The Protection/Hardening of California's Coast: Times Are Changing

Authors: Griggs, Gary, and Patsch, Kiki

Source: Journal of Coastal Research, 35(5) : 1051-1061

Published By: Coastal Education and Research Foundation

URL: https://doi.org/10.2112/JCOASTRES-D-19A-00007.1

Journal of Coastal Research	35	5	1051–1061	Coconut Creek, Florida	September 2019

www.JCRonline.org

REVIEW ARTICLES

www.cerf-jcr.org

The Protection/Hardening of California's Coast: Times Are Changing

Gary Griggs[†]* **and Kiki Patsch**[‡]

[†]Department of Earth and Planetary Sciences
University of California Santa Cruz
Santa Cruz, CA 95064, U.S.A.

[‡]Department of Environmental Science and Resource Management
California State University Channel Islands
Camarillo, CA 93012, U.S.A.

ABSTRACT

Griggs, G. and Patsch, K., 2019. The protection/hardening of California's coast: Times are changing. *Journal of Coastal Research,* 35(5), 1051–1061. Coconut Creek (Florida), ISSN 0749-0208.

Coastal hazards involve the interaction or effects of natural coastal processes on shoreline development, infrastructure, and human activities. Future sea-level rise will affect California's coastal development and infrastructure through both flooding of low-lying areas and erosion of cliffs, bluffs, and dunes. The global rate of sea-level rise is increasing and many low-lying developed shoreline areas are already experiencing flooding at extreme high tides, particularly during periods of large storm waves. The combined effects of short-term extreme wave and tide events and the global rate of sea level increase will present greater risks in the near future for coastal California. Protecting private development and public infrastructure along shorelines has become a pressing issue for many coastal communities and the state, with a limited number of management options, each with their own costs, benefits, and effects. These options include: do nothing, beach nourishment, hard armoring structures, living or green shorelines, and managed retreat or relocation. Hard armoring structures such as seawalls and revetments have been the typical historical response to coastal erosion, and in 1971, just 2.5% of California's entire 1760-km shoreline was armored. By 2018, armor totals reached 13.9% of the entire state's coastline, a 5.5-fold increase over 47 years. None of the past or present efforts to protect shoreline development and infrastructure from coastal storm damage and shoreline erosion will be effective over the long term with rising sea levels. A growing awareness of the cumulative effects of armoring the shoreline has led the California Coastal Commission to take an increasingly critical look at any new proposals for coastal armoring.

ADDITIONAL INDEX WORDS: *Coastal protection, seawalls, coastal erosion, sea-level rise, armoring.*

INTRODUCTION

Coastal hazards are primarily a function of the presence of human beings and their development and activities as they interact with coastal landforms and processes. Although coastlines differ widely in their dominant morphologies as a result of their tectonic setting and geologic history, with the global rise in sea level over the past 18,000 years, coastlines have retreated virtually everywhere. For low-relief coastlines such as the Gulf and Atlantic coasts of the United States, the dominant hazards are coastal flooding and shoreline retreat occurring during hurricanes, nor'easters, and extremely high tides. For the tectonically active Pacific Coast of the United States, although flooding and beach erosion are significant hazards, the added threats are related to coastal cliff, bluff, and dune erosion.

Of California's 1760 km of coastline, about 225 km consists of high-relief cliffs and coastal mountains, approximately 1040 km consists of lower relief sea cliffs and bluffs (ranging from 5 to perhaps 75 m in height and typically backed by uplifted marine terraces), and the remaining roughly 500 km consists of low-relief shorelines with some combination of beaches and dunes, as well as bays, estuaries, lagoons, and wetlands (Griggs, Patsch, and Savoy, 2005).

Processes Affecting California's Coastline

From approximately 18,000 to 8000 years ago, California's coastline retreated landward or inland in response to a relatively rapid rise in sea level. The last 8000 years were characterized by a comparatively slow rate of sea-level rise. That is quickly changing, however, as coasts around the world are now being affected by a significant increase in this rate because of anthropogenic global warming and the resulting (1) expansion of sea water as it warms and (2) increased melting of continental glaciers and the ice sheets of Antarctica and Greenland.

The hazards affecting California's coastal development and infrastructure include both flooding of low-lying areas and erosion of cliffs, bluffs, and dunes. Historically, both settings have been most affected by short-term or extreme events, which include larger than average waves coinciding with high tides, king or perigean high tides, and El Niño–Southern Oscillation (ENSO) events. The latter can elevate sea level 30 cm or more for weeks and often bring large waves from the W or SW, such as were experienced during the winters of 1978,

DOI: 10.2112/JCOASTRES-D-19A-00007.1 received 5 March 2019; accepted in revision 18 April 2019; corrected proofs received 31 May 2019; published pre-print online 26 June 2019.
*Corresponding author: griggs@ucsc.edu

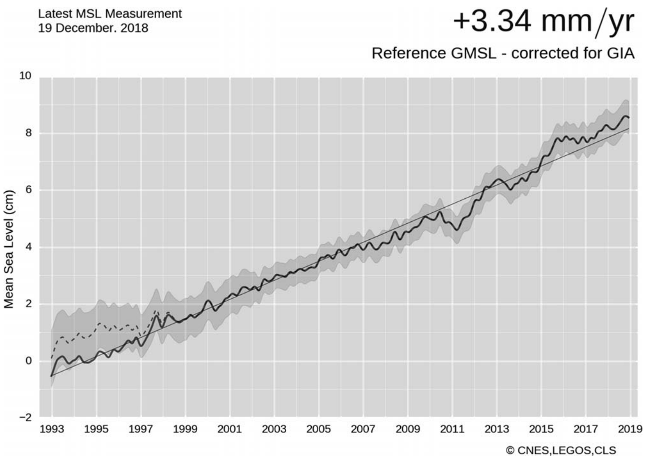

Figure 1. Satellites have been recording global sea level very precisely from space since 1993, which has averaged 3.34 mm/y (13 inches per century) although this rate is increasing. (Graph: AVISO CNES Data Center.)

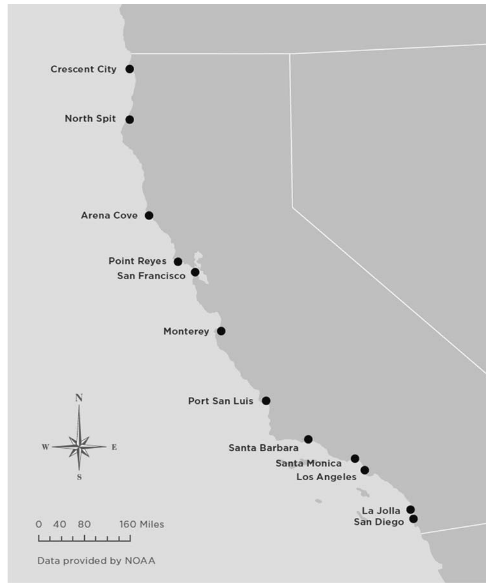

Figure 2. Locations of the 12 active NOAA tide gauges that cover the 1760 km of the ocean coast of California.

