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Author
Flick, R E

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The Myth and Reality of Southern California Beaches

By

Reinhard E. Flick

California Department of Boating and Waterways

Scripps Institution of Oceanography, La Jolla, CA 92093-0209

ABSTRACT

THE BEACHES ARE THE ESSENCE of California and provide its most important aesthetic and recreational asset. Yet, the widest sand beaches in southern California have been created and are maintained by human activity. Human interventions include massive amounts of sand placement and construction of groins, jetties and breakwaters. These structures compartmentalize and stabilize the artificial beaches. These ideas seem "radical" to many Californians who often regard any engineering works on the beach as an unnecessary intrusion into nature, regardless of the type or degree of development in the upland.

INTRODUCTION

The mythical southern California beach can be seen displayed on the greeting card racks at any beach area mini-mart or souvenir stand. This beach usually features suntanned beauties and hunks posing alluringly with surfboards or exotic cars along vast stretches of sand. The beauties, hunks, surfboards and cars may be real enough, but the pristine, broad, sandy shoreline, where it does exist, is not a natural condition in most places. This was noted by O'Brien,[22] even in the relatively sand-rich Santa Barbara littoral system.

An early review of beach conditions and development in Santa Monica Bay by Johnson[16] recognized that natural beach width, as well as other infrastructure, was not sufficient for the recreational demands being imposed even as early as 1935:

"Studies of existing public beaches in Santa Monica Bay show that certain portions of publicly owned beach frontage are too badly eroded to be of value as bathing beaches... All the public beaches are difficult of access, due to lack of a continuous highway along the shore, and because of inadequate areas for automobile parking."

Herron[9] may have been the first to emphasize and quantify the dominant role of sand nourishment and structures in the life of many southern California beaches over at least the last 50 years. In his paper, he refers to the "militant environmentalists" who often blame man's structures and other interventions for the destruction of beaches. Such environmentalist condemnation reflects an east coast bias seemingly based on misapplication of conclusions exemplified by Pilkey[27] and others, that may hold for the Atlantic and other low-relief coasts. There, the construction of navigation inlet structures is the biggest single cause of long-term beach erosion, particularly on the barrier islands from New Jersey to Florida. However, this has little or nothing to do with southern California for reasons outlined below.

In southern California, it is precisely the acts of humans that have made many previously narrow beaches wide, or created new ones altogether. The popular opinion, often reflected in the media, is that coastal development has somehow led to the erosion of beaches that were naturally wide and sandy. In contrast, the truth in many places seems to be the exact reverse: coastal development and other human intervention has widened naturally marginal beaches. This is especially true of the two widest beaches in southern California, Santa Monica Beach and Coronado City Beach.

It is the purpose of this paper to update the information presented by Herron[9] and to add several important points to the discussion.

First, we consider the coastal setting of southern California. The geological framework, particularly the tectonic history of the area, defines the region's geography. The geography, in turn divides the region into a number of coastal compartments called littoral cells.[12,21] These cells are delineated on the map in Figure 1. All the cells except Silver Strand are bounded by headlands with a submarine canyon on the down coast end. Each cell contains sand sources, transport mechanisms and paths. The littoral cell concept is useful in discussing sand budgets, since the geographical compartmentalization inhibits sand exchange between cells.

The most important physical factors affecting local sand transport and budgets are the wave energy input and the intermittent sediment supply. Tides, sea level changes, weather and climate also play a role. These have the important effects of making wave damage episodically more or less severe and modulating the natural sand supply reaching the coast. The coastal setting, wave effects and unreliable sand supply under natural conditions sustained only marginal beaches in most places most of the time.

Second, we compare the sediment supply brought to the shoreline naturally and by human activities. This shows that the average rate of nourishment over the past 50 years dwarfs the river sand supply in the Santa Monica and Silver Strand littoral

Based on a talk given by the author at the California Shore and Beach Preservation Association Annual Meeting, Session on Special Coastal Issues, 17 November 1992, in Huntington Beach, CA.

