Ann. N.Y. Acad. Sci. ISSN 0077-8923

ANNALS OF THE NEW YORK ACADEMY OF SCIENCES
Special Issue: *Pathways to Resilience: Adapting to Sea Level Rise in Los Angeles*
TECHNICAL REPORT

Pathways to resilience: adapting to sea level rise in Los Angeles

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Los Angeles (LA) County's coastal areas are highly valued for their natural benefits and their economic contributions to the region. While LA County already has a high level of exposure to flooding (e.g. people, ports, and harbors), climate change and sea level rise will increase flood risk; anticipating this risk requires adaptation planning to mitigate social, economic, and physical damage. This study provides an overview of the potential effects of sea level rise on coastal LA County and describes adaptation pathways and estimates associated costs in order to cope with sea level rise. An adaptation pathway in this study is defined as the collection of measures (e.g., beach nourishment, dune restoration, flood-proofing buildings, and levees) required to lower flood risk. The aim of using different adaptation pathways is to enable a transition from one methodology to another over time. These pathways address uncertainty in future projections, allowing for flexibility among policies and potentially spreading the costs over time. Maintaining beaches, dunes, and their natural dynamics is the foundation of each of the three adaptation pathways, which address the importance of beaches for recreation, environmental value, and flood protection. In some scenarios, owing to high projections of sea level rise, additional technical engineering options such as levees and sluices may be needed to reduce flood risk. The research suggests three adaptation pathways, anticipating a +1 ft (0.3 m) to +7 ft (+2 m) sea level rise by year 2100. Total adaptation costs vary between $4.3 and $6.4 bn, depending on measures included in the adaptation pathway.

Keywords: resilience; Los Angeles; flood risk; adaptation; cost; coastal area

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doi: 10.1111/nyas.13917

Summary

The Pacific Ocean shoreline is an iconic feature of Los Angeles (LA) County, reflecting its recreational opportunities and natural environment. Stretching over 74 miles between the Orange and Ventura County borders, LA County's coastal areas, beaches and bluffs are highly valued for their natural benefits and their economic contributions to the region. Significant effort is being devoted to maintaining the protective qualities of the sandy beaches and dunes that front many coastal areas and help protect recreational and infrastructure assets, enhancing their value for people, the economy and the environment.

California, including LA, has a high level of exposure to flooding, with millions of people living in flood zones (both coastal and riverine). Recent studies by the US Geological Survey, through its Coastal Storms Modeling System (CoSMoS) demonstrate that sea level rise (SLR) is expected to increase both the magnitude and frequency of coastal flooding, exacerbating the risk of flooding to people and assets in low-lying coastal areas. Socio-economic trends such as population and economic growth will also increase the exposure of assets and people to flooding. Given these trends, flood management in the coastal zone of LA must continue to include preparations for reducing flood risk. Some adaptation measures, such as beach nourishment and protection of critical infrastructure, are already in place. Federal and state agencies also regulate activities in the coastal zone. For instance, the Federal Emergency Management Agency (FEMA) sets standards for zoning and building practices in designated flood zones and manages the National Flood Insurance Program (NFIP), which compensates policyholders financially after a flood event. In California, the California Coastal Commission (CCC) enforces the CA Coastal Act, which works to ensure equitable coastal access and regulated coastal development.

The goal of this study is to provide an overview of the potential effects of sea level rise on the coastal zone of LA County (for people, economy, and the environment), and to develop descriptions of adaptation pathways and their costs in order to cope with these effects. An adaptation pathway in this study is defined as the collection of measures (floodproofing, zoning, barriers, levees, etc.) required to lower flood risk. A variety of individual adaptation measures and associated costs are discussed based on an extensive literature review and a participatory process with stakeholders in the region in 2015, 2016, and 2017.

The research has resulted in three adaptation pathways for LA County, based on the geography of the areas to be protected. Each adaptation pathway anticipates +1 ft (0.3 m), +3 ft (+1 m), and +7 ft (+2 m) SLR, respectively, until the year 2100. The total adaptation costs vary between \$4.3bn—\$6.4bn, depending on the SLR scenario and the measures included in the adaptation pathway. The aim of using different adaptation pathways is to enable a transition from one measure to another over time, allowing for flexibility among policies and to potentially spread the costs over time. Maintaining beaches and dunes in their current form through

dune restoration and periodic beach nourishment is the foundation of each of the three adaptation pathways, as much of the LA coastline consists of sandy beaches, which are important for recreation, environmental values and flood protection. However, in some scenarios with high levels of SLR, these solutions are not sufficient in the long term; thus, additional technical engineering options such as levees and sluices may be needed to reduce flood risk. Such options are primarily targeted to lower the probability of the flood hazards, especially near critical infrastructure facilities and ports. Building codes and land-use planning measures focus on lowering the vulnerability of buildings in the LA coastal zone.

The adaptation measures described in this research do not provide a complete overview of all possible adaptation strategies, nor have we assessed all cost categories that pertain to these strategies. For example, the considerable administrative and planning costs associated with climate adaptation have not been addressed. However, the adaptation measures outlined in this research provide a range of possible visions and their associated costs for flood risk management solutions for LA.

Recommendations from this study are summarized below:

All areas:

- **Offshore sand reserves**: Since most of the adaptation pathways depend on beach nourishment using offshore sand, it is important to improve assessments of the volume of available offshore sand reserves. The environmental impacts and economic viability of utilizing these offshore reserves must also be examined.
- **Sand berms and dunes**: For wider beaches, it may be possible to transform the current seasonal sand berms program into permanent dune restoration programs. The first pilot studies for such transformation are promising and currently ongoing.
- **Flood control and drainage**: Levees along the lower parts of channels that drain into the coastal zone need additional assessment to evaluate their viability against sea level rise (e.g. the Dominguez Channel, LA River, and Ballona Creek). The pumping capacity of low-lying areas, such as Venice and Wilmington, is currently being upgraded. However, they could require another upgrade in the future with the closing of tidal gates, and with increasing deluge-style precipitation events in combination with accelerating sea level rise.
- **Include climate change considerations in the design of coastal structures**: Efforts to build, maintain, or modify structures in coastal areas at risk of sea level rise should be evaluated based on sea level rise scenarios or trends in extreme precipitation to evaluate how robust these investments may be as well as to take increasing risk levels into account.
- **Green infrastructure and nature-based solutions**: It is important to consider green infrastructure and nature-based adaptation measures to reduce effects from sea level rise. Such approaches include strengthening natural dune development, and the restoration of vegetation. Nature-based solutions, or a “living shorelines approach” (Resilient Coastlines Project), show promise for their ability to reduce impacts from coastal storms.
- **Consider managed retreat and limits to future developments in areas at high risk from rising seas**: Long-term adaptation policies for managed retreat and setback could be applied to new buildings in both low-lying areas as well as cliff areas that will increasingly suffer from erosion. One option is to reassess current setback policies for new buildings; this could reduce risk to coastal areas in the short term, and create ‘buffer space’ along the coast against sea level rise and erosion.
- **NFIP**: There are different concerns with respect to the viability of the National Flood Insurance Program (NFIP) given future trends such as climate change and sea level rise, and whether the current program meets adaptation challenges for coastal California. Nonetheless, several regulatory improvements that go beyond the NFIP minimum standards can be implemented by local governments to meet future challenges. These include:

  - ○ *Improve flood hazard maps to include sea level rise considerations*: FEMA flood hazard maps are currently being upgraded. However, detailed regional-to-local simulations of flood events are required to evaluate the effect of adaptation measures. Such simulations should include sea level rise projections, such as the U.S. Geological Survey's (USGS) Coastal Storm Modeling System (CoSMoS), and could be used by local jurisdictions to bolster information as they evaluate new developments in the coastal zone.

- *Improvements to FEMA and City guidelines for building improvements*: City of LA guidelines for homeowners state that if a homeowner applies for a restructuring project for an existing home built prior to the initiation of the FEMA regulations, improvements are not required to comply with NFIP regulations if the permit valuation is less than 50% of the market value. In LA County, however, the value is based on the County Assessor's values, which differ from market value. The City of LA could use the size of the improvement area in addition to the value of the improvement provided by the County Assessor on a monthly basis to determine whether "significant improvement" occurs.
- *Adopt V zone regulations for A zones*: Local policies could consider stricter building codes based on existing flood hazard maps. For example, it would be useful to explore more strict foundation standards and dry flood-proofing measures for FEMA A flood zones, and some of the foundation standards that currently exist in the stricter regulated FEMA V zones could be made applicable to A zones.
- *Freeboard*: Local jurisdictions could consider adding additional freeboard to the current base flood elevation (BFE) requirements. For example, the current freeboard required for Category II buildings is +1 ft, while research demonstrates that the benefits of investing in freeboard of up to +4 ft exceed its costs, especially for coastal V flood zones. This analysis has been conducted for single-family homes.
- *Community Rating System (CRS)*: The City of LA and surrounding communities participating in the NFIP can examine the potential for lowering their CRS rating. This will achieve the dual goals of (1) lowering policy premiums and (2) building more resilience in coastal assets and communities.

Specific solutions:

- **Ports of Los Angeles and Long Beach**: The ports have several options for adaptation. The first option is to continue elevating their facilities when modifying existing structures or developing new structures. In conjunction with existing policy plans by the ports, critical infrastructure can be protected with (upgraded) flood walls. As an alternative, the ports could follow international examples, with seaward development of port facilities. In such a plan, old inland piers could be transformed into residential areas, separated from the new seaward port by small dams and/or sluices. This plan could create a win-win situation, where flood protection investments in new seaward port areas both enhance the new port facilities against sea level rise and protect the residents who work and live behind these upgraded facilities.
- **Harbors**: Associated LA agencies should assess the effectiveness of elevating roads surrounding Marina del Rey and King Harbor. Such elevated roads, when constructed as levees, may act to protect low-lying residential areas behind them.
- **Ballona Wetlands**: Planners and regulators should evaluate newly developed wetlands restoration plans against extreme sea level rise scenarios of +1 m (+3 ft), as well as to protect against coastal storms. This study could evaluate whether the new plans address the availability of enough sand to allow the wetland to adjust to rising sea levels, and to determine whether there are tipping points beyond which natural adjustment of the wetland to rising sea levels becomes challenging.
- **Naples**: The most recent simulations by CoSMoS show the Naples area of Long Beach as a vulnerable low-lying area. One option for Naples is to upgrade building codes and increase the elevation requirement for new buildings. When assuming an extreme +7 ft sea level rise scenario, protecting the bay area with a sluice could be considered to protect assets and people, while still allowing vessels to go in and out of the bay to the ocean.
- **Malibu**: Elevating buildings is one adaptation option for Malibu. To maintain accessibility

to and from the Malibu Coast, creative solutions are needed for the low-lying stretches of the Pacific Coastal Highway (PCH). These will require planning and coordinating policies among the City of Malibu, Los Angeles (and Ventura) County, Caltrans, other state agencies, as well as private property owners. Over the long term, beach nourishment could become increasingly challenging, due to a lack of sediment sources, cost and environmental factors.

1. Introduction

1.1 Overview

The Los Angeles (LA) County Pacific Ocean shoreline is approximately 74 miles long, and extends from the Ventura County line at the west end to the mouth of the San Gabriel River and Orange County in the southeast (CRSMP, 2012). LA County has a population of approximately 10 million people distributed over 88 municipalities. LA's coastal areas, beaches, and bluffs are defining features for California's recreational values and natural environment. In addition, coastal areas, sandy beaches, and dunes offer protection to the people of LA and their assets, and many efforts are ongoing to preserve and manage coastal areas, and enhance their value for the people, economy, and environment (e.g. City of LA, 2009, Port of Long Beach, 2014; Grifman *et al.*, 2013).

Sea level rise (SLR) will increase both the magnitude and frequency of high coastal water levels, exacerbating the risk of flooding for people and assets in low-lying coastal areas when no additional action is taken (NRC, 2012; Griggs *et al.*, 2017). Climate change and climate variability may also increase extreme precipitation events, which cause (flash-) flooding from creeks and watersheds in the backcountry that drain into low-lying coastal areas. Without adaptation, these events may increasingly cause local flooding due to undercapacity of the stormwater draining systems (Barnard *et al.*, 2014). Furthermore, socio-economic trends such as population and economic growth will also increase the exposure of assets and people to flooding (e.g., Heberger *et al.*, 2009; King *et al.*, 2016).

SLR will also increase the intrusion of salt water from the ocean into coastal aquifers. Although cities in the coastal zone of LA County have already begun implementing measures to maintain the fresh water aquifer and preserve its drinking water supply, increased SLR will cause new challenges for water supply management (e.g. City of LA, 2009). SLR and extreme flooding could also reduce the value of ecosystem services provided by coastal wetlands such as Ballona Wetlands (Grifman *et al.*, 2013), by reducing the function of coastal wetlands as natural buffers against floods and decreasing their ability to infiltrate stormwater and provide a safe habitat for wildlife.

Beaches are already threatened by coastal flooding and coastal erosion (Vitousek *et al.*, 2017). Although coastal erosion affecting beaches is cyclical (erosion during winter storms and accretion during summer), beach erosion has become increasingly more severe as sea levels rise, threatening beach facilities and thus tourism (Flick, 2013) as well as beach ecosystems (CEVA, 2017).

1.2 Adaptation challenges and goals

Given these trends, LA County coastal managers must continue to prepare for increasing flood risk. Some flood management measures are already in place to reduce flooding risk, through beach nourishment, armoring of coastal cliffs and the shoreline, and the use of stabilizing structures to maintain beaches. Insurance programs can financially compensate policyholders after a flood event. However, it is unclear whether such measures are sufficient—or even still appropriate—for reducing the impact of sea level rise, and which additional measures are required to cope with long-term trends such as SLR and socio-economic developments. The timing of adaptation measures, too, is an important consideration (e.g., King *et al.*, 2016). For example, the City of LA owns and maintains critical infrastructure such as two power plants, two wastewater treatment plants, and the Port of LA (Grifman *et al.*, 2013) on its coast. Assessing future impacts of sea level rise may affect long-term planning of investments in infrastructure, including roads and these public utilities; thus is it incumbent upon the City to prepare and implement adaptation measures necessary to maintain these assets.

Other adaptation challenges include the preservation of beaches and their environmental and recreational values. Solutions to this challenge may come in the form of traditional beach nourishment/back passing, sediment stabilization techniques (e.g., groins), and armoring. However, novel strategies such as dune restoration, living shorelines, and other creative techniques offer an additional approach to these challenges. Ultimately, it will also be important to consider managed retreat and when and how that should be implemented.

Even after incorporating adaptation measures, there will still remain considerable flood risk as SLR continues to accelerate. To cover this "residual risk," and to compensate for the losses households may endure in the aftermath of a flood event, FEMA operates the federally run flood insurance program. This program offers financial relief after flood events and aims to provide incentives for adaptation and flood risk mitigation before an event. The program sets minimum regulations; thus, there is an opportunity for the City of LA to consider improving current zoning policies in LA beyond FEMA regulations to provide maximum benefits from reducing flood risk for LA households.

Existing studies at the regional scale reflect initial attempts to conduct analyses of the effects of SLR and the costs of adaptation measures for reducing flood risk (e.g., Heberger *et al.*, 2009). Other studies have conducted economic analyses of different cases in California (e.g., King *et al.*, 2016). However, there is currently no study that has developed a comprehensive coastal flood adaptation plan for the entire Los Angeles County, including all adaptation options and their costs, varying from green infrastructure, flood insurance, flood protection, watershed management, beach nourishment, and ultimately managed retreat.

Goals and structure of this study. The goals of this study are to provide an overview of the impacts of sea level rise on the coastal zone of LA County and its Cities, and to describe potential adaptation measures to cope with climate change and sea level rise. Based on literature and expert interviews (Appendix O), the study lists climate change and sea level rise impacts on natural resources (e.g. beach erosion, wetlands), the inhabitants of the coastal zone, buildings and infrastructure, and the economy. The study aggregates adaptation measures to cope with these effects into three primary adaptation pathways for LA County until the year 2100. Each pathway anticipates different SLR scenarios of 0.3 m (1 ft), 1 m (3 ft) and 2 m (7 ft). For each adaptation measure, an estimate of costs can be used in a cost–benefit analysis of adaptation pathways aimed at reducing flood risk. The development of adaptation pathways has been conducted through a series of stakeholder workshops in LA County.

The report is structured as follows: Section 2 provides an overview of future trends in (climate change, sea level rise and socio-economic projections), and a compilation of the effects of those trends on the LA County coastal zone (Section 3). Section 4 describes current flood risk—management policies that pertain to the coastal zone. Section 5 proposes and discusses adaptation measures that may reduce future impacts from climate change and SLR. Finally, Secction 6 compiles individual adaptation measures into three potential adaptation pathways.

1.3 Coastal sub-regions of LA County

Impact assessments of sea level rise, and descriptions of adaptation pathways were developed for different coastal areas of LA County, including: Malibu, Santa Monica, the South Bay/Redondo Beach, Ports of Los Angeles and Long Beach and the Naples district in Long Beach (Fig. 1.1). A short description of each region is presented below (a description of LA watersheds that drain into the coastal zone is provided in Appendix B):

Malibu: Malibu's coastline is approximately 24 miles long and extends from Ventura County to Topanga Canyon in LA County. The orientation of the majority of the narrow sandy beaches is east—west, many located near the mouths of streams that supply sediment to beaches under natural conditions. Rocky outcrops ensure some degree of sand retention capacity. Other stretches of the coastline are backed by high cliffs, formed by the Santa Monica Mountains. Some of Malibu's wider sandy beaches include Zuma Beach, Malibu Colony, and the mouth of Topanga Creek. Coastal land use is a mixture of mostly private development and public infrastructure.

Santa Monica/South Bay/Redondo Beach: The Santa Monica Bay Region extends for 21 miles from Topanga Canyon to Malaga Cove on the east-facing part of the Palos Verdes Peninsula, and is the most densely populated coastal zone in Los Angeles County. Beaches in the western part of Santa Monica Bay are wide because of historic nourishment and the construction of groins and breakwaters developed between the 1930s and 1960s. The eastern

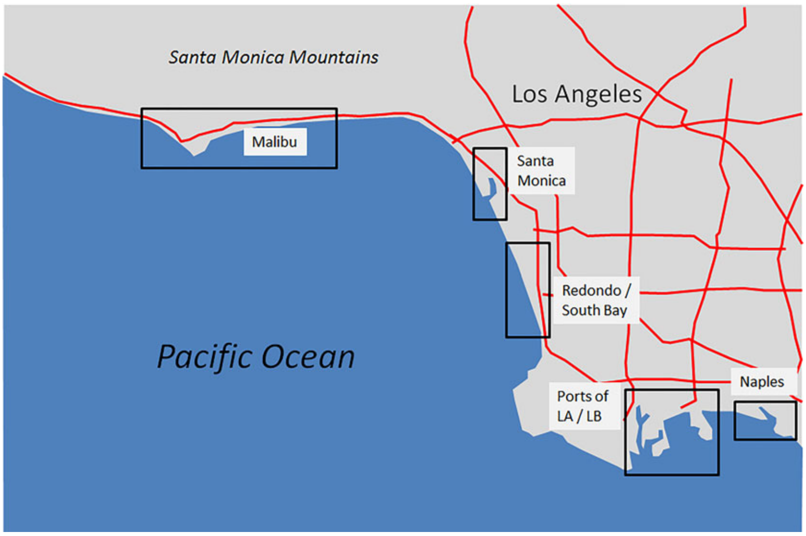

Figure 1.1. The five LA County coastal regions addressed in this study: Malibu, Santa Monica, Redondo-South Bay, Ports of Los Angeles and Long Beach, and Naples.

part (between Dockweiler Beach and Manhattan Beach) includes industrial land uses such as the Hyperion Sewage Treatment Plant, the El Segundo power generation facility, and the Chevron Oil Refinery. Low-lying areas that are vulnerable to sea level rise are Redondo/King Harbor, Venice, Playa Del Rey and Marina Del Rey. Further to the east, the Palos Verdes Peninsula coastline is approximately 16 miles long and extends from Malaga Cove to San Pedro. The shoreline consists of narrow, rocky, often small sandy beaches, backed by high cliffs of up to 45 m (150 ft). Sediment contribution to the few beaches is primarily from sea cliff erosion. Over the last decades, the shoreline has experienced few changes, except for the Abalone Cove and Portuguese Bend areas, where landslides occur.

Ports of Los Angeles and Long Beach/Naples: The 12-mile San Pedro to Long Beach coastal stretch is dominated by the industrial Ports of Los Angeles and Long Beach (Ports of LA and LB). Beaches consist of man-made Cabrillo Beach, and the City of Long Beach beaches (Belmont and Peninsula Beaches). Historically, sediment supply came from the Los Angeles River; today however, most of its sediment is unsuitable grained silt and clay (Flick, 2013). Further to the east, near Naples and Peninsula Beach, the west jetty of Alamitos Bay and the San Gabriel River retains sand from the natural littoral sand supply of Peninsula Beach and creates a local erosion hot spot.

2. Socio-economic and Geographical Characteristics

2.1 Socio-economic context

California currently has approximately 39 million residents. Although the rate of growth has slowed, it is still one of the highest in the United States. LA County's population grew by over 43,700 people from July 2015 to July 2016; the total population in LA County is currently estimated at 10.2 million (LA County, 2017c).

The City of LA is the largest city in California, with an estimated population of four million. It is also the state's largest city by area, at 465 square miles, of which approximately 70% is characterized as urban development (56% residential, 8% commercial, and 7% industrial) covered by impervious surfaces. The average per capita income in the City of LA is $27,345 per year; the median household income is $47,812 per year (City of LA, 2015). It is estimated that 11% of households have an annual income between $100,000 and $149,999 per year, and another 11% are above $150,000 annually. On the other hand, 23% of the population in the City of LA lives below the poverty level (City of LA, 2015). Thirty-nine percent of the population is foreign-born; census data indicate that 43% of the total population speaks Spanish at home. Census data also shows that 29% of the residents speak English "less than very well" (City of LA, 2015). This information is important, for example, to adequately communicate flood risk and evacuation options during a disaster (Ekstrom and Moser, 2012).

Los Angeles is the third largest metropolitan economy in the world, with a GDP of over $700 billion. Industries are diverse, ranging from aerospace, entertainment, and fashion to biomedical services, consumer products, and tourism. Per the latter, in 2015, LA received 45.5 million tourists, many of whom visited LA's wide beaches (LAT, 2016).

2.2 Climate and climate variability

In general, the LA region has a mild Mediterranean climate, with an annual mean temperature of about 64 degrees Fahrenheit (°F, City of LA, 2015). Temperature and precipitation vary considerably with elevation, topography, and distance from the Pacific Ocean. Annual precipitation mostly falls in the winter months, and ranges from 335 mm (13.2 inches) in the coastal plains to more than 500—800 mm (20-33 inches) in the San Gabriel mountain areas, respectively (DWR, 2017), although in recent years near-drought conditions have reduced the amount of rainfall significantly below previous norms.

El Nino and climate change. El Niño and La Niña are opposite phases of what is known as the El Niño-Southern Oscillation (ENSO) cycle. The ENSO cycle describes the fluctuations in wind patterns, sea-surface temperatures, and ocean-atmosphere interactions across the Equatorial Pacific. El Niño events are characterized by higher than normal sea surface temperatures in the eastern and central tropical Pacific Ocean, and can result in higher rainfall for the California coast (Wang *et al.*, 1999). La Niña is the opposite of El Niño, and represents periods of below-average sea surface temperatures across the east-central Equatorial Pacific.

El Niño has a major impact on the weather and flooding conditions of the Pacific coast. During El Niño winters, storm tracks often dip further south than their normal track and directly impact Southern California with more frequent storms, increased chances of heavy rainfall and higher wave heights with accompanying floods, landslides, and coastal erosion. Strong El Niño winters with enhanced storm conditions occurred in 1982—1983, 1997—1998, and 2015—2016.

Cai *et al.* (2014) used 20 climate models to assess changes in El Niño behavior assuming climate change over the next 100 years. They found a consistent pattern across most models, doubling the frequency of intense El Niño events. The probability of a 1/20-year intense El Niño (such as those in 1982—83 and 1997—98) will increase roughly to 1/10 years. Overall, wind direction might change and with more frequent El Niño events, with more westerly winds, expected in California (Cai *et al.*, 2014). Although there remains much uncertainty over the effects of climate change on climate variability such as El Niño, the most damaging events in California will likely be driven by El Niño storms in combination with high tides.

Tropical cyclones and storms. There is a low frequency of tropical cyclones making landfall in Southern California due to low seawater temperatures and increasing vertical wind shear when hurricanes move northward (e.g., Blake *et al.*, 2009). Such cyclones usually require warm water (>26.5°C; 80°F), but the coastal waters in California rarely rise above 24°Celsius (°C, 75°F). Another reason for the low probability of hurricanes in California is the general northwestward or westward direction of tropical cyclones, steering them away from land. The only known hurricane that made landfall is the 1858 San Diego Hurricane, which came onshore as a category 1 hurricane (Chenoweth and Landsea, 2004). This storm hit the entire coastline from San Diego to the Long Beach area with tropical storm–force winds. Hurricane Linda was the second-strongest eastern Pacific hurricane on record, and developed into a category 5 cyclone in September 1997. It developed during a strong El Niño year, which brought warmer than normal water temperatures and contributed to the high intensity of several storms. Forecasts showed the hurricane could have made landfall in Southern California as a weak tropical storm, but the storm took a different track (NHC, 1997). It still brought 5.5 m (18 ft) waves to the coastal areas.

El Niño events are associated with an increase in tropical cyclone activity in the eastern North Pacific (Larson *et al.*, 2005) due to the warming of ocean waters, weaker upper-level winds, and reduced vertical wind shear, which favor hurricane activity (NOAA, 2014.) Accordingly, the recorded tropical storms that have affected Southern California developed during El Niño years (e.g. Kimberlain, 1999). A study by Pyke (1972), conducted over the period of 1889 to 1970, showed six tropical storms making landfall in California. Other research on tropical storms in the 20th century describes four tropical storms in California: the Long Beach Tropical Storm in 1939, Tropical Storm Joanne in 1972, Tropical Storm Kathleen in 1976, and Tropical Storm Nora in 1997 (Chenoweth and Landsae, 2004). Of described tropical storms, the 1939 Long Beach Tropical Storm was the strongest (FEMA, 2008). This tropical storm made landfall on September 25th, 1939, in the Los Angeles Area near San Pedro, and brought 13–30 cm (5–12 inches) of rain. In Belmont Shore, ten houses were destroyed by storm-surge waves over six feet high (AOP, 2015). Further, the low-lying areas in Malibu and Huntington Beach were flooded by up to 1 m (3 ft) in some places—45 people died (NASA, 2012). Translated to 2004 values, the 1939 storm caused $200–$500 million in damages (Chenoweth and Landsae, 2004; Landsae, 2005). Research estimated that for any given location, the return period of a tropical cyclone coming ashore in Southern California is approximately 1/600 years (AOP, 2015).

Climate change may affect the frequency, intensity, and location of tropical cyclones. The study by Mendelsohn *et al.* (2012) used four different models to estimate synthetic tropical cyclone tracks in the current and future climate. They observed increasing storm power in the northeast Pacific consistently over the four models, which may indicate increased future storm activity in Southern California. However, there are currently few studies that have investigated the effect of climate change on tropical cyclones and storms for this area.

Historic floods. Most flood events in California are related to extreme precipitation. Since 1975, Los Angeles County has experienced twelve federally declared flood disasters; three of these disasters occurred under El Niño conditions (1983, 1998, 2010) and two occurred under La Niña conditions (1988, 1995). Many of these caused heavy rainfall, flashfloods, and flood damage to residential properties. During the 1997–1998 El Niño season, nearly 400 flood insurance claims were filed (LA County, 2017a). Table 2.1 shows examples of historic coastal storm surge events that inundated parts of coastal areas and inflicted damage. Most of these events were related to tropical cyclones or winter storms that strengthened through El Niño conditions.

Tsunamis. A tsunami is a series of ocean waves generated by an earthquake that displaces a large volume of water. Powerful tsunamis, such as the 2004 Indian Ocean event or the 2011 Tohoku earthquake and tsunami in Japan, can devastate entire coastal regions. Tsunami waves can travel for thousands of miles; for example, after the 2011 earthquake in Japan, a tsunami alert was issued for almost the entire Pacific region. A tsunami is often barely noticeable in deep ocean water, but as it approaches land and enters shallow water, the waves slow and increase in height. The largest historical local-induced tsunami in California occurred in 1927 near Point Arguello, following a magnitude 7.1 earthquake. It produced seven-foot waves in the coastal area (City of LA, 2017). Tsunami inundation maps for California (DOC, 2009) indicate worst-case scenarios; research indicates that the recurrence intervals of such events is 1/2,500 years (MN, 2013). The Ports of LA and LB commissioned a tsunami study in 2007 (Port of LB, 2007) which shows a worst-case scenario, in which a tsunami is triggered through a landslide in Palos Verdes. The tsunami could result in water levels of up to 7 m (23 ft). Such a scenario or a similar tsunami generated by seismic activity would likely not occur more than 1/10,000 years (MN, 2013).

2.3 Sea level rise projections

Figure 2.1 shows a range of sea level projections for the globe. Over the past century, global mean sea level has increased by 18–20 cm (7 to 8 inches) and sea levels have risen by approximately 18 cm along the California coast (7 inches; NRC. 2012). Historic sea level rise in California has been lower than the global average because of wind patterns over the Pacific Ocean that suppressed expected changes (NRC, 2012). The Intergovernmental Panel on Climate Change (IPCC, 2014) projects a global sea level rise of 0.3–0.9 m (1-3 ft), whereas a study by Vermeer and Rahmstorff (2009) projects sea level rise of 1.4 m (4.6 ft) by 2100. The median sea level rise projection by the National Research Council (2012) for California is between these two projections, at approximately 0.93 m (2.8 ft) by 2100. A recent study by Griggs *et al.* (2017) reports sea level rise projections for California of about 0.15 m (6 inches) by 2030 and 0.3 m (1 ft) by 2050. Until 2050, there are only minor differences in sea level rise projections (Griggs *et al.*, 2017); however, a worst-case scenario predicts that the ocean will rise by more than 0.3m (1 ft) by 2030 and 0.6 m (2 ft) by 2050 (Griggs

Table 2.1. Examples of historic coastal storm surge events in Southern California

Date	Name	TS/TC* Landfall	El Nino	Frequency	Wave height M (ft)*	Characteristics	Losses (2015 $ values) **
Oct. 1858	San Diego Hurricane	Y		1/200[4]		Hurricane made landfall. 10−18 cm Precipitation[8]	$250−$627 mln[5]
Sep. 1939	Tropical storm	Y		1/600[3]		300 mm rain/flooding in street +1 m[4].	$34 mln[3] 45 people killed in LA area[4]
Jan 1983	Winter storm		Y		7 m (23 ft)[9]	32 inches rain, damage in Santa Monica and Malibu. Record TWL[6] ***	Santa Monica Pier ($4 mln); Malibu Colony $9.5 mln[7]; $3.5 mln in Ventura County/Channel Islands Harbor[9]
Jan. 1988	Winter storm (South Easter)		Y	Wave: 1/250[6]; TWL:1/33[6]	5 m (17 ft)[6]	Record high waves[6]. Breakwater Redondo breached; With high tide, waves would have been +5 ft higher[6]	$40mln in LA/$32 mln in Redondo[6]; $4.5 mln Huntington B.[6]; $6.7 mln San Diego[6]; HWY 101 flooded in Ventura
Sep. 1997	Hurricane Linda	N			5.5 m (18 ft)[12]	NHC put advisory for S. California, but storm turned into ocean	Several millions[4]
Jan. 1998	Winter storm		Y			Homes in Malibu were damaged	50mln damage in Ventura County[10]
Dec/Jan. 2004–5	Winter storm				6.1 m (20 ft)[12]	Storm surge + high tide. Extreme precipitation[11]	Damage in Newport B[11], Dana Point (Orange C.); Damage parking Carlsbad; PCH flood
Jan. 2010[1]	Winter Storm			1/100[1]	7.5 m (25 ft)	Severe coastal erosion	Severe flooding damage
Aug. 2014	Hurricane Marie	N			6.1 m (20 ft) [12]	Hurricane Cat 5. At Baja California. Breakwater at Port of LA/LB breached	$10 mln in Port of LA/LB Breakwater

*TC = Tropical Cyclone/Hurricane; TS = Tropical Storm; **mln = million; *** TWL = Total Water Level.+
[1]Grifman *et al.* (2013); [2]Flick (2013); [3]AOP (2015); [4]NASA (2012); [5]Chenoweth and Landsae, 2004; [6]Harris (2014); [7]NYT (1983); [8]Landsae (2005); [9]NRC (1984); [10]Griggs *et al.* (2005); [11]City of Newport (2014); [12]City of Long Beach (2015).