1982–83, 1997–98, and 2015–16. These are the events that will continue to present the highest risks to coastal development to perhaps 2050, when long-term sea-level rise will become increasingly important (Griggs *et al*., 2017).

The global or absolute rate of sea-level rise measured by satellite altimetry has averaged 3.34 mm/y (13.1 inches/100 y) since 1993 (Figure 1), which is more than twice as fast as the rate over the past century as averaged from tide gauges or water level recorders around the world (ranging from 1.2 to 1.7 mm/y). The 10 National Oceanic and Atmospheric Administration (NOAA) tide gauges along the central and southern coast of California (Figure 2) have records ranging from 40 to 163 years in length and have recorded local or relative rates of sea-level rise varying from 0.69 to 2.17 mm/y (2.7–8.50 inches/100 y). Two additional gauges in Northern California are situated on the edge of a tectonic collision or subduction margin and have recorded both higher (Eureka, 4.6 mm/y) and lower rates (Crescent City, –0.81 mm/y).

Recent research (Nerem *et al*., 2018) indicates that the global rate of sea level is increasing and many low-lying California shoreline areas are already experiencing flooding at extreme high tides. These short-term events are additive with long-term sea-level rise, however, and the combined effects of both processes will present greater risks in the future.

Accurate predictions of future sea levels are difficult to make because of uncertainties in future climate, although two recent studies in California provide important guidance for local governments and state agencies that must deal with rising seas and the future location of the shoreline. *Rising seas in California: An update on sea-level rise science* (Griggs *et al*., 2017), completed at the request of the governor, provides probabilistic projections for future sea levels at the locations of three NOAA coastal tide gauges at future dates (2030, 2050, 2100, and 2150) on the basis of different greenhouse gas emission scenarios.

A subsequent report by the California Ocean Protection Council (2018) provides a bold, science-based methodology for state and local governments to use to assess the risks associated with sea-level rise. It incorporates sea-level rise values from the *Rising seas* report (Griggs *et al*., 2017) into their planning, permitting, and investment recommendations. This more recent report included future sea-level projections for all 12 of California's coastal tide gauges.

RESPONSES TO COASTAL RETREAT

What should be done with the homes and hotels, streets and parking lots, airports and power plants, sewage treatment plants, pump stations and transmission lines, or other infrastructure built on the beach or at the edge of a cliff or bluff? This challenge has affected and will increasingly continue to affect nearly every coastal community in California and elsewhere and will only become more acute and costly over time. A limited number of options all come with some costs, benefits, and effects, and some of these require successfully navigating and negotiating through a complex, expensive, and time-consuming permitting and environmental impact review process.

Do Nothing or Wait and See

The approach with the lowest cost, least effects, but potentially highest risk for a structure or infrastructure threatened by shoreline or bluff erosion is to do nothing and wait. Depending on the setback of a particular structure from the shoreline or bluff edge, its elevation relative to sea level, age or condition, past erosion or flooding problems, and the local sea-level rise and storm climate for the near-term future, this approach may work for a limited period of time. This approach incurs no costs until a major event finally does occur, which cannot be predicted very far in advance, and then the losses may be very high because last minute emergency protection might not be permissible, possible, or effective.

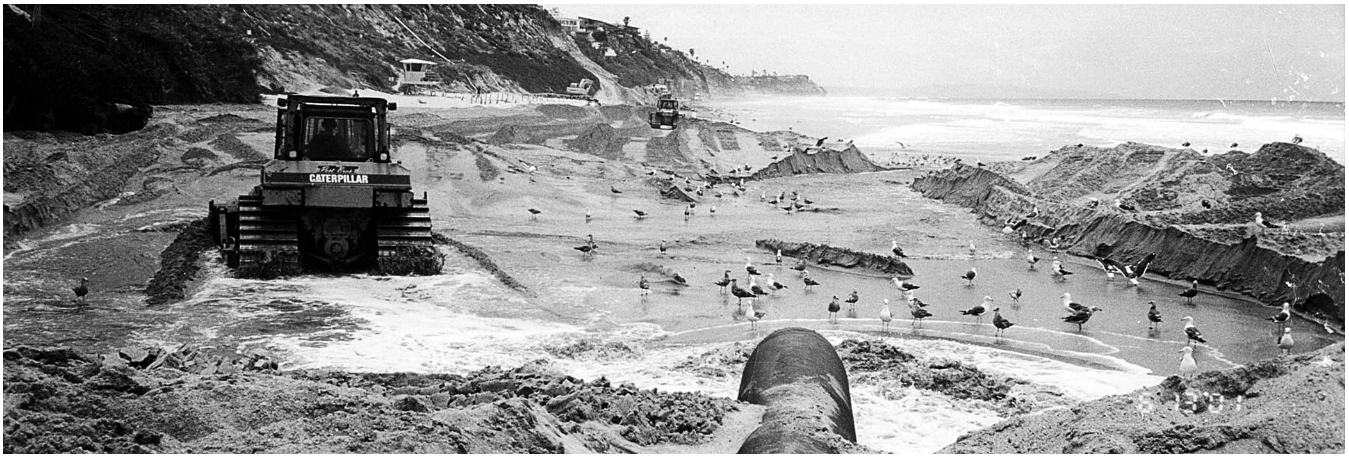

Figure 3. Offshore sand being pumped onto a beach in northern San Diego County and redistributed along the shoreline during Regional Beach Sand Project I in 2001. (Photo courtesy of James Dickens, Great Lakes Dredge and Dock.)

Beach Nourishment

Beach nourishment has been employed extensively along the broad sandy shorelines of the Gulf and south Atlantic coasts as a way to slow shoreline retreat temporarily. From the 1930s to 2006, nearly 700 million m^3 of sand was placed on the beaches of New Jersey, New York, Delaware, Maryland, Virginia, the Carolinas, Georgia, and Florida at a cost of more than $4.6 billion (ASBPA, 2018). This volume is difficult to visualize, but it would build a beach 50 m wide, 5 m deep, and 2800 km long, or a beach extending all the way down the Atlantic coast from New Hampshire to the tip of Florida. Most of these projects have been federally funded and have required frequent renourishment. With sea-level rise, extreme events, and the landward migration of barrier islands, this process needs to be recognized as a short-term and expensive response to shoreline retreat.

