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Sand volume needs of southern California beaches as a function of future sea-level rise rates

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ABSTRACT

The littoral sand supply in southern California is already insufficient to maintain every beach at an adequate width to satisfy all recreational desires and shore protection needs. This has been true since at least the past century, which saw a modest amount of sea-level rise on the order of 20 cm, and over the past several decades, which showed little or no net sea-level rise. Sand shortages are largely due to urbanization and the construction of dams and other conflicting uses, such as sand mining and interruptions of longshore transport. Some beaches received large volumes of sand as a by-product of the many coastal construction projects that were undertaken from the 1940s through the 1960s. Owing to the coast's compartmentalization, sand supplies are not evenly distributed alongshore and shortages exist at many beaches despite massive volumes of sand delivered to others. With accelerated rates of sea-level rise likely over the next century, southern California beach sand replenishment needs are likely to increase and become more widespread both at beaches that never received nourishment and at those that have. This paper outlines a simple approach for calculating the sand volumes and related costs of the nourishment that may be required to maintain the beach width in southern California as a function of the rate of sea-level rise, effective beach slope, closure depth, and recurrence of major storm events. We consider only sand needs related to sea-level rise and assume these volumes can be calculated using a Bruun-rule approach. We recognize that this crude method must be refined in the future as better data become available and as improved numerical models of long-term shoreline response to sea-level rise are applied to the area. We conclude that the current cost of at least \$19 million up to \$48 million per year for the mid-range (50-cm by 2100) of future sea-level rise rate scenarios is surprisingly small compared with the dollar value of coastal-dependent economic activity, estimated at about \$14 billion per year.

The 1,725-km California coast is geologically young, steep, and eroding, with dune-backed beaches or coastal cliffs backing relatively thin and narrow sand beaches. Long-term sea level rise and fall, together with tectonic uplift and wave action, have shaped the coast and are responsible for its main features (Shepard and Emery 1941; Inman and Nordstrom 1971). Tectonically-formed headlands in southern California naturally divide the coast into a series of relatively isolated coastal compartments called littoral cells (Inman and Frautschy 1964).

River and coastal stream flooding and cliff erosion provide the main natural sources of beach sand. Large coastal construction projects in the early to mid-20th century have provided over 90 million m^3 of sand that has widened some beaches much beyond what their natural configurations would have been (Figure 1). Engineered jetties, breakwaters, groins and other structures, as well as natural reefs and headlands act as effective sand-retention devices. These have preserved many of the beaches in southern California, with or without sand nourishment (Herron 1980; Flick 1993).

ADDITIONAL KEYWORDS: Sea-level rise, California, beach nourishment.

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Seasonal changes in wave activity drive corresponding changes in beach configuration. Storminess and the closely-related wave action along the southern California coast are strongly correlated to warm El Niño episodes in the tropical Pacific, as well as to longer, inter-decadal climate cycles (Bromirski *et al*. 2003; 2005). These processes in turn influence beach width change.

The geologic and physical oceanographic processes and the observed historical changes known to have occurred in the past provide an understanding of how the California coast works. For detailed information on a cell-by-cell basis, see Griggs *et al.* (2005). This understanding in turn provides insights as to the effects that might be expected from increased sea level rise rates. All beaches in California stand to be negatively affected by likely future increases in the rate of sea level rise. Beach nourishment, especially in conjunction with sand retention, can undoubtedly effectively offset beach losses due to modest rates of sea level rise.

*This paper has not been reviewed by the California Coastal Commission or Viterbi School of Engineering.

Large, but manageable, volumes of sand added to the coast can likely maintain beach area and the shoreline position in the face of future rising sea levels along the California coast.

In the following sections we briefly review the southern California coastal setting and its beaches. This paper focuses on southern California, mainly because negative impacts due to sea level rise in this region will affect the largest number of people and the most development. After reviewing the coastal setting we discuss the causes and rates of past sea level rise, and outline the range of currently plausible future sea level rise scenarios. We then use these to estimate the sand volumes and related costs that may be incurred to maintain the beaches of southern California over the next century.

SOUTHERN CALIFORNIA COASTAL SETTING

Headlands in southern California, and the related low-lying areas often associated with bays and lagoons, were tectonically formed by the right-lateral, strike-slip Newport-Inglewood-Rose Canyon Fault system. As the crustal sections on each side of the faults slide past each other, some blocks had to rise because of the sinuous characteristics of the system. About 20 major cycles of sea-level rise and fall, and many smaller ones were superimposed on this tectonic activity. During relative still-stands in the sea level, wave action cut flat, low-sloping marine terraces, or shore platforms into the bedrock, which formed the sea cliffs at the same time. These processes account for the broad features of the coastline that we see today, including the gently-sloping shore platform that most of the sandy beaches overlie.

The headlands, such as Point Conception, Point Dume, Palos Verdes, Dana Point, Point La Jolla, and Point Loma naturally divide the coast into a series of coastal compartments called littoral cells (Inman and Frautschy 1964). Each littoral cell is from several tens of km up to almost 200 km long. Recent work by O'Reilly (unpublished) at Scripps Institution of Oceanography suggests that nearshore topography alters wave patterns to create littoral sub-cells, only a few kilometers long, with boundaries often located at lagoon mouths.

Sand contributions from rivers, cliffs, and anthropogenic sources in varying proportions provide each littoral cell with sand. This sand is moved cross-shore and alongshore, on average toward the east or south by wave action, thus sustaining the beaches. Sand is funneled offshore through submarine canyon systems at the southern, down-coast end of each major littoral cell, or by wave action in each smaller sub-cell. Sand is also lost offshore during larger-than-usual or persistent wave events.

Because of the structure of the southern California coast with its more-or-less short and isolated littoral cells and sub-cells, the sand budget of a particular beach is largely localized. In other words, if sand shortages, surpluses, or interruptions to transport occur from place-to-place or time-to-time, the beach width effects are relatively isolated and localized, spreading at most some tens of kilometers. This is an important point when considering beach nourishment strategies and is an important difference between southern California and other locations with much longer littoral systems, such as the barrier islands of the southeastern U.S.

