288	297	302	9	14		330	34	16	34	49	30	30	0.80	175000
Will Rogers Beach SP	34.03052	118.52679	groin	288	299	308	11	20		330	39	18	36	52	30	30	0.80	175000
Sunset Blvd.	34.03778	118.55499	groin	295	300	298	5	3	43	620	11	24	230	220	30	20	0.80	175000
west of Sunset Blvd.	34.04049	118.56341	groin	293	288	296		3		220		24		31	18	14	0.85	175000
west of Sunset Blvd.	34.04075	118.56402	groin	279	291	294		15		58		27		35	19	35	0.85	175000
Las Tunas	34.03880	118.60006	groin	270		294		14	50	90		5		40	8	4	0.85	175000
Point Dume	34.00133	118.80749	rocky headland		320	322				1350	30	16	360	360	30	25	0.85	165000

Name of structure	**Latitude**	**Longitude**	**kind**	**gamma**	**alpha** summer	**alpha** winter	**fang** summer	**fang** winter	**fpdist** winter	**fldist** winter	**bdistf** summer	**bdistf** winter	**bdistd** summer	**bdistd** winter	**wu**	**wd**	**ngtr**	**ntr**
Lechuza Point	34.03444	118.86066	rocky headland	290		296		6	40	330	37	17	190	180	30	10	0.85	190000
Sequit Point	34.04277	118.93658	rocky headland	290	286	297	-4	7	44	390	64	5	72	87	30	14	0.85	120000
Bass Rock	34.06468	118.99239	rocky headland		297	306			40	190	32	16	70	87	23	23	0.85	100000
Bass Rock	34.06531	118.99756	rocky headland		302	306			36	160	47	12	94	120	19	23	0.85	90000
Sycamore Beach	34.06769	119.00884	rocky headland		302	310			50	680	47	12	410	420	30	30	0.85	80000
La Jolla Beach	34.07223	119.01719	rocky headland	306	307	310	1	4	42	550	65	18	21	70	30	30	0.85	70000
Point Mugu-east	34.08449	119.05183	rocky headland		290	303			16	225	19	3	600	600	30	30	0.85	60000
Point Mugu	34.08530	119.06030	rocky headland	302	304	309	2	7	106	790	85	17	310	310	30	16	0.85	50000
no. 3, US Navy, Point Mugu	34.10714	119.14191	groin	309	310	314	1	5	55	211	59	39	91	60	30	30	0.85	840000
no. 2, US Navy, Point Mugu	34.10856	119.14355	groin	309	314	315	5	6	65	210	52	26	52	30	30	30	0.85	840000
no. 1, US Navy, Point Mugu	34.10997	119.14561	groin	309	311	314	2	5	59	1100	51	26	51	26	30	30	0.85	840000
no. 7, Ventura	34.25427	119.27059	groin		342	344				405	128	128	168	202	30	30	0.78	380000
no. 6, Ventura	34.25749	119.27205	groin		336	339				421	102	107	122	149	30	30	0.80	380000
no. 5, Ventura	34.26076	119.27381	groin		331	333				336	77	66	93	104	30	30	0.81	380000
no. 4, Ventura	34.26339	119.27605	groin		327	329				400	68	59	110	97	30	30	0.82	380000
no. 3, Ventura	34.26652	119.27846	groin		321	324				545	42	35	72	73	30	30	0.83	380000
no. 2, Ventura	34.27013	119.28258	groin		313	316				475	48	16	65	75	30	30	0.84	380000
no. 1, Ventura	34.27296	119.28670	groin		309	309				400	37	20	60	70	30	30	0.85	380000
west of Ventura	34.29352	119.33940	highway revetment	330	335	331	5	1	20	260	14	12	62	69	15	19	0.85	228,000
Seacliff	34.35006	119.42348	revetment at a pier	313	322	323	9	10	61	400	9	7	17	19	30	5	0.85	228,000
Punta Gorda	34.35539	119.44186	groin at pier	322	328	328	6	6	140	1200	24	24	86	91	30	0	0.85	228,000

Name of structure	**Latitude**	**Longitude**	**kind**	**gamma**	**alpha** summer	**alpha** winter	**fang** summer	**fang** winter	**fpdist** winter	**fldist** winter	**bdistf** summer	**bdistf** winter	**bdistd** summer	**bdistd** winter	**wu**	**wd**	**ngtr**	**ntr**
(canyon)																		
El Rincon	34.38595	119.50921	small headland	299	305	303	6	4	23	305	20	19	27	31	15	0	0.85	228,000
Carpinteria State Beach	34.38903	119.51741	small reef/headland	307	312	312	5	5	63	290	18	9	22	27	20	0	0.85	228,000
Sandyland	34.40398	119.54519	revetment	315	315	315	0	0	24	740	23	22	52	61	20	26	0.85	228,000
Serena	34.40969	119.55268	revetment	308	312	312	4	4	21	210	15	11	33	30	13	20	0.85	228,000
Fernald Point-east side	34.41918	119.61883	groin	219	234	237	15	18	35	86	6	12	20	28	5	12	0.85	228,000
Santa Barbara Harbor	34.40307	119.69080	west breakwater	248	265	261	17	13	160	560	19	1		430	30	30	0.85	228,000
Port Orford. East	34.46795	120.23863	rocky headland		266	266	19		44	170		14		136	5	4	0.75	90000
Point Sal	34.90300	120.67073	rocky headland	376	377	376	1	0		1500	76	110	2400	2400	28	18	0.10	5000
Mussel Point	34.93317	120.66333	rocky headland	376	380	376	4	0		1200	130	160	310	290	30	25	0.10	5000