Beach nourishment in California historically has primarily involved opportunistic placement of sand on beaches from (1) moving sand impounded updrift from harbor entrances or dredged from harbor navigation channels and placing it on the downdrift side of a harbor, or moving the sand back updrift to renourish adjacent beaches or (2) taking sand from river channel dredging, construction of new marinas or harbors, or from construction projects in coastal dunes, where the beach was a convenient place to put sand rather than a project designed specifically for nourishment (Flick, 1993; Wiegel, 1994). From 1933 to 2017, for example, nearly 20 million m^3 of impounded sand from the Santa Barbara Harbor was dredged and placed on downdrift beaches, averaging 235,000 m^3/y. From 1964 to 2017, more than 23.5 million m^3 of sand impounded by the Ventura Harbor, or 454,000 m^3/y, was placed on downdrift beaches. From 1927 to 2018, approximately 500 projects of the sorts described above resulted in the placement of 307.4 million m^3 of sand on California's beaches.

The major exceptions to opportunistic beach nourishment have been two San Diego County Projects (known as Regional Beach Sand Projects, RBSP, I and II), which were two episodes of nourishment in which sand was dredged from offshore and placed on a number of San Diego County beaches (Figure 3). These two projects were carried out in 2001 and 2012 and added 2.6 million m^3 of sand to the shoreline at a total cost of $46 million (average of $17.70/$m^3$).

Because of the detailed beach monitoring that accompanied RBSP I and II, important conclusions can be drawn from nourishment along the Southern California coast (Griggs and Kinsman, 2016). Most of the 2.6 million m^3 of sand added to the beaches of San Diego County during RBSP I and II were eroded from the exposed subaerial beach during the first year after nourishment. Much of the sand placed in front of the eroding bluffs at Solana, Moonlight, and Batiquitos beaches during RBSP II was gone from the beach within the first 6 months, not even lasting until the first summer beach season.

Most natural California beaches have a certain normal or equilibrium width, which is primarily a function of (1) the wave climate, (2) coastline configuration and the presence of embayments or bays where sand can collect, (3) littoral sand input or supply, and (4) natural or artificial barriers to littoral drift. The dimensions, orientation, and location of barriers to littoral drift control the configuration and position of the beaches they retain (Everts Coastal, 2002).

Without either regular or repeated nourishment or the construction of retention structures, such as a groin or groin field, to stabilize or hold a beach fill, there is no reason why in an area with narrow beaches, a high littoral drift rate, and a moderate to strong seasonal wave climate that any nourished sand should stay on an exposed beach and widen it for any extended period of time. Recent research has also shown that beach nourishment is not a sustainable strategy to mitigate climate change and sea-level rise, particularly in California (Parkinson and Ogurcak, 2018); pre- and postnourishment monitoring studies have frequently been inadequate to answer the questions of environmental impacts (Peterson and Bishop, 2005); and the negative ecological consequences of beach nourishment are significant (Wooldridge, Henter, and Kohn, 2016).

Figure 4. The O'Shaughnessy Seawall along San Francisco's Ocean Beach is one of the oldest in California and was designed and built to withstand every potential type of failure. (Photo courtesy of Kenneth and Gabrielle Adelman, California Coastal Records Project.)

Figure 5. This masonry seawall in Capitola, constructed in the 1930s, is still functioning today.

Shoreline Armoring in California

Hard armoring structures of one type or another have been the most common historical response to coastal or shoreline erosion along the California coast for nearly a century. Few issues today along the state's coast, however, are more complex, poorly understood, and divisive or controversial than the use of coastal protection structures. It is important to understand that coastal armoring (including seawalls and revetments) protect what is *behind* the armor, at the cost of the fronting beach. This trade-off faces much of California's coast as sea level continues to rise and beaches move farther inland, encroaching on existing homes and infrastructure. Combating erosion with a hard structure parallel to the shoreline is a choice to *not* protect the beach at that location. It is only a matter of time before beaches in front of hard armoring structures will disappear with a rising sea level (Griggs, 2005).

The railroad companies built the earliest armor of any extent to protect their tracks adjacent to the shoreline along the Southern California coast. A century ago there was little concern with environmental impacts or sea-level rise; the primary objective was to protect the railroad or any other infrastructure from wave attack. Along the coast from Point Conception east toward Santa Barbara, the Southern Pacific Railroad laid tracks at the turn of the last century, with the first trains running along the coast by 1901. Coastal erosion was apparently recognized early on because the first concrete seawalls designed to protect the tracks in this area were constructed as early as 1909 (Griggs, Patsch, and Savoy, 2005).

During the 1920s and 1930s, as coastal development and infrastructure followed the human migration to the California coast, the construction of seawalls become increasingly more common as the best solution at the time for an eroding coastline, whether construction on cliffs, bluffs, or along the back beach.

The O'Shaughnessy seawall along Ocean Beach in San Francisco was arguably one of the earliest, largest, and best engineered structures built along the California shoreline in the last century. O'Shaughnessy, the city engineer for San Francisco, considered every possible way in which a seawall might fail and then designed the wall to withstand all of those possibilities. The 1407-m-long (4600-ft-long) structure was completed in 1929 and has effectively protected the Great Highway ever since (Figure 4). The wall extends about 6 m (20 ft) above and below sea level, was built in freestanding sections such that failure of one part would not compromise the adjacent sections, and has a drainage system to deal with overtopping and runoff. An additional factor in the long-term survival of this massive wall was its construction on the back beach, such that it has not been regularly exposed to the impacts of large waves. It was built for a total cost of $600,000 at that time (or $425/m; $130/ft) and was extended southward about a decade ago at a cost of just over $38,260/m ($11,700/linear ft, in 2018 dollars). Constructing the original 1407 m of seawall today would cost about $53 million.

The beachfront village of Capitola on the northern Monterey Bay shoreline began as a summer tent camp (Camp Capitola) on the low floodplain at the mouth of Soquel Creek. Development followed with a large hotel built just landward of the beach between 1895 and 1897. The hotel was soon protected by a masonry seawall, part of which is still standing today (Figure 5). Timber bulkheads were also built in the early 1900s to support a number of oceanfront businesses behind the beach and lagoon. Two decades later in 1923, the first reported condominiums on the California coast, the Venetian Courts, were constructed on the beach at Capitola (Figure 6). The condominiums were elevated just a few feet off the sand and were offered minimal protection from waves and storm surge by a low concrete seawall that still stands. These condominiums, as well as the back beach businesses and downtown streets, are frequently flooded by high tides and wave surge

Figure 6. The Venetian Court condominiums, built essentially on the beach in Capitola in 1923, are repeatedly flooded by the combination of storm waves and high tides.

and run-up, particularly during large El Niño years (Griggs, 2018).

Seacliff State Beach, a few miles to the SE, has an 86-year history of seawall construction and destruction (Griggs and Fulton-Bennett, 1987). Steel sheet piles followed by timber pile wooden bulkheads were used repeatedly but were regularly battered by logs and debris from winter stream runoff, particularly during the El Niño winters of the last half of the 20th century (Figure 7). The earlier protection structures were built and then damaged or destroyed nine times.

