STATE CAPITOL
SACRAMENTO, CA 95814

Assembly
California Legislature

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Assembly Select Committee on Coastal Protection
Briefing Document
"Beach Erosion and Declining Sand Supplies"

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California Coastal Sediment Master Plan

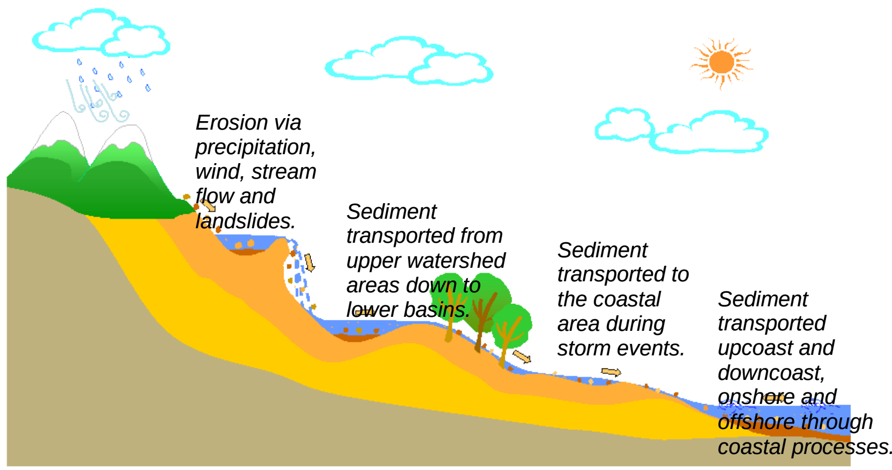
Mission

Develop a comprehensive master plan for the conservation, restoration, and preservation of the valuable sediment resources along the coast of California, in order to reduce shoreline erosion and coastal storm damages, provide for environmental restoration and protection, increase natural sediment supply to the coast, restore and preserve beaches, maintain or improve coastal access, improve water quality along coastal beaches, and optimize the beneficial use of material dredged or excavated from ports, harbors, wetlands, and other opportunistic sediment sources.

The California Coast – An Important Resource

The California coastline consists of a variety of landforms such as sand and cobble beaches, rocky intertidal areas, rocky cliffs, wetlands and lagoons, and partially consolidated bluffs. These landforms provide habitat for hundreds of wildlife species covering the spectrum of birds, mammals, reptiles, amphibians, fishes, and invertebrates. The California shoreline also provides residential, industrial, commercial, and military land uses for humans as well as recreational and educational opportunities.

Natural Sediment Processes



Natural erosion due to precipitation, wind, stream flow, and landslides makes sediment (i.e., gravel, sand, silt, and clay) from the upper watershed available for transport by streams and creeks down to lower basins. A majority of this sediment is then transported to the coast during storm events. The volume and size of the sediment transported by streams depends upon the stream forces. Larger storms cause increased volumes of sediment with higher proportions of sand and gravel to be transported to the coast. Upon reaching the coast, waves, currents, and wind transport the sediment upcoast and downcoast as well as onshore and offshore, contributing to the dynamic nature of coastal beaches. Beaches represent temporary storage areas for coastal sediment and require an ongoing source of sand to maintain their width.

Beneficial Uses of Coastal Sediment


Recreation


Shoreline Protection


Infrastructure Development

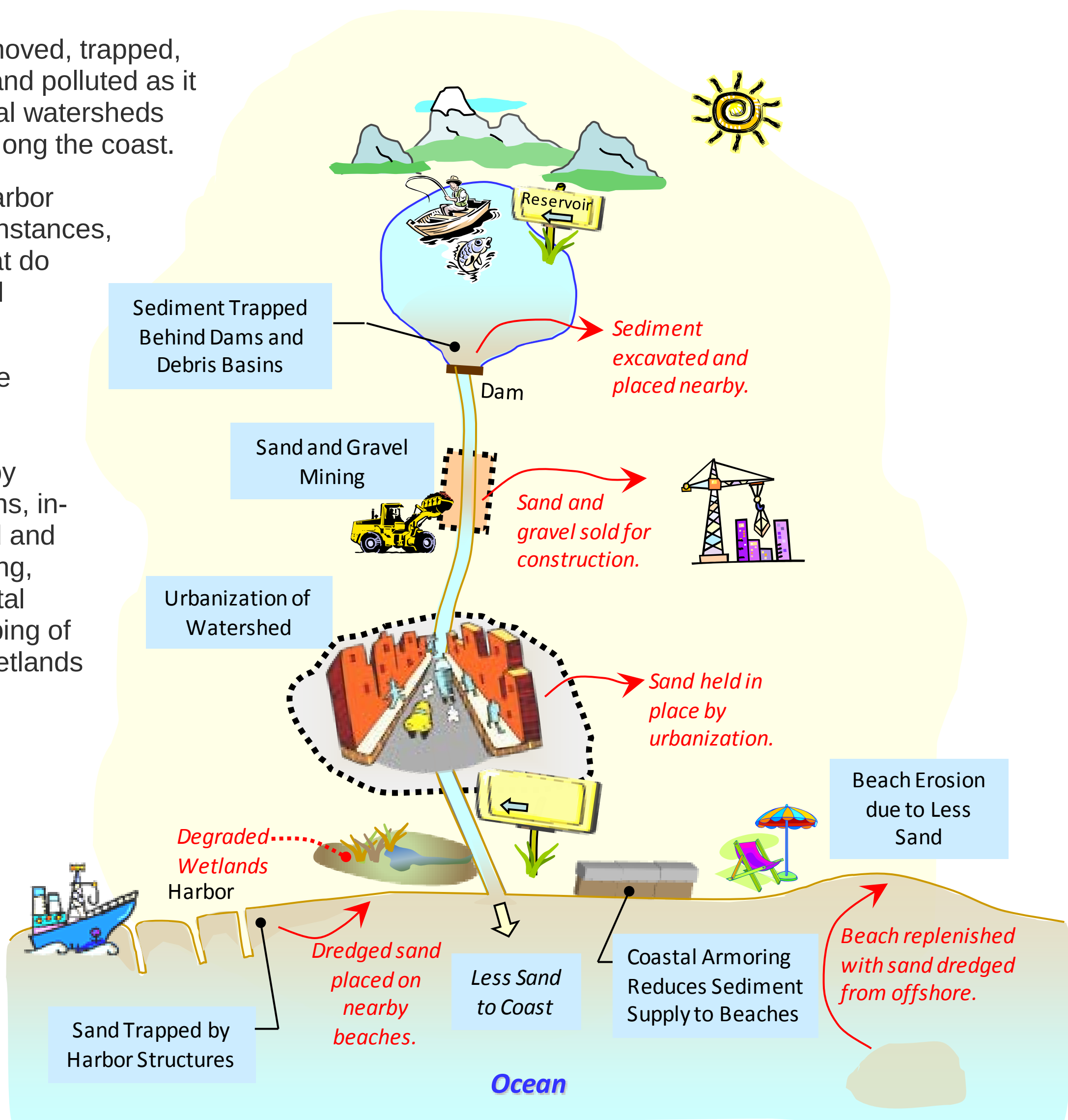

Wildlife Habitat

Coastal sediment provides many beneficial uses for humans and wildlife. Sand and gravel provide habitat for various wildlife species that use streams and beaches, while sand also provides recreational beach space for humans, lateral beach access, and shoreline protection. Additionally, silt and clay from river substrates supply needed nutrients for nearshore habitats. Sand and gravel, extracted from in-stream, back-beach and offshore sources, is used by the construction industry for infrastructure development. Easy access to this important construction material has been a factor in California's economic growth.

The Problem – Human Modifications Have Altered Processes and Impacted Uses

Humans have substantially altered natural sediment transport processes within California's coastal watersheds, reducing storm protection, habitat and recreation along the coast. Dams, built to control floods and store water, trap sediment in reservoirs and reduce peak flows that move most of the coarse sediment to the coast. Sand and gravel are mined from stream systems for use in construction, removing materials that would eventually replenish coastal habitats. Timbering, grading, and earth moving strip off vegetation and expose the watersheds to excessive erosion. Conversely, construction of concrete-lined channels, roads, and buildings hardens the watershed, reducing bank erosion and associated amounts of coarse sediment available for delivery to the coast via streams. Some coastal structures such as harbors, jetties, groins, and breakwaters alter movement of sediment along the shoreline, while other coastal structures such as riprap and seawalls decrease the amount of sediment supplied directly to the shoreline, caused by the reduction of bluff and cliff erosion. Human modifications to the coastal watersheds and shorelines of California have resulted in the following sediment-related problems:

- Beaches are undergoing accelerated erosion, reducing recreational opportunities and coastal access, contributing to loss of habitat, and increasing the probability of storm damage along the coast.
- Coastal stream water quality has become impaired.
- Many coastal wetlands and lagoons are experiencing either accelerated erosion or excessive sedimentation.
- Sediment is being removed, trapped, redirected, modified, and polluted as it moves from the coastal watersheds to the shoreline and along the coast.
- Sand dredged from harbor channels is, in many instances, placed in locations that do not optimize beneficial reuse of that material.
- Sediment supply to the coast continues to be reduced as a result of interruptions caused by dams and debris basins, in-stream mining of sand and gravel, coastal armoring, hardening of the coastal watersheds, and trapping of sediment in coastal wetlands and lagoons.

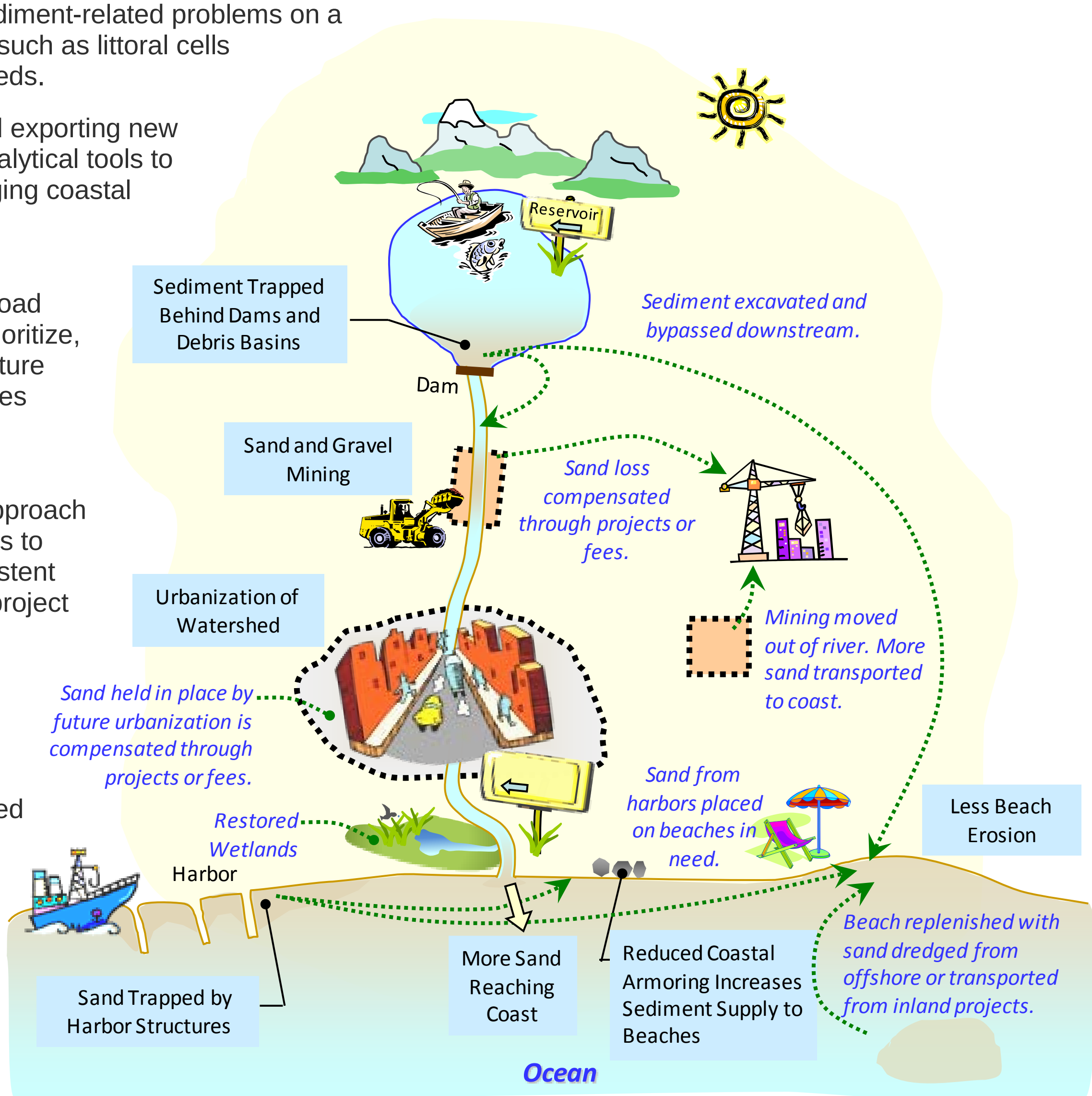


Existing Sediment (Sand) Management

The Road to Solutions – The California Coastal Sediment Master Plan

Many watershed and shoreline problems caused by human modifications can be solved or minimized through the development of a new approach known as Regional Sediment Management (RSM). The California Coastal Sediment Management Workgroup (CSMW), a partnership of several federal and state agencies and non-governmental organizations, is developing and implementing the California Coastal Sediment Master Plan (SMP) to foster a regional sediment management approach for the entire state. Through this effort, region-specific issues and solutions are coordinated with local/regional partners through a series of Coastal RSM plans designed around littoral cell management. Although development of the SMP is ongoing, the SMP already provides a framework for finding solutions through RSM by:

- Identifying sediment-related problems along the California coast, such as beach erosion, wetland erosion/sedimentation, habitat loss, and water quality impairment.
- Defining the causes of sediment-related problems such as dams, debris basins, dredging, sand and gravel in-stream or back-beach mining, coastal structures, lack of project coordination, and inconsistent policies, procedures, and regulations.
- Providing a solid scientific framework and database regarding technical issues within the coastal environment to help visualize and support sediment management decisions.
- Providing a framework, through collaboration with federal, state, regional, and local governments, to address the sediment-related problems on a regional scale, such as littoral cells and/or watersheds.
- Developing and exporting new and existing analytical tools to assist in managing coastal resources.
- Providing a programmatic road map to plan, prioritize, and program future coastal resources projects.
- Fostering a collaborative approach among agencies to provide a consistent framework for project proponents.
- Establishing a streamlined process for coastal resources related project approvals.



Regional Sediment (Sand) Management

What Will The Sediment Master Plan Do?

Implementation of the Sediment Master Plan is expected to:

Surfside-Sunset Project 2009

- Improve beach conditions and reduced erosion attributed to human causes.
- Improve wetland and beach habitat quality through smaller changes in localized sedimentation and erosion.
- Improve water quality through better sediment management.
- Improve use of federal and state agency resources through leveraging of funds and technical resources, improved staff coordination, and the formulation of regional solutions.
- Optimize project execution by programmatically assessing environmental impacts of regional coastal projects, streamlining the permitting process, and holistically integrating discrete solutions into comprehensive regional solutions.

The California Coastal Sediment Management Workgroup (CSMW)

The California Coastal Sediment Management Workgroup (CSMW) was established by the U.S. Army Corps of Engineers and the California Natural Resources Agency in 1999 to develop regional approaches to protecting, enhancing and restoring California's coastal beaches and watersheds through federal, state and local cooperative efforts. The CSMW is the first state and federal partnership developed in California for on-going, multi-agency interaction on statewide coastal sediment management issues.

Coastal Sediment
Management Workgroup

Federal Participation

U.S. Army Corps of Engineers, South Pacific Division
U.S. Army Corps of Engineers, Los Angeles District
U.S. Army Corps of Engineers, San Francisco District
U.S. Geological Survey
National Oceanic Atmospheric Administration
U.S. Environmental Protection Agency
U.S. Bureau of Ocean Energy Management, Regulation and Enforcement
National Ocean Service

State Participation

California Natural Resources Agency
Department of Boating and Waterways
California Coastal Commission
Department of Parks and Recreation
California Geological Survey
San Francisco Bay Conservation and Development Commission
State Water Resources Control Board
Department of Fish and Game
State Coastal Conservancy
State Lands Commission
Ocean Protection Council

Non-governmental Participation

California Coastal Coalition
California Marine Affairs and Navigation Conference

For More Information

To learn more about the Sediment Master Plan, visit: *http://dbw.ca.gov/csmw/default.aspx*.

Beach changes along the southern California coast during the 20th century: A comparison of natural and human forcing factors

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ABSTRACT

Rectified vertical aerial photographs and topographic LIDAR sets, geographic information systems, field observations, and historical data are combined to investigate morphological changes for 75 beaches around the Southern California Bight over a period of 56-77 years. These beaches occur within five discrete units: the Santa Barbara, Zuma, Santa Monica, San Pedro and Oceanside littoral cells. No cell-wide net erosional or net depositional trends are identified. Relatively natural beaches, lacking major human impacts, reveal modest cyclic narrowing and widening related respectively to El Niño and La Niña climatic forcing, and longer-term trends weakly related to the Pacific Decadal Oscillation. For beaches influenced by engineering structures, no such correlations occur but net changes over the period reveal two interrelated types of variation. First, hard structures predictably disrupt littoral drift within cells, with accretion occurring updrift and erosion downdrift of jetties and breakwaters. Sand-bypassing and other forms of artificial nourishment usually counter these effects. Passive erosion also occurs seaward of seawalls and riprap. Second, the longevity of artificial nourishment reflects the volume of fill introduced and whether or not retention structures are present. In most cases, the effects are short-lived, with nourished beaches eroding over a few years, leading to repeated and costly cycles of re-nourishment.

Beaches around the Southern California Bight protect backshore development and related infrastructure from potentially destructive storm waves and high tides, provide habitat for plants and animals, and attract recreation and tourism. However, these beaches are often narrow, and in many cases, no longer in a natural state.

ADDITIONAL KEYWORDS: Beach change; littoral cell; sediment transport; beach nourishment; coastal engineering; ENSO; Pacific Decadal Oscillation; Southern California Bight.

Manuscript submitted ??????? ?????????????, revised and accepted ???????????????????

Southern California beaches vary in size in response to natural forcing factors, notably to seasonal sediment inputs from contributing drainage basins typified by a Mediterranean-type climate, and to variations in wave climate. Over periods from a few hours to several days, wave conditions cause changes at the beach face, which complicate interpretation of monthly and seasonal trends. At seasonal scales, and despite winter inputs of fluvial sediment, exposed beaches typically experience net winter erosion by storm waves, and net summer accretion by long-period swells, such that year-to-year changes are less obvious (Orme 2000). Sheltered beaches suffer less seasonal variability. Over the medium term of a few years, El Niño-Southern Oscillation (ENSO) events may also force beach changes (Flick 1998; Inman and Jenkins 1999; Storlazzi and Griggs 2000). Because of this variability, longer-term trends lasting decades or more are poorly understood but may involve secular changes in ocean-atmosphere forcing and sea level related to the Pacific Decadal Oscillation (PDO) and longer cycles (Flick 1998; Allan and Komar 2000; Graham and Diaz 2001; Bromirski *et al.* 2003, 2005; Mantua and Hare 2002). Understanding natural trends in beach behavior is thus fraught with sampling and analytical problems. Trends may reflect individual storms, seasonal storm series, episodic ENSO events, or factors functioning over decades or more; and the longer the period of record, the greater the complexity. The occurrence of large waves during periods of high tides, however, is the single most important factor producing coastal flooding, coastal erosion and shoreline damage.

Many southern California beaches also reflect human interference over the past century or more, typically involving construction of seawalls, groins, jetties and breakwaters, harbor dredging, and beach nourishment, all designed to coun-

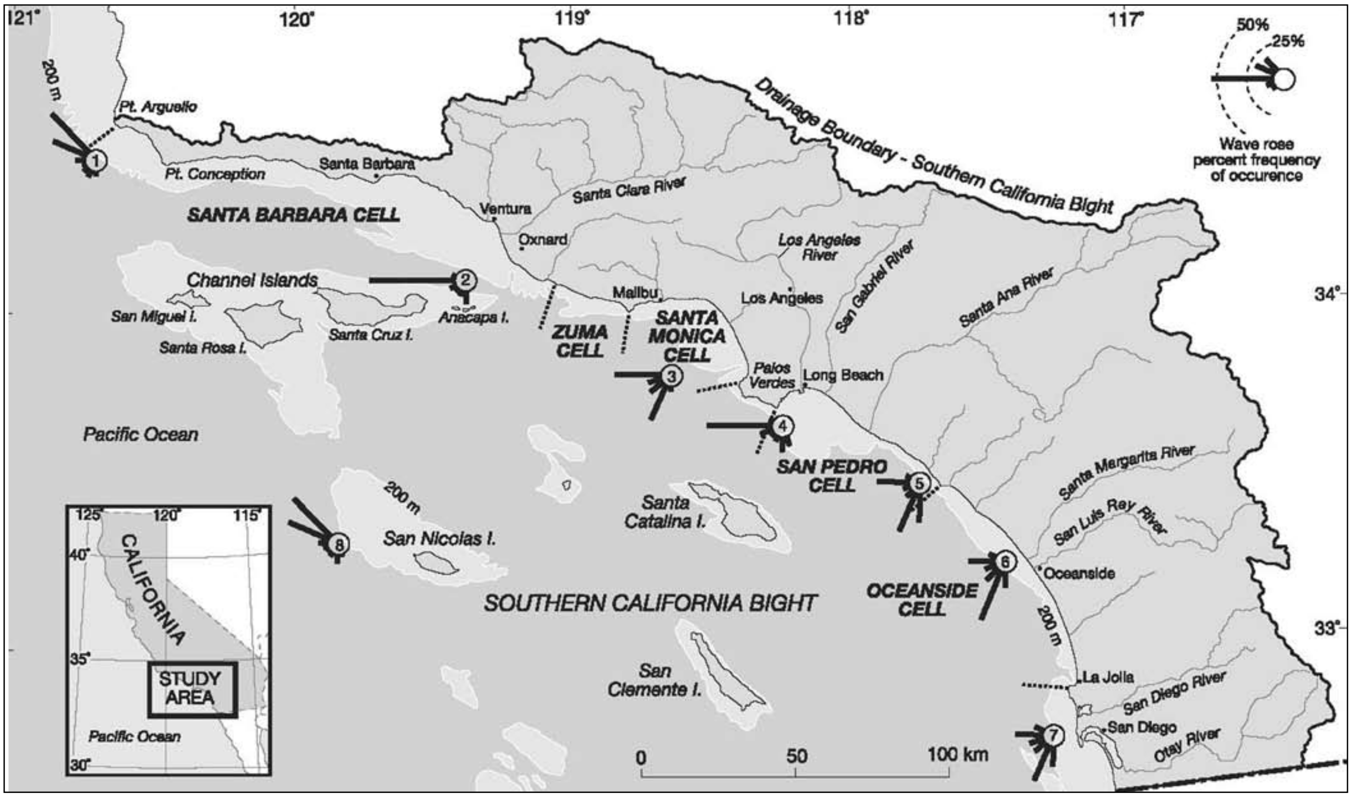


Figure 1. Southern California Bight: littoral cells, contributing rivers, and wave roses (1 Harvest, 2 Anacapa Passage, 3 Santa Monica Bay, 4 San Pedro, 5 Dana Point, 6 Oceanside Offshore, 7 Point Loma, 8, San Nicolas Island; CDIP 2008).

ter real or perceived erosion problems or to promote beach growth (Flick 1993; Wiegel 1994; and references therein). Furthermore, these beaches rely mostly on sediment delivery by rivers, which in recent decades have been curtailed by the construction of debris basins and dams, as well as aggregate mining and stream channelization. Statewide, under undisturbed or natural conditions, California rivers delivered about 10 million m^3/yr of sand to the coast, but dams have reduced this flux by about 2.3 million m^3/yr (Willis and Griggs 2003). Reduction varies regionally but in southern California has approximated 50% (Slagel and Griggs 2008). Armoring of seacliffs against erosion has also curtailed sediment availability (Runyan and Griggs 2003). Conversely, changing land uses, notably preparation for urban development, have accelerated the volume of sediment reaching the coast.

With the above considerations in mind, this paper seeks to measure and explain changes in beach width within the Southern California Bight over the 56-77 years before 2002. This bight, a broad embayment extending 400 km along shore from Point Conception to San Diego (Figure 1), comprises five littoral cells, each more-or-less distinct in terms of its sediment budget. These are the Santa Barbara, Zuma, Santa Monica, San Pedro, and Oceanside cells. Small pocket beaches of the Palos Verdes peninsula supply little sediment to nearby cells and are not included, while beaches fronting the Camp Pendleton Marine Corps base are inaccessible.

Driven in winter by recurrent cyclonic systems over the North Pacific Ocean and in summer by the Hawaiian anticyclone, wave trains and related currents direct littoral drift mostly eastward along the south-facing beaches of the Santa Barbara, Zuma, Santa Monica, and San Pedro cells (Figure 1). Reversals to this pattern occur locally when southerly waves, generated ahead of winter cyclones or in summer by hurricanes off western Mexico and by Southern Hemisphere winter storms, penetrate windows between offshore islands (Pawka *et al.* 1984). Northward littoral drift is most significant along the southwest facing beaches of the San Pedro and Oceanside cells, and of the Santa Monica and eastern Santa Barbara cells in summer (Orme 1982).

This research addresses three basic questions. First, is it possible to identify trends in beach width over a period of several decades? Second, if such trends can be defined, what is their explanation? Third, and despite limited records for many engineering projects, is it possible to distinguish between beach trends attributable to natural conditions and those affected by documented human interference and, if so, is there a systematic and predictable response to changes in sediment supply effected by that interference?

METHODS

This research combines photogrammetric analysis of vertical aerial photographs and topographic LIDAR sets, fieldwork, geographic information systems, and historical information to quantify changes for 75 target beaches within the Southern California Bight over a period of 56-77 years, depending on image availability. Vertical aerial photographs began to be acquired locally in the 1920s, with coverage extending throughout the bight during the 1930s and 1940s. Since then there have been many aerial photographic flights.

The aerial photographs were scanned, rectified and georeferenced to a base digital orthophoto quadrangle (USGS 2006). In general, accuracies associated with rectification fell within +/-10 m RMS.

From these rectified images, two reference features were digitized in ArcGIS — a backshore reference line identifying the back of the beach and a wet/dry line identified by tonal contrast (Figure 2). The wet/dry line was then adjusted to a tidal datum based on tide elevation at the time of the photograph and the slope of the beach face (Moore *et al.* 2006). The distance between these two features represents beach width. The dry-sand portion of each beach (wet-sand limit) was identified from successive survey images relative to a constant backshore baseline and to an arbitrary offshore baseline. Between these baselines, cross-beach transects were cast at 20-m or 50-m intervals alongshore using the USGS Digital Shoreline Analysis System (DSAS) extension to ArcGIS (Thieler *et al.* 2005). Whereas many shoreline studies focus on the migration of a single reference, such as Mean High Water Line, evaluation of two shoreline features and beach width permits temporal assessment of beaches and estimates of changes in beach volume.

Beach-width changes and shoreline change rates were calculated from these data, and compared with other beaches in each cell. Errors associated with using vertical aerial photographs involve source materials, interpretation, and short-term natural variability (Morton and Speed 1998; Moore 2000, Ruggiero *et al.* 2003; Hapke *et al.* 2009). Source errors result from photo distortion, scale, and scanning issues. Interpretation errors come from difficulty in locating shoreline reference features. Short-term variability errors arise from seasonal changes in beach profiles, water-level variations, and wave run-up that change the location of shoreline reference features. Where possible, seasonal variations in the wet-sand limit were controlled by using images acquired during the same time of year, usually summer and autumn. These methods also provided information on the nature of beach response, sand volumes, and human interference, if any. In addition, repeat field surveys of selected target beaches were conducted from 2004 to 2007, designed to quantify recent seasonal changes in beach dimensions.

Attempts to define long-term trends in beach behavior from aerial imagery encounter problems with respect to temporal sampling intervals. These problems, which are troublesome when imagery is acquired infrequently and when shorter-term (e.g. seasonal) beach changes are used to extrapolate longer-term (e.g. decadal-scale) trends, are partly offset where beaches have been surveyed at more frequent intervals and available data are adjusted for anticipated seasonal changes. Although beach changes within each cell were studied by different investigators using different data sets, the guiding principles were everywhere comparable.

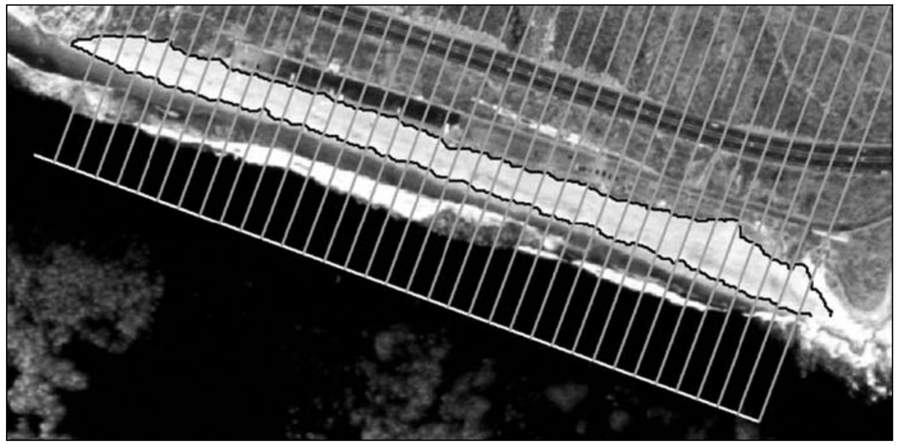


Figure 2. Method exemplar: Sequit West beach digital orthophoto (12 June 2002), showing backshore and offshore baselines, wet-sand limit, and transects at 20-m intervals.

SANTA BARBARA LITTORAL CELL

General Setting and Specific Methods

The Santa Barbara littoral cell, which for the purposes of this study, extends 175 km from Point Conception to Mugu submarine canyon (Figures 1 and 3). Narrow beaches in the 115-km long, south-facing, western part of this cell, from Point Conception to Ventura, receive sediment from small streams draining 900 km^2 of Cenozoic sedimentary rocks forming the Santa Ynez Mountains. Using vertical aerial photographs at scales of 1:24,000 or larger with transects cast at 50-m intervals, a 77-year record (1929-2005) of beach widths was developed for 27 beaches along 70 km of this coast between Ellwood and Pierpoint beaches (Figure 4). Small rocky headlands separate these beaches, and revetments, seawalls and breakwaters now protect over 70% of this shoreline.

Sediment transport along the south-facing beaches is nearly unidirectional, from west to east, owing to the narrow wave window between Point Conception and the Channel Islands (Figure 1). Longshore transport volumes for this cell are approximated by the Santa Barbara and Ventura harbor dredge records, which show a mean annual rate of ~245 000 m^3 and ~505 000 m^3 of sand removed since 1930 and 1961, respectively (Patsch and Griggs 2006, 2008). Fluctuations in annual dredge yardage, reflect both sediment supply and variability in calculating dredge volumes. Despite the damming of the three major rivers discharging updrift of these two harbors, and the apparent reduction in fluvial sediment supply, there has been no systematic or significant reduction in the dredging rates.

Results

Although sequential measurements from the historic aerial photographs reveal oscillations in beach width along the 70-km study reach from 1929 to 2005, the overall picture or net changes to the beaches over the entire period of photo coverage (Figure 4) do not indicate any consistent pattern of beach width decline throughout this area associated with reductions in sand supply. There are well-documented differences in the beaches updrift and downdrift of Santa Barbara Harbor, however (Revell and Griggs 2006; Barnard *et. al.* 2009). Four oscillating beaches west (updrift) of the harbor (Ellwood, Isla Vista, UCSB, Goleta) show maximum widths coinciding with a cooler (negative) phase of the Pacific Decadal Oscillation, while minimum widths follow major El Niño events. East (downdrift) of the harbor no such trend is identified.

Construction of the harbor in 1928-29 triggered an erosion wave that narrowed beaches by over 100 m as it moved downcoast over the next ten years, notably at Carpinteria (Barnard *et al.* 2007, Revell

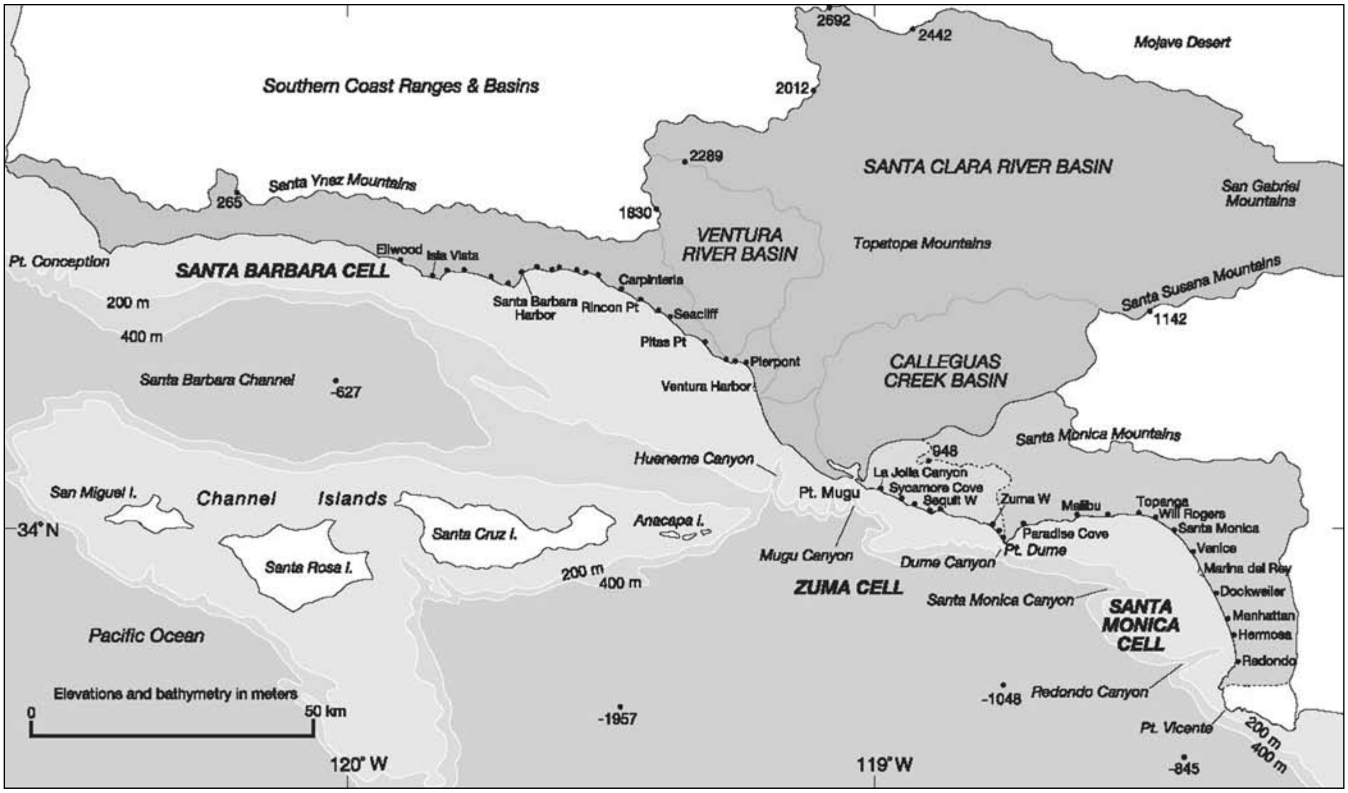


Figure 3. Santa Barbara, Zuma, and Santa Monica littoral cells, showing relief, rivers, bathymetry, and study beaches (selectively named from Figures 4 and 5).

et al. 2008). To counter this effect, from 1933 on, harbor dredging was coordinated with sand bypassing downdrift, thereby controlling beach widths. Successive aerial photographs show pulses of sand moving cohesively through the littoral system along relatively stable beaches with a large minimum width.