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Name of structure	**Latitude**	**Longitude**	**Remarks**
Coronado groin (pre-1946)	32.67857	117.17926	difficult to assign values due to sheltering effect of curved structure
Oceanside Harbor	33.21390	117.40471	sand does not naturally pass the entrance to Oceanside Harbor
Dana Point	33.46258	117.71483	major impediment to longshore sand transport
King Harbor	33.84996	118.39988	end of effective part of breakwater appears to be at landward location where structure begins its curve to the south
El Segundo-power plant	33.91077	118.42617	groins are sometimes buried by opportunistic beachfill
LAX	33.93997	118.44250	groins are sometimes buried by opportunistic beachfill
Santa Monica breakwater fillet	34.01005	118.49850	salient in the lee of the breakwater functions as a sediment-blocking structure and retains a large upcoast fillet
Will Rogers Beach SP	34.03443	118.53644	easternmost structure
Will Rogers Beach SP	34.03321	118.53324	east-central structure
Will Rogers Beach SP	34.03189	118.52996	west-central structure
Will Rogers Beach SP	34.03052	118.52679	westernmost structure

Name of structure	Latitude	Longitude	Remarks
Sunset Blvd.	34.03778	118.55499	very effective in retaining an upcoast fillet
west of Sunset Blvd.	34.04049	118.56341	groin may no longer be functioning, not found in 1985 photos
west of Sunset Blvd.	34.04075	118.56402	groin may no longer be functioning, not found in 1985 photos
Las Tunas	34.03880	118.60006	groin deteriorating in 1987, no longer there
Point Dume	34.00133	118.80749	massive rocky headland
Lechuza Point	34.03444	118.86066	headland functions as a diffraction point for a hooked bay to the east
Sequit Point	34.04277	118.93658	large, complex low-lying headland
Bass Rock	34.06468	118.99239	small fillet between two small headlands
Bass Rock	34.06531	118.99756	small fillet between two small headlands
Sycamore Beach	34.06769	119.00884	small fillet between two small headlands east of Point Mugu, fillet extends from headland to headland
La Jolla Beach	34.07223	119.01719	beach lost width in recent years as the sand supply passing Point Mugu declined
Point Mugu-east	34.08449	119.05183	small fillet between two small headlands east of Point Mugu
Point Mugu	34.08530	119.06030	large well developed fillet
no. 3, US Navy, Point Mugu	34.10714	119.14191	retains a sandy fillet, a revetment prevents a hook-shaped bay from forming downcoast
no. 2, US Navy, Point Mugu	34.10856	119.14355	largely ineffective, sandy fillet is mostly retained by the groin to the east
no. 1, US Navy, Point Mugu	34.10997	119.14561	largely ineffective, sandy fillet is mostly retained by the groin to the east
no. 7, Ventura	34.25427	119.27059	retains a sandy fillet
no. 6, Ventura	34.25749	119.27205	retains a sandy fillet
no. 5, Ventura	34.26076	119.27381	retains a sandy fillet
no. 4, Ventura	34.26339	119.27605	retains a sandy fillet
no. 3, Ventura	34.26652	119.27846	retains a sandy fillet
no. 2, Ventura	34.27013	119.28258	retains a sandy fillet
no. 1, Ventura	34.27296	119.28670	retains a sandy fillet
west of Ventura	34.29352	119.33940	where the coast highway ramp joins the freeway
Seacliff	34.35006	119.42348	in 1985-87 was near a now-removed oil pier
Punta Gorda (canyon)	34.35539	119.44186	possible creek delta that retains a shoreline bulge, but with a small groin at the tip
El Rincon	34.38595	119.50921	rocky projection at point
Carpinteria State Beach	34.38903	119.51741	tar sand outcrop at east end of Carpinteria Beach
Sandyland	34.40398	119.54519	curved revetment stabilizes upcoast shoreline
Serena	34.40969	119.55268	curved revetment stabilizes upcoast shoreline
Fernald Point-east side	34.41918	119.61883	small hook has developed north and east of groin
Santa Barbara Harbor	34.40307	119.69080	west breakwater greatly changed the oriention of the upcoast beach
Port Orford. East	34.46795	120.23863	small fillet in winter; wider beach but no fillet in the summer.

