Title: Lost neighborhoods of the California coast
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Source: ***Journal of Coastal Research.*** 31.1 (Jan. 2015): p129.
Document Type: Article
DOI: http://dx.doi.org/10.2112/13A-00007.1

Full Text:
ABSTRACT

Griggs, G.B., 2015. Lost neighborhoods of the California coast. Journal of Coastal Research, 31(1), 129-147. Coconut Creek (Florida), ISSN 0749-0208.

Each coastal disaster is followed by the inevitable debates about whether rebuilding is the right decision. Hurricanes Sandy and Katrina are good examples, as were the damaging El Nino events along the California coast in 1982-83,199798, and 2009-10. Coastlines globally have been migrating landward since the last Ice Age ended about 18,000 years ago, and all indications are that this trend will continue in the decades and centuries ahead, most likely at an increased pace as the rate of sea-level rise increases. Retreating from the shoreline is not a new approach, and there are many communities and neighborhoods along the coasts of the United States and elsewhere where relocation has occurred and where formerly developed parcels are now underwater. Documenting these lost neighborhoods and those that are in the process of disappearing today is important in providing a longer-term perspective of what we face as a state and as a nation. Coastlines are in constant flux, and with few exceptions, they are migrating inland, either gradually or more rapidly during extreme events. Although there are short-term or temporary approaches that have been used for decades to hold back the ocean, they all have their limits. Communities need to assess their vulnerabilities to future sea- level rise and begin to adapt or prepare for the inevitability of a changing shoreline.

ADDITIONAL INDEX WORDS: Coastal erosion, shoreline retreat, coastal protection, armor, seawalls.

INTRODUCTION

In the wake of Hurricane Sandy, there was no shortage of articles, editorials, interviews, and other written and spoken statements and opinions regarding either the need for, or the folly of, rebuilding the destroyed and heavily damaged oceanfront communities of New Jersey and New York.

One representative example is an editorial from the January Coastal Voice: Newsletter of the American Shore & Beach Preservation Association (ASBPA, American Beach News Service; http://www.asbpa.org/publications/monthly_news/ 0113asbpa.pdf), entitled "Retreat is not the Answer":

> People won't walk away from their properties (or their fond memories of the coast) without a fight. The media was filled with stories of people who had grown up at the beach and then retired to their summer homes. Many wanted to pass on this experience to their children and grandchildren. That makes even the discussion of retreat an issue fraught with emotion and expense ... something no government official wants to wade into unless there is an overwhelmingly good reason to do so (and, so far, storm damage does not seem to be that reason). The economic hit from abandoning the coast would be enormous. First, there's the coastal economy--the juggernaut of tourist economic dollars, affordable recreation and a way of life would be lost. Entire oceanfront communities would have to be abandoned if retreaters had their way. Then there's the cost of acquiring all those properties, because if you don't want people to rebuild, you'd better be ready to buy that land to ensure it doesn't happen (and don't forget to pay for all the lawyers). Add in the cost of physically retreating, the removal of structures and infrastructure to return that coast to a more "natural" state. Finally, there's the need to manage the land that's left, even at a minimal level ... unless your plan is to turn it back to nature and banish people from ever setting foot on it again. In all likelihood, managing the new oceanfront would embrace some beach nourishment to ensure any recreational area remains big enough for recreation. All told, the real cost of retreat has never been calculated--and it will be shockingly enormous when someone finally does it.

An article and an opinion editorial in the New York Times, both from November 2013 provide a striking contrast in viewpoints:

> As ocean waters warm, the Northeast is likely to face more Sandy-like storms. And as sea levels continue to rise, the surges of these future storms will be higher and even more deadly. We can't stop these powerful storms. But we can reduce the deaths and damage they cause. [...] Yet there is already a push to rebuild homes close to the beach and bring back the shorelines to where they were. The federal government encourages this: there will be billions available to replace roads, pipelines and other infrastructure [...] But this "let's come back stronger and better" attitude, though empowering, is the wrong approach to the increasing hazard of living close to the rising sea. Disaster will strike again. We should not simply replace all lost property and infrastructure. Instead, we need to take account of rising sea levels, intensifying storms and continuing shoreline erosion.

(Pilkey, O.H., 14 November 2012. We need to retreat from the beach. New York Times, p. A35, New York edition; corrected 23 November 2012).

> Across the nation, tens of billions of tax dollars have been spent on subsidizing coastal reconstruction in the aftermath

of storms, usually with little consideration of whether it actually makes sense to keep rebuilding in disaster-prone areas. If history is any guide, a large fraction of the federal money allotted to New York, New Jersey and other states recovering from Hurricane Sandy--an amount that could exceed $30 billion--will be used in the same way. Tax money will go toward putting things back as they were, essentially duplicating the vulnerability that existed before the hurricane.

(Gillis, J. and Barringer, F., 18 November 2013 online; 19 November 2013 in print. As coasts rebuild and U.S. pays, repeatedly, the critics ask why. New York Times, p. Al, New York edition).

A LONGER-TERM PERSPECTIVE ON COASTAL EROSION

Along the English Channel, the Yorkshire coast of England has had a similar battle with the sea, but a battle with a much longer history. Records of the locations of coastal settlements in the United Kingdom go back almost 2000 years to the time of Roman occupation. Although the Yorkshire coastline consists of clay bluffs, in contrast to the low-lying sandy barrier islands of the U.S. Atlantic coast, their problems are similar.

