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

By

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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.

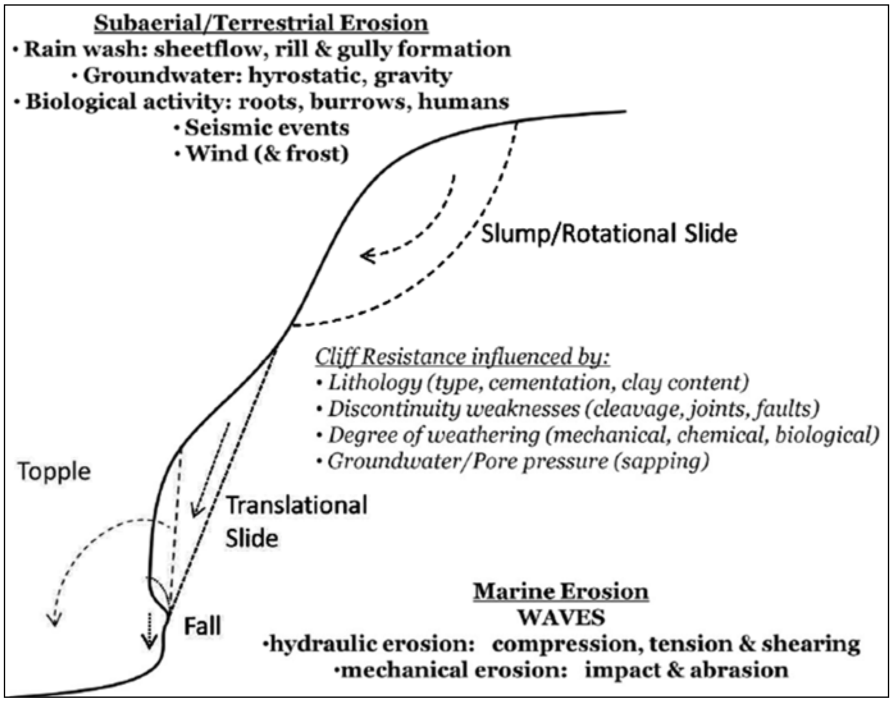
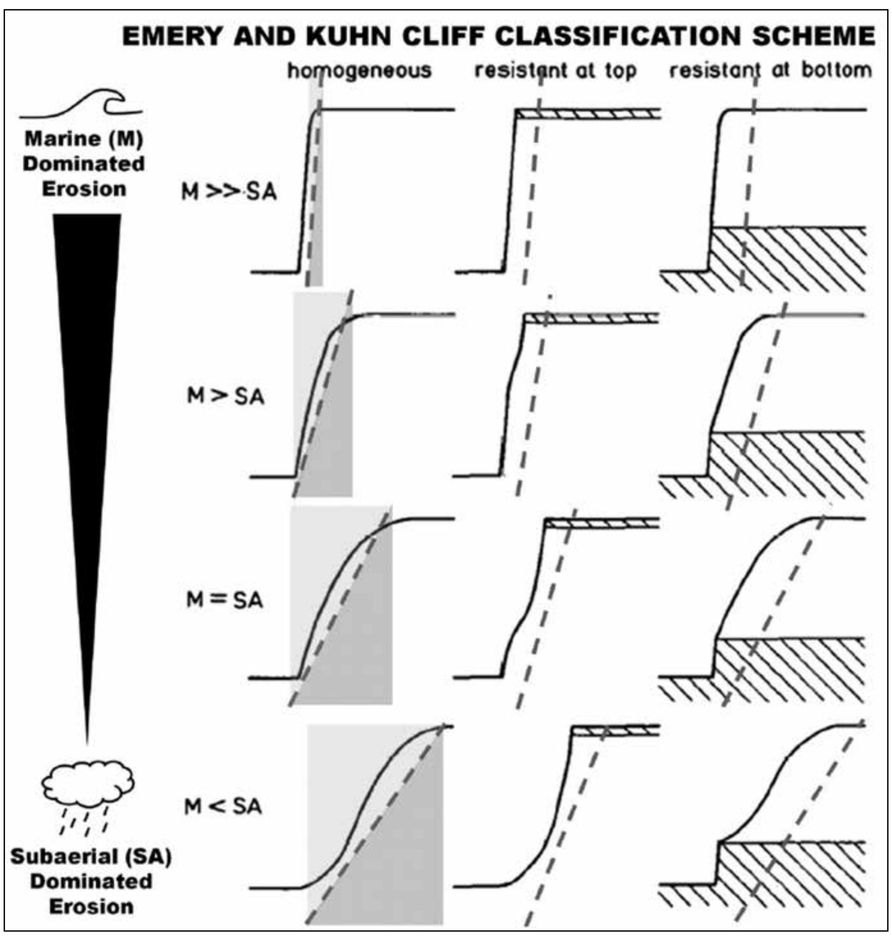