Name of structure	Latitude	Longitude	Remarks
Point Sal	34.90300	120.67073	fillet in the small hooked bay between Point Sal and Mussel Point
Mussel Point	34.93317	120.66333	smaller rocky projection north of Mussel Point, is the anchor end of a the Santa Maria River hook-shaped bay; fillet not detectable in summer

NOTATION

alpha is the bearing of the fillet shoreline in degrees (TN)

gamma is the bearing of the shoreline as it would be if the sediment-blocking structure were not there (difficult to estimate where the coastline is irregular), in degrees (TN)

fang is the fillet angle equal to the difference in alpha and gamma, in degrees

fpdist is the fillet projection distance normal to shore equal to the shore-normal distance between the fillet shoreline junction with the structure and the shoreline as it would be if the sediment-blocking structure were not there (difficult to measure if the coastline is irregular), in meters based on the wetted-bound shoreline position

fldist is the alongshore length of the fillet (difficult to measure where the coastline is irregular) in meters

bdistf is the blocking distance on the fillet side of the structure, equal to the shore-normal distance between the end of the structure and the junction of the fillet (wetted-bound) shoreline and the structure, in meters

bdistd is the blocking distance on the downcoast side of the structure, equal to the shore-normal distance between the end of the structure and the junction of the downcoast shoreline (wetted-bound) and the structure, in meters

wu is the width of the beach upcoast of the fillet equal to the shore-normal distance from the wetted-bound shoreline to the vegetation line, seacliff, or revetment or seawall, in meters

wd is the width of the beach downcoast of the fillet, equal to the shore-normal distance between the wetted-bound shoreline and the vegetation line, seacliff, revetment, or seacliff

ngtr is the net to gross longshore sediment transport ratio

ntr is the net longshore sediment transport rate, in cubic meters per year

A3 PERIMETER BEACHES RETAINED BY NEAR-COAST SUBMARINE CANYONS

PERIMETER BEACHES: SUBMARINE CANYONS (n = 8)

Name	Latitude	Longitude	scr	Qn	yrint	mdisr	mdepr	soff	shlgth	area	remarks
La Jolla	32.85668	117.26057	750	750	1984-87	560	6	-87	2300	115000	most sand is captured just upcoast in Scripps Canyon
Scripps	32.87486	117.25204	21500	22800	1984-87	210	5.5	-146	1300	130000	capture rate varied by an order of magnitude from the 1960's to the 1980's
Carlsbad	33.12750	117.34933	0	23000	1984-87	1350	30	180	2200	195000	too far offshore to capture much littoral sand
Newport	33.60649	117.93016	750	22000	1987-95	240	7	979	7200	3230000	without this canyon Balboa Peninsula and West Newport would not exist
Redondo	33.83875	118.39131	38000	38000	1990's	180	8.5	-175	6800	250000	losses to this canyon have increased in recent years as the shoreline adanced out along the north King Harbor breakwater
Dume	33.99967	118.81122	500	150000	1990's	540	18	2400			canyon lies off rocky Pt Dume
Mugu (1990's)	34.09878	119.09792	840000	840000	1990's	20	0	-926	4600	2460000	Mugu Canyon headwall retreat intercepted a revetment
Mugu (pre-1966)	34.09878	119.09792	720000	840000	<1960	50	2	-926	4600	2460000	some sand passed the shallow rim because the canyon is not at the end of the littoral cell
Hueneme	343.14308	119.21269	38000	880000	<1938	200	7	564	7300	2010000	the shoreline projection here is much like that at Newport Canyon

NOTATION

latitude & **longitude** are based on NAD 27

scr is the rate at which sand is trapped in the canyon, in cubic meters per year

Qn is the net longshore sediment transport rate in the vicinity of the canyon, in cubic meters per year

yrint is the year interval for which the sand capture rate in the canyon, scr, was measured or estimated

mdisr is the distance from the shoreline to the rim of the canyon at its closest position to shore, in meters

mdepr is the water depth at the rim of the canyon at its closest position relative to shore, in meters (mllw)

area is the plan area of the bulge or embayment in square meters

A4 PERIMETER BEACHES RETAINED BY RIVER AND STREAM DELTAS

PERIMETER BEACHES: STREAM AND RIVER DELTAS (n = 22)