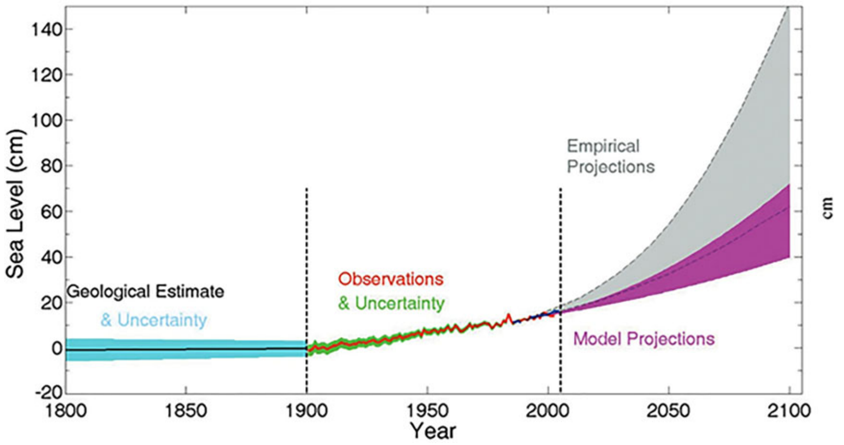

Figure 2.1. Projections of sea level rise to 2100. The dark pink projections are from the IPCC FAR (2014). Projections in gray are from Vermeer and Rahmstorff (2009). The NRC (2012) sea level rise projections for California fall between the two projections (Source: National Research Council–NRC, 2012).

et al., 2017). After 2050, sea level rise is expected to accelerate, and recent studies show projections for Southern California range from 0.6-3 m (2-10 ft) by 2100 (Griggs *et al.*, 2017). Such extreme sea level rise scenarios might occur in case of accelerated loss from the Greenland ice sheet and instability of the West Antarctica ice sheet. For every foot of global sea level rise caused by the loss of ice in West Antarctica, sea level will rise by approximately 0.4 m (1.25 ft) along the California coast (Griggs *et al.*, 2017).

2.4 Stormwater levels and design criteria

Several factors are important in the design of flood risk—protection measures in the coastal zone. To estimate the "design water level" required to develop protective structures, or to determine the minimum elevation of the base flood of a building, a site-specific analysis, often called a "total water level assessment," is required. This assessment, followed by a standard FEMA assessment, consists of three different components: (1) the storm surge still water level (SWEL), which is composed of the mean water level, tide, and surge level (barometric + wind set-up); (2) wave setup; and (3) wave run-up above storm wave-set-up (Fig. 2.2). The most important factors that influence wave run-up are bathymetry, shape of the beach/bluff slope, and elevations of proposed improvements on the site. In addition, barometric pressure influences surge height, and warmer water during El Niño conditions, for example, can create seasonally higher water levels, as much as 0.5 m (1.6 ft) above normal. (Flick, 2013).

Along the LA County coast, the extreme tide range is almost three meters (10 ft) or nearly 1.5 m (4.9 ft) above and below mean sea level (MSL) (Flick, 2013). Wave impact and runup on the coast can

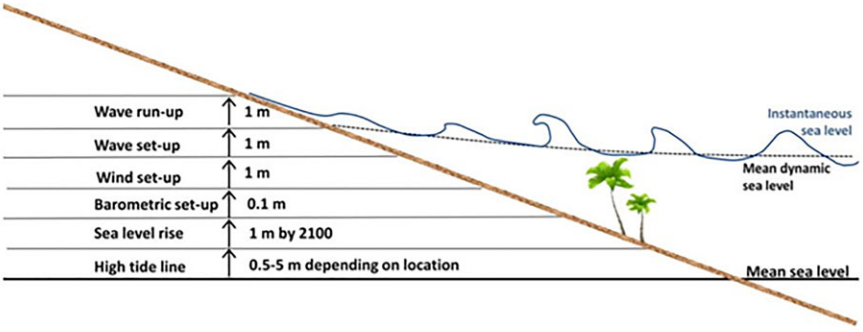

Figure 2.2. Different components of a total water level assessment to estimate the height of proofing measures of buildings or to estimate the design height of beaches, berms, and other protective structures (Source: Hansen, 2016).

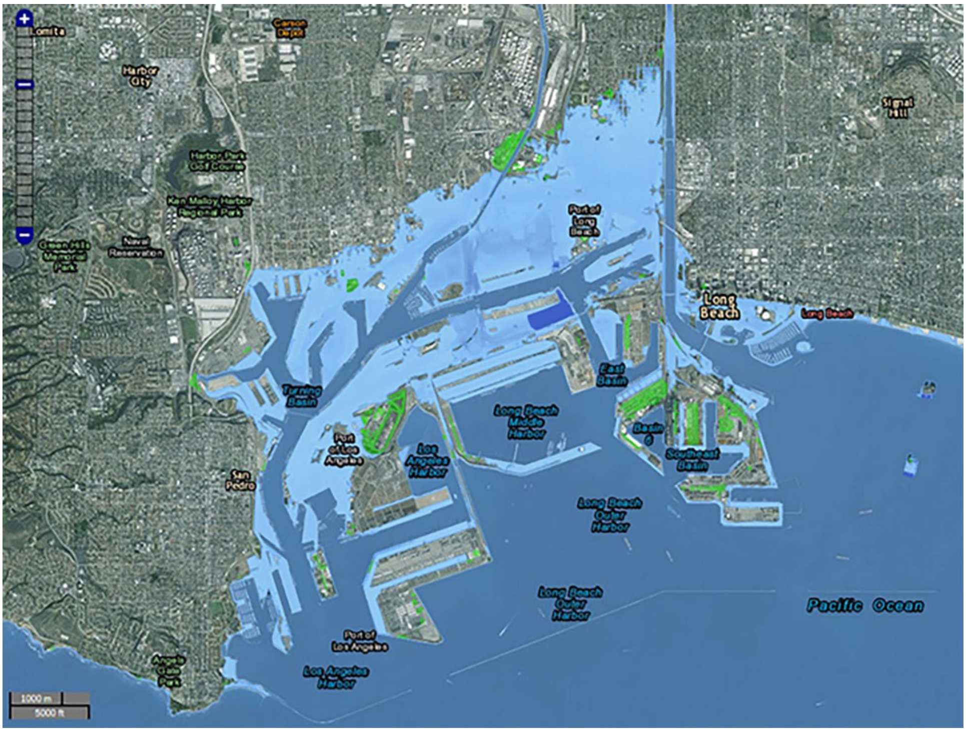

Figure 2.3. Example of a CoSMoS inundation scenario (light blue area) for the Ports of Los Angeles and Long Beach, for a 1/100 storm and 2 m (6.6 ft) sea level rise in 2100 (Source: http://data.pointblue.org/apps/ocof/cms/).

be significant, and large offshore storm waves of eight to ten meters (26—33 ft) can produce shoreline runup of approximately one to two meters (3—6 ft) on the beach. Large runup with an extreme tide, storm surge, and El Niño conditions can potentially produce maximum total water levels at the shoreline of four meters (13 ft) above ambient MSL under extreme conditions (Flick, 2013).

2.5 CoSMoS: Storm simulations

In this study, storm simulations for current and future climate conditions were calculated using the U.S. Geological Survey (USGS) Coastal Storm Modeling System (CoSMoS 3.0; Barnard *et al.*, 2014). These simulations form the basis for determining what assets and people are vulnerable to sea level rise in combination with storms, and which locations require (or may require) adaptation measures to reduce future flood risk. CoSMoS couples atmospheric and hydrodynamic computer models to estimate flood hazard potential from coastal storms, sea level rise, and shoreline change. Winds, sea level pressures, and sea surface temperatures are derived from global climate models to compute regional-scale total water levels until 2100 (Fig. 2.3; for details see: Barnard *et al.*, 2014). Regional storm conditions are then dynamically downscaled using a set of nested Delft3D wave (SWAN) and tide (FLOW) models, and linked at the coast-to-river discharge projections and fine-scale estuary models, and along the open-coast to closely spaced XBeach (eXtreme Beach) cross-shore profile models. The results provide projected total water levels along the California coast for different storms (annual, 1/20, and 1/100 events), and include modeling of 10 different sea level rise scenarios ranging from 0–2 m (0—6.6 ft) as well as an extreme five-meter (16 ft) sea level rise. A 1/100 year storm is defined as a flood event that statistically has a 1-percent chance of occurring.

The elevation of the coast is updated for each sea level rise scenario based on the projected long-term evolution of sandy beaches and cliffs. Baker/AECOM (2016) conducted a study that compared the FEMA modeling approach to simulating coastal inundations with the CoSMoS model. The key differences between FEMA and USGS data

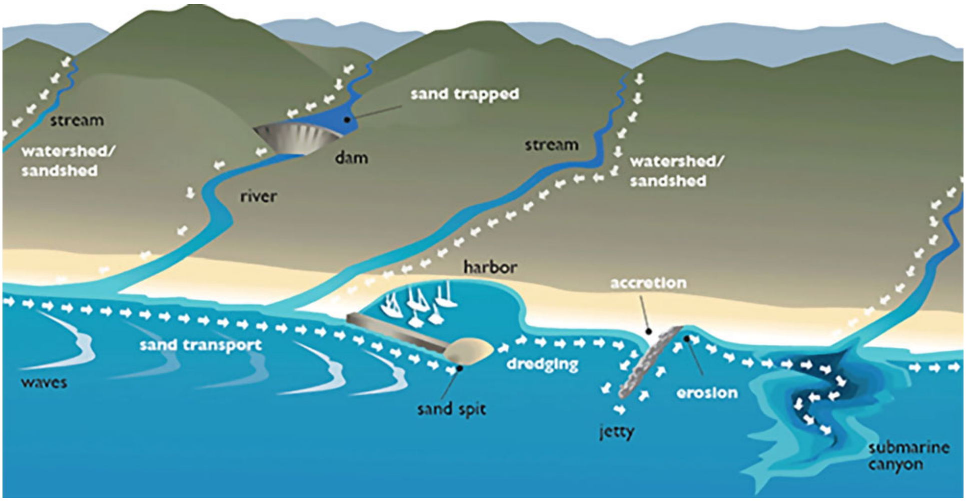

Figure 3.1. Sediment transport along the coastal areas (Source: Dave Hubbard, Monica Pessino, and Molly Thomson; adapted from M. Myers (Explore Beaches, 2017)).

are that the FEMA wave run-up elevations use one-percent-annual-chance water levels based on a two percent exceedance wave run-up formulation (as determined by a 50-year water level and wave hindcast from 1960–2009), whereas the USGS data are maximum sustained water level elevations (minimum 2 minutes) associated with a one-percent-annual-chance offshore wave height (as determined from a GCM-derived projection of 21st century storm climatology). Despite differences in data input, model selection, and conceptual design, the two approaches showed general agreement on maximum calculated TWLs. The largest differences appear at steep bluffs and armored shorelines. FEMA overestimates max run-up by up to 9 ft in these locations compared to CoSMoS, although in some locations CoSMoS simulations are up to 5 ft larger.

3. Impacts of Climate Change and Sea Level Rise

3.1 Coastal erosion and sea level rise

Sandy beaches in Southern California are constantly in motion. Waves and currents (littoral drift) transport sand alongshore and offshore. Littoral drift along the coast in California can occur alongshore in two directions, upcoast or downcoast, depending upon the dominant angle of wave approach. For most of California, the general wave direction comes from the northwest, creating a southward (downcoast) net littoral drift (Patsch and Griggs, 2006). In summer months, general wave direction is from the south, and the general direction of sediment transport is northwest for most of Southern California. During El Niño winters, the general wave direction is mostly west or southwest, and the southward transport is reduced. Sediment deposition and transport also vary throughout the year, and beaches tend to recede in the winter months and accrete during summer. During winter storms and high storm surges, however, waves can carry significant volumes of sand offshore, resulting in temporary and sometimes permanent losses to beach width (Noble, 2016). For example, El Niño events with intense winter storms (e.g. 1982–1983 and 1997–1998) have caused severe beach erosion along California's shoreline and damaged buildings and infrastructure (Patsch and Giggs, 2006). Over the long term, climate change and sea level rise may impact the shoreline with increased erosion rates, which may affect the environmental value and attractiveness of beaches and reduce economic revenues in the tourism sector (Vitousek *et al.*, 2017, King *et al.*, 2016).

In Southern California, 14 rivers deliver approximately 3.8 million m^3/yr (5.0 million cy/yr) of sand, and bluffs have historically provided 10–30% of coastal sediments. Over the past decades, however, natural sediment supply to Californian beaches has decreased due to the impounding of sand in reservoirs and dams (Fig. 3.1). Furthermore, channelized rivers, coastal armoring, and inland sand mining

Table 3.1. California sea level rise projections for the years 2050 and 2100, and estimated rates of beach recession

	Sandy beach	Sandy beach	Sandy beach	Cliff	Dunes
	Current	SLR 0.5−2 m (1.6−6.6 ft) [2050]	SLR 0.5−2 m (1.6−6.6 ft) [2100]	SLR 2 m (6.6 ft) [2100]	
Del Norte Country				170 m (557 ft)[1]	170 m (557 ft)[1]
Humboldt County					600 m (1968 ft)[1]
Coronado Beach	50 m (160 ft)[1]	5−25 m (15−80 ft)[1]	20−80 m (65−260 ft)[1]		
California Average		60 m (197 ft)[2]			

[1]Flick (2013); [2]Heberger *et al.* (2009)

further decrease erosion rates and sediment supply to beaches. Over 100 miles of the Californian coast is armored; of these coastal stretches, 44 miles are armored bluffs that further reduce sand flows to beaches. Because of human intervention, the total sediment supply in California has been reduced by approximately 50% (Slagel and Griggs, 2008), with a total estimated 125 million m^3 (163 million cy) of sand impounded in dams (Slagel and Griggs, 2008).

Sea level rise and beach erosion in Southern California. Due to sea level rise, beach widths in California will gradually decrease without periodic nourishment (Flick, 2013, Vitousek *et al.*, 2017). In Flick's analysis (2013), coastal erosion estimates that assume various sea level rise projections have been simulated using the Bruun (1962) method (e.g. Heberger *et al.*, 2009; King *et al.*, 2016); this approach assumes the shoreline maintains an equilibrium profile with a depth and slope determined by the current and wave regime. However, the Bruun rule has several limitations: "Firstly, the rule does not account for longshore interactions, and secondly, the rule assumes the wave climate is steady and hence the equilibrium profile remains the same - simply translated landwards and upwards with the rise in mean sea level. Such limitations should be considered when the Bruun rule is applied" (CSIRO, 2017).

In a recent study, Vitousek *et al.*, (2017) simulates that with limited human intervention, 31–67% of Southern California beaches could completely erode by the year 2100, assuming sea level rises of 1 m (3.3 ft) and 2 m (6.5 ft), respectively. In an older study, Heberger *et al.* (2009) estimated 1−1.5 m (3.2-4.9 ft) of shore recession per centimeter (0.4 inch) of sea level rise, and that for 2100 and 1.4 m sea level rise (4.6 ft), cliffs will erode an average distance of 66 m (216 ft) by the year 2100. Flick (2013) used the model by Yates *et al.* (2009) to estimate erosion rates under different sea level rise scenarios (see Table 3.1).

Sediment, beach erosion, and sea level rise in Los Angeles. The California coast can be divided into several individual segments or cells; each cell has its own source(s) of sand delivered by rivers, littoral drift, and subsequent closure offshore or submarine canyons. The largest cell in LA County is the 40-mile long Santa Monica Bay cell. The Santa Monica coastline is relatively stable in terms of erosion and accretion dynamics, and its beaches have largely been shaped by nourishment (CRSMP, 2012). El Segundo and Redondo beaches are less stable, and erosion rates at Redondo Beach are relatively high, losing sediment to nearby Redondo Submarine Canyon. However, both Redondo and El Segundo beaches were nourished in the 1960s, and since that time, have only lost 50% of their width because of stabilizing measures such as jetties, offshore breakwaters, and groins (CRSMP, 2012). Since 1920, when Devil's Gate Dam—the first dam on the Los Angeles River—was built, new dams in the Los Angeles, San Gabriel, and Santa Ana Rivers, have trapped approximately 33.3 million cy (25.5 million m^3) of sand (Slagel and Griggs, 2008). Table 3.2 shows that sediment supply to LA beaches decreased by 14–66%. Estimates by Patsch and Griggs (2006; Table 3.2) show that current (post damming) natural sediment supply to Santa Monica, San Pedro and Malibu, from rivers and bluffs is roughly 532,000 cy/yr: 70,000 + 278,000 + 34,000 + 148,000 + 2,000 = 532,000 cy/yr (406,000 m^3/yr).

Table 3.2. Average annual sand contributions from rivers, sea cliff erosion, dune recession, and beach nourishment to the sediment cells in Southern California (upper part of table). Nourishment data is for the period of 1930–1993. Below: Human reductions to the sand supplied to the major littoral cells in Southern California (source: Patsch and Griggs, 2006;[1] Malibu: Slagel and Griggs, 2008)

	Current Sand Supply to beaches (Post damming)				
Littoral Cell	Rivers [cy/yr]	Bluff erosion [cy/yr]	Dunes [cy/yr]	Nourishment [cy/yr]	Total Sand supply [cy/yr]
Santa Monica	70,000	148,000	0	526,000	744,000
San Pedro	278,000	2,000	0	400,000	680,000
Malibu[1]	34,000				

	Human induced reductions of sand supply				
Littoral Cell	Rivers (Dams) [cy/yr]	Bluff Erosion (armoring) [cy/yr]	Total Reduction [cy/yr]	Nourishment [cy/yr]	Balance (nourishment-reduction) [cy/yr]
Santa Monica	29,000	2,000	31,000	526,000	495,000
San Pedro	532,000	0	532,000	400,000	-132,000
Malibu[1]	19,000	–	19,000		

Sea level rise and sediment transport in Los Angeles. Table 3.3 shows future beach-width losses assuming different sea level rise scenarios, using CoSMoS simulations (Noble, 2016). The simulations indicate future beach widths for LA County beaches, assuming a 1/100 storm and sea level rise scenarios of 0, 0.5, 1, 1.5, and 2 m (0—6.6 ft). The results show that beaches in the Malibu region may be significantly reduced in width, with some stretches losing their sandy beaches entirely (Fig. 3.2). Dockweiler State Beach and Torrance County Beach may be reduced by at least half of their current widths (Noble, 2016). Noble (2016) also analyzed beach erosion at a high sea level rise scenario of 1.7 m using the Bruun rule (1962), and an approach to estimating wave runup. These results are also displayed in Table 3.3, showing beach width losses similar in magnitude to the CoSMoS simulations at 47—100% by the year 2100 (Noble, 2016). Long-term and short-term erosion of areas protected by bluffs or hard structures was not included in the analysis.

3.2 Impacts on wetlands

If wetlands are permanently inundated in the future, they might lose their habitat value. Heberger *et al.* (2009) used the National Wetlands Inventory (NWI) to delineate Californian wetlands and estimate the potential loss in value of wetlands due to sea level rise, using methods developed by Costanza *et al.* (1997). Their study estimates that a 1/100-year storm threatens approximately 875,000 hectares (2,162,000 acres) of wetlands in California.

LA County has lost most of its coastal wetlands, with small vestigial wetland areas of 10 km^2 (2,400 acres) remaining. The primary wetland in LA is the Ballona Wetland, comprised of a 600-acre ecological reserve primarily owned by the State of California—a portion of the site is in unincorporated LA County and the rest is in the City of LA (Fig. 3.3). Elevation ranges from 0 to 7.6 m (0—25 ft) above sea level (Johnston *et al.*, 2015). The original wetland complex was much larger, but much of the former wetland areas were filled with up to 25 ft layers of dirt excavated during the development of Marina del Rey (BR, 2017).

The remnant wetland areas include Del Rey Lagoon, Ballona Lagoon, Marina del Rey, Oxford Basin, and the Venice canal area. These wetlands provide many ecosystem services such as sheltering and resting places for wildlife, sediment accretion, and rainwater storage to prevent flooding elsewhere. Extreme wet weather sometimes causes additional flooding in urban areas and roadways adjacent to the wetlands that are below sea level (e.g. Culver Boulevard and Playa Del Rey).

Johnston *et al.* (2015) state that the levees surrounding the Ballona Wetlands are designed to protect the area from up to a 1/100-year storm

Table 3.3. Shoreline width loss using CoSMoS 3.0 simulations, assuming a sea level rise scenario of 0.5−2 m and a 1/100-year storm; additional beach recession distance simulations using Bruun (1962)/FEMA wave runup methods assuming sea level rise +1.7 m

Facility	Owner[2]	2010[1] Width M (ft)	CoSMoS[3] 2100 sea level rise **1m** (3.3 ft) Loss %	Bruun/FEMA[3] 2100 sea level rise **1.7 m** (5.5 ft) Loss % (ft)	CoSMoS[3] 2100 sea level rise **2m** (6.6 ft) Loss %
Nicholas Canyon County Beach	DBH	31 (100)	50%	100% (100)	100%
Zuma Beach	DBH	119 (390)	25%	47% (184)	50-90%
Point Dume Beach	DBH	79 (260)	20%	67% (173)	90%
Dan Blocker Beach	DBH		100%		100%
Malibu Surf Rider Beach	DBH	73 (240)	25%	100% (240)	50%
Topanga Beach	DBH	58 (190)	100%	100% (190)	100%
Will Rogers Beach West	State of CA	76 (250)	30%	100% (250)	90%
Will Rogers Beach East	State of CA		50%		50−100%
Venice Beach	City of LA	198 (650)	10-20%	54% (354)	25−50%
Dockweiler State Beach	State of CA	180 (590)	10%	60% (354)	40%
Manhattan Beach	DBH	128 (420)	25%	85% (359)	50%
Hermosa Beach	City of Hermosa	143 (470)	50%	71% (335)	60%
Redondo Beach	DBH	43 (140)	25%	100% (140)	60%
Torrance Beach	DBH	76 (250)	25%	100% (250)	60%
Whites Point/ Royal Palms Beach	DBH		100%		100%

DBH, LA County Department of Beaches and Harbors.
[1] From the CRSMP plan (2012) providing beach width in the year 2005; [2] LA county (2017b); [3] Noble (2016).

event. ESA (2017) states the "Ballona Creek is bordered on both sides by flood protection levees with elevations sloping from approximately elevation 20 feet NAVD 88, at Culver Boulevard down to approximately elevation 15 feet NAVD 88." The area, however, is vulnerable to sea level rise and storm surge impacts (Bergquist *et al.*, 2012). ESA (2017) writes that "between approximately 2070 and 2100, the tide gates would be permanently closed to prevent flooding from sea-level rise, and the existing tidal wetland habitats in West, South, and Southeast Area would be cut off from the estuary". Tide gates are an opening in bulkheads or other protective structures, through which water may flow freely when the tide sets in one direction but which closes automatically and prevents the water from flowing in the other direction.

Other small wetland areas remain in LA County, e.g., the mouth of Malibu Lagoon at the base of Malibu Creek at Surfrider Beach. This wetland has undergone restoration and serves now as a buffer between inputs from the Creek and the beach area, providing flyover, resting and feeding space for a multitude of seabirds and freshwater fowl. Completed in March of 2013, the restoration has undergone four years of monitoring. Post restoration conditions have shown healthy vegetative communities, channel stability, and overall criteria that support the goals of the restoration (Bay Foundation, 2017). Although, this project was not designed with flood control or shoreline protection goals, the natural setting helps stabilize sediment and provides space to buffer from coastal flooding. At Zuma Beach and Trancas, further up the Malibu

Figure 3.2. Eroded beach at Broad Beach in Malibu, protected with rip-rap. Future sea level rise may challenge the protective value of nourishment for these structures. Alternative options for adaptation include elevation of individual buildings or, eventually, managed retreat. (Photo: J. Aerts)

Coast, small vestigial wetland areas provide similar ecosystem services—capturing freshwater flows, providing space and habitat for birds and other terrestrial animals. Maintaining these natural coastal amenities is important for ensuring some natural space for beach migration and fluvial management.

There is strong interest in California in exploring experimental living shoreline projects in wetland environments, geared at both restoring habitat and biodiversity, and coastal hazards protection (Boudreau *et al.*, 2018). The U.S. Army Corps of Engineers developed a nationwide permit system

Figure 3.3. Ballona Wetland area (Adopted from Johnston *et al.*, 2015).

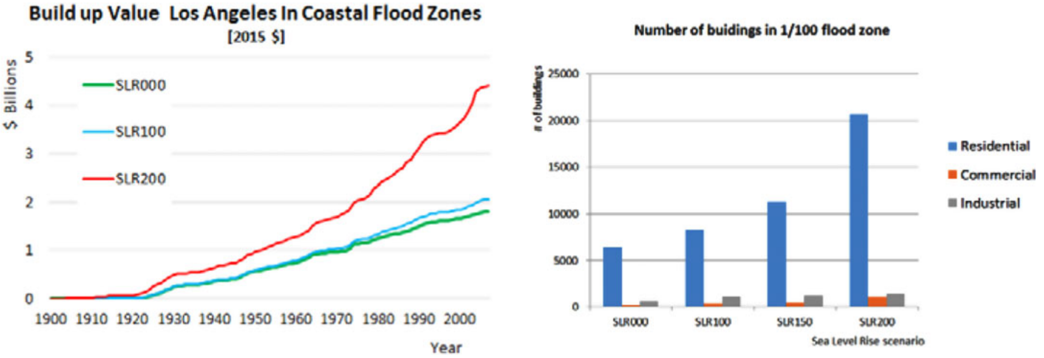

Figure 3.4. The historical development of the value of buildings in different flood zones *(left)*. Each flood zone is a simulation of a 1/100 year storm (a flood event that statistically has a 1-percent chance of occurring), assuming a different sea level rise scenarios (SLR) of 0 m (0 ft), +1 m/ (3 ft), and +2 m (7 ft). The simulations were conducted using the U.S. Geological Survey's Coastal Storm Modeling System (CoSMoS, Barnard *et al.*, 2014) (Section 2.4).

for living shoreline projects focused on sheltered coastal environments. In California, a number of state laws and climate change planning documents (Executive Order B-30-15, Senate Bill 246, Safeguarding California Plan, CA Coastal Commission Sea Level Rise Policy Guidance) encourage the use of nature-based solutions and provide some guidance on implementation. However, there is still a need for more demonstration projects on the California coast as well a streamlined permitting process to support the implementation of such projects (Boudreau *et al.*, 2018). The Malibu Lagoon restoration project has shown promising results in terms of enhanced ecological function through increased circulation and restored habitat in the first four years of the project (Bay Foundation, 2017). However, the project is not widely considered a "living shoreline" project because it was not originally designed to provide coastal hazard protection and monitoring does not track this issue.

3.3 Socio-economic impacts

A study by Grifman *et al.* (2013) and accompanying research by Ekstrom and Moser (2012) highlighted the degree of social vulnerability for different communities in the City of LA vulnerable to flooding. Ekstrom and Moser (2012) assessed vulnerability factors such as income, poverty, education, race, linguistic isolation, and age. The results show that low-lying communities around the Port of Los Angeles (San Pedro and Wilmington) are more vulnerable to the impacts of sea level rise than other coastal communities in LA. This is primarily due to lower per capita income, lower education levels, and linguistic isolation. Other indicators for social vulnerability include housing type and a high percentage of renters. In areas such as Venice and the Port of LA, for example, a high proportion of older housing stock is vulnerable to flooding due to the absence of enforced building codes and flood-proofing measures (Ekstrom and Moser, 2012). In studies estimating the number of people exposed to coastal flooding, Heberger *et al.* (2009) found a relatively low number of people vulnerable to flooding in LA. For a 1/100 storm as many as 3,600 people are within the flood zone, and with 1.4 m of sea level rise, this number increases to 13,000. Hauer *et al.* (2015) estimated that the number of people in LA exposed to 0.9 m of sea level rise is between 8,000—23,000 people. Similar social vulnerability assessments have yet to be conducted for other cities within LA County, such as Long Beach, which has a high level of variability in its population. Fig. 3.4 (*left*) shows the historical development of the value of buildings in the 1/100 flood zone. In the 0 m (0 ft) SLR scenario ("the current situation"), the total value of all exposed buildings is approximately $1.8 billion. This value increases to slightly more than $2 billion, with a sea level rise of +1 m (3 ft). When applying an extreme sea level rise scenario of +2 m (7 ft), the total value of the buildings in Los Angeles County exposed to a 1/100 year flood is $4.4 billion. Fig. 3.4 (*right*) shows the number of buildings within the 1/100 flood zone, for the different sea level rise scenarios. The number of exposed residential buildings is the largest, with 6,454 to 20,707 buildings for the current and future with a +2 m sea level rise, respectively (Data source: USC Geoportal, 2017).