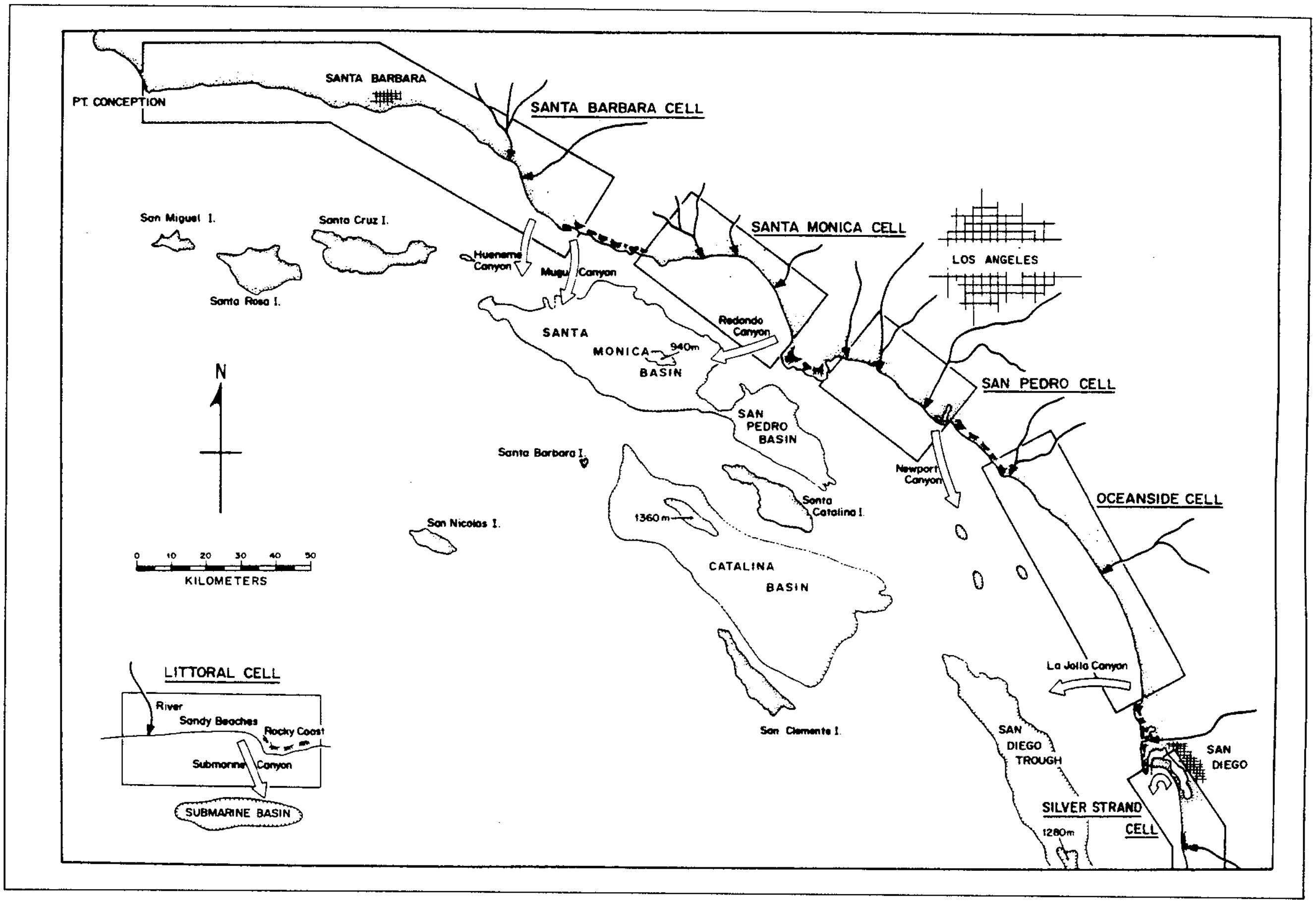

Fig. 1 Location map of southern California from Point Conception to the Mexican border, showing the 5 major littoral cells of the region after Inman and Frautschy.[12] The Mission Bay cell is located in San Diego, between the Oceanside and Silver Strand cells.

systems. In the remaining coastal areas south of Ventura, artificial nourishment has been roughly equal to the natural supply. Only in the Santa Barbara littoral cell does river yield greatly outweigh sand nourishment. By now, over 100 million m^3 of sand have been placed on southern California beaches by human activity.

The final, more subtle point concerns the fact that, in all areas, the rate of artificial supply has decreased dramatically over the past 30 years. On many beaches, wave induced transport now removes sand faster than it is being replaced. For this reason beaches previously widened by nourishment are now in retreat at a rate greater than that prevailing under more natural, but now unacceptably narrow, configurations. This situation, along with occasional catastrophic events, like the winter of 1982-83, are the basis for the public's perception that the beaches are rapidly retreating.

Beach retreat is a cause for genuine concern and action, since many miles of artificially widened strands have been built upon or behind. It has serious implications for the ability of the southern California beaches to sustain the recreational demands and provide the property protection to which southern Californians have become accustomed and which are needed by the ever increasing population. The four basic options: doing nothing, abandoning property, continuing nourishment and armoring the shore, all have economic, social and political benefits and costs. The evolution of decisions about what to do should be based on an understanding of the conditions prevailing in southern California, and not on what may be appropriate for, say, Ocean City, Maryland.

The overall conclusion is that once human interference has intruded on the coast it may be inevitable that human involvement continue. However, it is distinctly ***not inevitable*** that this involvement will be harmful to the beach.

COASTAL SETTING

Southern California is a geologically young and erosional coast.[15] This is due to the area's position on the boundary between the North American Plate and the Pacific Plate which are haltingly grinding past each other. The region exhibits the characteristics of its 80 million year old collision and uplift history and the complicated interplay with sea level fluctuations. These produced the salient features of the shoreline, including the coastal marine terraces, cliffs, lagoons and drowned river channels as well as the inland topography such as the coastal mountain ranges, mesas and the coastal basins. For example, the Los Angeles basin was formed in a gap left by rotating and uplifting blocks of crust about 15 million years ago.[19] Tectonic crustal deformation including faulting, uplift, down drop and warping, continues in southern California today.

The present coastal topography began to be established when the North American Plate overrode the Pacific Plate, forming the San Andreas Fault system and the beginnings of the Gulf of California in the last half of the Tertiary, starting about 25 million years ago. The result was a massive block tilting that uplifted the coastal margins of southern California and Baja, eventually forming the steep coastal mountains, cliffs and headlands. These cliffs were in turn composed of huge volumes of sediment eroded and transported seaward as early as the Cretaceous (135 million years ago) or as late as the various Tertiary epochs (60 million years old) and the Quaternary (the last 2 million years). While the cliffs are subject to erosion at differing rates, they do provide a relatively stable, high relief shoreline anchor. This relief and relative on-offshore stability of shoreline position is a key difference between the southern California coast and the low-relief shorelines on much of the east coast and Gulf of Mexico.

As the uplift continued, wave cut marine terraces were formed during extended periods of relative sea level still-stand. The terraces are prominent features in the region and provide the flat, easily developed mesa land that much of the city of San Diego, for example, is built upon. The marine terraces near the shoreline include the submerged terrace near low tide level being cut by wave action at the present time.

This low tide terrace started forming about 6000 years ago, during the present relative still-stand of sea level.[11] It comprises the flat, rocky, shallow part of the foreshore common along southern California and often visible during low tide. The terrace is a relatively stable bedrock platform that erodes slowly and serves to limit the seasonal vertical excursion of the beach profile in many places. It also furnishes a solid surface to anchor seawalls. It is another key feature that makes southern California beaches different from most of those on the east and Gulf coasts.

Most of the region's sandy beaches form over the low tide terrace where it is covered with a veneer of sand. Normal wave action pushes the sand landward over the terrace and piles it up in a berm against the base of the sea cliff. This sand layer varies in thickness from zero to several meters, depending on location, season and other factors.[31] During periods of erosive waves, or when there is a shortage of sand, the low tide terrace becomes exposed and offers a starkly contrasting shoreline to the usual southern California ideal of the broad, sandy beach.

Rivers and streams flowing toward the coast cut through the uplifted terrain during past lower stands of sea level. This formed a number of valleys, flood plains and wetlands that are also prominent features of the southern California landscape. In these areas the absence of cliffs forms gaps and beach sand depths are much greater than over the low tide terrace. After the catastrophic 1938 flood in Los Angeles, a massive effort was undertaken to channelize and stabilize the position of rivers and creeks in order to prevent flooding of the developing city. The Los Angeles River was stabilized in its present location at about that time. It had diverted naturally in 1825 from a westward course and its outlet at Ballona Creek, to a southerly flow and discharge at Long Beach.[9]

WAVE PROCESSES

Waves provide nearly all of the energy input that drives shoreline processes in southern California. In particular, waves provide the energy that moves sand on beaches. This movement has both on-offshore and longshore components and the magnitude and direction of sand transport changes with wave height, period and incoming direction.[13,28] The prevailing wave conditions, or wave climate, change depending on conditions in the Pacific Ocean, where waves are generated by storms. If the storms are far from land, the waves can travel over enormous distances to reach this coast. If the storms pass nearby, the waves will be locally generated and much more confused than the typical long-crested swell from distant storms.