Delta	Latitude degrees north	Longitude degrees west	Orientation degrees (TN)	Length meters	Projdist meters	Bwidth meters	Remarks
Tijuana River	32.56314	117.13188	171	2900	200	22	anchor structure for the Silver Strand hooked bay
San Onofre Creek	33.3805	117.57996	105	540	85	32	probable delta just west of the outlet of San Onofre Creek
San Mateo Creek	33.38503	117.59307	132	3600	750	77	double shoreline bulge
Santa Ynez Cyn	34.03774	118.5545	95	1080	190	9	possible creek delta at ocean end of Sunset Blvd.
Topanga Cyn	34.03745	118.58271	86	960	190	52	popular surf site
Piedra Gorda Cyn	34.03641	118.60855	70	1100	100	22	possible creek delta that retains a shoreline bulge
Las Flores Cyn	34.03602	118.63468	87	430	80	45	possible creek delta that retains a shoreline bulge
Carbon Cyn	34.03736	118.64782	85	490	80	26	possible creek delta that retains a shoreline bulge
Malibu Creek	34.03062	118.68157	74	2400	550	34	large delta, popular surf site
east of San Nicholas Cyn	34.03652	118.86907	108	410	48	24	possible creek delta
San Nicholas Cyn	34.04149	118.91459	106	1300	210	8	popular surf site
Little Sycamore Cyn	34.05219	118.96329	118	350	60	33	probable creek delta that retains a shoreline bulge
Ventura River	34.27324	118.30475	109	2900	620	14	huge delta, popular surf site
Dulah (canyon)	34.30996	119.35733	131	790	60	2	possible creek delta that retains a shoreline bulge
Padre Juan Cyn	34.31764	119.38798	118	2800	900	2	Pitas Point, possible creek delta
Rincon Creek	34.37287	119.47716	109	2100	610	12	Rincon Point, possible creek delta that retains a shoreline bulge
Toro Cyn	34.41242	119.57569	97	2400	440	14	Loon Point, possible creek delta
Romero Cyn	34.41847	119.6198	81	1100	210	11	Fernald Point, creek delta; small groin on the east side of point

Delta	**Latitude** degrees north	**Longitude** degrees west	**Orientation** degrees (TN)	**Length** meters	**Projdist** meters	**Bwidth** meters	**Remarks**
Gato Cyn	34.44956	119.98881	116	1400	280	7	creek delta, cobbles at low tide elevation
Canada del Capitan	34.45771	120.02134	95	1900	490	7	El Capitan State Park, possible creek delta
Canada del Molino	34.46973	120.16792	87	920	140	13	probable stream delta, very similar to San Onofre to the west
Canada San Onofre	34.46973	120.1859	87	890	100	14	probable stream delta; less likely a shore-connected reef
Canada del Cojo	34.453	120.438	73	350	70	14	possible stream delta, could be a bedrock shore platform

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NOTATION

orientation is the bearing of a line connecting the north or west end of the shoreline bulge to its south or east landward end

length is the distance between the north or west end of the bulge and the south or east end

projdist is the distance between the outer end, or apex, of the bulge and the line connecting the north or west end and the south or east ends of the bulge

bwidth is the average width of the sandy beach at the apex based on spring 1985 and late summer 1987 aerial photos

A5 PERIMETER BEACHES RETAINED BY REEFS

PERIMETER BEACHES: REEFS (n = 34)

Reef	Latitude degrees north	Longitude degrees west	Orientation degrees (TN)	Length meters	Projdist meters	Bwidth	Remarks
San Onofre Beach	33.37132	117.56298	130	1700	150	52	double shoreline bulge, reef is south of the outlet of San Onofre Creek, but might be a delta
Halfway Rock	33.53187	117.77614	141	480	57	15	reef is at south end of Main Beach, Laguna Beach
Reef Point	33.5657	117.8322	127	990	190	27	partly exposed reef at Crystal Cove
west of Reef Point	33.56883	117.83715	134	150	67	38	partly exposed reef at Crystal Cove
west of Reef Point	33.57098	117.83715	142	110	45	23	partly exposed reef at Crystal Cove
Pelican Point	33.57967	117.85294	122	350	63	8	partly exposed reef at Crystal Cove
east of Las Flores	34.0367	118.62711	86	790	58	27	partly exposed reef
Amarillo Beach	34.0294	118.70566	87	700	90	6	probable reef below Malibu Bluff State Park
Puerco Beach	34.03107	118.71828	95	310	85	46	partially exposed reef
Puerco Beach	34.0318	118.7238	99	580	25	25	partially exposed reef
Latigo Point	34.02581	118.75443	67	1400	270	10	possible reef, large projection of the shoreline
east of Dume Cove	34.00719	118.7934	51	860	270	4	likely reef
east of San Nicholas Cyn	34.03803	118.882	95	340	55	11	small partially exposed reef
east of San Nicholas Cyn	34.03875	118.89098	95	240	62	13	small partially exposed reef
east of San Nicholas Cyn	34.03916	118.89489	90	280	45	9	small partially exposed reef
east of San Nicholas Cyn	34.03961	118.89704	112	335	20	15	small partially exposed reef
east of San Nicholas Cyn	34.04152	118.90557	98	420	46	11	partially exposed reef
Solromar	34.0494	118.95671	115	1000	60	15	partially exposed reef
west of Solromar	34.05859	118.97414	131	340	40	30	partially exposed reef
Sand Point	34.39582	119.53616	125	2300	360	12	documented reef retrains a huge wetland, El Estero
Serena Park	34.41396	119.56842	60	600	75	11	small, probable double reef complex