Figure 1. Illustration of typical failure modes in coastal cliffs, the subaerial and marine forces that drive them and the inherent properties of the cliff material which contribute to resisting erosion.

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).

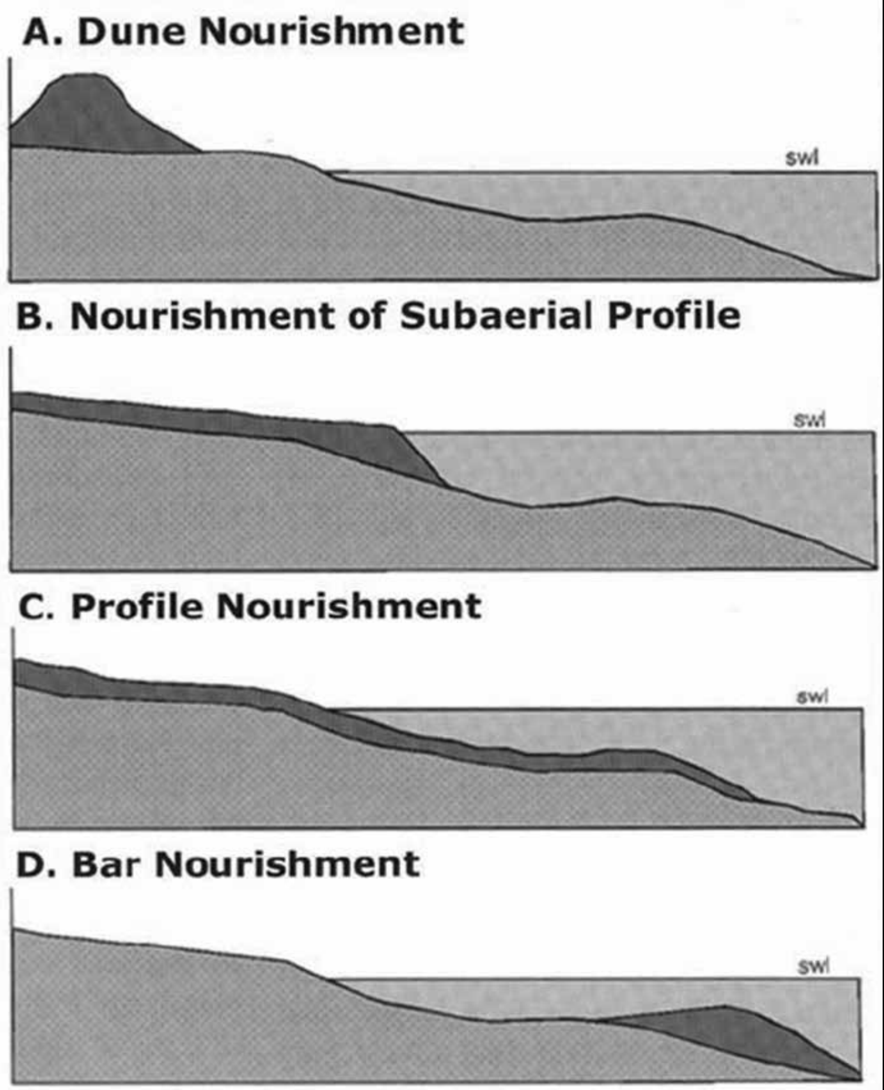


Figure 4. Methods of beach nourishment defined on the basis of where the fill materials are placed (from Finkl, Benedet, and Campbell 2006). (a) Dune nourishment: Sand is placed in a dune system behind the beach. (b) Nourishment of subaerial beach: Sand is placed onshore to build a wider and higher berm 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