ENSO and Pacific Decadal Oscillations

Although ENSO events or El Niños and their effects along California's shoreline have been known for many years, it took longer for Pacific Decadal Oscillation (PDO) cycles to be recognized and their relationship with ENSO events to be appreciated. The period between the mid-1940s and about 1978 is now recognized as a cool or negative PDO interval that was characterized by generally calmer conditions along California's coast. This meant overall lower rainfall and fewer El Niño events and damaging coastal storms. Interestingly, this roughly three-decade-long period was precisely when California's population exploded and many shoreline areas were developed. The state's population grew from 9.3 million in 1945 to 22.8 million in 1978, or a 2.4-fold increase. In 1978, however, the climate over the North Pacific and along California's coast transitioned abruptly to a warm or positive PDO period characterized by larger, more frequent, and damaging El Niño events (Figure 8), which took their toll on coastal development and infrastructure (Griggs, Patsch, and Savoy, 2005).

Figure 7. Timber and sheet pile bulkheads have been built and destroyed nine times over the past 86 y.

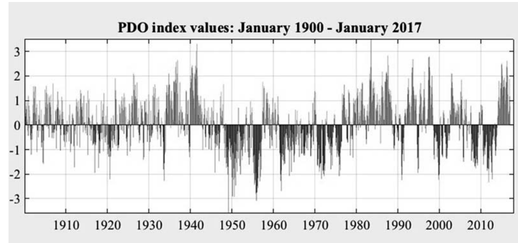

Figure 8. The climate over the North Pacific and the related weather along the California coast have been related directly to Pacific Decadal Oscillation (PDO) cycles that oscillate between warmer, stormier, El Niño–dominated periods (in light gray) and generally cooler, calmer, La Niña–dominated periods (in dark gray). (Graphic courtesy JISAO University of Washington.)

Armoring or some type of coastal protection was the typical response to the threats or damage to oceanfront homes and other development, as well as public infrastructure, as the coastal climate changed. In 1971, just 43.4 km (or 2.5%) of California's entire 1760-km shoreline was armored (Table 1). The totals were considerably higher in the state's four southernmost counties (Ventura, Los Angeles, Orange, and San Diego), where development was the most intense; 27.2 km of the shoreline (7.3%) had been hardened with some type of structure.

By 1998, 27 years later, after the damaging El Niño events of 1977–78, 1982–83, and 1997–98, 176.5 km (10.3%) of the coast of California had been protected. Along the four most populated and developed southern California counties, the total length of armor had grown to 124.2 km (33.4%) of the entire shoreline.

A decade later in 2018, seawall and revetment totals had reached 239.3 km (13.9%) of the entire state's coastline and 141.8 km (38%) of southern California's 373-km shoreline (Figure 9). For all of California, this represents a 5.5-fold increase in shore protection in 47 years.

Concerns That Developed with Coastal Armoring

Whether broken concrete, a rock revetment, concrete seawall, or timber bulkhead, many protective structures eventually fail by scour or undermining, outflanking, overtopping, battering by waves or logs and other floating debris, or some combination of these. In a study along the Central Coast after damage or destruction of a number of coastal protection structures during the severe ENSO event of 1982–83, Fulton-

Table 1. *Progressive increase in the length and percentage of armoring along the shoreline of California's coastal counties in 1971, 1998, and 2018.*

	Miles				% Armoring		
Location	Total Shoreline[†]	1971 Armor[‡]	1998 Armor[§]	2018[||]	1971 Armor[‡]	1998 Armor[§]	2018 Armor[||]
Del Norte County	45.40	1.20	0	8.06	2.64	0.00	17.76
Humboldt County	121.60	0.00	0	3.67	0.00	0.00	3.02
Mendocino County	122.20	0.00	0	1.18	0.00	0.00	0.97
Sonoma County	62.50	0.00	0.01	0.76	0.00	0.02	1.22
Marin County	70.20	1.00	1.4	3.30	1.42	1.99	4.70
San Francisco City/County	8.40	1.20	1.4	2.26	14.29	16.67	26.85
San Mateo County	55.90	0.00	6.3	5.11	0.00	11.27	9.14
Santa Cruz County	41.80	2.90	8	10.20	6.94	19.14	24.41
Monterey County	111.30	0.00	0.9	6.48	0.00	0.81	5.82
San Luis Obispo County	92.30	0.30	0.6	6.74	0.33	0.65	7.30
Santa Barbara County	109.80	3.50	14	12.87	3.19	12.75	11.72
Ventura County[¶]	41.20	11.20	18.7	23.55	27.18	45.39	57.16
Los Angeles County[¶]	73.80	2.00	23	22.48	2.71	31.17	30.46
Orange County[¶]	41.90	0.20	12.2	16.28	0.48	29.12	38.86
San Diego County[¶]	76.10	3.60	23.8	25.78	4.73	31.27	33.87
Totals	1074.40	27.10	110.31	148.72	2.52	10.27	13.84
Southern California[¶] totals	233.00	17.00	77.7	88.09	7.30	33.35	37.81

[†]*California Natural Resources Agency (1977)*
[‡]*USACE and Dames & Moore (1971)*
[§]*From 1998 aerial oblique digital photography transferred to GIS (Adelman and Adelman, 2013).*
[||]*From 2015 to 2018 aerial oblique digital photography transferred to GIS (Adelman and Adelman, 2013; Google, 2018).*
[¶]*Totals were considerably higher in the four southernmost counties, where development was the most intense.*

Bennett and Griggs (1986) investigated the engineering and history of each of the structures along 225 km of coastline between San Francisco and Carmel, for which permit or repair information existed, to determine which type of structures fared best and worst and why structures failed. Of the three major types of protective structures, concrete seawalls have been the most durable over the long term, although concrete in and of itself does not guarantee a long life and success. Many engineering issues associated with concrete can lead to success or failure. Riprap or revetments typically fared less well than concrete walls, but better than timber and wood structures. The success of riprap has been a function of the foundation on which it is placed (rock or sand); the size, slope, and elevation of the rock; and the internal layering. Wooden walls or bulkheads have usually been the least successful in preventing erosion and are most easily damaged during storms.

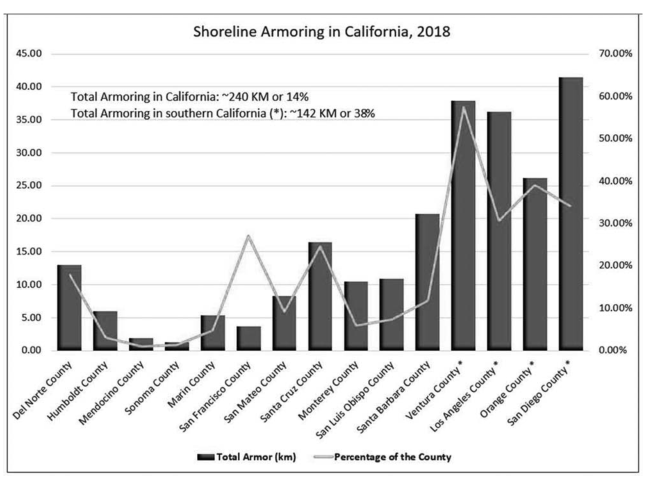

Figure 9. Total kilometers and percentage of coastline armored by county in California in 2018.