Table 3.4. Indirect economic losses to buildings in Los Angeles for different sea level rise scenarios (in $ million 2010 value) (Source: Wei and Chatterjee, 2013)

	Current Sea Level		+0.5 m (1.6 ft) Sea Level Rise		+1.4 m (4.6 ft) Sea Level Rise	
	1/10 flood [$ mln 2010]	1/100 flood [$ mln 2010]	1/10 flood [$ mln 2010]	1/100 flood [$ mln 2010]	1/10 flood [$ mln 2010]	1/100 flood [$ mln 2010]
Output losses	3	7	6	11	9	22
Income losses	2	5	4	7	6	14
Employment losses	24	52	41	74	64	158

Socio-economic impacts such as loss of beach quality (area, sand quality, wave quality for surfing, etc.) and associated recreational uses, loss of private property, and damage to public infrastructure may occur due to decreasing beach width (ERG, 2012). Thus, shoreline changes affect the tourism sector (Lew and Larson, 2004; Pendleton *et al.*, 2011); other studies correlate a decrease in beach width with a decline in beach attendance in order to estimate changes in economic revenue (CRSMP, 2012; Appendix C). Using economic valuation methods, ERG (2012) shows that a 50% increase in beach width could generate $3.1 million in consumer surplus per year (Pendleton *et al.*, 2011). At one beach in San Diego, it was estimated that maintaining current beach width could result in over $300 million in increased revenue from beach spending (ERG, 2012). A study by King and Symes (2002) indicated that for Venice Beach, reduced width would result in tourist income losses of approximately $218 million/year for the LA region, and an economic loss of $105 million/year for the entire U.S. economy.

King *et al.* (2011) modeled the economic impacts of a 100-year flood, including beach erosion for five coastal California communities, using sea level rise scenarios of +1 m (3.3 ft) and +1.4 m (4.6 ft). For Venice Beach, the study indicates that a 100-year storm under current conditions with no sea level rise would cause $7 million in damages, and a 100-year storm with a +1.4 m sea level rise in 2100 would cause $15.1 million in damages. Wei and Chatterjee (2013) calculated economic losses for LA County from a 1/10 flood event using an input-output model, without addressing impacts from beach erosion on tourism (Table 3.4). For business interruption losses, output losses increase from $3.4 million under current conditions to $6 million in a +0.5 m (1.6 ft) sea level rise scenario, and to $9 million in the +1.4 m (4.6 ft) sea level rise scenario. For a 100-year flood event, the output losses increase from $7 million under current conditions to $11 million in a 0.5 m sea level rise scenario and $22 million in a 1.4 m sea level rise scenario. The reason for the relatively low business interruption losses is that approximately 95% of the damaged buildings are residential, rather than buildings of producing sectors. Consequently, the economic losses are relatively low compared to the direct damage (∼10%).

3.4 Potential flood damage to buildings

Wei and Chatterjee (2013) analyzed the economic impacts of sea level rise and associated storm surge for the City of LA, including direct property damage losses and indirect business interruption losses. Using the HAZUS (the FEMA GIS–based natural hazard analysis tool) model developed by FEMA, they estimated that direct building losses for a ten-year flood event and 0.5 m (1.6 ft) of sea level rise would be $410.3 million; this figure doubled with 1.4 m (4.6 ft) of sea level rise (Table 3.5). Losses to residential buildings comprise about 50% of total losses, with the other 50% of losses split evenly between commercial buildings and industrial buildings in most simulated scenarios. A more recent study by the City of LA (2017) estimated similar numbers and projected between $85 million and $787 million in losses to buildings, assuming 25 cm and 150 cm of sea level rise respectively, and a 1/100-year storm.

3.5 Infrastructure and flood risk

Roads: In Southern California, 1,678 miles of roads are located within a quarter mile of the coastline and are vulnerable to flooding (ERG, 2012). Flick (2013) specified that the Pacific Coast Highway (PCH or Highway 1) is vulnerable in some low-lying sections of the Malibu coast, and anticipated that with sea level rise, enhanced armoring could be needed to reduce erosion and undermining of the road. CoSMoS simulations show that the system of highways (freeways or high

Table 3.5. **Direct losses to buildings in Los Angeles for different sea level rise scenarios (in millions of dollars 2010 value) (Wei and Chatterjee, 2013)**

	Current Sea Level		+0.5 m Sea Level Rise		+1.4 m Sea Level Rise	
	1/10 flood [$ mln 2010]	1/100 flood [$ mln 2010]	1/10 flood [$ mln 2010]	1/100 flood [$ mln 2010]	1/10 flood [$ mln 2010]	1/100 flood [$ mln 2010]
Building	103	260	179	364	315	649
Content	132	312	219	435	380	759
Inventory	7	15	11	20	19	31
Total	242	588	820	820	714	1441

capacity roadways) around the Port of LA area in San Pedro and Wilmington are vulnerable. This includes Paseo Del Mar running in an east-west direction, and Harbor Boulevard running in a north-south direction along the harbor shoreline. Other vulnerable roads in the City of LA are Culver Boulevard and West Jefferson Boulevard in the region of the Ballona Wetlands (City of LA, 2017).

Cables and pipes: The vulnerability assessment for the City of LA, by Grifman *et al.* (2013) briefly examined different line infrastructure elements such as cables and pipes, which were evaluated as having low vulnerability to sea level rise. Sites included the 230 KV Scattergood-Olympic Cable in the Dockweiler Beach/Venice Area, an underground cable that connects to a high voltage interstate line.

Water treatment plants and pumping stations: The Sea Level Rise Vulnerability Study for the City of LA (Grifman *et al.*, 2013) and the EPA (Environmental Protection Agency) Los Angeles Sanitation Exercise Report for Wastewater Assets highlight two important issues related to sewers and wastewater pumping plants regarding climate change and sea level rise. First, a 100-year storm surge could flood the wastewater pumping plants and cause electrical equipment, such as pumps, to fail. Second, pumping failures caused by flooding could result in wastewater spills and have negative environmental consequences. Vulnerable pumping and electrical stations are listed in Appendix J.

Ports of LA and LB: The Ports of LA and LB are among the largest ports in the United States, handling 45%–50% of containers shipped into the United States (City of LA, 2017). This contributes more than $63 billion to the economy of the State of California, and more than $230 billion to the U.S. economy (Port of Los Angeles, 2012). Of these containers, 77% leave the state by train and truck (Christensen, 2008). The container terminals at LA and Long Beach are currently situated approximately 1.8 m (+6 ft) above mean high tide. The City of LA (2017) estimates that the exposed value of harbor assets is between $386 million and $3.9 billion for sea level rise scenarios of 25 cm and 150 cm respectively, assuming a 1/100-year storm. Grifman *et al.* (2013) estimated a similar number of $4.3 billion for the exposure of harbor assets to flooding and sea level rise distributed over:

- Container terminals: $2.85 billion replacement cost/$1 billion per day cost of shut down
- Electric facilities container terminal: $350 million replacement cost
- Transportation facilities: $1 billion replacement cost
- Breakwater: $500 million replacement cost

3.6 Salt-water intrusion and soil subsidence

According to the City of LA Department of Water and Power (2017) salt-water intrusion can be a serious problem for drinking water facilities and may require expensive desalination treatment. Groundwater depletion in Los Angeles was an issue in the first part of the 20th century when groundwater extractions were greater than natural rainfall and natural recharge. This net loss of groundwater lowered the groundwater level from six to twelve feet below sea level, and in some locations to approximately 100 feet (30 m) below sea level (LADPW, 2017b), which increased the extent of saltwater intrusion and contaminated groundwater with chloride. As a solution, the city developed a "sea water barrier" program, in which fresh water is injected into the ground to recharge groundwater levels and push back intruding seawater (Fig. 3.5).

Three different seawater barriers within LA County, including the West Coast, Dominguez Gap,

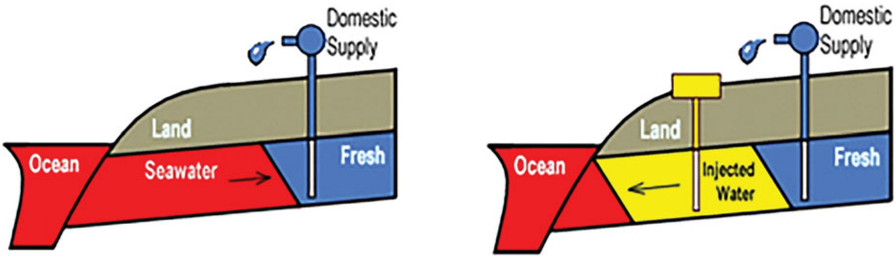

Figure 3.5. Confined aquifer with seawater intrusion (left); confined aquifer with freshwater injection wells (seawater barriers) to push back salt water from the sea (right) (Source: Department of Public Works, LA County).

and Alamitos barrier projects were built approximately 2,000 feet (700 m) inland, with wells positioned at intervals of 500 feet (152 m). The Water Replenishment District of Southern California purchases 1.5 million acres-ft (1850 million m^3) of imported water from the Sacramento-San Joaquin Delta, Colorado River, and other sources outside of LA County to use for the injector wells. In addition, LA County uses 184,000 acres-ft (226 million m^3) of reclaimed water from the West Coast Municipal Water District (www.westbasin.org). The three water barrier projects currently comprise 230 freshwater injection wells, 758 observation wells, and 4 extraction wells, which protect 15 miles (24 km) of coastline against salt intrusion. LA County continues to reduce the amount of imported water to lower costs, and to increase reclaimed water use and enhance rainwater recharge by promoting green infiltration infrastructure (e.g. parks). Sea level rise may increase salt-water intrusion in the coastal zone of LA. In order to reduce these effects in the future, additional freshwater injector wells should be developed.

Land subsidence. Land subsidence can be a problem in low-lying coastal areas, since subsiding land surface may lead to increased flood inundation levels. Land subsidence has been an issue in LA County due to groundwater extraction and oil and gas production. For example, in the 1940s oil and gas production from the Wilmington Oil Field created a "subsidence bowl" that was up to 10 m (29 ft) deep in and around the Port of Long Beach and along the coastal strand of the City of Long Beach (Mayuga and Allan, 1970). As a counter measure, water injection has been stabilizing the geologic underground, successfully stopping soil subsidence (Mayuga and Allan, 1970; City of LB, 2017).

4. Flood Risk Management Policies

Many governmental institutions, from federal, state, and city levels conduct flood risk management in the coastal zone of California and the United States. The most important organizations and plans are listed in Appendices H and I. This chapter focuses on the main pillars of coastal zone flood risk management in LA County:

1. Flood management of buildings through the National Flood Insurance Program (NFIP);
2. The California Coastal Act;
3. Coastal protection, including management of beaches and protection of infrastructure;
4. Stormwater management in the watersheds that drain into the coastal zone.

4.1 The National Flood Insurance Program

The federal government provides flood insurance administered through the Federal Emergency Management Agency (FEMA) National Flood Insurance Program (NFIP). NFIP currently underwrites five million policies in the U.S, and around 70,000 in LA County, which joined in December 1980 (Table 4.1). Flood insurance can be bought from most insurance agents, and the cost of a flood insurance policy depends upon the type of property, level of flood risk, deductible, and amount of coverage selected. Coverage can also be purchased for the contents of the building. Purchasing flood insurance is mandatory for homeowners either with a mortgage from a federally regulated lending institution or who apply for federal disaster assistance and are located in the 1/100-year flood zone ("special flood hazard area"). The 1/100 flood zones are mapped by FEMA, and are the areas that statistically have a 1-percent chance of flooding. The objective of this requirement is to stimulate the market penetration

Table 4.1. Total coverage and premiums collected for Los Angeles and surrounding counties (Source: Pinter, 2016)

County	# NFIP Policies	Total Coverage [$]	Annual Premium income [$]
Los Angeles	33,653	9,802,768,000	24,410,506
Orange	23,842	6,595,794,400	21,226,598
Ventura	8,119	2,284,323,200	4,857,563
San Bernadino	6,212	1,563,712,700	5,306,639

of flood insurance and limit potential problems with adverse selection (Aerts and Botzen, 2011). This insurance can be voluntarily purchased outside of the 1/100-year flood zone where more than 25% of flood insurance claims occur (SFHA, LA County, 2017a).

Cities within LA County, e.g., City of LA and others, have agreed to comply with FEMA regulations, which specify minimum requirements for flood zoning and flood-proofing for new structures in flood zones, or the SFHA (Table F1, Appendix F). Moreover, California building code regulations established in 1983 are enforced by most cities in LA County on top of the FEMA regulations (State of California, 2017). In many cases, these codes go beyond FEMA/NFIP regulations (called ‘freeboard’), and state that the design and construction of buildings and structures located in flood hazard areas, must be in accordance with Chapters 5, 7 and 24 of the American Society of Civil Engineers (ASCE) (FEMA, 2017; State of California, 2007). For the City of LA, this means that California building codes apply to the approximately 30 square miles of 1/100 flood zones in the city. These regulations have been adopted in the City’s 1980 Flood Hazard Management Specific Plan (FHSP), amended in 1988 (LADBS, 2014).

To obtain a discount on the insurance premium, one can elevate or flood-proof (by dry or wet flood-proofing) a building in the SFHA zone. An elevation certificate is required by FEMA to ensure compliance with this requirement, and is then used by the insurer to determine (reduced) insurance rates. Regular auditing by FEMA evaluates the compliance of buildings with regulations and provides community ratings, which are used to establish flood insurance rates. Regulation and enforcement of building codes and zoning regulations involve cooperation among different departments. The City of LA Department of Public Works, Bureau of Engineering (BOE) reviews and approves building design for compliance with FHSP and FEMA regulations, and stamps flood elevation certificates. The City of LA Department of Building and Safety (LADBS) identifies projects located within the flood zone, and refers to BOE for plan approval. A plan includes flood-proofing measures such as raise base elevation of ground floor, structural re-enforcements, and flood-proofing (sealing and barriers). Implementing a plan may reduce risk and insurance rates. Finally, LADBS reviews the entire process of plan initiation for final approval.

Since 1994, the program has received $3.5 billion in premiums annually for California and NFIP damage payouts in California have totaled 14% of the total premiums collected (Pinter, 2016). California has 290,000 NFIP policies in force, covering nearly $82.6 billion of insured assets and generating $212.8 million in annual premiums (Pinter, 2016). However, the NFIP is $24 billion in debt, and is undergoing reform due to the Biggers-Waters Reform Act of 2012 and the Homeowner Flood Insurance Affordability Act of 2014. These acts require the NFIP to gradually raise rates to reflect true flood risk and eliminate subsidized (low-) premiums for pre-FIRM (Flood Insurance Rate Map) policyholders (Kousky, 2017). There is a transition time, allowing homeowners to adapt and implement damage mitigation measures to lower risk and premiums or sell their homes. Since 81% of NFIP policies in the City of LA are pre-FIRM subsidized policies, the law will have a profound impact on the cost of flood insurance (City of LA, 2017). An advantage of NFIP shifting to more risk-based premiums is that they offer a price signal for flood risk, which may give policyholders incentives for risk reduction. These reforms, however, can create problems with the affordability of flood insurance among low-income households in areas with a high flood risk (Kousky, 2017). More information on the NFIP is provided in Appendix F.

Additional zoning measures near bluffs. Local development standards may add to general FEMA rules. LA County regulations state that all new construction and significant improvements to existing buildings within Zones V and VI-30 on the LA Flood Hazard Map must be located landward of the reach of mean high tide. Furthermore, structures must address the potential hazard from erosion. For example, Malibu development standards state that any development "... shall be set back a sufficient distance landward and elevated to a sufficient finished floor height to eliminate or minimize to the maximum extent feasible hazards associated with anticipated sea level rise over the expected 100-year economic life of the structure." However, the same plan also states that if this is not feasible, all new buildings must be elevated above the base flood elevation (as defined by FEMA) and sited as far landward as possible; setback is a minimum of ten feet landward of the mean high tide line. Developments on a bluff must have a minimum setback of 100 feet from the edge of the bluff, but this can be reduced to 50 feet if City geotechnical staff conditions permit a lower setback, considering 100 years of expected erosion rate (City of Malibu, 2017).

Community rating system (CRS). The NFIP's community rating system (CRS) was implemented in 1990 as a voluntary program to encourage community flood management exceeding the NFIP's minimum standards. The main motivation for joining the CRS is to reduce the cost of flood insurance for homeowners, and to identify and reduce repetitive losses. In the City of LA, there are 145 buildings that have been classified as being in a repetitive loss area (City of LA, 2017). Any community that is in full compliance with the NFIP's minimum floodplain management requirements may apply to join the CRS. Credit points for the CRS floodplain management activities determine a community's CRS Class. As of May 2017, there are 1,466 communities participating in the CRS, which represents only 6% of the 22,000 communities that participate in the NFIP (EDF, 2017). For these CRS participating communities, flood insurance premium rates are discounted in increments of 5% (i.e., a Class 1 community would receive a 45% premium discount, while a Class 9 community would receive a 5% discount; a Class 10 would not participate in the CRS and would receive no discount). The CRS classes for local communities are based on 18 creditable activities, organized into four categories: (a) public information, (b) mapping and regulations, (c) flood damage reduction measures (e.g. levees), and (d) flood preparedness.

Ongoing initiatives stimulate the cooperation between FEMA and regional- and local policy to manage flood risk. For example, NOAA (2018) provides support for regional collaboration and offers data, tools, training, and other relevant resources, and to connect to the FEMA hazard mitigation assistance program (www.fema.gov/hazard-mitigation-assistance). FEMA funding assistance exists to help communities plan and undertake the actions needed to reduce natural hazard risk, including support for pre-disaster resilience planning, climate adaptation actions, living shorelines, and green infrastructure projects. Furthermore, a recent workshop organized by Environmental Defense Fund (EDF, 2017) explored whether and how the CRS program might be used to reduce flood losses and advance use of natural infrastructure. This workshop identified the need to understand the barriers and drivers for communities in joining (or not joining) CRS. For example, there are 120 coastal communities in coastal states that have policy counts of over 1,000 but do not participate in CRS (EDF, 2017). In a longitudinal study of CRS communities in Florida, researchers found that communities tend to engage in point-earning activities that are less expensive and more politically viable, such as distribution of information, community outreach and strengthening of existing regulations, and do not pursue higher point-achieving activities such as relocation of structures or projects addressing structural issues, which would achieve lower CRS designations (Brody *et al.*, 2009).

The City of LA has participated in the CRS program since 1991. The city has a Class 7 rating, so residents who live in a 100-year floodplain can receive up to a 15% discount on their flood insurance; outside of the 100-year floodplain, they receive a 5% discount (Table 4.2). This equates to annual savings ranging from $58 to $475 per policy, for a total citywide premium savings of almost $770,000 (City of LA, 2015, 2017). To maintain or improve its CRS rating, the City of LA completes all recertification every five years. The Floodplain Management Plan helps the city to maximize its credit potential under the CRS and has identified

Table 4.2. Credit points earned, classification awarded, and premium reductions for communities in the NFIP CRS

Credit Points	Class	Premium reduction SFHZ	Premium reduction Non-SFHZ
4500+	1	45%	10%
4000–4499	2	40%	10%
3500–3999	3	35%	10%
3000–3499	4	30%	10%
2500–2999	5	25%	10%
2000–2499	6	20%	10%
1500–1999	7	15%	5%
1000–1499	8	10%	5%
500–999	9	5%	5%
0–499	10	0	0

80 mitigation and flood control projects and plans (City of LA, 2015, 2017). Finally, the recent Local Hazard Mitigation Plan (City of LA, 2017) specifically aims to maintain and enhance its CRS classification through improved risk assessment and development of local hazard mitigation plans. For the City of LA – and other jurisdictions across the United States – barriers to maintaining and lowering the CRS score, however, do exist. For a city the size of LA, administrative costs primarily related to documentation requirements can be quite high (both financially and through staff resources). Cities that have successfully lowered the CRS ratings often have dedicated staff focused solely on CRS compliance and documentation. Thus, while these costs have prevented the City from lowering its CRS rating for the present, the City is looking into opportunities to strengthen its participation in CRS.

Home improvement and grandfathering. FEMA regulations describe that if the costs of home improvements (any reconstruction, rehabilitation, addition, or other improvement of a structure) exceeds 50% of the market value of the existing structure, it is considered a "significant improvement" and homeowners need to comply with the NFIP to ensure elevation or flood-proofing measures are applied (FEMA 2014). The City of LA follows these guidelines, and states that if a homeowner applies for a building permit for an existing structure that was built prior to the initiation of the FEMA regulations, improvements do not need to comply with current NFIP regulations if the permit valuation is less than 50% of the existing building value (LADBS, 2014). The City of LA uses County Assessor's data to perform the initial calculation. If the permit value prepared by the City staff exceeds 50% of the existing structure value based on County assessor's data, the proposed improvements must comply with NFIP. However, if the permit applicant wants to challenge the determination, he/she can provide the most current appraisal report prepared within 6 months by a State licensed appraiser and a detailed construction estimate signed and certified by a state-licensed contractor. The City will review both documents to determine whether the proposed improvement is a "significant improvement" or not. Some property owners skirt this issue by spreading the property modifications over a series of permit applications so that they remain under the 50% "significant improvement" designation, as determined by individual permits.

Expert interviews have suggested several mechanisms for addressing this issue:

1. Use of the size of the improvement area in addition to the value of the improvement provided by the County Assessor to determine if "significant improvement" occurs.
2. Require improvements to be calculated cumulatively over several years, for instance to three years. Expanding the cumulative years would also provide more credits for the Community Rating System (CRS), which then leads to increased premiums discounts. Proposed measures would require coordination between the LADBS (Dept of Building and Safety), LABOE (Bureau of Engineering).

"Grandfathering" is another issue under debate. The grandfathering rule is a FEMA regulation, which states that for properties that are remapped to a more costly zone classification (e.g. through new FEMA mapping), they are still charged the lower insurance premium of the former flood zone. Under this policy, the number of properties that pay grandfathered subsidized rates will increase even with new flood hazard mapping, continuing the problem of rates not matching risk. If the effects of climate change, such as sea level rise, are incorporated in FEMA mapping products in the future and the grandfathering policy continues, the number of subsidized insurance policies will increase considerably in the future (Aerts and Botzen, 2011).

4.2 California Coastal Act

Land-use planning and development in the California Coastal Zone is subject to the California Coastal Act, enacted in 1976 to protect public access and recreation along the coast, protect coastal habitats and natural resources, and balance development and conservation (Diamond *et al.*, 2016). This act also requires minimizing the risks of coastal hazards, such as flooding, which makes it an important policy instrument in stimulating climate-adaptation activities.

Urban development along California's coast increases the flood risk to which its buildings and residents are exposed. Sea level rise is expected to further exacerbate those risks and poses a challenge to the future protection of residents and coastal resources. Therefore, the California Coastal Commission (CCC) adopted the Sea Level Rise Policy Guidance (CCC, 2015), to provide guidelines for cities addressing the impacts of sea level rise. Such guidelines may be used to develop strategies and measures by which a local jurisdiction can reduce the effects of sea level rise, as well as update that jurisdiction's Local Coastal Program (LCP) and zoning ordinances. Local Coastal Programs are essential planning tools for communities and contain standards for the future development and protection of resources in the coastal zone. Further, the draft Residential Adaptation Policy Guidance (CCC, 2017) provides more detailed guidance on the measures and policies by which a community can address sea level rise in LCPs. For example, local governments can incorporate zoning restrictions, buyout programs, transfers of development rights, and setback requirements into their LCPs during updates.

Local Coastal Programs are prepared by local governments and submitted to the CCC for review and certification of consistency with Coastal Act requirements. Each LCP includes a Land Use Plan (LUP) and an Implementation Plan (IP). The LUP specifies the type, location, and intensity of land use, and contains a description to ensure maximum recreational opportunities and provide public access to the coast. The IP includes measures by which to implement the LUP, such as zoning ordinances. One important issue in the certification process is whether the LCP addresses the impacts of accelerated sea level rise related to coastal hazards, and whether it describes how to manage such risks through land-use planning, community outreach, and regional coordination.

For the LCP's land use and implementation plans, different adaptation measures are available to reduce the risks and impacts associated with sea level rise. The CCC (2017) categorizes proactive adaptation strategies into three types: protect, accommodate, and retreat.

- *Protection* against flooding refers to enhance beaches through nourishment, dune rehabilitation, and armoring coastal stretches with levees or seawalls. Although these may reduce risk from flooding, they can influence natural aesthetics and the functioning of ecosystem services (e.g., the natural supply of sediments to beaches).
- The process of *accommodation* refers to measures and policies that increase the strength of residential development (flood-proofing, elevation), as well as building structures that can easily be moved and relocated, and using larger setbacks. Rebuilding- and redevelopment-restriction strategies may be used to limit rebuilding or renovating structures located in a sea-level-rise hazard zone.
- *Managed retreat* involves relocating or removing existing development from hazard areas and limiting the construction of new development in vulnerable coastal areas. Examples of managed-retreat measures include acquisition and buy-out programs, transfer of development rights programs, and conditioning the removal of structures.

The California Coastal Commission (CCC) is responsible for ensuring that cities within the Coastal Zone implement the Coastal Act. Hence, any of the adaptation pathways proposed in Chapter 6 will need regulatory review by local and state agencies, consistency with the Local Coastal Program, the California Coastal Act, and to have been undertaken with consideration of the appropriate guidance, such as the Coastal Commission's Sea Level Rise Policy Guidance (CCC, 2015) and/or the Residential Adaptation Policy Guidance (CCC, 2017).

Figure 4.1. San Gabriel River near Naples, Long Beach. These levees along the river probably need an upgrade when sea levels rise in the future, and will influence (flood-) water levels in the river *(Photo: J. Aerts)*.

4.3 Coastal protection: management of beaches, protection of infrastructure

Management of beaches: beach nourishment. Beaches in LA County offer natural protection against flooding, and as such, are the first line of defense to protect people and assets situated behind the beaches. Most of the beaches located in Los Angeles are either owned or operated by the Los Angeles County Department of Beaches and Harbors (DBH) (see Table 3.5 in Section 3). LA County DBH maintains 130 beach facility assets (e.g. parking lots, access roads, etc.) and other amenities to provide public access, ensure safety, and facilitate recreation (Noble, 2016). In 2012, LA County launched a comprehensive Coastal Regional Sediment Management Plan (CRSMP, 2012) to prevent

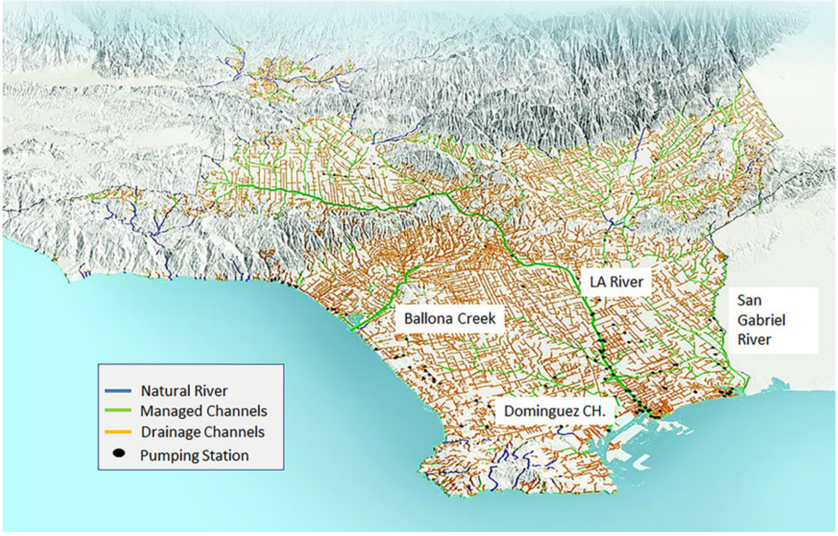

Figure 4.2. Drainage network for Los Angeles County (Source: Adopted from LAT; data from LA County Department of Public Works).

erosion, maintain safety, and conserve and restore sediment resources along the LA coastline. The plan addresses the issue of sea level rise and future challenges for maintaining beaches in LA, and the importance of the continuation of beach nourishment as the primary policy for maintaining the protective strength of beaches to reduce flood risk.

The US Army Corps of Engineers (USACE) maintains and develops beach nourishment projects, although a city can also initiate such activities. The availability of sand is critical for the sustainable management of beaches and beach nourishment. Most sand for nourishment comes from harbor dredging programs, and for some areas from natural sediment supply by creeks (USACE, 2004). In the future, however, the volumes of sand provided by rivers and dredging programs are likely to be insufficient to sustain beach nourishment. Therefore, it is important to quantify the characteristics and extent of offshore sand reserves (CRSMP, 2012).

Protection of infrastructure and design criteria. While municipal regulations protect coastal infrastructure through building codes and locally based beach nourishment and stabilization programs, state and federal agencies are responsible for the protection and maintenance of other coastal infrastructure (Fig. 5.1). The California Department of Boating and Waterways (DRB) has jurisdiction in state waters for the maintenance of navigable waters. The federal USACE is charged with protecting infrastructure such as harbors and other coastal facilities, and the maintenance of protective structures (revetments, breakwaters, etc.). The USACE is also responsible for many maintenance, beach nourishment, and water infrastructure projects (e.g. constructing levees) in coastal and watershed areas. The USACE has several civil works authorities and programs related to flood risk and flood hazard management, including federally funded programs as well as cost sharing projects (structural and non–structural), to address flood risk at locations or watersheds (City of LA, 2017). The USACE also provides emergency response assistance to local authorities during and following natural disasters such as floods.

Table 4.3. **Wave run-up elevations of sand berms for various return periods (source: Noble, 2016)**

Return period	Hermosa m (ft)	Dockweiler m (ft)	Venice m (ft)	Zuma m (ft)
1	4.7 (15.5)	4.2 (13.7)	3.7 (12.0)	3.7 (12.1)
2	5.7 (18.7)	5.6 (18.4)	4.2 (13.6)	4.3 (13.8)
5	6.5 (21.4)	6.3 (20.8)	4.8 (15.7)	4.8 (15.9)
10	7.1 (23.2)	6.7 (22.2)	5.3 (17.3)	5.4 (17.6)
25	7.7 (25.3)	7.5 (23.7)	5.9 (19.4)	6.0 (19.8)
50	8.3 (26.8)	7.6 (24.8)	6.4 (21.0)	6.5 (21.4)
100	8.6 (28.1)	7.8 (25.7)	6.9 (22.6)	7.0 (23.1)

USACE primarily uses the 1/100 flood event as a "design level" to develop and maintain infrastructure. A 1/100 storm, is a storm that statistically has a 1-percent chance of occurring in any given year based on the current empirical data available (e.g. USGS, 2017). Another example of using design protection levels is a local engineering study in Malibu to assess the risk for a parking lot on the beach (TS, 2014). This study used tide levels (still water levels) of 1.4 m (4.5 ft) and LA County guidelines of 1.8 m (+6 ft), and added a 0.6 m (+2 ft) storm surge based on 1998 storm surge water levels. Adding these numbers yields a design water elevation of 2.4 m (+8 ft), which is close to the highest mean water level measured at the gauging station at Santa Monica of 2.6 m (8.5 ft; Appendix D), and the still water level of +8 ft used by USACE (1990). The study then added 0.6m (+2 ft) of sea level rise, resulting in an overall water level of three meters (∼+10 ft). Adding these numbers, in addition to other factors (e.g. beach shape) in a wave run-up analysis results in total wave run-up elevations of 3.7-5.2 m (12−17 ft; TS, 2014).