The Southern California Bight is a region noted for its offshore islands, shallow banks, coastal submarine canyons and generally complicated bathymetry. The coastal orientation and the offshore islands greatly influence swell waves propagating into the region.[24,25,32] The islands and banks partially shelter the coastline from the deep ocean waves, and as a result, the wave climate within the bight is one of the most complicated in the world. The spatial complexity is due to the reflection, refraction, diffraction and dissipation of the incident deep ocean wave trains. The first high resolution field measurements of these island sheltering effects have been made only during the past 15 years.[24,25,26]

Recent work has demonstrated how drastically coastal wave energy varies in the bight because of relatively small changes in the incoming direction of the deep ocean waves. Equally dramatic, is how much the wave height from the same offshore source can change over a short distance on the beach.[23,24] For example, waves might be three times higher at Torrey Pines Beach than at La Jolla Shores, only three km to the south. This represents an energy difference of a factor of 9. Wave energy and direction also vary over time and this variability is important on time scales of days to decades.[14,28]

Model simulations demonstrate that the wave field within the bight is very sensitive to the detailed shape of the incident deep ocean directional distribution.[23,24] Or, put another way, accurate predictions of wave conditions in the bight require accurate estimates of the deep ocean wave directions. Unfortunately, high resolution directional measurements cannot be made on a routine basis using conventional wave measuring instruments.

The problems of wave prediction and the influence of the islands and other topographic complexities in southern California, are areas of ongoing research. While this work has already greatly expanded our appreciation of the correct questions, it has not as yet provided enough answers on which to base engineering calculations. However, ongoing work on improved hindcasting of the offshore wave conditions during the largest events of the past decades will soon lead to a much better capability to quantify wave statistics at any location in southern California.

These factors demonstrate the high degree of uncertainty associated with estimates of longshore and on-offshore rates of sand transport. The uncertainty can be very high, even to the point of not getting the direction of sand transport right, let alone the magnitude, even for wave observation based calculations. This is so since local wave measurements may not apply over a large enough area, or because the measurements themselves are hopelessly inadequate, which is the case with visual observations.

TIDES AND SEA LEVEL

On time scales varying from days to seasons to decades, tides and other sea level changes in southern California act mainly to make the erosive power of storm waves more or less severe. Tides and sea level fluctuations together determine coastal engineering design water levels. Several factors contribute to local sea level, but the tide is the largest, with open coast elevation changes of up to 2.7 m. It is also the only component of sea level change that is predictable. Additional factors that are important in southern California include storm surges and large scale changes in water temperature, wind forcing and climate related el Niño events.[6] On time scales longer than about 50 years, rising mean sea level is likely to cause serious flooding problems in its own right, in addition to contributing to the ever increasing ill effects of waves.

On the California coast, tides are mixed with nearly equal semi-daily and daily components, and this has a number of interesting consequences.[34] California's tide regime is distinctly different from the semi-diurnal conditions that dominate the east coast of the United States. The most important tidal fluctuations on the west coast occur once and twice daily, twice monthly, twice yearly and every 4.4 years.

Storm surge is that portion of the local, instantaneous sea level elevation that exceeds the predicted tide and which is attributable to the effects of low barometric pressure and high wind associated with storms. Storm surge in southern California, excluding the effect of waves, rarely exceeds 30 cm in amplitude.[5,6] However, wave induced surge on a beach can be of the order of the significant breaker height and can reach 2 m during high wave events.

Large scale, Pacific Ocean wide warming episodes occur episodically and are related to the el Niño phenomenon.[20] During these events, mean sea levels in southern California can be elevated by up to 15 cm above normal for several months to a year.[6] This occurred during the later half of 1982 and for most of 1983. Combined with the peak in tidal heights corresponding to the summer-winter and 4.4 year cycles mentioned above, the higher than usual sea level set the stage for the wave caused flooding and erosion that marked the 1982-83 winter.

There is much interest in the subject of sea level rise. In particular, it is important to consider the question of what future rates of rise are likely to be, and if these rates will be greater than in the past due to the effects of global warming. Tide gauges indicate that relative sea level in southern California has risen about 20 cm over the past century.[33] There is no evidence that there is an acceleration of sea level rise in the region. The variability in the tide gauge data from year to year is too large and the records too short to distinguish any changes in the upward trend.

Because of its relatively steep coast, southern California is much less vulnerable to sea level rise than most of the east coast and the entire Gulf coast of the United States. Furthermore, peak high tides, storm surges and el Niño effects together can temporarily raise water levels by several centuries worth of mean sea level rise. It is these factors coupled with high wave events, not sea level rise, that pose the greatest potential for flooding and coastal retreat. Finally, most coastal engineering works need regular maintenance on 25 to 50 year intervals. Modifications to compensate for increases in sea level can be accommodated in this schedule.

CLIMATE

Variations in climate, particularly rainfall, also modulate the amount of sand reaching some beaches. The climate of southern California is classified as "Mediterranean," and semi-arid, but this does not describe the extreme variability of storminess that characterizes this coast. While the region is free of the most severe storms and hurricanes that affect the east coast, storminess in southern California is important for two reasons. First, Pacific storms, particularly when they occur in clusters, can generate substantial wave energy that with elevated sea levels can erode beaches and cause coastal flooding and damage.[14] Second, storms generally bring rain, sometimes in great quantities over short times, especially at higher elevations in the coastal mountains. Large amounts of rainfall are rapidly followed by strong flows in rivers which cause further flooding, but generally also bring sand to the beaches.

The climate is greatly influenced by the conditions over the Pacific Ocean. Episodes of extreme weather in southern California are determined by the tracks storms follow over the North Pacific.[20] The winter storms that affect the region generally originate in the North Pacific or Gulf of Alaska and follow paths that depend on the relative position of the Aleutian low and Pacific high pressure systems. During winters when high pressure prevails along the west coast, storms are deflected northward into Canada and Alaska. When the high pressure cell moves to the south and west, storm trajectories shift south toward the coasts of Oregon and California.