In contrast to the oceanfront homeowner, coastal engineer, or contractor's concern for the lifespan or effectiveness of a coastal protection structure, considerable concern and opposition has arisen over the past several decades regarding the direct or indirect effects of these structures on the shoreline (Griggs, 2005), including (1) visual impacts, (2) restrictions on beach access, (3) reduction of sand supply from a previously eroding cliff or bluff, (4) placement loss or covering the beach beneath the riprap or seawall, (5) passive erosion or the loss of beach from sea-level rise where the back beach is fixed and can no longer migrate inland, and (6) active erosion or the loss of a fronting beach because of wave interaction with a structure. Many of these concerns revolve around the issue of to what degree private property owners should be allowed to affect the public's beaches as they attempt to protect their own homes and property. In the case of government-funded armoring projects, how much taxpayer money should be spent on efforts to stabilize temporarily the position of an eroding coastline? What should be clear is that seawalls or riprap revetments are not designed or built to protect beaches, but to reduce wave impact and erosion of dunes, bluffs, cliffs, or beach-level development and infrastructure.

The distinction here between the armoring of private property, which has private benefits but public costs, and the protection of public infrastructure, which has public benefits and public costs, is important.

The California Coastal Act (1976) and Coastal Armoring

The California Coastal Act of 1976 (CAPRC Div 20, 2019) requires statewide planning and regulation for development in hazardous areas, including strict regulation of proposed shoreline protection structures, such as seawalls and revetments. The Coastal Act includes specific language that new development shall minimize risks from coastal hazards (Lester, 2005). Section 30253(b) states in part that any new development shall "Assure stability and structural integrity, and neither create nor contribute significantly to erosion, geologic instability, or destruction of the site or surrounding area or in any way require the construction of protective devices that would substantially alter natural landforms along bluffs and cliffs."

Put simply, this policy specifically states that new development shall not require the construction of a shoreline protection device, such as a seawall, to ensure long-term stability or survival. Section 30253 makes property owners assume the risks of developing along the coast by requiring that new development be located and designed to be safe without artificial means of protection from the forces of the ocean. This requirement is an explicit effort to halt the proliferation of seawalls, revetments, and other shoreline structures that cumulatively can negatively affect the coastline (Lester, 2005).

The Coastal Act also sets standards for when and how existing development can be protected from coastal hazards. Section 30235 states in part: "Revetments, breakwaters, groins, harbor channels, seawalls, cliff retaining walls, and other such construction that alter natural shoreline processes shall be permitted when required to serve coastal-dependent uses or to protect existing structures or public beaches in danger from erosion, and when designed to eliminate or mitigate adverse impacts on local shoreline sand supply."

A large part of the motivation for the Coastal Act of 1976 was the need to provide protection for marine life and coastal habitats and to preserve public access to the shoreline, which was often under threat. It was written during the end of an approximately 30-year-long, relatively calm period in California's coastal climate (a cool or negative PDO cycle; Figure 8). Issues of coastal erosion and protection were less apparent than they would become in the subsequent warm or positive PDO period that began around 1978 and continued for the next 20 years. The Coastal Act was also written primarily by lawyers, rather than coastal geologists or engineers, which helps explain why revetments and seawalls were combined with breakwaters, groins, jetties, and harbor channels, which are quite different structures with very different purposes. Additionally, with the exception of groins, none of these other engineering structures are built to protect public beaches from erosion. Seawalls and revetments are designed and built to protect cliff, bluff, dune, or back beach development or infrastructure, and breakwaters and jetties are usually designed either to protect or provide safe access into ports or harbors, although offshore breakwaters have also been used to reduce wave energy at the shoreline and encourage beach widening.

Two other parts of Section 30235 were ambiguous enough to lead to conflicts and legal battles over the next four decades. One was the use of the word "shall," as in coastal protection structures "shall be permitted," and the other was the wording "to protect existing structures." The word *shall,* in contrast to the word *may*, opened the door for many homeowners who wanted to build some type of coastal protection structure. *Shall* is quite clear whereas *may* implies some uncertainty.

Since 1976, the Coastal Commission has also had to deal with the issue of what constitutes an "existing structure" (Lester, 2005). Early in its history, the Commission drew a clear distinction between structures, such as residences or commercial buildings, and accessory structures, such as bluff-top gazebos, patios, or decks. The Commission made it clear that coastal armoring would not be approved for the protection of some accessory structure, patio, or landscaping.

The larger issue, however, on the use of the words "existing structure" has been whether a home or other structure built after 1976 should be considered as "existing" and therefore eligible for shoreline protection (Lester, 2005). This concept has been argued both ways. If a structure was legally in existence at the time the Coastal Act was implemented (1 January 1977) and has not been redeveloped since that time, it clearly falls under the definition of an "existing structure" and is therefore eligible for consideration for a coastal protection structure if other conditions can be met. The Commission currently considers redevelopment to mean that, since 1 January 1977, alterations including demolition, renovation, replacement, and additions of 50% or more of the major structural components or that lead to a 50% or more increase in gross floor area have occurred or will occur if a proposed project moves forward.

On the other hand, homes or other structures built after 1 January 1977 should have passed the test of not requiring a seawall or revetment during their lifetime to have obtained a coastal development permit in the first place. Many owners of structures that were built after 1976, however, have made the case that their homes are now threatened or in imminent danger from cliff, bluff, dune, or beach erosion, often because of inadequate or poorly documented coastal erosion studies that led to the initial conclusion that particular building sites were safe for the lifetime of a proposed home. Nonetheless, in a few instances such "existing structures" are sited in precarious locations where, in fact, the Commission has historically approved coastal armoring, even though construction or redevelopment took place after 1 January 1977 (California Coastal Commission, 2018).