There is an extraordinary record of Yorkshire's struggles against the waves, documented in a book published a century ago, The Lost Towns of the Yorkshire Coast (1912). The author, Thomas Sheppard, documents the progressive disappearance of 28 towns during the previous 2000 years (Figure 1). That list includes Wilsthorpe, Auburn, Hartburn, Hyde, Withow, Cleton, Northord, Hornsea Burton, Hornsea Beck, Southorpe, Great Colden, Colden Parva, Ringbrough, Monkwell, Sand-le-Mere, Waxholm, Owthorne or Sisterkirke, Newsham, Old Withernsea, Out Newton, Dimlington, Turmarr, Northorp, Hoton, Old Kilnsea, Ravenspurn, Ravenser Odd, and Old Aldbrough. This is an impressive set of lost communities, which does make one wonder if there is any collective memory in the region.

A 24 September 2012 article in The Guardian (Wainwright, M., http://www.guardian.co.uk/uk/the-northemer/2012/sep/24/ coastal-erosion-yorkshire-north-sea-lost-towns) explains that the Yorkshire coast was being lost in 2012 at rates up to three times as fast as the previous year and ascribes the sharply increasing rates of coastal retreat to a dry spring and a soggy summer (Figure 2). Average annual retreat of the boulder clay cliffs near the village of Aldborough has been about 1.7 m (5.5 ft), whereas during the past year, the bluffs lost a startling 7 m (22 ft).

[FIGURE 1 OMITTED]

New Jersey and New York are not alone in dealing with coastal hazards and shoreline retreat, nor is the Yorkshire coast. The difference is that, in England, they have been building on the coast for quite a few more centuries, and they have kept track of their losses. Whether castles or churches, it hasn't made any difference to the waves, and they have all ended up in the sea.

One well-cited example along the U.S Atlantic coast of the magnitude of long-term retreat is the Cape Hatteras Lighthouse on North Carolina's Outer Banks, for which there is a well-documented history. At 61 m tall (200 ft), it is the nation's tallest lighthouse and the highest in the world that is constructed of brick.

Originally built in 1870 to warn passing ships of the shallow shoals known as the "Graveyard of the Atlantic," the lighthouse was originally built 457 m (1500 ft) inland from the shoreline on the Cape Hatteras barrier island. In subsequent years, it became apparent that the shoreline of the island was migrating, and the ocean was coming closer to the light. By 1919, high water had encroached within 91m (300 ft) of the structure as shoreline retreat continued at an average rate of 7.5 m/y (24 ft/y.). Waves first reached the base of the lighthouse in 1935, and in subsequent years, a number of engineering attempts were made, including dikes, groins, breakwaters, and wooden revetments, to protect the structure from hurricanes and large waves. None of these provided much long-term protection (Trujillo and Thurman, 2008).

The National Park Service took over the lighthouse in 1935 and, in 1999, decided to relocate the 4830-ton lighthouse further inland. At a cost of about U.S.$12 million, the lighthouse was severed from its foundation and moved on wheeled dollies along a specially constructed track 870 m (2900 ft) inland. At the historic rate of shoreline retreat, the lighthouse will be safe from wave attack for at least a century, although there is no guarantee that the rate of retreat will not increase with an acceleration in the rate of sea-level rise.

[FIGURE 2 OMITTED]

In a recent book, The Rising Sea, Pilkey and Young (2009) chronicle the histories of a number of American towns and villages that have succumbed to the sea over time. Isle Derniere (Lost Island), Louisiana (1856), Edingsville Beach, South Carolina (1893), Diamond City, North Carolina (1899), Thompson's Beach, New Jersey (1950), and Baytown's Brownwood Subdivision, Texas (1983), are some of the best examples of our past history of abandoning a retreating shoreline.

CALIFORNIA'S RETREATING COASTLINE

The 1760 km (1100 mile) coastline of California includes (1) lowlands with estuaries, lagoons, dunes, and beaches; but also (2) steep mountains; and (3) lower-relief coastal cliffs and bluffs (Figures 3-5). Coastal retreat and the challenges this has posed to infrastructure and development have been well documented (Griggs, Patsch and Savoy, 2005; Hapke and Reid, 2007; Hapke, et al., 2006). California has the longest coastline in the lower 48 states and is the most populated state in the nation with 38 million people. Sixty-seven percent of the population (25.5 million people) resides in coastal counties, and many of them live virtually on the edge or as close as they can get to the water (Figure 3).

Following World War II, California's population, particularly in coastal counties, exploded (Figure 6). Development of cliffs, bluffs, and beachfront areas attracted new residents and immigrants who were happy to trade the weather elsewhere for the sunny skies and moderate climate of central and Southern California. The state's population nearly doubled from about 8 million in 1945 to almost 16 million in 1960 and has continued to add about a one-half a million new residents each year in the following decades.

The period between 1945 and about 1978, however, was a cool Pacific Decadal Oscillation (PDO) cycle (Figure 7), characterized by a relatively calm coastal climate overall (Mantua et al., 1997). That meant fewer large El Nino Southern Oscillation (ENSO) events, with their accompanying damaging coastal storms and lower rainfall and, therefore, less coastal erosion and flooding. That period of benign coastal climate coincided with the time of most rapid growth in California, particularly in coastal counties. Subdivisions and development occurred along the coastline, and people moved closer to the edge. Not that those areas hadn't been built on in earlier decades, but the construction intensified with significant new coastal development during that calm interval.