As an extreme example, scores of isolated pocket beaches that are at most several kilometers long exist all along the California coast. Many of these pocket beaches exist at the base of sheer cliffs along the headland areas that form the boundaries between littoral cells in the 160 km stretch between Point Conception and Point Dume. Since they are isolated and their sand supply relatively limited, these pocket beaches could progressively narrow, flood, or become inundated and ultimately disappear as sea-level rise rates increase. This process would be hastened by passive erosion if the cliffs are armored to prevent loss of development and infrastructure, as is already evident along Point La Jolla and Point Loma, among other places.

SOUTHERN CALIFORNIA BEACHES

Southern California beaches exist in a delicate balance controlled by the local sand budget, which encompasses sand supply, transport, and loss. When the rate of sea level rise is low and the sand supply large, shorelines advance and beaches widen. As the rate of sea-level rise increases or the rate of sand supply decreases, the shorelines retreat until the sea cliffs are undermined and also retreat. The balance between long-term shoreline retreat and cliff or dune retreat determines whether or not a beach exists. During times of very high rates of sea-level rise, or if the cliffs are more resistant at sea level, such as at the aforementioned headlands, or if they are armored, they cannot retreat fast enough relative to the shoreline to maintain space for a beach.

The California coast, like all the world's coasts, has undergone notable change during the most recent interglacial beginning about 18,000 years ago. During the rapid rise in sea level from 18,000-5,000 years ago, the entire coast retreated landward by 8-25 km, depending upon the slope and resistance of the shore material. This amounts to a shoreline retreat rate of 0.6-2 m/yr. For modern-day coastal dune areas like Monterey, Nipomo Dunes, and Santa Monica Bay, the retreat represented an inland migration of the beach and dune system, with large volumes of sand carried inland by wind and waves. Importantly, large volumes of sand were left offshore as well, mostly as drowned beaches and river channels. Along the narrow, cliff-backed beaches that are typical of San Diego and other areas (Figure 1), much of the shoreline change was from waves causing landward erosion of the cliffs and down-wearing of the shore platform (Figure 2).

More or less permanent sand beaches began to form along the southern California coast about 6,000-5,000 years ago. Wetter weather produced more terrestrial sand supply, which accumulated on the nascent shore platform fast enough to outpace the beach-drowning effect of sea-level rise as its rate slowed (Masters and Aiello 2007). During previous periods of more rapid rise, beaches could not form to the same degree because the coast was continuously inundated, even though there may have been supplies of littoral sand. Sand beaches were certainly a persistent feature of the southern California coast by the time Europeans arrived.

Practically all of the sand on California beaches comes from terrestrial sources — inland erosion of sediment that is carried to the coast by rivers or streams or gullying and surface erosion of sea cliffs. Many human activities have modified the delivery systems and natural volumes of sand that reach the coast. Conversion of forest and grasslands to

Figure 1. Photo of Huntington Beach showing a typical, wide southern California beach (Photo credit: Ewing).

crop lands, trails, and cleared land during the early development of the state caused a large increase in mobile sediment available for transport to the coast. However, flood control and debris basins, and water-storage reservoirs were built as population grew in the late 19th and early 20th centuries. These have trapped and continue to trap terrestrial sediments, offsetting the potential benefits of increased sediment availability (Willis and Griggs 2003).

Dams and flood control structures have had the added impact of reducing peak flood flows, which were responsible for mobilizing most of the sand and transporting it to the coast. In southern California alone, there are over 300 reservoirs, 150 debris basins, and 77 current or historic sand mining operations that have reduced coastal sand supplies from rivers by 98 million m^3 (Slagel and Griggs 2006), or by about one-half. Cliff contributions to the coastal sand budget have also been reduced by human efforts to reduce the rate of cliff retreat through the construction of seawalls, revetments, and other shore protection devices.

During much of the 20th century, the effects of these large reductions in natural coastal sand supply were muted or offset by large coastal construction projects, including small craft harbors, power and sewer plants, harbor dredging, and other works. A total of over 90 million m^3 of sand by-product from coastal and inland projects have been placed on various southern California beaches, most notably Santa Monica Bay in Los Angeles County and the Silver Strand in southern San Diego County.

From 1938 to the late 1960s, sand was added to the Santa Monica Bay littoral system by human activity at a rate of nearly 800,000 m^3/yr (Flick 1993). Over the same time, numerous large sand retention structures were built, including groins at Will Rogers State Beach, the Santa Monica and Venice offshore breakwaters, and the Marina del Rey and King Harbor jetties. Since the late 1960s, this anthropogenic sand supply rate dropped to only about 50,000 m^3/yr with no new, large sources of opportunistic sand evident. The construction of large engineered retention structures also stopped with the cessation of large-scale coastal projects as the coast was built out, and as their negative environmental impacts became a concern. However, beach surveys in the 1990s found that almost all of the added sand was still in the Santa Monica Littoral Cell, indicating that these massive, incidental nourishment and retention activities have been a long-term benefit to beach width (Leidersdorf *et al.* 1994).

Seasonal changes in wave activity drive changes in beach configuration. The generally mild waves of summer push sand up the shore slope and widen the beach, while larger waves during winter strip sand from the beach and move it offshore. This normal seasonal beach cycle is generally confined between the dry beach berm and the “closure” depth of less than 10 m. Rainfall patterns are also seasonal, with almost all precipitation in southern California falling between November and April. This means nearly all river sand discharge and most cliff-derived sand contributions also arrive on the beach in the winter months.

Most beaches in southern California have large fluctuations both in seasonal and episodic beach width, and related sub-aerial sand volume that can obscure long-term erosion or accretion trends. For example, beach width at Del Mar Beach, situated about 30 km north of San Diego, has been surveyed regularly since

Figure 2. Photo of Solana Beach showing a narrow, cliff-backed beach underlain by a low-slope wave-cut platform (Photo credit: Ewing).

1978. Over this period, the beach shows an average seasonal width variability of about 15 m to 30 m and an extreme decrease of up about 75 m during the 1982-83 El Niño winter. Over the 30-year record, the mean and maximum summer beach width has decreased by about 15 m, for an erosion rate of about 0.5 m/yr. However, the erosion has not been steady. Large decreases in width are clear after big wave storms, but recovery is often rapid, albeit not always to prior levels. Years of steady average beach width or accretion are also evident.