Noble (2016) conducted wave run-up analyses to determine the heights of temporary sand berms used seasonally to protect beaches in LA (Noble, 2016). In this analysis, 10% wave run-up is defined as the average of the highest 10% of run-ups during a wave event. The wave run-up analysis was based on the USACE Coastal Engineering Manual (USACE, 2003). A statistical analysis was conducted based on 36-year annual maximum wave run-up elevations, and extended using the Weibull distribution to determine low frequencies (Table 4.3). Based on this table, wave run-up heights for a 1/100 storm vary between 22.6 and 23.1 ft. In addition, the Ports of LA and LB have applied a +2 m (6 ft) design criterion for tsunamis for their infrastructure (FEMA, 2008; Port of LA/LB, 1990).

The California Department of Transportation (Caltrans) recently identified sea level rise as a serious threat to residents and existing infrastructure (Caltrans, 2011). Caltrans provides steps and guidelines to address sea level rise in the programming and design of new infrastructure projects with a lifetime of more than 20 years. If a project is within the zone that is vulnerable to sea level rise and has a lifetime of +20 years, then the Project Initiation Document (PID) should include a discussion of the potential impacts of sea level rise on the projects and options for adaptation. Other factors that determine whether sea level rise should be considered in the design of new projects include potential delays from flooding, availability of alternative routes, safety, and critical commercial routes (Caltrans, 2011).

4.4 Stormwater management

The stormwater system in LA is connected to the coastal zone, canals and rivers drain into the Ocean. This means that if future sea levels will rise, the water levels in the San Gabriel- and LA Rivers will rise as well. Therefore, the levees along the rivers will most likely need to be upgraded when sea levels rise in the future (Fig. 4.1). Although the LA area receives relatively little rainwater on an annual basis, intensive storms have historically caused flooding and destruction along rivers. A 1938 flood was a turning point, and since that time, a large drainage network was developed, measuring over 3,500 miles (Fig. 4.2). Natural rivers have been transformed into concrete-lined channels to accommodate flash floods and many neighborhoods adjacent to these rivers and canals are protected by levees. Some of them do not meet FEMA standards; 7.82 miles of levees only provide protection for a 1/25-year flood (City of LA, 2017). The Army Corps of Engineers has jurisdiction over 83% of the levee systems; the remainder is under the jurisdiction of the Los Angeles County Flood Control District (City of LA, 2017). In addition, an estimated 120,000 catch basins are used to temporarily collect peak rainwater. Numerous pumping stations collect water in low-lying areas and pump it to the main drainage channels that drain towards the ocean. Most pumping stations operate in conjunction with detention ponds often located in nearby parks. The pumps operate to drain surplus rainwater to the discharge channels, and the nearby pond collects peak flows, which are drained towards the ocean by gravity or a pump after the storm. The City of LA also has an extended emergency response and early warning system, to advise households in vulnerable areas. For immediate response, sand bags are available through local fire stations to protect against local flooding (CMB, 2015).

Many governmental agencies in LA play a role in regulating and managing flood control risk from rainwater. USACE maintains water infrastructure (e.g., levees), and at the county level, the LA County Department of Public Works (LACDPW) is responsible (under the guidance of USACE) for managing county flood control facilities (e.g., drainage reservoirs) to reduce the impacts of extreme storms, and the LA Bureau of Engineering (LABOE, City of LA) oversees the city's storm drain system, which is designed to drain 1/50-year precipitation events. In LA, the sanitary sewer system and the municipal storm drain system are separate water drainage systems; most stormwater flows during storms do not receive treatment because their volume is too high for treatment plants. Thus, many of the pollutants carried in stormwater drain directly into coastal waters, threatening public health and the environment. The most common pollutants that cause impairments include trash, metals, coliform bacteria, oil and grease, nutrients, and toxic organic compounds such as pesticides and herbicides (City of LA, 2009).

Storm water management and water quality control are often intertwined (e.g., through the water quality improvement programs initiated by the EPA's National Pollutant Discharge Elimination System). This program incentivizes owners and operators of municipal separate storm sewer systems (MS4s) to develop, implement, and enforce a stormwater management program (SWMP). Although the focus of SWMPs is to describe how the MS4 will reduce the discharge of pollutants, there is a clear link to stormwater management, and most of these plans also address runoff from rivers and channels.

Stormwater management plan. In recent decades, the region has struggled with repeated droughts; thus, water managers are increasingly seeking strategies to capture rainwater and re-charge shrinking groundwater tables. Best management practices (BMP), such as green roofs

Figure 5.1. Manhattan Beach, LA County, currently has an elevated parking lot *(left side of photo)*. Continued beach nourishment in combination with armoring vulnerable public facilities could be one option for LA's sandy beaches. For wider beaches, beach nourishment and dune restoration may be considered to ensure protection and sand supply. (Photo: J. Aerts)

and the development of parks to infiltrate rainwater, are addressed in the Standard Urban Stormwater Mitigation Plan (SUSMP); for example, a network of spreading grounds was built along the region's rivers (ENR, 2016). In other places, rubber dams are used to redirect the flow of water and enhance infiltration and recharge.

Increases in pollutants flowing without treatment to the ocean, and the worsening drought lowering groundwater tables, led to the LA Water Quality Compliance Master Plan for Urban Runoff (WQCMPUR). This plan aims to reduce pollution from urban runoff in the City of LA (City of LA, 2009). The WQCMPUR Plan was developed by the Bureau of Sanitation, Watershed Protection Division.

A challenge for the integrated management of different watersheds in LA is the shared responsibility of municipalities located in these watersheds for meeting water quality and quantity regulations. For example, 42 cities and agencies are located in the LA River Watershed and have developed several watershed management plans. These plans have a broad mission that goes beyond compliance with water quality regulations—examples include the LA River Revitalization Master Plan, the City's Water Integrated Resources Plan (Water IRP), the Ballona Creek Watershed Management Plan, the Dominguez Watershed Management Master Plan, and the Greater Los Angeles County Integrated Regional Water Management Plan. Implementation of the WQCMPUR builds upon ongoing watershed management planning work to use resources efficiently and maximize water quality benefits. It is estimated that the total cost for implementation of the WQCMPUR over the next 20 to 30 years will be between $7 billion to $9 billion. Under the Stormwater Capture Master Plan, the City of LA could collect 100,000 to 200,000 additional acre-feet of rainwater each year by 2035, depending upon how fast the plan is executed. One acre-foot of water is equal to 326,000 gallons. The plan would cost $600 to $1,100 for each acre-foot of additional stormwater captured—or $60 million to $220 million, depending on what elements are implemented (LAT, 2015).

5. Adaptation Measures and Costs

5.1 Beach nourishment

Beach nourishment has been a widely used strategy for combating coastal erosion and sea level rise along the coast of California (ERG, 2012; Dean and Houston, 2016). The purpose of beach nourishment is to restore and maintain the width of an eroding beach on a temporary basis (Noble, 2016), providing two primary benefits: increasing and maintaining an area for recreation and preserving the protective values of the coastline against storm surges (see Appendix G). Other (indirect) benefits from beach nourishment include increased tourism revenues, increased public access to beaches, reduced need for hard protective structures, higher property values, and enhanced public safety. Although the placement of sediment on a beach may provide more space for potential wildlife habitat, the placement of the sand as well as the equipment used to place the sand can negatively affect biota in the region. Additionally, environmental impacts may also arise from the removal of sediment from its original location (i.e. offshore). Due to high to very high erosion rates in California, beach nourishment in Southern California has been often coupled with structures that hold sand in place (e.g., groins and jetties). Additionally, management agencies implement strategies, such as windscreens, to help stabilize beach sand landward sometimes in an effort to prevent sand from migrating onto public service infrastructure (e.g. parking lots, roads, bathrooms, etc.). LA County is in the process of completing and implementing its Coastal Regional Sediment Management Plan (CRSMP, 2012), which describes several options for maintaining beaches, and addresses the importance of a long-term vision for the impacts of sea level rise. In addition, the Noble (2016) report states that beach nourishment can be a key adaptation strategy for reducing impact from coastal flooding and sea level rise. Often sediment from harbor dredging is a source for periodic beach nourishment in California.

Sources of sand in Los Angeles County. Sediment sources for beach nourishment projects usually comes from nearby harbor dredging or offshore dredging, and is pumped onto the desired site. Sand can also be excavated from river channels or dunes. Sand can also come from inland quarries. This process typically involves careful screening and mixing to ensure a grain size, color, and material suitable for the specific beach. Historical coastal excavation projects, however, have delivered most of the sand to the beaches in Santa Monica Bay. Table 5.1 shows the volumes of sand supplied to LA beaches over the period 1930–1993. For beaches in LA County, it is estimated that over 35 million cubic yards (cy) (26.8 million m^3) of sand has been placed to widen the beaches (Noble, 2016). For example, excavations for the El Segundo Power Plant and the Hyperion Sewage Treatment Facility delivered 17.1 million cy (13.1 million m^3), and the dredging of Marina del Rey provided approximately 10 million cy (7.6 million m^3) from 1960 to 1963. As a result, the shoreline in Santa Monica Bay has widened from 150 feet to 500 feet (45–150 m). Groins and other structures assist in keeping the sand in place. The modified shoreline of Santa Monica Bay has even, by design or convenience, reused some structures as makeshift sediment barriers (e.g. Venice breakwater). The historic sources and volumes of sand, from adjacent coastal dunes and dredging spoils of an entire marina, are not a viable option today due to the developed nature of LA's coast. Future nourishment projects will require additional offshore sand sources in order to maintain beaches at their current size (Noble, 2016). That is why it is critical to continually assess how much offshore sand is available in LA County (CRSMP, 2012).

In the San Pedro littoral cell, which includes Long Beach, nourishment has been applied to reduce the erosion caused by the construction of the Anaheim jetties. The area is nourished with sand at an approximate rate of 0.4 million cy/yr (0.3 million m^3/yr). Herron (1980) stated that historically, 22 million cy (16.8 million m^3) of sand from harbor and river projects has been placed on the 15 miles of public beaches of the San Pedro littoral cell. Flick (1993) estimated that for the entire LA area, between 1942 and 1992, a total of 100 million cy (76.5 million m^3) of sand was deposited on beaches, with approximately half of the sand derived from harbor or marina projects. This is comparable to the total volume of sand, 106 million cy, that has been used for nourishment on beaches in New York City (Aerts *et al.*, 2013).

Current sources of sand:

- *Local stream delivery*: The Santa Clara River in Ventura County is the largest relatively natural river system in Southern California, but most of its sediment is lost to the Mugu Submarine Canyon before it can reach the LA County coast. Contributions from Ballona Creek and the Santa Monica Mountains range from 0.024 to 0.05 million cy/yr (~0.018–0.038 million m^3/yr), but most of the sediment from Ballona

Table 5.1. **Yearly beach nourishment and post damming/cliff armoring erosion volumes [million cy] (source: Patsch and Griggs, 2006; Noble, 2016; Heron, 1980)**

	Total Nourishment 1930–2015 [million cy]	Yearly Nourishment (1930-1993) [million cy]	River Erosion [million cy]	Bluff Erosion [million cy]	Dune Erosion [million cy]	Total Supply [million cy]	Total Reduction (dams/armoring) [million cy]	Balance: Nourish – Reduction [million cy]
Santa Monica Cell	35	0.53	0.07	0.15	0	0.74	0.03	+0.5
San Pedro Cell	22	0.4	0.28	0.002	0	0.68	0.53	−0.13
LA Total	57	0.93	0.36	0.15	0	1.4	0.56	

is too contaminated for use in beach nourishment (CRSMP, 2012).

- *Harbor entrapment*: Sand from harbor development is currently the most important source of nourishment. Sand can be found north of the Marina del Rey entrance jetties and breakwaters, where it accumulates. In this area, maintenance dredging is required on a regular basis to remove sand and transfer it down the coast. Between 1969 and 2007, 1.5 million cy (1.14 million m^3) of sand was dredged (about 0.04 million cy/yr; ~0.03 million m^3/yr) (Ryan, 2010).

Offshore sand. The CRSMP plan (2012) explicitly states that available sediment resources near the coastline (e.g. suitable for dredging) for maintaining nourishment of beaches are finite and limited, especially when facing accelerated rising sea levels. One option is to continue investigating the significant offshore sand deposits from the late Quaternary or Holocene geologic time periods. These deposits may be found offshore on the inner continental shelf (Fig. 5.2). Welday and Williams (1975) show linear belts of predominantly fine-grained sand, with local areas that have medium-grained to coarse-grained sand; these observations are for the seafloor surface only (CGS, 2005). Research, for example, Osbourne *et al.* (1983), states that 325 million cy of offshore sand is available with a grain size of 0.13 mm (Appendix K) and 198 million cy of offshore sand should be available with a coarser grainsize between 0.44—0.59 mm. Other research describes similar totals of 372 million cy yards of sand and gravel deposits believed to exist offshore of LA County's coast (CRSMP, 2012). The thickness of these deposits could measure over 60 feet (18 m). The USACE performed an assessment between 1973 and 1978 near Santa Monica and Torrance, where sand deposits were estimated at 26 million cy (19.9 million m^3). However, most of these sediments are in deep waters offshore (Fig. 5.2), where it may not be economically feasible to excavate all of these sediment deposits. One caveat for this sediment source is that it is unknown how much of this volume would consist of sand with the required grain size for beach nourishment. More recent studies to locate suitable offshore sand closer to west Malibu have not been successful as the sediment was too finely grained for beach nourishment (CRSMP, 2012). In addition, California's system of marine managed areas, mandated by the state's Marine Life Protection Act (i.e. marine protected areas, NPS, 2018) needs to be considered in the context of developing adaptation plans. Balancing environmental concerns of habitat impacts (from both extraction and placement) of dredging with maximizing beneficial use of available offshore sediment resources will be a continual challenge for coastal managers.

Inland sand sources. Los Angeles County operates and maintains over 160 debris basins and dams, most of them located in the San Gabriel Mountains (LA County, 2013). They are designed to capture sediment and gravel flows during storm runoff, before they can clog drainage systems and cause flooding. These debris basins are regularly cleaned out to prevent buildup of sediment as well as to make room to capture new sediment flows. The Los Angeles County Department of Public Works

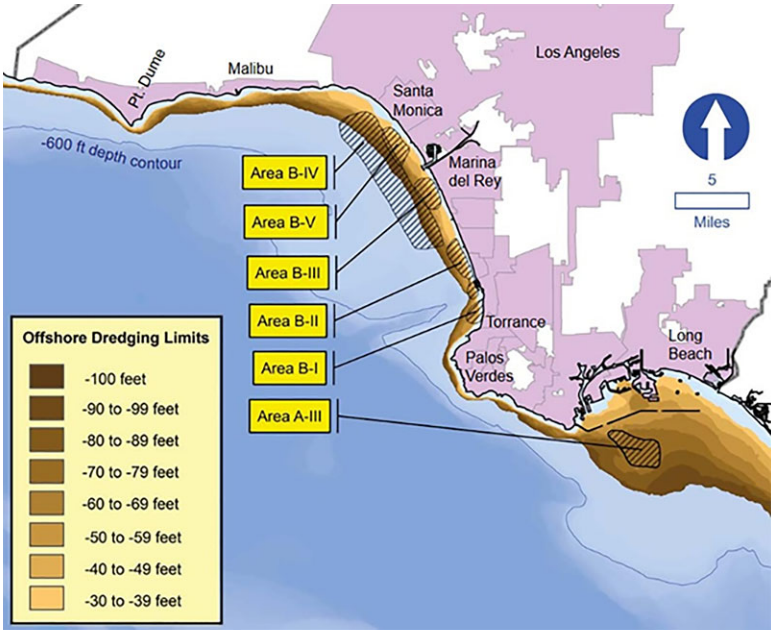

Figure 5.2. Location of offshore sediment deposits near Santa Monica Bay; the hatched areas contain the largest reserves of beach-compatible sand (Source: CRSMP, 2012).

indicates that over 18 million cy of sediment has been collected since the 1930s at an average annual total capture rate of over 300,000 cy (CRSMP, 2012). Most of this sediment, however, is trapped in the Los Angeles and San Gabriel rivers, which *do not* supply sediment to LA County beaches.

Trapped sediment behind dams near Ventura and Malibu may be feasible inland sources for beach nourishment: namely, the Matilija Dam on the Ventura River and Rindge Dam on Malibu Creek. Some lessons learned can be derived from other dam removal projects on the West Coast (Elwha Dam and San Clemente Dam) that have restored habitat and sediment connectivity (Duda *et al.*, 2011; Steinmetz and Smith, 2018). Given the complex nature of dam removal and fluvial dynamics, there is much debate about how practical dam removal will be for restoring natural sediment regime:

1. Dam removal and creek restoration projects would need to be carefully engineered, to protect downstream habitats as well as development that has taken place since construction of the dams. Sediment removal from these two dams will likewise take careful planning, design, and considerable financing.
2. Current EPA guidelines do not normally allow sediment to be placed on beaches when the proportion of fines (silt and clay) is over 20% (the 80:20 guideline, in which acceptable sediment for beach nourishment must consist of at least 80% sand and no more than 20% silt and clay). Unfortunately, the likely sediment that would be transported if the dams were removed exceed the 20% silt and clay guideline. Regardless of this obstacle, developing engineering strategies to achieve acceptable sediment guidelines is an important research direction.

Required future nourishment volumes considering sea level rise. Few studies have assessed the volumes of sand required to maintain current beach width assuming different scenarios of sea level rise. Ewing and Flick (2011) considered averaged beach characteristics to calculate an estimate of sediment needed for Southern California, for all beaches from Point Conception to the Mexican Border (320 km; ~200 miles). They assumed an average beach height of 12 m (~39 ft) and +1 m sea level rise, an average beach slope of 1:50, and a required nourishment volume of 6,000 m^3/km/yr (12,553 cy/mi/yr). Dean and Houston (2016) estimated a comparable beach

Table 5.2. Total nourishment volumes for LA beaches (35 miles of sandy beach) in million cy/100 years for different beach slopes, berm heights, and sea level rise scenarios (Source: Flick and Ewing, 2009)

Beach slope	Berm height	SLR 0.2 m mln cy/100yr	SLR 0.5 m mln cy/100yr	SLR 1 m mln cy/100yr	SLR 1.5 m mln cy/100yr	SLR 2 m mln cy/100yr	SLR 2.5 m mln cy/100yr	SLR 3 m mln cy/100yr
1:20	8 ft	0.9	2.3	4.6	6.8	9.1	11.4	13.7
1:20	12 ft	1.4	3.4	6.8	10.2	13.7	17.1	20.5
1:50	8 ft	2.3	5.7	11.4	17.1	22.8	28.4	34.1
1:50	12 ft	3.4	8.5	17.1	25.6	34.1	42.7	51.2
1:75	8 ft	3.4	8.5	17.1	25.6	34.1	42.7	51.2
1:75	12 ft	5.1	12.8	25.6	38.4	51.2	64.0	76.8
1:100	8 ft	5.7	14.2	28.4	42.7	45.5	56.9	68.3
1:100	12 ft	6.8	17.1	34.1	51.2	68.3	85.3	102.4

nourishment volume assuming a moderate sea level rise (~0.32 m, 1 ft) in the year 2065: 4,300 m^3/km/yr. When applying these numbers to the Californian coast, 1.9 million m^3/yr or 190 million m^3 (248 million cy) of sand is needed over the next 100 years (Ewing and Flick, 2011).

The total length of the LA coastline is 72 miles, of which approximately 35 miles can be classified as sandy beach according to visual analysis in Google Earth. Table 5.2 shows sand nourishment volumes for different beach slopes, berm heights, and sea level rise scenarios. Following Flick and Ewing (2009; Appendix G), required future nourishment volumes for the LA coastline vary from 320 m^3/km/yr (668 cy/mi/yr) for a low sea level rise scenario of +0.2 m (0.6 ft) to 36,000 m^3/km/yr (77,337 cy/mi/yr) for an extreme +3 m (9.8 ft) scenario, and a wide beach slope.

Table 5.3 shows cumulative volumes of nourishment for different sea level rise scenarios over 100 years. Volumes vary from 0.9 million cy to 102 million cy. In an additional calculation, following Flick and Ewing (2009), three storms were simulated in the years 2020, 2055, and 2090, which would each erode 40% of beach volumes. These additional losses are added to total sand nourishment volumes. Approximately 160 million cy of sand is required until the year 2115, assuming 3 m of (9.8 ft) sea level rise and a berm height of 12 m (39 ft).

Cost of future beach nourishment. From 1984 to 2010, more than $67 million was spent to renourish California beaches, according to the California Department of Boating and Waterways (Fig. 5.3; ERG, 2012). The Army Corps has spent $48.5 million on re-nourishment projects in California between 1990 and 2011, for a total volume of approximately 7.9 million cy (2011 dollars; ERG, 2012). The cost of material can vary greatly depending on its origin and associated transportation costs (Magoon & Lent, 2005). In San Diego County in 2001, approximately two million cy of sand was dredged from six offshore sites and placed on 12 beaches in northern San Diego County for a total cost of $12.25 million or $6/cy of sand (2001 dollars). Other cost estimates by King (1999) for all of Southern California estimate a need for 248 million cy (190 million m^3) of sand over 100 years. This estimate is lower than that of Flick and Ewing (2009), who estimate that the average cost of nourishment is $19-$48 million/yr for the low-range sea level rise scenario of 0.5m (1.6 ft) by 2100. Similar estimates for New York City (NYC) were used by Aerts *et al.* (2013), who estimated

Table 5.3. Total nourishment volumes and unit cost

Location	Type	Year	Volume	Total Cost $	Unit Cost $/$m^3$/ ($/cy)
Southern California	Offshore	1984–2010		$67 million	
Southern California	Offshore	1990–2011	7.9 million cy	$ 48.5 million	$4.7/$m^3$ ($6.2/cy)
Southern California	Offshore	2010–2110	248 million cy	$1.9 billion	$6/$m^3$ ($8/cy)
Monterey	Inland	2002	240,000 cy	$5.5 million	$17.6/$m^3$ ($23/cy)

Table 5.4. **Total nourishment cost for LA beaches (35 miles of sandy beach) in $ million/100 years, for different beach slopes, berm heights, and sea level rise scenarios**

Beach slope	Berm height	SLR 0.2 m mln $/100yr	SLR 0.5 m mln $/100yr	SLR 1 m mln $/100yr	SLR 1.5 m mln $/100yr	SLR 2 m mln $/100yr	SLR 2.5 m mln $/100yr	SLR 3 m mln $/100yr
1:20	8 ft	13	32	64	96	127	159	191
1:20	12 ft	19	48	96	143	191	239	287
1:50	8 ft	32	80	159	239	319	398	478
1:50	12 ft	48	119	239	358	478	597	717
1:75	8 ft	48	119	239	358	478	597	717
1:75	12 ft	72	179	358	538	717	896	1075
1:100	8 ft	80	199	398	597	637	796	956
1:100	12 ft	96	239	478	717	956	1195	1434

nourishment costs at $10/cy ($8/m^3) in 2012 dollar values.

Nourishment costs from inland sand sources were estimated for the Monterey Bay area. For truck-delivered, beach-quality sand, the costs were approximately $23/cy. Based on this figure, the estimated cost associated with delivering 240,000 cy of sand to nourish a beach that is 3,000 feet long and 100 feet wide from an inland source would be $5.5 million. It would take 1440 truckloads and 18 months to deliver 240,000 cy of sand. Additional indirect effects from the process of nourishment, such as air quality impacts and traffic concerns in communities located along routes between sediment source and the beach, have been raised as barriers for using trucks to deliver sand for beach nourishment projects. These added ‘costs’ are not reflected in these nominal estimates.

An offshore cost estimate of $13/cy is used here, which is approximately $14/cy ($10.7/m^3) in 2015 values. If this number is applied to the required future sand volumes displayed in Table 5.4, the adaptation cost of future beach nourishment, assuming different beach shapes and sea level rise scenarios, can be estimated.

Temporary seasonal berms on beaches. The policy of LA County over the last 30 years has been to develop seasonal sandy berms on the beaches lining Santa Monica Bay. These sand berms protect public beach assets at Zuma Beach, Venice Beach, Dockweiler State Beach, and Hermosa Beach from storm waves and run-up during winter months. Sand berms are 3.6 to 4.9 m (12–16 ft) high (7–8.8 m [23–29 ft] above mean low water level) and are designed to protect facilities from a 50-year storm (Fig. 5.3). However, these berms need at least 60 m (200 ft) of beach width, and therefore may not be functional in the future when beaches further erode; hence this finding in a recent Long Beach study—“However, given the anticipated rise in sea level and the projected increase in the frequency and severity of storms, continuing to maintain the berm, or even attempts to elevate the berm crest, are not likely to provide sufficient protection” (AOP, 2015). Thus, continued and additional beach nourishment is required to maintain present levels of protection (AOP, 2015). Shoveling sand on a beach to create a single sand berm costs approximately $9,000 (SN, 2011). Around 15 to 25 sand berms (of different lengths) are constructed and leveled every year (Noble, 2016). Total costs estimates range from $150,000 to $250,000 per year.

Groins. A groin is a structure oriented perpendicular to the shore that reduces the flow of sediment along that shore. Retention structures (e.g. groins or offshore breakwaters) can help to capture sand and sustain the lifetime of beach nourishment. Sand collects on the updrift side of the groin until it is filled and the amount of sand on the beach stays the same. Multiple groins are often used to protect a stretch of beach; for example, groins throughout the Santa Monica littoral cell and groins placed on beaches in Capitola, Ventura, Redondo Beach, and Newport Beach have all been successful at stabilizing beach fill projects. However, at Imperial Beach in San Diego County, there was not enough sand in the littoral cell, and groins were not effective at combating erosion (Noble, 2016). Furthermore, sea level rise will submerge existing groins, decreasing

Figure 5.3. Example of a seasonal berm in Venice (Source: N. Sadrpour).

their stabilizing effect on sand. Cost estimates for new groins differ depending upon different factors such as length and height. Aerts *et al.* (2013) estimated reconditioning or new development of existing groins for NYC beach nourishment projects at approximately $1.6 million per groin, including 15% contingencies. Los Angeles groins and jetties include: Malibu and Pacific Palisades (Sunset through Potrero Canyon) groins, Venice tombolo/breakwater and jetty, Ballona Creek/ Toes jetty, Gillis jetty, Dockweiler jetties, Chevron groin/ El Porto jetty, Redondo/Topaz jetty, and Alamitos Bay jetties (Naples).

5.2 *Living shorelines: green infrastructure and nature-based solutions*

Apart from beach nourishment, additional green infrastructure and nature-based adaptation measures are important to consider as flood protection measures, where appropriate. There are, for example, opportunities for the construction and maintenance of more landward dune systems. Although larger volumes of sand are required, dunes provide a natural buffer against storms and can "naturally" re-nourish beaches impacted by high storm surge. Dunes are most practical when sufficiently wide and high backlands are available; at least 45—60m (150—200 ft) of beach width is required to develop dunes (Noble, 2016). As with sand berms, artificial dune construction involves the placement of sediment deposits, which are then reshaped into dunes using bulldozers. To make sure the sand of the newly formed dunes remains stable at its position, fences can be used on the seaward side to trap sand and help stabilize any bare sand surfaces (USACE, 2003; Nordstrom and Arens, 1998). Vegetation may be planted to stabilize natural or artificial dunes and promote the accumulation of sand from wind-blown sources (USACE, 2003b) In addition, dunes can provide habitat for plants, birds and other terrestrial and beach organisms. Experimental dunes have been shown to attract endangered least terns, once a common resident of Southern California beaches. New nests have been observed within the first year of new dune projects. Pilot studies in Los Angeles have tested the viability of dune rehabilitation on urban coastlines (Bay Foundation, 2017). While dune fields may cause disturbances to nearby communities from windblown sand or hinder ocean views, adequate vegetation cover should reduce some of these effects.

Other approaches, such as living shorelines, have shown promise for their ability to reduce impacts and rebound following significant coastal storms (Cunniff and Schwartz, 2015; Narayan *et al.*, 2017), and long-term stability. For example, at San Buenaventura State Beach in Ventura County, beach grooming was halted to determine whether natural dunes and vegetation would return. After four years, all four natural vegetation species returned, and after 13 years, dune hammocks measured 2—3 feet tall and demonstrated an ability to store sand, build topography and self-repair following extreme wave erosion (Boudreau *et al.*, 2018; Dugan and

Table 5.5. Types of flood protection measures, investment costs, and yearly maintenance costs (all in 2015 dollar values)

Type of Flood protection	Unit Cost	Maintenance
RipRap[2,8]	\$750/ft −\$2000/ft	2−4%
New Levee 6:1, 16ft[7,3]	\$16.8−\$26 million/mile	\$0.02–0.1 million/km[9]
Raise Existing Levee [1,7]	\$16.8 million/mile	\$0.02–0.1 million/km[9]
Cliff Retaining Seawall[1,2,4]	\$5,300/ft−\$10,000/ft	\$0.02–0.1 million/km[9]
Flood T-wall (24 ft) [5,6]	\$10−\$20 million/mile	\$0.15 million/mile[5]
Elevate Existing T Wall (7 ft)	\$2.4 million/ft/mile	\$0.15 million/mile[5]
Hurricane Dike[5]	\$41 million/mile	\$0.15 million/mile[5]
(Retrofit-) Bulkhead[5]	\$7−\$26 million/mile	\$0.15 million/mile[5]
Mix Highway on Floodwall[5]	\$43−\$50 million/mile	\$0.25 million/mile[5]
Hidden Levee + Nourishment[5]	\$19−28 million/km	\$0.15 million/mile[5]
Marshland Stabilization[5]	\$21−\$40/ft^2	\$0.8/ft^2
Land Fill	\$50/cy	

[1]Heberger *et al.*, 2009; [2] PPIC (2008); [3]Hillen (2010); [4]Griggs (2005); [5]Aerts *et al.* (2013); [6]Bos (2008); [7]Dijkman (2007); [8]ERG (2012); [9]Jonkman *et al.* (2013).

Hubbard, 2010). In recent years, California has begun to explore and experiment with living shorelines projects on the coast. However, there are only a limited number of demonstration projects particularly along the open coast, and many are in early stages of monitoring. In 2017, USC Sea Grant partnered with the Resilient Coastlines Project of Greater San Diego to host a series of dialogues throughout Southern California to discuss the potential use and design of living shorelines in the Southern California context and barriers and opportunities in implementing these types of projects in the region (Boudreau *et al.*, 2018)

The volume of sand for dune restoration is expected to cost the same as beach nourishment (\$14/cy, 2015 values). Additional costs are dependent on the type of vegetation used and the maintenance of the area. In an extensive study for a dune restoration project in the Monterey area, Dorell-Canepa (2005) described the cost of a habitat restoration plan for a 62-acre dune area. Costs include planning and permitting, fencing, sand stabilization, debris removal, seed collection, planting, and irrigation. The total cost in 2005 was estimated at \$146,443, or \$2,362/acre (\$0.59/m^2). However, the restoration cost of a similar project in Alabama for a 52-acre dune area was estimated at \$1,480,000, or \$28,461/acre (\$7/m^2; NOAA, 2012).