[FIGURE 3 OMITTED]

The climate shift in 1978 to a warm PDO cycle (Figure 7; Mantua et al., 1997) brought more-frequent and more-intense ENSO events, with widespread storm damage. That came as a surprise to many private property owners, as well as to local government and state agency staff, who hadn't experienced such events in their short memories. The winters of 1978, 1982-83, and 1997-98 were particularly damaging and brought the long-term stability of those oceanfront homes, businesses, and infrastructure into question (Griggs, 1999; Griggs, Patsch and Savoy, 2005; Storlazzi and Griggs, 2000).

[FIGURE 4 OMITTED]

[FIGURE 5 OMITTED]

Although the issues of "retreat" or "hold the line and resist the advance of the ocean" are still fiercely debated, as evidenced from the references in the beginning of this article, there is, in fact, already a long history of disappearing or lost neighborhoods and retreat along California's coastline.

DIFFERENT TYPES OF COASTAL RETREAT

When speaking of coastal erosion or coastal retreat, it is important to distinguish between several different processes because they affect the long-term decisions we, as a society, make on the most-appropriate response at any particular location.

[FIGURE 6 OMITTED]

[FIGURE 7 OMITTED]

Seasonal Beach Retreat

Along California's coast, and indeed along most coastlines, beaches come and go, or accrete and erode, on a seasonal basis in response to a changing wave climate. Although the extent of these year-to-year changes varies depending on the actual winter and summer wave conditions, fluctuations in beach width are expected and predictable (Figures 8a and b).

Long-Term Beach Retreat

Where sand delivery to the shoreline has been reduced, where sand has been mined or removed, or where large engineering structures have impounded or diverted large volumes of sand, beaches can undergo progressive narrowing over time. Beaches can also advance and retreat in response to climate cycles (Figure 9; Orme et al., 2011).

Shoreline Migration

With a long-term rise in sea level, shorelines that have no barriers on their landward edges will simply migrate inland. That is not a problem unless development has occurred on or landward of those beaches, such as along many of the Atlantic and Gulf Coast barrier islands, or along many of California's beachfront developments. In these cases, passive erosion takes place, where the beaches are progressively narrowed or gradually flooded as sea level continues to rise. Backbeach barriers, whether seawalls, revetments, bulkheads, homes, highways, hotels, or any other structures, will prevent a beach from retreating landward, but the beach can also return if the barrier is removed (Figures 10a and b).

Cliff or Bluff Erosion

Virtually all coastal cliffs or bluffs in California are eroding (Griggs and Patsch, 2004; Griggs, Patsch and Savoy, 2005; Hapke and Reid, 2007). Rates may vary from millimeters per year to meters per year, depending on the nature or strength of the cliff- or bluff-forming materials, the presence of absence of a protective beach, and the combined physical forces acting on those cliffs or bluffs (waves, tides, rainfall and runoff, storms, etc.). Within our lifetimes, those losses are permanent and not recoverable.

Each of those processes can present problems or threats to coastline development, depending on how close to the shoreline or the bluff edge the development has encroached, the rate of retreat or erosion, the elevation of the development above sea level, and the nature of the physical processes impinging on the shoreline at any particular location.

[FIGURE 8 OMITTED]

CASE STUDIES OF SOME LOST CALIFORNIA NEIGHBORHOODS

Big Lagoon, Humboldt County

In 1929, about 60 beach cottages were built on the low terrace at the south end of Big Lagoon along the Humboldt County coast in northern California (Figure 11); 15 of those cottages (25%) were within 9-12 m (30-40 ft) of the bluff edge. During the winter of 1935-36, and again in the winter of 1939-40, unfavorable combinations of storm waves and high tides removed the entire beach. All of the most vulnerable cottages were gone by November 1941, probably having been relocated farther inland. Up to 20 m (~66 ft) of bluff were lost between 1931 and 1941. During the 1941-42 winter, the lack of a protective beach encouraged further bluff retreat, reaching up to 10 m (~33 ft) by February 1942 (Griggs, Patsch and Savoy, 2005).

Those disastrous winters were followed by a long period of generally benign conditions, from the mid-1940s to the late 1970s, now understood as a cool and calm PDO cycle, characterized by few large El Nino events, and, with fewer intense storms, less wave energy and erosion took place along the California coast. In 1962, parcels for the Big Lagoon/ Ocean View subdivision were laid out along the top of the bluffs to the south of the original community but on the same low, eroding terrace (Figure 12). In subsequent years, additional homes were built along the bluff top to the south on Oceanview Drive. Long-term average erosion rates of the low bluffs south of the Big Lagoon development have been very high, ranging from 0.45 to 1.4 m/y (Griggs, Patsch and Savoy, 2005).

With the transition to a warm PDO cycle in 1978, the coast of California entered a period of more-intense and more-frequent El Nino events, accompanied by elevated sea levels and large waves (Griggs, 2010a). Erosion of the bluffs again increased. The 1982-83 El Nino winter waves and elevated water levels cut back the cliffs up to 10 m in another catastrophic erosion event. Two more cottages had to be moved, and sand was stripped away below the cliffs bordering the new subdivision, threatening many new bluff-top homes. Erosion continued during the 1983-84 winter, with up to 10 m of additional erosion at the north end of the community. One cottage that sat more than 27 m from the bluff edge in 1931 was within 3 m of the edge by 1985, an average retreat rate of 0.4 m/y for more than 50 years.