Beach conditions are in greatest flux during storms, when waves move significant amounts of sand offshore to deep water, and coastal gullies, streams, creeks and rivers carry new supplies of sand to the coast. Storminess along the southern California coast is strongly related to the occurrence of El Niño, or warming conditions in the tropical Pacific, as well as to longer-span climate cycles represented by the Pacific Decadal Oscillation (PDO). Many repeated episodes of warm, stormy, and wet (El Niño) conditions alternating with cool, dry, and calm (La Niña) periods have been observed in the southwestern United States and in southern California (Inman and Jenkins 1999). Furthermore, a general increase in storminess in the region since at least 1980 is evident from Bromirski *et al.* (2003; 2005).

During very large or unusually persistent wave storm events sand may be moved offshore to depths of 30 m or more — far beyond the normal closure depth for these beaches. This offshore loss may be permanent, since milder waves are subsequently unable to transport this material back up the slope to the beach. Net beach sand loss volumes during major persistent storm events may be as large as 500-1,000 m^3/m. Such large storm systems have occurred only a few times per century; the 1982-83 and 1997-98 El Niño storms were two of the largest events in the 20th century. When they do occur, they can essentially "reset" coastal conditions by stripping away a large fraction of the beach sand.

As the history of southern California coastal development proves, beach nourishment and sand retention can widen or maintain California beaches. Yet, the only formal, long-term, sustained beach nourishment effort in California is the Orange County Newport-Surfside-Sunset project. This jointly sponsored state-federal-local program has added an average of about 280,000 m^3 of sand annually to the beach system since 1964 in a series of 12 separate nourishments at approximately four-year intervals. These nourishment episodes have fed beaches in much of the Orange County littoral system. Together with groins and harbor jetties, the replenishment has maintained stable beaches for 25 km from Anaheim Bay south through Huntington Beach (Figure 1) to Newport for decades. The Newport-Surfside-Sunset project can act as a template for future large-scale beach nourishment programs that may be required in southern California as sea level rise accelerates.

PAST SEA LEVEL RISE

Over the past 2 million years, Earth's climate has undergone periodic warming and cooling with characteristic periods of about 100,000 years, 40,000 years, and 20,000 years. These periods are respectively set by the ellipticity, tilt, and precession perturbations of the earth's orbit around the sun (Milankovitch 1920) caused by the other planets. The orbital fluctuations produce small changes in high-latitude solar power, which then pace the periodic warming and cooling that are amplified by feedbacks related to albedo and greenhouse gas concentrations. The temperature cycles in turn drive glacial retreat and advance (Hays *et al*. 1976), ultimately leading to large rises and falls of mean sea level.

Over the past 18,000 years, there has been a general, if erratic, warming with associated ocean water expansion and glacial and icecap melting. In all, sea-level has risen about 125 m over this period. However, the rates of sea level rise have varied radically. A rise of nearly 120 m occurred from about 18,000 to 5,000 years ago, which amounts to an average rate of almost 100 centimeters per century (cm/cy). The rate of sea level rise slowed to an average of about 10 cm/cy for the past 5,000 years, and to an even slower rate of about 2 cm/cy for the past 2,000 years.

Sea level rise from 18,000 to 5,000 years ago appears to have occurred in episodes of rapid rise and periods of slower rise. For example, melt Pulse 1A, approximately 14,000 years ago raised sea level by about 20 m over only about 500 years, which was a 400 cm/cy rate of rise. Even during the past 2,000 years, sea-level rise has varied, increasing during the medieval warming period (from about 800 to 1300 CE), and slowing during the Little Ice Age (from about 1500 to the mid-1800s).

Over the past 100-150 years relative sea level change at the coast has been accurately measured by tide gauges. The tide gauge at San Francisco has recorded water levels continuously since 1855 at least hourly, while La Jolla extends back to 1924 (Flick *et al.* 2003). These records indicate a relative mean sea level rise of about 20 cm/cy over the past century, which is similar to estimates of global sea level rise over the same period (White *et al.* 2005). Interestingly, tide gauge data from La Jolla suggest that local sea level off southern California rose much more slowly *or may actually have dropped slightly*, since about 1980.[1] The reason for this is not known; it may relate to influences from the Pacific Decadal Oscillation. But, the trend is consistent with global satellite data, which show much higher rates of sea level rise in the western Pacific and much lower rates in the eastern Pacific since about 1994 (see Fletcher 2009, this volume).

Satellite records covering the entire world ocean since 1994 suggest that the global average rate of sea-level rise has now reached over 30 cm/cy, but with very large variations in rates in different areas. Whether this higher global rate is a new symptom of the awaited global acceleration of sea level rise due to the "greenhouse effect" is hard to tell. However, there is now evidence of 19th and 20th century acceleration in the rate of sea-level rise commencing as early as 1870, coinciding with the Industrial Revolution, and related to anthropogenic global warming (Church and White 2006). A more complete review is given by Fletcher (2009).

POSSIBLE FUTURE SEA-LEVEL RISE

Few geophysical phenomena can be accurately predicted, including sea-level rise.[2] However, projections of future sea-level rise can and are being made based either on general understanding of the processes involved, or projecting into the future empirical relationships that are derived from past observations. Each approach requires certain assumptions, which can only be refined as time goes on and observations become available. Because sea level "predictions" are always uncertain, it is most useful to consider them as "scenarios." Scenarios imply a set of likely future consequences that can be evaluated. Depending on the consequences, courses of action can be planned. These are usually focused on alteration, avoidance, adaptation, or mitigation.