Beach-width responses to large El Niño events match long-term shoreline change patterns of shoreline reorientation, indicating that El Niño events play a major role in large-scale, longer-term coastal evolution. For most beaches, longer-term changes in beach width did not indicate any systematic narrowing attributable to reductions in sediment supply (Figure 4). The one exception was at Pierpoint, where beach narrowing followed dam construction on the Ventura River during the relatively dry 1948-1959 period, later offset by construction in 1962-1967 of a nourished groinfield (Orme 2005).

ZUMA LITTORAL CELL
General Setting and Specific Methods

The Zuma littoral cell extends alongshore for 30 km from Point Mugu to Point Dume (Figure 3). This is a little altered, south-facing cell, backed by Cenozoic sedimentary and igneous rocks of the Santa Monica Mountains drained by several short, steep, mostly seasonal streams. Although its 200 km^2 watershed is small, we believe that the Zuma cell is a nearly distinct unit because most of the littoral drift moving east through the Santa Barbara cell at present appears to be lost down Hueneme and Mugu submarine canyons (Everts and Eldon 2005), and because Zuma beaches include heavy minerals almost wholly derived from local rocks (Handin 1951; Zoulas and Orme 2007). Point Dume to the east traps and then diverts a significant quantity of littoral drift offshore into Dume Canyon, thus partially starving downcoast beaches (Patsch and Griggs 2007). The construction of the Pacific Coast Highway in 1924-1929 altered 8 km of shoreline east of Point Mugu, as road-cut debris and short reaches of seawall and riprap were added to protect the new highway, but the impact of these events on the cell's sand supply has long since disappeared.

Predominant littoral drift within the Zuma cell is strongly eastward, driven by storm waves and swells approaching from between west and southwest, north and south of the Channel Islands. Southerly summer swells approaching nearly normal to the shore set up strong onshore-offshore currents, but eastward drift is briefly reversed only along beaches just west of Point Dume (Zoulas and Orme 2007).

Eight beaches within the Zuma cell were analyzed using vertical aerial photographs at scales of 1:24,000 or larger and transects at 20-m intervals for the period of record (Figure 5; Zoulas 2005). To quantify recent seasonal beach changes against which to evaluate longer-term widths, photogrammetric data were augmented in 2004-2005 by repeat field surveys along 13 profiles, which showed seasonal fluctuations in width of about 10 m for all beaches. Thus, only changes in beach width exceeding this value are viewed as reflections of longer-term change.

Results

Beach changes within the Zuma cell for the period 1928-2002 reveal overall long-term stability with no cell-wide trend toward net erosion or net accretion, although six more westerly beaches narrowed modestly while two easterly beaches widened slightly (Figure 5). However, these net changes for the period conceal episodic alternations of erosion and accretion averaging up to 30-40 m for transects within individual beaches. The more westerly beaches, with greater exposure and more restricted sediment supply, saw larger fluctuations in width than the more easterly beaches. Riprap protecting the Pacific Coast Highway has inhibited seacliff erosion near La Jolla Canyon and Sycamore Cove since 1929, but because these cliffs are mostly slate, supplies of beach-forming sand have been little affected. Zuma West Beach remained relatively stable from 1947 to 1990 but then began narrowing east of Lechuza Point. Erosion has since progressed downdrift and may be due to sand supplies being reduced by a combination of berm manipulation, beach grooming, and, perhaps, changing wave climate.

Significantly, regarding the alternations noted above, most beaches reveal a cell-wide cycle of fluctuating widths that function on a multi-decadal time scale over the period of record. As examples, Figure 6 plots trends for La Jolla Canyon (A) and Sequit West (B) beaches. Figure 7 shows average widths for all beaches in the Zuma cell in terms of differences between observed beach widths for each date and the overall mean beach widths for each time series. Wider beaches occur in the late 1920s and again from the late 1950s to the mid-1970s; narrower beaches typify the 1940s and early 1950s, and the late 1970s to around 2000. This cyclicity suggests correlation with changes in wave climate linked to the Pacific Decadal Oscillation (Mantua 2007), with PDO warm phases associated with increased storm activity and beach erosion, and cool phases with reduced storm activity and wider beaches (Figure 7). Zuma cell beaches have not experienced a unidirectional erosional trend for the period of record but instead reveal multi-decadal cyclicity within long-term stability.

SANTA MONICA LITTORAL CELL
General Setting and Specific Methods

The Santa Monica cell extends for 60 km around Santa Monica Bay and is backed by small watersheds draining ~1,000 km^2 (Figure 3). The north shore extends 30 km east from Point Dume to Will Rogers beach, along the south front of the Santa Monica Mountains from which sediment reaches the coast via short streams, the largest being Malibu Creek (285 km^2 watershed). The shore is backed by unstable cliffs, locally fronting Pleistocene marine terraces eastward to Santa Ynez Canyon, and then by cliffed

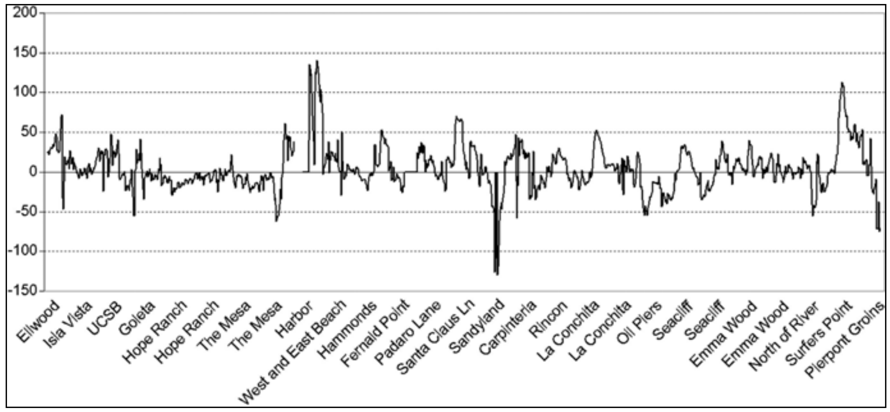


Figure 4. Santa Barbara littoral cell. Net beach-width changes (as specified in Methods) from start date to 2005. Start dates: 1929, Carpinteria, Isla Vista; 1934, west of Santa Barbara Harbor; 1947, all others. Negative change indicates net beach narrowing; positive change indicates net widening.

Figure 5. Zuma, Santa Monica, San Pedro, and Oceanside cells. Net beach-width changes (as specified in Methods) from start date to 2002. Negative change indicates net beach narrowing; positive change indicates net widening. The plot emphasizes net widening of nourished beaches and limited change at natural beaches over the study period, but conceals repeat nourishment and episodic erosion of nourished beaches and quasi-cyclic behavior of natural beaches, as exemplified in Figure 6.

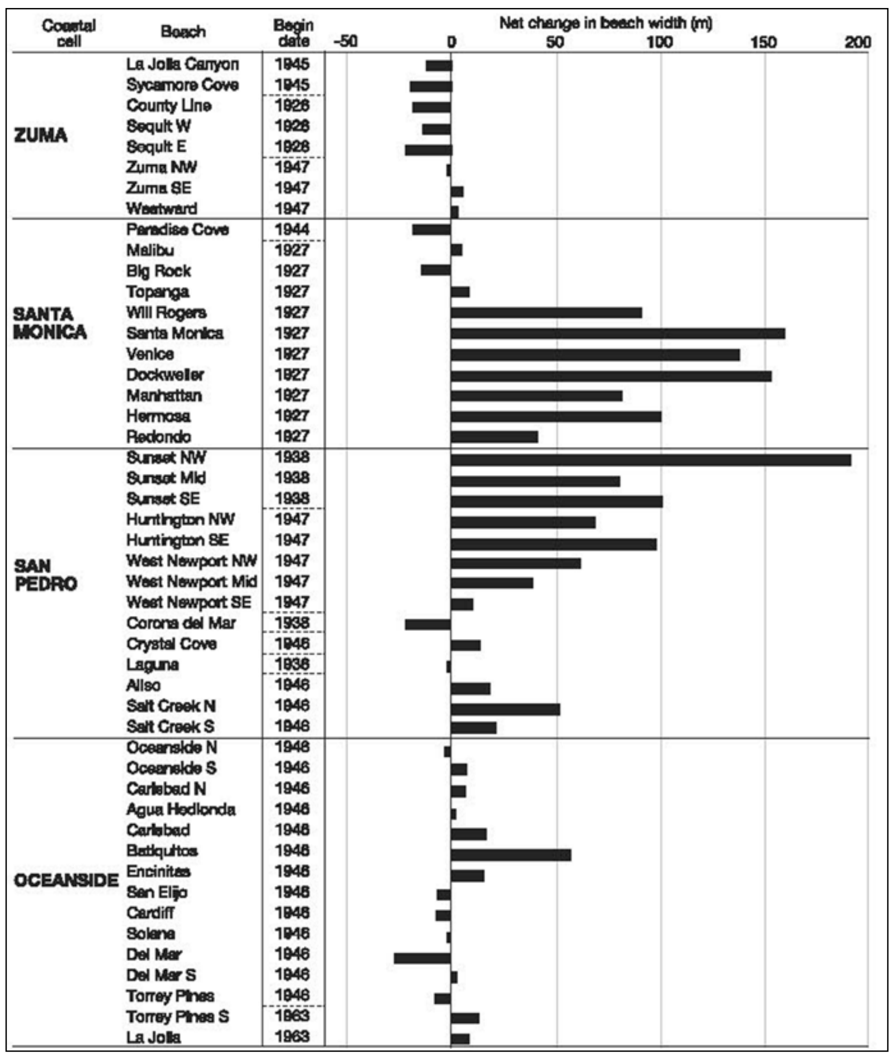
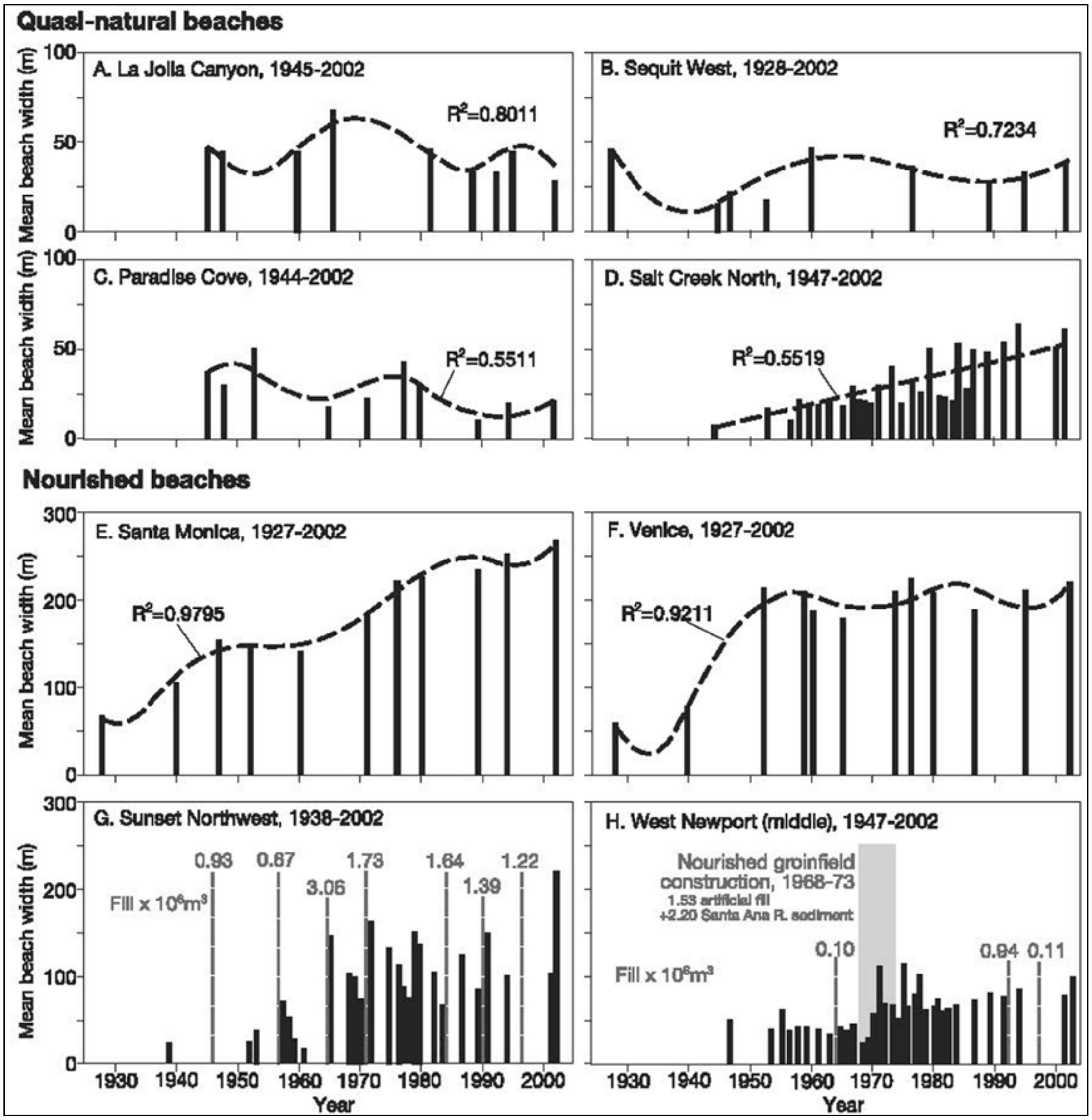


Figure 6. Examples of different types of beach change at natural and nourished beaches over study periods indicated; the vertical scale for beaches A-D is twice that of beaches E-H. La Jolla Canyon, Sequit West and Paradise Cove are natural beaches; originally natural, Salt Creek North shows incidental effect of inland development on beach width. Santa Monica, Venice and Sunset NW are frequently nourished beaches; middle West Newport shows effect of nourished groinfield construction, 1968-1973.



alluvial fans toward Santa Monica. Beach widths here have been affected by a few groins, but more so by backshore housing and coastal highways, which inhibit seacliff erosion, and by reduction of sand supply resulting from dams on Malibu Creek (Orme 2005).

The east shore extends a further 30 km south along the western edge of the Los Angeles lowland, between Santa Monica and Redondo submarine canyons. The former canyon, related to an earlier Los Angeles River outlet, is a partial sink for sediment moving along the north shore; the latter canyon is the ultimate sink for the Santa Monica cell. Although much sediment remains stored on the broad shelf between these canyons, little fresh sediment has reached this shore naturally since the diversion of the Los Angeles River southward to San Pedro Bay by early 19th century floods. Ballona Creek, the atrophied former outlet of this river, provides the largest, mostly paved, contributing watershed (340 km^2), but despite urban runoff during winter rains, delivers little natural sediment to the shore. Accordingly, during the 20th century, many hard engineering and beach-nourishment projects were implemented to protect beaches and marinas.

Predominant littoral drift is driven eastward along the north shore, and then southward along the east shore, by storm waves and swells approaching from between west and southwest (Patsch and Griggs 2007; Figure 1). In summer, occasional swells approaching from south-southwest, between San Nicolas and Santa Catalina islands, temporarily redirect littoral drift weakly northward along the east shore but are not strong enough to offset net southward drift.

Eleven beaches within the Santa Monica cell were targeted for study, four facing south along the north shore, and seven facing nearly west along the east shore (Figure 3). Beach changes were measured from vertical aerial photographs at scales of 1:24,000 or larger for the period 1927-2002, and transects were cast at 50-m intervals. The photogrammetric data were augmented in 2005 and 2006 by repeat field surveys along 20 profiles, which like the Zuma cell showed seasonal fluctuations in beach widths of about 10 m.

Results

Overall, the four south-facing beaches show little net change between 1927 and 2002 (Figure 5). Only Paradise Cove and Big Rock show net erosion exceeding seasonal fluctuations, and only Paradise Cove appears to have experienced a trend of reduced width (Figure 6C). Because Paradise Cove lies leeward of Point Dume, its net loss of 19 m in beach width is viewed as natural but the net

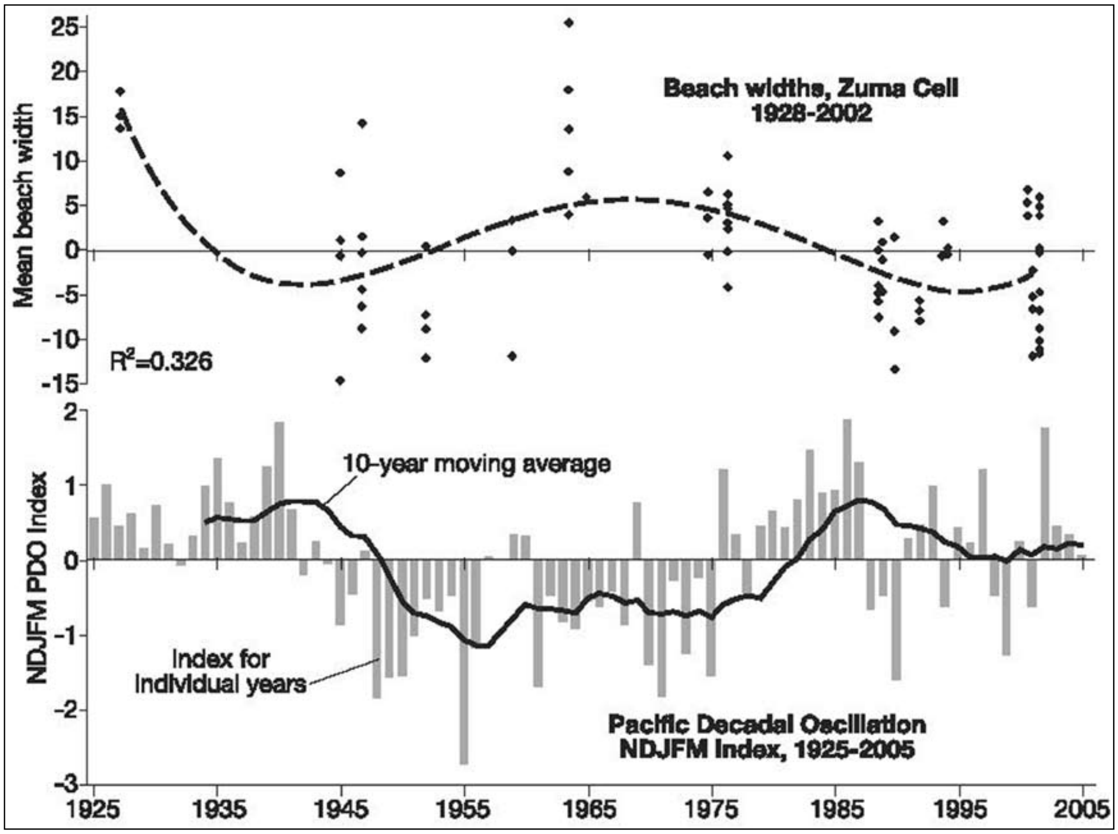


Figure 7. Zuma cell, showing difference between mean beach width and time-series mean width for all beaches, 1928-2002 (modified from Zoulas and Orme 2007), compared with the Pacific Decadal Oscillation index, November-March, 1925-2005, with 10-year moving average (from Mantua 2007).

loss of 15 m at Big Rock is likely due to narrowing caused by riprap placement protecting the Pacific Coast Highway. Linear trends at the other south facing beaches are insignificant, but do show some cyclicity, with Paradise Cove, Big Rock and Topanga reaching maximum widths around 1950, narrowing into the mid-1960s, widening again toward 1980, narrowing into the mid-1990s, and then recovering toward 2000 (e.g., Figure 6C). These trends suggest cycles of approximately 30-year duration, but out of phase with those observed in the Zuma cell. Their interpretation is confounded by El Niño storm events in 1978-1980, 1982-1983, 1992-1993, and 1997-1998, which shed abundant sediment to the coast during the warm PDO phase of 1977-1998. This PDO phase should have been linked with significant erosion but instead produced initial accretion and later erosion. It seems that sediment discharged from local creeks during this warm phase was retained nearshore rather than flushed farther seaward (Schwarz and Orme 2005). Thus, nearshore storage of fluvial sediment and its presumed reworking onshore complicate direct correlations between beach behavior and PDO cyclicity.

In striking contrast, the seven west-facing beaches show major net widening, from 42 m to 160 m, over the study period (Figure 5). This relates directly to repeated beach nourishment. Predictably, beaches showing persistent widening are those where direct nourishment occurred often, as at Santa Monica (Figure 6E), or where large quantities of sediment moved south from nourishment projects updrift, notably from frequently nourished Dockweiler beach to Manhattan and Hermosa beaches. Between 1939 and 1958, Santa Monica beach received ~1.4 million m^3 of sand, which it largely retained owing to the storage impact of an offshore breakwater (built 1933, mostly destroyed 1983) (Leidersdorf *et al.* 1994). From 1945 to 1960, Venice beach received ~10.8 million m^3 of sand, mainly from onshore excavation of the Hyperion wastewater treatment facility (Figure 6F). Although prone to erosion, this wide beach has been maintained by repeat fills and sand moving south from Santa Monica. Between 1938 and 1988, Dockweiler beach received at least ten major infusions of fill, totaling 22.2 million m^3, from excavations at Hyperion and Scattergood power plant, and from dredging and bypassing at Marina del Rey. However, as these fills moved south Dockweiler beach suffered recurring erosion, although it has yet to return to pre-fill widths (Figure 6F). Farther south, Redondo beaches, denied natural replenishment by King Harbor breakwaters (1939-1964), have also seen episodic nourishment, notably from 1968 to 1975 (Leidersdorf *et al.* 1994). Most nourished west-facing beaches of the Santa Monica cell, notably along the Dockweiler-Manhattan reach, narrowed significantly during El Niño events in 1982-83 and 1997-98 because, unlike the south-facing beaches, there was no recent river sediment stored nearby to offset erosion.

SAN PEDRO LITTORAL CELL
General Setting and Specific Methods

The San Pedro cell extends 70 km southeastward from Point Fermin to Dana Point (Figure 8). West of Newport pier, this cell fronts the Los Angeles alluvial lowland and has been massively impacted by the San Pedro-Long Beach port complex, although beaches backed by erodible bluffs occur locally. From Newport to Dana Point, the Laguna coast comprises exposed shorelines and pocket beaches fronting cliffs of Miocene sedimentary rock and has few engineering structures.

Drainage basins feeding the San Pedro cell cover 9200 km^2. Prior to dam construction in the 20th century, the Santa

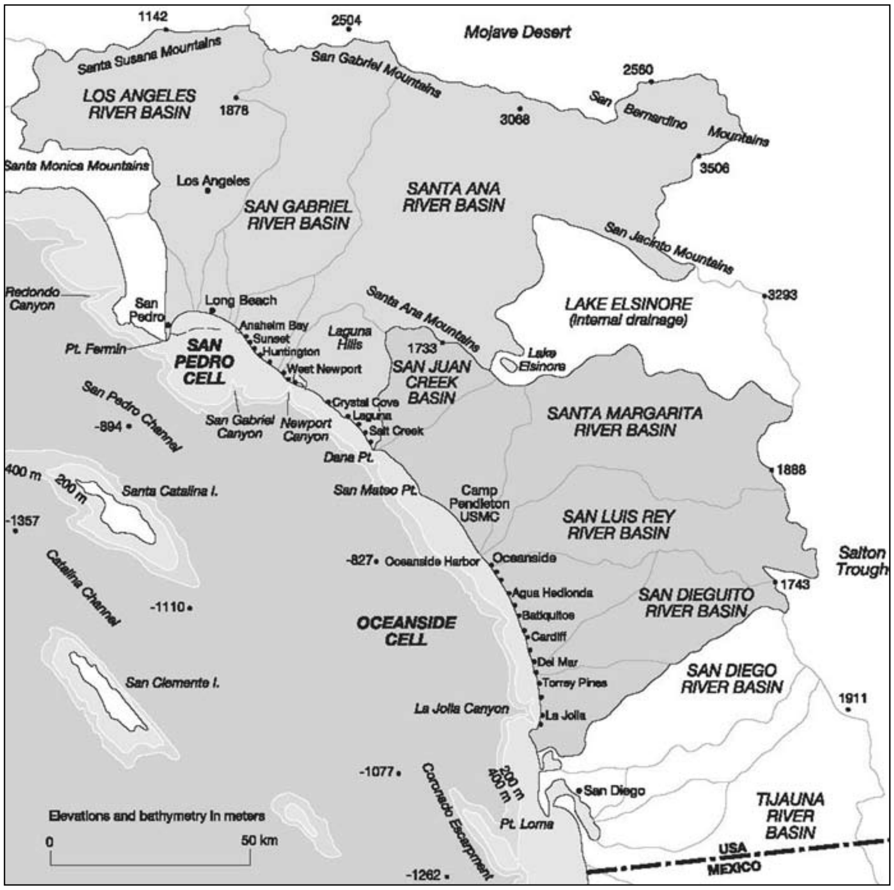


Figure 8. San Pedro and Oceanside littoral cells, showing relief, rivers, bathymetry, and study beaches (selectively named from Figure 5).

Ana, San Gabriel, and Los Angeles river basins (4400 km^2, 1670 km^2, 2200 km^2, respectively) provided abundant sediment to local beaches. Because these rivers often changed course, barrier-lagoon systems between their mouths were also unstable. The Santa Ana River, which flowed into Anaheim Bay until shifting eastward in 1825, was fixed in its present location in 1920 (USACE 2002). Although the Prado Dam (built 1941) now controls discharge from 88% of its basin, Santa Ana River flow increased six-fold from 1968 to 2001, reflecting increased impermeable surfaces and imported water (Warrick and Rubin 2007). Thus, the river still has a sediment flux averaging 96 000 m^3/yr (Willis and Griggs 2003). In contrast, owing to extensive pavement, dams and channelization, sediment deliveries from the San Gabriel and Los Angeles river basins are now negligible (USACE 2002).

Sediment transport in the San Pedro cell reverses seasonally in response to changing wave approach and coastal orientation (Figure 1). In the northwest part of the cell, predominant littoral drift is eastward, strongly in winter when storm waves pass through the San Pedro Channel, and much sand is believed to be lost down Newport submarine canyon, which heads inshore near Newport pier. Thus, when littoral drift reverses weakly in summer in response to long-period southerly swells, less sand is available to renourish northwest beaches. Here, engineering structures ranging from modest groinfields to large breakwaters have altered sediment movement and enhanced downdrift erosion over the past century. Beach losses have in turn generated nourishment projects. The Laguna coast is more exposed to southerly swells, so that predominant littoral drift is northward with weaker drift southward in winter. Engineering structures here are small.

Aerial photographs, at scales from 1:3000 to 1:48 000 derived from 77 individual flights from 1938 to 2002, were analyzed for 14 beaches within this cell (Figure 5; Zoulas 2008). All photographs were analyzed regardless of season, and each beach was subject to repeat field surveys during 2006-2007 in order to incorporate measures of seasonal change into the analysis.

Results

Long-term trends vary for individual beaches within the cell. Northwest Sunset Beach exhibited a strong trend of increasing mean beach width, from 20 m in 1938 to 212 m in 2002, but this trend reflects repeat nourishment projects alternating with chronic erosion caused by the Anaheim Bay entrance jetties, which restrict sand transport from the San Gabriel River (Figure 6G). Thus the overall trend is a statistical anomaly imposed artificially on a naturally narrow beach. Southeast Huntington Beach also exhibited a net widening of 98 m from 1947 to 2002, related to the influx of nourished sand from Sunset Beach (Figures 5 and 6G). West Newport beach also saw net widening from 1947 to 2002, linked to groinfield construction between 1968 and 1973, but this trend decreased southward (Figure 6H). At sheltered Corona del Mar, after artificial loss to a parking lot (1948-1955), the beach stabilized around a mean width of 65 m after 1955. On the Laguna coast, Crystal Cove, Laguna and Aliso beaches saw few changes (Figure 5). In contrast, Salt Creek north beach showed a strong accretionary trend, with mean width increasing from 10 m in 1946 to 61 m in 1994 (Figure 6D). Salt Creek south beach saw a smaller net increase.

Beaches within the cell thus present a contrast between those along the populated, relatively exposed coast from Sunset Beach to Newport submarine canyon, which showed significant net widening between 1938 and 2002, and the more sheltered beaches of the Laguna coast which, except for north Salt Creek, were relatively stable. In reality, this is a contrast between beaches that were artificially nourished and those that were not. Thus, downdrift of the Anaheim Bay entrance jetties, erosion of Sunset Beach to a width of 10 m or less by 1960 was countered in 1964 by placement of 3 million m^3 of fill derived from the Seal Beach Naval Weapons Station and then, following erosion, by repeat nourishment at more-or-less decadal intervals until more than 12 million m^3 of fill had been placed by 2002 (Figure 6G; USACE 2002). Huntington and West Newport beaches gained sand eroded from Sunset Beach, until this was lost down Newport canyon. To combat persistent erosion attributable to the decreased sediment flux from the Santa Ana River, West Newport beach was directly nourished with 1.53 million m^3 of sand in a field of eight groins constructed between 1968 and 1973; this was fortuitously augmented by over 2.2 million m^3 of sediment discharged from the Santa Ana River during the 1969 floods (Figure 6H). Since 1970, as recurring erosion has been countered by repeat nourishment, beach widths have ranged from <60 m to >100 m. Without the groinfield, greater beach loss would occur. The coast from Sunset Beach to Newport is thus an artificial system where repeated nourishment tends to maintain unnaturally wide beaches in the face of a long-term narrowing trend.

In contrast, most beaches along the Laguna coast are more natural. Crystal Cove, Laguna, and Aliso beaches weakly reflect variable ocean-atmosphere forcing and seasonal reversals in littoral drift. There are two exceptions: Corona Del Mar beach owes its stability to the Newport Bay entrance jetties, which offer shelter from westerly swells and trap northward littoral drift in summer; and Salt Creek north beach has widened, notably since 1980, in response to suburban development inland which has released considerable sediment to local streams (Figures 5 and 6D). As disruption diminishes and the basin becomes paved and landscaped, less sediment will reach this beach. No significant relationships between mean beach width and the Pacific Decadal Oscillation were observed in this cell.

OCEANSIDE LITTORAL CELL

General Setting and Specific Methods

The Oceanside cell extends 80 km from Dana Point to La Jolla submarine canyon (Figure 8). Its 5,500 km^2 watershed is underlain inland by Mesozoic granite, metavolcanic and sedimentary rocks, and at the coast by cliff-forming Cenozoic sedimentary rocks. The Santa Margarita (1,900 km^2) and San Luis Rey (1450 km^2) river basins provide most sediment but these sources have been reduced in recent decades by dams. Shoreline armoring has also reduced cliff erosion. Nevertheless, the average annual sand supply to the coast since 1940 has actually increased from artificial beach nourishment, averaging 300,000 m^3/yr and ranging from near zero to more than 3.5 million m^3/yr (Patsch and Griggs 2006; Grandy and Griggs 2009). Winter storm waves approach this cell from the northwest and, although dampened by Santa Catalina Island, promote southward littoral drift. During late summer and when winter storms take a more southerly track, waves approaching from the south to southwest inshore of San Clemente Island promote northward littoral drift (Patsch and Griggs 2007).

To reduce the potential signal from seasonal variability, analysis of this cell examines only aerial photographs taken between late summer and early autumn when beaches are usually widest and most stable. This limits the available data but offers more comparable results. Of the seven data sets used, four (1963, 1975, 1986, 2001) were rectified using Erdas Imagine software with USGS Digital Ortho Quarter-Quads (DOQQs) for ground control. The other three sets (1946, 1955, 1980) involved block orthorectification using USGS Digital Terrain Models (DTMs) for ground control. To minimize errors linked with natural short-term variability, wet-sand limits were measured relative to mean high water based on tidal data from the previous 24 hours at La Jolla (NOAA 2007) and an average beach slope of 3 degrees calculated from beach profiles (Coastal Frontiers 2002). Beach widths for the period were measured at 50-m intervals for 15 beaches over 50 km of coast from Oceanside to La Jolla, distinguishing in the process between cliff-backed beaches and estuarine barriers fronting lagoons (Figures 5, 8).