[FIGURE 9 OMITTED]

[FIGURE 10 OMITTED]

During the large 1997-98 El Nino, 11 additional homes were threatened by accelerated bluff failure as a 15-m stretch of one parcel was lost, and a section of roadway dropped into the ocean (Figure 13). Humboldt County tagged several structures as unsafe to occupy, and some have been removed.

Although the beach fronting the bluffs will accrete and erode, depending on wave and tidal conditions and sediment supply, the long-term trend is clear from the bluff-erosion rates and the temporary accumulation of talus at the base of the slope. The bluffs will continue to retreat, and houses closest to the bluff edge will eventually have to be relocated or demolished. The erosion problems at Big Lagoon have been readily identifiable for decades and demonstrate the importance of determining long-term bluff erosion rates before creating oceanfront lots and building new homes.

[FIGURE 11 OMITTED]

Gleason Beach, Sonoma County

This steep and unstable section of Sonoma County coastline is underlain by the rocks of the Franciscan complex, which is a melange (French for mixture) of rock types, some quite weak and erodible and others more resistant, which persist because the offshore sea stacks provide some protection to the steep cliffs (Figure 14). The homes either built on, or protected by, the resistant rock types (generally at either end of this development) have fared far better than those in the middle that were built on sheared and weakened sandstone, siltstone, and shale.

Gleason Beach (Figure 11) is a clear example of the problems associated with building too close to an eroding sea cliff. Twenty-one homes were originally built in the 1930s on a narrow strip of marine terrace between Highway 1 and the cliff edge. Septic tanks were built on the beach, perched behind concrete seawalls. Although there are a few resistant areas of bedrock in the section of melange, most of the cliffs have continued to fail from a combination of winter high tides and wave runup, as well as rainfall and runoff, which have produced shallow landslides and failure of the underlying materials. Only 10 (48%) of the original homes remain, and the rest have been destroyed or demolished, with only portions of concrete foundations and seawalls still remaining (Figure 15). The San Andreas Fault runs virtually along the shoreline at this point, which contributes to the long-term instability of the eroding cliff top.

[FIGURE 12 OMITTED]

[FIGURE 13 OMITTED]

Bolinas Bluffs, Marin County

Located approximately 40 km north of San Francisco, the Bolinas Peninsula forms the southernmost extension of the larger Point Reyes Peninsula (Figure 11). Most of the peninsula is a broad, flat plateau or marine terrace, which is bordered by steep sea cliffs that are 40 to 60 m high. In 1880, the first summer-home subdivision was developed in what is now the town of Bolinas. Since that time, sea cliff erosion has been a continuing hazard.

The entire cliff appears to be a nearly continuous zone of landslides (Figure 16). Resistant, wave-truncated outcrops of shale at beach level create a narrow, shingle-covered tidal platform. As is common throughout the area, most retreat occurs during the wet winter months. Groundwater seeps can be seen along the base of the sea cliff during winter and spring. Most of that water originated from rainfall percolating through the fractured bedrock underlying the marine terrace. Heavy winter rains also tend to cause gullying of the cliff face.

Surveys of the position of the cliff edge, which began in 1913, show that erosion has continued at average rates of several centimeters per year on the west to more than a meter per year to the east, where the mudstone is more fractured and less competent. Attacking waves cause landslides by undercutting the base of the cliffs. Failure is facilitated by increased subsurface flow of water and saturation because of septic effluent from cliff-top homes as well as winter rainfall (Griggs, Patsch and Savoy, 2005).

[FIGURE 14 OMITTED]

The combination of inherent bedrock weakness, groundwater seepage, and wave attack leads to rapid cliff recession. Since the area was initially subdivided in 1927, many of the original oceanfront lots, the fronting Ocean Parkway, and several homes have been either partially removed or damaged by cliff erosion.

The cliffs just west of the entrance to Bolinas Lagoon support the most densely developed residential area in Bolinas, with 20 houses located on the brow of the cliff, some of which are precariously perched on the face (Figure 17). With each winter, the location of the homes, road, and utilities located at the terrace edge becomes increasingly hazardous. This is not a new problem; the hazards resulting from wave attack and erosion have threatened Bolinas for more than 100 years.

[FIGURE 15 OMITTED]

[FIGURE 16 OMITTED]

In an attempt to stabilize the beach and halt cliff erosion, bulkheads and groins were first emplaced in the 1880s beneath the cliffs that back the beach. Those early wooden structures were regularly maintained by the community for many years and provided a beach of sufficient width to shield the cliff base from wave attack. Winter storms, however, gradually destroyed many of the protective structures in addition to some homes (Griggs, Patsch and Savoy, 2005).

During the prolonged and intense rains of the January 1982 storms, significant cliff failure occurred. Four homes along Terrace Avenue above Bolinas Beach were irreparably damaged and subsequently condemned. With the winter wave attack of 1983, one cliff-top home was destroyed and several others suffered damage (Figure 18). The effects of cliff erosion have been damaging to this community. Had the geological conditions been evaluated before development, much of the erosion "problem" could have been forestalled through better planning and setbacks. An 1882 plot of the Terrace Avenue area shows the road at one location to be situated 27 to 39 m inland of the cliff edge; in 2005, the same road was at the edge of the cliff.