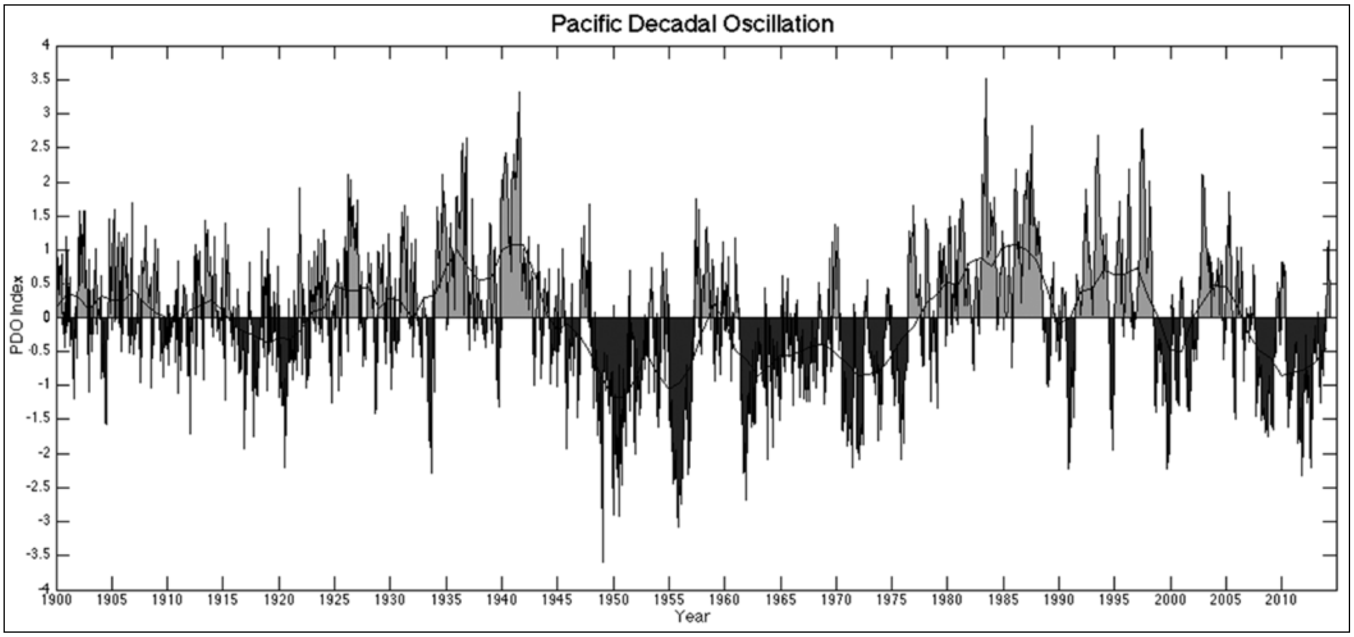


Figure 5. Pacific Decadal Oscillation cycles with positive or warm periods in light gray, and negative or cool cycles in dark gray. Vertical axis is sea surface temperature anomalies or departure from the mean in the Pacific Ocean in degrees C.

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

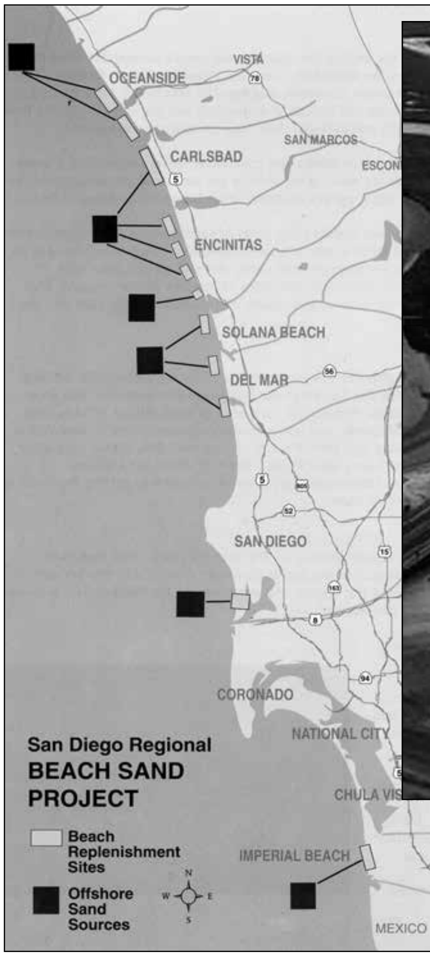


Figure 6.(left) Offshore sites where sand was dredged and beaches where sand was discharged during RBSP I.