Results

Beach widths fluctuated between 1946 and 2001 but showed no net erosion or accretion trends, nor any longer-term correlations with ENSO or PDO climate cycles, but they did respond to episodic storm events. Cyclonic winter storms during 1978-1979 and 1980-1981, and the powerful El Niño event of 1982-1983, generated large floods, powerful waves, and frequent cliff failures, which all contributed abundant sediment to the littoral system. The 1978-1981 storms delivered more fluvial sediment to the cell than all other years of record combined (Grandy and Griggs 2009). Large floods on the San Luis Rey River yielded more than 3.5 million m^3 of sediment to the coast south of Oceanside in 1979 and more than 1 million m^3 in 1980 (Inman and Jenkins 1999). Despite this influx, beaches in the cell were much narrower in 1980 than earlier, essentially because southerly storm waves promoted strong scour at the beach face and cliff base, notably from San Elijo northward to Oceanside (Kuhn and Shepard 1984).

In contrast, by 1986, these beaches had not only recovered to pre-1980 widths, but on average were wider than for any other year studied. Most pronounced widening occurred near the San Luis Rey estuary and decreased away from there. In the south, beaches beneath Torrey Pines cliffs and La Jolla were much wider than average in 1986. These changes from 1980 to 1986 suggest that fluvial sediment and cliff debris introduced to the littoral zone during the earlier stormy years had now moved back onshore.

By 1996, beaches throughout the cell were again relatively narrow. In 1995, this coast was impacted by 19 storm events, each lasting longer than nine hours, with deep-water significant wave heights greater than 4 m (Seymour 1998). These events were more intense and more frequent than between 1981 and 1998, and probably explain the anomalously narrow beaches in 1996.

Overall, during the study period, barrier beaches fronting estuarine lagoons at Agua Hedionda, Batiquitos and Del Mar fluctuated in width by +/-15 m, due mainly to the episodic delivery of sediment by stream floods breaching the barriers. The only large natural pulses of sediment that affected other beaches were those from the San Luis Rey River. Cliff-backed beaches, as at Carlsbad, Encinitas and Solana, fluctuated within a smaller range of +/-10 m. In both settings, time-lags, often of several years, occurred between triggering flood or storm-wave events and subsequent recovery to pre-storm conditions.

In contrast to the modest effects of natural events, human activities had a major impact on beach widths. Dams and armored seacliffs both restricted sediment delivery to the shore, while artificial nourishment generated rapid changes in beach widths, which far exceeded normal ranges. Nourishment projects often involved large volumes of fill, notably south of Oceanside (1963) and Batiquitos (2001), and the placement of fill dredged from Agua Hedionda Lagoon (1955). Between 1942 and 2002, nourishment projects added more than 21 million m^3 of sediment to local beaches, an average of ~350 000 m^3/yr (USACE

1987, 1991; Flick 1993; Wiegel 1994; Coastal Frontiers 2002). Of this total, 13.5 million m^3 were placed between 1950 and 1979, augmented after 1980 by a further 6 million m^3 (Grandy and Griggs 2009). However, no nourished beaches remained wide in later years and no nourishment project benefited downcoast beaches. In short, nourishment has had a marked but transient impact on local beaches, which need floods or repeated nourishment and some form of sand retention to maintain their widths.

Other engineering projects also affected beach dimensions. North Carlsbad widened after jetty construction at the mouth of Agua Hedionda to the south, although this gain was later lost to parking facilities. Similarly, housing encroachment at Del Mar between 1946 and 1955 led to beach loss. Construction of the Oceanside harbor complex between 1942 and 1963 involved placing 5.2 million m^3 of dredged sand onshore, which widened beaches near the harbor but had little or no effect farther south. While the Oceanside breakwaters stabilized the harbor beaches, as well as those farther north, they also diverted much sand offshore (Dolan *et al.* 1987; Patsch and Griggs 2007).

In summary, between 1946 and 2001, beach-width changes in the Oceanside cell were caused by both natural and artificial factors. Large storm events between 1978 and 1983 delivered abundant sand to the coast, which was stored offshore and moved onshore later during less stormy times. There was a time lag between natural sediment delivery and increases in beach width. In contrast, artificial nourishment produced immediate increases in beach widths but these effects did not persist. Overall it seems that beaches in this cell have been historically narrow and tend to remain so unless augmented by artificial nourishment or, after some time lag, by the natural return of sediment stored temporarily offshore (Figure 5).

DISCUSSION

In principle, two major climate patterns affect beach widths along the California coast over the longer term: individual El Niño Southern Oscillation (ENSO) events and the Pacific Decadal Oscillation (PDO). These climate patterns are associated with decadal and multidecadal scale shifts in water temperature, ocean level, wave properties, precipitation magnitude and frequency, and thus in sediment delivery to the shore (Flick 1998; Allan and Komar 2000; Graham and Diaz 2001; Bromirski *et al.* 2003; Bromirski *et al.* 2005; Adams *et al.* 2008).

At first glance, this study would appear to yield mixed results, with spatial and temporal differences in the nature and range of beach changes occurring within and between individual beaches in a cell, and also within and between different cells over the study period. Such variability is generally predictable, bearing in mind the noise inherent in the natural system and the complicating effects of human interference. And, in the absence of large sediment inputs from El Niño events and beach nourishment, many beaches (notably along the Laguna and Oceanside coasts) changed little (+/-10 m) during most of the years of record. On closer inspection, however, four distinct factors emerge, specifically evidence for (1) ENSO forcing at many beaches; (2) modest PDO forcing at beaches largely unaffected by human interference; (3) the confounding effect of engineering structures on beach dimensions; and (4) the transience of modest-scale beach nourishment projects in the face of natural coastal processes.

ENSO Effects

The impacts of ENSO events on beach change are evident for many beaches throughout the Southern California Bight. This is not unexpected because previous studies have described the effects of El Niño events for California beaches (e.g. Storlazzi and Griggs 2000; Schwarz and Orme 2005). This study confirms the importance of enhanced storm wave activity and sediment delivery to the coast during El Niño events. In the Oceanside cell, for example, exposed beaches narrowed dramatically during El Niño events of 1978-1979 and 1982-1983, but subsequently widened in response to calmer conditions during which a portion of the sediment flushed seaward earlier was returned onshore. Beaches at or near river mouths respond more rapidly to ENSO conditions, as shown at Malibu Creek where El Niño storms of 1997-1998 flushed the barrier beach from the river mouth, but La Niña conditions of 1998-99 returned most of the sand temporarily stored offshore to the beach (Schwarz and Orme 2005). Sediment discharged to the nearshore zone by Malibu Creek during the 1982-1983 El Niño event returned to the beach face within a few weeks. There is thus a lag effect on beach responses to ENSO conditions, shortest near river mouths where beaches may be restored within a few weeks or months. When sediment is stored farther offshore, as at Goleta beach, beach reconstruction may take much longer. These responses contrast with those influenced by artificial nourishment projects where beach widening is instantaneous but where nourished beaches quickly erode during major storm events, as shown by west-facing beaches of the Santa Monica cell in 1982-1983 and at Torrey Pines in 2001.

PDO Effects

The effects of PDO cycles on beach widths is likely related to the shift in the subtropical jet stream and its effect on wave approach and magnitude, and water elevation. Given the wave sheltering of the Southern California Bight by Point Conception and offshore islands, the effects on beaches are more subtle and spatially more confined than on fully open coasts. In the western Santa Barbara cell and across the Zuma cell, a weak PDO signature suggests that narrow beach widths are linked with increased storm-wave activity during PDO warm phases, whereas the PDO cool phase from 1947 to 1977 coincides with wider than average beaches (Figure 7; Revell and Griggs 2006; Zoulas and Orme 2007). Narrower than average beaches in the 1980s and 1990s coincide with the PDO warm phase that began in 1978 (in which the major El Niño events of 1982-1983 and 1997-1998 were embedded). The beaches in these sectors differ from those elsewhere in the bight in that they have remained more-or-less natural, little affected by human activity. This difference suggests that beaches free from major engineering works and nourishment activity exhibit identifiable responses to changes in wave climate forced by the PDO. Suggestions of cyclicity characterize south-facing beaches of the Santa Monica cell but these appear out-of-phase with those of the Zuma cell, probably because of the confounding effects of terrigenous sediment flushed seaward during El Niño events.

Effect of Hard and Soft Engineering Structures

Given near-unidirectional littoral drift in the western Santa Barbara cell, a distinction exists between those beaches west (updrift) of Santa Barbara Harbor, where few engineering structures exist, and those farther east where the impacts of the harbor breakwater and episodic sand bypassing disrupt the natural system (Barnard *et al.* 2007, Revell *et al.* 2008). In addition, seawalls and riprap designed to counter backshore erosion have led to narrowing of many beaches eastward to Ventura, while a nourished groinfield has promoted beach widening at Pierpoint (Norris and Patsch 2005; Orme 2005; Revell and Griggs 2006). The few minor engineering structures in the Zuma cell interfere little with natural beach-forming processes.

Most beaches within the Santa Monica cell have been modified by development, hard structures, and artificial nourishment. South-facing beaches between Malibu and Santa Monica have lost considerable volume from construction of the Pacific Coast Highway, which ended sea cliff erosion, and of dams on Malibu Creek. Conversely, the wide recreational west-facing beaches between Santa Monica and Redondo Beach reflect repeated nourishment from large onshore construction projects, aided by groins and two offshore breakwaters since the 1930s. Sand starvation caused by the entrance jetties to Marina del Rey and Ballona Creek has required remedial nourishment of Dockweiler beach, which has in turn fed beaches farther south.

In the San Pedro cell, from Long Beach harbor to Newport canyon, human activity has been the primary driving force behind observed changes in beach width, notably from repeat nourishment at Sunset Beach and downdrift movement of this added sand onto Huntington and West Newport beaches. Farther southeast, beaches have been widened by a nourished groinfield and by the entrance jetties to Newport Bay, but beaches along the Laguna coast remain relatively natural and, apart from widening at Salt Creek north beach following inland development, have changed little since the 1930s. Changes in beach width within the Oceanside cell occurred immediately following major nourishment projects, notably at Oceanside, Agua Hedionda, and Batiquitos.

Transience of Beach Nourishment

Beach nourishment has been practiced in southern California since the 1920s, including (1) opportunistic nourishment, where sand from coastal construction projects has been disposed of on beaches, notably along the west-facing Santa Monica cell, (2) bypassing, where sand dredged from updrift of breakwaters and jetties has been discharged downdrift; and (3) dedicated nourishment, where sand has been added for specific beach widening. In the last case, the rationale in recent years has argued that nourishment is needed in order to rebuild beaches seemingly undergoing long-term erosion. This study shows that, while many beaches of southern California have been affected by coastal engineering structures, most beaches that have remained essentially undisturbed have been influenced by decadal scale climatic changes but have experienced little net long-term erosion.

For those beaches widened by nourishment, the response has usually been transient, with beaches returning to pre-nourishment widths within a few years, leading in turn to repeat nourishment. In the Santa Monica cell, massive nourishment projects widened Venice and Dockweiler beaches in 1945-1960 but, with recurring erosion, re-nourishment has been common. At West Newport in the San Pedro cell, a nourished groinfield in 1968-1973 widened a narrow beach but continuing erosion has necessitated re-nourishment. In the Oceanside cell, removing measurements of beaches artificially widened by beach nourishment revealed a cell-wide trend toward narrower-than-normal beaches following storms in 1978-1980 and 1993-1996, and wider-than-normal beaches in 1986, the latter a lag response to large fluvial sediment inputs during the 1982-1983 El Niño event. Beaches respond to temporal changes in wave climate and sediment supply, but there is no reason why sand added to a naturally narrow beach should remain for any length of time. Thus maintenance of wide beaches in areas with naturally narrow beaches usually needs frequent and substantial renourishment or the placement of retention structures such as groins.

Implications for Coastal Management

This research has implications for beach management around the Southern California Bight. Beaches that have escaped the influence of coastal engineering projects have mostly remained relatively stable over the period of record, notably west of Santa Barbara, throughout the Zuma cell, and in the Laguna sector of the San Pedro cell. This long-term stability suggests that, excepting changes in wave climate or a rapid rise in sea level, beaches here are not presently at significant risk from chronic erosion. Where longer-term changes have occurred they are commonly related to ENSO and PDO events and cycles. Such changes should be seen as predictable longer-term gains and losses within a naturally variable system, and managed accordingly.

In contrast, many beaches within the eastern Santa Barbara, Santa Monica, northwest San Pedro, and Oceanside cells have experienced chronic erosion as a result of indirect and direct human interference with the natural system. Indirectly, the reduction of sediment yields to the coast, as a result of dams built along contributing rivers, has led to net beach erosion. Directly, hard structures, such as seawalls, revetments and bulkheads built to counter local cliff and bluff erosion problems, have commonly led to passive beach erosion, for example between Malibu and Topanga. At larger scales, sediment trapped updrift of jetties and breakwaters has become unavailable to downdrift beaches, resulting in chronic erosion that has spurred massive sand bypassing and other forms of nourishment or armoring. These effects are epitomized by the jetties and breakwaters at Santa Barbara Harbor, Marina del Rey, King Harbor, San Pedro-Long Beach Harbor, Anaheim Bay; and Oceanside Harbor. Whereas these impacts were predictable, the effects of subsequent nourishment projects on downcoast beaches have proven transitory. Erosion has removed much of the fill within a few years, requiring repeat nourishment. At Sunset and West Newport beaches, episodic beach nourishment must be continued indefinitely in order to maintain protective beaches. Even the massive fills placed on Venice and Dockweiler beaches in 1946-1948 have gradually migrated downdrift. This study, by revealing the behavior of artificially maintained beaches over several decades, calls into question the wisdom of repeated beach nourishment projects without retention structures. In the context of rising sea level, it is questionable whether repeated nourishment is a viable, cost effective long-term strategy, or whether relocation of the shoreline makes more sense.

A recent analysis of shoreline change along the entire California coast, based on historical marine charts, aerial photographs from 1920-1940 and 1950-1980, and LIDAR data from 1998-2001, suggests that about 40% of the state's beaches have been eroding over the past 120 years, increasing to 66% over the past 25 years (Hapke *et al.* 2009). Our study, based on large data sets derived for 75 southern California beaches, extends and qualifies these observations for the period between 1927 and 2002, particularly with respect to the distinction between relatively natural beaches, which have changed little, and those influenced by hard and soft engineering projects, which have seen massive changes but often of a transient nature.

CONCLUSIONS

This study has addressed three basic issues related to southern California beaches: first, the possibility of identifying trends in beach widths over several decades, based primarily on the interpretation of sequential aerial photographs; second, the probable explanation of those trends; and third, the likelihood of distinguishing between trends attributable to natural conditions and those affected by human interference.

This research reveals the dynamic character of southern California beaches over a period of 56-77 years. Beach changes from individual storms and seasonal climate forcing were to be expected, as were erosion spells and subsequent recovery related to quasi-cyclic ENSO events. Less expected were the natural oscillations in beach width of 30 m or more that occurred over decadal and multi-decadal time scales, and which for the western Santa Barbara and Zuma cells we link with the Pacific Decadal Oscillation (PDO). In other words, beaches may experience erosional regimes lasting a decade or more, only for the situation to be reversed and beaches widened over a subsequent decade. This phenomenon suggests that much beach sand, rather than being lost offshore or down submarine canyons at the downdrift end of littoral cells, is stored nearshore following erosional phases, within the reach of shallow-water waves and currents, and thus available for return onshore during depositional phases. Explanations of cyclicity observed in south-facing beaches of the Santa Monica cell are complicated by fluvial sediment stored nearshore following El Niño floods and its delayed return onshore during calmer times.

In addition to natural variability in wave climate and sediment supply, human activities have forced significant changes in beach width in the Southern California Bight, most directly through the impact of large engineering structures on sediment mobility. The site-specific changes found along engineered coasts are readily distinguishable from changes observable on more natural beaches. Erosion and deposition are conditioned primarily by the structures involved rather than by climate forcing, which assumes a secondary role. However, whereas sand bypassing and other nourishment forms may counter beach erosion downdrift of cross-shore structures, our results suggest that the effects of individual nourishment projects are relatively short-lived, more so in the absence of retention groins. In most instances, erosion of artificial fill begins soon after its placement and continues until only a narrow beach remains. Thus, in order to maintain wider beaches, artificial nourishment must be repeated frequently. Coastal managers need to consider the sustainability and long-term costs of embarking on repeated nourishment projects.

Overall, our observations suggest that engineers and policy makers should integrate a longer-term perspective into coastal management scenarios, including decisions regarding development and construction guidelines and property setbacks. In the recent past, there has been a tendency for managers to provide short-term reactive solutions to beaches and property exposed to erosion during storms, when there is a good probability of a return to wider beaches during later years. Conversely, the protection afforded by wide natural or nourished beaches should not be assumed over the longer-term. In short, managers should seek to integrate into their plans considerations of longer-term cyclicity of coastal change and the inevitable loss of nourished beaches. Additionally, a significant increase in the rate of sea level rise in the decades ahead will lead to passive erosion and gradual inundation of all of those beaches that have a back edge fixed by a hard structure, whether seawall, revetment, highway, parking lot or other infrastructure or development.

ACKNOWLEDGMENTS

This project was funded by the atate of California to the University of California Marine Council for the Coastal Environmental Quality Initiative (G.B. Griggs and A.R. Orme, principal investigators). For historical imagery, we thank Greg Hajic, Map and Imagery Laboratory, UC Santa Barbara; UCLA Department of Geography; and Pacific Aerial Surveys. Chase Langford of UCLA prepared final versions of the figures.

REFERENCES

Adams, P., D.L. Inman, and N.E. Graham 2008. "Southern California deep-water wave climate: characterization and application to coastal processes." *J. Coastal Res.* 24, 1022-1035.

Allan, J., and P. Komar 2000. "Are ocean wave heights increasing in the eastern North Pacific?" *EOS Transactions of the American Geophysical Union* 81, 561-567.

Barnard, P.L., D.L. Revell, J.L. Eshleman, and N. Mustain 2007. "Carpinteria Coastal Processes Study, 2005-2007." U.S. Geological Survey Open-File Report 2007-1217, 130 p.

Barnard, P.L., D.L. Revell, D. Hoover, J. Warrick, J. Brocatus, A.E. Draut, P. Dartnell, E. Elias, N. Mustain, P.E. Hart, and H.F. Ryan 2009. "Coastal processes study of Santa Barbara and Ventura Counties, California." U.S. Geological Survey Open-File Report 2009-1029, 904 p.

Bromirski, P.D., R.E. Flick, and D.R. Cayan 2003. "Storminess variability along the California coast: 1858-2000." *J. Climate* 16, 982-993.

Bromirski, P.D., D.R. Cayan, and R.E. Flick 2005. "Wave spectral energy variability in the northeast Pacific." *J. Geophysical Res.* 110, C0300, 1-15.

CDIP 2008. Coastal Data Information Program, Scripps Institution of Oceanography.

Coastal Frontiers 2002. "SANDAG Regional Beach Monitoring Report." San Diego Association of Governments, 37 p.

Dolan, T., P. Castens, C. Sonu, and A. Egense 1987. "Review of sediment budget methodology: Oceanside littoral cell, California." In: Krauss, N.D., editor; *Proc. Coastal Sediments '87*, American Society of Civil Engineers, New Orleans, LA, 1289-1304.

Everts, C.H., and C.D. Eldon 2005. "Sand capture in southern California submarine canyons." *Shore & Beach* 73, 3-12.

Flick, R.E., 1993. "The myth and reality of southern California beaches." *Shore & Beach* 61, 3-13.

Flick, R.E., 1998. "Comparison of California tides, storm surges, and mean sea level during the El Niño winters of 1982-1983 and 1997-998." *Shore & Beach* 66, 7-11.

Graham, N.E., and H.F. Diaz 2001. "Evidence for intensification of north Pacific winter cyclones since 1948." *Bulletin of the American Meteorological Society* 82, 1869-1893.

Grandy, C., and G.B. Griggs 2009. "Natural and anthropogenic changes to beach sand supply in the Oceanside Littoral Cell, San Diego, California." *Shore & Beach* 77, 30-38.

Handin, J.W., 1951. "The source, transportation, and deposition of beach sediment in southern California." Technical Memorandum 22, Beach Erosion Board, U.S. Army Corps of Engineers, Washington, D.C., 113 p.

Hapke, D.J., D. Reid, and B. Richmond 2009. "Rates and trends of coastal change in California and the regional behavior of the beach and cliff systems." *J. Coastal Res.* 25, 603-615.

Inman, D.L., and S.A. Jenkins 1999. "Climate change and the episodicity of sediment flux of small California rivers." *J. Geology* 107, 251-270.

Kuhn, G.G., and F.P. Shepard 1984. *Sea cliffs, beaches, and coastal valleys of San Diego County: some amazing histories and horrifying implications*. University of California Press, Berkeley, 193 p.

Leidersdorf, C., R. Hollar, and G. Woodell 1994. "Human intervention with the beaches of Santa Monica Bay, California." *Shore & Beach* 63, 29-38.

Mantua, N.J., and S.R. Hare 2002. "The Pacific Decadal Oscillation." *J. Oceanography* 58, 35-44.

Mantua, N.J., 2007. "The Pacific Decadal Oscillation (PDO)," University of Washington. website: http://jisao.washington.edu/pdo/.

Moore, L.J., 2000. "Shoreline mapping techniques." *J. Coastal Res.* 16, 111-124.

Moore, L.J., P. Ruggiero, and J.H. List 2006. "Comparing Mean High Water and High Water Line shorelines: should proxy-datum offsets be incorporated in shoreline change analysis?" *J. Coastal Res.* 22, 894-905.

Morton, R.A., and F.M. Speed 1998. "Evaluation of shorelines and legal boundaries controlled by water levels on sandy beaches." *J. Coastal Res.* 18, 329-337.

NOAA 2007. National Oceanographic and Atmospheric Administration. Tides Online, Historic Tide Data website: http://tidesandcurrents.noaa.gov/.

Norris, R.M., and K. Patsch 2005. "Point Conception to Rincon Point." In: Griggs, G., Patsch, K., and Savoy, L. (eds.), *Living with the Changing California Coast*, University of California Press, Berkeley, 359-393.

Orme, A.R., 1982. "Temporal variability of a summer shorezone." In: Thorn, C.E. (ed.) *Space and Time in Geomorphology*. Allen & Unwin, London, 285-313.

Orme, A.R., 2000. "Evolution and historical development." In: Ambrose, R.F., Orme, A.R. (eds.), *Lower Malibu Creek and Lagoon Resource Enhancement and Management*. California State Coastal Conservancy, 1.1-1.37.

Orme, A.R., 2005. "Rincon Point to Santa Monica". In: Griggs, G., Patsch, K., and Savoy, L. (eds.), *Living with the Changing California Coast*, University of California Press, Berkeley, pp. 394-426.

Patsch, K.B., and G.B. Griggs 2006. "Littoral cells, sand budgets and beaches: understanding California's coastline." Report for California Coastal Sediment Management Workgroup, 37 p. (http://dbw.ca.gov/csmw/PDF/LittoralDrift.pdf)

Patsch, K.B., and G.B. Griggs 2007. "Development of sand budgets for California's major littoral cells." Report for California Coastal Sediment Management Workgroup, 111 p. (http://dbw.ca.gov/csmw/pdf/Sand_Budgets_Major_Littoral_Cells.pdf).

Patsch, K.B,. and G.B. Griggs 2008. "A sand budget for the Santa Barbara littoral cell, California." *Marine Geology* 252, 50-61.

Pawka, S.S., D.L. Inman, and R.T. Guza 1984. "Island sheltering of surface gravity waves: model and experiment." *Continental Shelf Research* 3(1), 35-53.

Revell, D.L., and G.B. Griggs 2006. "Beach width and climate oscillations along Isla Vista, Santa Barbara, California." *Shore & Beach* 74, 8-16.

Revell, D.L., P. Barnard, N. Mustain, and C.D. Storlazzi 2008. "Influence of harbor construction on downcoast morphological evolution: Santa Barbara, California." *Coastal Disasters '08.*

Ruggiero, P. G.M. Kaminsky, and G. Gelfenbaum 2003. "Linking proxy-based and datum-based shorelines on a high-energy coastline: implications for shoreline-change analyses." *J. Coastal Res.* 38, 57-82.

Runyan, K., and G.B. Griggs 2003. "The effects of armoring seacliffs on the natural sand supply to the beaches of California." *J. Coastal Res.* 19, 337-347.

Schwarz, K.M., and A.R. Orme 2005. "Opening and closure of a seasonal river mouth: the Malibu estuary-barrier-lagoon system, California." *Zietschrift für Geomorphologie* 141, 91-109.

Seymour, R.J., 1998. "Effects of El Niño on the west coast wave climate." *Shore & Beach* 66, 3-6.

Slagel, M.J., and G.B. Griggs 2008. "Cumulative losses of sand to the major littoral cells of California by impoundment behind coastal dams." *J. Coastal Res.* 252, 50-61.

Storlazzi, C.D., and G.B. Griggs 2000. "Influence of El Niño-Southern Oscillation (ENSO) events on the evolution of central California's shoreline." Geological Society of America Bulletin 112, 236-249.

Thieler, E.R., E.A. Himmelstoss, J.L. Zichichi, and T.L. Miller 2005. "Digital Shoreline Analysis System (DSAS), Version 3.0." United States Geological Survey Open-File Report 2005-1304.

USACE 1987. "Coastal cliff sediments, San Diego region, Dana Point to the Mexican border." United States Corps of Engineers, Los Angeles, California, 242 p.

USACE 1991. "Coast of California: storm and tidal waves study: south coast region, San Diego region." U.S. Army Corps of Engineers, Los Angeles, California, 785 p.

USACE 2002. "Coast of California: storm and tidal waves study: south coast region, Orange County." U.S. Army Corps of Engineers, Los Angeles, California, 452 p.

USGS 2006. United States Geological Survey, Digital Orthophoto Quadrangles website: http://edc.usgs.gov/products/aerial/doq.html.

Warrick, J.A., and D.M. Rubin 2007. "Suspended sediment rating curve response to urbanization and wildfire, Santa Ana River, California." *J. Geophysical Res.* 112, F02018.

Wiegel, R.L., 1994. "Ocean beach nourishment on the USA Pacific coast." *Shore & Beach* 62, 11-36.

Willis, C.M., and G.B. Griggs 2003. "Reductions in fluvial sediment discharge by coastal dams in California and implications for beach sustainability." *J. Geology* 111, 167-182.

Zoulas, J.G., 2005. "Long-term beach behavior in the Zuma littoral cell, southern California." University of California, Los Angeles, M.A. thesis. 104 p.

Zoulas, J.G., 2008. "Beach changes in the San Pedro littoral cell, southern California, 1930-2007." Ph.D. Dissertation, University of California, Los Angeles, 162 p.

Zoulas, J.G., and A.R. Orme 2007. "Multidecadal-scale beach changes in the Zuma littoral cell, California." *Physical Geography* 28, 277-300.

Beach widths, cliff slopes, and artificial nourishment along the California Coast

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ABSTRACT

Wide beaches provide a buffer that can prevent wave run-up and storm surges from reaching back beach areas, whether dunes, cliffs or bluffs. The dissipative role of beaches is especially important on cliffed coastlines where cliff or bluff retreat is an irreversible natural process that can lead to the destruction of cliff top development. Because changes in bluff morphology are process-linked, cliff slope is generally indicative of the relative importance of marine and terrestrial erosional processes. Steep cliffs are usually reliable indicators of the dominance of marine erosion, and their presence provides evidence for the lack of a permanent protective beach. While beach nourishment in California has historically been primarily opportunistic and the by-product of a coastal dredging or construction project, two recent projects in San Diego County (RBSP I and II) were the first large-scale efforts where sand was added to the shoreline from offshore sources for the sole purpose of widening the beaches for both protecting back beach development and increasing recreational opportunities. Every stretch of shoreline has some equilibrium beach width; however, that is a function primarily of 1) the wave climate, 2) coastline configuration, 3) presence of natural barriers to littoral drift, and 4) sediment supply. Overall, the sand added to the relatively narrow San Diego County beaches had a very short life span on the exposed subaerial beach. In a region with relatively high littoral drift rates, and particularly for shorelines fronting steep cliffs, which historically have not had wide beaches, without either repeated nourishment or the construction of retention structures, there is no reason why artificially added sand should widen and remain on subaerial beaches for any extended period of time.

Keywords?

R&A dates?

Nearly two-thirds (~60%) or a little over 1000 km of California's coastline consists of bluffs or low cliffs <100 m high, often fronted by beaches of varying widths (Griggs 2010). Sandy beaches provide important buffer zones between marine and terrestrial environments as well as important recreational areas. While unaltered beaches tend to have some long-term equilibrium width, they also fluctuate naturally due to seasonal changes in wave energy and tidal variations, but also in response to variations in sediment input and littoral transport gradients (Hayes and Boothroyed 1969; Komar 1998; Nordstrom 2000). Humans have altered the supply and movement of sand on California beaches; however, both through the construction of dams on coastal rivers and also the emplacement of littoral barriers that trap sand and create artificially widened beaches upcoast, but may also produce sand deficits downcoast.

There is generally a close correlation between beach width and cliff or bluff steepness along California's coast. Where beaches are very narrow or only present seasonally, marine erosion dominates the process of cliff formation, producing steep profiles. Where beaches are very wide, waves rarely reach the back beach area and bluff and cliff evolution tend to be dominated by terrestrial processes, which produce more gentle slopes (Kinsman 2011).

Human impacts on sand delivery to and transport along the shoreline, major storm events associated with a recent warm phase of the Pacific Decadal Oscillation (PDO), short-term increases in local sea level, as well as a gradually rising global sea level, have combined to inflict significant damage on private development and public infrastructure along the California coastline in recent decades. While coastal armor, whether revetments or seawalls, has historically been the most common response to coastal cliff or bluff erosion, concerns regarding potential impacts of protection structures on beaches (Griggs 2005) have led to a significant reduction in permit approval for new armor.

Artificial beach nourishment has long been a common practice along the low-relief, typically barrier island-backed Atlantic coast for mitigating shoreline retreat and beach loss. Until recently this was not the case for California, where almost all beach nourishment was a by-product of large coastal construction and dredging projects (Flick 1993 and Wiegel 1994). Two major beach nourishment projects have recently been carried out in San Diego County (Regional Beach Sand Project I and II or RBSP I & II), which were intensively monitored and provide insight and lessons regarding this approach on California's coast, which differs in many fundamental ways from the Atlantic coast. While additional proposals for large-scale and long-term beach nourishment projects have been proposed and continue to move forward in the planning process in California, the ability of nourished beaches to effectively buffer bluff and cliff backed coastlines from marine erosion for extended periods of time has not been critically evaluated or fully quantified.

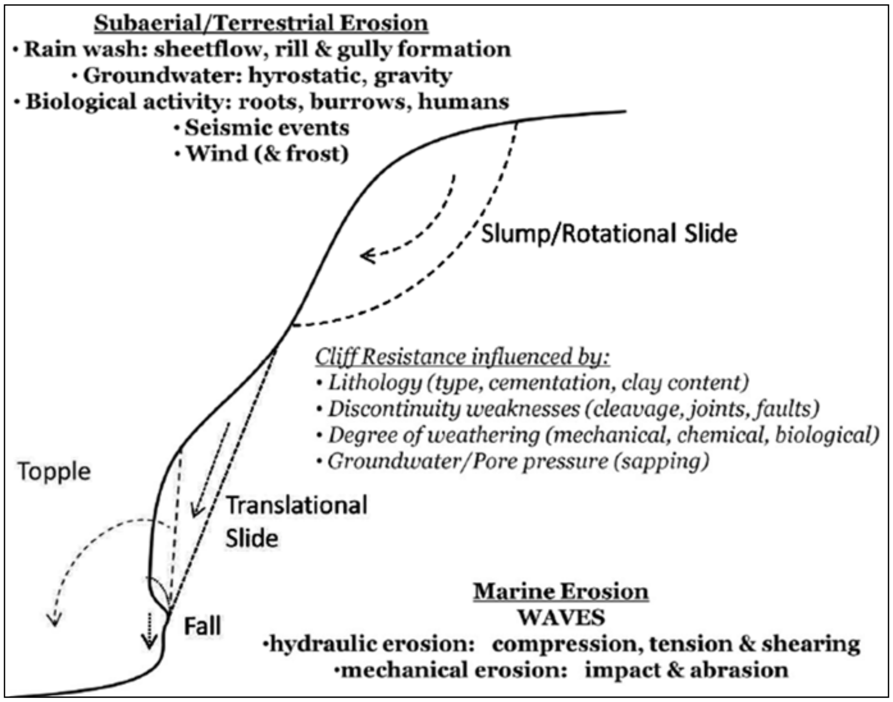
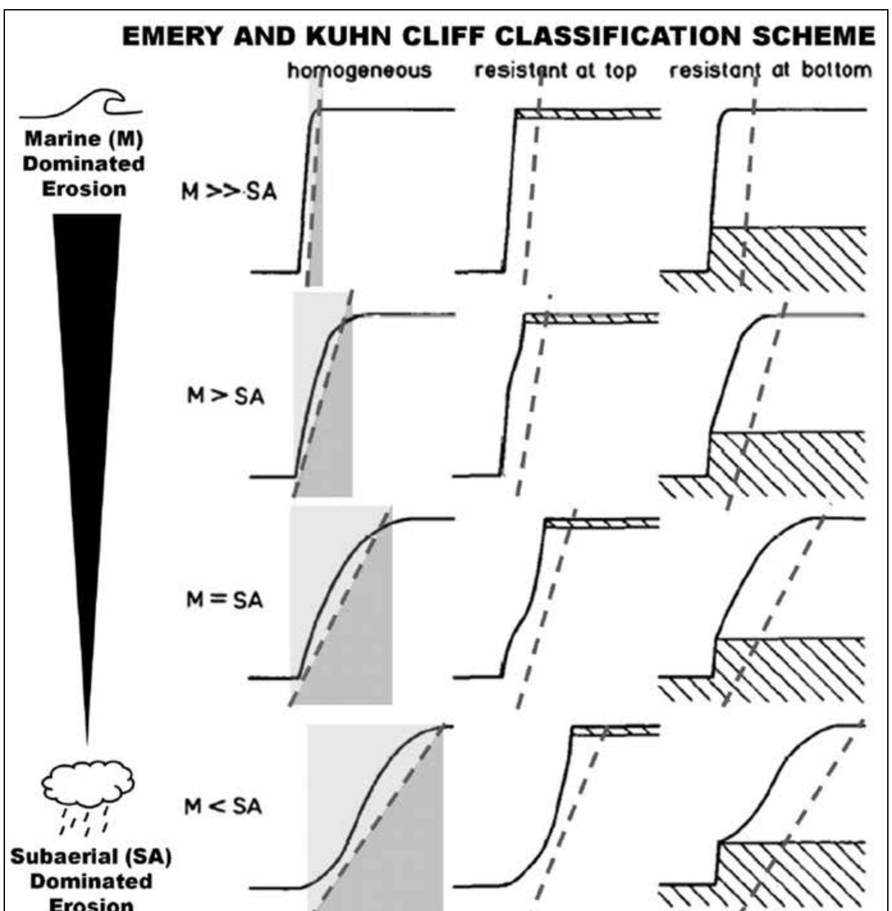


Figure 1. Illustration of typical failure modes in coastal cliffs, the subaerial and marine forces that drive them and the inherent properties of the cliff material which contribute to resisting erosion.