The United Nations Intergovernmental Panel on Climate Change (IPCC) leads global efforts to periodically publish consensus assessments of future climate scenarios, including sea-level rise. Most commonly, possible future mean sea levels are calculated from global, coupled ocean-atmosphere general circulation (computer) models (GCMs). These models are driven by scenarios of future greenhouse gas concentrations that are in turn determined by such variables as future population, and level of economic activity and wealth, among others. The models predict global temperature, among many other variables, including sea level. Judging from the generally close agreement of future temperature predictions from different models running the same greenhouse gas input scenarios, future temperature change scenarios are likely to be fairly reliable.[3]

In contrast to the temperature predictions, different models using different methods show considerable differences between future sea-level rise results for the same underlying greenhouse gas input scenarios. This range is one measure of the uncertainties, and suggests sea-level predictions are much less robust than temperature predictions. Some amount of future increase in sea level is already locked in, since there are lag times between greenhouse gas input, atmospheric temperature increase, and sea-level rise. Other changes will depend upon current and future anthropogenic activity, as well as uncontrollable natural events related to the aforementioned feedbacks.

The IPCC (2007) Fourth Assessment of future sea-level rise could not reach a unanimous conclusion for the possible contributions from glacial and ice-cap melting, particularly from Antarctica and Greenland. It is well known that these are the largest potential contributors to future global sea-level rise, amounting up to about 70 m and 7 m, respectively, were all of the ice to melt. Rapid melting of Greenland and ice sheet collapse in Antarctica is being observed. However, there is inadequate understanding about how much of this ice is likely to melt, or how fast this could occur. Therefore, the Fourth Assessment sea-level rise scenarios left out these potential contributions, while acknowledging they are crucially important.

1. The trend is uncertain over this short 30-year period owing to several large peaks in annual mean sea level due to El Niño conditions and other factors. However, the trend in the lowest annual mean values is level or slightly downward.

2. Due to the regularity of the underlying astronomical forces, the tides are an example of a phenomenon that can be usefully predicted, provided observations exist at the place of interest.

3. The greenhouse gas and warming scenarios span a low, moderate, and high range, commonly referred to as "A1," "A2," "B1," and "B2" scenarios (and various additional sub-scenarios), generally in decreasing order of impact, or increasing order of "eco-friendliness" (IPCC 2000).

The resulting IPCC (2007) scenarios projected global sea-level rise by 2090-2099 (relative to 1980-1999) to range from 18-59 cm, corresponding respectively to the (lowest) B1 and (highest) A1F1 scenarios. The upper limit of the "glacial melt excluded" scenarios was about 20% higher than the equivalent glacial melt excluded scenarios in the IPCC (2001) Third Assessment. However, the Third Assessment also included up to 38 cm of sea-level rise due to potential contributions from land-ice melt. Thus, the upper limit of possible sea-level rise in this earlier assessment was 87 cm by 2100, almost 50% higher than the later IPCC (2007) result.

The most widely cited effort to extrapolate past global temperature and sea-level observations into the future is the work by Rahmstorf (2007). This approach calculates the correlation of sea-level rise rate as a function of global average temperature from historic records. The correlation is then used to derive future sea-level rise rates from future global temperature scenarios from GCM outputs, which are presumably more reliable, as already discussed. This technique bypasses the sea-level rise output results from the GCMs. However, in order to calculate sea-level curves from the temperature rise rates, Rahmstorf (2007) must make certain assumptions about the sea-level response time.

These future sea-level rise scenarios range from 50-140 cm above 1990 levels by 2100, depending on the underlying greenhouse gas scenarios. Curves are also concave upward. This upper limit is between about 60% and 140% higher (respectively) than the highest Third and Fourth assessment values (IPCC 2001; 2007).

The California Climate Action Team (CCAT) sponsored regional sea-level projections suitable for the California coast that are based on the Rahmstorf (2007) curves. The CCAT analysis included modifications due to surface-water storage and ground-water pumping (Chao *et al.* 2008), and projected regional mean sea-level rise of 30-45 cm by 2050 and 80-145 cm by 2100, relative to 2000 (Cayan *et al.* 2009).

A rise in sea level of 145 cm would certainly have significant impacts on the California coast, but even smaller increases could be expected to enhance erosion and cause substantial flooding of many coastal areas. Cayan *et al.* (2008) attempted to enhance the Rahmstorf (2007) sea-level rise curves by adding projected storm surge and El Niño sea-level fluctuations, as well as tide predictions, in order to examine the changes in future peak-high sea-level event frequencies and durations. As sea level rises, extreme-high sea levels that now occur only rarely will be reached and exceeded with increasing frequency and have longer duration. Thus, coastal flooding and erosion, which occur when wave storms coincide with peak high tides, will become progressively worse (Cayan *et al.* 2008). Virtually all of the increase in frequency and duration of peak-high sea level exceedance can be ascribed to the underlying secular increase in mean sea level, rather than being caused by any projected changes in storm activity (Cayan *et al.* 2009).

OBSERVED SHORELINE CHANGES IN SOUTHERN CALIFORNIA

Approximately 80% of the California population lives within 50 km of the coast, and almost 50% the state's population live in the five coastal counties in southern California from Santa Barbara to San Diego. Southern California's beaches are important recreational resources for these areas as well as economic drivers. California beaches generated $14 billion in direct revenues and 883,000 jobs in 1998 (King 1999). All beaches in California will be negatively affected by sea-level rise, including those in northern, central, and southern California. However the negative impacts to beaches throughout southern California will affect a large fraction of the state's population, and significant amounts of public and private coastal development.

The southern California coast is about 420 km long, of which about 320 km are beaches. Historic changes in shoreline position and cliff retreat reflect local geologic conditions, shoreline armoring, construction of harbors, inlets, groins, jetties and breakwaters, inland reservoirs and debris basins, sand mining, beach nourishment, wave storm frequency, intensity and orientation, and sea-level rise.

Long-term cliff erosion for the region averaged 20 ±20 cm/yr, while maximum localized retreat ranged from 180-100 ±20 cm/yr, based on end-point analysis of cliff edge positions from 1920/1930-1998 (Hapke *et al*. 2009). Long-term beach trends based on linear regression of four mean high water (MHW) shoreline positions from 1852/1889-1998 showed average erosion of 20 ±10 cm/yr on 36% of the beaches in southern California and average accretion of 60 ±10 cm/yr on 64% of the beaches. For the short-term changes based on end-point analysis of MHW shoreline positions from 1972/1976-1998, 65% of the shoreline exhibited erosion averaging 80 ±40 cm/yr (Hapke *et al.* 2009).