Wetland restoration: Ballona Wetlands as a case study for living shoreline development. Numerous wetland restoration projects have been initiated around San Francisco Bay, where restoration costs range from \$5,000 to \$200,000 per acre. The South Bay wetland restoration project, for example, costs approximately \$67,000 per acre (Heberger *et al.*, 2009). Wetland and salt marsh restoration can be effective for stabilizing existing wetlands because they serve as flood protection and shoreline erosion control. Marshland stabilization aims to preventing further degradation by providing a mechanical supply of sediment to the marshland islands for a longer period (Dijkman, 2007; Aerts *et al.*, 2013). This measure assumes a dynamic connection between the marshland and the tidal influence of the ocean, which is not currently the case at the Ballona Wetlands in Los Angeles; stabilization cost are estimated at \$21−\$40/ft^2.

In Ballona Wetlands, planning for a wetland restoration project is ongoing, and proposed measures range from simple actions such as removing weeds and fixing fences, to more elaborate projects that would recreate salt marshes and meandering creeks for wildlife such as migratory birds, and provide nursery space for fish (Johnston *et al.*, 2015; BR, 2017). A recent Environmental Impact Study (EIS) (ESA, 2017) evaluated the effects of different restoration plans for Ballona Wetlands. One proposal recommends restoring the freshwater marsh that collects water from Centinela Creek during the dry season, and stores stormwater during extreme precipitation events. Another alternative is depicted in Figure 5.4. In this plan, existing levees along Ballona Creek would be removed, allowing

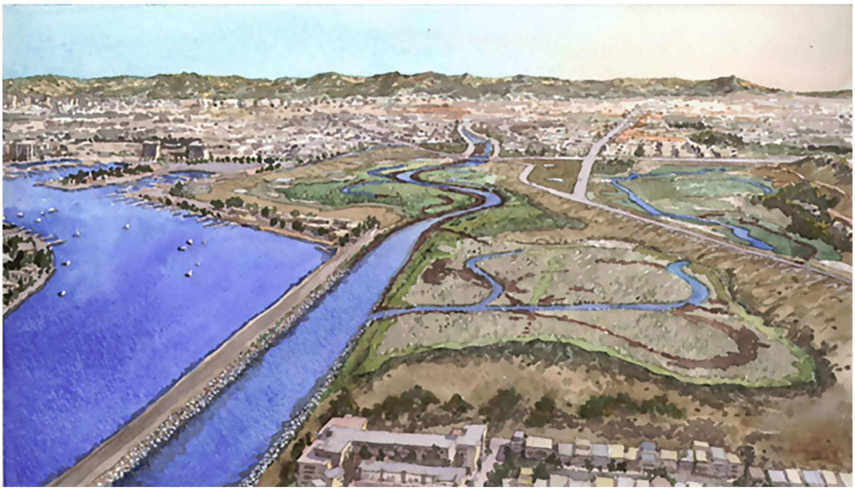

Figure 5.4. An alternative restoration plan to restore salt marches in the Ballona Wetlands, allowing more salt water to enter the area (Source: Ballona restoration project; ESA, 2017).

more salt water from the ocean to flow into the salt marshes. This would be accomplished by installing new floodgates and removing parts of the levees along Ballona Creek. The Creek would be realigned into a natural meandering pattern and land north of the creek would be lowered so that it would also connect to the creek. New earthen levees would be needed to surround the Reserve in order to protect the area and roads, such as Culver Blvd., from flooding (Johnston *et al.*, 2015).

The Environmental Impact Report (EIR) for Ballona Wetlands has addressed the issue of SLR, and some alternative restoration plans have been designed assuming 2–3 ft of SLR. With sea level rise, the proposed earthen wall will most probably have to be re-enforced when tides and other seawater enter the area on a daily basis. In addition, when assuming extreme sea level rise of 7—8 ft, another alternative would raise Culver Blvd. as an elevated pier bridge. This will reduce engineering requirements for the earthen levees, and even open possibilities to further develop the area southeast of Culver Blvd. into a tidal area. The community of Playa Del Rey may also be vulnerable to flooding; especially with sea level and a more open tidal Ballona Wetlands area, flooding danger will increase at the 'backside' of the community. Therefore, re-enforcements would be needed to protect buildings and infrastructure of Playa del Rey at the Ballona side.

5.3 Other flood protection measures

Apart from nature-based protection measures, there are different types of 'hard' engineered protection measures. These are often applied in high-density urban areas, since they are relatively expensive. For example, *seawalls* are designed to resist the forces of large coastal storm surges. They have different designs and often reinforce existing bluffs with concrete against erosion and flooding impact. *Dikes* and *levees* are embankments that protect low-lying land, and these structures are made from various materials such as concrete, clay, and boulders; with a top layer of resistant vegetation or armoring material such as asphalt. Other types of levees can be made from steel piles or concrete and are often designed as steel T-walls. In addition *bulkheads* retain fill, for example in piers within ports, and *rip/rap revetments* are structures that consist of large boulders to protect the (often sandy) coast against erosion from light waves (see Aerts *et al.*, 2013 for an overview of such flood protection measures and their costs). Climate change and sea level rise can result in reduced stability and increased overtopping of existing protective structures. Whether existing structures can be modified to accommodate sea level rise depends, for example, on the suitability of the foundation material to support the additional weight of the structure, and whether space is available for widening the base of the structure (Aerts *et al.*, 2013).

Figure 5.5. Elevated road in the City of Rotterdam, the Netherlands (Source: City of Rotterdam).

Over ten percent of California's coast is armored, with approximately 136 miles of seawalls and levees (PPIC, 2008; ERG, 2012). The total capital cost for these measures for all of California is estimated between $7 and $14 billion (Heberger *et al.*, 2009; ERG, 2012). A study commissioned by the State of California estimated the cost of upgrading existing levees and other defenses to meet future conditions for the whole of California (including the San Francisco Bay Delta) at more than $34 billion (PPIC, 2008).

Discussion of hard engineering measures. Many proposed flood protection measures will be considered as communities develop and update local coastal programs (LCPs), which must be approved by the California Coastal Commission (CCC). The CCC allows armoring to protect existing structures or public beaches that are in danger from erosion. However, it stipulates that alternative 'soft solutions,' such as nourishment, should be sought, because armored measures may have negative impacts on the environment, and may enhance beach erosion when not properly designed (Loughney-Melius, 2015). Flood protection measures may lead to the loss of beach through scouring, or can block public beach access as shown in Broad Beach in Malibu. Furthermore, the aesthetics of flood protection measures and the debris from damaged seawalls often affect views, and are therefore negatively valued (ERG, 2012). Finally, surfing experiences can be altered by protective structures built perpendicular or parallel to the shore, affecting recreational use and important economic returns (PTE, 2013; Benedet *et al.*, 2007). Due to the highly dynamic nature of surf breaks and the historic alteration of LA's shoreline, some surf spots have developed around hard structures left in place. For example, the original end of the Venice pier (located at Windward Ave) was left in place during the massive nourishment of Santa Monica Bay. A surf spot now exists at the Venice breakwater, around this feature that provides structure for waves to shoal and break. This structure also slows the longshore transport of sediment.

Cost of hard protection measures. Table 5.4 provides investment and maintenance costs for various flood protection types, and beach nourishment per length unit:

- *Levee/seawall*: Heberger *et al.* (2009) estimated that, assuming an average levee of 10–20 ft in height, with a waterside slope of 3:1, a levee would cost approximately $2,250/ft (2015 $). Dijkman (2007) and Hillen (2010) estimated unit cost prices for upgrading a similar levee in New Orleans (water side slope 6:1) at $27.1 million/km ($16.8 million/mile); the cost of a new levee cost would be $16.8−$26 million/mile (all 2015 $). Average maintenance costs for levees are $0.02–0.1 million/km per year (Jonkman *et al.*, 2013). Estimated maintenance costs for seawalls range from 1%–4%

Table 5.6. Breakwater types and their characteristics in Los Angeles (2015 $ values)

Major Los Angeles Breakwaters						
	Year	Type	Length	Height	Yearly Maintenance Cost	Replacement Cost
Santa Monica Breakwater	1934	Rubble Mound (original design: caisson)	502 m	0 ft	0.1%	$30 million
Marina del Rey Breakwater	1963	Rubble Mound	710 m[1]		0.1%	$42 million
King Harbor: [3]	1939	Rubble Mound			0.1%	$55 million
North Breakwater			North: 741 m	North: +6.7 m (20 ft)		
South Breakwater			South: 183 m	South: +4.3 m (14 ft)		
Federal Breakwaters (San Pedro, Middle, Long Beach)	1899–1942	Rubble Mound	∼1700 m	+4.3 m (14 ft) [4]	4% (repair in 2014: $20 million[2])	$500 million
			∼3800 m	+4.3 m (14 ft) [4]		
			∼2600 m	+4.3 m (14 ft) [4]		

[1]USACE (2004); [2]LAT (2014); [3]Smith *et al.* (1990); [4]McGehee *et al.* (2002).

per year (Heberger *et al.*, 2009), reflecting the higher level of engineering required for their initial construction.

- *Riprap*: The unit cost for riprap is estimated at $750/ft–$2000/ft, and the maintenance cost of riprap revetment can amount to 2%–4% of the construction cost per year over the life of the project (ERG, 2012).
- *Raise/fill existing structures (roadways, railroads, and other structures)*: In some regions, building levees or seawalls that protect a small number of structures may not be cost effective. In these instances, raising structures such as roadways, railroads, and other structures may be a better alternative to avoid damage from flooding. An elevated road can also act as a levee, and additional materials are needed on the waterside of the structure to anticipate wave impact and water logging; costs are estimated at $70–$80 million/km (Aerts *et al.*, (2013).
- *Elevated road/road as a levee*: In densely populated areas, there is little space for the development of levees or dikes. In such locations, roads may be elevated with fill. For example, in the Westzeedijk in the City of Rotterdam (the Netherlands), the road acts as a seawall. Houses on waterfront side of the road are approximately 1.5 m (4–5 ft) lower than the road, and must be flood proofed. Landward, buildings are protected against flooding by the elevated road, and are situated up to 4 m (12 ft) below the crest of the road (Figure 5.5).

Reinforced dunes: "Dike in dune." Many beach facilities managed by the LA County Department of Beaches and Harbors (LA DBH) are vulnerable to beach erosion, flooding, and long-term sea level rise. In total, 129 assets are located on vulnerable beaches, including lifeguard buildings, parking lots, and other utilities (Noble, 2016). Beaches and dunes provide protection from coastal storms for people living behind the beaches; thus, periodic nourishment is required to keep beaches at their current strength and maintain their protective service. There are scenarios, however, in which beach nourishment and the supply of sand is not sufficient (e.g. Peninsula Beach, Fig. 5.7). Such future conditions may arise when sea levels rapidly increase, for example, through rapid ice melting of the Antarctic ice sheets. Offshore sand reserves may not be sufficient nor economically feasible to excavate, and beaches

Figure 5.6. **"Dike in dune" project in the City of Katwijk, the Netherlands. A reinforced concrete parking caisson was buried within a dune. The waterside of the concrete caisson of the parking facility acts as a levee, in case a storm washes away the beach and dune. As compensation for losing their view, hotel and restaurant owners can operate pavilions in the beachfront during summer months. (Source: City of Katwijk, 2018)**

may further decline through erosion. In such scenarios, additional protection may be needed for nourished beaches, using flood walls or levees. Since such concrete or steel frame structures often do not fit into the coastal landscape, and can even enhance erosion (Loughney-Melius, 2015), novel techniques have been developed to hide levee structures within dunes.

Such a technique has been recently implemented in the coastal city of Katwijk in the Netherlands (Aerts *et al.*, 2013). Dunes are heightened (or created) by adding offshore sand until the dune crest reaches an elevation of +8.5–10 m (+25–30 ft) above MSL. A new concrete caisson serving as an underground parking lot is then placed inside the new system of dunes. The seaward wall of the parking lot is re-enforced, and acts as a levee providing protection in case a major storm washes away the beach and dunes. The beach in front of the dunes is nourished to raise the coastline, creating a smooth transition from the widened dunes to the existing beach. The benefit of such a dune/levee is that it maintains the ecological and recreational value of the beach, and in the case of a storm event, even when all sand from the beaches is flushed away, the levee still offers protection to the back shore area. Additional public parking is an added benefit that could increase the recreational value of the beaches. The 'dike in dune' project in Katwijk (Fig. 5.6) cost approximately $50 million (2017 values) for dune widening and a 'hidden levee' within the dune with a length of 1.1 km (0.7 mile). The unit cost price

Figure 5.7. Peninsula Beach, Long Beach. Buildings on this low-lying (former) sand bar are protected both by periodic beach nourishment, and flood-proofing houses by enforcing building codes. With extreme sea levels, beach nourishment will probably be not sufficient, and additional protection such as the dike in dune option would be an option to protect flooding from the ocean. In addition, with extreme sea level rise, a sluice will be required to protect the area from flooding from the bay side. (Photo: J. Aerts)

is $45 million/km without periodic beach nourishment to maintain the beach and the dune profile (Aerts *et al.*, 2013). Since the view of the hotels and restaurants on the boulevard was reduced by the increased dune height, hotel owners can develop temporary and easy to build/remove beach pavilions in front of the dunes during the summer (Fig. 5.6).

5.4 Protection of ports and harbors

The most common adaptation measure for ports is to periodically elevate their facilities to adjust for rising sea levels. This means, for example, that when retrofitting or rebuilding structures, additional fill or piles can be used to elevate structures on piers and docks. With elevation of buildings and piers, bulkheads must be elevated and reinforced as well. Other adaption measures include upgrading and elevating jetties and breakwaters to allow safe entrance of vessels into the harbor. Finally, additional measures may further protect a port from coastal storm surges, such as levees and a sluice at the entrance of a harbor. A sluice, however, is not often used for large ports as it may slow shipping movements, and cause economic damage through delays. We here discuss the following adaptation measures that pertain to marinas and ports: elevation, upgrading breakwaters, and a sluice.

Breakwaters. Offshore, mostly attached, breakwaters are above-water structures parallel to the shore, which reduce wave heights and provide shelter for a harbor. They prevent sediment deposition in the entrance channel of a port and erosion in the harbor. Detached breakwaters (e.g. the Santa Monica Breakwater) are constructed away from the shore and designed to promote beach deposition on their leeside. There are three main types of breakwaters: (a) rubble mound breakwaters, which consist of a core of small rocks covered with large rocks or concrete elements; (b) vertical wall breakwaters, which are filled with concrete blocks or sand; and (c) vertical composite breakwaters, which are concrete structures founded on rubble substructures where the caissons (or concrete blocks) are placed on a high rubble foundation. Sea level rise will increase overtopping of breakwaters and reduce their ability to mitigate wave energy in the sheltered port region. Tutuarima and d'Angremond (1998) suggest that for water depths larger than 8–10 m (24—30 ft), caisson types of breakwaters are more cost effective than rubble-mound breakwaters due to increasing volumes of rocks at the base of the rubble mound types. However, the composite breakwaters are more cost effective at depths over 20 m (60 ft), as the increased heights of the caissons require additional base widths (Tutuarima and d'Angremond, 1998).

Table 5.6 summarizes the most important breakwaters in the Los Angeles area. In the 1930s, The *Santa Monica Breakwater* was developed, to safely dock boats in the Santa Monica Yacht Harbor (now closed), and to protect Santa Monica Pier. However, the breakwater was poorly engineered and gradually sank into the water (WT, 2017) and today is almost completely submerged. The *Marina Del Rey breakwater* was built in 1963 to protect the new marina. The *King Harbor Breakwater* consists of north and south parts. A 2.7 m (8 ft), 260 m (1,020 ft) long seawall was added to the northern end of the north breakwater in 1962 by the City of Redondo Beach. *The Port of LA/Long Beach Federal Breakwater* consists of three parts that are between 1.7–3.8 km (1.1–2.4 miles). The entire breakwater is managed by the USACE and has a $0.5 billion replacement value ($0.06 million/m) (Grifman, *et al.*, 2013). The breakwater is more than 17 m (50 ft) deep in some locations (PTE, 2013). An assumption is made here that breakwaters can be regularly maintained and upgraded to keep up with sea level rise.

Ports of Los Angeles and Long Beach. The Ports of Los Angeles and Long Beach (Ports of LA and LB) regularly assess their vulnerable infrastructure such as on Piers S and D, and under more extreme conditions also parts of Pier A (Port of Long Beach, 2014). The ports regularly maintain levees and protective measures such as pumps, although some of those measures need upgrades. Therefore, recent reports discuss different options such as temporary 3 ft high inflatable Tiger dam installation or re-enforcing an existing cantilever flood wall to +10 ft (Port of Long Beach, 2014). Other measures include elevating critical assets such as Fire Station #24 and the Pier S Southern California Edison (SCE) electrical substation.

In order to make sure new buildings and piers address future sea level rise, the Ports of LA and LB propose to add sea level rise analysis to the Harbor Development permit (Port of Long Beach, 2014). This means that all proposed developments that apply for permitting must show they are protected against sea level rise. For new piers, the simplest route for adaptation is to ensure the new facility is elevated to appropriate heights. As an example, the newest, Pier S, was raised to an elevation of 6 m (+20 ft). The Pier measures 484–590 acre; about 58 million cy of dredged sediment from the harbor flood was used to fill the Pier in two stages between 1994 and 1997 (LAT, 2002; SW, 2000). Eleven million tons of rock were used to create dikes, which protect the perimeter of the Pier. The cost for the fill is estimated at $338 million (yr 2000 value) and total development costs amount to $900 million (SW, 2000; SK, 2017). Several environmental programs were associated with the development of Pier 400, such as the restoration of lagoons and wetlands in the region.

5.5 Stormwater control and pumping

The Los Angeles County Flood Control Act was adopted in 1915, to provide flood risk management and water conservation. Floodwater management is coordinated by the County of Los Angeles Department of Public Works (LADPW). This department is responsible for all drainage infrastructure within Los Angeles County, which includes 14 major flood control dams and reservoirs, 162 debris basins, 36 sediment placement sites, 500 miles of open channel, 2,800 miles of underground storm drains, 120,000 catch basins, 62 pump stations, 3 seawater barrier projects, 27 spreading facilities, and 21 low flow diversions.

Stormwater drainage channels: Most areas in LA rely on the gravity flow of stormwater discharge through stormwater drainage channels. Maintenance of these channels typically consists of trash removal, clearing of vegetation, and removal of sediment from concrete channels. Maintenance costs are high, costing the County nearly $500,000 per year for the Dominguez Channel, Wilmington Drain, and the Torrance drainage area (LA County, 2004). If drainage pipes are situated at or slightly above sea levels, valves can be used to prevent backflow; for example, to prevent seawater from entering drainage channels, the City of Newport Beach installed a valve system on Balboa Island and the bay side of the peninsula to keep storm drains from backing up with too much water. For all low-lying areas in LA county (Venice, San Pedro/Wilmington, Long Beach, Naples), increased pumping capacity will be needed to mitigate losses from extreme precipitation under future climate change. A new pumping station such as the Boone-Olive low flow diversion pump in the Marine Del Rey area costs approximately $200,000 (LA County, 2005).

Table 5.7. **Costs of one foot of elevation of new buildings with a pile or masonry pier foundation in US$/ft^2 of building footprint (Adapted from Aerts *et al.*, 2013; 2010 $ values)**

Type of building	Cost in US$/ft^2 of building footprint A Zone (average quality house)	Cost in US$/ft^2 of building footprint Coastal A Zone (good quality house)	Cost in US$/ft^2 of building footprint V Zone (very good quality house)
30 × 50, 1-story, 1,500 sf.	0.17−0.33	0.23−0.45	0.27−0.54
30 × 50, 2-story, 3,000 sf.	0.28−0.57	0.39−0.78	0.50−1.00
40 × 60, 1-story, 2,400 sf.	0.15−0.31	0.21−0.42	0.25−0.50
40 × 60, 2-story, 4,800 sf.	0.26−0.52	0.36−0.73	0.47−0.94

Spreading grounds/green infrastructure: Los Angeles shows strong interest in pursuing green solutions to stormwater runoff. This is part of LADWP's Stormwater Capture Master Plan, which aims to (1) reduce the city's reliance on imported water and (2) increase local stormwater capture through low impact development projects (LID) to store 150,000 acre-ft of rainwater per year by 2035. These LID projects include green parks or wetland areas (also referred to as 'spreading grounds') that can clean water from pollutants and store stormwater. The City of LA has currently developed 27 spreading grounds; for example, the Los Angeles River Park project offers public space for recreation and captures water for stormwater management. Another project is the South Los Angeles Wetlands Park, which can store 680,000 gallons of stormwater per day. The Stormwater Capture Master Plan aims to save 74,600–152,500 acre-feet of imported water per year by 2030 (Economides, 2014).

Levees along main channels and rivers: In some areas, roads can be elevated as an adaptation strategy to protect the land behind them from coastal flooding (e.g. W. Harry Bridges Blvd. and Anaheim St. in Wilmington). However, peak discharges from rivers and channels that cross these roads and still have a connection to the ocean, such as the Dominguez Channel, may still flood the area. Therefore, the levees for each of these channels must be heightened as well, starting at the point where they connect to the port or sea, and then a few miles landward. The cost for heightening levees is listed in Table 5.5, Section 5.2.

Table 5.8. **Costs of 1 ft of elevation of new buildings with a masonry wall foundation in US$/ft^2 of building footprint (Adapted from Aerts *et al.*, 2013; 2010 $ values)**

Type of building	Cost in US$/ft2 of building footprint A Zone (average quality house)	Cost in US$/ft2 of building footprint Coastal A Zone (good quality house)
30 × 50, 1-story, 1,500 sf.	0.53−1.00	0.72−1.35
30 × 50, 2-story, 3,000 sf.	0.91−1.70	1.25−2.34
40 × 60, 1-story, 2,400 sf.	0.49−0.92	0.67−1.26
40 × 60, 2-story, 4,800 sf.	0.84−1.57	1.16−2.18

5.6 Salt-water intrusion

Since 1995, salt-water intrusion has been mitigated by injecting up to five million gallons of purified, recycled water per day into the groundwater (WBMWD, 2006). These injection costs will be significantly reduced by raising groundwater elevations and using recycled water. The percentage of purified recycled water has increased from 50% to currently 75% (12.5 million gallons per day) and will increase to 100% (17.5 million gallons per day) in the near future (Johnson, PC; May 2017). Through increasing the use of recycled water, the use of imported water may be reduced and eventually eliminated, potentially decreasing the cost of maintaining the salt-water barrier (230 wells) to approximately $575,000 per year (Johnson, 2007). However, this potential solution is at odds with an ever-increasing population and water demand, where future costs of

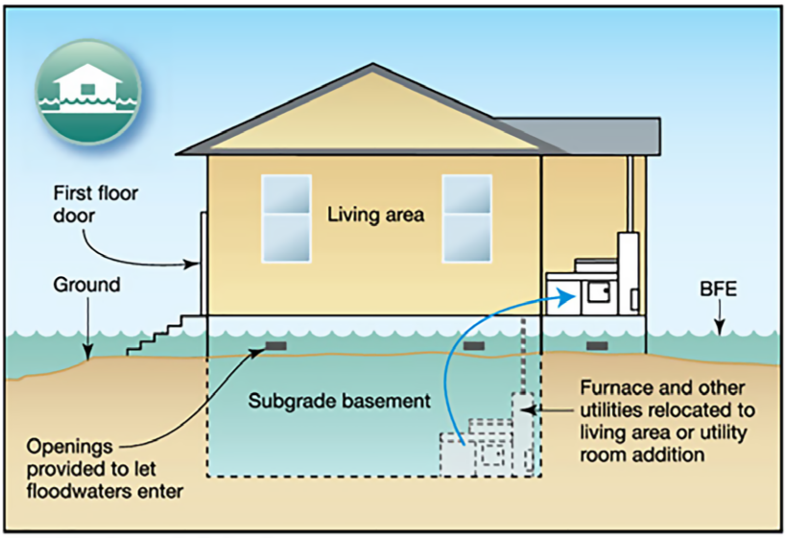

Figure 5.8. Schematic representation of wet flood-proofing measures (Source: FEMA, 2009b).

water needed by the barrier systems competes with providing water for a larger population. In 2016, a total of $26.9 million was spent on water injections, of which $8.5 million was for imported potable water ($1400/af) and $18.4 million was for recycled water ($800/af; Johnson PC, May 2017). The impact of increased pumping to meet water demands and the impacts of sea level rise will require additional injection and/or additional wells. The current cost of new injection wells is approximately $1 million each (Johnson, PC, May 2017).

5.7 Managed retreat

As the sea continues to rise and the coast continues to erode, some coastal communities will also need to consider managed retreat. To date, this option has been seldom utilized, but there are several important examples. The first is an area in Seaside, California, in which high erosion rates (> 8 ft/yr–244 cm/yr) threatened buildings. The Fort Ord soldier's club in Seaside (Stillwell Hall), California, "was torn down in 2004 because the cost of both coastal armoring and relocating were too high" (NOAA, 2005). The City of Pacifica is another example of retreat in a municipality that, in partnership with a non-profit organization and the California Coastal Conservancy, purchased two homes and surrounding land that were vulnerable to flooding. The homes were purchased for $2.2 million and demolished, after which 4,000 cubic acres of sand was brought in to rebuild dunes and restore the beach (NOAA, 2007).

Retreat does not necessarily have to be induced by government action, and over time, real-estate market dynamics may lead to "voluntary" retreat (Hauer *et al.*, 2015; HR, 2017). Future sea level rise may further spark the discussion about retreat options between property owners, since the boundary between public tidelands and privately owned uplands may shift landward because of sea level rise. This boundary is currently marked by the mean high water mark: the mean high tide line (APA, 2017).

5.8 Flood-proofing buildings

As explained in Section 3.1, Los Angeles building codes generally follow the standard FEMA/NFIP building code guidelines. In this section, we discuss three main flood-proofing measures that can be implemented to comply, or go beyond, the NFIP regulations: (a) elevation of new buildings, (b) wet flood-proofing (Fig. 5.8), and (c) dry flood-proofing (Fig. 5.9). These measures align with building code guidelines provided by LADBS (2014). Elevation of existing buildings is only applicable to buildings that are not too large to be lifted and, as Table 5.7 shows, is not applied to large apartment blocks and commercial building types in this study. Wet and dry flood-proofing of existing buildings can be applied

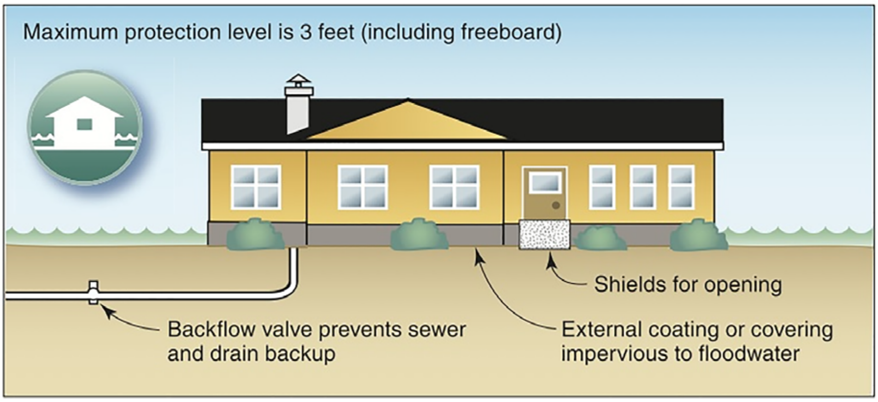

Figure 5.9. Example of a dry flood–proofed building (Source: FEMA, 2009b).

to all building types, but according to the LA County building codes, dry flood-proofing is not allowed in FEMA V-zones. In the case of existing buildings, the level of implementation of one of the three measures implies that the measure will be applied +2 ft, +4 ft, or +6 ft in addition to the current base floor height of the building. For new buildings, the FEMA base flood elevation (BFE) is used as a reference for elevation, and dry and wet flood-proofing. The BFE is the elevation of the 1/100 flood levels provided by FEMA. Many of the cost estimates presented below are compiled from a study into the cost of climate adaptation for New York City (Aerts *et al.*, 2013).

Elevation of new buildings. Jones *et al.* (2006) estimated the costs of adding freeboard (elevation above BFE) to the construction of new buildings for different foundations types, and expressed these costs as a percentage of total building costs. Costs vary according to the different types of building material and foundations: (a) the costs of adding freeboard for pile and masonry pier foundations range between 0.25–0.5% per foot of freeboard, (b) the costs of adding freeboard for masonry wall foundations range between 0.8–1.5% per foot of freeboard, and (c) the costs of adding freeboard for slab on fill foundations range between 0.8%–3% per foot of freeboard. These cost estimates can be translated to costs/ft^2 of the building footprint using the total building costs for four types of buildings that are constructed in the A zone with either average or good quality materials, and for one- or two-story buildings. In V zones, buildings with very good quality materials are listed, as they must withstand wave impacts (Jones *et al.*, 2006; p. 32). These results are shown in Tables 5.7 to 5.9.

Table 5.9. Costs of 1 ft of elevation of new buildings with a fill foundation in US$/ft^2 of building footprint (Adapted from Aerts *et al.*, 2013; 2010 $ values)

Type of building	Cost in US$/ft^2 of building footprint A Zone (average quality house)	Cost in US$/ft^2 of building footprint Coastal A Zone (good quality house)
30 × 50, 1-story, 1,500 sf.	0.53–2.00	0.72–2.70
30 × 50, 2-story, 3,000 sf.	0.90–3.40	1.25–4.68
40 × 60, 1-story, 2,400 sf.	0.49–1.84	0.67–2.51
40 × 60, 2-story, 4,800 sf.	0.84–3.15	1.16–4.37

Elevation of existing buildings. For elevation of existing buildings, the entire house is lifted including the base floor. This method involves separating a house from its foundation, raising the house and temporarily supporting it, and creating a new foundation or extending foundation below (Aerts *et al.*, 2013). The new foundation consists of continuous walls, separate piers, posts, columns, or piles. If houses are built without a basement or open foundation, but instead have a slab foundation, then both the house and the slab can be lifted (for more details see FEMA (2009b). Table 5.10 shows the costs of elevating different existing building types, as reported in FEMA (2009b). These costs include extending

Table 5.10. Costs of elevating an existing building (Adapted from Aerts *et al.*, 2013; 2010 $ values)

Construction type and foundation	Cost in US$/ft^2 of the building footprint 2 ft elevation	Cost in US$/ft^2 of the building footprint 4 ft elevation	Cost in US$/ft^2 of the building footprint 8 ft elevation
Frame construction with a basement or crawlspace	$29	$32	$37
Frame construction with a slab-on-grade	$80	$83	$88
Masonry construction with a basement or crawlspace	$60	$63	$68
Masonry construction with a slab-on-grade	$88	$91	$96

Source: FEMA (2009b).