Figure 2. Idealized active sea cliff profiles formed by varying degrees of marine (M) and subaerial (SA) erosional processes, as described and illustrated by Emery and Kuhn (1982). The original Emery and Kuhn figure has been modified to illustrate how the cliff slopes (in dashed line) decrease as relative marine erosion decreases.



COASTAL CLIFF EVOLUTION AND MORPHOLOGY

Both marine and terrestrial processes shape coastal cliffs and bluffs, with spatial variation arising from differences in both *intrinsic* and *extrinsic* factors (Benumof and Griggs 1999; Figure 1). Intrinsic factors are those inherent to the materials making up the cliff (lithology and intact rock strength; joint orientation, spacing, and width; rock weathering, and groundwater seepage, being the major parameters). Extrinsic factors are those external processes acting on the sea cliff, whether marine or terrestrial, which drive erosion (rainfall and runoff, mass wasting, wave attack, tidal range, for example), which lead to cliff degradation and retreat.

Emery and Kuhn (1982) described coastal cliff profiles in terms of the relative importance of marine and subaerial erosion imposed upon preexisting geology (Figure 2). Within this classification scheme, cliff slopes recline as marine erosional processes diminish in importance relative to terrestrial processes. Coastal steepening is initiated when wave action undercuts the base of the cliff or bluff, leading to failure of the overlying materials, and also removes protective talus from the cliff toe. The amount of basal steepening and/or notching of coastal cliffs is controlled by the intensity, frequency and duration of exposure to marine energy (Sunamura 1977; Sallenger *et al.* 2002; Carter and Guy 1988; Benumof *et al.* 2000; Ruggiero *et al.* 2001), as well as the stratigraphy and structure (joint orientation and spacing) of the bluff materials.

Where wide beaches exist and cliffs or bluffs are exposed to weaker, less frequent and shorter periods of wave attack, subaerial weathering and erosional processes will increasingly prevail. This results in the gradual decline of cliff slopes as the backshore matures in a terrestrially dominated environment buffered from direct wave attack (Hampton *et al.* 2004; Trenhaile 1987). This terrestrial cliff denudation is the result of surface runoff, groundwater seepage and diffusive hill-slope processes, including rain splash, soil creep, and mass wasting such as landslides and slumps (Carson and Kirkby 1972; Selby 1993).

Beach width is widely accepted as one of the primary controls on the amount of marine erosional energy able to act upon

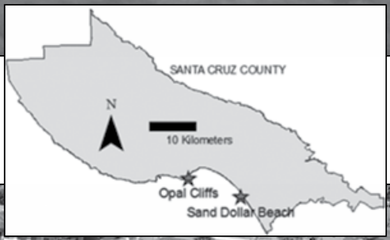


Figure 3. Oblique aerial photographs taken at two locations in Santa Cruz County, October 2013 (Adelman and Adelman 2009). The wider beach at Sand Dollar Beach (a) is backed by a more gradually sloping bluff than the narrow beach at Opal Cliffs, which is backed by a near vertical cliff (b).

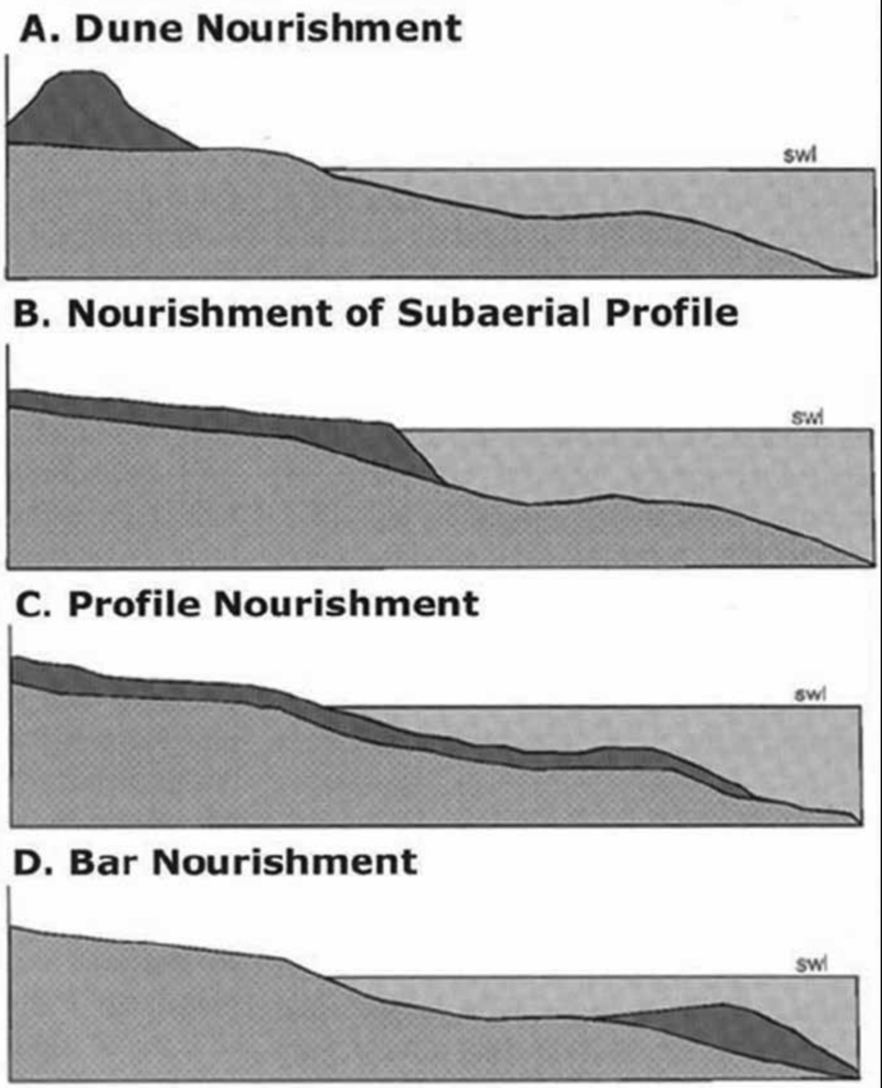


Figure 4. Methods of beach nourishment defined on the basis of where the fill materials are placed (from Finkl, Benedet, and Campbell 2006). (a) Dune nourishment: Sand is placed in a dune system behind the beach. (b) Nourishment of subaerial beach: Sand is placed onshore to build a wider and higher berm above mean water level. (c) Profile nourishment: Sand is distributed across the entire beach and nearshore profile. (d) Bar or nearshore nourishment: Sediments are placed offshore to form an artificial feeder bar.

backshore morphology. The presence of a wide sandy beach reduces the total number of wave inundation hours during a normal tidal cycle or during extreme storm events. This typically translates into a decline in rates of sea cliff retreat (Sallenger *et al.* 2002; Brunsden and Lee 2004; Giese and Aubrey 1987). Recent work by Hapke *et al.* (2006, 2009) has demonstrated a strong positive correlation between rates of shoreline position change in low- to moderate-height cliffed areas and long-term cliff retreat rates. Additionally, Cruz de Oliveira *et al.* (2008) have documented a decline in decadal cliff retreat rates along the coastline of Portugal subsequent to artificial beach nourishment projects. These documented retreat rates combined with the patterns of denudation illustrated in Figure 2, leads to the concept that cliff slopes are inversely correlated with beach width. This is supported by the observation that gently sloped cliffs are commonly observed backing wide beaches, while steep or near vertical slopes frequently back narrow beaches or shorelines without beaches throughout California (Figure 3).

BEACH NOURISHMENT AS A RESPONSE TO SHORELINE EROSION

Beach nourishment is the placement of sand on the shoreline with the intent of widening beaches that are naturally narrow, or building beaches where none existed or where the natural supply of sand has been significantly reduced through human activities. The general expectation, realistic or not, by those in support of a typical beach nourishment project is that the added sediment will not just increase the net volume of the shoreface but that this sediment will widen the visible, subaerial portion of the beach. Although there are several different approaches to beach nourishment, procedures are generally distinguished by methods of fill placement, design strategies, and fill densities (Figure 4; Finkl *et al.* 2006; NRC 1995; Dean 2002).

Nourished shorelines provide two primary benefits: increased beach area for recreation and greater protection of the coastline (whether beaches, dunes, bluffs or cliffs) against coastal storms and wave attack. Large-scale beach nourishment has been employed for decades along the low relief, typically barrier island-backed sandy shorelines of the Atlantic coast of the United States (in particular New Jersey, New York, and Florida). The total volume of sand dredged from offshore and channel maintenance sources and placed on New York beaches since the 1930s is around 80 x 10^6 m^3 (Finkl *et al.* 2006). For New Jersey beaches, the volume of added sand totals about 60 x 10^6 m^3. Florida beaches on both Gulf and Atlantic coasts have benefited from a combined 80 individual nourishment projects since the 1940s totaling about 103 x 10^6 m^3 of sand (Finkl *et al.* 2006). Delaware, Maryland, Virginia, the Carolinas and Georgia have received an additional 89 x 10^6 m^3 of sand, for a total since the 1930s from Delaware to Florida of about 332 x 10^6 m^3 of sand. This volume is difficult to visualize, but it would build a beach 50 m wide, 3 m deep, and 2,200 km long, or a beach extending all the way down the Atlantic coast from Maine well into South Carolina.

Beach nourishment in California has been much more limited and has been concentrated primarily in the southern part of the state. Flick (1993) summarized the history of beach nourishment in southern California and determined that over 100 x 10^6 m^3 of sand were added to those beaches between 1930 and 1993. About half of this amount was divided evenly between the Santa Monica and

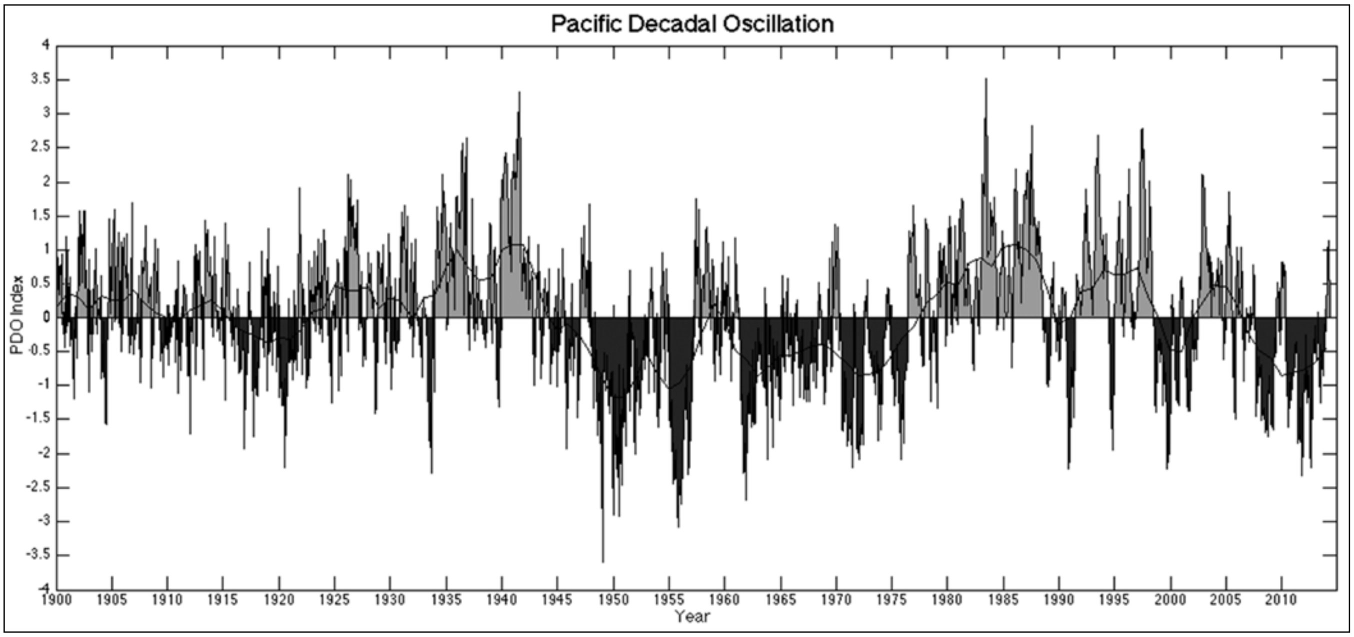


Figure 5. Pacific Decadal Oscillation cycles with positive or warm periods in light gray, and negative or cool cycles in dark gray. Vertical axis is sea surface temperature anomalies or departure from the mean in the Pacific Ocean in degrees C.

the Silver Strand littoral cells where the beaches widened significantly in response to this nourishment. Wiegel (1994) prepared a detailed evaluation of ocean beach nourishment along the entire USA Pacific Coast.

There are major differences between the tectonic, geomorphic, oceanographic, climatic, and wave conditions along the Pacific Coast as compared to the Atlantic and Gulf Coasts. In addition to these inherent geological and oceanographic differences, there is a pronounced difference in the practice of beach nourishment (Finkl *et al.* 2006). Large nourishment projects using sand from offshore are common along the Atlantic and Gulf Coasts, but beneficial or opportunistic sediment (from coastal construction, channel maintenance and bypass operations) predominate on the West Coast (Flick 1993; Wiegel 1994). The sand placed on California beaches for much of the state's history has been primarily a by-product of construction or maintenance projects that were not undertaken with beach replenishment or nourishment as a specific goal, but rather as an added benefit.

CHANGES IN CALIFORNIA'S COASTAL CLIMATE

Increased storm damage and erosion

In 1978, the large-scale climatic regime in the Pacific (the Pacific Decadal Oscillation or PDO; Mantua *et al.* 1997; Figure 5) that is now understood to alter California's coastal storm climate, sea level and precipitation, shifted to a warm or positive phase, which continued until about 1998. During this approximately 20-year period, several large and damaging ENSO (El Niño-Southern Oscillation) events, notably 1978, 1982-1983 and 1997-1998, impacted the California coast and brought elevated sea levels, heavy rainfall, and large storm waves from the southwest (Flick 1998; Storlazzi and Griggs 1998, 2000). These events generated widespread coastal flooding of low-lying areas, accelerated retreat of coastal cliffs, bluffs and dunes, and caused significant damage to oceanfront development and infrastructure (Griggs and Brown 1998).

Damage in the 1978 ENSO event reached $64 million (in 2014 dollars), which was surpassed by the 1982-1983 event, the largest in half a century, with damages totaling about $235 million. Fifteen years later, the 1997-1998 El Niño again had major impacts although far more properties were now armored so damages were reduced. Peak high tides were also lower in 1997-1998 and there was less coincidence of high tides with storm waves, which also reduced coastal damage (Flick 1998). The preceding period from about 1945 to 1978, in contrast, was a cooler or negative PDO interval, with overall less rainfall, fewer large coastal storms and damaging waves. This was precisely the time when most of California's oceanfront development took place, during a calm and less stormy period.

This was also the time period when opportunistic beach nourishment rates were highest along many developing areas of the southern California shoreline (Flick 1993), which may have influenced the development of many oceanfront properties.

Following World War II, California's population grew rapidly, doubling between 1944 and 1964. Coastal land was subdivided as homes, apartments, and businesses were built on the cliffs, bluffs, dunes, and back beaches. The 1978 El Niño was an abrupt awakening and the conditions it introduced were to last intermittently for the next 20 years. During the 1982-1983 winter, 33 oceanfront homes were completely destroyed, and 3,000 homes and 900 businesses were damaged. Public recreational facilities along the shoreline suffered about $80 million in damage (2014 dollars; Griggs *et al.* 1992). Many older coastal protection structures were damaged or destroyed (Fulton-Bennett and Griggs 1986; Griggs and Fulton-Bennett 1988), and many coastal homeowners realized that without some type of protection they were at risk of future storm damage. The California Coastal Commission, the statewide permitting agency for coastal development, was subsequently inundated with applications for permits for new seawalls and riprap revetments. In the 33 years

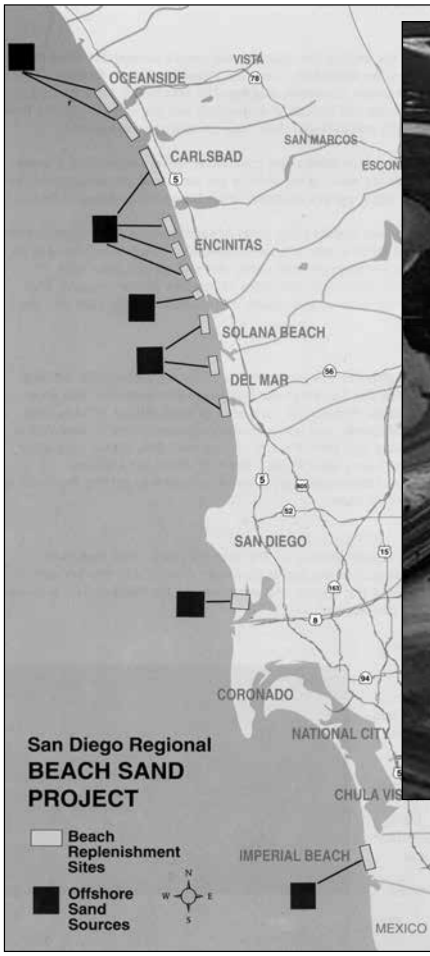


Figure 6.(left) Offshore sites where sand was dredged and beaches where sand was discharged during RBSP I.

Figure 7 (above). Beach fill at Torrey Pines during RBSP I (from Seymour *et.al* 2005).

between 1971 and 2004, the amount of California's outer exposed coast armored increased about 400 percent, from just 27 miles in 1971 to 110 miles in 2004 (California Dept. of Boating and Waterways and State Coastal Conservancy 2002; Griggs 2005).

While many emergency and new permits for armor were approved during this warm and stormier PDO period, the progressive increase in the amount of California shoreline armoring led to concerns regarding the potential future impacts of seawalls and revetments on the state's beaches. By 2000, 10% of the entire coastline of California had been armored. Not surprisingly, for the more densely developed southern California coastline, 34% of the 375 km shoreline of the four southernmost counties (Ventura, Los Angeles, Orange and San Diego) had been armored (Griggs *et al.* 2005)

While armoring had been the most common solution for eroding coastlines along much of the U.S. coastline for half a century, surprisingly, there had been no field work or surveys carried out over time to document any impacts of these structures. For the first time, repeated field surveys were initiated to document just what effects seawalls had on the shoreline (Tait and Griggs 1990; Griggs *et al.* 1997; Basco *et al.* 1997) and a set of potential effects were recognized (which include placement losses, passive erosion, potential loss of sand from previously eroding bluffs, reduction or loss of shoreline access, and visual impacts; Griggs [2005]). The potential impacts of additional armoring combined with the concerns for future coastal storm damage and erosion, as well as beach losses along the urbanized and intensively used southern California coastline, led to a proposal in San Diego County to use beach nourishment to mitigate coastal and shoreline erosion.

THE REGIONAL BEACH SAND PROJECTS I AND II

Regional Beach Sand Project I (RBSP I)

The most recent large-scale, non-opportunistic, beach nourishment project in California with the sole purpose of widening beaches was completed in San Diego County in 2001 (summarized in Patsch and Griggs 2007). There have been two significant earlier non-opportunistic beach fill projects in southern California as well. In 1968-1969, a little over 1 million m^3 of sand from offshore was placed in the Malaga Cove area adjacent to the Palos Verdes Peninsula in order to widen that beach. Between 1979 and 1990 about 3.8 million m^3 of sand dredged from offshore was placed on the Surfside-Sunset beach area (Wiegel 1994).

In the first San Diego project (RBSP I), approximately 1.6 million m^3 of sand were dredged from six offshore sites and placed on 12 beaches at a total cost of \$17.5 million dollars or \$11.67/m^3 (Figure 6). This project was coordinated by local governments working together through SANDAG (San Diego Association of Governments, an intergovernmental agency), and was funded by \$16 million in state and federal funds and about \$1.5 million from the region's coastal cities. It was seen as an initial step in overcoming what had been perceived as a severe sand deficit on the region's beaches. Sand being delivered by the region's streams has been significantly reduced from dam construction (Brownlie and Taylor 1981). Large storm events also appear to have moved littoral sand far enough offshore to hinder its return.

A total of 10 km of beaches were nourished from Oceanside in the north to Imperial Beach in the south. Eighty-five percent of the sand went to the beaches (between Oceanside and Del Mar-Figure 6), in the Oceanside Littoral Cell. It is notable that a comprehensive regional beach-profiling program had been in place since the 1983 El Niño event, which provided a baseline for monitoring the results or status of many of the individual nourished sites (Coastal Frontiers, 2005).

While it is difficult to summarize the vast amount of beach survey data that were collected here, if we are to derive any useful conclusions from this large, essentially first of its kind project along the west coast, it is important to try and extract some overall measures of performance or behavior following sand placement.

Along 17 surveyed transects from the 12 nourishment sites, the beach width (determined by the mean sea level shoreline position) narrowed significantly between the fall of 2001 (immediately following sand placement) and the fall of 2002, which was probably to be expected as the nourished sand was placed on the subaerial profile. While the surveyed beaches showed initial increases in width of 8 to over 30m following nourishment, most of these beaches narrowed 6 to 18m during the first year following sand emplacement. Twelve of the 17 sites showed further decreases in width over year two, and 13 of these sites continued to decrease in width in the third year.

A detailed study of the Torrey Pines State Beach fill project was carried out as part of the post-nourishment monitoring (Seymour *et al.* 2005). This fill was nearly 500 m long and included about 250,000 m^3 of sand, one of the larger fills. The fill was completed near the end of April 2001 (Figure 7). Wave conditions during the summer and fall were mild, with significant wave heights generally less than 1 meter.

At noon on 22 November 2001, significant wave heights reached 3 m and remained in the range of 2.8 to 3.2 m for seven hours. The fill was overtopped and began to erode quickly. By the next morning, the fill had been almost completely eroded to the riprap at the back of the beach (Seymour *et al.* 2005). The fill was stable for approximately seven months of low wave energy conditions, but was removed from the subaerial beach within a day when the first large waves of the winter arrived, suggesting that there may have been a significant sand deficit extending across the entire beach profile and offshore.

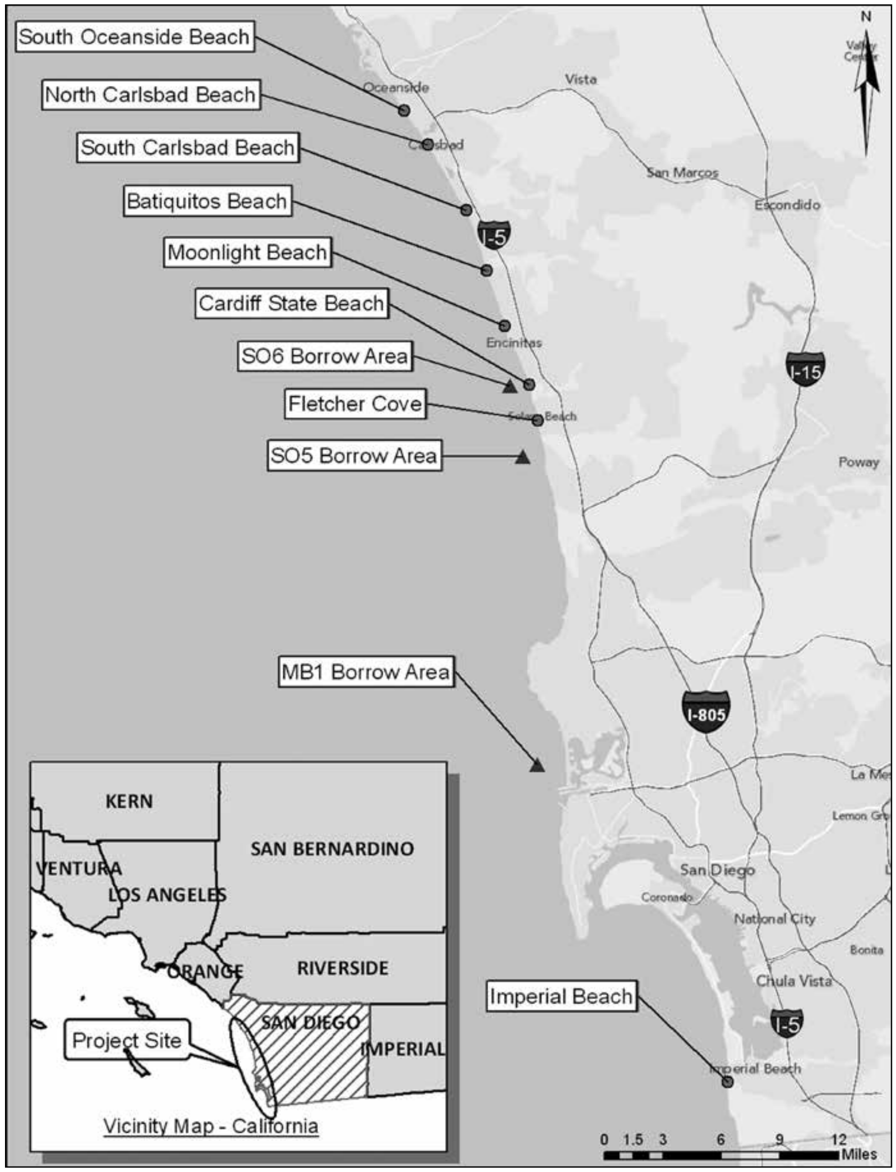


Figure 8. RBSP II showing offshore borrow areas and beaches where sand was placed.

Some overall conclusions can be drawn from the four years of published beach surveys in the nourished areas (Coastal Frontiers 2005). The performance of the individual beach fills varied considerably. At some sites, the gains that occurred during placement of fill were short-lived, at least on the subaerial beach. At other sites, the gains in the *shorezone* (defined as the subaerial or exposed portion of the beach as well as the nearshore sand out to the seasonal depth of closure) persisted through the time of the fall 2004 survey. Both the grain size of the sand and the volume of the fill were important factors in how long nourished sand remained on the subaerial beach, with finer-grained sand having a shorter retention time.

Nearly all of the sand added to the beaches in the RBSP I tended to move both offshore and also down coast with the arrival of winter waves. Much of the sand in this nourishment project was placed at the northerly or updrift portion of the Oceanside Cell because of the anticipation of southerly transport, so losses to downcoast areas was not unexpected. The offshore sand did provide some local benefits including the formation of bars that dispersed some of the storm wave energy and flattening of the beach profile, as well as positive downcoast contributions to the littoral sediment budget.

These expectations or outcomes raise a very important question: Do the local government agencies, the visitor-serving businesses that depend upon wide healthy beaches, the bluff-top property owners, and the general beach-going public expect to see a wider, exposed, subaerial beach as the benefit of a beach nourishment project? If so, then the transport of sand from the exposed usable beach to the offshore *shorezone*, while perhaps considered a success by the project planners and engineers because of its role in reducing wave energy at the shoreline, is likely going to be perceived as a failure by the users.

Regional Beach Sand Project II (RBSP II)

Eleven years later, between September and December 2012, RBSP II was completed, which added 1.16 million m^3 of sand dredged from three offshore sites to eight San Diego County beaches, again from Oceanside in the north to Imperial Beach in the south (Figure 8). Total cost was \$28.5 million or \$25/ m^3, just over twice as costly per cubic meter as the 2001 project. Nourishment quantities ranged from 68,000 m^3 at Cardiff to 342,000 m^3 at Imperial Beach.

Again, to the credit of the project planners and engineers, extensive beach monitoring began in December 2012, within a month of fill placement, and has been continued and reported until October of 2013 (Coastal Frontiers, 2013). The average shoreline position of mean sea level (MSL) is one of the primary indicators plotted in the monitoring reports, along with the total volume of sand in the shorezone. Overall, beach fill performance was very similar to RBSP I.

During the first year of monitoring, MSL shoreline and shorezone volume losses prevailed in the Silver Strand Cell, where the largest volume of sand was placed. A profile in the middle of the surveyed area selected "*to characterize the site*" indicates that the position of MSL was extended 49 m seaward during the nourishment process. During the 2013 monitoring year (which began in December 2012, one month after fill placement, and continued to October 2013) the sand placed at Imperial Beach on this profile nearly completely dispersed as evidenced by a major declines in both the position of MSL shoreline (44 m of retreat) and shorezone volume (Coastal Frontiers 2013). The average of all Silver Strand profiles for October 2013, nearly a year after 342,000 m^3 of sand nourishment, indicated that MSL position had retreated landward 9.5 meters.

Table 1.
Summary of beach survey results from bluff or cliff-backed beaches following nourishment during RBSP II (from Coastal Frontiers 2013).

Nourishment site	Change in position of outer edge of berm: November 2012 to December 2012	December 2012 to May 2013	Total November 2012 to May 2013
Solana Beach	- 18m (-58ft)	-18m (-58ft)	-36m (-116ft)
Moonlight Beach	-20m (-67ft)	-20m (-67ft)	-40.8m (-134ft)
Batiquitos	-30.6m (-100ft)	-33.6m (-110ft)	-64.2m (-210ft)

In the Mission Beach Cell, where there was no sand added in RBSP II, the shoreline position and shorezone volume were fairly stable during the 2013 monitoring year. The average of all profiles for October 2013 indicated that MSL position had advanced 1.3 meters (Coastal Frontiers 2013).

Changes also were modest in the Oceanside Cell, where approximately 822,000 m^3 of sand were added at seven sites. Averaging all of the surveyed profiles on these beaches indicates a very slight or negligible shoreline advance of two meters (Coastal Frontiers 2013).

Comparing specifically those "*characteristic*" profiles included in the monitoring report for nourishment sites that fronted higher bluffs or cliffs (Solana Beach, Moonlight Beach, and Batiquitos), very similar results are evident at each site (Coastal Frontiers 2013). Measuring the position of the outer edge of the berm, which defines the usable part of the beach from the public's perspective (rather than MSL position), each of these three sites experienced a nearly complete loss of the added sand within the first six months of monitoring (Table 1).

LESSONS LEARNED REGARDING BEACH NOURISHMENT IN CALIFORNIA

Some important conclusions can be drawn from the RBSP I and II projects, which placed a total of 2,600,000 m^3 on San Diego County beaches at a cost of \$36 million.

Most natural California beaches have some normal or equilibrium width, which is a function primarily of: 1) the average or typical wave climate, including direction of wave approach, wave height and length; 2) coastline configuration and the presence of embayments or bays where sand can collect; 3) littoral sand input or supply; and 4) natural barriers to littoral drift, such as headlands or points, stream deltas, or offshore reefs or rock outcrops. These transport barriers maintain beaches through refraction as waves enter shallow water, and thus the rate at which sand moves along the coast, and/or they alter the sand transport pathways. The dimensions, orientation, and location of barriers to littoral drift control the configuration and position of the beaches they retain (Everts Coastal 2002).

Without either regular or repeated nourishment or the construction of a retention structure, such as a groin or groin field, to stabilize or hold a beach fill, there is no reason why in an area with narrow beaches, a significant littoral drift rate, and a moderate to strong winter wave climate, that any nourished sand should stay on an exposed beach and widen it for any extended period of time. The considerations that need to be weighed prior to any beach nourishment project are whether the benefits of littoral cell or shorezone sand volume increases, and the potentially short-term or temporary subaerial beach width increases resulting from beach nourishment are worth the initial public investment and continuing costs. However, the public is not typically educated about differences in nourishment outcomes and cost benefit analyses are not adequately conducted prior to embarking on a nourishment project. In part this is because many political leaders and interest groups who depend on wide beaches will generally be supportive of any project that will put more sand on beaches, and because there is little understanding regarding how long the nourished beach will actually last. It is important that for a beach nourish-

Figure 9. Steep bluffs (armored on left side of photo with concrete) in the Solana Beach area (2008; Kenneth and Gabrielle Adelman, California Coastal Records Project, www.californiacoastline.org).

Figure 10. Steep bluffs at Moonlight Beach (2010; www.californiacoastline.org).

ment project on a high-energy beach to be deemed successful by *both* the engineers and general public, that these conversations about shoreface dynamics, re-nourishment requirements, and justified cost:benefit are held at the planning phase so that expectations are appropriate to the coastal setting of the project.

Most of the 2,600,000 m^3 sand added to the beaches of San Diego County during RBSP I and II was essentially eroded from the exposed subaerial beach during the first year following nourishment. Much of the sand placed in front of the eroding bluffs at Solana, Moonlight, and Batiquitos beaches during RBSP II, was gone from the beach within the first six months, not even lasting until the first summer beach season.

While there are bluff-top residents or homeowners in these areas who state that they formerly had wide beaches that are now gone, and that beach nourishment or replenishment is therefore necessary to return their beaches to their original condition, the evidence from the bluff configuration as well as the historic record from aerial photographs suggest that any wider beaches were the anomaly (Orme *et al.* 2011, Grandy and Griggs 2009).