Reef	Latitude degrees north	Longitude degrees west	Orientation degrees (TN)	Length meters	Projdist meters	Bwidth	Remarks
Summerland	34.41972	119.60539	98	750	59	5	possible reef, small projection of the shoreline
Montecito	34.41571	119.6367	84	1650	290	15	reef exposed in the littoral zone
Hope Ranch	34.41071	119.77169	115	530	63	12	reef exposed in the littoral zone
Goleta Point	34.40412	119.84327	77	2500	950	12	scattered rocky outcrops above msl, submerged reef
Coal Oil Point	34.4068	119.8771	118	2200	660	17	reef
Refugio Beach State Park	34.46073	120.07224	70	680	140	12	shore-connected reef exposed at low tide; sandy perimeter beach at least part of the year, nice hooked bay to the east
Tajiguas Creek	34.46364	120.10109	106	59	400	9	partially exposed reef
Canada de Alegria	34.46672	120.27703	96	1600	310	20	bedrock shore platform near msl
Drake	34.46654	120.30225	67	860	160	13	bedrock shore platform near msl
Santa Anita Ranch	34.45949	120.33566	58	520	140	8	bedrock shore platform
Las Agujas	34.45876	120.34071	18	360	60	18	bedrock reef exposed in the littoral zone
San Agustine	34.45749	120.35537	74	490	80	16	bedrock shore platform near msl
east of Cojo	34.44982	120.42153	74	940	230	15	bedrock shore platform near msl
Cojo Bay	34.44911	120.44468	50	380	75	18	low reef, possibly composed of cobbles and boulders

27794

NOTATION

orientation is the bearing of a line connecting the north or west end of the shoreline bulge to its south or east landward end

length is the distance between the north or west end of the bulge and the south or east end

projdist is the distance between the outer end, or apex, of the bulge and the line connecting the north or west end and the south or east ends of the bulge

bwidth is the average width of the sandy beach at the apex based on spring 1985 and late summer 1987 aerial photos

A6 BEACHES RETAINED WITHIN HOOK-SHAPED BAYS

HOOK-SHAPED BAYS AND BEACHES (n = 51)

Place Name	**Latitude** north/west structure	**Longitude** north/west structure	**Latitude** south/east structure	**Longitude** south/east structure	**a** meters	**β** degrees	**αr** degrees	**b** meters	**a'** meters	**d** meters	**ntgr**
HOOK-SHAPED BAYS LESS THAN 2-KM LONG											
San Elijo State Beach	33.03514	117.2938	33.02293	117.2851	1580	330	343	152	349	246	0.1-0.3
Salt Creek Beach	33.48406	117.73274	33.47393	117.72062	1602	315	339	414	517	976	0.1-0.2
Main Beach, Laguna Beach	33.54232	117.78802	33.53162	117.78802	1649	316	329	230	381	917	0.0-0.1
Las Varas Creek	34.0394	118.57566	34.03793	118.55501	1950	276	301	235	445	1252	0.7-0.9
Topanga	34.03655	118.60789	34.0389	118.59624	1120	256	296	294	675	595	0.8-0.9
Las Tunas	34.0369	118.62599	34.03633	118.60947	1526	273	271	140	530	520	0.8-0.9
Big Rock Beach	34.03614	118.63482	34.03682	118.62628	790	265	279	117	338	1068	0.8-0.9
Las Flores	34.03751	118.64782	34.03616	118.63506	1205	278	275	69	290	379	0.8-0.9
La Costa	34.03077	118.70014	34.03062	118.68212	1642	271	287	116	315	640	0.8-0.9
Malibu Lagoon- west	34.03109	118.71816	34.02943	118.70545	1175	279	286	201	692	627	0.8-0.9
Puerco - Amarillo	34.00038	118.80393	34.00687	118.79443	1168	234	287	96	420	738	0.8-0.9
Dume Cove	34.03436	118.86055	34.02879	118.8413	1876	290	266	290	504	224	0.8-0.9
Trancas Beach	34.04354	118.93379	34.04222	118.91539	1698	276	306	217	610	450	0.8-0.9
Sequit Point	34.41863	119.61977	34.41972	119.60574	1297	266	300	303	609	617	0.8-0.9
Fernald Point	34.41949	119.6187	34.41983	119.60632	1180	269	287	237	292	387	0.7-0.9
Santa Barbara West Beach	34.39791	119.70095	34.40308	119.69081	1115	238	259	173	410	427	0.7-0.9
Coal Oil Point	34.40691	119.87707	34.4086	119.86316	1320	282	273	144	371	623	0.7-0.9
Refugio	34.46084	120.07218	34.46104	120.05691	1411	266	278	203	309	956	0.7-0.9
Santa Anita Ranch	34.45958	120.33539	34.46353	120.319	1587	252	264	224	377	915	0.7-0.9
San Augustine	34.45762	120.35514	34.45855	120.34382	1064	262	274	130	264	575	0.7-0.9
VAFB	34.55614	120.58556	34.55328	120.57354	1205	286	313	202	384	234	0.1-0.6