During el Niño episodes, the high and low pressure systems are enhanced, leading to more frequent and more vigorous storm activity over the Pacific. But the storm tracks still depend on the position of the pressure systems. During the

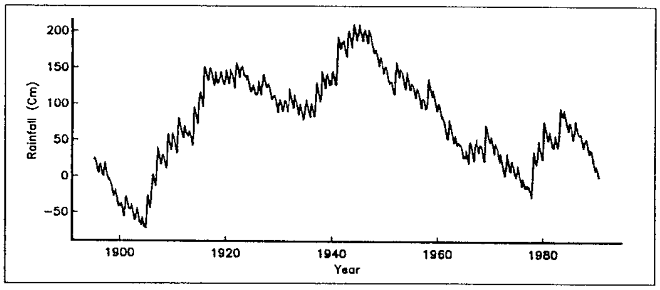

Fig. 2 Cumulative residual precipitation from Eq. 1 for the South Coast drainage basin. Times of drought are indicated by decreasing trend, while periods with above average rainfall show an upward trend. Mean annual rainfall is 43 cm.

el Niño winter of 1976-77, for example, storm tracks were wound tightly to the north, leaving California in the midst of a drought. In contrast, during the severe el Niño winter in 1982-83, several clusters of storms greatly impacted southern California, causing over $100 million in coastal damage.

Storminess varies from year to year and also shows variation over decades long time scales. If we assume that monthly regional rainfall is a valid index of storminess, we can examine long term variations by looking at precipitation records. Figure 2 shows the cumulative residual precipitation from 1895 to 1990 over the South Coast Drainage (Division 04-06) region of California, as defined by the National Climatic Data Center.[18] The cumulative residual rainfall, Pn, at month n after the beginning of the time series is calculated from the monthly rainfall data, p_i, by subtracting the mean, $\bar{p}$, and then accumulating, as shown by Equation (1),

$$P_n = \sum_{i=1}^{n} (p_i - \bar{p}), \quad n = 1,N \tag{1}$$

where N is the total number of months in the record.

The cumulative record is much smoother than the time series of monthly rainfall itself, and has an upward trend during periods of above average rainfall, and a downward trend during times of lower than average precipitation. The seasonal fluctuations, averaging 45 cm of precipitation, are clearly visible superimposed on the much larger decades long variations.

Figure 2 shows a wet period lasting from about 1906 to 1916, followed by a period of normal rainfall through about 1936. A long dry period, punctuated with occasional wet winters, started in about 1945 and was not broken until the floods of 1978. Much of the population increase and development along the California coast coincided with this period following World War II. This may account for the surprise many people expressed during the run of stormy winters from 1978 to 1983. The relatively small rainfall deficit at the end of the record starting in 1985, represents the much-publicized recent drought.

During prolonged dry periods, very little river sand reaches the coast, irrespective of any flood control structures. As a result, even before dams blocked up to half of the sand supply, many beaches were for extended periods in a marginal state with respect to sand cover. A single large storm or a series of moderate storms combined with other circumstances that support erosion have occasionally stripped the subaerial beaches clean of sand. Several miles of beach in northern San Diego County have never recovered from the sand losses suffered during the severe winter of 1982-83. Occasional large floods provided substantial quantities of sand on an episodic basis to coastal river deltas and thence to the beaches via longshore transport, but the pronounced long-term fluctuations frequently resulted in rocky shorelines and breached spits.

SAND SUPPLY AND STRUCTURES

Here we compare the amounts of sand produced by southern California rivers and other sources, such as cliff erosion and onshore transport, with the amount supplied by nourishment for each littoral cell in the region. Most of the information concerning sand nourishment sources, volumes and dates and locations of placement comes from the compilation prepared for southern California by Shaw.[29] That report also contains an inventory of the structures found along the coast.

Numerous studies have examined the sediment yield from southern California rivers and ephemeral streams, as well as the decrease in yield caused by flood control and water supply dams and debris basins. Table 1 summarizes the range of "natural" and actual river sand yields as reported in the referenced literature sources. The rivers are listed according to littoral cell and a total yield is given for each cell.

Natural sand yield refers to the estimated amount of sand supplied by the particular river under natural conditions, that is, before any structures inhibited the flood flows. Actual yield refers to the average amount of sand reaching the coast under actual, present day conditions. The estimated sand discharge rates for both natural and actual conditions vary according to the source of the estimate. Table 1 lists values from several published sources, but no attempt was made as part of this study to reconcile sometimes significantly different numbers.

Table 2 summarizes the river yields detailed in Table 1, and also gives the annualized amount of sand supplied to each littoral cell by beach nourishment. The purpose of presenting these numbers is simply to compare loosely the amounts of sand involved, not to make any new or definitive estimates.

The amount of sand contributed to the local sediment budget from cliff retreat varies from place to place and over time, since cliff erosion is highly site specific and episodic. Kuhn and Shepard[17] documented locations where a meter or more of retreat occurred in a few days at one part of a property, with no erosion at all 25 or 30 m away. How much beach sand comes from the cliffs is an important question that is often raised in emotional debates over whether it is justified to armor cliffs with sea walls to prevent their retreat.

Several interesting examples of cliff failures and gullying and their highly varying sand contributions have been noted. For example, a section of cliff at Torrey Pines collapsed in

Littoral Cell	River	Sand Yield (m^3/yr)	
		Natural	Actual
Santa Barbara	Ventura	180,000[1,3]	77-85,000[1,3]
	Santa Clara	674,000[1]	459-602,000[1,3]
	Calleguas	51-61,000[1,3]	51-61,000[1,3]
	Total	**905 - 915,000**	**587 - 748,000**
Santa Monica	Santa Monica Group	-	11,000[3]
	Ballona	35,000[3]	35,000[3]
	Total	**?**	**46,000**
San Pedro	Los Angeles/San Gabrial	600,000[1]	200,000[1]
	Santa Ana	330-500,000[1]	22-145,000[1,3]
	Total	**930 - 1,100,000**	**22-345,000**
Oceanside	San Juan	33-71,000[3,13,30]	30-71,000[3,13,30]
	San Mateo/San Onofre	22-30,000[3,13,30]	15-28,000[3,13,30]
	Santa Margarita	11-87,000[1,3,13,30]	9-18,000[1,3,13,30]
	San Luis Rey	42-86,000[1,13,30]	14-28,000[1,13,30]
	Agua Hedionda Group	22-25,000[3,30]	20-22,000[3,30]
	San Dieguito	16-53,000[1,13,30]	3-15,000[1,3,13,30]
	Los Penasquitos	24,000[30]	21,000[30]
	Total	**170 - 346,000**	**112 - 203,000**
Mission Bay	San Diego	7-37,000[1]	5-84,000[1,3]
	Total	**7 - 37,000**	**5 - 84,000**
Silver Strand	Tijuana	66-535,000[1,4,10,14]	32-115,000[1,4,14]
	Total	**66 - 535,000**	**32 - 115,000**

Table 1 River sand yield in southern California Littoral Cells.