As first recognized by Emery and Kuhn (1982) more than 30 years ago, the configuration of coastal bluffs provides a long-term record of the relative importance of marine and terrestrial processes in the maintenance of bluffs at any particular location. Vertical, near vertical or very steep bluffs provide strong evidence for regular wave attack and the dominance of marine erosion (Figures 3b and 9-11), and therefore, the absence of wide, protective or year round beaches. More gently sloping bluffs (Figures 3a and 12) are indicative of the dominance of terrestrial erosional processes such as runoff, gullying, slumping and other forms of mass wasting, which characterize areas with wide beaches that prevent waves from routinely reaching the base of the bluffs. There are intermediaries between these two end member conditions and the bluffs at South Carlsbad are a good example (Figure 11), where there is a steep, bedrock, basal portion of the bluff, which is overlain by a more gently sloping area of weaker terrace deposits and soils, where erosion has been dominated by terrestrial processes. The steep lower bluff, however, is consistent with the narrow beach and erosion dominated by marine erosion. The sand added to this beach in November 2012 was virtually gone by May 2013.

A long-term analysis of beach widths in the Oceanside Cell has been carried out and described by Chenault (2007) and Orme *et al.* (2011) using only orthorectified aerial photographs taken between late summer and early autumn when beaches are usually widest and most stable. While beach widths fluctuated between 1946 and 2001, they showed no net erosion or accretion trends, nor any longer-term correlations with ENSO or PDO climate cycles, although they did respond to major storm events (Orme *et al.* 2011).

In contrast to the modest effects of natural events, human activities had a major impact on beach widths in the cell. Dams and sea cliff armoring both restricted sediment delivery to the shoreline, while artificial nourishment produced rapid changes in beach widths, which far exceeded normal ranges. Between 1942 and 2002, nourishment projects added more than 21 million m^3 of sediment (of unknown grain size) to the beaches of the Oceanside Cell, an average of 350,000 m^3/yr. (USACE, 1987, 1991; Flick 1993; Wiegel 1994; Coastal Frontiers 2002). However, no nourished beaches in the cell remained wide in subsequent years and no nourishment projects significantly benefited downcoast subaerial beaches. In short, nourishment has had a marked but transient impact on beaches of the Oceanside littoral cell, which need large floods or repeated nourishment and some form of sand retention to maintain their widths (Orme *et al.* 2011; Grandy and Griggs 2009).

Along the California coast, steep cliffs are generally reliable indicators of the dominance of wave erosion over terrestrial erosional processes, and their presence provides natural evidence for the lack of a permanent protective beach. With this in mind, it has become clear that sand added to the shoreline in areas of steep cliffs, such as in the Oceanside Cell, cannot be expected to remain and provide either greater cliff protection or recreational area for any significant period of time. Repeated beach width and shore zone surveys following RBSP I and II nourishment projects have further demonstrated the transient nature of nourished sand fronting a cliffed coastline.

Figure 11. Steep bluffs at Batiquitos nourishment site (2008; www.californiacoastline.org).

Figure 12. Gently sloping bluffs and wide beach (Manresa State Beach, Santa Cruz County; 2013; www.californiacoastline.org).

REFERENCES

Adelman, G. and K. Adelman 2009. *California Coastal Records Project, Aerial Photographs of the California Coastline*. http://www.californiacoastline.org

Basco, D.R., D.A. Bellomo, J.M. Hazleton, and B.N. Jones 1997. *Influence of seawalls on subaerial beach volumes with receding shorelines.* Contract Report CHL-97-2, U.S. Army Corps of Engineers, Washington, D.C., 47 p.

Benumof, B.T., and G.B. Griggs 1999. "The dependence of seacliff erosion rates on cliff material properties and physical processes, San Diego, California." *Shore & Beach,* 67:4: 29-41.

Benumof, B., C. Storlazzi, R. Seymour, and G. Griggs 2000. "The relationship between incident wave energy and seacliff erosion rates: San Diego County, California." *J. Coastal Res.,* 16:1162-1178.

Brownlie, W.R., and B.D. Taylor 1981. "Sediment Management for Southern California mountains, coastal plains and shoreline, Part C. Coastal sediment delivery by major rivers in Southern California." California Institute of Technology, Environmental Quality Laboratory, EQL Report No. 17C, 314 p.

Brunsden, D., and E. Lee 2004. "Behavior of coastal landslide systems: an interdisciplinary view." *Seischrift für Geomorphologie* 134:101-112.

California Dept. of Boating and Waterways and State Coastal Conservancy 2002. "California Beach Restoration Study." Sacramento, California.

Carson, M., and M. Kirkby 1972. *Hillslope Form and Process.* Cambridge University Press, 483 p.

Carter, C., and D. Guy 1988. "Coastal erosion: processes, timing, and magnitude at the cliff toe." *Marine Geology,* 84:1-17.

Chenault, C.D., 2007. *Understanding long-term beach width change in the Oceanside littoral cell, California.* Unpublished Ph.D. dissertation, Earth Sciences Dept., University of California Santa Cruz, 165 p.

Coastal Frontiers 2013. *SANDAG 2013 Regional Beach Monitoring Program Annual Report (Draft)*, 119 p.

Coastal Frontiers 2005. *SANDAG 2004 Regional beach monitoring program: Annual Report and Appendices*.

Coastal Frontiers 2002. *State of the Coast Report. SANDAG Regional Beach Monitoring Program,* 44 p.

Cruz de Oliveira, S., J. Catalaño, O. Ferreira, and J. M. Alveirinho Dias 2008. "Evaluation of Cliff Retreat and Beach Nourishment in Southern Portugal Using Photogrammetric Techniques." *J. Coastal Res.,* 24(4):184–193.

Dean, R.G., 2002. *Beach nourishment: Theory and practice*. River Edge, New Jersey, World Scientific, 397 p.

Emery, K., and G. Kuhn 1982. "Sea cliffs: Their processes, profiles and classification." *Geological Society of America Bulletin,* 93:644-654.

Everts Coastal 2002. *Impact of Sand Retention Structures on Southern and Central California Beaches.* California Coastal Conservancy, 103 p.

Finkl, C.W., L. Benedet, and T.J. Campbell 2006. "Beach nourishment experience in the United States: Status and trends in the 20th century." *Shore & Beach,* 74(2): 8-16.

Flick, R.E., 1998. "Comparison of California Tides, Storm Surges, and Sea Level During the El Niño Winters of 1982-83 and 1997-98." *Shore & Beach,* 66(3), 7-11.

Flick, R.E., 1993. "The myth and reality of southern California beaches." *Shore & Beach,* 61(3), 3-13.

Fulton-Bennett, K.W., and G.B. Griggs 1986. *Coastal protection structures and their effectiveness.* Joint publication of California Department of Boating and Waterways and Institute of Marine Sciences, University of California Santa Cruz, 48 p.

Giese, G., and D. Aubrey 1987. "Bluff erosion on outer Cape Cod." *Proceedings of Coastal Sediments '87,* 1871-1876.

Grandy, C., and G.B. Griggs 2009. "Natural and anthropogenic changes to beach sand supply in the Oceanside littoral cell, San Diego, California." *Shore & Beach,* 77 (1):30-38.

Griggs, G.B., 2010. *Introduction to California's beaches and coast*, University of California Press, 311 p.

Griggs, G.B., 2005. "The impacts of coastal armoring." *Shore & Beach,* 73(1): 13-22.

Griggs, G.B., K. Patsch, and L.E. Savoy 2005. *Living with the changing California coast*, University of California Press, 340 p.

Griggs, G.B., and K. Brown 1998. "Erosion and shoreline damage along the Central California coast: a comparison between the 1997-98 and 1982-83 winters." *Shore & Beach,* 66 (3): 18-23.

Griggs, G.B., J.E. Pepper and M.E. Jordan 1992. *California's coastal hazards: A critical assessment of existing land-use policies and practices.* Special publication of the California Policy Seminar Program, University of California, 224 p.

Griggs, G.B., J.F. Tait, L.J. Moore, K. Scott, W. Corona, and D. Pembrook 1997. *Interaction of seawalls and beaches: Eight years of field monitoring, Monterey Bay, California,* U.S. Army Corps of Engineers, Waterways Experiment Station Contract Report CHL-97-1. 34p.

Griggs, G.B., and K.W. Fulton-Bennett 1988. "Rip rap revetments and seawalls and their effectiveness along the Central Coast of California." *Shore & Beach,* 56: 3-11.

Hampton, M., G. Griggs, T. Edil, D. Guy, J. Kelley, P. Komar, D. Mickelson, and H. Shipman 2004. *Processes that govern the formation an evolution of coastal cliffs. Formation and Evolution and Stability of Coastal Cliffs-Status and Trends.* U.S. Geological Survey professional paper 1639:7-38.

Hapke, C., D. Reid, and B. Richmond 2009. "Rates and trends of coastal change in California and the regional behavior of the beach and cliff system." *J. Coastal Res.,* 25(3): 603-615.

Hapke, C., D. Reid, B. Richmond, P. Ruggiero, and J. List 2006. "National Assessment of Shoreline Change Part 3: Historical shoreline change and associated coastal land loss along sandy shorelines of the California coast." U.S. Geological Survey open file report 2006-1219, 72 p.

Hayes, M., and J. Boothroyed 1969. "Storms as modifying agents in the coastal environment." *Coastal Environment*s, 290-315.

Kinsman, N.E.M., 2011. *Artificial retention of beaches in California: current extent, public opinion, and influence on backshore morphology*. Ph.D. dissertation, Earth and Planetary Sciences Dept., University of California Santa Cruz, 192 p.

Komar, P., 1998. *Beach Processes and Sedimentation*. Prentice Hall, Upper Saddle River, NJ, 544 p.

Mantua, N.J., S.R. Hare, Y. Zhang, J.M. Wallace, and R.C. Francis 1997. "A Pacific interdecadal climate oscillation with impacts on salmon production." *Bulletin of the American Meteorological Society*, 78: 1069-1079.

National Research Council 1995. *Beach nourishment and protection*, Washington, D.C. U.S. National Academy of Sciences, Marine Board, Commission on Engineering and Technical Systems, U.S. 290 p.

Nordstrom, K.F., 2000. *Beaches and Dunes of Developed Coasts*. Cambridge University Press, New Jersey, 338 p.

Orme, A.R., G.B. Griggs, D.L. Revell, J. G. Zoulas, C.C. Grandy, and H. Koo 2011. "Beach changes along the southern California coast during the 20th century: A comparison of natural and human forcing factors." *Shore & Beach,* 79(4): 1-13.

Patsch, K., and G.B. Griggs 2007. *Development of Sand Budgets for California's Major Littoral Cells*. Tech. Report., Institute of Marine Sciences, U.C. Santa Cruz, CA, 111 p.

Ruggiero, P., P. Komar, W. McDougal, J. Marra and R. Beach 2001. "Wave run-up, extreme water levels and the erosion of properties backing beaches." *J. Coastal Res.,* 17(2):407-419.

Sallenger, A., W. Krabill, J. Broch, R. Swift, S. Manizae, and H. Stockon 2002. "Sea-cliff erosion as a function of beach changes an extreme wave run-up during the 1997-1998 El Niño." *Marine Geology,* 187(3-4):279-297.

Selby, M.J., 1993. *Hillslope Materials and Processes*. Oxford University Press, Oxford, 451 p.

Seymour, R., R.T. Guza, W. O'Reilly, and W. Elgar 2005. "Rapid erosion of a small southern California beach fill." *Coastal Engineering,* 52(2): 151-158.

Storlazzi, C.D., and G.B. Griggs, 1998. "The 1997-98 El Nino and erosion processes along the central coast of California." *Shore & Beach,* 66(3): 12-17.

Storlazzi, C.D., and G.B. Griggs 2000. "The influence of El Nino-Southern Oscillation (ENSO) events on the evolution of Central California's shoreline." *Geological Society of America Bulletin,* 112 (2): 236-249.

Sunamura, T., 1977. "A relationship between wave-induced cliff erosion and erosive force of wave." *J. Geology,* 85:613-618.

Tait, J.F., and G.B. Griggs 1990. "Beach response to the presence of a seawall." *Shore & Beach,* 58(2), 11-28.

Trenhaile, A., 1987. *The Geomorphology of Rocky Coasts*. New York: Oxford University Press. 314 p.

USACE 1987. *Coastal cliff sediments, San Diego region, Dana Point to the Mexican border.* United States Army Corps of Engineers, Los Angeles, California, 242 p.

USACE 1991. *Coast of California: storm and tidal waves study: South coast region, San Diego region*. U.S. Army Corps of Engineers, Los Angeles, California, 785 p.

Wiegel, R.L., 1994. "Ocean beach nourishment on the USA Pacific Coast." *Shore & Beach,* 62(1), 2-28.

LITTORAL CELLS, SAND BUDGETS, AND BEACHES: UNDERSTANDING CALIFORNIA'S SHORELINE

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OCTOBER 2006
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CALIFORNIA COASTAL SEDIMENT MANAGEMENT WORKGROUP

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Understanding California's Shoreline

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October 2006

Brochure Design & Layout
Laura Beach
www.LauraBeach.net

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Table of Contents

EXECUTIVE SUMMARY

The coastline of California can be divided into a set of distinct, essentially self-contained littoral cells or beach compartments. These compartments are geographically limited and consist of a series of sand sources (such as rivers, streams and eroding coastal bluffs) that provide sand to the shoreline; sand sinks (such as coastal dunes and submarine canyons) where sand is lost from the shoreline; and longshore transport or littoral drift that moves sand along the shoreline. Sediment within each cell includes the sand on the exposed or dry beach as well as the finer-grained sediment that lies just offshore.

Beach sand moves on and offshore seasonally in response to changing wave energy, and also moves alongshore, driven by waves that usually approach the beach at some angle. Most beach sand along the coast of California is transported from north to south as a result of the dominant waves approaching the shoreline from the northwest, although alongshore transport to the north occurs in some locations and at certain times of the year in response to waves from the south. Average annual rates of littoral drift typically range from about 100,000 to 1,000,000 yds^3/yr along the California coast.

Sand budgets have been developed for many of California's littoral cells by calculating or estimating the amount of sand added annually from each source or lost to each sink, and by documenting the volume of sand moving alongshore as littoral drift by using harbor dredging records as proxies. It is the balance between the volumes of sand entering and leaving a littoral cell over the long-term that govern the long-term width of the beaches within the cell. Where sand supplies have been reduced through the construction of dams or debris basins in coastal watersheds, through armoring the seacliffs, by mining sand or restricting littoral transport through large coastal engineering structures, the beaches may temporarily or permanently narrow.

The impacts of human activities on the amount of sand supplied to California's beaches have been well documented. While there is a public perception that Southern California beaches have narrowed in recent years, fueled at least in part by the stormy 20-year El Niño dominated period that extended from 1978 to 1998 and severely eroded many beaches, long-term changes in beach width are still being studied.

Beach nourishment or beach restoration is the placement of sand on the shoreline with the intent of widening a beach that is naturally narrow or where the natural supply of sand has been significantly reduced through human activities. Nourished shorelines provide a number of benefits including increased area for recreation, increased revenue from tourism, habitat improvement for shore dependent species, greater protection of the coastline from coastal storms, reduced need for armor, and increased public access.

To date, opportunistic beach fill has provided the majority of sand historically used for beach nourishment in California. Over 130 million yds^3 of sand were added to the beaches of southern California between 1930 and 1993 as a by-product of several large coastal construction projects and from the dredging of existing harbors and new marinas. As a result, the beaches of Santa Monica Bay and the Silver Strand, for example, are much wider than they were under natural conditions. Although the amount of sand provided by these projects has dropped sharply, the use of sand retention structures, such as groins or offshore breakwaters, has been effective in stabilizing the sand and maintaining wider beaches at many locations.

Beach nourishment has emerged as an option in recent years for portions of the southern California coastline (northern San Diego County and portions of Santa Barbara and Ventura counties, for example) where beaches are narrow and back beach or cliff top development is being threatened. While nourishment may appear to be an attractive alternative to coastal armoring or retreat, there are a number of issues or considerations that need to be carefully considered and addressed. These include the source and method of obtaining appropriate sand, costs and impacts of removing and transporting large volumes of sand to the site, financial responsibility for the initial project and subsequent re-nourishment, the potential impacts of sand placement, and the lifespan of the nourished sand. Due to the high littoral drift rates that characterize most of the California coast, sand added to a beach that is narrow to begin with cannot be expected to remain at that location for any extended period of time. Sand retention systems have been used effectively at a number of sites in California, however, as a way to significantly extend the lifespan of a beach nourishment project.

Chapter 1

Introduction

People have been interested in beaches and coastal processes for many years. Researchers have observed that beach width can change significantly over a range of time periods, from hours and days to years and decades. Long-term erosion or narrowing of any California beach is of concern to coastal managers as well as the general public.

In an effort to better understand the processes that change beaches, scientists use the concept of sand budgets to identify and quantify, to the degree possible, additions and losses of sand that influence beach width. By the 1960's, researchers recognized that the coastline of California could be separated into distinct, essentially self-contained regions or cells that were geographically limited. For example, beach sand in the Santa Barbara area originated from the watersheds and the coastline in the Santa Barbara area, and beach sand in San Diego or Santa Cruz originated in those geographic areas.

Coastal geologists and engineers termed these essentially self-contained coastal units littoral cells. These cells are geographically bounded by specific physical features that act as barriers to sediment movement, and contain additional features that either provide or remove sand from the cell. Understanding this setting allows researchers to focus on the major elements influencing specific beach or shoreline areas. This report discusses the physical process (littoral drift) that moves sand from one location to another within littoral cells. Littoral cell boundaries, features within the cell that supply sand to the beaches (sources), or remove sand from beaches (sinks) are also explained.

The methods used to develop sand budgets are first illustrated and then summarized for California's major littoral cells. Information is provided on how development associated with California's urbanizing society has altered the sand budgets of many of California's littoral cells, generally by decreasing the input of sand into the cell. This report concludes with a discussion of how the state is attempting to replace the sand lost through human activities (dam removal and beach nourishment) and the issues raised by such restoration activities.

The California Coastal Sediment Management Workgroup (CSMW), a taskforce of state and federal agencies seeking to resolve coastal sediment management issues, and the University of California at Santa Cruz, have developed this report as part of their public outreach and education effort associated with the CSMW's Sediment Master Plan, or SMP. A more detailed report on specific sand budgets for California's major littoral cells has been completed and is a complement to and resource for this more general discussion (Patsch and Griggs, 2006). Funding for both studies was provided by the California Resources Agency as part of a Coastal Impact Assistance Program grant for the SMP. The document was prepared with significant input from CSMW members, but does not necessarily represent the official position of member agencies.

Chapter 2

An Overview of Littoral Cells and Littoral Drift

What Is Littoral Drift?

Researchers have learned that sand is in constant motion along California's coastline, and only resides "temporarily" on an individual beach. An alongshore or littoral current is developed parallel to the coast as the result of waves breaking at an angle to the shoreline. This current and the turbulence of the breaking waves, which serves to suspend the sand, are the essential factors involved in moving sand along the shoreline. As waves approach the beach at an angle, the up-rush of water, or swash, moves sand at an angle onto the shoreface. The backwash of water rushes down the shoreface perpendicular to the shoreline or a slight downcoast angle, thus creating a zigzag movement of sand (Figure 2.1). This zigzag motion effectively results in a current parallel to the shoreline. Littoral drift refers to the movement of entrained sand grains in the direction of the longshore current.

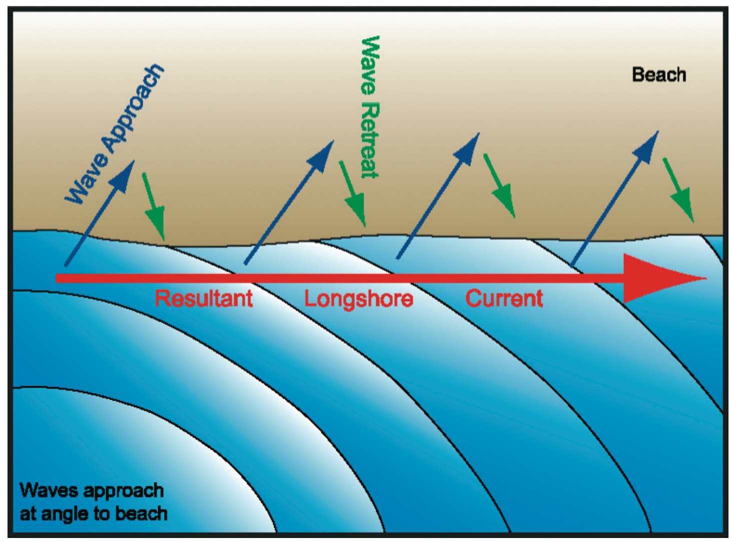

Figure 2.1: Development of longshore current as a result of waves approaching the beach at an angle. Littoral drift refers to the net movement of sand grains in the directions of the longshore current.

Littoral drift can be thought of as a river of sand moving parallel to the shore, moving sand from one coastal location to the next and so on until the sand is eventually lost to the littoral system. Littoral drift or transport in California can occur alongshore in two directions, upcoast or downcoast, dependent on the dominant angle of wave approach (Figure 2.2). Along the California coast, southward transport is generally referred to as downcoast and northward transport is considered upcoast. If waves approach perpendicular to the shoreline, there will be no net longshore movement of sand grains, no littoral current, and thus no littoral drift. Longshore transport for a reach of coast will typically include both upcoast and downcoast transport, often varying seasonally.

Gross littoral drift is the total volume of sand transported both up and downcoast, while net littoral drift is the difference between the two volumes. In other words, along a particular segment of coastline, there may be 200,000 yds^3 of sand transported in a southerly or downcoast direction each year, and 50,000 yds^3 transported in a northerly or upcoast direction. The gross littoral drift would be 200,000 + 50,000 or 250,000 yds^3, whereas the net drift would be 200,000 – 50,000 or 150,000 yds^3 downcoast.

For most of California, from Cape Mendocino south to San Diego, waves from the northwest have the greatest influence on littoral drift, and thus, a southward net littoral drift of sand dominates

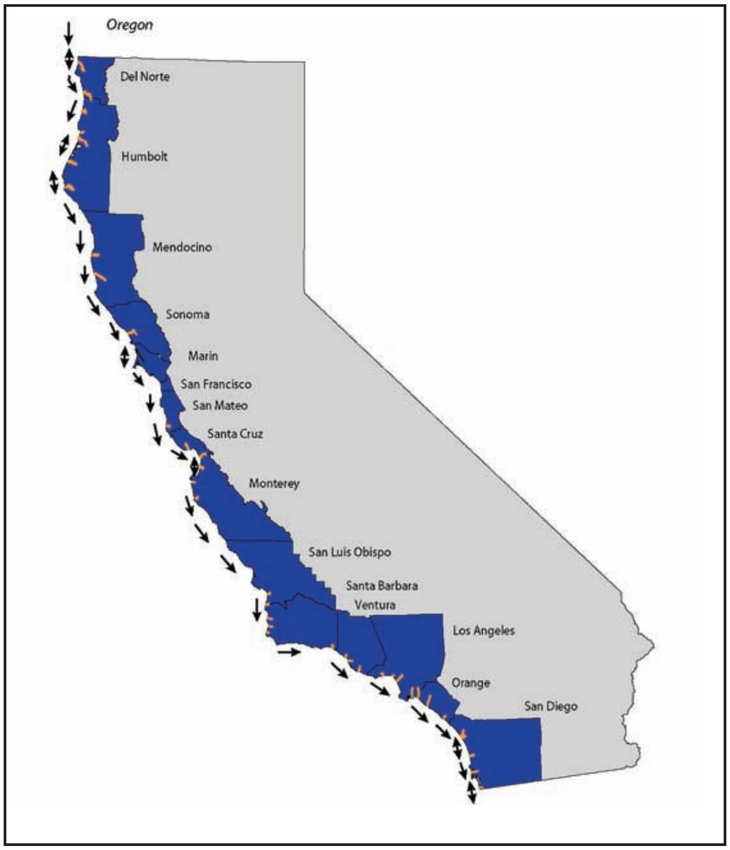

Figure 2.2: Net littoral drift directions in California

(Figure 2.2). The more energetic winter waves generally approach from the northwest direction, driving littoral drift southward or southeastward along the beaches. There are also areas such as southern Monterey Bay, and Oceanside, where longshore transport to the north may take place. During El Niño winters, waves generally come from the west or southwest and the predominance of southward transport is reduced. Transport may be to the northwest, or upcoast, in most of southern California during the summer months when southern swell dominates.

Coastal engineering structures designed to widen or stabilize beaches, such as groins, the construction of harbor entrance jetties and breakwaters, and also the stability or lifespan of beach nourishment projects, are all closely tied to littoral drift direction and rate. Interrupting or disrupting the littoral drift or “river of sand”, in addition to the benefits of retaining sand and widening beaches, can have serious consequences to the downdrift shorelines, including increased beach or cliff erosion and, in the case of a harbor entrance, costly dredging. Erosion of downdrift properties may necessitate the emplacement of additional coastal armoring, which extends the disruptions to the shoreline farther downcoast.

WHAT CONSTITUTES BEACH SAND?

Whereas it is common practice to refer to most beach sediment as “sand”, grain sizes on beaches in California range from very-fine grained sand to cobbles as a result of differences in the wave energy, and the material available to any particular beach. Geologists and engineers classify sediment by size (e.g. silt, sand, pebbles) because different size materials behave very differently and sediment of different sizes is stable on different beaches. The Wentworth scale is one of the classification schemes most commonly used and it groups sediment by grain diameter (millimeters) based on powers of two (Krumbein, 1936). According to this scale, sand is defined as all particles between 0.0625 mm and 2 mm in diameter, although sand is further broken down into fine-grained, medium-grained, etc. (Table 2.1). The phi scale was introduced as an alternate measure of sediment size based on the powers of two from the Wentworth scale and is commonly used in the coastal geology community. It is important to note that larger phi sizes correspond to smaller grain sizes (Table 2.1).

Wentworth Scale Size Description	Phi Units Φ	Grain Diameter (mm)
Boulder	-8	256
Cobble	-6	64
Pebble	-2	4
Granule	-1	2
Very Coarse Sand	0	1
Coarse Sand	1	0.5
Medium Sand	2	0.25
Fine Sand	3	0.125
Very Fine Sand	4	0.0625
Silt	8	0.004
Clay	12	0.00024

Table 2.1: Wentworth scale of sediment size classification–Note that larger Phi sizes indicate smaller grain size

LITTORAL CUT-OFF DIAMETER

Very fine-grained sand, ranging from 0.0625 to 0.125 mm in diameter (4ø to 3ø), typically doesn’t remain on the exposed (dry) portions of most California beaches due to the high-energy wave environment. An investigation of littoral transport processes and beach sand in northern Monterey Bay (Hicks, 1985), discovered that there is a littoral cut-off diameter, or a grain-size diameter, characteristic of any particular segment of coast. The cut-off diameter serves as a functional grain size boundary in that very little material finer-grained than this diameter actually remains on the exposed beach. The cut-off diameter along any particular beach or stretch of coast is primarily a function of wave energy at that location.

Studies along the coast of northern Santa Cruz County, which is a relatively high-energy, exposed coast, determined a littoral cut-off diameter of ~0.18 mm (2.5ø) for this stretch of coast, with very little finer sand remaining on the exposed beaches. In southern California, where much of the coast is protected from strong wave action by the sheltering effect of the Channel Islands, the littoral cut-off diameter is smaller, typically around 0.125mm (3ø). When estimating or calculating inputs to a sand budget or planning a beach nourishment project, it is important to consider the littoral cut-off diameter. Sand placed on the beach or entering a littoral cell that is finer than the littoral cut-off diameter will not remain on the dry beach.

THE BEACH PROFILE

The exposed (dry) beach is the visual portion of a profile of sediment that extends from the back of the beach to some depth (commonly referred to as “closure depth”) representing the point beyond which it is believed that there is little net seasonal movement of sand on- and offshore. The grain size distribution varies along this profile perpendicular to the shoreline, and the overall distribution of size can be represented by an "envelope" of grain sizes. The coarsest materials within this envelope reside on the beach itself; successively finer-grained materials are present further offshore along the profile. Materials within the nearshore are an important part of the beach and related system. . Sediment smaller than the cut-off diameter may move into the nearshore and help support the beach profile. It may also move alongshore as littoral drift.

We do not currently have the historical information needed to quantify changes in nearshore sand volumes. This report focuses on the changes and processes affecting beach sands, which provides an adequate surrogate for the total volume of sediment moving alongshore as littoral drift.

LITTORAL CELLS

The California coast can be divided into a number of individual segments within which littoral sediment transport is bounded or contained. These essentially self-contained segments have often been referred to as beach compartments (Figure 2.3; Inman and Frautschy, 1966) or littoral cells.

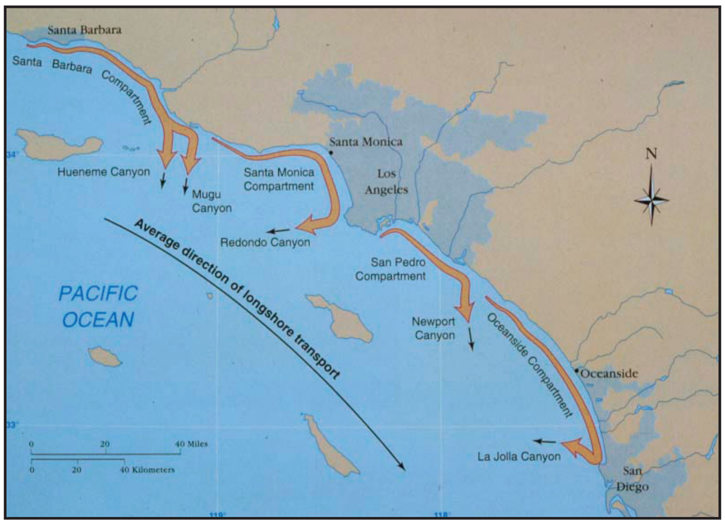

Figure 2.3: Littoral cells in southern California

Each cell has its own source(s) of sand, littoral drift, and ultimately, a sink or sinks where sand is lost permanently from the littoral cell (Figure 2.4). Sediment within a littoral cell consists of sand on the exposed or dry beach as well as the finer grained materials residing in and moving through the adjacent nearshore environment. Typical sources and sinks are described in detail in Chapter 3. The littoral cell concept has been perhaps the most important discovery in the field of coastal and beach processes in the last 50 years. It has enormous value in understanding coastal processes, sand input, output, storage and transport, and provides an extremely valuable and useful framework for assessing any human intrusions into the coastal zone.

The upcoast boundary of a littoral cell is typically a rocky headland, littoral barrier or sink such that littoral drift into the cell from the adjacent upcoast compartment is restricted or minimal. Sand enters the littoral cell primarily from streams and rivers draining to the shoreline and from bluff erosion, and is transported alongshore by littoral drift. Ultimately, sand is lost from the compartment offshore into the head of a submarine canyon or beyond the reach of longshore transport, onshore into coastal dunes, or in some cases, to sand mining.

CROSS-SHORE TRANSPORT

During large storm events, sand may be either transported offshore or onshore from the seafloor seaward of the surf zone. Thus the nearshore area may be either a source or sink for beach sand. However,

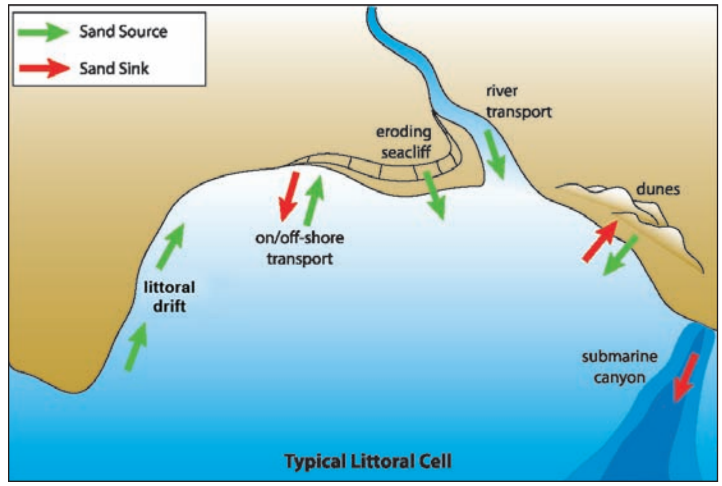

Figure 2.4: Sources and sinks in a typical littoral cell in California

for most littoral cells we simply don't have adequate information to quantify this cross-shore transport and, therefore, the importance of the sand in the nearshore area to littoral sand budgets is poorly understood.

LIMITATIONS TO THE LITTORAL CELL CONCEPT

Ideally, each littoral cell exists as a distinct entity with little or no transport of sediment between cells. It is believed that many headlands form nearly total barriers to littoral drift, but under particular conditions, such as during large storms, significant sand may be suspended and carried around points or across the heads of submarine canyons onto the beaches of adjacent cells. Fine-grained materials being transported in suspension behave differently than sand moving along the surface of the beach or nearshore zone, and the littoral cell boundary concept does not apply to these materials.

Nevertheless, while boundaries have been delineated for California's major littoral cells (Figure 2.5; also see Chapter 4), there are still uncertainties and information gaps on these often well-studied cells: Where are the actual boundaries of each littoral cell? Does significant sand transport take place around or across these "boundaries"? What is the dominant littoral drift direction throughout each cell? These are a few of the questions that remain partially unanswered.

The application of a budget to understand changes in and processes affecting beach sand is a useful tool in coastal land use management and coastal engineering. It is an essential step in understanding sand routing along the coast. One of the first sediment budgets for a littoral cell was created in the region from Pismo Beach to Santa Barbara, estimating each sand input and output along this portion of the central coast of California (Bowen and Inman, 1966). This budget has proven to be a valuable template for subsequent studies.

Our historic lack of understanding of littoral cells and their importance, or the failure to incorporate this type of information early on in the decision-making process in large watershed or coastal engineering projects has resulted in costly problems to society. For example, ongoing harbor entrance channel dredging is required where these projects were constructed in the middle or downcoast ends of littoral cells with high drift rates (Griggs, 1986). The reduction of sand delivery to beaches due to impoundment of sediment behind dams in coastal watersheds has contributed to cliff and beach erosion and the loss of recreational benefits. An improved qualitative and quantitative understanding of littoral cells and sand budgets can help us to resolve existing coastal sediment problems and also inform future planning so as to avoid the mistakes of the past.