Obtaining a Coastal Development Permit for some type of coastal protection has become a very lengthy, complex, and expensive process requiring extensive geological, geotechnical, biological, and frequently other studies, as well as a number of significant fees. Coastal development permits require an application or filing fee to cover administration of the permit, which is often in the thousands of dollars, depending on the type and size of the project. Additionally, each proposed project under the permit is analyzed to determine the value of the resources that may be lost or compromised, and impact mitigation fees, or mitigation payments, are determined. In many instances, hard structures (*e.g.*, seawalls and riprap) will result in the loss of the fronting beach; thus, applicants are charged an In Lieu Sand Replenishment Fee, a Recreation/Beach Loss Access Fee, or both. Mitigation fees can easily add up to several hundred thousand dollars or, in some cases, several million dollars, based on the value of the resources being lost. This does not include the cost to the applicant of all of the necessary technical studies or the actual cost of

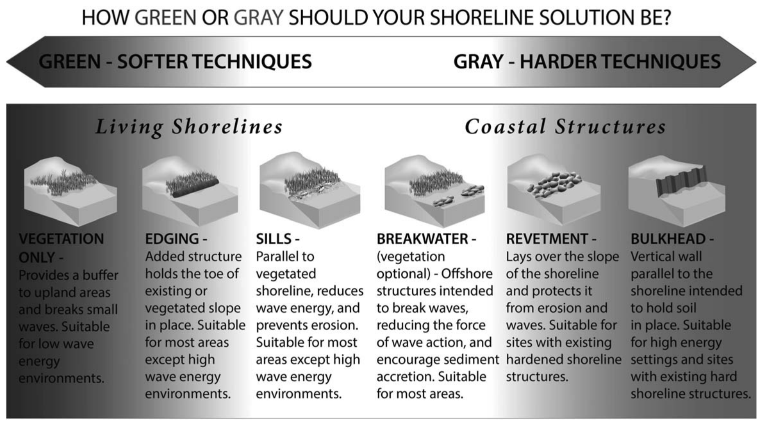

Figure 10. A continuum of green to gray shoreline stabilization or protection techniques, including living/soft/green, hybrid, and hard/gray armoring techniques (NOAA, 2015).

constructing the coastal protection structure if a permit is granted.

The decision on what is an existing structure has been somewhat inconsistent along California's coastline between different Coastal Commission staff and regional offices. In the Coastal Commission's (2018) *Sea-Level Rise Policy Guidance* document, however, it was clearly stated that the Commission intended to enforce the original intent of the Coastal Act, namely that "existing structure" means existing as of 1 January 1977 without significant alterations. This decision is going to reverberate along the cliffs, bluffs, and beaches of California from Crescent City to Imperial Beach. Most homeowners or homebuyers have historically assumed that when the waves began to threaten their homes that a permit for a seawall or revetment could be obtained. This is no longer necessarily the case, however, and this decision will have a profound effect on California's existing oceanfront development. Literally hundreds of millions if not billions of dollars in properties are at stake.

Living or Green Shorelines

In recent years, with a greater awareness of the effects of coastal armoring (Griggs, 2005) as well as the increased coverage of the shoreline with revetments or seawalls, the concept of natural, living, or green shorelines has been put forward as an alternative to hard or gray shorelines (Back and Lange, 2016; Judge *et al*., 2017; NOAA Living Shorelines Workgroup, 2015). This "natural shoreline infrastructure" includes things like coral reefs, mangroves, salt marshes, or other similar environments and involves coastal habitats or ecosystems that can provide some protection from sea-level rise, extreme tides, hurricanes, storm wave attack, and erosion. For some context, throughout the millions of years that these coastal ecosystems have existed, they have been able to keep pace with sea level fluctuations of more than 100 m, as evidenced by the very existence of these habitats or ecosystems along the shoreline at sea level today. Some of these ecosystems are restricted to particular latitudes and energy conditions, however, and are therefore limited in their distribution. Coral reefs and mangroves, for example, can only flourish in tropical environments. Salt marshes and similar wetland ecosystems require fine-grained sediment and cannot tolerate or survive high wave energy environments.

The California coastline is very diverse, and no single solution will address all shoreline erosion and sea-level rise challenges now or in the future. Protecting, encouraging, or rebuilding salt marshes and similar wetland environments has been successfully accomplished in a number of protected or low-energy environments in California, such as estuaries and lagoons (Judge *et al*., 2017). The concept has also been put forward that some combination of a living or green shoreline and a hard or gray shoreline may be appropriate in specific areas, dependent on energy conditions (Figure 10).

For the 1760 km of high-energy, exposed outer coast of California, there is no living, green, or organic approaches that are capable of significantly reducing the effects of storm waves, high tides, or long-term sea-level rise. Conditions for utilization of each of the "green" or "living" solutions illustrated in Figure 10 all state that they are "suitable for most areas except high wave energy environments." Although vegetation is often listed in the alternatives that must be considered and evaluated in applications for shoreline protection structures along the California coast, realistically, there are no vegetative solutions, other than improved drainage and landscaping atop a bluff to divert runoff away from the bluff face, for the bluffs and cliffs that make up about 1264 km or 72% of the state's outer coast. Solutions involving green or living solutions may be used in tandem with other protective measures but will not be effective along most of California's high-energy coastline.

Planned or Managed Retreat

Each major storm, hurricane, or other coastal disaster is followed by the inevitable debate about whether rebuilding is the right decision. Relocation of oceanfront structures or infrastructure (houses, utilities, roads, *etc*.) is becoming a more common, or at least considered, response, now often called *managed or planned retreat* (in contrast to unmanaged or unplanned retreat; Griggs, 2015). The Cape Hatteras light-

Figure 11. Erosion of the bike path and bluff along the Promenade in Ventura California during the large wave event of January 9th, 2019.

Figure 12. (A) Gleason Beach, Sonoma County coast, in 1979. This group of 21 homes was built on a narrow strip of land adjacent to State Highway 1 on one side and a steep bluff dropping to the shoreline on the other. Septic tanks were placed behind concrete retaining walls on the beach. (Photo courtesy of Kenneth and Gabrielle Adelman, California Coastal Records Project.) (B) Gleason Beach in 2013. Although just 10 homes remained in 2013, many of these were not safe for habitation because of continuing erosion. By 2018 only few houses remained at both ends of this development, and plans are underway to relocate Highway 1 further inland. (Photo courtesy of Kenneth and Gabrielle Adelman, California Coastal Records Project.)

house relocation is one of only a few well-publicized and expensive example of managed retreat, as is the Surfer's Point Managed Shoreline Retreat Project in Ventura, California. This project involved the relocation of a California State Park bike path, public parking lot, and pedestrian path as an alternative to building a seawall or revetment. A portion of this project involved incorporating a living shoreline with dunes stabilized by native vegetation along the backshore. While Phase I of this project was completed in 2011 and deemed successful, the ENSO winter waves of 2015 once again proved their power, eroding parts of the bike path and eroding the beach, necessitating the planning for phase II of this project (Figure 11). Nonetheless, managed retreat is likely to become more and more common as sea level continues to rise and risks and damages are amplified through short-term events such as hurricanes, extreme tides, and large storm waves.

Although managed retreat, relocation, or moving back from high-risk or already affected coastal sites is viewed favorably by coastal planners and policy makers, as well as some coastal geologists and engineers, it is understandably far less palatable to those who own homes or property along the shoreline. Retreat is often ruled out for several reasons before any serious discussion or cost-benefit analysis has taken place (Young, 2018). Landowners are concerned that even the mention of retreat can negatively affect property values. Even when proposed by a government entity, to date it has rarely been implemented as too unpopular and too costly, with no source of funds to buy out property owners or cover the costs. There are also two key flaws in arrangements whereby government acquires threatened coastal properties at prehazard prices: it acts as a distorting effect on the market, and it incentivizes increased risk exposure because homeowners know there is a guaranteed solution down the road (Young, 2018).