If erosion and accretion are aggregated, southern California beaches showed net accretion of 30 cm/yr for the long-term, but net erosion of 10 ±4 cm/yr over the short term, even while local sea level has been static. This implies that the supply of sand to the beaches in southern California is currently insufficient to maintain beach width everywhere even with little or no net sea-level rise. This supply deficit is a result of decreases in the natural sand supply from rivers, the insufficient and isolated supply of sand from cliff and terrace erosion, and the cessation of large-scale sand contributions from construction projects (Flick 1993).

Assuming sea level will eventually resume rising in southern California, and especially if it rises at an accelerating rate in the future, sea level may pose the greatest challenge to the long-term existence of beaches in southern California. This is true for even the modest 49-87 cm of maximum sea-level rise projected by the IPCC (2001; 2007) for the next century. Much more beach loss is likely for the up to the 145 cm rise scenario used by the CCAT (Cayan *et al*. 2008; 2009).

FUTURE BEACH CHANGES ASSOCIATED WITH ACCELERATED SEA-LEVEL RISE

In the future, southern California beaches will be adversely affected by more frequent and higher levels of flooding and consequent erosion due to ever higher sea levels (Cayan *et al.* 2009). This will be true even if other effects such as the frequency and intensity of storm conditions remain unaltered. A problematic consequence of coastal erosion has been the increasing necessity to protect valuable public and private coastal development and other assets from flooding, erosion, and storm dam-

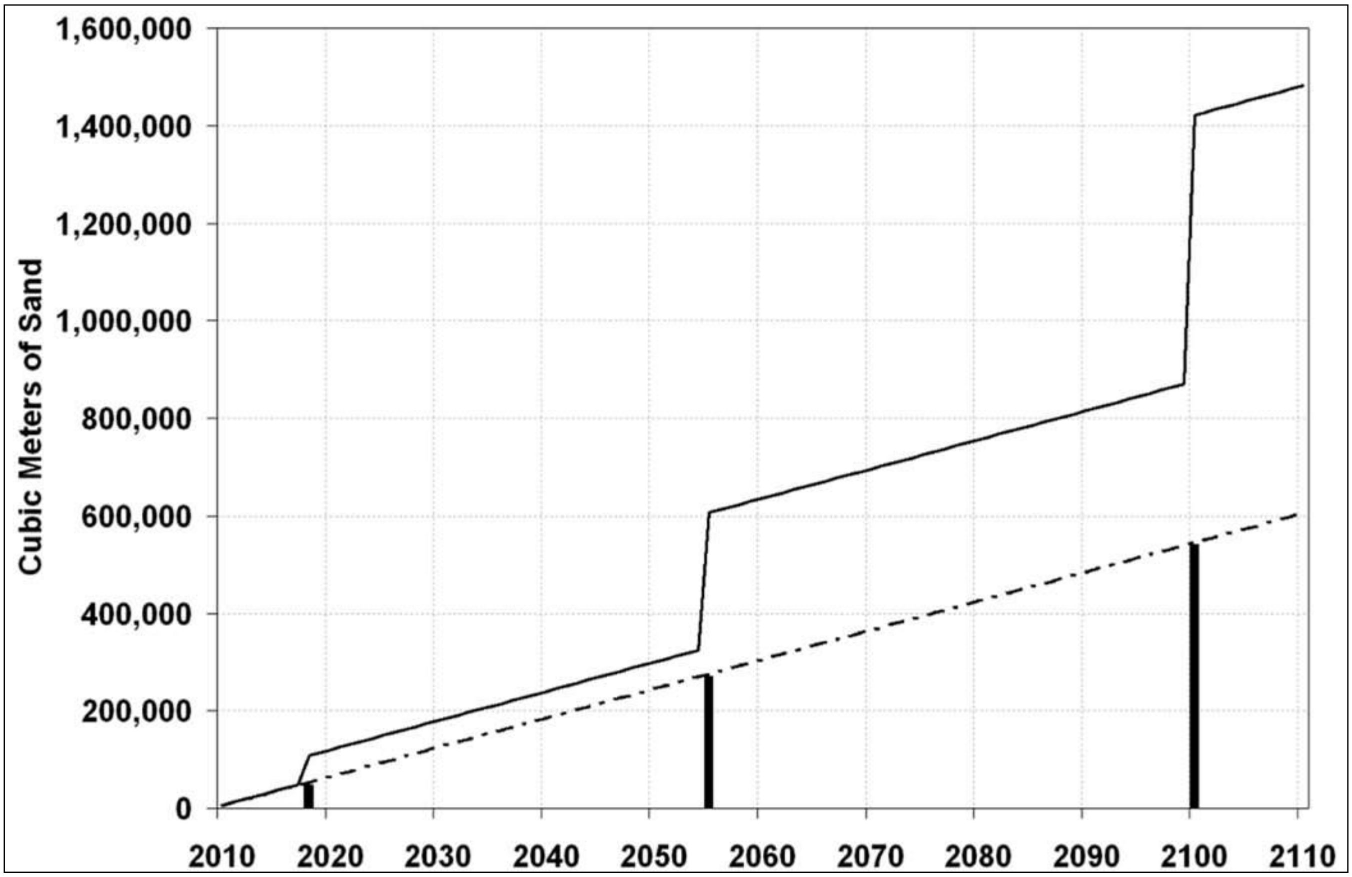

Figure 3. Sand volumes per kilometer of beach needed to keep pace with hypothetical sea-level rise over the next century (starting in 2010) of 50 cm/cy. Straight broken line: Cumulative amount of "regular nourishment" assuming 6,000 m^3/yr; Solid bars: Three additional wave-storm replenishments in years 8, 45, and 90 (see text); Solid line: Total cumulative amount.

age. This is most often accomplished by building seawalls or rock revetments, or with beach sand nourishment. Already, about 150 km of the southern California coast is protected by shoreline armoring (California Department of Boating and Waterways 2002).