Littoral Cell	River Yield (m^3/yr)		Nourishment (m^3/yr)
	Natural	Actual	Actual (1940-90)
Santa Barbara	905 - 915,000	587 - 748,000	260,000
Santa Monica	?	46,000	440,000
San Pedro	930-1,100,000	22-345,000	300,000
Oceanside	170 - 346,000	112 - 203,000	190,000
Mission Bay	7 - 37,000	5 - 84,000	75,000
Silver Strand	66 - 535,000	32 - 115,000	565,000

Table 2 Mean annual sand supply to southern California Littoral Cells.

January 1982. This slide was about 160 m wide and averaged 8 m thick, with a total volume of nearly 1 million m^3. While this represents a substantial amount of sand, it will undoubtedly take many years to completely incorporate this mass into the littoral system.

Accelerated subaerial canyon cutting in the Camp Pendleton area resulted from badly managed drainage of heavy rainfall in 1978, 1980 and 1982-83.[17] Several canyons were greatly increased in size by eroding landward 150 to 250 m during these unusually wet winters. The coastal cliffs from San Onofre to Oceanside are particularly heavily incised with gullys and barrancas, suggesting that subaerial cliff erosion in this area contributes a significant amount of sediment to the local budget. One notable event at San Onofre State Park occurred during a storm with intense rainfall in February 1980. A small ravine eroded landward about 70 m overnight, yielding about 40,000 m^3 of sediment. Many much smaller slides and cave collapses occur all along the San Diego coast. For example, seven cliff failures together contributed only 840 m^3 of sand to a 250 m long stretch of Solana Beach between about 1976 and 1989.[8]

Substantial amounts of "artificial," or human induced, sand supply began influencing southern California's beach configuration in the late 1930's. Between about 1940 and 1990, over 100 million m^3 of sand was placed on the region's shoreline between Santa Barbara and Silver Strand. Almost all of this sand came as a side benefit of harbor dredging, or from beach nourishment projects as such. Rates of sand supply were greatest in the earlier years when the needs to develop naval facilities and small craft harbors were pressing. Sand from harbor dredging sources tapered off after about 1960, as the coast became saturated with facilities. At about the same time, environmental objections to massive harbor dredging projects and the associated wetland losses began to be taken seriously.

SANTA BARBARA LITTORAL CELL

Beginning in the north, Table 1 shows that the river yields of sand in the Santa Barbara cell are the largest in southern California.[1] Furthermore, the yield under actual, present day conditions is 60 to 80% of the natural amount. This represents the highest percentage contribution in the region and suggests that the effects of dams on the littoral sand supply is not as serious a consideration as in the rest of southern California. Finally, Table 2 shows that the amounts of sand artificially supplied to this littoral cell amount to only about 40% of the river sources.

SANTA MONICA LITTORAL CELL

DNOD[3] is the only published reference that could be found giving estimated sand yields from the ephemeral streams flowing out of the Santa Monica Mountains. These include Malibu and Topanga Creeks and Ballona Creek, south of Marina del Rey. Under present conditions, the yield from the Santa Monica Mountains is small, since the watersheds are modest, the flows intermittent and regulated by catchment basins. It is not clear what the yields were under natural, preflood control conditions. However, other evidence, such as

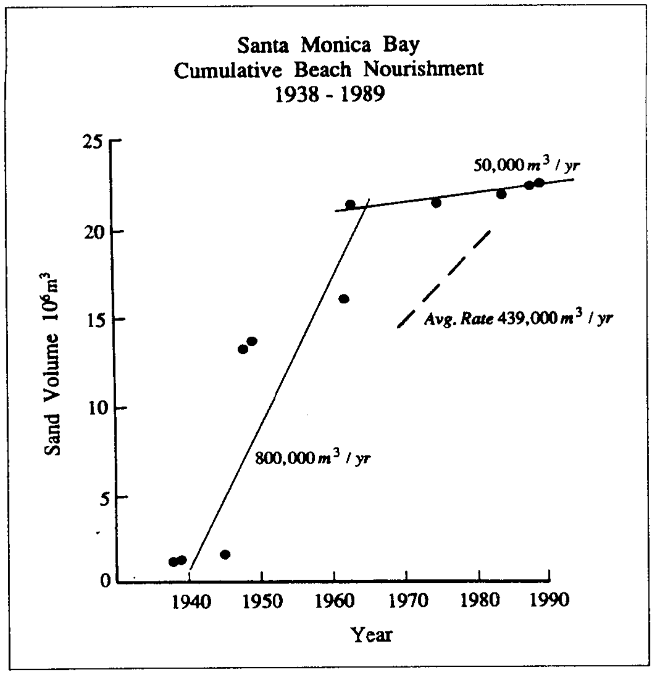

Fig. 3 Cumulative beach sand nourishment in the Santa Monica Bay littoral cell. Nourishment rates have decreased considerably since 1963, when the last dredge spoils from Marina del Rey were placed on Dockweiler Beach, but the overall annualized rate (dashed) still far exceeds that of natural or actual river sand supply.

historical photos and beach profile data,[2,9] indicate that the Santa Monica Bay beaches were relatively narrow, suggesting that sand supplies were inadequate to provide wide beaches.

Herron[9] mentions that Ballona Creek has only delivered fine material to the coast ever since the Los Angeles River changed course and abandoned its mouth there in 1825. This is a significant point, since there is no major river to bring sand into any part of the entire Santa Monica littoral cell. The important conclusion is that there are no substantial contributions of river sand to the Santa Monica littoral system, and there likely have not been any for at least 165 years. Most of the sand that was on the beaches in the cell before nourishment probably came from transport around Point Dume.

As illustrated in Table 2, the amount of beach sand from nourishment activity in the Santa Monica cell has been substantial. A total of nearly 23 million m^3 of sand has been placed on these beaches over the past 50 years, for an annualized nourishment rate of 440,000 m^3/yr, a value ten times larger than the only estimates of river input. An analysis of historical beach profiles[2] has shown that this massive rate of sand supply has caused the mean beach width to increase by 30 to 150 m during about the same period.