Table 5.11. Average costs per building of elevating existing buildings in LA floodplains for building classes RES1, RES2, RES3A, and RES3B (see Appendix E), using FEMA (2009b) cost estimates (left columns) and scaled-up estimates that reflect higher LA construction costs (right columns; Adapted from Aerts *et al.*, 2013; 2010 $ values)

	Costs based on FEMA per building category				Costs scaled-up for LA per building category			
Elevation level	RES1	RES2	RES3A	RES3B	RES1	RES2	RES3A	RES3B
+2 ft	$33,239	$40,550	$41,337	$62,029	$37,560	$45,822	$46,711	$70,093
+4 ft	$35,464	$43,499	$43,861	$65,816	$40,074	$49,154	$49,563	$74,372
+6 ft	$37,319	$45,958	$45,964	$68,971	$42,170	$51,933	$51,939	$77,937

Table 5.12. Costs of wet flood-proofing buildings per foot of wet flood-proofing height (Adapted from Aerts *et al.*, 2013; 2010 $ values)

Existing foundation of a frame or masonry building	Cost in US$/ft^2 of the building footprint 2 ft above basement floor or LAG[a]	Cost in US$/ft^2 of the building footprint 4 ft above basement floor or LAG[a]	Cost in US$/ft^2 of the building footprint 8 ft above basement floor or LAG[a]
Basement	$2.90	$6.00	$17.00
Crawlspace	$2.20	$5.60	Not available

Notes: In 2009 US$ values. [a]LAG = Lowest Adjacent Grade.

utilities and adding or extending staircases. If the house has a slab foundation, then it is assumed that it is raised along with the house. A distinction is made between elevation costs for houses with and without a basement or crawlspace because elevation costs are higher for houses with a slab-on-grade. Moreover, a distinction is made between the elevation of frame construction and that of masonry construction, since elevation costs are higher for masonry construction.

Table 5.11 shows the average elevation costs of existing buildings for three main HAZUS building classes: single-family dwellings (RES1), manufactured housing (RES2), and duplex housing (RES3A) and triples/quads housing (RES3B), using numbers from FEMA (2009a) for the USA. These numbers were scaled up with a factor 1.13 to reflect higher LA construction costs compared with the USA average (see Aerts *et al.*, 2013).[a] The increased costs per residential building class can be explained by the higher average building footprint of these categories. The estimates in Table 5.11 are within the range $30,000-$88,000, which represents the costs of actual projects

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[a] This is based on the Construction Cost Index by Metro Denver Economic Development Cooperation: see https://www.metrodenver.org/d/m/3PA. Note that New York City construction costs reported in Aerts *et al.* (2013) are 30% above the USA average, while this is 13% for LA.

Table 5.13. Average costs per building of wet flood-proofing houses in LA flood-zones for building classes RES1, RES2, RES3A, and RES3B, using FEMA (2009) cost estimates (left columns), and scaled-up estimates that reflect higher LA construction costs (right columns; Adapted from Aerts *et al.*, 2013; 2010 $ values)

Wet flood-	Costs based on FEMA per building category				Costs scaled-up for LA per building category			
proofing level	RES1	RES2	RES3A	RES3B	RES1	RES2	RES3A	RES3B
+2 ft	$2,151	$2,851	$2,440	$3,661	$2,861	$3,792	$3,245	$4,869
+4 ft	$4,451	$5,900	$5,047	$7,574	$5,920	$7,846	$6,713	$10,073
+6 ft	$8,531	$11,307	$9,674	$14,517	$11,346	$15,039	$12,867	$19,307

Table 5.14. Approximate costs of elements of a dry flood-proofing project (Adapted from Aerts *et al.*, 2013; 2010 $) values)

Type of dry flood-proofing measure	Costs are expressed per	Cost in US$
Sprayed-on cement (above grade)[a]	Linear foot of wall covered	$16.80
Waterproof membrane (above grade)[a]	Linear foot of wall covered	$5.70
Asphalt (two coats on foundation up to 2 feet below grade)	Linear foot of wall covered	$12.00
Drainage line around perimeter of the house	Linear foot	$31
Plumbing check valve	Each	$1,060
Sump and sump pump (with backup battery)	Lump sum	$1,710
Metal flood shield	Linear foot of shield surface	$375
Wooden flood shield	Linear foot of shield surface	$117

Notes: [a]Cement, membrane and asphalt are alternative sealant methods (Source: FEMA, 2009b).

to elevate existing buildings, as reported by Jones *et al.* (2006).

Wet flood-proofing. Wet flood-proofing is a measure that allows floodwater to enter a house, causing only minimal damage to the structure and its contents (Fig. 5.8). This minimizes the risk that the walls of the house will collapse because of the hydrostatic pressure from rising floodwaters on the outside. Measures include, for example, building utility installations and high-value areas above flood levels; walls should be built using water-resistant building materials.

Table 5.12 shows the costs of wet flood-proofing buildings using estimates by FEMA (2009b). These include adding wall openings for the entry and exit of floodwaters, installing pumps, and relocating utility systems. The cost estimates are applicable to frame and masonry types of buildings and are provided for wet flood-proofing of up to +2 ft, +4 ft, and +8 ft. The additional costs of applying water materials to walls is not included, since it is assumed that wet-proofing measures are only implemented when a building is substantially renovated and materials must be replaced anyway.

Table 5.13 shows the average wet flood-proofing costs of existing buildings for three main housing types: single-family dwellings (RES1), manufactured housing (RES2), and duplex housing (RES3A) and triples/quads housing (RES3B), using estimates from FEMA (2009b) for the USA. The Table 5.13 results include the same scaling factor of 1.13 to represent higher LA construction costs.

Dry flood-proofing. Dry flood-proofing measures aim to seal a building up to a certain height, making it watertight, such that floodwaters cannot enter (FEMA, 2009b). Figure 5.9 shows an example of a dry flood-proofed building. Measures include sealing walls with waterproof coatings, impermeable membranes, or supplemental layers of masonry or concrete. Doors and other openings must be protected by permanent or removable flood shields. Backflow valves must be installed in sewer lines and drains to prevent floodwaters from entering the building via the sewer system. Dry flood-proofing is not allowed in V-Zones where waves may impact the building, and it may not be effective during

Table 5.15. **Average costs per building of dry flood-proofing houses in LA flood zones up to 2 ft, 4 ft, and 6 ft for building classes RES1, RES2, RES3A, and RES3B, using FEMA (2009b) cost estimates (left columns), and scaled-up estimates that reflect higher LA construction costs (right columns; Adapted from Aerts *et al.*, 2013; 2010 $)**

Dry flood-proofing level	Costs based on FEMA per building category				Costs scaled-up for LA per building category			
	RES1	RES2	RES3A	RES3B	RES1	RES2	RES3A	RES3B
+2 ft	$8,290	$9,286	$8,717	$10,294	$9,368	$10,493	$9,850	$11,632
+4 ft	$10,433	$11,753	$10,999	$13,089	$11,789	$13,281	$12,429	$14,791
+6 ft	$12,576	$14,220	$13,281	$15,884	$14,211	$16,069	$15,008	$17,949

high flood depths. In both conditions, pressure on the walls of the building may cause the building to collapse. Therefore, FEMA (2009b) advises that dry flood-proofing should only be applied up to a flood depth of 3 ft.

Table 5.14 shows the average costs of dry flood-proofing houses up to a level of 3 ft (FEMA, 2009b). The total costs per house will depend on the size of the house, the depth of floodwaters for which the dry-proofing is implemented, the types of sealants and shield materials that are used, the number of plumbing lines that must be protected, and the number of door openings that need to be covered by shields. Table 5.15 shows the average dry flood-proofing costs for four main FEMA residential building classes in LA for 2 ft, 4 ft, and 6 ft.

6. Adaptation Pathways and Costs

This chapter describes how individual adaptation measures can be grouped into different flood adaptation pathways to provide a basis for decision-making for adaptation in Los Angeles. An adaptation pathway in this study is defined as the collection of measures (flood-proofing, zoning, barriers, levees, etc.) that is needed to lower flood risk (Aerts *et al.*, 2013). The adaptation pathways discussed here were partly developed through a series of bilateral expert consultations and seminars with stakeholders in 2015, 2016, and 2017. During these meetings, the aim was to explore measures that reduce flood risk, defined as a combination of the flood hazard, exposure of people and assets, and their vulnerability.

The term *adaptation pathways* anticipates the uncertainty inherent in current sea level rise projections (see Section 2). Estimates of sea level rise by the IPCC AR5 (2014) are lower than previous estimates, and project between 0.3-0.9 m (1—2.8 ft) of sea level rise by the year 2100, reflecting the higher end of the National Research Council (NRC) (2012) sea level rise projections for California. However, the rate at which sea level rise will develop is dependent upon many factors, such as the melting rate of large parts of the Antarctic and Greenland ice sheets. Recent studies of California, for example, indicate that sea level rise could reach +3 m (+10 ft) by the end of this century if the ice sheets melt rapidly (Griggs *et al.*, 2017). Therefore, long-term adaptation planning against uncertain future flood risk is complex and could result in suboptimal, irreversible choices. Hence, following research by Noble (2016) and Haasnoot *et al.* (2011), different adaptation pathways were developed that anticipate different rates of sea level rise until 2100: +1 ft, +3 ft, and +7 ft. Over time, more information will become available to gauge the rate of sea level rise and whether it will become necessary to adjust the selected adaptation pathway of +1 ft (The lower bound of SLR projections) to another pathway. Note that we have not quantitatively assessed the effectiveness of individual measures, nor have we assessed cost and benefits of the presented adaptation pathways. These activities will be analyzed in a follow-up study.

A variety of individual measures is presented in Section 5. Much of the coastline of Los Angeles consists of sandy beaches, which are important for both recreation and flood protection. Therefore, each of the proposed adaptation pathways includes measures, such as dune restoration and periodic beach nourishment, that aim to maintain these beaches in their current form. These nature-based solutions aim to strengthen the protective power of beaches against flooding and enhance coastal ecosystems that lower flood risk. Nature-based solutions are also developed inland, where green parks and wetlands can lower peak discharges from rivers higher in the watershed that may flood low-lying coastal communities. Wetlands and green parks also increase fresh water recharge to groundwater resources, and therefore reduce the threat of increased pressure from salt intrusion through sea level rise. In some instances, however, nature-based solutions alone—such as beach nourishment—are insufficient over time, and additional technical engineering options, such as such as pump stations, levees, and sluices, may be needed to reduce flood risk. Such options are mostly targeted at lowering the probability of flood hazards and keeping the water from the city. In addition, some measures focus on lowering the vulnerability (or enhancing resilience) of assets and people in the Los Angeles coastal zone. This can be achieved by developing more stringent building codes and zoning regulations that promote flood-proofing of buildings, or relocating buildings in flood zones. The National Flood Insurance Program (NFIP) is an important element in this kind of decision making, insofar as it sets minimum requirements and building codes for the development of structures in low-lying flood zones. NFIP also covers residual risk, in case homeowners suffer from losses even though adaptation measures and building codes have been implemented.

By enhancing flexibility in (future-) adaptation policies, adjustments can be made towards other sea level rise scenarios. This requires careful forward planning; for example, zoning and spatial planning departments must integrate potential adaptation measures in their policies. Planning and implementing larger-scale measures (see Section 5) such as "dike in dune", sluices, or dune restoration may take years to decades. Hence, maintaining flexibility means reserving space for measures such as levees or dunes that might be required when sea level rise accelerates, and ensuring that alternative measures and sea level rise scenarios are addressed in ongoing policies. Reserving space is also necessary for setback policies and to ensure that new buildings are not developed near the edges of cliffs or on beaches.

The adaptation pathways described in this paper do not provide a complete overview of all possible measures, and some cost categories that pertain to these pathways were not assessed. For example, some issues, such as the economic valuation of environmental impacts, are not included, nor are the considerable administrative and planning costs associated with climate adaptation. These criteria were not quantified and must be considered in follow-up studies to derive a comprehensive assessment of the advantages and disadvantages of different flood management measures. However, the adaptation pathways outlined in this research provide a range of possible visions and their associated costs for flood risk management solutions for the Los Angeles region. The name *resilient pathway* refers to the option of leaving the coastal inlets and harbors open to coastal surge influence, and allowing a continuation of tidal influence. However, additional measures of such open pathway ensure the assets and people near the harbor/coastal inlets will be protected, hence the term *resilience.*

Short description of the adaptation pathways (Fig. 6.1).

- **Resilient pathway +0.3 m (1 ft)**: This pathway aims to retain the coastline in its current position, with open harbors and maintaining sandy beaches with beach nourishment. The proposed adaptation measures are largely a continuation of ongoing efforts in LA County, and a strengthening of current policies that aim to manage flood risk. Adaptation pathways for each of the five coastal regions consist of the following main policies, described in detail in Section 5: Beach nourishment; NFIP and flood proofing; Flood protection of critical infrastructure; enhancing stormwater management measures (pumps, levees); and some additional measures, such as wetland restoration and reducing salt-water intrusion.
- **Resilient pathway +0.3 m (1 ft) to +1 m (3 ft)**: In this pathway, a continuation of policies is required to remain the current coastline, with open harbors (*Resilient* pathway). However, because sea level rise advances, more beach nourishment and flood-proofing of buildings is required. Some measures probably become ineffective, and have to be modified (e.g., winter berms transformed into dune restoration). Preparations for a transition will be implemented (e.g., reserve space for levees).
- **Pathways +2 m (7 ft)**: If it appears that sea levels continue to increase to +2 m (+7 ft) in 2100, preparatory activities are needed to

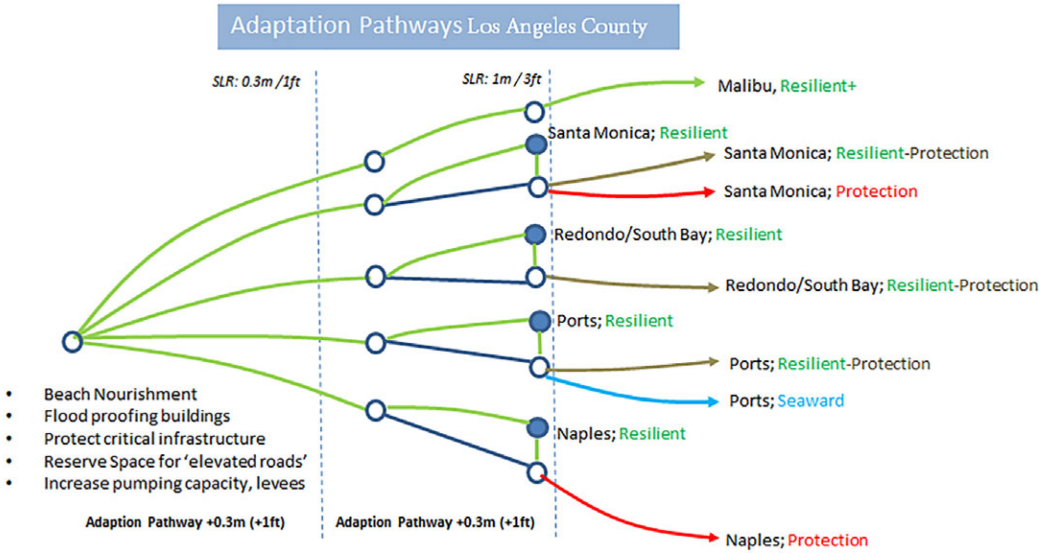

Figure 6.1. Adaptation pathways for the five coastal regions in Los Angeles.

advance from the *Resilient* pathway to facilitate a smooth transition into a different pathway. In such a scenario, the following pathways are suggested for the five coastal regions (Fig. 6.1):

- Adaptation Pathway **Seaward Ports**: In this pathway, the Ports of LA and LB will expand towards the ocean, using the perimeter of outer harbor breakwaters. The older—inland—port facilities will be transformed for residential use protected from ocean floods by a dam and a sluice.
- Adaptation Pathway **Resilient-Protection**: This pathway aims to have the Ports of LA and LB, Marina del Rey and Redondo/South-Bay all maintain open access to the ocean. Some low-lying (vulnerable) areas will need to be protected by both elevated roads acting as levees, and by re-enforced dunes.
- Adaptation Pathway **Protection**: In this pathway, Naples and Marina Del Rey may be closed with sluices. Vessels can still navigate to the ocean, but through a sluice complex.
- Adaptation Pathway **Malibu Resilient+**: Malibu will continue to elevate new buildings to > +7 ft in designated flood zones. However, retreat or relocation for some existing building to nearby higher ground will be necessary, since protection or elevation is not an option or proves too expensive. When assuming a SLR scenario of +2 m (7 ft), low-lying stretches of PCH need to be elevated or relocated landward.

6.1 Resilient pathway +0.3 m (+1 ft)

The +1 ft Resilient pathway is largely a continuation of ongoing efforts in LA County, strengthening current policies that manage flood risk. The aim is to keep the current coastline as it is, with open harbors, and to maintain sandy beaches with beach nourishment. Figure 6.2 shows different Resilient options for the five coastal regions.

Beach nourishment and dune preparation. Beaches are the primary defense against flooding for most of the coastline in LA County; rising sea levels will reduce their effectiveness as flood protection barriers. Thus, for all LA County regions, periodic beach nourishment constitutes the primary adaptation measure for managing coastal flood risk. This measure aims to maintain the current protective capacity of beaches by periodic nourishment and a continuation of the seasonal berm program (e.g.

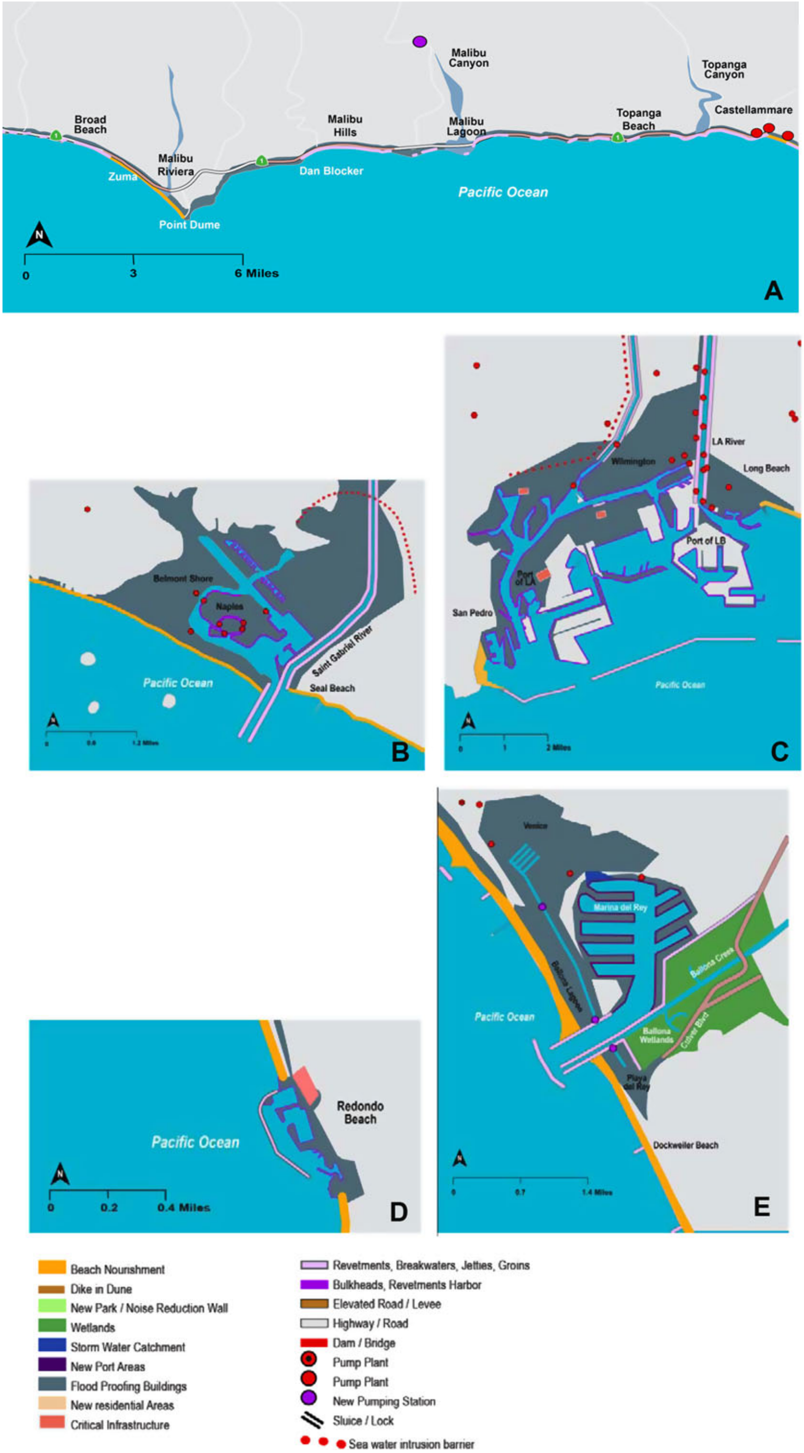

Figure 6.2. Adaptation pathway *Resilient* anticipating sea level rise from 0.3–1 m (1–3 ft). A. Malibu; B. Naples; C. Ports of Los Angeles and Long Beach; D. Redondo/South Bay; E. Santa Monica.

Noble 2016). Sea level rise and beach erosion will reduce beach width and therefore tourism revenue. By continuing to maintain beaches at their current shape and capacity, they can maintain current protective and recreational values. Existing groins should be strengthened to ensure stable beaches after nourishment activities. Research to assess the feasibility of long-term beach nourishment and the availability of offshore sand reserves will be required.

In order to already prepare for accelerated sea level rise, seasonal berm programs could be a stepping stone towards permanent dune restoration, including vegetation cover, on wider beaches (>45 m 150 ft) such as Dockweiler (Noble, 2016). This option also addresses the requests of some residents to reduce the noise produced by erecting annual winter berms. Dunes at the back end of beaches may provide additional sand reserves for nourishment, if in the future nourishment from offshore reserves becomes too costly. Dune restoration is already being addressed in several projects; for example, the Santa Monica Beach Restoration Project (Bay Foundation, 2017). Furthermore, residents are already used to seasonal berms during the winter, and a slow transition into dunes may be feasible considering the benefits: attractive beaches and enhanced protection against floods. Research is needed to assess the viability of dune restoration in terms of potential sediment supply, and to gauge impacts on communities (ocean views) and beach access.

Malibu, Palos Verdes, Peninsula Beach: Projections using different sea level rise scenarios for narrow beaches in Malibu (e.g. Broad Beach, Malibu Colony), Palos Verdes, and Peninsula Beach in Long Beach show these beaches will be largely lost, even under a low sea level rise scenario of +1−2 ft. For Malibu, releasing sand currently trapped in upstream reservoirs will probably not be sufficient to supply the required nourishment volumes. However, such release, along with additional groins, may extend the lifetime of some narrower beaches and provide for more time to plan future adaptation. Additional research is needed to assess to effectiveness of additional groins to extend the lifetime of these narrow beaches (Flick, 2013).

NFIP/flood-proofing. For some residential areas, beaches do not provide full protection against storm surges, extreme local precipitation, and peak discharges generated upstream. For those areas (e.g. Venice, Wilmington, Naples), flood-proofing and elevation of individual structures provide a secondary line of defense. The CoSMoS simulations show which areas are potentially vulnerable; however, these areas are not necessarily the same as flood zones identified by FEMA. FEMA flood zones are the official regulatory zones for which building codes and zoning regulations are enforced, and for which flood insurance is mandatory if a homeowner uses a federally backed mortgage. In this section, we apply flood zones identified by CoSMoS, since they provide the most recent future projections. In order to anticipate sea level rise, one proposal is to upgrade building codes with additional freeboard (measures that go beyond minimum FEMA requirements). Flood-proofing is suggested for all buildings within a 1/100 +50 cm sea level rise scenario flood zone. For those areas CoSMoS identifies that overlap with FEMA A-zones, dry flood-proofing is considered the most cost-efficient option. Thus, for Santa Monica/Venice, Wilmington, South Bay, and Naples, dry flood-proofing is suggested for existing buildings that can potentially be inundated during storm surge events but are not subject to wave impacts.

Malibu: For Malibu, and other coastal V zones, where it is expected that narrow beaches will disappear in the future and no longer offer protection, both existing and new buildings should be elevated. We recommend a proposed elevation of at least +4 ft for new buildings in the 1/100-year flood zone since additional elevation of +2 ft is relatively cheap and these buildings will have lifespans during which sea level rise will likely exceed +2 ft.

Naples: For Naples, upgrading buildings codes with additional freeboard—similar to Malibu—will be required, even under the lowest sea level rise scenarios. For Naples and the Alamitos Bay, flood-proofing measures will probably not mitigate all impacts from extreme sea level rise scenarios (+3 ft, +7 ft), we still recommend applying those upgrades to buy time to develop and implement alternative—larger scale—flood protection measures.

Critical infrastructure: ports, plants, and roads. As FEMA building codes only pertain to residential structures, additional flood protection measures are needed to protect (critical-) infrastructure such as ports, power plants and roads.

Harbors, Ports of LA and LB: Existing flood protection measures in ports should be upgraded by +1−2 ft, including all jetties and breakwaters at Marina Del Rey, Redondo Beach, Shoreline Marina (Long Beach), Naples, and the LA and LB ports complexes. Breakwaters and jetties are essential for marinas to break waves and mitigate storm surges, while groins reduce erosion on beaches. Port facilities, docks, and piers must be raised periodically, and their bulkheads require upgrading to maintain safety under sea level rise levels +2 ft. To reduce costs, the timing of those investments is best when new buildings or harbor facilities are developed. *Marina Del Rey, Redondo Beach* and *Wilmington* should start assessing the effectiveness of elevating roads surrounding ports and harbors, such that they can act as levees in the future, protecting low-lying areas such as Venice and Wilmington from higher sea levels.

Critical infrastructure: Critical infrastructure along the coast, such as the Hyperion wastewater treatment plant and El Segundo power plant, should assess, and possibly upgrade, their current defenses by +2 ft. As an alternative to investment in enhanced flood protection such as flood walls, we recommend that larger facilities conduct sea level rise vulnerability studies to determine whether it would be more efficient to relocate before the lifespan ends or to protect the facilities using structural protection measures. For example, if the Port of LA or LB expand and elevate piers and docks, those areas might be will be resilient to flooding than the current low-lying locations. Then, relocating the El Segundo plant and other infrastructure to the newly elevated LA/LB port areas might provide additional logistic and other economic benefits.

Malibu: Some stretches of the Pacific Coastal Highway (PCH) in Malibu (i.e. Dan Blocker County Beach and Malibu Lagoon to Will Rogers State Beach) are the most vulnerable to sea level rise. Assessment studies should be conducted to determine whether these stretches should be armored, elevated, or protected with nourished beaches or other measures to protect the highway from incoming waves (Fig. 6.3). A potential redevelopment of the highway along the lower lying stretch could be significantly more expensive if the current development of new buildings along PCH continues. Therefore, both the City of Malibu and Caltrans should jointly assess these critical stretches of PCH to gauge the effects from sea level rise (Flick, 2013). For those areas, new policies could prohibit the development of new structures adjacent to PCH in order to allow for smooth relocation if that becomes necessary. Such policies could be addressed in new zoning plans.

Palos Verdes: For the Palos Verdes' cliff region, continuous monitoring is needed to assess undermining and possible collapse of cliffs, leading to potential cliff retreat in the future. Enhancing the setback policy could be an option for all areas that suffer from cliff erosion near residential areas and roads.

Stormwater and groundwater management. To reduce effects from peak discharges and future flooding from higher in the watershed, future pumping capacity needs to be upgraded in low-lying areas (e.g. Venice, Wilmington). Furthermore, all levees along main channels that drain into the coastal zone (Dominguez Channel, LA River, San Gabriel River, etc.) need to be upgraded. This pertains to the lower stretches where the (tidal-) influence of the ocean affects water levels in the creeks. In addition, the three salt-water barrier projects must expand the number of injector wells to reduce increasing salt-water intrusion from sea level rise.

Ballona Wetlands, Ballona Lagoon. In addition to ongoing wetland restoration projects (BR, 2017; Jonhston *et al.*, 2015), further assessment is needed to determine whether the proposed plans do, or do not, enhance flood risk, and whether they affect nearby beaches because of enhanced sediment flows into the wetlands. Such a study could also assess the vulnerability of Culver Boulevard in its current position. While a wetland area with more tidal influence will enhance recreational and environmental values, it may also exacerbate flood risk for Playa Del Rey. Therefore, we recommend assessing flood risk (including sea level rise) to Playa del Rey if the levee system would allow seawater to enter the wetlands. Thorough analysis is also necessary to understand sediment availability for such a tidal area. Without additional future sediment supply, the wetland may drown when sea levels rise. In addition, a study is needed to assess whether beaches are impacted by the loss of sediment to the Ballona Tidal area.

To protect low-lying Venice, the tide gates of the Ballona Lagoon may have to be closed because of

Figure 6.3. Low-lying stretch of PCH in Malibu. Beach nourishment is an important option to protect residents and infrastructure located behind beaches. However, with extreme sea level rise scenarios, some beaches cannot be augmented with nourishment, and will lose their protective capacity. In such situations, PCH could be relocated to higher ground, or elevated with fill (Photo J. Aerts).

sea level rise, since draining the lagoon can no longer occur under gravity. This means the lagoon will no longer be tidally (salt water) influenced, and the tide gates will not function. In order to drain excessive storm water from the lagoon into the ocean, additional pumping capacity will be required (Fig. 6.4).

In summary, measures for Adaptation pathway *Resilient* (SLR +0.3 m [1 ft]) include:

- Beach nourishment to keep up with sea level rise of +1 ft, and transformation of the seasonal berm program into dune restoration;
- Flood-proofing of buildings in the 1/100 +50 cm sea level rise flood zone through dry flood-proofing or elevation of +2 ft up to +4 ft for new buildings;
- Elevation of port facilities with protection for critical infrastructure (+2 ft);

Figure 6.4. Venice. With rising sea levels, tidal influence will be reduced, and stormwater drainage into the ocean will be difficult. This means tide gates will be closed, and additional pumping capacity will be needed to drain stormwater into the ocean. (Photo J. Aerts).

- Preparation for long-term adaptation and reserve space along roads that may need to be elevated in the future;
- Increased pumping capacity in low-lying areas (Venice, Wilmington, Long Beach); increased number of wells in the three water barriers;
- Increase height of levees of the Dominguez Channel, San Gabriel River, and LA River in lower stretches with tidal influence on creek water levels;
- Increase setback policy for development near cliffs for areas near buildings and infrastructure;
- Assessment studies: PCH, Ballona Wetlands, Hyperion wastewater treatment plant, El Segundo power plant, and offshore sand reserves.

6.2 Resilient pathway up to +1 m (+3 ft)

The +3 ft Resilient pathway is a continuation of the +1 ft pathway. The focus remains on beach nourishment, and the current elevation of beaches along with rising sea levels will be continuously adjusted to maintain current strength and protection levels. The aim is to keep the current coastline as it is, with open harbors, and to maintain sandy beaches with beach nourishment. However, additional measures (on top of those mentioned under +1 ft sea level rise) are required to manage flood risk related to sea level rise of +3 ft.