What is not often appreciated in California is that retreating from the shoreline is not a new approach, and there have been a number of neighborhoods or locations where legal parcels and homes are now gone. Big Lagoon in Humboldt County, Gleason Beach in Sonoma County (Figure 12A, B), Bolinas Bluffs in Marin County, the Pacifica Esplanade in San Mateo County (Figure 13), Carpinteria in Ventura County, West Newport Beach in Orange County, and Encinitas in San Diego County are all examples where portions of or entire neighborhoods have been lost to coastal erosion (Griggs, 2015). Documenting these lost neighborhoods and those that are in the process of disappearing today is important in providing a longer term perspective of what California faces as a state.

Figure 13. These apartment buildings in Pacifica were built on a high eroding bluff in the early 1970s, and despite efforts to protect them, they were declared unsafe to occupy and then demolished in 2016.

In addition to relocating individual houses or structures is the concept of larger scale managed retreat or relocation. Such a regional approach has not been considered along the west coast to date, but with the magnitude of shoreline retreat taking place along the Atlantic coast of the United States, particularly along individual barrier islands suffering major hurricane damage, this approach becomes a very real option. Planned or managed retreat on a regional basis will almost certainly require legislation or other government involvement or intervention, however. Currently, some 40 local governments are considering full Local Coastal Program updates, some of which are considering or have considered managed retreat on a larger geographic scale as an alternative. Ultimately, however, because of feasibility concerns, lack of funding, or opposition from vocal constituents, managed retreat is not often pursued, even when it pencils out financially in terms of long-term trade-offs and resources lost.

CONCLUSIONS

Coastlines in California and around the world are in a constant state of flux and, with few exceptions, are migrating landward or inland, either gradually or more rapidly during extreme events. Although some short-term approaches have been used to forestall the inevitable retreat of the coastline (*e.g.*, beach nourishment, seawalls, and revetments), some being more short-term than others, they all have their limits and trade-offs. Those limits are dependent on both the rate of acceleration of global and local sea-level rise in the decades ahead and the frequency and magnitude of extreme events (*e.g.*, hurricanes, ENSO events, storm waves and high tides) and whether these increase in frequency and magnitude in the future. Increases in wave heights over the past several decades have been documented along portions of the U.S. West Coast (*e.g.*, Allan and Komar, 2006; Menendez *et al.*, 2008; Wingfield and Storlazzi, 2007), but these trends have more recently been considered to be largely insignificant when adjusted for wave buoy hardware modifications (Gemmrich, Thomas, and Bouchard, 2011). The use of global climate models to project future wave climate shows a poleward migration of storm tracks and, overall, a slight decrease in wave heights for California in general compared with the historic record (Erickson *et al.*, 2015; Graham *et al.*, 2013). If this were the case, it would be welcome news for oceanfront homeowners.

Strong El Niño events have had major impacts on the coastline of California, in part driven by elevated sea levels (as high as 30 cm above normal for weeks) and in part driven by elevated winter waves typically approaching from the SW. The frequency and magnitude of future El Niño events, combined with continuing sea-level rise, will be major factors affecting shoreline vulnerability in the decades ahead (Langridge, 2018). Research to date on future El Niño patterns is largely inconclusive (Collins *et al.*, 2010), although one recent study suggests a potential doubling in the frequency of extreme El Niño events (Cai *et al.*, 2014) such as those that occurred in 1982–83, 1997–98, and 2015–16. This news would be bad for California's coastal residents and communities.

The increasing rate of sea-level rise is more unfortunate news for the California coast. Scenarios for sea level and their probabilities at different times in the future have been developed, but there is still considerable uncertainty because of the unknowns in future greenhouse gas emissions, as well as the future uncertainty in the timing of ice sheet collapse in Antarctica. Sea-level rise is a ramp with an increasing slope that will be additive with extreme events. None of the past efforts to protect shoreline development and infrastructure from coastal storm damage and shoreline erosion will be effective over the long term. The shoreline will move inland and people and their structures are in the way. Although it is often difficult for elected officials, for example, to look very far into the future, all of California's coastal communities must assess their vulnerabilities to future sea-level rise and extreme events and develop adaptation and response plans for the inevitability of a changing shoreline.

The trade-off when choosing to battle sea-level rise with hard armoring structures is detrimental to one of California's most beloved resources, the sandy beach. Choosing to protect houses, infrastructure, or development behind a hard armoring structure is a direct choice to sacrifice the fronting sandy beach and its ecosystem. California's beaches are a valuable resource, providing billions of dollars of direct revenue to the state and a barrier to storm surge and large waves, and are part of the state's cultural identity. Additionally, beaches provide innumerable environmental benefits, including water filtration, providing important habitat for many endangered and threatened species, and nutrient cycling. Management of the coastline as it relates to coastal hazards and hard armoring structures will determine the fate of sandy beaches and the aesthetic and function of California's shoreline for generations to come.

ACKNOWLEDGMENTS

The authors thank Jacqueline Green, a student at California State University Channel Island, for her help in digitizing the coastal armoring structures into the GIS environment and Kenneth and Gabrielle Adelman for their repeated flights along the entire coast of California and for creating and maintaining the California Coastal Records Project website (https://www.californiacoastline.org/) for open use by anyone.

LITERATURE CITED

Adelman, K. and Adelman, G., 2013. *California Coastal Records Project*. https://www.californiacoastline.org

Allan, J.C. and Komar, P.D., 2006. Climate controls on US West Coast erosion processes. *Journal of Coastal Research*, 22(3), 511–529.

ASBPA (American Shore and Beach Preservation Association), 2018. *National Beach Nourishment Database*. https://gim2.aptim.com/ASBPANationwideRenourishment

Beck, M.W. and Lange, G.-M. (eds.), 2016. *Managing Coasts with Natural Solutions: Guidelines for Measuring and Valuing the Coastal Protection Services of Mangroves and Coral Reefs*. Washington, D.C.: World Bank, *Wealth Accounting and the Valuation of Ecosystem Services Partnership (WAVES), Technical Report 103340*, 166p.

Cai, W.; Borlace, S.; Lengaigne, M.; van Rensch, P.; Collins, M.; Vecchi, G.; Timmerman, A.; Santoso, A.; McPhaden, M.J.; Wu, L.; England, M.H.; Want, G.; Guilyardi, E., and Jim, F.F., 2014. Increasing frequency of extreme El Niño events due to greenhouse warming. *Nature Climate Change*, 4, 111–116.