As sea level rise accelerates, as the backshore is increasingly armored, and as sand supply deficits continue or worsen, beach width will be reduced. Many beaches will eventually disappear between the fixed backshore position and the landward movement of the shoreline. In extreme cases where there is no sand beach covering the rocky shore platform, progressively deeper water will occur at the base of the cliff during high tide.

If nothing is done to preserve beach width under likely future sea-level rise conditions, four stages of coastal degradation are likely to result. First, sandy beaches may narrow and ultimately disappear. Second, the exposed shore platform will be drowned, impeding access to and along the coast and exposing the cliffs and backshore development to ever-increasing threats of wave damage and flooding. Third, and simultaneously, demand for coastal armoring will accelerate to an unprecedented pace as public and private development becomes increasingly threatened. Fourth, occasional catastrophic events will occur, such as barrier-spit breaches, harbor and lagoon damages, road and railroad overwashing and collapse, and increasingly widespread and severe flooding and wave damage when large wave storms coincide with episodes of peak high tides.

FUTURE SAND NOURISHMENT NEEDS

Assuming initially that no severe winter storm events that strip the sand off the beaches during the next century occur, an estimate of the unit rate of additional sand supply needed to maintain the current beach width would be only a factor of the rate of sea-level rise, the beach slope, and the active beach height.[4] This simple approach relies on the geometric principle relating long-term beach retreat with sea-level rise first outlined by Bruun (1962).

We recognize there is criticism of this approach based on the fact that actual beach conditions are usually so complicated that the underlying assumptions are rarely justified in practice (*e.g.* Pilkey and Cooper 2004). Nevertheless, since some evidence exists that the Bruun approach explains long-term coastal retreat along the U.S. east coast (Zhang *et al*. 2004) and because no alternative method exists, it is applied herein to compare the unit volumes and associated costs for several sea level rise rate scenarios on various beach configurations. In the future, these estimates can be refined as systematic, local shoreline change data and models relating these to wave forcing such as Yates *et al.* (2009) are developed and adapted to address the response of beaches to sea-level rise.

Table 1 summarizes estimates of the rate of nourishment that would be

4. The active beach height is the vertical distance between the closure depth and the berm height. This formulation simplifies the unit volume calculations, since variations in these two parameters do not have to be considered separately.

needed to keep pace with different rates of sea level rise for various beach slopes ranging from 1:20 to 1:100 (vertical to horizontal), and a range of active beach heights from 8 m to 12 m. The unit volume of sand required to keep pace with sea level rise is simply the slope times the active height times the rate of sea level rise. The values shown in Table 1 result from accounting for the sea level rise units, dividing each result by 100 yrs/cy to obtain annual values, and then multiplying by 1,000 m/km to obtain unit volumes per km of beach.

For example (Row 11, bottom of Table 1), a beach with an overall slope of 1:100 and a nominal active profile height of 12 m (such as a beach berm elevation of +2 m and closure depth of -10 m) would require 6,000 m^3/yr of nourishment per km to keep pace with a 50 cm/cy rate of sea level rise. If the beach was steeper or the active beach height smaller, less sand would be needed; if the rate of sea-level rise was higher, more sand would be needed.

The examples shown in Table 1 represent only the sand needed to compensate for given sea-level rise rates, without any large storm events removing large quantities of sand and thereby "resetting" the beach sand volume. We recognize that this sand volume calculation method breaks down for many pocket beaches or cliff-backed beaches when the shore is totally or partly stripped of sand, as exemplified by Solana Beach (Figure 2).

In cases where there is little or no sand overlying the bedrock shore platform, it makes no sense to consider a "beach slope," or an "active beach height" to calculate shoreline retreat rates as a function of sea-level rise rates. On the other hand, this geometrical approach is perfectly sensible to calculate necessary sand volumes or unit volume rates when considering the "functional design" of a beach restoration or nourishment project.

The rates at which sand would be needed to compensate only for static sea-level rise depend directly on the rates of sea-level rise. If future sea level rises linearly, equal increments of sand will be required at equal time intervals. If sea-level rise accelerates (concave upward curve), lesser incremental amounts will be needed initially, but progressively larger amounts will be needed as time passes.

Table 1. Nourishment volumes needed to keep pace with sea-level rise

(Sand volume units are m^3/yr/km of beach)

Beach slope and (active beach height*)	Relative sea-level rise rate (cm/cy)				
	20	30	50	100	150
1:20 (8 m)	320	480	800	1,600	2,400
1:20 (10 m)	400	600	1,000	2,000	3,000
1:20 (12 m)	480	640	1,200	2,400	3,600
1:50 (8 m)	800	1,200	2,000	4,000	6,000
1:50 (10 m)	1,000	1,500	2,500	5,000	7,500
1:50 (12 m)	1,200	1,800	3,000	6,000	9,000
1:75 (8 m)	1,200	1,600	3,000	6,000	8,000
1:75 (10 m)	1,500	2,250	3,750	7,500	11,250
1:75 (12 m)	1,800	2,500	4,500	9,000	13,500
1:100 (10 m)	2,000	3,000	5,000	10,000	15,000
1:100 (12 m)	2,400	3,600	6,000	12,000	18,000

* Active beach height is measured from the beach berm to the depth of closure.
Note: Volumes are based on geometric model of shoreline change, assuming no major storm losses.

COST OF FUTURE SAND NOURISHMENT

The unit volume rates of sand nourishment shown in Table 1 suggest that the beaches of southern California can be maintained in the face of moderate rates of sea-level rise. Assuming the same example presented above, which has the lowest slope (1:100) and largest active beach height (12 m) considered in Table 1, we note that 6,000 m^3/yr/km would be required to keep pace with a hypothetical 50 cm/cy sea-level rise rate. This amounts to 1.9 million m^3/yr of sand for the approximately 320 km of beaches from Point Conception to the Mexican border, or 190 million m^3 over the next 100 years.

At a nominal cost of \$10/m^3 this amounts to about \$19 million per year. This is less than 0.2% of the \$14 billion *per year* of direct economic activity associated with coastal recreation and tourism (King 1999). The total cost over the next century would be about \$1.9 billion, not accounting for inflation.