Pacifica, San Mateo County

Pacifica is within easy commuting distance of San Francisco (Figure 11), about 16 km south of the Golden Gate Bridge. During the past 30 years, Pacifica has become densely populated with homes, apartments, businesses, and a mobile home park, all built close to the bluff edge on a 15-30 m high marine terrace consisting primarily of poorly consolidated Pleistocene sediments. Photographs from the 1970s show eroding and unvegetated bluffs (Figure 19), but the only armor at that time was a retaining wall and riprap protecting the mobile home park and some scattered concrete slabs that had been dumped at the base of the bluff. Houses along the Esplanade (right side of Figure 19) were close to the bluff edge at that time, and ample evidence existed for recent bluff failure. The Esplanade area has a well-documented history of coastal change that provides a useful long-term perspective (Griggs, Patsch and Savoy, 2005). According to older maps, this fragile coast had been relatively stable from 1853 to 1946. When 12 houses were built on the seaward side of Esplanade Drive in 1949, the 20 m high coastal bluff was still 50 m west of the street.

[FIGURE 17 OMITTED]

[FIGURE 18 OMITTED]

[FIGURE 19 OMITTED]

Between 1941 and 1970, 10 m or more of bluff retreat occurred, with the mobile home park construction taking place in 1966-67. By 1969, riprap and concrete rubble that had been placed at the base of the low bluff had been washed away by wave action. Around 1970, a timber bulkhead, fronted by riprap, was constructed, but within several years, additional rock had to be placed at the north end because of outflanking. The retreating conditions may be due, at least in part, to a reduced sediment supply from San Francisco Bay during the latter half of the 20th century (Barnard, Hansen, and Erikson, 2012; Dallas and Barnard, 2011).

During the elevated sea levels and repeated high tides and storm wave attack of the 1983 El Nino winter, waves rapidly eroded the weak, unconsolidated materials making up the bluffs, threatening a number of structures. In February, the timber wall was breached, extreme beach scour occurred, and the riprap collapsed, followed by bulkhead failure. Wave attack, bulkhead destruction, and bluff erosion continued, and by March 1983, 23 mobile homes were moved to prevent further losses (Figure 20). The bluff was cut back 12 m at the southern end of the mobile-home park and 25 m at the north end, where a three-story building was moved back to prevent damage (Figure 21). To the south, 11 homes along the oceanfront Esplanade were threatened by accelerated bluff erosion. Within a year, a rock revetment had been constructed at the base of the bluff to protect the homes (Figure 22).

The new revetment settled into the sand beach over time, despite the use of filter cloth and careful layering of the rocks. By the time the high tides and storm waves of the next large El Nino arrived in early 1998, there was little of the rock left to protect the weak bluffs. High tides and large waves again combined to remove about 12 m of bluff, despite the efforts of the homeowners to install additional rock. Heavy equipment working under emergency conditions on the beach was damaged when caught by high tide. Continued bluff erosion through March and April led to undercutting of house foundations (Figure 23), condemnation of all but two homes, and the ultimate demolition of 10 homes in April 1998.

[FIGURE 20 OMITTED]

Losses at this location were among the most dramatic along the California coast during the 1997-98 winter and provided evidence of the potential limitations of riprap or revetments placed on deep sand foundations, as well as the ability of heavy surf to strip sand from narrow beaches and directly attack soft bluff materials already weakened by groundwater saturation. Breaking waves undercut the bluff face, inducing block falls and slumps in the oversteepened bluff. Following demolition of the homes, additional riprap, funded by the Federal Emergency Management Agency (FEMA), was placed at the base of the bluff along the entire Esplanade, even though most of the houses were gone at that point (Figure 24). A concrete, caisson structure, combined with riprap, was built to protect the mobile home park, but a portion of the park was damaged when some of the piles rotated seaward (Figure 25).

Winter waves during a relatively weak El Nino in the winter of 2002-03 eroded 6-10 m of the poorly consolidated bluffs at the north end of Pacifica and threatened several large apartment complexes on the bluff top. Emergency rock was brought in to protect the toe of the bluff below the apartments (Figure 26), and a request was made in early 2003 for a permit to place 2500 tons of 6-8 ton stones along the base of the eroding bluffs below a group of townhouses directly to the north. By 2010, continued erosion had reached the front edge of the apartment buildings leading to their being posted as unsafe for occupancy. Emergency tiebacks and gunite were used to try to stabilize the foundations with additional rock placed at the base of the bluff (Figure 27).

[FIGURE 21 OMITTED]

Presently, almost the entire 2.5-km bluff frontage of Pacifica has been armored with riprap, seawalls, gunite, or some combination of these reinforcements. The high, weak bluffs are unstable under wave attack, yet the bluffs have been nearly completely urbanized. Erosion problems can be expected in the area in the future, and more property and structures will be threatened and gradually lost.

[FIGURE 22 OMITTED]

[FIGURE 23 OMITTED]

Moss Beach, San Mateo County

The small, residential community of Moss Beach in San Mateo County (Figure 11) is built on an uplifted marine terrace fronted by a 25-30 m high, steep coastal cliff eroded into weak sandstones and mudstones. There is no significant beach along that stretch of coastline, so that waves attack the base of the cliff year-round, leading to long-term average erosion rates of about 30 cm/y. A number of residential lots have been lost, and three homes located on the cliff edge in the 1972 aerial photographs have been removed or destroyed by continuing bluff retreat (Figure 28).