Place Name	Latitude north/west structure	Longitude north/west structure	Latitude south/east structure	Longitude south/east structure	a meters	β degrees	αr degrees	b meters	a' meters	d meters	ntgr
HOOK-SHAPED BAYS BETWEEN 2 AND 3-KM LONG											
Sunset Blvd.	34.03774	118.55289	34.03007	118.52449	2830	288	298	345	752	1923	0.7-0.8
Bass Rock	34.06605	119.00477	34.06075	118.98344	2072	287	303	220	631	621	0.8-0.9
Pitas Point	34.31792	119.38815	34.31001	119.35721	2970	288	318	714	1272	875	0.7-0.9
W Coal Oil Point	34.42129	119.89977	34.40772	119.87849	2459	308	325	387	1028	1220	0.7-0.9
Sacate	34.46656	120.30225	34.46744	120.27814	2208	266	286	445	822	1041	0.7-0.9
Cojo	34.44249	120.45113	34.44986	120.42525	2536	249	279	659	990	892	0.6-0.8
Bass Rock	34.92924	120.66612	34.909791	120.66802	2253	184	196	325	460	1297	0.0-0.2
HOOK-SHAPED BAYS BETWEEN 3 AND 4-KM LONG											
Carbon Canyon	34.03087	118.68133	34.03751	118.64782	3193	258	281	618	1062	674	0.8-0.9
Dan Blocker	34.02581	118.75445	34.03109	118.71816	3426	261	281	531	1114	1112	0.8-0.9
La Jolla Beach	34.08438	119.05022	34.07086	118.01542	3562	296	310	441	1161	892	0.8-0.9
Seacliff	34.35556	119.44174	34.33818	119.41168	3371	306	322	623	937	2029	0.7-0.9
Rincon Point	34.37285	119.4768	34.35708	119.44303	3574	300	326	881	1335	1369	0.7-0.9
Sandyland Cove	34.39604	119.53585	34.38896	119.51738	1886	295	307	224	701	959	0.7-0.9
Loon Point - Serena	34.4125	119.5755	34.39857	119.53927	3627	295	316	797	1185	1414	0.7-0.9
Santa Barbara Harbor breakwater	34.40471	119.68675	34.41692	119.65751	3029	245	267	755	517	1291	0.7-0.9
Goleta Beach County Park	34.40469	119.84311	34.41661	119.81251	3110	245	276	724	1154	456	0.7-0.9
El Capitan	34.45757	120.02141	34.4503	119.98957	3028	285	310	667	1259	729	0.7-0.9
Black Canyon	34.48809	120.48869	34.45796	120.47242	3680	336	357	540	1430	820	0.7-0.9
HOOK-SHAPED BAYS BETWEEN 4 AND 5-KM LONG											
Escondido	34.0074	118.79324	34.02581	118.75445	4148	241	267	907	1559	776	0.8-0.9
Hueneme Beach	34.14292	119.21106	34.12524	119.16845	4422	298	313	574	1488	1972	0.85-0.95
Bell Canyon	34.43448	119.95001	34.42144	119.90131	4732	289	307	701	2009	1587	0.7-0.8

Place Name	**Latitude** north/west structure	**Longitude** north/west structure	**Latitude** south/east structure	**Longitude** south/east structure	**a** meters	**β** degrees	**αr** degrees	**b** meters	**a'** meters	**d** meters	**ntgr**
HOOK-SHAPED BAYS GREATER THAN 5-KM LONG											
Silver Strand	32.66311	117.23938	32.56196	117.13189	15405	318	360	5613	4509	3610	0.1-0.4
Mission Beach	32.80752	117.26718	32.75898	117.25364	5523	347	370	675	2105	433	0
Dana Point	33.46	117.71355	33. 42526	117.62566	9110	295	324	1500	2980	400	<0.1
San Pedro	33.70433	118.28931	33.67765	118.02902	24500	277	321	7790	9790	4120	0.2-0.6
Pierpont	34.27339	119.3042	34.2352	119.26493	5760	322	351	1435	2160	1590	0.7-0.9
Jalama Beach	34.54056	120.55257	34.49634	120.4957	7199	313	343	1236	4119	1473	0.1-0.4
Santa Ynez	34.75573	120.63914	34.6409	120.62187	12857	353	377	2774	5947	4387	0.0-0.2
Casmalia	34.90267	120.67039	34.757	120.63584	16457	348	377	4523	6014	4233	0.0-0.3
Santa Maria River bay	35.15951	120.7589	34.93416	120.66166	26510	340	374	9090	7350	8500	0.0-0.1
Morro Bay	35.45993	121.002319	35.29008	120.88099	21833	330	378	7529	8364	2693	0.0-0.1
					240428						

NOTATION

a is the length of the control line, i.e, the distance between the tip of the diffraction structure and the anchor structure, in meters

β is the bearing of the control line between the diffraction and anchor structures, in degrees (TN)