However, one of the main factors that influence beach erosion and large losses of sand from the littoral cell are the large, but infrequent storm events that "reset" the coastal beach systems by stripping much of the beach sand cover. Any plan for long-term beach nourishment would have to anticipate several of these events over the lifetime of the nourishment, where each event could be expected to remove much of the nourished beach sand.

In order then to "keep pace" with sea-level rise, occasional nourishment projects would need to both restore the pre-storm beach profile as well as augment the beach for the losses from ongoing sea-level rise. The volume of sand to restore the beach to its pre-storm condition could be as much as all the sand already added to the shoreline to maintain the beach previously. We assume three such "El Niño-like" events over the next century *for illustration purposes only*. If a major storm were to occur early in the effort, the volume of extra sand to make up for the storm losses would be small; for storms later into the effort, the accumulated volume of sand would be larger and the needed volumes of sand to compensate for storm losses would also be larger.

Figure 3 shows a graph of nourishment volumes, assuming the same steady sea-level rise of 50 cm/cy, but with three major storm events that hypothetically occur early in the coming 100 years (say, the eighth year), in the middle (45th year), and near the end (90th year).[5] After each storm, all the sand added to keep pace with sea-level rise has to be replaced to restore beach conditions. This inclusion of storm-driven changes to the beaches requires up to 2.5 times the volume of sand needed to just keep pace with sea-level rise alone, assuming all the sand is stripped each time. If the number of large-wave storm events is more than three, the volume of sand would be larger; if the number of large storm events is less than three, or if the storm events cluster in the early part of the 100-yr period, or if not all of the sand is removed each time, the additional volume of sand would be smaller.

The total annual volume for nourishment including this three-large-wave-storm scenario would be 2.5 times 1.9 million m^3, or about 4.8 million m^3. The cost would be 2.5 times \$1.9 billion, which is about \$4.8 billion. This amounts to about \$48 million per year, or less than 0.4% of economic activity.

WHAT NEXT?

Several critical questions arise that must be considered further in order for a long-term regional beach sand maintenance program to succeed. The most obvious may be whether a strategy of regional beach-width preservation is itself worthwhile, desirable, and supportable, or whether other options such as armoring alone or retreat are preferable.

Assuming nourishment is chosen, the first consideration is whether there is in fact sufficient sand available in southern California either offshore or on land to satisfy the demand for a century or longer. Surveys to locate, quantify, and characterize offshore sand deposits have been conducted since at least the 1970s (*e.g.* Osborne *et al.* 1983), but much more widespread and systematic geophysical sampling needs to be done. The California Coastal Sediment Management Workshop program is considering these and many related data and information needs through its Master Plan process.[6]

5. It must be stressed again that these are not "predictions" of big wave storms in 2017, 2054, or 2099, but only illustrative examples of how alternate nourishment scenarios may be quantified.

6. http://dbw.ca.gov/csmw/default.aspx.

The second question concerns the large array of environmental and the closely-related permitting issues raised by large-scale, sustained nourishment projects, both at the borrow sites and at the receiver beaches. The San Diego Association of Governments conducted extensive environmental reviews to consider some of these effects in order to obtain permitting for a 1.5 million m^3 sand replenishment demonstration project in 2001. Large, infrequent nourishment efforts may be effective and appropriate for some locations; smaller but more frequent nourishment may be effective and appropriate for other locations; and non-intervention may be the most appropriate option for still other locations. A growing body of scientific knowledge is emerging about both the positive and negative effects of nourishment on sandy beaches, and perhaps more importantly, how to minimize or mitigate the adverse impacts (*e.g.* Defeo *et al*. 2008). Additionally, it is recognized that beach width maintenance through nourishment can be an effective mitigation strategy for the negative effects of coastal armoring (Sarb and Ewing 1997).

Finally, and most important from the physical science and coastal engineering points of view, observation-based shoreline change models are needed so that possible future changes can be much more reliably predicted. This is critical to developing reliable estimates of how much and where sand will be needed in response to sea-level rise, and therefore how much this might cost. To accomplish this, it will be crucial to join coastal change modeling efforts much more closely with the existing and future data gathering efforts, among other strategies (Flick and Bromirski 2008).

CONCLUSIONS

- The littoral sand supply in southern California is already insufficient to maintain every beach at an adequate width to satisfy all recreational desires and shore protection needs.

- This has been true since at least the past century, which saw a modest amount of sea-level rise on the order of 20 cm, and over the past several decades, which showed little or no net sea-level rise.

- Owing to the coast's compartmentalization, shortages exist at many beaches despite massive volumes of sand delivered to others as a by-product of major coastal development projects culminating in the late 1960s.

- With accelerated rates of sea level rise likely over the next century, beach sand needs are equally likely to increase and become more widespread.

- A simple approach to calculating the sand volumes and related costs of the nourishment that may be required to maintain the beach width in southern California over the next century suggests that the price to maintain beach widths is a small fraction of the total coastal-dependent direct economic activity.

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REFERENCES

Bromirski, P.D., R.E. Flick, and D.R. Cayan 2003. "Storminess Variability along the California Coast: 1858-2000," *J. Climate*, 16(6), 982-993.

Bromirski, P.D., D.R. Cayan, and R.E. Flick 2005. "Wave Spectral Energy Variability in the Northeast Pacific," *J. Geophys. Res*., 110, C03005, 15 pp.

Bruun, P., 1962. "Sea level rise as cause of shore erosion," *J. Waterways Harbors Div*., Amer. Soc. Civil Eng., 88, 117-130.

California Department of Boating and Waterways 2002. *California Beach Restoration Study*, Sacramento, CA, http://www.dbw.ca.gov/beachreport.htm.

Cayan, D.R., P.D. Bromirski, K. Hayhoe, M. Tyree, M.D. Dettinger, and R.E. Flick 2008. "Climate change projections of sea level extremes along the California coast," *Climatic Change*, 87 (Suppl. 1), S57–S73.

Cayan, D.R., M. Tyree, M. Dettinger, H. Hidalgo, T. Das, E. Maurer, P. Bromirski, N. Graham, and R.E. Flick 2009. *Climate Change Scenarios and Sea Level Estimates for the California 2008 Climate Change Scenarios Assessment*, Draft Paper, CEC-500-2009-014-D, 62 pp, http://www.energy.ca.gov/2009publications/CEC-500-2009-014/CEC-500-2009-014-D.pdf.