Although cliff erosion is a serious problem in Moss Beach, an even greater hazard is seaward movement and headward expansion of the large landslide on which part of the community is built. This slope failure has badly damaged a number of homes and threatens others, as well as threatening roads in the area. A second large landslide south of Moss Beach is also active and is expanding northward; at that point, blocks up to 60 m wide are slowly sliding seaward. Wave erosion at the base of the steep cliffs and groundwater infiltration from above contribute to the instability in this area. The road closest to the cliff, which provided access to the homes, is now damaged and impassable (Figure 29).

[FIGURE 24 OMITTED]

[FIGURE 25 OMITTED]

[FIGURE 26 OMITTED]

[FIGURE 27 OMITTED]

Depot Hill, Capitola, Santa Cruz County

Depot Hill, in the village of Capitola on the northern edge of Monterey Bay (Figure 11), saw its first grand old Victorian homes built in the late 1800s. Although the original houses were built well back from the cliff edge, within a few decades, an ocean front street had been built and lots on the inland side were created. Before long, summer homes had been built on many of those parcels, although they were originally separated from the 25 m high vertical sea cliff by Grand Avenue, a sidewalk with benches known as Lover's Lane, and a row of Monterey cypress trees. By the 1940s, the row of trees and the sidewalk had fallen away, and in subsequent years, Grand Avenue was threatened and eventually undermined.

The cliffs fronting Depot Hill are highly prone to failure for a combination of reasons. The underlying bedrock consists of mudstone, siltstone, and sandstone, which is capped by 8 m of poorly consolidated marine terrace sands. The bedrock is extensively jointed in several directions, and the dominant trend is NE-SW, dipping or tilting about 80[degrees] seaward, a trend followed by the cliffed coastline at this point. There is a weak layer exposed at the base of the bluff, which, as it was eroded by wave attack, lead to loss of support for the overlying joint-bounded blocks, which subsequently failed (Figure 30). Groundwater from both landscape watering on the developed cliff top terrace, as well as winter rainfall, percolates down to the bedrock and then moves seaward toward the bluff edge. That flow penetrates into the joints, increasing the pore pressure, and weakening the rock. Because of the orientation of the coastline at this point, littoral drift doesn't allow sand to accumulate at the base of the cliff because high tides and wave runup reach the base of the cliff virtually every day.

[FIGURE 28 OMITTED]

Large blocks, a few to as much as 3 m thick, regularly fail, producing average long-term erosion rates of about 30 cm/y (Griggs and Johnson, 1979; Griggs, Patsch and Savoy, 2005).

Several houses have been relocated away from the cliff edge to parcels further inland (Figure 31). During the 1989 Loma Prieta earthquake, cliff failure led to loss of support for some of the concrete caissons supporting a cliff-top apartment complex and also cracked the slab and walls. Several units were subsequently demolished (Figure 32). Grand Avenue, the former cliff top roadway is now nearly completely gone, and erosion continues. Although there have been numerous proposals over the years to stabilize the 25 m high cliffs, no project has ever been agreed upon and approved.

[FIGURE 29 OMITTED]

[FIGURE 30 OMITTED]

Stilwell Hall, Fort Ord, Monterey County

The smooth, gently curved shoreline of Monterey Bay with its wide sandy beaches (Figure 33) suggests an equilibrium coast, or one essentially in balance with the forces or processes acting upon it. Although this may be the long-term picture, historical and photographic records combined with recent measurements and observations indicate that the shoreline is as dynamic here as elsewhere (Griggs and Jones, 1985). The beaches advance and retreat, and the frontal dunes along the central and southern portions of the bay are periodically eroded back and subsequently rebuilt.

Erosion along the southern coastline of the bay is the most severe. The entire 25 km of southern Monterey Bay shoreline from Moss Landing to Monterey consists of essentially unconsolidated Pleistocene dunes that, when reached by waves, are highly prone to erosion. Measurements from aerial photographs taken during the past 40-50 years indicate average retreat rates of the sandy bluffs of about 0.6 to more than 2 m per year (Griggs et al., 2005). An important contributing factor to erosion along the southern shoreline of the bay has been a century of sand mining, directly from the beach (Figure 34). At continuing removal rates of about 150,000 [m.sup.3]/y, a strong case has been made that this volume is equivalent to the volume of sand being eroded from the bluffs each year along the southern bay shoreline (Griggs and Jones, 1985; Thornton, 2007).

Stilwell Hall, a World War II soldiers club near the bluff edge at the former Ft. Ord military base, was built overlooking the bay during the early 1940s (Figure 11). As erosion proceeded at about 2 m/y, the army repeatedly dumped rock and broken concrete onto the beach in front of the structure in attempts to slow or halt erosion and save the historic building (Figure 35). By early 1984, the edge of the eroding bluff was within 5 m of the structure, which led the Army Corps of Engineers to prepare a feasibility study analyzing all options for the building. Based on the high rate of regional erosion, the conclusion reached was that complete relocation, reconstruction, or demolition was far more cost-effective than trying to halt bluff erosion. The entire military base was ultimately decommissioned as a Department of Defense cost saving measure, leaving Stilwell Hall perched high above the beach on what was rapidly becoming a peninsula. The California Department of Parks and Recreation ultimately took ownership of the property, and the structure was subsequently demolished, and all rock and concrete from the beach removed. Although the armoring had led to a well-documented case of passive erosion, with the removal of the rock and concrete, a beach has returned (Figure 10b).