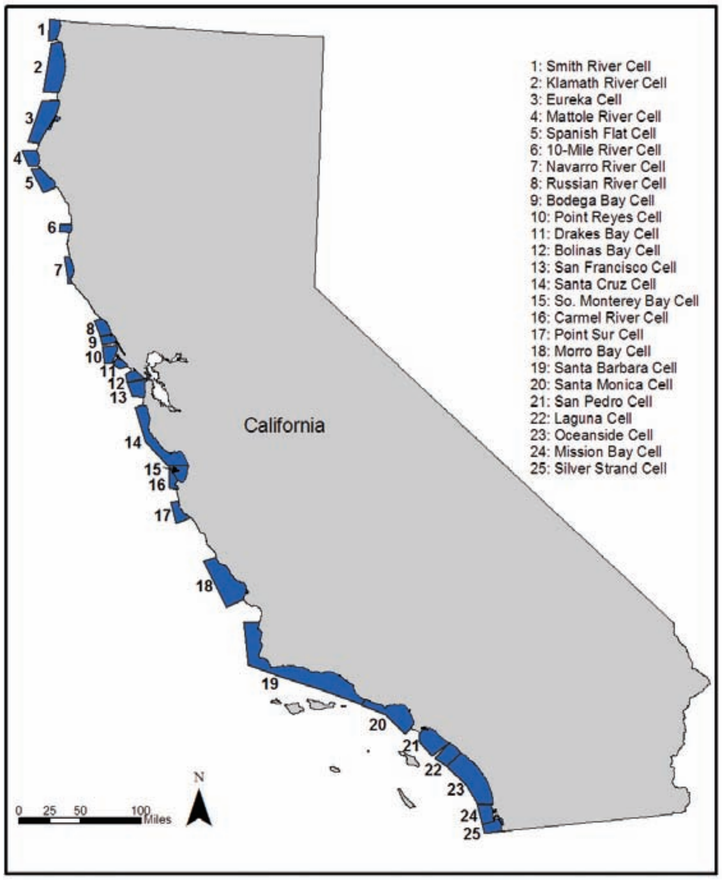

Figure 2.5. California's littoral cells (Habel and Armstrong, 1978)

SEASONAL AND DECADAL MOVEMENT OF SAND WITHIN A LITTORAL CELL

The shoreline within a littoral cell is dynamic, changing with the rhythms of the tides, seasons, and long-term climatic shifts, including fluctuations of sea-level. Beaches respond with great sensitivity to the forces acting on them, primarily wind and waves. Waves provide the energy to move sand both on- and offshore as well as alongshore. The beach is a deposit of well-sorted material that appears to be stable, but in reality, the beach and sand in the nearshore are in constant motion on-, off-, and alongshore. This motion occurs underwater and on both short term (individual waves) and long-term (seasonal and decadal) time scales.

As sea level changes with tidal cycles, so does the width of the exposed beach. In addition to daily variations, long-term fluctuations in sea level occur over hundreds and thousand of years as a result of global climate change. Sea level has been rising for about 18,000 years, and it is assumed by virtually all coastal and climate scientists that it will continue to rise into the foreseeable future. Over the past century, sea level has risen relative to the coastline in southern California by about 8 inches (20 cm), and at San Francisco by about 9 inches (23 cm).

Beach widths in California also change on a seasonal scale, due to changes in weather, storm intensity, and wave climate (Figures 2.6 and 2.7). Seasonal beach erosion is typically a recoverable process; beach width narrows each winter and generally widens the following summer. In the winter, the coast experiences an increase in storms and wave energy. The increased wave energy tends to erode the beach, and moves sand into the nearshore where it is stored in sand bars. These sand bars tend to reduce the wave energy hitting the shoreline because the waves will break farther offshore (over the bars), losing some of their energy before reaching the shoreline. As the winter storms pass and the wave intensity is reduced, the smaller, less energetic spring and summer waves begin to dominate. These smaller waves rebuild the beach with the sand moved offshore during the winter storms. Figure 2.7 shows a beach in central California (A) during the summer when smaller waves have moved sand onshore to build a wide beach, and (B) in winter when large storm waves have narrowed the beach by moving sand onto offshore bars.

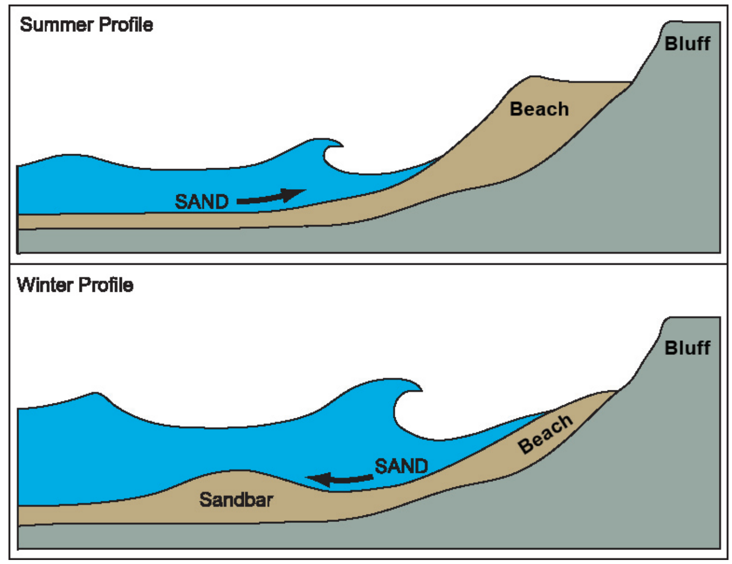

Figure 2.6: Summer profile (also known as the swell profile) results from waves with low heights, and long periods and wavelengths. The beach is characterized by a steep foreshore and a broad berm (a terrace formed by wave action along the backshore of a beach). The winter beach profile (also known as the storm profile) is a response to higher waves, shorter wave periods, and shorter wavelengths. Waves become erosive and cut away at the berm, transporting sand onto offshore bars where it is stored until the following summer.

Over years and decades, beaches can erode (narrow), advance (widen), or remain in equilibrium, as a result of available sand within a littoral cell. When sand supply is reduced through the construction of dams or altered by large coastal engineering structures such as breakwaters or jetties, affected beaches can experience permanent erosion or take years or decades to re-establish equilibrium. This loss of sand and beach width may be recoverable, however, if the sand supply is restored.

Large-scale ocean warming episodes related to El Niño occur in the Pacific Ocean when mean sea level in California can be elevated by up to 15 cm or more for several months to a year. El Niño winters are also characterized by more frequent and vigorous storms over the Pacific, and severe beach erosion can result when large waves approaching from the west or southwest arrive simultaneously with very high tides. Research on changing climate conditions has identified periods, sometimes lasting several decades, when El Niño events are much more severe than those occurring during La Niña periods (characterized by cooler temperatures, decreased storm intensity and rainfall), such as the period from the mid-1940's to 1978. Although the timing of these decadal-scale changes are not predictable, cycles of more frequent El Niño events have been recognized when increased storm intensity and duration result in increased beach loss and cliff erosion. The most recent cycle of intense El Niño events began in 1978. Winter storms of 1982-1983 and 1997-1998, in particular, caused severe beach erosion along California's shoreline and significant damage to oceanfront structures and coastal infrastructure.

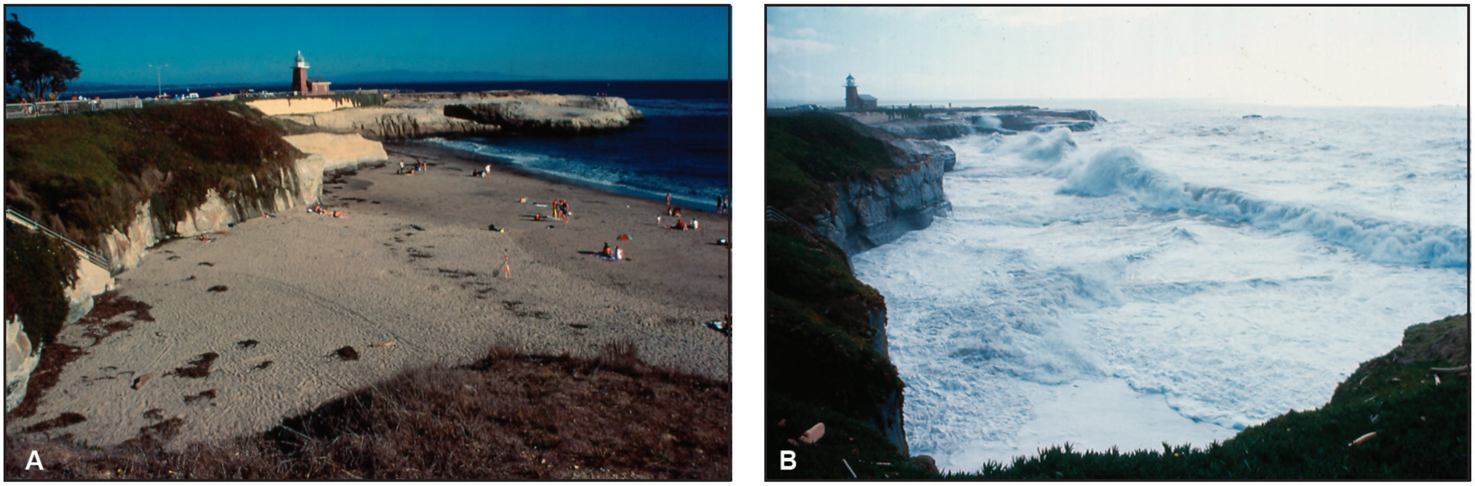

Figure 2.7: Seasonal beach changes
A. Wide, summer beach at Its Beach in Santa Cruz (October 1997) B. Narrow winter beach at Its Beach in Santa Cruz (February 1998)

Chapter 3

Elements Involved in Developing Sand Budgets for Littoral Cells

Beach sand is in a constant state of flux, moving on-, off- and alongshore under the influence of waves and currents. Sand is transported to beaches from a variety of sources, including rivers, seacliffs or dunes, updrift beaches and possibly offshore sources (Figure 2.4). Sand generally remains at a given location on a beach for only a short time before it is entrained and moved on as littoral drift. When the removal of sand (output) exceeds that being transported in (input), beach erosion or narrowing results. Conversely, beach widening results when sand input exceeds output, or when some barrier to littoral transport (a groin or jetty for example) is constructed that leads to sand storage (output is reduced). Beaches are said to be in equilibrium when sand inputs are approximately equal to sand outputs.

A sand budget is an attempt to quantify changes in the on-shore sand volume along a stretch of coast by applying the principle of conservation of mass. In order to develop a sand budget, estimates must be made of the primary sand sources (input) and sand losses (output) for a stretch of shoreline. Balancing or creating a sand budget for a reach of coast is similar to balancing a checkbook. Sand sources such as river inputs, seacliff or dune erosion, longshore transport from upcoast areas, beach nourishment and onshore transport from the nearshore can be thought of as deposits (inputs) into the account (Figure 2.4). Sand sinks (e.g., submarine canyons, dune growth, longshore transport out of an area, offshore transport and sand mining) represent outputs from the system or debits to the account (Figure 2.4). The difference between the total volume of sand provided by all sand sources and the volume lost to all sinks within a particular littoral cell will equal the change in sand volume or storage within that compartment and provide insight on the stability of the beach or particular stretch of coast (Table 3.1).

Sources of Sand	Sinks for Sand	Balance
Longshore Transport In	Longshore Transport Out	Accretion
River Inputs	Offshore Transport	Erosion
Seacliff or Bluff Erosion	Dune Growth	Equilibrium
Gully Erosion	Sand Mining	
Onshore Transport	Submarine Canyons	
Dune Erosion		
Beach Nourishment		

Table 3.1: Sources and sinks of sand and the resulting balance in the development of a sand budget.

A sand budget can be developed to represent short-term conditions, such as seasonal or yearly changes. However, when planning a large engineering, restoration or nourishment project or other alteration to the coast, it is best to construct a long-term sand budget that includes historic and present conditions. Many assumptions and errors involved in the data analysis and interpretation of a sand budget can be reduced when a budget spans a greater length of time and averages out year-to-year variations in the components.

It is the balance between sand sources and sinks within each littoral cell that govern the long-term width of beaches within a beach compartment. If there is a significant reduction in the amount of sand reaching a particular stretch of coast, the beach should gradually erode or narrow. Conversely, if there is an increase of sand in a particular area, the beach should advance seaward, or widen.

COMPONENTS OF A SAND BUDGET

The main challenge in developing a sand budget is quantitatively assessing all sources and sinks to a reasonable degree of accuracy. A thorough literature search should be performed to find the most up-to-date information on each component. Along the California coast, most of the naturally supplied beach sand comes from river and stream runoff with a lesser amount derived from the erosion of coastal cliffs and bluffs. Sand is lost from littoral cells predominantly to submarine canyons, to sand dunes to a lesser extent, and perhaps to offshore transport during extreme storm events. Sand mining directly from the beach historically was a major loss for some littoral cells, but most of this has now been eliminated.

Sand contributions from seacliff erosion, rivers, and dunes as well as other components of the budget, have been or can be quantified or calculated with some effort for many of the state's littoral cells (Patsch and Griggs, 2006; Patsch, 2005). The volume of materials dredged from harbors within the littoral cell can serve as a surrogate (or check point) for the volume of littoral drift at a specific location. The following sections give more specific information on the difficulties and limitations involved in calculating or estimating contributions and losses for a sand budget.

River Inputs (Source): Rivers contribute the majority of sand to most beaches in California. Physical and chemical weathering slowly breaks down the rocks from coastal mountains into smaller fragments. The broken-down boulders, cobbles, gravel, sand, silt and clay move into mountain streams and creeks through rainfall, runoff, and slope failures, and the sediments are sorted and transported downstream into larger streams or rivers. As sediments travel down stream, they break down and become smaller. Large cobbles and boulders are often left upstream because the river does not have enough energy to transport them downstream. Sediment is transported in streams either as suspended load (the finer-grained sediment which makes it look muddy), or as bedload (the coarser material that is transported along the bed of the stream). Most of the suspended load consists of clay and silt, except during high discharge events when significant volumes of sand can be transported in suspension and delivered to the shoreline. Although the total amount of sediment carried as bedload is much less than that carried in suspension, most of the bedload is sand and will contribute directly to the littoral sand budget.

Eventually, the smaller cobbles, sand, silt and clay will reach the shoreline. The finer silt and clay particles are too small to settle and remain on the beach, and consequently are carried offshore by coastal and offshore currents, and eventually deposited on the seafloor nearby or perhaps many miles away. Offshore mudbelts are fairly common, where much of the fine-grained sediment eventually ends up. Most sand-sized material will remain on the beach, and gradually be moved alongshore by littoral drift, thereby feeding down-coast beaches. The finer-grained sand may, however, move into the nearshore zone and also be transported alongshore.

Sand contributions for the majority of the coastal rivers and streams in California have been determined using daily measured values of water discharge, or probabilities of discharge events, to develop "sediment-rating curves". These curves show the relationship between the volume of water discharge and sand loads for individual streams.

Sediment rating curves can be used to estimate the annual sediment yield from individual rivers and streams. Using these curves, average sand loads (sediment sufficiently coarse to remain on the beach) have been calculated for most of the rivers and streams in California (Willis and Griggs, 2003; Slagel, 2005). Under historical or natural conditions about 13-14.5 million yds^3 of sand was being delivered annually to the coast of California from 37 major rivers and streams. This volume has been reduced about 23% statewide through impoundment behind dams, such that, on average, about 10,000,000 yds^3 of sand is presently delivered to the coast each year.

The methodology used in these two studies is believed to be the most reliable approach currently available for determining sand contributions to the shoreline from rivers; however it is not without error. Some gauging stations are often well upstream from the mouth of the river; thus, sediment loads may differ significantly between the gauging station and the shoreline due to deposition or erosion that may occur along the stream channel or flood plain between the gauging station and the river mouth.

Sediment delivery by rivers to California's littoral cells is extremely episodic. Most sediment discharged by any particular stream typically occurs during several days of high flow each year. Additionally, sediment discharge during a single year of extreme flood conditions may overshadow or exceed decades of low or normal flow. For example, the Eel River transported 57 million tons of suspended sediment on December 23, 1964, representing 18% of the total sediment discharged by the river during the previous ten years. This one-day discharge is greater than the total average annual suspended sediment discharge for all rivers draining into the entire California coastline. On some streams, however, little or no sediment discharge data may exist for the flood or large discharge events that transport the greatest volumes of sediment. As a result, rating curves may not adequately predict sand transport from water discharge records during the high discharge events. Data or calculations for sediment impounded behind dams can help fill such gaps or deficiencies in sediment discharge records (Slagel, 2005).

Fluvial sediment discharge has also been shown to vary widely from El Niño to La Niña periods (Inman and Jenkins, 1999), such that the length of historic streamflow record from any particular gage may or may not be representative of long-term conditions. In Southern California, mean annual stream flow during wet El Niño periods exceeded that during the dry periods by a factor of about three, while the mean annual suspended sediment flux during the wet periods exceeded the sediment transported during dry periods by a factor of about five (Inman and Jenkins, 1999).

At their best, data on fluvial sand discharge are believed accurate to within about 30% to 50% (Willis and Griggs, 2003). Yet, the amount of sand transported and delivered to the shoreline by streams is an extremely important component of all sand budgets for California.

Reductions to Fluvial Inputs: Damming of rivers or streams reduces sediment delivery to the coast by both trapping sand in the reservoirs and reducing peak flows that transport the greatest amount of sediment. Most of California's large dams, under good management, have reservoir capacities sufficient to absorb all incoming water during a normal winter, releasing low flows to downstream areas during the spring and summer months. The magnitude and frequency of peak flows are therefore reduced, decreasing the river's ability to transport material downstream (Figure 3.1). Dams act as complete barriers to bedload and trap most of the suspended sediment load, except during large flood events when flows overtop the dam or pass through the spillway. The average trapping efficiency (the amount of suspended sediment trapped by the dam) for most coastal dams in California is about 84% (Brune, 1953; Willis and Griggs, 2003).

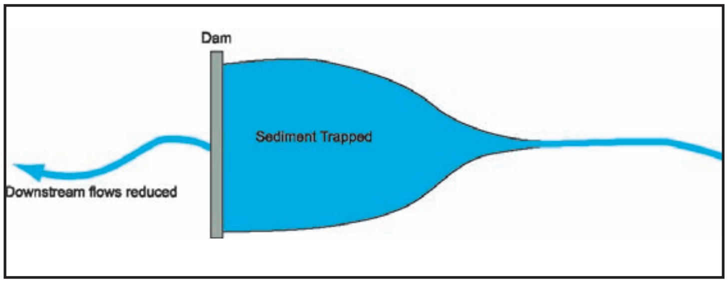

Figure 3.1: Dams trap sediment, preventing it from moving downstream to the shoreline, in addition to reducing the river's flow volume and thus its ability to transport sediment.

Recent work by Willis and Griggs (2003) and Slagel (2005) indicate that the present day delivery of sand to the shoreline has been reduced to about 10 – 11 million yds^3/year, or approximately a 23-25% reduction from natural conditions, due to the more than 500 dams on California's coastal streams. Approximately 3 million yds^3 of sand is trapped each year and a total of about 163 million cubic yds^3 of sand has now been deposited behind dams on the state's 21 major rivers (Slagel, 2005). The great majority of this reduction is concentrated in southern California (Tables 4.1 and 4.2; These two tables list only the amounts of sand provided to California's ten major littoral cells under natural and present-day conditions, and do not include all of the state's major coastal rivers and dams analyzed by Slagel [2005] and Willis and Griggs [2003])

Sand mining in Northern California coastal watersheds and along stream channels has removed an estimated 9 million yds^3 (11 million tons) of sand and gravel annually on average, and similar operations in Southern California have removed about 41.5 million yds^3 (55.8 million tons) annually on average (Magoon and Lent, 2005). It is unclear how much of this sand and gravel would naturally be delivered to the coast by rivers, but sand mining may play a major role in the reduction of sand delivery by rivers to the shoreline.

If sand supply from rivers is continually reduced through impoundment behind dams, as well as through sand and gravel mining from stream beds, then beaches should eventually be deprived of a significant portion of their predominant sand source. Over decadal time scales, beaches should, therefore, narrow or erode, assuming no change in littoral transport rates (Figure 3.2). Littoral drift rates are a function of the amount of wave energy, the angle of wave approach, and the sand available for transport. More wave energy and a greater angle of wave approach will generate larger littoral drift rates.

Seacliff erosion (Source): Seventy-two percent of California's 1,100-mile coast consists of seacliffs or coastal bluffs, which, when eroded, may contribute sand to California's beaches. Coastal cliffs that consist of materials such as sandstone or granite that break down into sand-sized grains will contribute directly to the beaches. Fine-grained rocks that consist of silt and clay (shales or mudstones), on the other hand, will not contribute significantly to beaches.

The geology of the seacliffs along the coast of California varies widely alongshore and, therefore, the amount of sand contained in the cliffs or bluffs also varies from place to place. Typically, where the coastal cliffs consist of uplifted marine terraces, there is

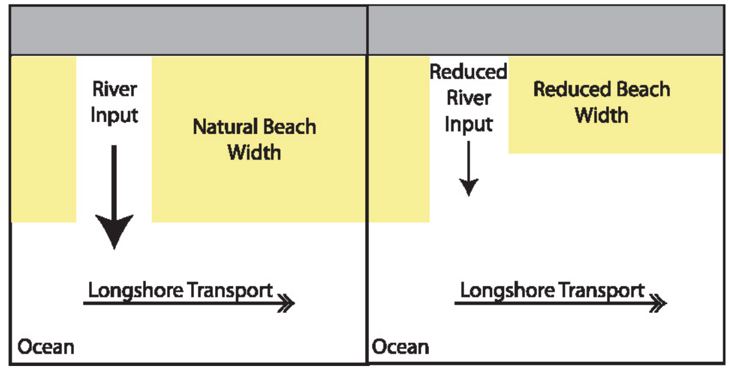

Figure 3.2 illustrates beach narrowing expected from a reduced sand supply. A simplified littoral cell is presented with a single river as the only sand source, thus ignoring sand contributions from cliffs and other budget components. If the amount of sand delivered by the river is reduced, and the littoral drift remains the same, then the downdrift beach volume or width should decrease over time.

an underlying, more resistant bedrock unit and an overlying sandy deposit, consisting predominantly of relict beach sand. Each unit will have its own particular sand content. In order to make qualitative assessments or quantitative measurements of the contribution of coastal cliff retreat to beaches, it is necessary to divide the coast into manageable segments somewhat uniform in morphology and rock type. Estimates of sand contributions from individual segments can then be combined to arrive at a total contribution of beach sand over a larger area, such as an individual littoral cell.

The annual production of sand coarse enough to remain on the beach resulting from seacliff erosion (Qs) along a segment of coastline is the product of: 1- the cross-sectional area of seacliff (Area = alongshore cliff length x cliff height); 2- the average annual rate of cliff retreat, and; 3- the percentage of material larger than the littoral cutoff diameter (Figure 3.3):

Qs (ft^3/yr)= Lc*E*(Hb*Sb+ Tt*St)

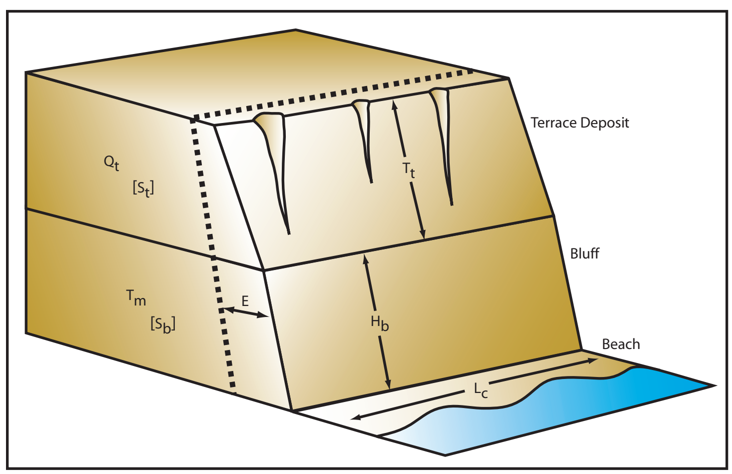

Figure 3.3: Seacliff showing the components involved in calculating sand contribution: Lc is the alongshore length of the cliff (ft); E is erosion rate (ft/yr); Hb is bedrock height (ft); Sb is percentage of sand size material larger than the cutoff diameter in bedrock; Tt is thickness of the terrace deposit (ft); and St is percentage of sand larger than the cutoff diameter in the terrace deposit. Tm (Tertiary Marine) represents geology of the bedrock, and Qt (Quaternary Terrace) represents geology of the capping terrace deposit.

The methodology for determining sand contributions from seacliff erosion is simpler than the process used to determine river contributions of sand. However, these calculations still have a high degree of uncertainty. The most difficult element of this methodology to constrain is the long-term seacliff erosion rates due to the high spatial variability and episodic nature of cliff or bluff failure. Seacliff erosion rates are typically determined by precisely comparing the position of the cliff edge over time on historical stereo aerial photographs (Griggs, Patsch and Savoy, 2005).

On a state-wide basis, contributions to beach sand from seacliff erosion tend to be much less than those from streams. However, such contributions may be very important locally where very sandy cliffs are rapidly eroding and there are no large streams (Runyan and Griggs, 2003). For example, while bluff erosion contributes less than one percent of the sand to the Santa Barbara littoral cell, bluff erosion is believed to contribute about 31% and 60% of the sand to the Laguna and Mission Bay littoral cells, respectively. Also, recent research in the Oceanside littoral cell, utilizing composition of sand in the bluffs and beaches, as well as very precise LIDAR (a very precise, laser-based, topography measuring system) measurements of coastal bluff retreat (over a relatively short 6-year period) concluded that bluffs may contribute 50% or more of the sand to beaches in this littoral cell.

Beach Nourishment (Source): Beach nourishment is used to describe sand artificially added to a beach and/or the adjacent nearshore that would not have otherwise been provided to the littoral cell. It is a way to artificially widen otherwise narrow or eroding beaches, and has occurred more frequently in southern California than in other region of the state. Historically, sand placed on the beach or just offshore has come from a variety of sources, including: dredging of coastal harbors, lagoons, bays, estuaries or river channels; coastal construction projects where dune or other excavated sand is placed on the beach; and, dredging of offshore areas. Most beach nourishment projects have served dual purposes, i.e., the primary purpose was to create a marina, clear a river channel for flood control, restore a coastal wetland or excavate a construction site, and the secondary purpose of the project was to nourish or widen the beach.

When developing a littoral budget, sand excavated from offshore, coastal or inland sources is considered to be an additional source of sand to the littoral cell, and thus labeled as nourishment. Harbor entrance bypassing operations or channel maintenance dredging do not represent new sources of sand, because they are simply moving the sand to a new location within the same cell, and so are not considered nourishment.

Cross-shore exchange (Source/Sink): Quantifying the potential movement of sand between beaches and the nearshore and offshore areas is the most challenging and poorly evaluated sand budget element. Cross-shore transport can result in either a net gain or loss for the beach. A comparison of sediment composition (e.g., distinct minerals contained in the sand) between beach, nearshore and shelf sand is often used as evidence for a net onshore or offshore transport; however, the similarity in composition only indicates that an exchange has taken place. It rarely indicates direction of transport or volumes of sand moved, which are necessary for development of a sand budget.

Whether or not sand is moved on- or offshore is controlled by factors such as wave energy and tidal range, bottom slope and the grain size of the sand. In order to thoroughly evaluate this component it would be necessary to have data on the precise thickness or depth of beach-sized sand over large offshore areas and to know how this has changed over time. With the large shelf areas typically involved, a small increase in the thickness of the sediment veneer over an extensive area can produce a large volume of sand in storage. We simply don't have these data, and it would require long-term studies to determine how the distribution of sand changes over time. In developing sand budgets, it is often assumed that net cross-shore exchange of sand is zero, such that the volumes of sand transported on- and offshore are balanced, unless sediment data are available on a particular area of interest. In other cases, however, unaccounted for losses are usually ascribed to offshore transport.

Offshore dredge disposal: There are several littoral cells where large volumes of beach size sand that have been dredged from harbors or channel entrances have been or continue to be transported offshore for disposal, thus removing this material permanently from the littoral system. Offshore disposal can, therefore, be a significant littoral sand sink.

Close to a million cubic yards of sand on average is dredged from the Humboldt Bay entrance channel every year and transported to EPA's Humboldt Open Ocean Disposal Site (HOODS; Tom Kendall, USACE). Sediment lost to the littoral cell from dredging and offshore disposal was also a major issue in San Diego. About two million cubic yards of sediment was scheduled for dredging as part of the deepening of San Diego Bay for larger U.S. Navy vessels. This sediment was originally intended for the SANDAG nourishment project, but was disposed of offshore due to ordinance found in the dredge spoils from the bay. These are very large volumes of potential beach sand that are being removed more-or-less permanently from the littoral system for different reasons. This is an issue that merits further investigation in order to document how extensive these losses are, where they are taking place, and what options exist for possible utilization of these materials in the adjacent littoral cells.

Dune Growth/Recession (Sink/Source): Sand dunes occur adjacent to and inland from beaches at many locations along the coast of California. Dunes are created where ample fine-grained sand is available with a persistent onshore wind and a low-lying area landward of the beach where the sand can accumulate. Typically, if the shoreline is backed by seacliffs, dunes can't accumulate or migrate, and thus will not grow to any significant size. In many areas of California, such as the area north of Humboldt Bay, Golden Gate Park in San Francisco, southern Monterey Bay, The Pismo Beach area, and areas along Santa Monica Bay, wind-blown sand has created large dune complexes.

Dunes commonly represent sand permanently lost from littoral cell budgets, constituting a significant sink to a cell. For example, it has been estimated that an average of 200,000 yd^3/yr of wind-blown sand is permanently lost from the beaches along the 35-mile coastline from Pismo Beach to Point Arguello (Bowen and Inman, 1966; Figure 3.4). On the other hand, in areas such as the Southern Monterey Bay littoral cell, dune erosion and recession play an important role as a sand source to the littoral budget. While uncommon, sand may be blown onto the beach from a coastal dune area (representing a source).

Dune migration, growth and erosion (or deflation) can be measured from aerial photographs or in the field and converted into sand volumes. Dune growth and deflation illustrate the need to introduce a time element into sand budgets. One major storm can erode the portion of dunes closest to the ocean (i.e., the foredune), which were previously considered a sink, returning the sand to the beach. However, many studies have concluded that this type of foredune erosion may occur for only a few days during a major storm event and is followed by a prolonged period (from years to decades) of foredune growth.

Figure 3.4: Pismo Dunes in San Luis Obispo County. Copyright © 2002 Kenneth & Gabrielle Adelman California Coastal Records Project, www.Californiacoastline.org.

Losses into Submarine Canyons (Sink): Submarine canyons that extend close to shore (e.g., Mugu, Redondo, Newport and Monterey submarine canyons) (Figure 3.5) serve as effective barriers to littoral drift and terminate most littoral cells in California. These canyons are the largest permanent sink for sand in California. Sand accumulates at the heads of these submarine canyons and, through underwater sand flows or turbidity currents, is funneled away from the shoreline and deposited in deep offshore basins.

Figure 3.5: Monterey Submarine Canyon

It is believed that an average of over a million cubic yards of sand is annually transported down into Mugu Submarine Canyon, thus terminating the littoral drift within the Santa Barbara littoral cell. Monterey Submarine Canyon (Figure 3.5), located in the center of Monterey Bay, is one of the world's largest submarine canyons and is over 6,000 feet deep. An average of at least 300,000 yds^3 of sand is annually lost down this canyon. As part of sand budget calculations, after all sand sources and other sinks are first accounted for, any remaining sand in the budget is assumed to be directed into a submarine canyon, where one exists and reaches close enough to the shoreline to trap littoral drift, and is permanently lost to the littoral cell.

Sand Mining (Sink): Sand and gravel removed from riverbeds, beaches, dunes and nearshore areas for construction and/or commercial purposes, represents a significant permanent sink for some of California's littoral cells. Sand mining along the beaches of California and Oregon began in the late 1800s when there seemed to be an overabundance of sand and no obvious impacts from mining. Overall in northern California, (i.e., from the Oregon border to the Russian River), about 8 million yds^3 (11 million tons) of sand and gravel are removed each year from the coastal streambeds (Magoon and Lent, 2005). In southern California, the annual total is nearly 41.5 million yds^3 (56 million tons), primarily in the greater Los Angeles and San Diego areas.

Beach or streambed sand mining has historically been a large sink for beach sand in some specific locations; however the volumes removed are difficult to quantify for the purposes of a sand budget. Due to the proprietary (and therefore publicly unavailable) nature of sand mining operations, gathering information on specific mining practices for a given river or beach within a littoral cell may not be possible. Information on mining should be included in long-term sand budgets when available. While there are still extensive sand and gravel mining operations along many streambeds in California, direct removal of sand from the beach along the coast of California was mostly terminated by the early 1990's. However, mining of the back beach still occurs at some sites (e.g., near Marina in southern Monterey Bay) (Figure 3.6).

Figure 3.6: Sand is still mined directly from the back beach in the Marina area of southern Monterey Bay (2005). Copyright © 2005 Kenneth and Gabrielle Adelman, California Coastal Records Project, www.Californiacoastline.org.

LITTORAL DRIFT CHECK POINTS

Direct measurement of the volume of sand moving as littoral drift would confirm estimated sand inputs from streams and bluffs; however, such direct measurement is unfortunately not feasible. However, California's four large ports and 21 small craft harbors (Figure 3.7) can serve as constraints, or check points, on this volume when developing sand budgets. Half of the littoral cells in California (10 of the 20 cells) contain at least one harbor that effectively traps the littoral drift. These coastal sand traps, however, are very different from dams and reservoirs, which keep sand from ever entering the littoral system.