Figure 3 illustrates the cumulative sand volume placed on the Santa Monica Bay shoreline as a function of time since the late 1930's to about 1990. From 1940 to 1963 the averaged annualized rate of sand supply was a staggering 800,000 m^3/yr. This material originated from two main sources. About 11 million m^3 came from major expansion of the Hyperion sewage treatment facility in 1947, and about 7.7 million m^3 came from the dredging of Marina del Rey between 1960 and 1963.

Marina del Rey was the last large scale construction project in the Santa Monica cell, and as Figure 3 shows, the rate of sand supply has dropped to about 50,000 m^3/yr since its completion. The beach nourishment that has been done subsequent to 1963 involved amounts of about 1 million m^3 of sand, or less. This has been mined from the Hyperion site and from offshore and placed mainly on Dockweiler Beach. The most recent nourishment was completed in 1989 when about 840,000 m^3 of sand was transported by conveyor belt from Hyperion across Pacific Coast Highway to Dockweiler Beach.

The role of structures is crucial in stabilizing the nourished beaches of Santa Monica Bay. Inventories[2,29] of structures in the bay list 5 harbor breakwaters, 3 jetties, 19 groins, and 5 revetments in the 30 km from Topanga Canyon to Malaga Cove. The offshore breakwater at Santa Monica and the harbor structures at Marina del Rey have the greatest effect in retaining sand and preventing its migration. The groin field between Marina del Rey and El Segundo also seems to be effective in holding much of the nourished sand at Dockweiler Beach. The beaches in this reach are over 150 m wider now than they were in 1935. The fact that the longshore transport of sand is mainly unidirectional to the south[16] may account for the outstanding capacity of these structures to so effectively hold sand.

Since the 700 m long rubble mound detached breakwater was built adjacent to Santa Monica pier in 1934, the beach has widened by about 200 m for a distance of nearly 2 km up coast. This accretion occurred despite the fact that no nourishment has actually been placed on Santa Monica Beach. After construction of the breakwater, a tombolo formed which acted as a sand groin inhibiting longshore transport. Initial beach widening to the north of the structure was consequently accompanied by narrowing to the south, as these beaches were starved. Sand was then bypassed mechanically until a new equilibrium was established. No further maintenance has been needed, but the breakwater did suffer damage during the heavy winter of 1982-83 and lost some of its effectiveness.

The beach adjacent to the north side of the Marina del Rey breakwater has widened by over 300 m since 1935.[2] About half of the increase in beach width occurred since the 1953 profile data were taken, and is attributable to the interruption of the longshore transport and the resulting formation of fillet beach. Similar fillets were formed at Mission Bay entrance, and to a lesser degree at Oceanside harbor.

SAN PEDRO LITTORAL CELL

In effect, the San Pedro littoral cell actually begins at Sunset Beach, since the nearly 15 km long Los Angeles - Long Beach harbor breakwater isolates the coast from wave action from there up coast to San Pedro. An entirely new, sandy recreational beach was created by the construction of the breakwater. This is Cabrillo Beach, located at the west end of the breakwater in San Pedro.[9] Cabrillo Beach must be nourished with sand periodically, as it has no natural sand sources. However, due to its convenient location and amenities, it provides recreational opportunity for many Los Angeles residents.

In the San Pedro cell, up to about 1.1 million m^3/yr of sand would have been delivered to the coast under natural conditions by the Los Angeles, San Gabriel and Santa Ana Rivers. Under actual present day conditions, flood control works have reduced this amount by two-thirds or more, to a maximum of 345,000 m^3/yr. Of that, 200,000 m^3/yr comes from the Los Angeles and San Gabriel Rivers, as shown in Table 1. The Los Angeles River discharges in the middle of the Los Angeles - Long Beach Harbor, directly behind the Queen Mary. The mouth of the San Gabriel lies farther south, at Seal Beach, but still inside the harbor breakwater.

Sand discharge from the San Gabriel River does provide benefit to the Long Beach strand inside the harbor, and to Seal Beach to the south. In contrast, any sand or other sediment originating from the Los Angeles River only serves to clog the harbor and cause maintenance dredging problems. The Los Angeles River can no longer contribute sand that directly benefits the beaches because its mouth is cut off from the natural transporting power of waves. Only costly sand transportation efforts or an unimaginably expensive river diversion could salvage the sand remaining in the Los Angeles River. But from the viewpoint of harbor maintenance, it is an advantage that the sand yield from at least this river has been so greatly reduced.

However, reduction in sand delivery from the San Gabriel River and the Santa Ana River, which discharges between Huntington Beach and Newport Beach, has undoubtedly contributed to sand shortages south of Long Beach. Another major contribution to beach retreat in the area, particularly in the vicinity of Huntington Beach, was noted by Habel.[7] Up to 1.2 m of subsidence had occurred over a large nearshore area due to oil withdrawal from local oil fields between 1933 and 1964. The subsidence was equivalent to the loss of over 5 million m^3 of sand, which corresponded almost exactly to the amount that had been found "missing" in repeated beach profile measurements of the area over the same time. This finding implied that the reductions of river sand supplies did not have as great a negative impact on the local beaches as was thought.

In any case, the federal, state and local governments have had to institute and fund an ongoing beach nourishment program using Sunset Beach, just down coast from Seal Beach, as a feeder location. This has been necessary to maintain adequate beach width for recreation and property protection in the heavily utilized and developed area from Seal Beach to Huntington and Newport Beach. This beach nourishment program contributes sand at the rate of about 300,000 m^3/yr (Table 2).

OCEANSIDE LITTORAL CELL

In the Oceanside littoral cell, the contributions of sand from rivers and artificial nourishment are approximately equal, depending on which numbers one chooses to believe (Table 2). The figures in Table 1 display a fair amount of disagreement about the exact yields from the numerous streams in the reach from Dana Point to La Jolla. San Juan Creek and the Santa Margarita and San Luis Rey Rivers seem to have been the major contributors of material. There is one high estimate each for the Santa Margarita[3] and the San Dieguito[13] rivers, but again, no attempt is made here to reconcile the various studies.