[FIGURE 31 OMITTED]

[FIGURE 32 OMITTED]

[FIGURE 33 OMITTED]

Isla Vista, Santa Barbara County

Isla Vista (Figure 11) is the student community for the adjacent University of California, Santa Barbara, campus and is home to about 15,000 college students living primarily in apartments. The 12 m high sea cliffs in this area are made up of the Sisquoc formation, which consists dominantly of shale and siltstone. The beaches here narrowed during the severe El Nino events of the past three decades and have never returned to their historic widths, such that waves frequently reach the base of the cliff at high tides. The offshore Channel Islands play an important role, however, in sheltering much of this coastline from direct wave attack.

The Isla Vista sea cliff area was essentially undeveloped until the 1940s and 1950s when homes and apartments began to be built following the conversion of the terrace immediately to the east from a World War II Marine Corps base to the University of California, Santa Barbara, campus. By the 1980s, many of the oceanfront parcels had been built out with small, typically two-story apartment complexes. Many of those units were built nearly to the cliff edge, often with decks extending to or cantilevered over the edge, which had great appeal to students (Figure 36).

[FIGURE 34 OMITTED]

Because of the narrowed beaches during the past several decades, erosion has proceeded at average rates of between 15 and 30 cm/y (Griggs, Patsch and Savoy, 2005). Although a few low-budget timber seawalls have been constructed, for the most part the cliffs are unprotected, and erosion has proceeded to undercut the decks and foundations and has exposed and destroyed the concrete caissons supporting some of the structures (Figure 37). As cliff erosion has proceeded, the overhanging decks and the front units of a number of apartments have gradually been removed or demolished (Figure 38). The neighborhood is getting smaller, and this is likely to continue well into the future.

[FIGURE 35 OMITTED]

[FIGURE 36 OMITTED]

Carpinteria, Ventura County

Following the construction of the Santa Barbara harbor breakwater between 1928 and 1930, sand began to accumulate up coast of the breakwater, eventually widening the beach to as much as 250 m (Figure 39). This area of former seafloor now supports a college stadium, several large parking lots, park facilities, and a number of buildings associated with the harbor complex. Although the up coast beaches widened, the beaches as far east as Carpinteria (Figure 11), about 20 km down coast, suffered varying degrees of sand deprivation and, subsequently, erosion. There was a well-documented erosion wave that migrated down coast at about 1.7 km/y following construction of the breakwater (Wiegel, 1965). The greatest effect was along the low sand spit that enclosed the Carpinteria salt marsh, where erosion removed the protective beach, which led to the loss of foundation support and collapse of a number of homes (Figure 40). In January 1940, the beach at Sand Point in Carpinteria eroded landward 75 m and caused more than $2 million in property damage. Ultimately, riprap was brought in to protect that shoreline, but the initial damage had been done and property and houses had been damaged and, in some cases, destroyed. Despite nearly continuous dredging of the Santa Barbara harbor entrance, narrow beaches and threats of storm damage exist today at Carpinteria.

West Newport Beach, Orange County

The shoreline at Newport Beach is a highly developed, low-lying sand spit in Orange County (Figure 11). The low spit has been attacked intermittently and overwashed by waves from tropical storms off Baja California and the southern hemisphere. The coastline faces nearly south and, therefore, lacks protection from the offshore Channel Islands like much of the rest of southern California. Beach homes and cottages were undermined during 1934 when the beach was severely eroded (Figure 41; Kuhn and Shepard, 1984). In the summer of 1965, the beach eroded 50 m before being stabilized by sandbags just a few meters from property lines. Similar severe erosion occurred in 1968.

[FIGURE 37 OMITTED]

The greatest threats have been at West Newport Beach, and that area has been subject to numerous shoreline protection and nourishment efforts, primarily as a result of Army Corps of Engineers regional projects. Rock and sheet pile groins were installed in the 1960s and 1970s (Figure 42), and several nourishment projects have added more than 1.2 million [m.sup.3] of sand to the beach. In 1991, another 1 million [m.sup.3] was dredged from the Santa Ana River and used to create an offshore mound. Some of that sand migrated landward to widen this beach. Groins have helped to widen and stabilize the shoreline, but large southern swells are still hazardous to the expensive beachfront development. Sea-level rise will only exacerbate the existing risks.

Encinitas, San Diego County

In 1938, the Self-Realization Fellowship constructed a temple on the bluffs at Encinitas (Figure 11), just 3-5 m back from the cliff edge, where it had a spectacular view of the Pacific Ocean (Figure 43). Known as "Swamis," the Golden Lotus Temple was built by Paramahansa Yogananda, a native of India, who was widely revered at the time as a preeminent spiritual leader.

Cliffs consisting of a thick sequence of sandy marine-terrace deposits overlying mudstone and claystone, which are unstable in the area because of both wave attack at the base of the bluff during high tides and landslide-prone cliff materials. In 1942, just 4 years after completion, the Golden Lotus Temple collapsed and slid downslope as the bluff failed from a combination of large waves and heavy rainfall (Figure 44). The temple was dismantled and hauled away, and today a plaque marks the original location.

Following the collapse of the temple, the fellowship's monks and nuns consulted with experts and came up with a plan in the 1980s they believed would save the site. It involved a combination of geology and engineering and included (1) installing wells and pumps to lower ground water on the site, (2) planting deep-rooted vegetation on the bluff face, and (3) building a 457 m (1500 foot) long riprap revetment at the toe of the bluffs to dissipate wave energy. Overall, their approach has survived subsequent wave attack and heavy rainfall that has caused bluff failure elsewhere along the Encinitas coast (Figure 45).