Much of the sand moving along the coast as littoral drift is caught in either harbor entrances or designed trapping areas, dredged, and, with few exceptions, placed downdrift. The configuration and

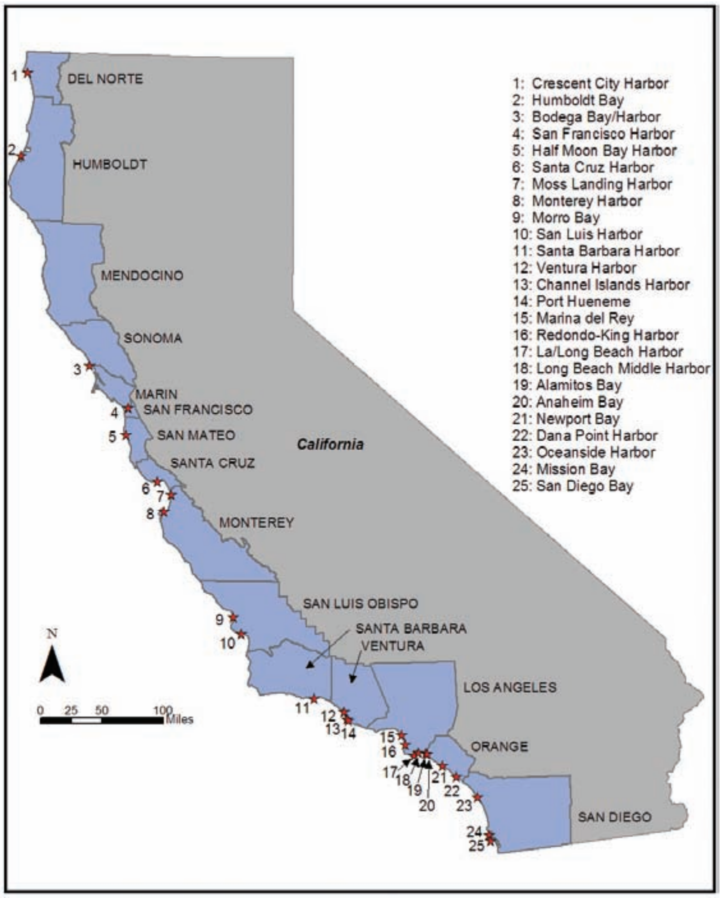

Figure 3.7: California's harbors and location by county.

geometry of some harbors (e.g., Ventura and Channel Islands; Figure 3.8) were designed to trap littoral drift before it enters the harbor's navigation channel. Sand resides in these sediment traps until it is dredged, typically once or twice a year. Other harbors (e.g., Humboldt Bay, Oceanside, and Santa Cruz harbors) were not designed with a specific sediment trapping area. Thus, once the sand residing upcoast of the first jetty reaches the jetty tip, littoral drift travels around the jetty and accumulates in the harbor entrance channel, often forming a sandbar. While some littoral drift may naturally bypass the entrance channel, especially at those harbors designed without a specific trapping area, harbor dredging records are the most dependable numbers currently available for estimating long-term annual gross and, occasionally, net littoral drift rates.

For purposes of sand budget calculations, there must be enough sand being added to the littoral cell to balance the average dredged volume. Some littoral cells have more than one harbor, and thus multiple check points for quantifying the cell's littoral drift. These cells provide optimum conditions for developing reliable sand budgets.

Inherent errors do exist when using harbor entrance dredging volumes to estimate littoral drift as checkpoints in the development of

Figure 3.8: Ventura Harbor: maintenance dredging in 1972. Copyright © Kenneth and Gabrielle Adelman, California Coastal Records Project www.Californiacoastline.org

littoral cell sand budgets, however. Errors involved in estimating dredging volumes include, but are not limited to, the type of equipment used to dredge, and the time frame of sand removal and placement. There can also be uncertainties involved in the pre-dredge conditions and the method used to determine the reported volume of sand dredged from a location.

Other uncertainties include: 1–harbors, (e.g., Oceanside) where detailed studies indicate that littoral drift reverses seasonally, such that sand can be dredged twice, and; 2- significant natural bypassing of sand beyond the dredging area can also occur (e.g., again at Oceanside, where sand appears to have been transported offshore and formed a permanent bar) (Dolan, Castens, et al., 1987; Seymour and Castel, 1985).

It is believed, however, that the margin of error involved in estimating dredged sand volumes is still significantly lower than the error associated with quantifying the annual volumes of most sand sources and sinks within littoral cells (such as the sand contribution from streams and cliff erosion and sand lost to submarine canyons). For most harbors, entrances or trapping areas form nearly complete littoral drift traps. Where long-term data exist, which tend to average out year to year fluctuations, harbor dredging records provide rational check points for littoral cell sand budgets.

Chapter 4

SAND BUDGETS FOR CALIFORNIA'S MAJOR LITTORAL CELLS AND CHANGES IN SAND SUPPLY

The beaches of southern California are intensively used recreational areas that generate billions of dollars of direct revenue annually. Wide, sandy beaches, used by people playing volleyball, sunbathing, swimming, jogging and surfing, are the quintessential image of southern California. Wide, sandy beaches, however, were not always the natural condition. Many of these beaches have been artificially created and maintained through human intervention, including placement of massive amounts of sand and the construction of groins, jetties and breakwaters (Flick, 1993). The rate at which sand was added to these beaches, however, has diminished over the past 30 years, fueling the public's perception of erosion and the narrowing of the beaches. Sand sources for most of the littoral cells in southern California are minimal to begin with, and have been reduced further through stream channel sand mining and the damming of rivers, and, to a lesser extent, armoring of seacliffs and reduction in beach nourishment projects.

Sand is naturally supplied to the beaches of California's littoral cells from a combination of river discharge, seacliff erosion, and dune deflation or erosion. In addition, sand has been added to the beaches historically through various beach nourishment projects. These elements are included as inputs for the sand budgets presented in this summary for the major littoral cells in California. The cells described include (Figure 2.5) Eureka, Santa Cruz, Southern Monterey Bay, Santa Barbara, Santa Monica, San Pedro, Laguna, Oceanside, Mission Bay, and Silver Strand littoral cells.

Table 4.1 summarizes selected major littoral cells and the relative importance of individual sand sources to the total sand supplied to the cells. These data were developed for and derived from the more detailed companion study which quantified sand budgets for these littoral cells (Patsch and Griggs, 2006). Under present-day (i.e., dams in place) conditions (excluding beach nourishment), and based on all data published to date, fluvial inputs constitute about 87% of the sand entering California's major littoral cells and 90% of the sand provided to southern California beaches (from Santa Barbara to the Mexico border). Seacliff erosion contributes 5% of the sand to the major littoral cells statewide, and about 10% of the sand reaching the beaches in southern California. Dune recession statewide accounts for 8% of the sand in the statewide analysis but is 0% in southern California

When beach nourishment is taken into account as a contributing source of sand, the relative importance of rivers, bluffs, and dune erosion statewide drops to 72%, 4% and 7% respectively in California's major littoral cells, with beach nourishment accounting for the remaining 17% of the sand input. In southern California, beach nourishment represents 31% of the sand supplied to the beaches, thus reducing the importance of river and bluff inputs to 62% and 7% respectively.

Table 4.2 is a summary of the anthropogenic reductions to the sand supplied to the major littoral cells in California and to southern California from armoring of seacliffs and damming of rivers. In addition, these reductions are contrasted against the sand supplied through beach nourishment, and a net balance associated with these anthropogenic changes is shown. The greatest reduction in sediment supplied to southern California results from the damming of rivers. Such damming has reduced the apparent volume of sand

Littoral Cell	All Sand Volumes in yd3/yr	Rivers	Bluff Erosion	Dunes	Beach Nourishment	Total Sand Supply
Eureka	Total "Actual" sand contribution	2,301,000	0	175,000	0	2,476,000
	% of Budget	93%	0%	7%	0%	100%
Santa Cruz	Total "Actual" sand contribution	190,000	33,000	0	0	223,000
	% of Budget	85%	15%	0%	0%	100%
Southern Monterey Bay	Total "Actual" sand contribution	489,000	0	353,000	0	842,000
	% of Budget	58%	0%	42%	0%	100%
Santa Barbara	Total "Actual" sand contribution	2,167,000	11,000	0	0	2,178,000
	% of Budget	99%	1%	0%	0%	100%
Santa Monica	Total "Actual" sand contribution	70,000	148,000	0	526,000	744,000
	% of Budget	9%	20%	0%	71%	100%
San Pedro	Total "Actual" sand contribution	278,000	2,000	0	400,000	680,000
	% of Budget	41%	0%	0%	59%	100%
Laguna	Total "Actual" sand contribution	18,000	8,000	0	1,000	27,000
	% of Budget	66%	31%	0%	4%	100%
Oceanside	Total "Actual" sand contribution	133,000	55,000	0	111,000	299,000
	% of Budget	23%	9%	0%	19%	51%*
Mission Bay	Total "Actual"sand contribution	7,000	77,000	0	44,000	128,000
	% of Budget	5%	60%	0%	35%	100%
Silver Strand	Total "Actual"sand contribution	42,000	0	0	256,000	298,000
	% of Budget	14%	0%	0%	86%	100%
Total	Total "Actual" sand contribution	5,695,000	335,000	528,000	1,338,000	7,896,000
	% of Budget	72%	4%	7%	17%	100%
Southern CA Total: (Santa Barbara cell to Mexico)	Total "Actual" sand contribution	2,715,000	301,000	0	1,338,000	4,354,000
	% of Budget	62%	7%	0%	31%	100%
Total: Without Beach Nourishment	All	87%	5%	8%	N/A	6,558,000
	Southern CA	90%	10%	0%	N/A	3,016,000

Table 4.1: Summary of the average annual (post-damming and seacliff armoring) sand contributions from rivers, seacliff erosion, dune recession, and beach nourishment to the major littoral cells in California. * Gully erosion and terrace degradation accounts for the remaining 49% of the sand in the Oceanside littoral cell. This category is not accounted for in this table. Nourishment data is for the period 1930–1993. (For data sources see Patsch and Griggs, 2006)

reaching the beaches within the state's major littoral cells and to southern California cells by about 43% and 47%, respectively. The reduction in southern California equates to nearly 2.4 million yds^3 of sand annually (Willis and Griggs, 2003). Seacliff armoring has reduced the sand supplied to the major littoral cells and southern California's beaches by 11% and 10%, respectively. The southern California reduction is about 35,000 yds^3 annually, still less than 7% of the total sand input to all of these littoral cells.

Littoral Cell		Rivers (dams)	Bluff Erosion (armor)	Total Reduction	Beach Nourishment	Balance (nourishment-reductions)
Eureka	Reduction yd^3/yr	N/A	N/A	N/A	0	N/A
	Percent Reduction	N/A	N/A	N/A		
Santa Cruz	Reduction yd^3/yr	6,000	8,000	14,000	0	-14,000
	Percent reduction	3%	20%	6%		
Southern Monterey Bay	Reduction yd^3/yr	237,000	N/A	237,000	0	-237,000
	Percent reduction	33%	N/A	33%		
Santa Barbara	Reduction yd^3/yr	1,476,000	3,000	1,479,000	0	-1,479,000
	Percent reduction	41%	19%	40%		
Santa Monica	Reduction yd^3/yr	29,000	2,000	31,000	526,000	495,000
	Percent reduction	30%	1%	13%		
San Pedro	Reduction yd^3/yr	532,000	0	532,000	400,000	-132,000
	Percent reduction	66%	0%	66%		
Laguna	Reduction yd^3/yr	0	1,000	1,000	1,000	0
	Percent reduction	0%	13%	4%		
Oceanside	Reduction yd^3/yr	154,000	12,000	166,000	111,000	-55,000
	Percent reduction	54%	18%	47%		
Mission Bay	Reduction yd^3/yr	65,000	17,000	82,000	44,000	-38,000
	Percent reduction	91%	18%	50%		
Silver Strand	Reduction yd^3/yr	41,000	0	41,000	256,000	215,000
	Percent reduction	49%	0%	49%		
Total	Reduction yd^3/yr	2,540,000	43,000	2,583,000	1,338,000	-1,245,000
	Percent reduction	43%	11%	39%		
Southern CA Total	Reduction yd^3/yr	2,297,000	35,000	2,332,000	1,338,000	-994,000
	Percent reduction	47%	10%	44%		

Table 4.2: Summary of the anthropogenic reductions to the sand supplied to the major littoral cells in California and to southern California, due to seacliff armoring and the damming of rivers. In addition, sand supplied to the cells through beach nourishment is shown for the period 1930–1993. Note: sand bypassing at harbor entrances is not included in the nourishment volume.

CHAPTER 5

DISCUSSION OF BEACH NOURISHMENT IN CALIFORNIA

Beach nourishment or beach restoration is the placement of sand on the shoreline with the intent of widening beaches that are naturally narrow or where the natural supply of sand has been significantly reduced through human activities. Although there are several different approaches to beach nourishment, procedures are generally distinguished by methods of fill placement, design strategies, and fill densities (Finkl, et. Al. 2006; NRC, 1995; Dean, 2002). Types of nourishment according to the method of fill emplacement include the following (Figure 5.1; Finkl, et. al. 2006)):

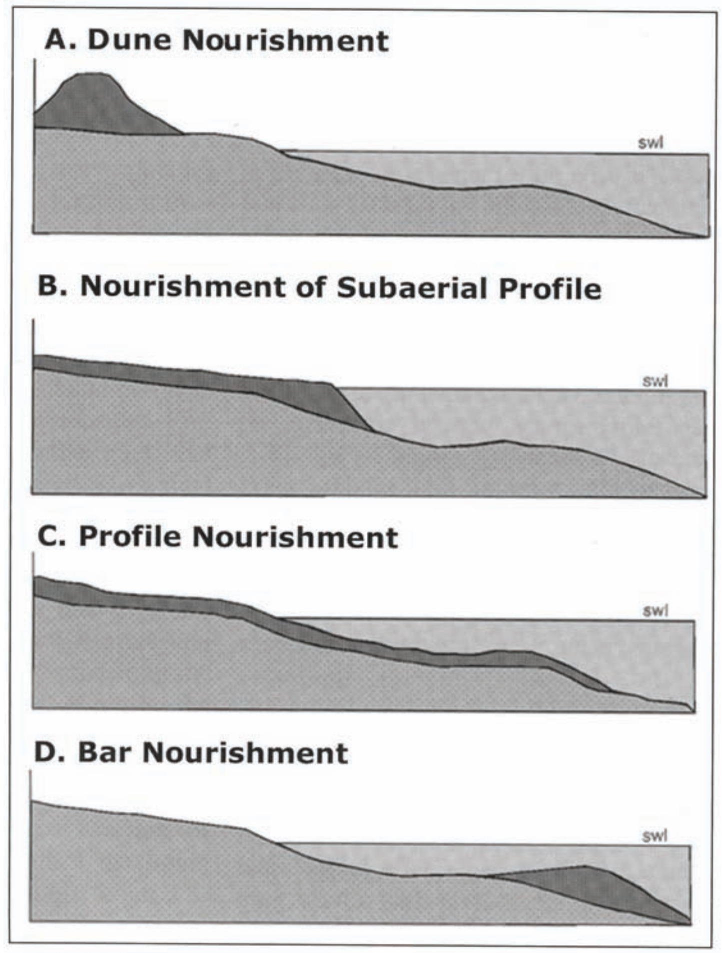

Figure 5.1. Methods of beach nourishment defined on the basis of where the fill materials are placed (from Finkl, Benedet and Campbell, 2006).

(a) Dune nourishment: sand is placed in a dune system behind the beach.

(b) Nourishment of subaerial beach: sand is placed onshore to build a wider and higher berm above mean water level, with some sand entering the water at a preliminary steep angle.

(c) Profile nourishment: sand is distributed across the entire beach and nearshore profile.

(d) Bar or nearshore nourishment: sediments are placed offshore to form an artificial feeder bar.

Nourished shorelines provide two primary benefits: increased area for recreation and greater protection of the coastline against coastal storms. Other potential benefits include, but are not limited to, increased tourism revenues, increased public access, reduced need for hard protective structures, higher property values, enhanced public safety and restored or expanded wildlife habitats.

Beach nourishment in California has been concentrated primarily in the southern part of the state. Flick (1993) summarized the history of beach nourishment in southern California and determined that over 130 million yds[3] of sand was added to those beaches between 1930 and 1993. About half of this amount was divided evenly between the Santa Monica and the Silver Strand littoral cells where the beaches widened significantly in response to this nourishment. Wiegel (1994) prepared a very thorough evaluation of ocean beach nourishment along the entire USA Pacific Coast; however, the report is mostly about Southern California because of the numerous beach nourishment projects that have taken place there.

What is clear is that there are major differences between the tectonic, geomorphic, oceanographic, climatic, and wave conditions along the Pacific Coast as compared to the Atlantic and Gulf Coasts. In addition to these inherent geological and oceanographic differences, there is a pronounced difference in the practice of beach nourishment (Finkl, et. al., 2006). Large nourishment projects using sand from offshore are common along the Atlantic and Gulf Coasts, but beneficial or opportunistic sediment (from coastal construction, channel maintenance and bypass operations) predominate on the West Coast (Herron, 1987; Flick, 1993; Wiegel, 1994).

The California Beach Restoration Study (2002) is a comprehensive assessment of California's beaches and their economic benefits, beach nourishment and restoration, as well as an evaluation of the major sources of sand to the state's beaches and how these have been impacted by human activity (http://www.dbw.ca.gov/beachreport.htm). The report concludes that continued loss of many public beaches could be substantially reduced by beach nourishment.

Opportunistic beach nourishment, which has provided the majority of sand historically used for beach nourishment in southern California, occurs when beach-compatible sand from a harbor development or expansion project, excavation for a large coastal construction project (e.g., El Segundo Power Plant or Hyperion Sewage Treatment Plant construction) or other construction or maintenance project is placed on nearby beaches. In other words, such sand is a byproduct of some construction or maintenance project that was not undertaken with beach replenishment or nourishment as a specific goal, but rather as an added benefit.

In addition to opportunistic beach nourishment there are other projects (the largest example being the 2001 SANDAG project in San Diego County) where sand has been delivered to the coastline with the sole purpose of widening the existing beaches. Sand may come from either terrestrial (stream channels or dunes, for example) or offshore sources (the inner shelf).

Beach nourishment, unless it takes place where there is a headland or other natural barrier to littoral transport, or unless it is accompanied by some structure or mechanism of holding the sand in place (e.g., groins), may not provide a long-term solution to narrow beaches or beach erosion in California, simply because the high to very high littoral drift rates that characterize most of California's shoreline will tend to move any additional sand added to the shoreline alongshore.

In the absence of any major reductions in littoral sand supply (due to either large-scale climatic fluctuations or human activities), beaches over the long-term will tend to approach some equilibrium size or width; e.g. a summer width that will vary about some mean from year to year. This width is a function of a) the available littoral sand, b) the location of barriers or obstructions to littoral transport (Everts and Eldon, 2000; Everts, 2002) c) the coastline orientation, and d) and littoral drift direction and rate, which is related to the amount of wave energy incident on the beach and the angle of wave approach.

In northern Monterey Bay, for example, because of the direction of dominant wave approach and the coastline orientation, those shorelines oriented northwest-southeast, or east-west (and where littoral transport barriers exist), such as the Santa Cruz Main Beach, Seabright Beach, or the inner portion of Monterey Bay, have wide well-developed beaches (A. Figure 5.2). In contrast, where the coastline is oriented essentially north-south (from Lighthouse Point to Cowell's Beach (B. Figure 5.2) and the Opal Cliffs shoreline between Pleasure Point and New Brighton Beach, for example), and where no significant littoral drift barriers exist, beaches are narrow to nonexistent because littoral drift moves the sand along this stretch of coast rapidly without any retention.

Figure 5.2. The coastline of northern Monterey Bay at Santa Cruz illustrating how the orientation of the coastline determines whether or not a beach forms. Where the shoreline is oriented essentially east-west and littoral barrier exist (A), wide stable beaches have formed. Where the coastline is oriented essentially north-south and there is no barrier, beaches rarely form (B). North is up in the photograph.

FACTORS AFFECTING THE LONGEVITY OF A BEACH NOURISHMENT PROJECT

It has often been assumed that the important parameters in the durability or longevity of a beach nourishment or replenishment project include the alongshore length of the nourishment project, the density or volume of fill placed, grain size compatibility with the native beach, the use of sand retention structures such as groins in conjunction with sand placement, and storm activity following nourishment. Those nourishment projects that had the greatest alongshore dimensions have been shown to last longer than shorter beach fills.

Fill Density: Density of the fill refers to the volume of sand per unit length of shoreline. The longevity of a nourishment project has often been assumed in the past to be directly related to fill density, with greater fill densities yielding longer life spans. In California, the initial fill densities range from 20,000 cubic yards per mile to 2,128,000 cubic yards per mile.

Grain Size: Grain size compatibility between the native beach and the fill material is also perceived to be an important factor in the longevity or durability of a nourished beach. Beach fill must be compatible with the grain sizes of the native sand (as coarse as or coarser than the native sand) such that the waves will not immediately carry the sand offshore. If the fill sand is to remain on the dry or exposed beach under prevailing wave conditions at the particular site, it must be larger than the littoral cut-off diameter.

Sand Retention Structures: Coastal structures aimed at retaining sand, such as groins or detached offshore breakwaters, have been successful in extending the life span of nourishment projects. For example, groins throughout the Santa Monica littoral cell and groins placed on beaches in Capitola, Ventura, Redondo Beach and Newport Beach have all been successful at stabilizing beach fill projects. However, if there is not enough sand in the system to begin with, groins will not be effective, as was the case at Imperial Beach where a series of groins has not been adequate to combat erosion. Groins will continue to trap littoral drift in the years following a beach nourishment project, thus maintaining the updrift beach. Groins must be considered on a regional scale, however. While beaches updrift of groins will be stabilized or widened, beaches downdrift of a groin may experience erosion once their sand supply is cut-off. A series of groins along the shoreline of interest in conjunction with beach nourishment may be an effective way to address downdrift beach erosion.

Offshore breakwaters have been widely used in Europe and in a few locations in the United States to stabilize or widen beaches by reducing wave energy and littoral drift in the lee of the breakwater. These offshore structures can be either slightly submerged, at sea level, or slightly above sea level. The offshore breakwater at Venice is a good example of the effects of such a structure in California, where the beach landward of the breakwater significantly widened (Figure 5.3). The Santa Barbara breakwater was completed in 1929 as a detached offshore structure. Although the purpose of the breakwater was to provide a protected anchorage for boats, accretion of littoral sand in the lee of the structure by the fall of 1929 had become so serious that the breakwater was extended to the beach at Pt. Castillo, a distance of about 600 feet. This was followed by rapid deposition of sand on the west or up-coast side of the structure (Griggs, Patsch and Savoy, 2005).

Detached offshore breakwaters can effectively reduce wave energy at the shoreline, thereby widening or stabilizing otherwise narrow or eroding beaches. They are not without their impacts, however: high construction costs, navigation hazards for vessels, dangers for recreational coastal water users, as well as a reduction in sand transport to down coast beaches are all important considerations.

Storm Intensity: The life span of beach nourishment projects has been correlated with storm intensity to which a fill is exposed. Large or extreme storms, such as those that have occurred during El Niño years, have caused increased beach erosion, whether nourished or not. Sand removed from the beaches during these large storm events is often deposited on offshore bars where it is stored until the smaller waves associated with the summer months carry the sand back to the beach. During conditions of elevated sea levels and very large waves, sand may be transported offshore into deep enough water where summer waves cannot move the sand back onshore. Longshore transport may also increase with the larger storm waves, thus reducing the residence time of the sand on a nourished beach.

During the strong 1997-98 El Niño, however, monthly beach surveys collected along 22 miles of Santa Cruz County coastline showed that although the beaches experienced extreme erosion during the winter months, by the end of the summer of 1998 all but one beach had returned to their original pre- El Niño widths (Brown, 1998).

Figure 5.3. Offshore breakwater at Venice where beach has widened in protected area behind breakwater (2004). Photo © Kenneth and Gabrielle Adelman, California Coastal Records Project, www.Californiacoastline.org

ISSUES INVOLVED WITH BEACH NOURISHMENT

While beach nourishment appears to be an attractive alternative to either armoring the coastline with seawalls, riprap or revetments, or to relocating threatened structures inland, as with any large construction project, there are a number of issues or considerations that need to be carefully evaluated and addressed. In California, littoral cells span large stretches of the coastline, from 10 miles to over 100 miles in length, and, in most locations, experience high net littoral drift rates (from 150,000 yd^3/yr to over 1 million yd^3/yr). As a result, the life span or longevity of sand placed on a particular beach may be short (less than a single winter, in some cases) due to the prevailing winter waves transporting the sand alongshore as littoral drift. Properly constructed and filled retention structures (groins, for example) can help increase the longevity of beach fill.

In addition, potential considerations associated with beach nourishment in California include costs, financial responsibility for the initial project and subsequent re-nourishment, the source and method for obtaining sand, transportation of large quantities of sand to the nourishment site, and the potential smothering or temporary loss of marine life or habitats when placing the sand.

The availability of large quantities of beach compatible sand is a significant issue that has not been completely explored. Sand exists offshore in large volumes but it may not always be beach compatible. In addition, there are environmental and habitat issues that need to be evaluated and possibly mitigated. Some offshore areas are protected, such as the 400 miles of coastline included within the Monterey Bay National Marine Sanctuary, and for which dredging sand from the seafloor is a complex issue with a long list of environmental concerns and probable opposition.

While consideration is being given to removing sediment from behind dams essentially completely filled (e.g., Matilija Dam on the Ventura River and Rindge Dam on Malibu Creek) and placing such sediment on the beach, there is not yet any agreed upon approach for accomplishing this objective. Dam removal followed by natural fluvial transport, trucking, and slurry pipelines have all been studied and each has their costs and impacts. Even though this sediment would have been delivered to the shoreline by these streams under pre-dam natural conditions, accomplishing the same "natural process" today is far more complex. The release of all of the impounded sediment would overwhelm any downstream habitats that are now being protected. In addition, the current USEPA guidelines do not normally allow any sediment to be placed on beaches when the amount of fines (silt and clay) is over 20% (the so-called 80:20 guideline, or acceptable sediment for beach nourishment must consist of at least 80% sand and no more than 20% silt and clay). Unfortunately, the sediment transported by streams and trapped behind dams doesn't follow this 80:20 guideline and contains far more than 20% silt and clay. As a result, most sediment impounded in reservoirs might not be acceptable to the EPA for beach nourishment under such criteria, even though these same streams naturally discharge such sediment every winter to the shoreline, where waves and coastal currents sort out all of this material. The USEPA has and is working with project proponents to identify appropriate conditions that allow the use of sediments with a fine-grained content greater than 20% to be used for beach restoration purposes. These conditions are described in CSMW's Sand Compatibility and Opportunistic Use Program (SCOUP) report. (http://www.dbw.ca.gov/csmw/csmwhome.htm).

If inland sources of beach compatible sand can be located, approved, and transported to the coastline, there are additional challenges of getting the material onto the beach and spreading it out in a timely manner. A 200,000-yds^3 beach nourishment project, for example, would require 20,000 10-yds^3 dump trucks.

In California, obtaining sand from an inland source to place on the beach is far more costly than sand from offshore sources, primarily due to significantly higher removal and transport costs. Inland sources provided by trucking would also have environmental impacts associated with the quarrying, transport, and placement of the sand. Estimates in the Monterey Bay area for truck delivered beach-quality sand in 2004 were around \$21/yd^3. The offshore area in this location is a National Marine Sanctuary such that dredging sand from the seafloor is not acceptable under existing policies. The estimated cost associated with delivering ~240,000 yd^3 of sand (to build a beach ~3,000 feet long and 100 feet wide) from an inland source from a recent proposal for a nourishment project in southern Monterey Bay would be ~\$5.5 million dollars (~\$23/yd^3) (O'Connor and Flick, 2002).

It is also important to look objectively at the logistics of a nourishment project of this scale. Placing 240,000 yd^3 of sand on the beach would require 24,000 10-yd^3 dump truck loads of sand. If a dump truck could deliver a load of sand to the beach and dump it every 10 minutes, 48 truckloads could be dumped in an 8-hour day. Keeping this process going 7 days a week could deliver 1440 truckloads or 14,400 yd^3 each month. At this rate, it would take over 16 months to complete this nourishment project. There are also issues of delivering sand in the winter months when high wave conditions might make truck traffic on the beach difficult; placing sand in the winter-months would also reduce the lifespan of the nourished sand. However, beaches are used the most during the summer months. While none of these are overwhelming obstacles, beach nourishment from inland sources by truck is not a simple or straightforward process. Smaller-scale maintenance projects would take proportionally less time to deliver smaller amounts of sand, and while more logistically feasible, don't have the impacts of larger projects.

Beach nourishment projects using terrestrial or inland sources of sand can be very expensive undertakings and any such project will probably have to be re-nourished on a regular basis unless the sand is retained. The limitations and costs associated with beach nourishment and re-nourishment must be balanced by the ultimate benefits of the project, including the recreational, environmental, and economic value of widening a beach, in addition to the back-beach protection offered to development by a wider beach.

NOURISHMENT HISTORY OF INDIVIDUAL LITTORAL CELLS

In California, beach nourishment (not including harbor bypassing) has historically provided on average ~1.3 million yd^3 annually to the beaches in southern California (Point Conception to the international border), representing 31% of the overall sand budgets in the area (Table 4.1). Large quantities of sand excavated during major coastal construction projects, such as the excavation associated with the Hyperion Sewage Treatment Facility (17.1 million yd^3 from 1938-1990) and Marina del Rey (~10 million yd^3 from 1960-1963) in the Santa Monica littoral cell, as well as the dredging of San Diego Bay (34 million yd^3 between 1941-1985) have provided millions of cubic yards of sand to the beaches of southern California (see comprehensive summary articles by Flick, 1993 and Wiegel, 1994 for detailed discussion of southern California beach nourishment projects.). Between 1942 and 1992 about 100 million yd^3 of material were placed on the beaches with approximately half of the sand derived from harbor or marina projects (Flick, 1993).

Santa Monica Littoral Cell: In the Santa Monica littoral cell, over 29 million yd^3 of sand has been placed on the beaches since 1938 for projects where the primary objective was not specifically beach nourishment. As a result, the shoreline in many areas of Santa Monica Bay advanced seaward from 150 to 500 feet from its earlier natural position. Although the majority of beach fill was placed prior to 1970, beaches in this area are still wider than their natural pre-nourished state, due, in large part, to the construction of retention structures to hold the sand in place. Currently, there are 5 breakwaters, 3 jetties and 19 groins along the nearly 19 miles of shoreline from Topanga Canyon to Malaga Cove, effectively retaining the sand before it is lost into Redondo Submarine Canyon. Sand retention structures have been very effective at maintaining the wide artificial beaches in the Santa Monica littoral cell because of the nearly unidirectional longshore transport to the southeast.

San Pedro Littoral Cell: In the San Pedro littoral cell, federal, state and local governments fund ongoing beach nourishment at Sunset Beach (just downcoast of Seal Beach) to maintain a wide enough beach to meet the recreational needs of the area and to mitigate for the erosion caused by the construction of the Anaheim jetties. The area is nourished with ~390,000 yd^3 of sand annually. Herron (1980) stated that 22,000,000 yd^3 of sand from harbor and river projects have been placed on the 15 miles of public beaches of the San Pedro littoral cell.

Oceanside Littoral Cell: Nearly 11.9 million yds^3 of sand were placed on the beaches of the Oceanside Cell between 1943 and 1993 (Flick, 1993). This represents an annual average rate of about 250,000 yd^3. Most of this sand has come from the dredging of Agua Hedionda Lagoon and Oceanside Harbor which each contributed about 4 million yd^3 in 1954 and 1961, respectively. About 1,300,000 million yd^3 were trucked from the San Luis Rey River bed to the Oceanside beaches in 1982. Two smaller projects, construction of the San Onofre Nuclear Power Plant and nourishment of Doheny Beach, each generated about 1,300,000 million yd^3.

Mission Bay Littoral Cell: The beaches in the Mission Bay littoral cell have also benefited from large construction projects along the coastline. Nearly 4 million cubic yards of sand dredged from Mission Bay to create the aquatic park and small craft harbor were placed on the beaches to create wider recreational areas. The upcoast jetty at

Mission Bay now holds the southern portion of Mission Beach in place. A concrete seawall about 13 feet above mean sea level backs the Mission Beach area but was overtopped during both the 1982-83 El Niño and the unusual storm of January 1988 (Flick, 2005).

Silver Strand Littoral Cell: The Silver Strand littoral cell is somewhat unique in the region in having an overall net littoral transport from south to north. The nearly 35 million yds^3 of sand placed on its beaches since 1940 represents the most highly altered stretch of beach in southern California (Flick, 1993). Much of this volume, about 26 million yds^3, was excavated from the massive expansion of naval facilities in San Diego Bay just after WWII. Prior to this effort, the Silver Strand had been a relatively narrow sand spit separating San Diego Bay from the ocean, which was occasionally overwashed by storm waves.

THE SAN DIEGO ASSOCIATION OF GOVERNMENTS (SANDAG) BEACH NOURISHMENT PROJECT

The most recent large-scale, non-opportunistic beach nourishment project in California with the sole purpose of widening the beaches was completed in San Diego County in 2001. Approximately 2-million yds^3 of sand were dredged from six offshore sites and placed on 12 beaches in northern San Diego County at a total cost of $12.25 million dollars or $5.83/yd^3 (Figure 5.4). This project was coordinated by local governments working together through SANDAG and was funded by $16 million in state and federal funds and about $1.5 million from the region's coastal cities. It was seen as an initial step in overcoming what has been perceived as a severe sand deficit on the region's beaches.

A total of six miles of beaches were nourished from Oceanside on the north to Imperial Beach on the south (Figures 5.4 & 5.5). Eighty-five percent of the sand went to the beaches of the Oceanside Littoral Cell. A comprehensive regional beach-profiling program had been in place since the 1983 El Niño event, which provided a baseline for monitoring the results or status of many of the individual nourished sites. Sixty-two beach profile lines were surveyed, typically in the fall and in the spring. Seventeen of these profile lines either already existed or were established at the individual beach nourishment sites (Coastal Frontiers, 2005).

While it is difficult to completely evaluate and summarize the vast amount of beach survey data that have been collected in this report, it is important to try and extract some overall measures of performance or behavior following the nourishment if we are to derive any useful conclusions from this large project.