California Coastal Commission, 2018. *Sea Level Rise Policy Guidance. Interpretive Guidelines for Addressing Sea Level Rise in Local*

Coastal Programs and Coastal Development Permits. San Francisco, California: California Coastal Commission, Ocean Protection Council, 305p.

California Natural Resources Agency, 1977. *Assessment and Atlas of Shoreline Erosion along the California Coast*. Sacramento, California: Department of Navigation and Ocean Development [now Division of Boating and Waterways].

California Ocean Protection Council, 2018. *State of California Sea-Level Rise Guidance. 2018 Update*. Sacramento, California: OPC, 84p.

CAPRC Div 20, 2019. *California Coastal Act of 1976*, §§ 30000–30900 (2019). https://www.coastal.ca.gov/coastact.pdf

Collins, M.; An, S.I.; Cai, W.; Ganachaud, A.; Guilyardi, E.; Jin, F.F.; Jochum, M.; Lengaigne, M.; Power, S.; Timmermann, A.; Vecchi, G., and Wittenberg, A., 2010. The impact of global warming on the tropical Pacific Ocean and El Niño. *Nature Geoscience*, 3, 391–397.

Erickson, L.H.; Hegermiller, C.A.; Barnard, P.L.; Ruggiero, P., and van Ormondt, M., 2015. Projected wave conditions in the eastern North Pacific under the influence of two CMIP5 climate scenarios. *Ocean Modeling*, 96(1), 171–185.

Everts Coastal, 2002. *Impact of Sand Retention Structures on Southern and Central California Beaches*. Oakland: California Coastal Conservancy, *CCC contract 00-149*, 103p.

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

Fulton-Bennett, K.W. and Griggs, G.B., 1986. *Coastal Protection Structures and Their Effectiveness*. Sacramento, California: Department of Boating and Waterways and Santa Cruz, California: Institute of Marine Sciences, University of California Santa Cruz, 48p.

Gemmrich, J.; Thomas, B., and Bouchard, R., 2011. Observational changes and trends in northeast Pacific wave records. *Geophysical Research Letters*, 38(22), 1–5.

Google, 2018. *Google Earth* (Pro). http://www.google.com/earth/download/ge/agree.html

Graham, N.E.; Cayan, D.R.; Bromirski, P.D., and Flick, R.E., 2013. Multi-model projections of twenty-first century North Pacific winter wave climate under the IPCC A2 scenario. *Climate Dynamics*, 40(5–6), 1335–1360.

Griggs, G.B., 2005. The impacts of coastal armoring. *Shore and Beach*, 73(1), 13–22.

Griggs, G.B., 2015. Lost neighborhoods of the California Coast. *Journal of Coastal Research*, 31(1), 129–147.

Griggs, G.B., 2018. *Between Paradise and Peril: The Natural Disaster History of the Monterey Bay Region*. Santa Cruz County, California: Monterey Bay Press, 212p.

Griggs, G.B.; Cayan, D.; Tebaldi, C.; Fricker, H.A.; Arvai, J.; DeConto, R.; Kopp, R.E., and Whiteman, E.A. (California Ocean Science Protection Council Advisory Team Working Group), 2017. *Rising Seas in California: An Update on Sea-Level Rise Science*. Oakland: California Ocean Sciences Trust, 71p.

Griggs, G.B. and Fulton-Bennett, K.W., 1987. Failure of coastal protection at Seacliff State Beach, Santa Cruz County, California. *Environmental Management*, 11(2), 175–182.

Griggs, G.B. and Kinsman, N., 2016. Beach widths, cliff slopes, and artificial nourishment along the California Coast. *Shore and Beach*, 84(1), 1–12.

Griggs, G.B.; Patsch, K.B., and Savoy, L.E., 2005. *Living with the Changing California Coast*. Berkeley, California: University of California Press, 540p.

Judge, J.; Newkirk, S.; Leo, K.; Heady, W.; Hayden, M.; Veloz, S.; Cheng, T.; Battalio, B.; Ursell, T., and Small, M., 2017. *Case Studies of Natural Shoreline Infrastructure in Coastal California: A Component of Identification of Natural Infrastructure Options for Adapting to Sea Level Rise* (California's Fourth Climate Change Assessment). Arlington, Virginia: The Nature Conservancy, 38p.

Langridge, R., 2018. *Central Coast Summary Report. California's Fourth Climate Change Assessment*. Sacramento: California Natural Resources Agency Publication, *SUM-CCCA4-2018-006*, 115p.

Lester, C.L., 2005. An overview of California's coastal hazards policy. In: Griggs, G.B.; Patsch, K.B., and Savoy, L.E. (eds.), *Living with the Changing California Coast*. Oakland: University of California Press, 540p.

Menendez, M.; Mendez, F.J.; Losada, I.J., and Graham, N.E., 2008. Variability of extreme wave heights in the northeast Pacific Ocean based on buoy measurements. *Geophysical Research Letters*, 35(L22607), 6p. doi:10.1029/2008GL035394

Nerem, R.S.; Buckley, B.D.; Fasullo, J.F.; Hamlington, B.; Masters, D., and Mitchum, G.T., 2018. Climate-change-driven accelerated sea-level rise detected in altimeter era. *Proceedings of the National Academy of Sciences of the United States of America*, 115(9), 2022–2025. https://doi.org/10.1073/pnas.1717312115

NOAA Living Shorelines Workgroup, 2015. *Guidance for Considering the Use of Living Shorelines*. Silver Spring, Maryland: National Oceanic and Atmospheric Administration, 36p.

Parkinson, R. and Ogurcak, D., 2018. Beach nourishment is not a sustainable strategy to mitigate climate change. *Estuarine, Coastal and Shelf Science*, 212, 203–209.

Peterson, C.H. and Bishop, M.J., 2005. Assessing the environmental impacts of beach nourishment. *Bioscience*, 55(10), 887–896.

USACE (U.S. Army Corps of Engineers) and Dames & Moore, 1971. *National Shoreline Study: California Regional Inventory*. San Francisco, California: Department of Defense, USACE, South Pacific Division, 106p.

Wiegel, R.L., 1994. Ocean beach nourishment on the USA Pacific Coast. *Shore and Beach*, 62(1), 11–28.

Wingfield, D.K. and Storlazzi, C.D., 2007. Spatial and temporal variability in oceanographic and meteorological forcing along Central California and its implications on nearshore processes. *Journal of Marine Systems*, 68(3–4), 457–472.

Wooldridge, T.; Henter, H.J., and Kohn, J.R., 2016. Effects of beach replenishment on intertidal invertebrates: A 15-month, eight-beach study. *Estuarine, Coastal and Shelf Science*, 175, 24–33.

Young, A.W., 2018. How to Retreat: The Necessary Transition from Buyouts to Leasing. *Coastal Management*, 46(5), 527–535. doi:10.1080/08920753.2018.1498716