Beach nourishment and dunes: We recommend expanding seasonal berm projects to other areas along the coast. Dune restoration projects could be developed in those areas where winter berms are implemented on a yearly basis.

Flood-proofing: FEMA flood zones should probably be reassessed to reflect the effects of sea level rise. In the 1/100 (+3 ft) flood zone, dry flood-proofing requirements will increase to probably +4 ft. This pertains to areas in Santa Monica/Venice, Wilmington, South Bay and Naples (Fig. 6.5). Malibu will need to continue elevating new buildings to +4 ft in designated flood zones. Over the long term, however, elevation of existing buildings may become too expensive, and retreat or relocation to nearby higher ground will be the only option.

Infrastructure: In terms of hard adaptation structures, existing breakwaters, jetties, and groins should be elevated to +4 ft to keep up with rising sea level. To maintain the efficiency of beaches, additional beach nourishment and dune restoration efforts should be supported. Protective structures for critical infrastructure, such as the Chevron Refinery or El Segundo Power plant, need to be upgraded to +4 ft, for flood walls or levees, by reinforcing existing structures or installing new ones. The low-lying stretches of PCH probably need to be elevated, or where feasible, relocated landward.

Other: The tidal gates between Ballona Lagoon and Ballona Creek probably have to be closed, since water levels in Ballona Creek will be permanently higher than those in the Lagoon and the connected Venice area. Because natural flushing of the lagoon area using tidal waters will no longer be possible, assessment studies are needed to ensure water quality in the lagoon and Venice will remain at EPA standards. In all low-lying areas (Venice, Wilmington, San Pedro, Long Beach) the capacity of pumping stations must be expanded compared to current levels. The number of wells for maintaining the saltwater barrier also need to be expanded. In addition, Dominguez Channel, San Gabriel River, and the LA river should increase flood walls to +4 ft.

In summary, measures for the Adaptation pathway *Resilient* (1 m [3 ft]) include:

- Continue beach nourishment to keep up with sea level rise;
- Dune restoration at sites where seasonal berms are currently constructed annually, and preparation of dune restoration in other locations with wide beaches;
- Flood-proofing of buildings in the 1/100 (+3 ft) flood zone, either by dry flood-proofing or elevation of +4 ft;
- Reinforcement of breakwaters, jetties, and groins (+4 ft);
- Start preparing to elevate roads around harbors, so they can act as levees for low lying communities;
- Elevate or relocate low lying stretches of PCH in Malibu;
- Increase pumping capacity in low-lying areas (Venice, Wilmington, Long Beach) and increase the number of wells for the three water barriers;
- Increase levees height for the Dominguez Channel, San Gabriel River, and LA River by +4 ft.

Figure 6.5. Buildings and bulkheads in Naples, Long Beach. Options for adaptation include dry and wet flood-proofing, or small flood walls where there is space. However, with accelerated sea level rise of +3-7 ft, the area will be permanently inundated, and additional flood protection is required, such as protecting the Bay area with a sluice. (Photo J. Aerts).

6.3 Adaption pathways up to +2 m (7 ft)

The adaptation pathways beyond 1 m/3 ft of sea level rise still rely heavily on flood-proofing buildings, beach nourishment and dune restoration. As in the previous pathways, the levees of the main channels (Dominguez Channel, LA River, San Gabriel River) should be further heightened to +7 ft, and pump capacity of low-lying areas (Venice, Wilmington, San Pedro, Long Beach) should be increased to prevent seepage or flooding because of under capacity of storm drains. Further, the number of wells for maintaining the salt-water barrier should be expanded, and preservation of existing conditions at San Pedro/Palos Verdes are needed, as well as sand retention structures at Cabrillo beach.

However, additional measures are required to cope with coastal storm impacts. Different combinations of measures are available, and these are compiled in various adaptation pathways: *Resilient+, Resilient—Protection, Protection, and Ports—Seaward.*

Malibu Resilient+. The Malibu resilient pathway basically continues with measures described under the Adaptation Pathway +3 ft (Figure 6.2). In this pathway, Malibu will continue to elevate new buildings to +7 ft in designated flood zones. Over the long term, however, elevation of existing buildings may become too expensive, and will likely need to be elevated, or where feasible, relocated landward.

Resilient—Protection. In this pathway, we suggest elevating roads around ports and marinas, so they serve as levees to protect low-lying residential areas behind them (Fig. 6.6), such as Venice and Wilmington. By combining the regular maintenance of roads with flood protection measures, costs can be efficiently allocated. Further, breakwaters and jetties should be elevated to maintain their efficiency (+7 ft). Port facilities and piers need to be elevated to +7 ft in the 1/100 +250 cm sea level rise zone, or if prohibitively expensive, be relocated.

(a) *Redondo/South Bay Resilient-Protection*: roads around the marina (e.g., W Torrance Blvd) could be elevated (+7 ft) to act as levees for nearby residential housing. Businesses in the marina (on the ocean side of the elevated road) should be elevated or relocated to higher areas.

(b) *Santa Monica Resilient—Protection*: The lower-lying parts of the roads around *Marina Del Rey* (Via Marina, Admiralty Way, Fiji Way) should elevated to +7 ft to act as levees. Santa Monica beaches might require additional reinforcement with levees underneath the beaches

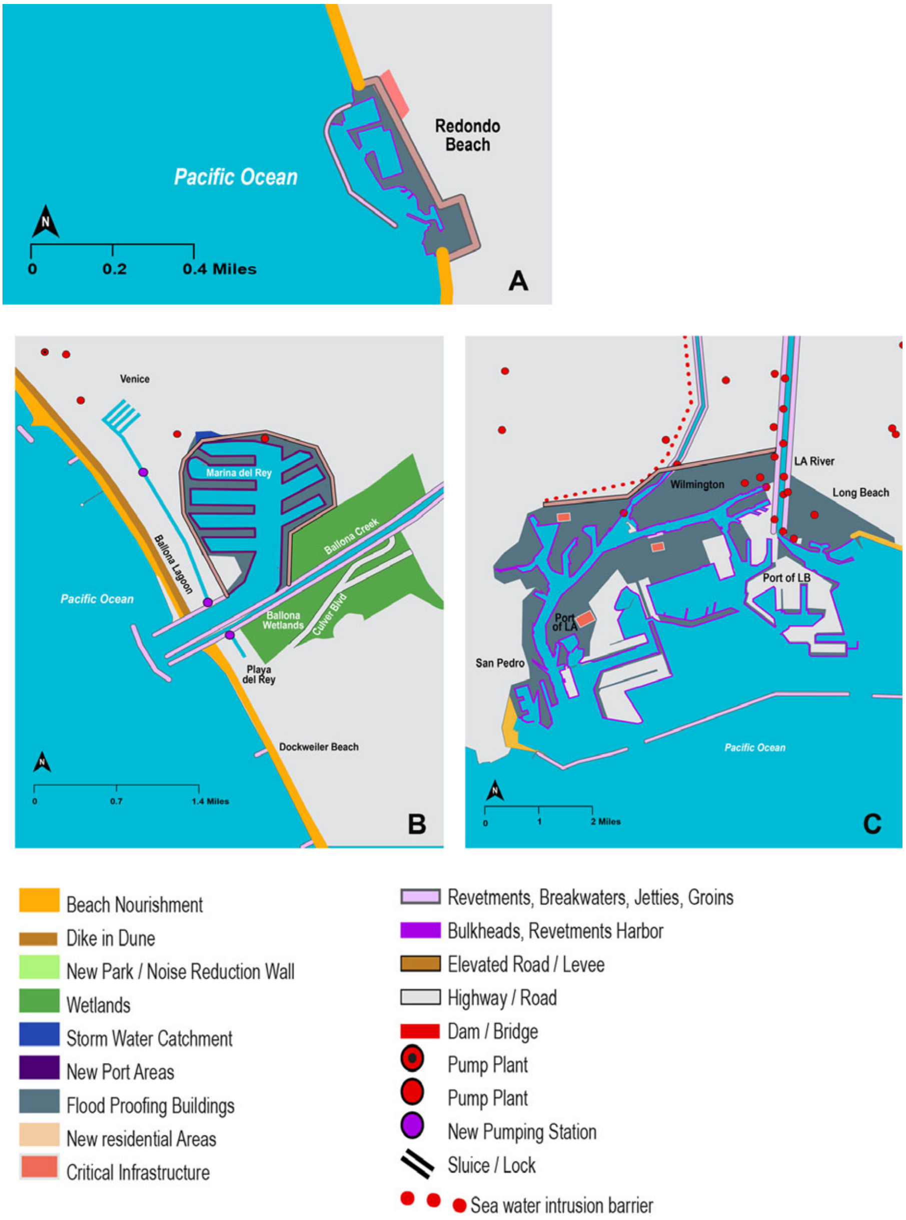

Figure 6.6. Adaptation Pathway *Resilient-Protection* for: A. Redondo/South Bay; B Santa Monica and C. The Ports of Los Angeles and Long Beach.

and dunes in locations where beach facilities such as parking lots are threatened (see Section 5). Parts of the beach (or dune) can be excavated and replaced by underground parking structures reinforced by levees on the ocean side.

(c) *Ports Resilient—Protection*: Elevating roads to serve as levees to protect low-lying areas in *Wilmington* (e.g. W Harry Bridges Blvd and E Anaheim St).

Protection. There are three adaptation pathways that include enhanced coastal engineering measures to protect areas against flooding under a +7 ft (+2 m) sea level rise scenario:

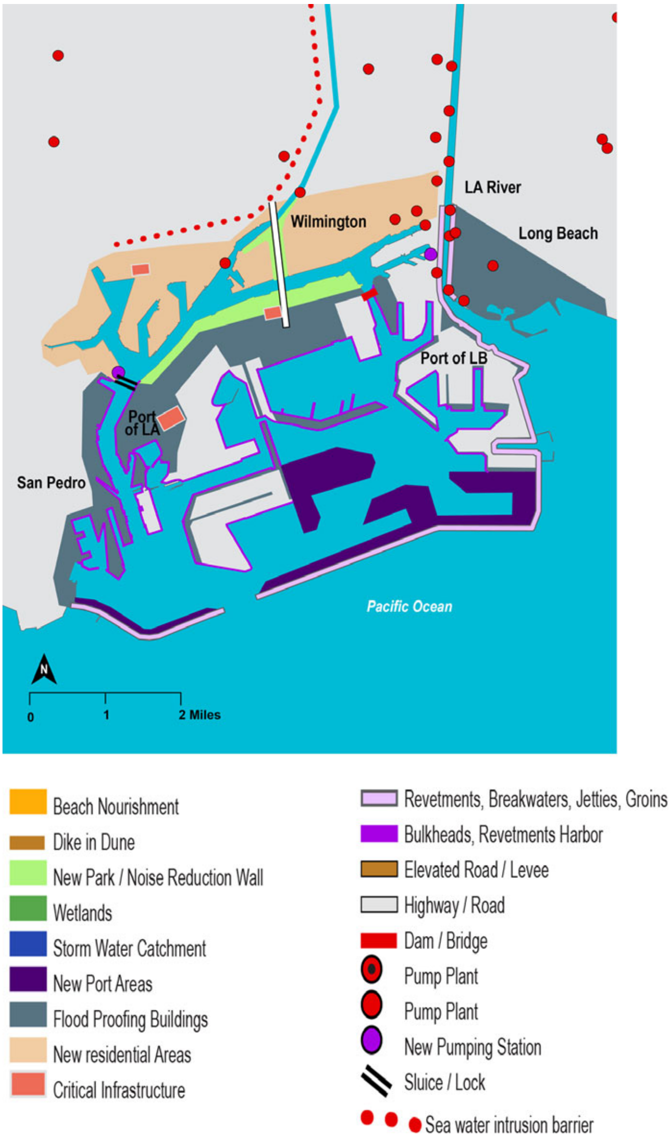

Figure 6.7. Adaptation Pathway *Seaward Ports*: Following the examples from Hamburg (Germany) and Rotterdam (the Netherlands, Appendix M), the Ports of Los Angeles and Long Beach could expand towards the outer breakwater with new elevated piers that accommodate sea level rise. The old piers would be transformed into residential areas protected against flooding from the ocean by two dams.

- *Ports Seaward*: Following the international example of the Port of Rotterdam (Fig. 6.7; Appendix M), in this adaptation pathway, the Ports of LA and LB will expand towards the ocean with new elevated Piers, within the perimeter of the outer harbor breakwaters. The older—inland—port facilities would be transformed into residential uses, protected from ocean flooding by a dam and sluice (see Appendix L). Although these new residential areas would no longer be connected to the ocean, small vessels would still navigate to the ocean using the sluice complex. Between the ports and new residential areas, developed green parks and berms would provide opportunities for recreation and reduce noise from the ports, similar to the function of the existing Wilmington Park. These would provide

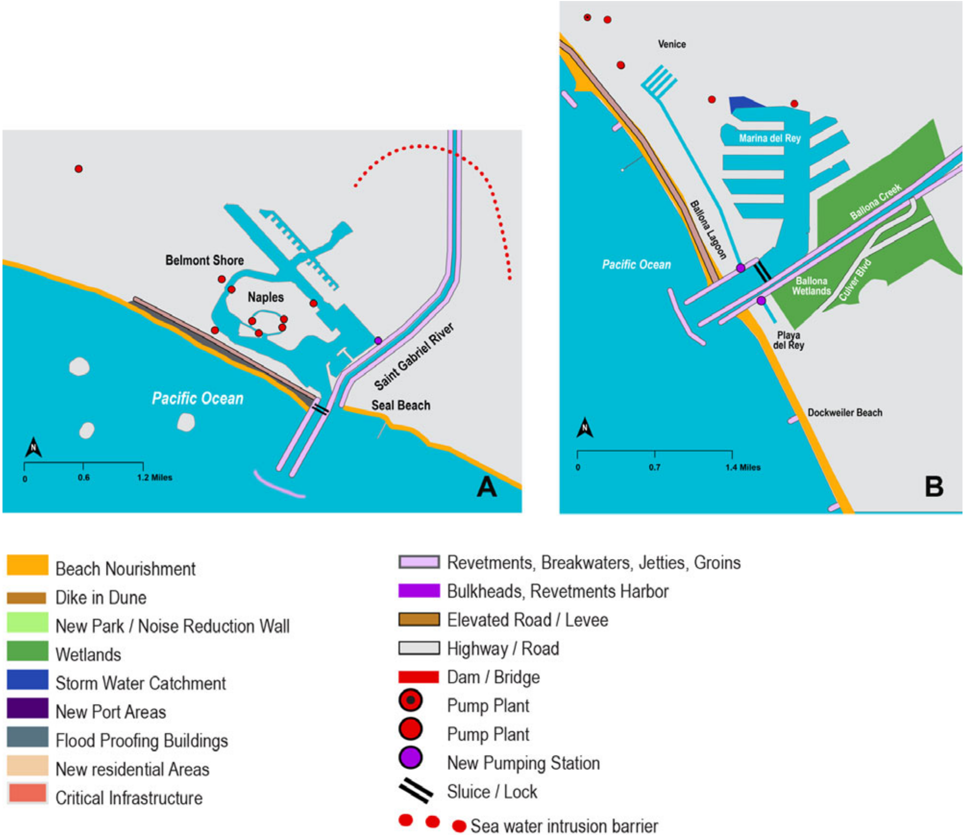

Figure 6.8. The pathway *Protection* involves developing sluices for Naples (A) and Marina del Rey (B).

green space along California routes 47 and 103 that serve as main transport lines from and to the ports. Two pumping stations can support water quality by regularly flushing, where one pumping station pumps water from the ocean into the now closed lagoon area, and the other pumping station pumps water out to the LA River. This would create a current to flush contaminated water. Expanding the ports with safe, elevated facilities also provides opportunities for new business, such as the relocation of vulnerable infrastructure (El Segundo, Chevron refinery). Using the cost for Pier 400 as a basis, the estimated cost of the new port facilities would be around $3.5 billion. Similar costs are probably associated with developing the residential area, but those costs will be paid by the new homeowners in the area.

- *Santa Monica protection (Marina de Rey)*: For the Marina Del harbor, the pathway Protection involves developing a sluice that protects the harbor from sea level rise (Fig. 6.8). A more detailed description of a sluice is provided in Appendix L. A sluice complex artificially maintains low water levels within the area protected by the sluice, while ocean levels outside the sluice complex may rise. With a sluice installed, Marina del Rey will still be functional as a recreational harbor, as vessels can navigate through the sluice gates. The low-lying areas behind the sluices would be protected from permanent inundation caused by high sea level rise scenarios. Measures are needed to control water quality in the harbor, since tidal influence with ocean water flushing is reduced.
- *Naples Protection*: The pathway Protection involves developing a sluice for Naples

Table 6.1. **Adaptation costs for the five different regions in LA County assuming two sea level rise scenarios of +3 ft (1 m) and +7 ft (2 m) ($2015 price level)**

Sea level rise scenario *Adaptation pathway*	**SLR 3 ft (1m)** *Resilience*	**SLR 7 ft (2m)** *Resilience-protection*	**SLR 7 ft (2m)** *Protection*
Malibu Resilient	$0.5 bn		
Malibu resilient +		0.7 bn	0.7 bn
Santa Monica Resilient	$0.6 bn		
Santa Monica Resilient-Protection		$1.2 bn	
Santa Monica Protection			$0.7 bn
Redondo/South Bay Resilient	$0.4 bn		
Redondo/South Bay Resilient-Protection		$0.9 bn	$0.8 bn
Naples Resilient	$1.4 bn		
Naples Protection		$0.7 bn	$0.7 bn
Sub-total (no Ports)	**$2.9 bn**	**$3.5 bn**	**$2.9 bn**
Ports of LA/LB Resilient	$1.4 bn		
Ports of LA/LB Resilient-Protection		$2.3 bn	
Ports of LA/LB Seaward			$3.5 bn
TOTAL (including Ports)	**$4.3 bn**	**$5.8 bn**	**$6.4 bn**

(Fig. 6.8). A more detailed description of a sluice is provided in Appendix L. A sluice complex artificially maintains low water levels within the area protected by the sluice, while ocean levels outside the sluice complex may rise. With a sluice installed, Naples will still be functional as a harbor, as vessels can navigate through the sluice gates. The low-lying areas behind the sluices, however, would be protected from permanent inundation caused by high sea level rise scenarios. In Naples, Peninsula beaches might require additional reinforcement by a levee under the beaches and dunes in locations where beach facilities such as parking lots are threatened (see Section 5). Part of the beach (or dune) is excavated and replaced by an underground parking structure that is reinforced by a levee on the ocean side. Furthermore, water quality in the Naples area might decrease if there is upstream pollution that accumulates in the marina after closing it off. To address water quality problems, a system of pumps and tidal gates may be needed to maintain flushing capacity of the Naples area and water quality standards.

6.4 *Costs of adaptation pathways*

This section provides cost estimates for the adaptation measures listed under each of the adaptation pathways in the previous sections. The calculations are based on the unit cost estimates provided in Chapter 5. The detailed cost estimations per measure can be found in Appendix N. Yearly maintenance cost can be estimated at roughly 0.1–1% of the investment cost (e.g., Jonkman *et al.*, 2013). Cost estimates are provided only for the sea-level rise (SLR) scenarios of +3 ft (1 m) and +7 ft (2 m), respectively. Total adaptation costs for the protection of LA County against SLR scenarios of +3 ft (1 m) and +7 ft (2 m) are shown in Table 6.1 and vary between $2.9 and 3.5bn, excluding the adaptation costs for the Ports of LA and LB. When including the adaptation costs for the ports, these numbers increase to $4.3–$6.4bn for SLR scenarios of +3 ft (1 m) and +7 ft (2 m), respectively.

These numbers show that a considerable investment is required for the Ports of LA and LB, equivalent to the total adaptation costs of the other four areas (Malibu, Santa Monica, Redondo/South Bay, and Naples). Results also show that the difference in adaptation costs between the SLR scenarios of 3 ft (1 m) and 7 ft (2 m) is significant, except for Malibu. This exception is due to the more expensive engineering measures (sluices, levees) suggested for the protection of Santa Monica, Redondo/South Bay, the Ports of LA and LB, and Naples. In Malibu, the type of measures (flood-proofing buildings, protecting the PCH, nourishment) are similar under the SLR scenarios of both 3 ft (1 m) and 7 ft (2 m).

For the Ports of LA and LB, the costs for adaptation are considerably higher under the SLR 7 ft (2 m) scenario ($2.3–$3.5 bn) than under the SLR 3 ft (1 m) scenario ($1.4 bn). This difference is due to additional measures that extend both the ports (by adding new piers) as well as to new protection measures such as sluices and dams intended to protect the residential areas of Wilmington. Note that by expanding the ports, not only are the costs higher but the economic benefits are probably also higher. For example, in the Seaward Ports pathway, benefits include not only lowered flood risk but also additional economic revenue from the expanded ports. These tradeoffs between adaptation cost and benefit should be addressed in further research.

Uncertainties and recommendations. The presented cost estimates are first-order calculations and some assumptions are surrounded with uncertainty. Future research and more detailed economic analyses, focusing on specific geographic areas, should increase the accuracy of the estimates provided in this report. The following issues provide recommendations to further refine cost estimates in future research (Aerts *et al.*, 2014):

- The estimates for dry/wet flood-proofing and the elevation of buildings apply to all existing buildings in the 1/100 flood-zone, for each SLR scenario. This results in high costs, as some (existing) buildings would require significant change, especially when elevating. However, the lifetime of these buildings may be exceeded when adaptation becomes necessary. In other words, some buildings will be rebuilt anyway, before adaptation is needed, and in such cases adaptation costs are relatively minor compared to the construction cost of a new building. Future research could address the effects of adding building lifespan to costs estimates for dry/wet flood-proofing or elevation.
- The presented cost estimates are probably an underestimation of the total cost, since not all adaptation measures have been included in the analyses. For example, the cost of retreat and setbacks have not been valued in the investment cost.
- Adaptation measures have been targeted to reducing flood risk. Future research could assess both the positive and negative effects of measures for other issues such as environmental values, coastal erosion, or the effects (positive and negative) on tourism.
- Beach nourishment: We have applied a conservative cost/cy of sand of $15/cy. The required volumes of sand are estimated using Ewing and Flick (2011), for different SLR scenario curves up until 2100 (3—7 ft), and for different public beach lengths (Zuma, Point Dume, Santa Monica, Venice, Dockweiler, Manhattan, Hermosa, Redondo, Torrance, Cabrillo, and Long Beach). For these beach stretches, the required volumes (cy) are estimated, and multiplied by $15. In practice, however, not the full required nourishment volume will be applied at one point in time, but will be spread out gradually over time. Especially with the expected increase of future erosion, and a more rapid SLR pace, a significant share of sand will be required in the relatively distant future (~40—50 years from now). Such a dynamic approach could be addressed in future research. In the cost table in Appendix N, we show the total costs of beach nourishment in 2015, anticipating future SLR.
- This paper only provides the cost estimates for adaptation pathways, but this is still an incomplete analysis, and less costly adaptation pathways are not necessarily the most preferred. Therefore, future research has to develop a full cost-benefit analysis, where benefits are expressed as the reduced risk over the lifetime of the adaptation measures. This would improve the economic feasibility of the proposed pathways.

Acknowledgments

We thank the University of California, Santa Barbara (UCSB) and the Netherlands Organisation for Scientific Research (NWO; VICI Grant no. 453.14.006) for supporting this research. We thank the five reviewers for providing valuable suggestions to improve draft versions of the report. We also greatly acknowledge experts and policy officials in LA County for their valuable feedback during workshops and earlier drafts of the report. This publication has been produced with support from the National Sea Grant College Program provided by the National Oceanic and Atmospheric Administration, the U.S. Department of Commerce, under Grant number NA14OAR4170089. The views expressed herein do not necessarily reflect the views of NOAA or any of its sub-agencies. The U.S. Government is authorized to reproduce and distribute copies for governmental purposes. Maps were designed by Madeline Maingay, http://maadinholland.nl/.

Competing interests

The authors declare no competing interests.

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APPENDIX A: Stormwater management; Marina del Rey

The MS4 Permit includes provisions that allow permittees to voluntarily implement an enhanced watershed management program (EWMP). The EWMP for the Marina del Rey (MDR) watershed is a collaborative effort of the EWMP agencies, and includes the County of Los Angeles (County), Los Angeles County Flood Control District (LACFCD), the City of Los Angeles, and Culver City.

The **Oxford Retention Basin** is a flood control basin located at the intersection of Washington Boulevard and Oxford Avenue. The project is designed to enhance flood protection and reduce stormwater pollution while significantly improving the quality of the ecosystem within the facility.

Several streets and properties in the area surrounding the Oxford Basin are near or below the level of high tides in the marina. Without the Oxford Basin, these areas could flood during a rain event. Prior to a storm, the Oxford Basin's tide gates are opened to empty it at low tide, creating a storage capacity that allows surrounding streets to drain into Oxford Basin during high tide. These storm flows are then emptied into Marina del Rey at the subsequent low tide. Work on the basin also included the dredging of 10,000 cubic yards of long-accumulated sediment and debris to improve the basin's aging flood control and stormwater capture apparatus. The Oxford Basin is operated by the LACFCD. It drains into Basin E (Northern docks part of the Marina) through two tide gates and storm drain piping.

The **Oxford Basin Pump Station**, constructed in 1991, provides protection from flood waters for the low-lying surrounding neighborhood. During rain events, it pumps discharge stormwater into the Oxford Basin, reducing the risk of flooding in the streets of the surrounding neighborhood. The Boone-Olive pump station is a low-flow diversion station and the project value for developing this station was approximately $200,000 (http://file.lacounty.gov/SDSInter/bos/bc/032948_BooneOlivePumpPlant.pdf)

The **Ballona Lagoon and Venice channels** drain subwatershed 2, South of Washington Blvd, and Venice Beach, from Ballona Grand Canal (East) to the West Canal then discharge it at the Marina del Rey harbor mouth as shown in Figure A1. These channels are generally surrounded by residential areas with habitat protection buffer strips on both banks. Tide gates control flooding and regulate tidal flushing (with seawater) in the Venice Canal system north of Washington Boulevard. The Grand Canal is an integral part of the larger Venice Canals/Ballona Lagoon wetlands system and the Ballona Creek watershed; it is connected to the northern end of Ballona Lagoon (Exhibit #2). Seawater enters the wetlands system through tide gates, which control the flow from the Marina del Rey entrance channel into the Ballona Lagoon. There are three tidal gates (one of which is maintained in the open position) connected to the Marina del Rey entrance channel. The lagoon varies in width from 150 to 250 feet and is approximately 4000 feet long. The lagoon is connected to the Venice Canals at the northern end by the Grand Canal. The average tidal regime is restricted and ranges from approximately −2 feet to +2.5 feet NGVD. The seawater then flows through the Ballona Lagoon and into the Grand Canal to a second set of tide gates at Washington Boulevard. These gates are subject to replacement in the near future.

Sea level rise and the Venice Auxiliary Pumping Plant (VAPP)

(*Source*: *City of LA*, 2017); http://eng.lacity.org/techdocs/emg/venice_aux_pumping_plant.htm).

The Venice Pumping Plant (VPP) is the largest pumping plant in the City of LA. It collects sewage from the coastal areas of the City. The VPP, central drain basin, and pumping plant is installed beneath Kinney Plaza (the present Traffic Circle) and is sufficient to handle discharge from 9,160 feet of storm drains. The City of LA is currently constructing a new force main sewer extending from the existing VPP at 140 Hurricane Street in the community of Venice, to a junction structure on the Coastal Interceptor Sewer in the community of Playa Del Rey on Vista Del Mar near Waterview Street; this new sewer will prevent overflow. The old VPPs, built in 1958, are force mains (pressurized pipelines) that convey wastewater flows to the Hyperion Treatment Plant. Currently, the existing force main sewer can only handle approximately 60% of the flows that could otherwise run through the VPP when all five of its pumps are running at full capacity. When flows into the VPP exceed flows out of the plant, wastewater will overflow directly into the Ballona Lagoon. During heavy storms, such as those that occurred during the winters of 1994–1995 and 2004–2005, the excess wastewater at the plant came within minutes of overflowing into the Ballona Lagoon, the Grand Canal, and the surrounding streets (City of LA, 2017).

APPENDIX B: LA watersheds

Four watersheds drain into the coastal area of Los Angeles County: Los Angeles River, Ballona Creek, Dominguez Channel, and Santa Monica Bay (Fig. B1).

The *Los Angeles River watershed* is 51 miles long, originates in western San Fernando, and discharges into San Pedro Bay. The steep slope of the river, results in rapid drainage to the San Pedro Bay at Long Beach. The LA Department of Public Works and CalTrans operate numerous pumping stations

Figure B1. LA Watersheds (Source: LA Stormwater Program; www.LAstormwater.org)

that collect and pump local runoff into the river. Furthermore, flood walls along the river are designed for a 1/50 runoff. Some runoff is collected in the Dominguez spreading grounds on the east bank south of Del Amo Boulevard, for example, to supply water to the sea water barrier system. The engineered Dominguez Gap Wetlands in Long Beach filters stormwater and runoff from Los Angeles.

The *Santa Monica Bay watershed* runs along the coast from the Ventura-Los Angeles County line in the north to the Ballona Creek Watershed in the east. It has 55 miles of coastline and covers 385 square miles (182,000 acres), and its northern boundary extends to the Santa Monica Mountains and drains into the Ocean along the Ballona Wetlands. The entire watershed has approximately 200 separate storm-drain outlets that convey over 30 billion gallons of runoff to the bay each year. The *Marina del Rey watershed* could be viewed as a sub-watershed of the surrounding Santa Monica Bay watershed. In the Marina del Rey watershed, much effort has been applied to enhancing the water quality and flood water control of the watershed (e.g. the Marina del Rey Enhanced Watershed Management Program Plan; EWMPP, 2016). Recent adaptation measures include the re-development of the Oxford retention basin and the tidal flushing of the Ballona Lagoon.

The *Ballona Creek watershed* is located in the Santa Monica Mountains in the north and the Baldwin Hills in the south. It is a channelized watershed that is highly developed with residential and commercial properties. Most of the storm drainage system within the watershed is managed through flood-control structural features consisting of debris basins, storm drains, underground culverts, and open concrete channels. The few channels that remain open include the Sepulveda Wash and Centinela Creek. Since most channels are concrete–lined, the natural processes of erosion and sedimentation runoff have been altered. Under current conditions, eroded sediment is deposited at the mouth of Ballona Creek, where it causes periodic closure of the entrance at Marina del Rey as this sediment must be dredged periodically to maintain open access to the Marina.