[FIGURE 38 OMITTED]

Southwest Fisheries Sciences Center, La Jolla, San Diego County

A National Marine Fisheries Service Laboratory (National Oceanic and Atmospheric Administration [NOAA]) (Figure 11) was built in the early 1960s on the edge of a 60 m high cliff at the north end of the Scripps Institution of Oceanography (Figure 46). The sedimentary rock making up the sea cliff is fractured and highly permeable, and is also characterized by a steeply seaward-dipping joint set and relatively high groundwater seepage. As a result, many small and large mass movements have occurred, including translational block slides and slab failures. One large slide mass lies directly below the building (Figure 46). Just to the north, a 180 m long slide in 1982 brought an estimated 1.8 million [m.sup.3] of rock, sand, and soil onto the beach. An earlier landslide in 1949 was even larger and extended alongshore for approximately 500 m (Griggs, Patsch and Savoy, 2005).

[FIGURE 39 OMITTED]

[FIGURE 40 OMITTED]

Soon after the Fisheries Laboratory was built, it was determined that the facility straddled an active landslide whose movement was correlated with distant earthquakes. Shifts of several cm in the most-seaward building soon became evident (Griggs, Patsch and Savoy, 2005). Average long-term cliff-top erosion rates have been documented at about 30 cm/y (Benumof and Griggs, 2000).

[FIGURE 41 OMITTED]

[FIGURE 42 OMITTED]

The facility sits atop an eroding coastal cliff, with future failure over time being inevitable. This erosion has placed two of the four buildings in the complex within 6 m of the cliffs edge and forced NOAA to implement plans to abandon the two buildings and move into temporary, off-site, leased space. The relocation of staff from these two buildings was completed on June 2008, and federal money was appropriated to build a new building directly inland from the existing building, which is now completed (Figure 47).

DISCUSSION AND CONCLUSIONS

Many coastal areas around the United States are threatened by a combination of winter wave attack, high tides, storm surges, and periodic extreme events (hurricanes and ENSO, for example). Although global sea level is rising at what appears to be an increasing rate based on satellite altimetry measurements made since 1993 (NRC, 2012), it will be the extreme events such as hurricanes Sandy and Katrina or the El Ninos of 1982-83 and 1997-98 that will pose the greatest risks to coastal development during, at least, the next several decades. The history of shoreline retreat and the loss of buildings, neighborhoods, and entire communities has been well documented (Griggs, Patsch and Savoy, 2005; Griggs, Pepper, and Jordan, 1992; Hapke and Reid, 2007; Pilkey and Young, 2009). There are expensive lessons here that should be heeded.

[FIGURE 43 OMITTED]

[FIGURE 44 OMITTED]

Throughout the past century, the most common response to an eroding coastline was armor along the West Coast and beach nourishment and armoring along the East and Gulf coasts. Today the hold-the-line view is being tempered by both a well-documented increase in the rate of global sea-level rise, a growing awareness of climate change, and a number of very costly coastal natural disasters. Despite this history, there are still differing views on how to respond, as expressed in the introduction to this article. The greatest difference in approaches are understandably those of coastal businesses or shoreline homeowners, on the one hand, who don't want to give up their oceanfront property and homes, and the coastal scientists, on the other hand, who are well aware of the long-term retreat trends.

[FIGURE 45 OMITTED]

[FIGURE 46 OMITTED]

In California, 10% of the entire 1760 km coastline has now been armored, with fully one-third of the coastline of the four most-populated Southern California counties now protected by hard coastal engineering structures (Griggs, 2010b). The California Coastal Commission, which is the statewide permitting agency for new development or coastal protection structures, has developed a general policy of discouraging additional armor unless primary structures are in imminent danger.

Although there is a general attitude among oceanfront property owners of resisting retreat and engaging in rebuilding, often with federal disaster relief funding, in the United Kingdom, retreat has been going on for centuries, and in California, we have been retreating for decades. There are examples from one end of the state to the other of lost or disappearing neighborhoods, whether streets, homes, or other buildings. All indications are that sea-level rise rates will increase in the future. There are also some indications that storms are getting more frequent, and wave heights are increasing along the West Coast, particularly off northern California, Oregon, and Washington (Bromirski, Flick, and Cayan, 2003; Graham and Diaz, 2001; Ruggiero, Komar and Allen, 2010; Seymour, 2011; Storlazzi and Wingfield, 2005), although that is still a topic of active research.

[FIGURE 47 OMITTED]

The combination of a long and well-documented history of cliff erosion and shoreline retreat, rising sea levels, and a possible increase in the frequency and height of storm waves suggests that we need to expand our efforts in adapting and preparing for a different future. The State of California has just released new guidelines about sea-level rise to be used by all State agencies (CO-CAT, 2013), and the State's Ocean Protection Council has recently (2013) issued a Request for Proposals to communities for $2.5 million in funds to support the development of sea-level rise adaptation plans. The California Energy Commission's Public Interest Environmental Research Program funded a study that has now been published by the State's Ocean Sciences Trust, Adapting to Sea-Level Rise: A Guide for California's Coastal Communities (Russell and Griggs, 2012, 2013). The state of California has lost a number of oceanfront structures and neighborhoods during the past century but is taking the lead nationally in beginning to prepare for the future risks faced by all coastal communities.

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DOI: 10.2112/13A-00007.1 received and accepted in revision 1 August 2013; corrected proofs received 14 October 2013; published pre-print online 18 November 2013.

Griggs, Gary B.