Estimates of the total sand supply in the cell under natural and present conditions varies by a factor of two. Overall, the figures suggest that approximately one third of the naturally occurring sand discharge from the rivers has been prevented from reaching the coast by flood control and water storage dams. Between 112,000 and 203,000 m^3/yr of sand reach the coast under present conditions. This is less than or equal to the approximately 200,000^3/yr widely held to be the net down coast, wave induced longshore transport rate.[14]

Altogether, about 9.3 million m^3 of sand have been placed on the Oceanside littoral cell beaches over the past 50 years.[29] This represents an annualized rate of about 190,000 m^3/yr. As shown in Table 2, this rate is about the same as the most optimistic estimate of the actual rates of river sand supply over the same period, and exceeds the lowest estimate by a factor of two. Most of the sand placed on the area's beaches came from the dredging of Agua Hedionda Lagoon and Oceanside Harbor, which each contributed about 3 million m^3 in 1954 and 1961 respectively. In addition, several smaller projects, such as nourishment of Doheney Beach and construction of San Onofre Nuclear Generating Station, produced about 1 million^3 each. Finally, about 1 million m^3 of sand were trucked from the San Luis Rey river bed to the badly eroded Oceanside beaches in 1982.

The harbor structures at Oceanside were built in stages starting in 1942 and ending in 1968 with the completion of the small craft harbor. Beach accretion to the north and erosion to the south was noted soon after harbor construction began, and the erosion has been a vexatious problem ever since. The harbor structures in effect cut the Oceanside cell in half and seem to divert substantial quantities of sand offshore.[14] This has caused a serious maldistribution of sand which may be related to sand shortages as far south as Solana Beach and Del Mar. Photo 1 shows one of the down coast cobble beaches-Carlsbad. In this instance, as in Santa Barbara, harbor structures have beyond much doubt had a negative impact on the stability of beaches down coast. Sand bypassing around the harbor may not offer a complete solution because of the large amounts of sand lost offshore. Sand replenishment from inland or offshore sources seems likely to be the only cost effective answer to restoring and maintaining beach width south of Oceanside harbor.

A new public access structure, and low bluff are shown in Photo 2.

MISSION BAY LITTORAL CELL

Estimates of sand yield from the San Diego River, which empties in the Mission Bay cell, vary even more widely than

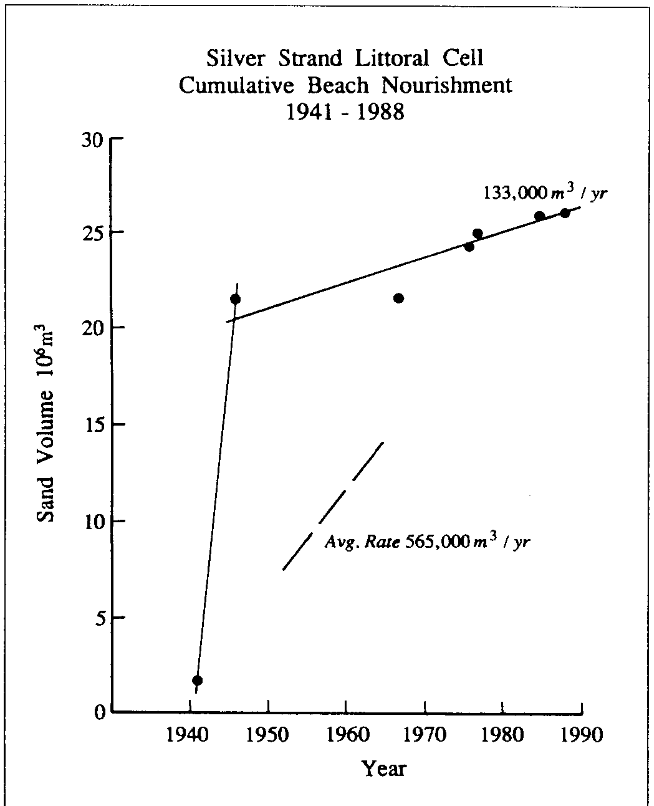

Fig. 4 Cumulative beach sand nourishment in the Silver Strand littoral cell. Most of the nourishment sand came from expansion of San Diego Bay naval facilities after WW II. The overall annualized nourishment rate (dashed) still far exceeds the actual river sand supply.

those in the Oceanside cell (Table 1). DNOD[3] gives a figure under present conditions of 84,000 m^3/yr, which greatly exceeds the 15,000 m^3/yr estimate given by Brownlie and Taylor[1] for natural conditions, before dams obstructed the flow. The actual yield of the San Diego River under present conditions estimated by Brownlie and Taylor[1] is a paltry 5,000 m^3/yr. In any case, the nourishment rate has been about 70,000 m^3/yr. This represents the annualized rate of the approximately 3 million m^3 of sand which was dredged from Mission Bay to create the aquatic park and small craft harbor starting about 1955.

SILVER STRAND LITTORAL CELL

The Silver Strand cell is located south of San Diego and extends from San Diego Bay past the international border into Mexico (Figure 1). It is unique in the region, since the net littoral sand transport, at least in the reach north of the Tijuana River, is from south to north. This is because Point Loma serves to shelter it from waves from the north, so that the predominent wave forcing ends up being from the south. The northern part of the cell is bounded by the entrance to San Diego Bay and the 2300 m long Zuniga Jetty, completed in 1904. The other significant structure in the system is a 425 m long curved groin built adjacent to the Hotel del Coronado for a boat anchorage around 1900. The 5 km long strand along Coronado and North Island, between the hotel groin and Zuniga Jetty, is likely the widest beach in southern California. It is also one of the most stable, since it is at the down coast end of the Silver Strand littoral system, is highly sheltered to all but waves from the due south and is held in place by the two structures.

It is likely that the Silver Strand littoral cell represents the most highly altered stretch of beach in southern California, if only for the fact that over 26 million m^3 of sand have been placed there over the past 50 years. As shown in Figure 4, most of this, or about 20 million m^3, was the result of massive expansions of the naval facilities in San Diego Bay just after World War II. The Silver Strand prior to this time had been relatively thin, marginal sand spit that formed a tenuous barrier between the ocean and the bay. Photos and other documentation from the late 1800's suggest that Silver Strand was occasionally overwashed by ocean waves. After nourishment, the beaches from Silver Strand State Beach past Coronado and to Zuniga Jetty widened by up to several hundred meters. The beach widths increased to such a degree that their evolution could easily be followed on successive USGS quad sheets.

The natural supply of sand in the cell comes from the Tijuana River, which has its outlet located near the international border. The watershed straddles Mexico and the U.S. and dams have been built on both sides of the border. Here too, sand yield estimates, as shown in Table 1, both under natural and controlled conditions vary wildly. Brownlie and Taylor[1] give a low estimate of 66,000 m^3/yr, while Inman[10] gives a high number of 535,000 m^3/yr under natural conditions.