αr is the bearing of the straight shoreline adjacent to the anchor structure, in degrees (TN)

b is the distance, normal to the control line, of the deepest indentation of the hook-shaped bay, in meters

a' is the distance along the control line from the diffraction structure to the origin of the indentation line, in meters

d is the length of the straight shoreline adjacent to the anchor structure, in meters

ntgr is the net to gross longshore sediment transport ratio

A7 BEACHES RETAINED WITHIN POCKET BAYS

POCKET BAYS AND BEACHES (n = 61)

location	**Latitude** north or west str	**Longitude** north or west str	**Latitude** south or east str	**Longitude** south or east str	**a**	**β**	**γl**	**y1**	**y2**	**ε1**	**ε2**	**φ**	**b**	**a'**
Point Loma - east	32.67122	117.23537	32.668	117.23601	354	369	na	28	61	332	227	364	39	117
Point Loma - west	32.669	117.24464	32.66802	117.24415	155	345	346	42	30	92	65	349	13	32
Ocean Beach	32.75587	117.25806	32.7462	117.25425	1141	342	350	480	100	82	55	362	119	506
La Jolla Hermosa Park	32.81796	117.27481	32.81557	117.2731	312	329	325	93	126	43	44	323	53	139
La Jolla Strand Park	32.83253	117.3813	32.82192	117.28005	1158	354	354	23	127	121	15	349	70	547
Nicholson Point	32.83906	117.28226	32.83253	117.2813	745	353	354	98	0	54	17	361	53	466
Seal Rock	32.84735	117.27916	32.84352	117.28001	435	370	378	153	27	82	62	387	65	157
Mussel Cove	33.4885	117.73698	33.48468	117.73356	518	325	321	126	222	35	38	314	69	164
N Mussel Cove Pocket Beach	33.48956	117.73733	33.4885	117.73698	114	345	321	65	110	72	69	322	15	43
South Laguna	33.49889	117.74278	33.49222	117.73821	863	330	321	49	77	105	4	328	5	391
Thousand Steps Beach	33.50685	117.75001	33.50278	117.74648	550	323	321	63	89	53	17	320	14	147
Aliso Beach	33.51148	117.75374	33.50685	117.75001	621	326	321	0	0	69	360	326	54	306
N Aliso Beach	33.51339	117.75668	33.51148	117.75374	356	308	321	0	0	84	5	308	69	173
Treasure Island Beach	33.5136	117.75995	33.51381	117.7574	193	264	321	71	29	10	0	277	20	77
Victoria Pocket Beach	33.51969	117.76287	33.51406	117.76	689	337	321	44	54	102	44	336	36	327
N Arch Beach	33.52485	117.7682	33.52229	117.76497	394	315	321	70	74	74	2	314	7	150
Woods Cove	33.52673	117.77064	33.52485	117.7682	317	313	321	40	43	36	47	313	12	158
Heisler Park	33.5428	117.79875	33.54234	117.78801	310	278	306	58	48	47	330	280	12	97
Shaws Cove - Recreation Pt	33.54482	117.79875	33.5428	117.79149	730	288	306	58	34	38	347	290	127	310
Crescent Bay	33.5462	117.80289	33.45488	117.79961	340	295	306	83	70	48	21	297	43	140
Emerald Bay	33.55061	117.81388	33.54835	117.80625	746	290	306	228	129	35	18	297	99	224
Irvine Cove	33.55362	117.81897	33.55061	117.81388	574	306	306	131	175	54	39	301	59	217
Abalone Point - Moro Cove	33.56407	117.82888	33.55362	117.81897	1532	321	306	0	272	100	23	311	154	651
Crystal Cove	33.57973	117.85283	33.56578	117.83238	2438	310	307	0	0	110	346	310	262	1279
Pelican Point	33.58337	117.85979	33.57973	117.85283	754	302	307	40	11	48	328	304	45	390