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.

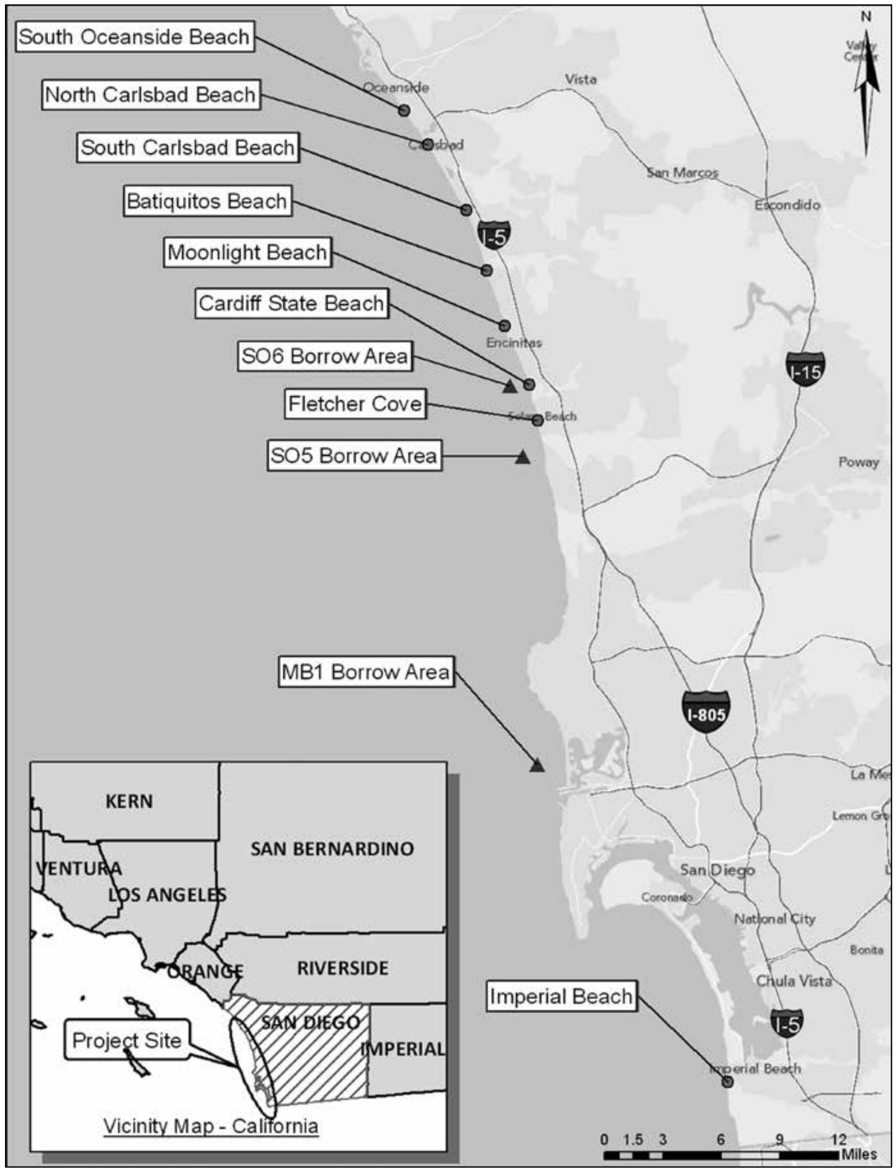


Figure 8. RBSP II showing offshore borrow areas and beaches where sand was placed.

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).

	Change in position of outer edge of berm		
Nourishment site	**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).

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