Present day yield estimates range from 32,000 to 115,000 m^3/yr. Whatever the correct number, the actual yield is dwarfed by the overall annualized nourishment value of 565,000 m^3/yr, as shown in Table 2. However, as shown in Figure 4, the present annualized nourishment rate is considerably smaller, and has been only about 133,000 m^3/yr since the 1960's. As a combined effect of decreased river yield and greatly decreased nourishment rates, the reach from Playas de Tijuana through Imperial Beach, Silver Strand State Beach, south Coronado to the Hotel del Coronado has shown a net retreat over the past decades.[4] The Naval Amphibious Base, just south of the hotel, has periodically imported modest amounts of sand to nourish this beach and keep it suitable for training exercises. Also, sand dredged from the entrance to San Diego Bay has recently been transported as far south as Imperial Beach and dumped just offshore of the surfzone.

CONCLUSIONS

The geographic setting and intermittent sand yield from rivers in southern California only sustained relatively narrow beaches in most places under the natural conditions that prevailed before large scale human interference began. This intervention took the form of massive beach nourishment and the building of many structures that mostly served to stabilize and trap the fill. Over 100 million m^3 of sand have been added to the southern California littoral system between 1930 and the present. About half this amount was evenly divided between the Santa Monica and Silver Strand littoral cells, where the beaches widened greatly in response to the nourishment.

Most of the artificial sand supply came as a byproduct of construction and expansion of harbors and other coastal works. The majority of the sand was placed before the mid-1960's, and the rate of beach nourishment has dropped sharply since then. The wide beaches that were created by fill and stabilized by structures will, in time, retreat as the consequences of decreased nourishment rates take hold. Many locations face net sand losses over the coming decades. This will likely happen in a series of catastrophes, since the shoreline of southern California remains relatively unchanged until a severe winter, or a series of severe winters, strikes.[14]

These considerations suggest that without continued intervention, larger parts of the southern California shoreline will be narrow and rocky in the future. Many pocket beaches will of course continue to exist. Many other beaches, particularly in the Santa Monica littoral cell and in Coronado, have been stabilized with structures, and could remain wide and stable for many decades.

In eroding areas, where recreational needs or shoreline protection benefits outweigh costs, beaches will have to be maintained artificially by trucking or pumping sand. Additional, carefully designed structures may be necessary to lengthen the life of future beach restoration projects. Other structures, such as sea walls, may be justified to protect public and private property, especially on the developed sea cliffs, in areas where maintaining a wide beach is not feasible.

In the face of beach retreat, the government and the public will be required to make decisions. These basically reduce to four options, including the decision to do nothing, abandoning public and private property, increasing the sand nourishment rate and building shoreline protection structures. The political, social and financial arrangements needed to reach consensus on this matter will be difficult to achieve. Some combination of the four choices will undoubtedly be implemented as it becomes necessary and expedient on different stretches of the coast. Perhaps better decisions can be made if the actual history and physical conditions of the southern California coast are explicitly taken into greater consideration by government officials, coastal residents, and the general public.

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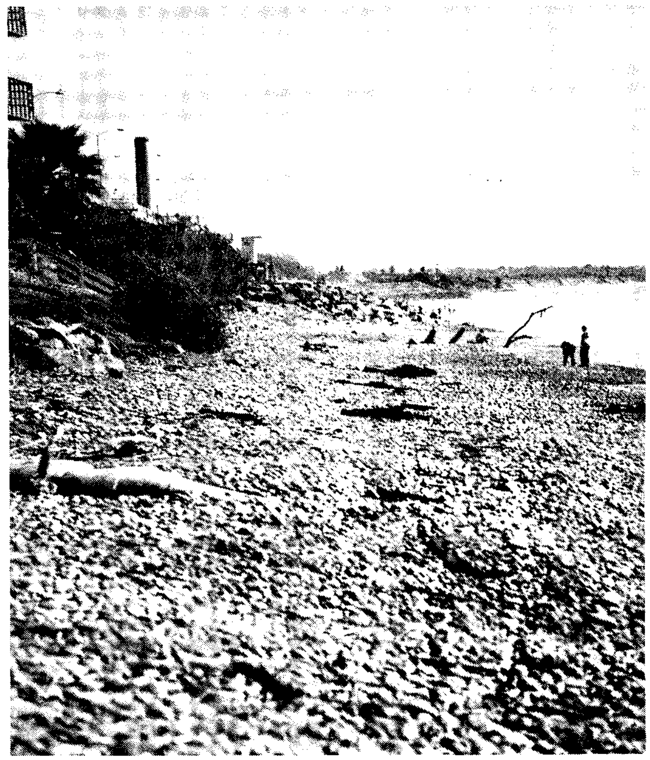

Photo 1 Carlsbad, CA, cobble beach, looking south, 27 February 1993. (Photo by Robert L. Wiegel)

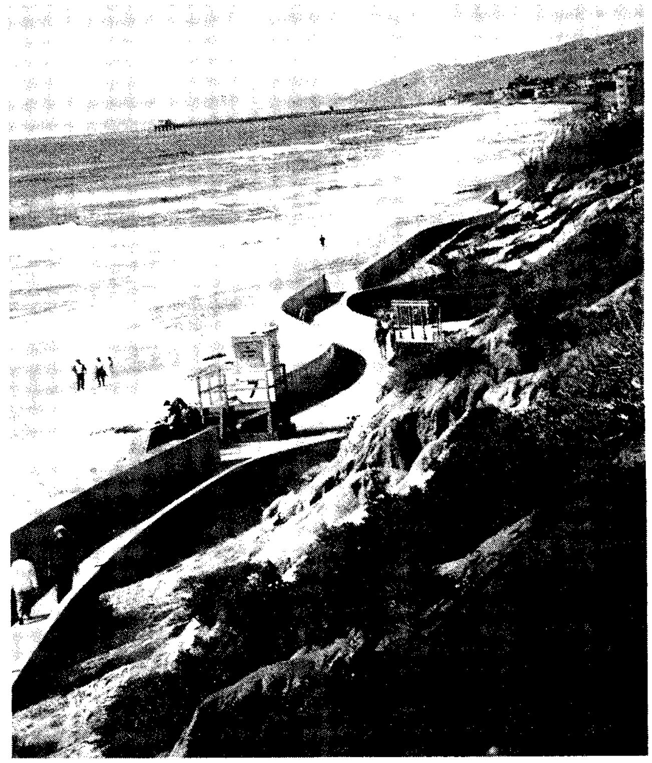

Photo 2 Carlsbad, CA public access at south end, 27 February 1993. (Photo by Robert L. Wiegel)

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