location	**Latitude** north or west str	**Longitude** north or west str	**Latitude** south or east str	**Longitude** south or east str	**a**	**β**	**γl**	**y1**	**y2**	**ε1**	**ε2**	**φ**	**b**	**a'**
Big Corona Beach	33.58955	117.87651	33.59218	117.87144	537	240	303	307	44	359	38	269	63	250
East Seal Beach	33.73818	118.10631	33.73369	118.10008	756	312	300	41	146	32	34	304	64	481
West Seal Beach	33.73962	118.11504	33.73818	118.10631	827	282	300	299	99	12	32	296	15	446
Cabrillo Beach	33.70685	118.28501	33.70578	118.27798	661	280	276	4	2	24	33	281	120	292
Point Fermin Pocket Beach	33.70983	118.29968	33.70468	118.29351	798	316	299	137	179	90	359	313	40	239
US Naval Reserve - south	33.7153	118.31819	33.71371	118.31664	225	319	303	49	29	80	1	324	37	80
US Naval Reserve - north	33.7173	118.32123	33.71606	118.31901	256	305	303	43	65	53	26	301	37	86
Royal Palms Park	33.71867	118.3245	33.7173	118.32123	324	298	303	0	41	90	29	291	65	178
Portuguese Bend	33.73642	18.36781	33.73088	18.36781	1482	295	294	163	81	14	350	298	296	678
N Portuguese Point	33.7371	118.37266	33.73639	118.36886	367	282	294	160	145	32	1	284	60	193
Abalone Cove	33.73957	118.38849	33.73727	118.37421	1345	281	294	417	49	58	11	297	215	543
Long Point	33.73815	118.39214	33.73957	118.38849	359	246	247	61	64	11	285	245	45	111
Long Point	33.73671	118.39558	33.73815	118.39214	356	242	247	39	23	29	355	245	47	171
Long Point	33.73874	118.40152	33.73725	118.39947	238	312	304	39	29	69	1	315	37	90
Point Vicente	33.74101	118.4106	33.73891	118.40195	826	287	304	334	93	83	17	304	60	193
Point Vicente	33.75148	118.41378	33.74684	118.41285	505	351	337	7	59	139	13	345	72	184
Point Vicente	33.75456	118.41472	33.75146	118.41378	361	346	337	94	25	134	52	357	103	131
Resort Point	33.76259	118.41896	33.76017	118.41766	286	334	337	101	35	82	29	347	91	96
Lunada Bay	33.77221	118.42567	33.76696	118.42354	605	341	337	190	300	69	62	330	99	229
Redondo Beach	33.84111	118.39407	33.79989	118.40369	4619	371	367	387	889	127	70	365	247	2169
Topanga	34.03749	118.58236	34.03937	118.57562	643	252	253	0	0	58	282	252	84	422
Point Mugu	34.08523	119.06027	34.08481	119.05196	777	271		83	85	68	299	278	26	132
Silver Strand	34.15583	119.22659	34.14377	119.21526	1684	323	324	177	120	56	3	325	130	594
El Rincon	34.38614	119.50893	34.37281	119.47711	3223	298	299	214	0	104	338	301	407	1688
Goverment Point	34.44447	120.45763	34.4434	120.4557	230	302	293	0	0	73	1	302	88	123
Government Point	34.44711	120.46126	34.44516	120.45833	343	306	293	124	107	33	38	309	44	179
Indian Head Rock	34.44852	120.46713	34.44721	120.46159	519	285	293	127	100	44	25	288	32	203
Vandenberg AFB	34.55351	120.61444	34.55353	120.61132	283	269	261	65	62	36	317	270	35	104
Point Arguello	34.57278	120.64038	34.57114	120.63831	243	312	343	224	84	91	96	348	52	67

location	**Latitude** north or west str	**Longitude** north or west str	**Latitude** south or east str	**Longitude** south or east str	**a**	**β**	**γl**	**y1**	**y2**	**ε1**	**ε2**	**φ**	**b**	**a'**
Point Pedernales	34.60091	120.64074	34.59828	120.63942	306	339	365	147	0	102	76	368	68	90
Point Pedernales	34.60596	120.63887	34.60483	120.64082	201	416	376	23	110	125	119	390	37	69
Mussel Point	34.93308	120.6633	34.93109	120.6646	241	389	385	33	62	122	111	382	12	106
Mallagh Landing	35.17392	120.71511	35.1746	120.71023	455	257	285	149	68	343	320	267	89	150
Avila Beach	35.1778	120.74005	35.17497	120.72505	1398	281	285	228	50	68	33	289	105	744
Point Buchon P	35.25109	120.8959	35.24795	120.8965	354	369	320	0	144	104	81	345	92	99
Montana Del Oro	35.27605	120.88849	35.27368	120.88921	282	372	380	96	81	121	135	375	69	170
San Geronimo	35.45947	120.96963	35.48817	120.96483	464	289	290	14	34	16	1	287	95	114

43716

NOTATION

a is the distance between the tips of the structures that retrain the pocket bay, in meters

β is the bearing of the control line between the structures, in degrees (TN)

γl is the average bearing of the 10-meter isobath in the vicinity of the pocket bay, in degrees (TN)

y1 is the distance the north or west structure projects beyond the sandy shoreline in the bay, measured from the tip of the structure to where the wetted-bound shoreline intercepts the structure, in meters

y2 is the distance the south or east structure projects beyond the sandy shoreline in the bay, measured from the tip of the structure to where the wetted-bound shoreline intercepts the structure, in meters

ε1 is the bearing of the north or west structure, in degrees (TN)

ε2 is the bearing of the south or east structure, in degrees (TN)

φ is the bearing of the sandy shoreline in the pocket bay, measured between the end points where it intercepts the retaining structures, in degrees (TN)

b is the maximum indentation distance of the sandy shoreline, measured normal to the line that connects its two ends, in meters

a' is the distance along the line that connects the ends of the sandy shoreline to the origin of the maximum indentation, from the north or west structure, in meters