At 14 of the 17 nourishment sites surveyed, the beach width (determined by the mean sea level shoreline position) narrowed significantly between the fall of 2001 (immediately following sand placement) and the fall of 2002. While the surveyed beaches showed initial increases in width of 25 to over 100 feet from the nourishment, most of these beaches narrowed 20 to 60 feet during the first year following sand emplacement. Twelve of the 17 sites showed further decreases in width over year two, and 13 of these sites continued to decrease in width in the 3rd year. Three of the beaches in the Oceanside Cell showed modest width increases (6 to 15 feet) in the first year following nourishment, but in the two following years all declined in width.

A very detailed study of the Torrey Pines State Beach fill project was carried out as part of the post-nourishment monitoring (Seymour, et al. 2005). This fill was 1600 feet long and included about 330,000 yds^3 of sand, one of the larger fills. Rather than being constructed as a sloping fill, the upper surface was level and terminated in a near-vertical scarp about 6 feet high. Profiles 65 feet apart were collected bi-weekly along 1.8 miles (9500 feet) of beach and extended

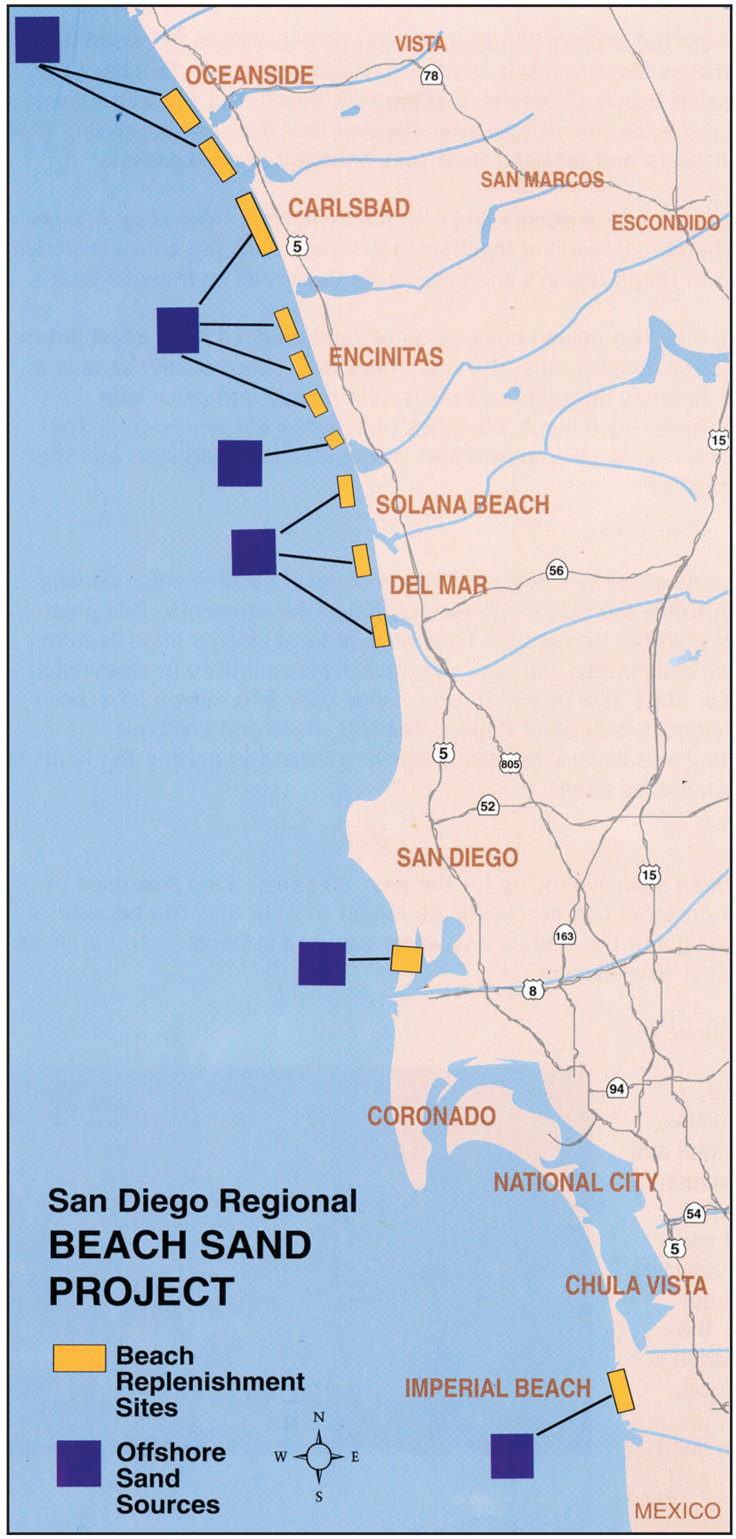

Figure 5.4. Offshore sand sources and nourishment sites for the 2001 SANDAG 2,000,000 yds^3 beach nourishment project.

offshore to a depth of 26 feet. The temporal and spatial resolution provided by this surveying program, in combination with offshore wave measurements, provided an exceptional database for documenting the relationship between wave conditions and the behavior of a beach fill (Seymour, et. al., 2005).

The fill was completed near the end of April, 2001 (Figure 5.6). Wave

Figure 5.5: Beach nourishment at South Carlsbad State Beach. In July 2001. 150,000 yds^3 of sand were placed on this beach in a fill that was 2000 feet long, 180 feet wide and up to + 12 feet msl.

conditions during the summer and fall were mild, with significant wave heights (the average of the highest 1/3 of the waves) generally less than 3 feet except for a few incidents of waves as high as 5 feet. The front scarp of the fill remained intact and there were only modest losses at the ends of the fill.

At noon on Thanksgiving Day, November 22, 2001, significant wave heights reached nearly 10 feet and remained in the range of 9 to 10.5 feet for seven hours. The fill was overtopped and began to erode quickly. By daylight on November 23, the fill had been almost completely eroded to the riprap at the back of the beach (Seymour, et al., 2005). The fill was stable for approximately 7 months of low wave energy conditions, but was removed within a day when the first large waves of the winter arrived.

Some overall conclusions can be drawn from the four years of published beach surveys in the nourished areas (Coastal Frontiers, 2005). The performance of the individual beach fills varied considerably. At some sites, such as Del Mar, Moonlight, and South Carlsbad, the gains in the shorezone (defined as the subaerial or exposed portion of the beach as well as the nearshore sand out to the seasonal depth of closure) that occurred during placement of fill were short-lived. At other sites, such as Mission Beach and Oceanside, the gains in the shorezone persisted through the time of the Fall 2004 survey. In many cases, dispersal of the fill was accompanied by shorezone volume gains on the downdrift beaches. Both the grain size of the sand and the volume of the fill were important factors in how long nourished sand

Figure 5.6. Aerial view of the Torrey Pines beach fill project (from Seymour, et.al., 2005).

remained on the beach. For the smaller fills, erosion or losses from the ends of the fills were significant. One very small nourishment site in the Oceanside cell (Fletcher Cove) received a small volume of very-fined grained sand and it was removed very quickly.

Nearly all of the sand added to the beaches in the SANDAG project tended to move both offshore and also alongshore with the arrival of winter waves although much of this has persisted just offshore in the shorezone. This sand does provide some benefits including dispersing some of storm wave energy and flattening the beach profile. However, most of the general public expects to see a wider exposed beach as the benefit of a beach nourishment project. It is important to understand for the SANDAG project or any nourishment plan or proposal, that most beaches have some normal or equilibrium width, as discussed earlier. Without either regular or repeated nourishment or the construction of a retention structure, such as a groin, to stabilize or hold a beach fill, there is no reason why in an area of significant longshore transport and moderate to large winter wave conditions that the sand should stay on the exposed beach for any extended period of time. The considerations that need to be weighed prior to any beach nourishment project are whether the benefits of littoral cell or shorezone sand increases, and the potentially short-term or temporary beach width increases resulting from beach nourishment are worth the initial investment and continuing costs.

CHAPTER 6

CONCLUSIONS

Before large-scale human influence or interference, the majority of beaches in southern California were relatively narrow. Large coastal construction projects, the creation and expansion of harbors and marinas, and other coastal works found a convenient and cost-effective disposal site for excavated material on the beaches in southern California, thus creating the wide sandy beaches that people have come to expect in this region, particularly along the beaches of the Santa Monica littoral cell and the Silver Strand cell. The majority of sand was placed before the mid-1960's, however. Since then, the rates of nourishment have dropped sharply. In many cases, sand retention structures such as groins, built in conjunction with the placement of beach-fill, have been successful in stabilizing the sand and maintaining wider beaches. Carefully designed retention structures have been shown to extend the life of beach nourishment projects and should be considered when planning beach restoration projects in the future. A single episode of beach nourishment, however, will not provide a permanent solution to areas with naturally narrow beaches or to problems associated with beach erosion. Any potential California beach nourishment program should be viewed as a long-term and ongoing process.

When assessing the success or failure of a nourishment project, one must look beyond the individual beach where the nourishment took place and examine the regional effects throughout the entire littoral cell. Often the nourished site serves as a feeder beach, providing sand to be transported by littoral drift to "feed" or nourish the down-drift beaches.Where littoral drift rates have been documented they are typically in the range of about a mile-per-year (Bruun, 1954; Wiegel, 1964; Griggs and Johnson, 1976), although this will depend upon the wave energy, the orientation of the shoreline, and the angle of the dominant wave approach. Depending on the potential littoral drift in an area, as well as the coastline configuration and barriers to littoral transport, nourishment projects may or may not have a fairly short residence time on a particular beach. However, if well planned on a regional scale, the placed sand should feed the down-drift beaches until ultimately ending up in a submarine canyon, offshore, or retained behind a coastal engineering structure.

Because of California's high littoral drift rates, the emplacement of a well-designed, properly constructed and filled retention structure is also a very important consideration in the success or longevity of any beach fill or nourishment project. Groins and offshore breakwaters have been used successfully in a number of locations in California to widen or stabilize beaches (Ventura, Santa Monica and Newport Beach, for example). Retention structures can make the difference in the long-term success of a beach nourishment project. It is recommended that all existing retention structures and their effectiveness and impacts be evaluated so as to learn from past experiences and improve on their use in the future by mitigating any potential negative impacts.

When engineering a beach nourishment project in California, it is important to consider such elements as grain size compatibility, fill density, or the volume of sand per unit length, possible sand retention structures and the effects on down drift beaches, the rate and direction of littoral drift, and wave climate (including storm duration and intensity).

Harbor maintenance and large construction projects along the coast may be excellent sources of opportunistic beach nourishment. There are many difficulties associated with nourishing the beach with sand taken from an inland or terrestrial source including the 80:20 rule, cost, financial responsibility of the project, the source and method for obtaining sand, transporting large quantities of sand to the nourishment site, and the potential for covering over marine life or habitats when placing the sand. Offshore sand sources also have their limitations and impacts including costs, location of compatible sand offshore, permit issues such as environmental impacts associated with disturbing the seafloor habitat, transporting and placing large quantities of sand (Figure 5.5) increased turbidity, etc.

The limitations and costs associated with beach nourishment must be balanced by the ultimate benefits of the project including public safety and access, expanded wildlife habitat and foraging areas, the economic and aesthetic value of widening a beach, in addition to the back-beach or coastal protection offered by a wider beach.

REFERENCES CITED AND OTHER USEFUL REFERENCES

Best, T. C. and G. B. Griggs (1991a).
A sediment budget for the Santa Cruz littoral cell. Soc. Economic Paleontologists and Mineralogists Spec. Pub. No. 46: 35-50.

Best, T. C. and G. Griggs (1991b).
The Santa Cruz littoral cell: Difficulties in quantifying a coastal sediment budget. Proc. Coastal Sediments '91, ASCE: 2262-2277.

Bowen, A. J. and D. L. Inman (1966).
Budget of littoral sands in the vicinity of Point Arguello, California. Technical Memorandum No.19, U.S. Army Coastal Engineering Research Center. 41pp.

Brownlie, W. R. and B. D. Taylor (1981).
Sediment management for southern California mountains, coastal plains and shoreline. Pt. C. Coastal sediment delivery by major rivers in southern California. Cal. Institute of Technology Env. Quality Laboratory Report No. 17-C: 314pp.

Brown, K.B., (1998).
The effects of the 1997-98 El Niño winter on beach morphology along the Santa Cruz County Coast. Unpublished MS thesis, University of California, Santa Cruz.

Brune, G.M. (1953).
The trapping efficiency of reservoirs. Trans. Am. Geophys. Union 34:407-418.

Bruun, P. (1954).
Migrating sand waves or sand humps, with special reference to investigations carried out on the Danish north coast sea Proc.5th International Coastal Eng. Conf.,New York, ASCE.

Clayton, T. (1989).
Artificial beach replenishment on the U.S. Pacific Shore: A brief overview. Proc. Coastal Zone '89.,O. T. Magoon. New York, American Society of Civil Engineers: 2033-2045.

Coastal Frontiers (2005).
SANDAG 2004 Regional Beach Monitoring Program: Annual Report & Appendices.

Converse, H. (1982).
Barrier beach features of California. Proc. International Coastal Engineering Conf., 1982, New York, American Society of Civil Engineers.

Dean, R.G. (2002)
Beach Nourishment: Theory and Practice. River Edge, New Jersey. World Scientific, 397 pp.

Dean, R. G. and R. A. Dalrymple (2001).
Coastal Processes with Engineering Applications, Cambridge University Press, 475 pp.

Diener, B. G. (2000).
Sand contribution from bluff recession between Point Conception and Santa Barbara, California. Shore and Beach 68(2): 7-14.

Dixon, K. and O.H. Pilkey (1989)
Beach Replenishment along the U.S. Coast of the Gulf of Mexico. Proc. Coastal Zone '89, O. T. Magoon. New York, American Society of Civil Engineers: 2007-2020.

Dolan, T., P. Castens, et al. (1987).
Review of sediment budget methodology: Oceanside littoral cell, California. Proc. Coastal Sediments '87, New Orleans, Louisiana, American Society of Civil Engineers.

Everts, C.H. and C. D. Eldon (2000).
Beach retention structures and wide sandy beaches in Southern California. Shore and Beach 68:3: 11-22.

Everts, C. H. and C. D. Eldon (2005).
Sand capture in Southern California submarine canyons. Shore and Beach 73(1): 3-12.

Everts C. H. (2002).
Impact of Sand Retention Structures on Southern and Central California Beaches. Oakland, CA: California Coastal Conservancy. 105pp.

Ewing, L., O. T. Magoon, et al. (1999).
Proc. Sand Rights '99, Ventura, California, American Society of Civil Engineers.

Finkl, C.W., L. Benedet, and T.J. Campbell (2006).
Beach nourishment experience in the United States and trends in the 20th Century. Shore and Beach 74:2:8-16.

Flick, R.E. (2005).
Dana Point to the Mexican Border, In: Living with the Changing California Coast, Griggs. G., Patsch, K., and Savoy, L. University of California Press: pp.474-514.

Flick, R. E. (1993).
The myth and reality of Southern California beaches. Shore and Beach 61(3): 3-13.

Flick, R. E. and D. C. Cayan (1984).
Extreme sea levels on the coast of California. Proceedings of the 19th International Conference on Coastal Engineering, American Society of Civil Engineers.

Griggs, G. B. (1985).
Beach Compartments, littoral drift and harbor dredging. Proc. West Coast Regional Design Conf., Oakland, Ca., USACE: 18-29.

Griggs, G.B., (1986).
Littoral cells and harbor dredging along the California coast., Environmental Geology 10: 7-20.

Griggs, G. (1987).
The production, transport, and delivery of coarse-grained sediment by California's coastal streams. Proc. Coastal Sediments '87, ASCE: 1825-1839.

Griggs, G. B. (2005).
California's Retreating Coastline: Where do we go from here? Proceedings of the Annual Mtg. American Meteorological Society, San Diego, California (CD-ROM).

Griggs, G. B. and J. R. Hein (1980).
Sources, dispersal, and clay mineral-composition of fine-grained sediment off Central and Northern California. Journal of Geology 88(5): 541-566.

Griggs, G.B. and R.E. Johnson (1976).
The effects of the Santa Cruz Small Craft Harbor on coastal processes in Northern Monterey Bay, California, Environmental Geology 1:229-312.

Griggs, G. B., K. B. Patsch, and L.E. Savoy (2005).
Living with the Changing California Coast. Berkeley, CA, U.C. Press: 525pp.

Habel, J. S. and G. A. Armstrong (1978).
Assessment and Atlas of Shoreline Erosion Along the California Coast. Sacramento, California, State of California, Department of Navigation and Ocean Development: 277 pp.

Heron, W.J. (1980).
Artificial beaches in Southern California. Shore and Beach 48 (1): 3-12.

Hicks, D. M. (1985).
Sand dispersion from an ephemeral delta on a wave-dominated coast. Unpub. Ph.D. dissertation. Earth Sciences Dept. Santa Cruz, University of California, Santa Cruz: 210pp.

Hicks, D. M. and D. L. Inman (1987).
Sand dispersion from an ephemeral river delta on the central California coast. Marine Geology 77: 305-318.

Inman, D. L. and T.K. Chamberlain (1960).
Littoral sand budget along the southern California coast (abstract). Report 21st International Geological Congress, Copenhagen.

Inman, D. L. and J. D. Frautschy (1966).
Littoral processes and the development of shorelines. Proc. Coastal Engineering Specialty Conf., ASCE

Johnson, A. G. (1935).
Beach protection and development around Los Angeles. Shore and Beach 3(4): 110-113.

Johnson, J. W. (1959).
The supply and loss of beach sand to the coast. Journal of Waterways and Harbor Division, Amer. Soc.Coastal Engineers 85: 227-251.

Kaufman, W. and O. Pilkey (1979).
The Beaches are Moving: The Drowning of America's Shoreline. Garden City, New York, Anchor Press/Doubleday.

King, P. (1999).
The Fiscal Impact of Beaches in California. A Report Commissioned by the California Department of Boating and Waterways: 29pp.

Komar, P. D. (1996).
The budget of littoral sediments: concepts and applications. Shore and Beach 64(3): 18-26.

Kraus, N. C. and J. D. Rosati (1999).
Estimating uncertainty in coastal inlet sediment budgets. Proc. 12th National Conf. on Beach Preservation Technology, FSBPA: 287-302.

Krumbein, W. C. (1936).
Applications of logarithmic moments to size frequency distribution of sediments. Journal of Sedimentary Petrology 6(1): 35-47.

Leidersdorf, C. B., R. C. Hollar, et al. (1994).
Human intervention with the beaches of Santa Monica Bay, California. Shore and Beach 62(3): 29-38.

Leonard, L. A., K. L. Dixon, et al. (1990).
A comparison of beach replenishment on the U.S. Atlantic, Pacific, and Gulf Coasts. Journal of Coastal Research SI(6): 127-140.

Leonard, L. A., O. H. Pilkey, et al. (1989).
An assessment of beach replenishment parameters. Beach Preservation Technology 88: Problems and Advancements in Beach Nourishment,Tallahassee, Fl, Shore and Beach Preservation Association, Inc.

Magoon, O.T., and L.K. Lent (2005).
The costs of sand mining: When beaches disappear, who benefits, who pays? California Coast & Ocean. Autumn, 2005: 3-8.

National Research Council (1995).
Beach nourishment and protection. Washington, D.C. U.S. National Academy of Sciences, Marine Board, Commission on Engineering and Technical Systems, U.S. 290 pp.

Norris, R. M. (1964).
Dams and beach sand supply in southern California. Shepard Commemorative Volume. Macmillan, NY: 154-171.

O'Connor, S.E. and R.E. Flick (2002).
Report on repair/mitigation alternatives to address the bluff retreat erosion problems with the Monterey Ocean Harbor House development. In: Environmental Impact Report for the Ocean Harbor House Seawall, Prepared for City of Monterey Planning Division: 96pp.

Patsch, K. B. (2004).
An Analysis of Littoral Cell Sand Budgets for California. Unpublished Ph.D. dissertation. Department of Earth Sciences. Santa Cruz, University of California Santa Cruz: 174pp

Patch, K.B. and G.B. Griggs, (2006).
Development of Sand budgets for California's Major Littoral Cells. Unpublished Report –California Sediment Management Work Group.

Rosati, J. (2005).
Concepts in Sediment Budgets. Journal of Coastal Research 21(2): 307-322.

Runyan, K. B. and G.B. Griggs (2003).
The effects of armoring seacliffs on the natural sand supply to the beaches of California. Journal of Coastal Research 19(2): 336-347.

Runyan, K. B. and G. B. Griggs (2002).
Chapter 8: Contributions from Coastal Cliff Erosion to the Littoral Budget. California Beach Restoration Study. M. Coyne and K. Sterrett. Sacramento, California, California Department of Boating and Waterways and State Coastal Conservancy.

Seymour, R.J. and D. Castel (1985).
Episodicity in longshore sediment transport. J. Waterway, Port, Coastal and Ocean Engineering, Proc. ASCE, 111(3): 542-551.

Seymour, R., R.T. Guza, W. O'Reilly, and W. Elgar, (2005).
Rapid erosion of a small Southern California beach fill. Coastal Engineering 52:2: 151-158.

Shaw, M. J. (1980).
Artificial Sediment Transport and Structures in Coastal Southern California. SIO Reference No. 80-41, Scripps Institute of Oceanography, University of California at San Diego: 109pp.

Slagel, M. J. (2005).
Cumulative Losses of Sediment to the Major Littoral Cells of California by Impoundment Behind Coastal Dams. Unpublished M.A. dissertation. Department of Ocean Sciences. University of California, Santa Cruz:

Stauble, D. K. and J. Hoel (1986).
Guidelines for Beach Restoration Projects: Part II- Engineering. Report #77. Gainesville, Florida, Sea Grant: 100pp.

Thom, B. G. and W. Hall (1991).
Behavior of beach profiles during accretion and erosion dominated periods. Earth Surface Processes and Landforms 16: 113-127.

Thornton, E. B., A. Sallenger, et al. (2006)
Sand mining impacts on long-term dune erosion in southern Monterey Bay. Marine Geology 220: 45-58.

Thurman, H. V. and A. Trujillo (1999).
Essentials of Oceanography. Upper Saddle River, New Jersey, Prentice Hall.

Walker, J. R. and R. Brodeur (1993).
The California Beach Nourishment Success Story. The State of the Art of Beach Nourishment. Proceedings of the 1993 National Conference on Beach Preservation Technology, 10-12 February 1993, St. Petersburg, FL, Shore and Beach Preservation Association.

Wiegel, R.L. (1994).
Oceanographical Engineering. Prentice-Hall, Englewood Cliffs, N.J.

Wiegel, R. L. (1994).
Ocean beach nourishment on the USA Pacific coast. Shore and Beach 62(1): 11-36.

Willis, C. M. and G. B. Griggs (2003).
Reductions in fluvial sediment discharge by coastal dams in California and implications for beach sustainability. Journal of Geology 111: 167-182.

Willis, C. M., D. Sherman, et al. (2002).
Chapter 7: Impediments to Fluvial Delivery of Sediment to the Shoreline. California Beach Restoration Study. M. Coyne and K. Sterrett. Sacramento, California, California Boating and Waterways and State Coastal Conservancy.

Winkelman, J., D. Schaaf, et al. (1999).
Humboldt Beach and dune monitoring. Sand Rights '99: Bringing Back the Beaches, Ventura, California, ASCE.

Dune erosion threatens the Ocean Harbor House apartment complex on Del Monte Beach, Monterey CA (October 2005). Copyright © 2005 Kenneth and Gabrielle Adelman, California Coastal Records Project, www.Californiacoastline.org.

Very wide beach at Venice Beach, CA (October 2002). Copyright © 2005 Kenneth and Gabrielle Adelman, California Coastal Records Project, www.Californiacoastline.org.

Climate Ready

Dave Revell

SAN FRANCISCO KING TIDE, FEBRUARY 2011

The impacts of climate change can be seen everywhere in California. Rising sea level is threatening communities in all parts of the coast and has proved particularly damaging when combined with extreme storm events. Changing rainfall patterns have led to severe droughts that are affecting water supplies, transforming agriculture, and increasing fire risk. Native habitats and wildlife are migrating to cooler climes as temperatures rise, and many species of animals and plants are facing possible extinction. The well-being of every resident, species, geographic area, and business sector of the State depends on an effective response to a changing climate.

The Coastal Conservancy has been working for more than 35 years to protect natural resources and development along California's coast and around San Francisco Bay. Much of this work has made waterfront areas and resource lands more resistant to the effects of climate change. In 2012, the legislature and governor empowered the Conservancy with a new authority to prepare for and mitigate the effects of climate change and take action against its causes.

In 2013 the Conservancy launched its Climate Ready program to provide a focus for this critical work. Through its first grant round the Conservancy awarded more than $3 million for 20 projects aimed at an array of objectives including assessments of shoreline vulnerabilities to flooding and rising seas, capture of rainwater in underground basins, reduction of greenhouse gases in the atmosphere, and protection of beaches. The strong response to the first grant announcement—76 proposals seeking more than $13 million—demonstrates the State's unmet needs and the willingness of diverse communities to join in preparation for the considerable challenges ahead.

Sea Level Rise

The Coastal Conservancy is helping many communities assess and counter threats of sea level rise to public infrastructure and natural environments.

VULNERABILITY ASSESSMENTS & PLANNING

- The cities of **Imperial Beach**, **Hermosa Beach**, and **Benicia**; the counties of **Santa Barbara**, **San Mateo,** and **Sonoma**; **San Francisco International Airport**, and communities around **Monterey and Humboldt bays** are analyzing risks from flooding, storm surges, and erosion related to expected sea level rise and identifying adaptation strategies.
- The **Los Angeles County Department of Beaches and Harbors** is preparing an adaptive management plan for protection of the County's iconic coastal beaches.
- The **South San Francisco Bay Salt Pond Restoration Project** is restoring 15,000 acres of wetlands that offer flood protection for many South Bay communities including parts of Silicon Valley.
- The **San Francisco Planning and Urban Research Association** (SPUR) developed the Ocean Beach Master Plan to address sea level rise, protect infrastructure, restore ecosystems, and improve public access.
- The **East Bay Dischargers Authority** is assessing the costs and benefits of decentralizing discharge facilities and using nutrient-rich treated wastewater to enhance the growth of wetlands vegetation for flood protection and capture of greenhouse gases.
- The **City of Arcata** is designing a 22-acre living shoreline on Arcata Bay to serve as a buffer against rising seas while sequestering greenhouse gasses from the atmosphere.

MANAGED RETREAT

- The **Surfers Point Shoreline Resilience Project** in the City of Ventura relocated bike trails, parking lots, and other facilities away from the shoreline, restoring the beach in the process.
- The **Pacifica State Beach Shoreline Resilience Project** employed a strategy that reduced flood hazards, enhanced habitat for steelhead trout, expanded recreational opportunities, and restored wetlands.

Greenhouse Gas Reduction

- The **Bay Area Ridge Trail Council** and the **San Francisco Bay Trail Project** are quantifying the potential reduction of green house gas emissions through increased use of public transportation and trail networks as ways to reduce car usage.
- **North East Trees** is working with **Los Angeles County** to transform a two-acre parcel of land in the Highland Park area into a community park with landscaping that reduces greenhouse gas concentrations, decreases stormwater pollution, and promotes groundwater infiltration. The park is expected to become a model for similar projects elsewhere.
- The **Marin Resource Conservation District** is working with farmers to demonstrate management techniques that decrease levels of atmospheric carbon dioxide and methane through improved pasture management.


Fred Hochstaedter

HIGH TIDE IN ELKHORN SLOUGH, MONTEREY COUNTY


Jim Nakagawa

ARMORED SHORELINE IN IMPERIAL BEACH


secretivemarshbird

KING TIDE IN SAUSALITO, DECEMBER 2012

Paul Sullivan

SAN FRANCISCO INTERNATIONAL AIRPORT

BAY AREA RIDGE TRAIL

Mark Stephenson

LIVING REDWOODS = CARBON STORAGE

Alan Grinberg

HIGH SURF ADVISORY IN PACIFICA, JANUARY 2010

Greenhouse Gas Reduction *continued*

- The **Sempervirens Fund** is investigating the feasibility of establishing a carbon bank for the **Santa Cruz Mountains** region that would provide an economic incentive to landowners for the protection of redwoods.

Green Infrastructure

- **Heal the Bay** is performing a cost-benefit analysis of three *Living Streets* programs to guide street maintenance and utility policies in the **City of Los Angeles**. *Complete Streets* encourages low carbon methods of transportation, *Green Infrastructure* captures rainwater, and *Cool Streets* uses materials to reduce the absorption of solar heat.

Water Catchment & Storage

- The **Council for Watershed Health** is analyzing the feasibility of large-scale capture of rainfall and storage in underground aquifers to augment water supplies and reduce reliance on imported water in the **Los Angeles** region.
- The **Resource Conservation District of Santa Cruz County** and **UC-Santa Cruz** are studying stormwater runoff patterns and identifying potential sites to capture rainwater and store it underground.
- **Sonoma County's Gold Ridge Resource Conservation District** is designing large-scale rainwater catchment and storage systems to help farmers adapt to changing rainfall patterns and water availability.

Wildlife & Habitat Conservation

- The **San Diego Zoo Institute for Conservation Research** is restoring 25 acres of endangered coastal sage scrub habitat to reduce the frequency of fires and provide a corridor for wildlife migration.

Regional Climate Collaboratives

The effects of climate change have emerged recently and rapidly. Coordination with other sectors and jurisdictions can help individual communities and institutions assess threats and develop effective responses. The Conservancy is supporting several regional initiatives and collaborations that include a diverse group of public, private, and nonprofit organizations committed to preparing for the emerging impacts of climate change. These groups include:

- The **San Diego Regional Climate Collaborative**, a network of public agencies organized to share expertise and leverage resources
- The **Los Angeles Regional Collaborative for Climate Action and Sustainability**, a network of local and regional governments, the business community, academia, labor, and environmental and community groups
- The **Bay Area Climate and Energy Resilience Project**, a collaborative of more than 100 public, private, and nonprofit organizations
- The **Bay Area Ecosystem Climate Change Consortium**, a group of natural resource managers, scientists, and others organized to sustain the natural environment
- The **Alliance of Regional Collaboratives for Climate Adaptation**, a network of regional collaboratives from across California.

Jose Bedolla

RESPONDING TO A STORM AT ZUMA BEACH IN MALIBU

The Coastal Conservancy is a State agency, established in 1976, that protects and improves natural lands and waterways, helps people get to and enjoy coastal areas, and sustains local economies along California's coast. The Conservancy works along the entire length of the coast, within the watersheds of rivers and streams that extend inland from the coast, and throughout the nine-county San Francisco Bay Area. The Conservancy is non-regulatory and achieves its goals by joining forces with local communities, nonprofit organizations, other government agencies, businesses, and private landowners.

CONSERVANCY PROJECTS:

- Protect, restore, and improve natural areas and wildlife habitats
- Help people get to and enjoy the outdoors by building hiking and biking trails, acquiring and improving parks and beaches, and creating campgrounds and hostels
- Keep our waterways clean and healthy for people and wildlife
- Help communities revitalize their waterfronts
- Support floodwater management and integrate flood-control projects into the life of a community
- Conserve commercial fisheries, working farmland, and forests.

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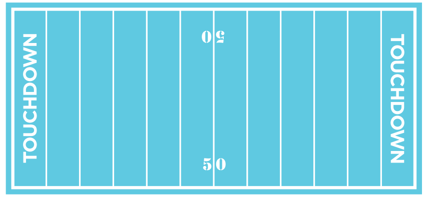
Visit our website: http://scc.ca.gov

The Threats

Over 80k acres of coastal wetlands are lost annually. That's seven football fields every hour.



Coastal erosion causes $500 million in coastal property loss annually.

The Good News!

Beaches are a unique and dynamic landscape that should be protected for the future. The Surfrider Foundation is leading efforts at the state and local levels to protect our shorelines on every coast. Our efforts are focused on establishing appropriate setbacks for development, opposing shoreline structures, and placing coastal lands in public trust.

JOIN US AND HELP PRESERVE OUR SHRINKING COASTLINES

We stand where the land meets the sea,
with one foot in the sand and the other in the water.
Learn more and join our growing network today.

SURFRIDER.ORG

SURFRIDER FOUNDATION

SURFRIDER FOUNDATION

COASTAL PRESERVATION

COASTAL PRESERVATION

Surfers cheer the waves generated by big storms, whether from North Pacific winters on the West Coast, hurricanes during the summer and fall, or Nor'easters along the Atlantic seaboard. But of course the best surf often comes with a price, eroding the shorelines and shrinking our beaches that offer a buffer between the powerful ocean and the land that we live on.

There is a constant struggle in many places to keep the sea at bay, whether building concrete seawalls or dredging up sand from the seafloor to dump on beaches. The wrong choices can lead down a path where beaches disappear, coastal tourism and recreation suffer or where billions of dollars are lost to storm-damaged and flooded properties. This is especially true in light of climate change and sea level rise. We cannot let our beaches and natural shorelines vanish before our eyes.

SHRINKING BEACHES AND RISING SEAS

Our dedicated network is fighting hard to defend and preserve our beautiful coastlines.

PROTECTING OUR COASTLINES

How the Surfrider Foundation Is Turning the Tide

The Surfrider Foundation's Coastal Preservation Initiative protects our shorelines. We proactively address threats like coastal development, sea walls and other types of shoreline armoring and beach dredge and fill projects to ensure the protection of our coast. Our network of volunteers work with community planners to make informed and responsible decisions on coastal development and to address the effects of rising sea levels.

On a national stage, our environmental policy and legal experts work with decision-makers to plan wisely and make the smart choices for the future of our coast.

Our Nationwide Network Taking Action

- California chapters are working with state agencies and local municipalities to update "Local Coastal Programs" to incorporate proactive planning measures related to coastal armoring, managed retreat and public infrastructure.
- Florida chapters successfully worked on insurance reform to reduce state subsidies for coastal development in high-risk areas, like barrier islands.
- Pacific Northwest chapters are grappling with ocean acidification and extreme erosion issues.
- Northeast and Mid-Atlantic Chapters are providing continued response to impacts of Hurricane Sandy through proactive planning and calculated restoration.

JOIN OUR EVERGROWING CHAPTER NETWORK!