Chao, B. F., Y.H. Wu, and Y.S. Li 2008. "Impact of Artificial Reservoir Water Impoundment on Global Sea Level," *Science*, 320(5873), 212–214.

Church, J. A., and N.J. White 2006. "A 20th century acceleration in global sea-level rise," *Geophys. Res. Lett*. 33, L01602, DOI: 10.1029/2005GL024826.

Defeo, O., A. McLachlan, D.S. Schoeman, T.A. Schlacher, J. Dugan, A. Jones, M. Lastra, and F. Scapini 2008. "Threats to sandy beach ecosystems: A review," *Est. Coastal and Shelf Sci*, 81(1), 1-12.

Fletcher, C.H., 2009. "Sea Level by the End of the 21st Century: A Review," *Shore & Beach*, 77(4), 4-11.

Flick, R.E., 1993. "The Myth and Reality of Southern California Beaches," *Shore & Beach*, 61(3), 3-13.

Flick, R.E. and P.D. Bromirski 2008. *Sea Level and Coastal Change*, Draft Report to the California Energy Commission, http://www.energy.ca.gov/research/notices/2008-08-22_25_research_plan_meetings/draft_papers/Sea_Level_and_Coastal_Change_Flick-Bromirski.PDF, 21 pp.

Flick, R.E., J.F. Murray and L.C. Ewing 2003. "Trends in United States Tidal Datum Statistics and Tide Range," *J. Waterway, Port, Coastal and Ocean Eng*., Amer. Soc. Civil Eng., 129(4), 155-164.

Griggs, G., K. Patch, and L. Savoy 2005. *Living with the Changing California Coast*, Univ. Calif. Press, Berkeley, CA, 540 pp.

Hapke, C.J., 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), 603-614.

Hays, J.D., J. Imbrie, and N.J. Shackleton 1976. "Variations in the Earth's Orbit: Pacemaker of the Ice Ages," *Science*, 194(4270), 1121–1132.

Herron, W.J., 1980. "Artificial Beaches in Southern California," *Shore & Beach,* (48)1, 3-12.

Intergovernmental Panel on Climate Change 2000. *IPCC Special Report, Emissions Scenarios, Summary for Policymakers*, 27 pp, http://www.ipcc.ch/pdf/special-reports/spm/sres-en.pdf.

Intergovernmental Panel on Climate Change 2001. *Climate Change 2001: Working Group I: The Scientific Basis*, http://www.ipcc.ch/ipccreports/tar/wg1/index.htm

Intergovernmental Panel on Climate Change 2007. *Climate Change 2007, Synthesis Report*, 73 pp, http://www.ipcc.ch/pdf/assessment-report/ar4/syr/ar4_syr.pdf.

Inman, D.L., and C.E. Nordstrom 1971. "On the Tectonic and Morphologic Classification of Coasts." *J. Geol.,* 79, 1–21.

Inman, D.L., and J.D. Frautschy 1964. "Littoral Processes and the Development of Shorelines," *Proc. Specialty Conf. Coastal Eng*., Amer. Soc. Civil Eng., 511-536.

Inman, D.L., and S.A. Jenkins 1999. "Climate change and the episodicity of sediment flux of small California rivers," *J. Geology*, 107, 251-70.

King, P., 1999. "The Fiscal Impact of Beaches in California," Research Report, Public Research Institute, San Francisco State University.

Leidersdorf, C., R.C. Holler, and G. Woodell 1994. "Human Intervention with the Beaches of Santa Monica Bay, California," *Shore & Beach*, 62(3), 29-38.

Masters, P.M., and I.W. Aiello 2007. "Postglacial Evolution of Coastal Environments," in: *California Prehistory, Colonization, Culture, and Complexity*, T.L. Jones and K.A. Klar, Editors, Alta Mira press, 394 pp.

Milankovitch, M., 1920. *Theorie Mathematique des Phenomenes Thermiques produits par la Radiation Solaire*, Gauthier-Villars Paris.

Osborne, R.H, N.J. Darigo, and R.C. Scheidermann 1983. *Report of Potential Offshore Sand and Gravel Resources of the Inner Continental Shelf of Southern California*, California Dept. Boating and Waterways and Univ. Southern CA, 2 vols.

Pilkey, O.H., and J.A. Cooper 2004. "Society and Sea Level Rise," *Science*, 303(5665), 1781-1782.

Rahmstorf, S., 2007. "A Semi-Empirical Approach to Projecting Future Sea-Level Rise," *Science*, 315(5810), 368–370.

Sarb, S., and L.C. Ewing 1997. "In-lieu Fee Beach sand Mitigation Program: Sand Diego County," http://www.coastal.ca.gov/pgd/sand1.html.

Shepard, F.P., and K.O. Emery 1941. "Submarine Topography Off The California Coast: Canyons and Tectonic Interpretation." Geological Society of America, Special Paper No. 31, p. 171 pp.

Slagel, M., and G. Griggs 2006. "Cumulative Losses of Sand to the California Coast by Dam Impoundment," Research Report, Institute of Marine Sciences, Univ. Calif., Santa Cruz, http://www.dbw.ca.gov/CSMW/PDF/Cumulative_Loss_of_Sand_from_Dams_Final_060706.pdf.

White, N.J., J.A. Church, and J.M. Gregory 2005. "Coastal and global averaged sea level rise for 1950 to 2000," *Geophys. Res. Lett*., 32, L01601, DOI: 10.1029/2004GL021391.

Willis, C.M., and G.B. Griggs 2003. "Reductions in Fluvial Sediment Discharge by Coastal Dams in California and Implications for Beach Sustainability," *J. Geol*., 111, 167-182.

Yates, M.L., R.T. Guza, W.C. O'Reilly, and R.J. Seymour 2009. "Overview of seasonal sand level changes on southern California beaches," *Shore & Beach*, 77(1), 39-46.

Zhang K., B.C. Douglas, and S.P. Leatherman 2004. "Global warming and coastal erosion," *Clim. Change*, (64), 41–58.