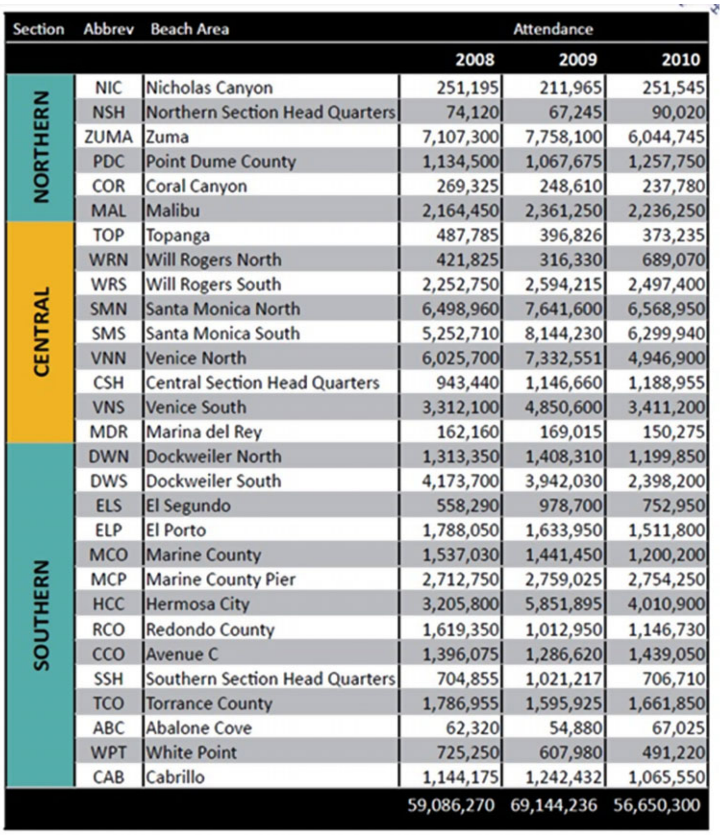
The *Dominguez watershed* historically consisted of a large marshy area, the Dominguez Slough. In the 20th century, channels were dredged and marshes were filled to provide flood protection to the San Pedro Bay Area. Furthermore, the Los Angeles River was diverted and a breakwater was constructed. The Dominguez Channel carries small flows throughout the year. At the intersection of Vermont Avenue and Artesia Boulevard near the Artesia Park and

Ride, the cross section of the channel transitions from rectangular to trapezoidal. From this point to its opening at the Los Angeles Harbor, the channel experiences tidal influence. The Dominguez Channel watershed includes storm drains that drain into the Los Angeles Harbor/Long Beach Harbor areas, such as Wilmington and San Pedro. The Dominguez Watershed Management Plan (2004) states that 70% of the stormwater is discharged to the harbor. The peak 100 yr discharge is estimated at 28,000 cf/s (792m^3/s) (LADWP, 2013). The objective of the plan is to increase recharging of stormwater, reducing runoff to the ocean. The Dominguez Channel is designed to address 50-year rain events. The largest area of potential flooding is an FEMA/AE zone at Long Beach harbor, which is associated with coastal flooding from the ocean.

The Dominguez Channel watershed includes the communities of Wilmington and San Pedro, and drains into the Los Angeles Harbor/Long Beach Harbor areas. Historically, the area consisted of marshes and mudflats with a large marshy area called Dominguez Slough to the north, and flows from the Los Angeles River entered where the Dominguez Channel now drains. The Dominguez Slough was completely channelized in the mid-1900s to provide flood protection to much of the South Bay area. Eventually, two more breakwaters enclosed the greater San Pedro Bay and deep entrance channels were dredged to allow for entry of ships that require 70 feet of clearance.

APPENDIX C: Beach attendance for beaches in LA County

Adapted from CRSMP (2012)



Section	Abbrev	Beach Area	Attendance		
			2008	2009	2010
NORTHERN	NIC	Nicholas Canyon	251,195	211,965	251,545
	NSH	Northern Section Head Quarters	74,120	67,245	90,020
	ZUMA	Zuma	7,107,300	7,758,100	6,044,745
	PDC	Point Dume County	1,134,500	1,067,675	1,257,750
	COR	Coral Canyon	269,325	248,610	237,780
	MAL	Malibu	2,164,450	2,361,250	2,236,250
CENTRAL	TOP	Topanga	487,785	396,826	373,235
	WRN	Will Rogers North	421,825	316,330	689,070
	WRS	Will Rogers South	2,252,750	2,594,215	2,497,400
	SMN	Santa Monica North	6,498,960	7,641,600	6,568,950
	SMS	Santa Monica South	5,252,710	8,144,230	6,299,940
	VNN	Venice North	6,025,700	7,332,551	4,946,900
	CSH	Central Section Head Quarters	943,440	1,146,660	1,188,955
	VNS	Venice South	3,312,100	4,850,600	3,411,200
	MDR	Marina del Rey	162,160	169,015	150,275
SOUTHERN	DWN	Dockweiler North	1,313,350	1,408,310	1,199,850
	DWS	Dockweiler South	4,173,700	3,942,030	2,398,200
	ELS	El Segundo	558,290	978,700	752,950
	ELP	El Porto	1,788,050	1,633,950	1,511,800
	MCO	Marine County	1,537,030	1,441,450	1,200,200
	MCP	Marine County Pier	2,712,750	2,759,025	2,754,250
	HCC	Hermosa City	3,205,800	5,851,895	4,010,900
	RCO	Redondo County	1,619,350	1,012,950	1,146,730
	CCO	Avenue C	1,396,075	1,286,620	1,439,050
	SSH	Southern Section Head Quarters	704,855	1,021,217	706,710
	TCO	Torrance County	1,786,955	1,595,925	1,661,850
	ABC	Abalone Cove	62,320	54,880	67,025
	WPT	White Point	725,250	607,980	491,220
	CAB	Cabrillo	1,144,175	1,242,432	1,065,550
			59,086,270	69,144,236	56,650,300

APPENDIX D: Water level from tidal gauge stations in LA County

(Source: CRSMP, 2012)
Data over the period 1981−2001

	Elevation (ft, MLLW)	
Tidal datum	Santa Monica (NOAA 9410840)	LA Outer Harbor (NOAA 9410660)
Highest Measured Water Level	8.50 (11/30/1982)	7.82 (01/27/1983)
Mean Higher High Water (MHHW)	5.42	5.49
Mean High Water (MHW)	4.69	4.75
Mean Tide Level (MTL)	2.81	2.85
Mean Sea Level (MSL)	2.79	2.82
National Geodetic Vertical Datum-1929 (NGVD29)	2.63	2.63
Mean Low Water (MLW)	0.93	0.94
North America Vertical Datum-1988 (NAVD88)	0.20	0.20
Mean Lower Low Water (MLLW)	0.00	0.00
Lowest Measured Water Level	−2.84 (12/17/1933)	−2.73 (12/17/1993)

Source: NOAA Tidal Bench Marks.

APPENDIX E: HAZUS building types in LA flood zones

(Adapted from FEMA, 2009a; Aerts *et al.*, 2013).

		Flood-proofing of existing buildings			Flood-proofing of new buildings		
HAZUS (occupancy) building class	Description	Elevation	Wet-proofing	Dry-proofing	Elevation	Wet-proofing	Dry-proofing
Residential buildings							
RES1	Single Family Dwelling	Yes	Yes	Yes	Yes	Yes	Yes
RES2	Manuf. Housing	Yes	Yes	Yes	Yes	Yes	Yes
RES3A	Duplex	Yes	Yes	Yes	Yes	Yes	Yes
RES3B	Triplex/Quads	Yes	Yes	Yes	Yes	Yes	Yes
RES3C	Multi-dwellings (5 to 9 units)	No	Yes	Yes	Yes	Yes	Yes
RES3D	Multi-dwellings (10 to 19 units)	No	Yes	Yes	Yes	Yes	Yes
RES3E	Multi-dwellings (20 to 49 units)	No	Yes	Yes	Yes	Yes	Yes
RES3F	Multi-dwellings (50+ units)	No	Yes	Yes	Yes	Yes	Yes
RES4	Temporary Lodging	Yes	Yes	Yes	Yes	Yes	Yes
RES5	Institutional Dormitory	Yes	Yes	Yes	Yes	Yes	Yes
RES6	Nursing Home	Yes	Yes	Yes	Yes	Yes	Yes

Continued

HAZUS (occupancy) building class	Description	Flood-proofing of existing buildings			Flood-proofing of new buildings		
		Elevation	Wet-proofing	Dry-proofing	Elevation	Wet-proofing	Dry-proofing
Commercial buildings							
COM1	Retail Trade	No	Yes	Yes	No	No	No
COM2	Wholesale Trade	No	Yes	Yes	No	No	No
COM3	Personal and Repair Services	No	Yes	Yes	No	No	No
COM4	Professional/Technical Services	No	Yes	Yes	No	No	No
COM5	Banks	No	Yes	Yes	No	No	No
COM6	Hospital	No	Yes	Yes	No	No	No
COM7	Medical Office/Clinic	No	Yes	Yes	No	No	No
COM8	Entertainment & Recreation	No	Yes	Yes	No	No	No
COM9	Theaters	No	Yes	Yes	No	No	No
COM10	Parking	No	Yes	Yes	No	No	No
Applied in flood zone type:		1/100 A and V zones	1/100 A zone	1/100 A zone	1/100 A and V zones	1/100 A zone	1/100 A zone

APPENDIX F: The National Flood Insurance Program (NFIP)

Flood insurance policies and building code requirements are designed for buildings in official FEMA flood zones, which are special flood hazard areas (SFHA) that are delineated in flood insurance rating maps (FIRM). These maps are publicly accessible on the internet (Appendix F). Flood zones are further specified as A and V zones (see Table 4.2). The NFIP sets minimum building requirements in the 1/100 A and V zones, and local governments can impose zoning regulations and building codes in addition to these minimum standards. The 100-year flood mapping delineated in the SFHA relies on historic runoff records but climate change effects and other current and future changes such as hardening, changes in drainage and runoff, are not addressed (LA County, 2006). Climate change effects are not addressed in the flood mapping on which the current building code policies are based, which might imply that buildings may not be constructed to withstand current and future flood impacts.

The base flood elevation (BFE) is the maximum inundation depth that results from a 1/100-year flood, and is used to determine the minimum height of the ground floor of new structures in the SFHA. As stated above, cities in LA County may develop their own building codes that go beyond these minimum standards, called ‘freeboards.’ Cities in LA County follow the California building code (State of California, 2017), outlined in the Flood Hazard Management Specific Plan (FHSP; LADBS, 2014). The building codes apply to new structures and substantial improvements to existing structures; building regulations apply to residential properties, commercial properties, and sport stadiums, but not to public infrastructure such as water treatment plants or railways.

In California, building code regulations for flooding consist of three main components: (1) building above the baseline flood elevation (BFE) level (called ‘freeboard’) required by the NFIP, (2) dry and wet flood-proofing of buildings, and (3) requirements per flood zone for four different types of buildings (I, II, III, IV, see Table F2). Wet flood-proofing aims to minimize the damage once flood water enters the structure, and involves raising electrical sockets, heating systems, and other vulnerable equipment that may fail during a flood. Dry flood-proofing aims to prevent flood water from entering the building. With dry flood-proofing, walls should be impermeable to water and flood shields are placed in front of doors and window openings. Utilities and equipment must be located within the dry flood-proofed

Table F1. Special flood hazard areas (SFHA) as defined by FEMA (LA County, 2017a)

Special Flood Hazard Areas (SFHA)	
Zone A	No base flood elevations determined
Zone AE	Base flood elevations determined
Zone AH	Flood depths of 1 to 3 feet (usually areas of ponding); base flood elevations determined.
Zone AO	Flood depths of 1 to 3 feet (usually sheet flow on sloping terrain); average depths determined. For areas of alluvial fan flooding, velocities are determined
Zone VE	An area that is inundated by tidal floods with velocity (coastal high hazard area), and wave heights of the 1/100 flood are > 3 ft.
Zone X (shaded)	Areas of 0.2% annual chance of flood; areas with 1% annual chance of flood with average depths of less than 1 foot or with drainage areas less than 1 square mile; and areas protected by levees from 1% annual chance flood
Zone X (unshaded)	Areas determined outside the 0.2% annual chance floodplain
Zone D	Areas in which flood hazards are undetermined, but possible

structure, or outside provided that it is at least as high as the BFE (Aerts and Botzen, 2011).

For most dwellings, LA County building code regulations require BFE + 1 ft freeboard (LADBS, 2014). Hence, the lowest floor of all *residential* structures must be constructed at least +1 ft above the FEMA base flood elevation (BFE). Although these requirements apply to the 1/100-year flood zones, they differ across A zones and the coastal V flood zones. Moreover, building codes are stricter for building categories III and IV that carry risk to human life in case of failure, such as hospitals and police stations. All building code requirements are further refined per building type as in the HAZUS (Hazards United States) flood risk model used by FEMA (2009a), both for residential (RES) and commercial (COM) buildings (Appendix E).

In A zones, elevation is required in low-lying areas except for storage, parking, building access, and crawlspace. The design flood elevation (DFE) equals the base flood elevation (BFE) level of the 1/100-year flood for building category I, while it is +1 ft and +2 ft higher for building categories II and IV, respectively (Appendix E). Below the BFE level, wet flood-proofing is required for all building categories. Instead of wet flood-proofing, dry flood-proofing is possible in certain cases for all building categories, except for residential buildings for which dry flood-proofing is not allowed.

Building requirements in coastal V zones are stricter. V zones are coastal areas where wave heights for the 1/100 flood event are three feet or more, and buildings must be developed on anchored pilings or columns to withstand wave impact. In V zones, only flood-damage resistant materials and finishes can be used below the DFE, and dry flood-proofing is not allowed. As in A zones, building components located below these elevation requirements should be wet

Table F2. NFIP classification of structures for flood resistant design and construction

Category	
I	Structures that represent a low hazard to human life in the event of failure including, but not limited to: Agricultural facilities, Certain temporary facilities, Minor storage facilities
II	All structures except those listed in Categories I, III and IV
III	Structures that represent a substantial hazard to human life in the event of failure including (Medical facilities, Schools, etc.)
IV	Structures designated as essential facilities including but not limited to: Hospitals, Fire Station, Hurricane Shelters, Power generating stations, Pump Structures, Fuel storage tanks, etc

flood-proofed. Garages that store private vehicles may be located below the BFE in A and V zones. New non-residential structures and/or substantial improvements to nonresidential structures located in a flood-prone area must be constructed with the lowest finished floor surface of at least +1 ft above the base flood level (LADBS, 2014).

For commercial and mixed use structures (where there is no residential house on the first floor), elevation is not required, and a FEMA certificate can be achieved by applying only wet flood-proofing (V zones) or either dry or wet flood-proofing in A zones. A "FEMA Elevation Certificate is a document completed by a land surveyor, engineer, or other such professional that provides relevant data about a property located within a Special Flood Hazard Area (SFHA) as designated by FEMA" (NS, 2017)

APPENDIX G: Nourishment types and volumes

Following Finkl *et al.* (2006), there are different types of beach nourishment (Figure G1): (a) Dune nourishment: sand is placed in a dune system behind the beach; (b) Nourishment of subaerial beach: sand is placed onshore to build a wider and higher berm above mean water level; (c) Profile nourishment: sand is distributed across the entire beach and nearshore profile; (d) Bar or nearshore nourishment: sediments are placed offshore to form an artificial feeder bar.

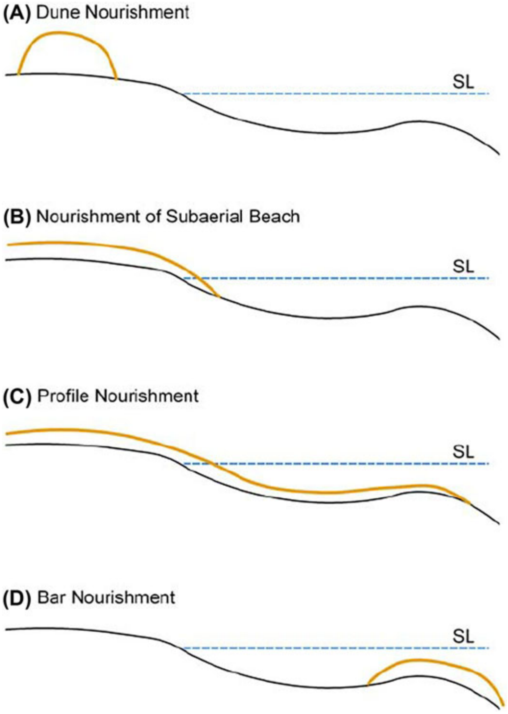


Figure G1. Methods of beach nourishment defined on the basis of where the fill materials are placed (source: Finkl *et al.*, 2006).

APPENDIX H: Flood risk management at governmental levels

Who	Level	Legislation/Program	What	Jurisdiction/Area
USACE	Federal		• Maintain safe navigation of the harbor entrances: regular dredging; maintenance breakwaters, jetties.	Marina de Rey King Harbor Port of LA
USACE/Coastal Sediment Management Work Group	Federal	Collaborative governmental partnership	• Providing direction and shaping coastal sediment management plans	Coastal zone
USACE	Federal		• Operation maintenance; performance of flood control	Ballona Creek: USACE has jurisdiction between Washington Boulevard to La Salle Avenue and Vista del Mar to the Pacific Ocean
FEMA	Federal	NFIP National Flood Insurance Program 1968	• Set minimum requirements for buildings in 1/100 flood zone; • Mapping flood zone; • provide incentives for risk mitigation	1/100 Flood zone
EPA	Federal	Clean Water Act/National Pollutant Discharge Elimination System (NPDES) permit	• Develop stormwater pollution prevention plan (SWPPP), and include BMP (Best Management practices)	City Level
FEMA	Federal	Disaster Mitigation Act	• Prepare for disasters through planning	City Level, Hazard Mitigation Planning
			• Risk mapping and Management	
California Coastal Commission	State	California Coastal Act 1976 (Following Coastal Zone Management Ac, 1972)	• Review Coastal Development projects (Local Coastal Plans, LCPs) proposed by e.g. local governments • plans and regulates the use of land and water in the coastal zone	Coastal zone as defined in the coastal act
LADPW LA County Department of Public Works	LA County	Following Clean Water Act/NPDES and coordinate SWPPP	• Managing County flood control facilities; e.g. Ballona Creek/Operation maintenance; water quality, aesthetics • Coordinate stormwater pollution prevention plan (SWPPP), which includes Erosion Control Plan (ECP)	e.g. Ballona Creek: LACDPW has jurisdiction over the stretches of the channel that are not maintained by USACE.

Continued

Who	Level	Legislation/Program	What	Jurisdiction/Area
BOE; Los Angeles Bureau of Engineering	City of LA	FEMA/NFIP & State of California Building Code	• Manages City's storm drainage system • guides the approval of flood mitigation measures for individual buildings and project to comply with FEMA regulation	City level
LADBS (City of LA Dpt. of Building and Safety)	City of LA	State of California Building Code	• identifies building projects located within the FHSP (Flood Hazard Management Specific Plan) • together with BOE approves flood mitigation plans	City level
City of Long Beach; Dpt. Parks and recreation	City of LB		• Maintaining Jetties/harbor entrance; • regular maintenance dredging entrance channel	City level; e.g. Alamitos Bay Marina (Naples)

APPENDIX I: Current adaptation plans in Los Angeles

Plan	Year	Areas	Agency	Goals	Future/ climate change	Website
Local Hazard Mitigation Plan	2017	City of LA	City of LA	To reduce risks from disasters to the people, property, economy and environment within the city. The plan complies with federal and state hazard mitigation planning requirements to establish eligibility for funding under Federal Emergency Management Agency (FEMA) grant programs.	Yes	http://www.emergency.lacity.org/
Enhanced Watershed Management plan for marina del Rey Watershed	2016	Marina del Rey	LA County/City of LA/Culver City/LA Flood control district	Following the MS4 permit, the plan aims at identifying water quality priorities and reduce pollutants, and optimize watershed control measures.	No	http://www.lastormwater.org/green-la/enhanced-watershed-management-plans/
Coastal Resiliency Assessment Report	2015	City of LB	City of LB	Incorporates adaptive measures related to projected climate change into policymaking and planning processes; Update the Local Coastal Program (LCP)	2100/SLR	http://www.aquariumofpacific.org/downloads/AOPs_2015_Report_on_Resiliency_(1-7-16).pdf
Climate Adaptation and Coastal Resiliency Plan (CRP)	2014	Port of LB	Port of LB	Manage risks associated with climate change; Identify Port assets that are most vulnerable; Identify potential adaptation strategies to protect the Port	2100/SLR	http://www.polb.com/environment/climate-change.asp

Continued

Plan	Year	Areas	Agency	Goals	Future/climate change	Website
Los Angeles Regional Collaborative for Climate Action and Sustainability (LARC)	2013	USC: UCLA		Adaption planning ensure community resilience	2100/SLR	http://www.laregionalcollaborative.com/
Los Angeles County 'Coastal Regional Sediment Management Plan' (CRSMP) 2012	2012	LA County coast	LA County	Address coastal sediment processes and options for adaptation to SLR & erosion	2100/SLR	http://www.dbw.ca.gov/csmw/pdf/LACO_CRSMP_DraftReport.pdf
Guidance on Incorporating Sea Level Rise	2011	Caltrans	State of California	Guidelines providing steps to address SLR in programming and design of new infrastructure projects with a lifetime more than 20 years	2100/SLR	http://www.dot.ca.gov/ser/downloads/sealevel/guide_incorp_slr.pdf
LA WQCMPUR Water Quality Compliance Master Plan for Urban Runoff	2009	City of LA	City of LA / Bureau of Sanitation, Watershed Protection	Seeking for strategies to both capture rainwater and re-charge decreasing groundwater tables. reducing pollution from urban runoff in the City of LA	2035	http://www.lastormwater.org/wp-content/files_mf/wqcmpur.pdf
Dominguez Watershed Management Master Plan	2004	City Dominguez watershed	LA County/ LACDPW	Coordinate Watershed management (flood control, Water conservation, reducing pollution)	No	http://www.ladpw.org/wmd/watershed/dc/DCMP/summary.cfm

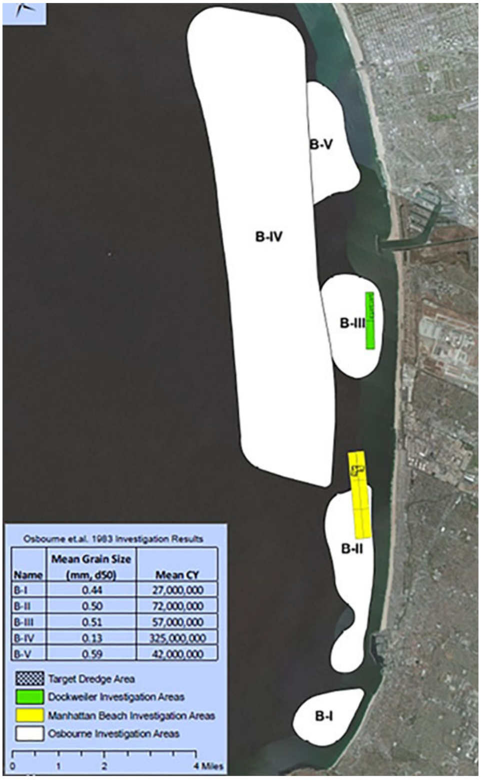
APPENDIX J: Pumping stations and critical infrastructure in the flood zone

(Source; Grifman *et al.*, 2013)

- *Wastewater pumping plants.* There are approximately 21 plants located in the sea level rise inundation zone. An example is the Venice Waste water pumping station that is being extended with a new pump (VAPP). The replacement value per plant is $2 million (Grifman *et al.*, 2013)
- The *Hyperion Wastewater Treatment Plant* is located next to Dockweiler State Beach at approximately 7m (32 ft) above sea level. Grifman *et al.* (2013) states that localized flooding and damage to equipment and structure of facility is possible due to extreme wet weather, if there are failure(s) to critical individual unit processes (facilities), failure of effluent pumping, or failure of influent bypass pumping of influent sewer flow.
- *Terminal Island Water Reclamation Plant* is located on Terminal Island, and is partly located below sea level. Grifman *et al.* (2013) states that the plant may be temporarily or partially disabled during a storm and may require emergency generators or pumps to be used to ensure that wastewater continues to be discharged to the outfall.
- *San Pedro Stormwater Collection System.* The San Pedro stormwater collection system includes the storm drain network in the San Pedro area. Many lines are located below sea level.
- *Low diversion Pumps*: There are four low flow diversion pumping plants located in the sea level rise exposure zone, and they are designed to move water during low flow periods from lower to higher elevation, so it can be transported through pipes by gravity for eventual processing and cleaning at a treatment plant. They do not usually operate during storm events. The replacement value of a plant is $1 million (Grifman *et al.*, 2013). An example is the *The Venice Stormwater/Urban Runoff Pumping plant.* The replacement value of this plant is $10 million (Grifman *et al.*, 2013)
- *El Segundo Electric Powerplant*: El Segundo Energy Center is a natural gas-fueled, combined-cycle generating facility located near Los Angeles, California. The plant produces 550 megawatts (MW) of efficient and flexible electricity to the California grid—enough to power nearly 450,000 homes.
- *Harbor Generating System (Wilmington)*: The Harbor Generation Station is a natural gas fired steam electric generating facility located in the Wilmington area. The sensitivity is low.
- *Haynes Generating Station*: Haynes Generation Station is a natural gas fired power plant located in the Long Beach. Outdoor assets are designed to withstand exposure to water. In addition, indoor facilities are protected with pumping stations.
- *Receiving Station (RS) Q* is located in the Wilmington area and is comprised of equipment that receives power from generation, transforms the voltage, and distributes the power out again into the distribution network. Vulnerability is low

APPENDIX K: Offshore sand reserves near Santa Monica Bay

Source: Osbourne *et al.* (1983)



Osbourne et.al. 1983 Investigation Results

Name	Mean Grain Size (mm, d50)	Mean CY
B-I	0.44	27,000,000
B-II	0.50	72,000,000
B-III	0.51	57,000,000
B-IV	0.13	325,000,000
B-V	0.59	42,000,000

APPENDIX L: Adaptation pathway, Naples Protection

In low-lying areas such as Naples in Long Beach, accelerated sea level rise may reduce the effectiveness of flood-proofing measures. Flood-proofing measures are applied to individual buildings, but are only effective up to a certain flood inundation height (<4−6 ft). Above this height, existing buildings must be further elevated to reduce damages from flood events. This is expensive and likely not feasible for all buildings. Another option is to close the entrance to the Alamitos Bay area and the Island of Naples with a dam, which would protect all buildings and people in the Bay area. However, with such a closure, ships could no longer move in or out. Another option to protect the Naples area against sea level rise and storm surges, and to allow vessels to move in and out of the area, is to develop a sluice. A sluice, or a lock device, is used for raising and lowering vessels between stretches of different water levels on rivers and waterways. The distinguishing feature of a lock is the fixed chamber in which the water level can be altered. A special type of sluice is a 'tidal lock', which is any lock that connects tidal with non-tidal water, such as between a canal and the sea. A lock consists of a chamber, with a pair of gates at each end (Figure L1) The chamber is the main feature of the lock; it is a watertight enclosure (masonry, brick, steel, or concrete) that can be sealed off from the waterways at both ends with gates. The chamber may slightly larger (for maneuvering room) than the largest vessel for which the waterway is designed, but is often larger to allow more than one vessel at a time to use the lock.

The sluice will change the salinity level in the Naples/Alamitos bay area, slowly transitioning it towards a fresh water area. This will result in some ecosystems disappearing, while new ecosystems will settle. Therefore, there are significant issues that would need to be addressed within the Alamitos Bay area if this option is to be considered. For example, water quality may deteriorate because there is no natural flushing of the water since tidal influence is reduced to nearly zero. Additional tidal gates should be installed to allow controlled tidal waters to enter, and regularly flush, the Bay area. Furthermore, pumping stations are needed to pump out excessive rainwater from the Bay area into the ocean. The cost of a lock depends on the size of the vessels that must pass through the lock. A sea-sluice that is capable of handling large commercial vessels may cost up to $1 billion (Rijkswaterstaat, 2016). A sluice for private vessels would potentially cost between $154 and $176 million.

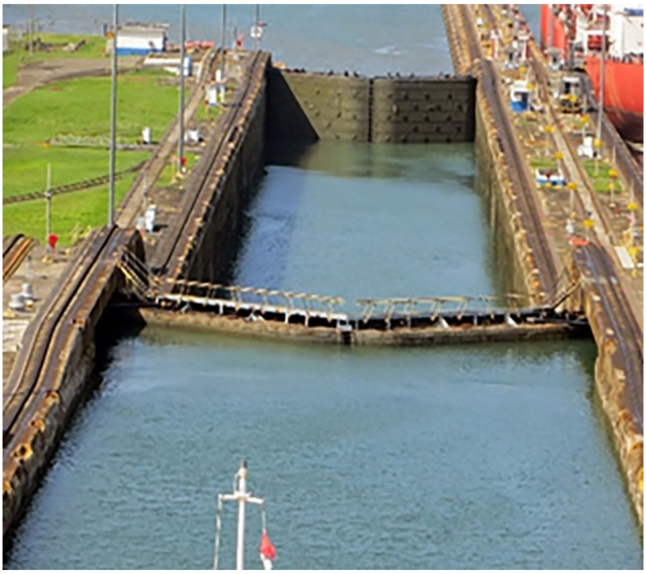


Figure L1. Sluice Lock and gates to overcome water level difference (Source: Rijkswaterstaat).

APPENDIX M: Adaptation Pathway Seaward Ports

In international ports such as Hamburg (Germany) and Rotterdam (The Netherlands), adaptation measures include raising facilities, and expanding new, elevated piers towards the sea. In Rotterdam (the Netherlands), for example, the new outer harbor Maasvlakte 2 (cost around $3 billion) has been completed recently by creating new elevated land at a height of 16 ft (+5 m) above mean sea level in open water at the coast near Rotterdam (Figure M1). The new area measures 2,000 ha (about 4,900 acres).

The older, piers located further inland have been converted into new residential areas. Because these older piers have a lower elevation, they are protected with a rotating surge barrier that closes off the waterway from the sea to the new residential areas in case of a storm. In this way, the areas do not need additional fill. Old port facilities are attractive for redevelopers, since waterfront residences have a high market value; for example, the old port Hafencity in Hamburg (Fig. M2), has been transformed into waterfront development at a cost of $650 million and is now one of the most expensive neighborhoods in the city. When completely developed it will be home to about 12,000 people and the workplace of 40,000 people, mostly in office complexes. (Aerts and Botzen, 2011) (Figure M1).

Following international examples and the recent expansion of Pier 400, the Ports of LA and LB may continue to expand towards the ocean, and use the outer breakwaters as the new perimeter of the ports. The low-lying old port facilities bordering San Pedro and Wilmington would be transformed into residential areas. In order to protect these new residential areas from flooding, both the LA channel and turning basin and the back channel would be closed off with a dam and/or sluice at the location of the Vincent Thomas and Gerald Desmond Bridges. The sluice and dam would protect the low-lying area behind the Port, including residential areas in Wilmington, and upgrading building codes there would no longer be required. The sluice would enable residents in the new residential area to navigate to the ocean with their vessels.

The 100-year discharge for the Dominquez Channel is estimated at 28,000cf/2 (792m^3/s), which would drain into the new residential area. Therefore, two large pumping stations would need to be installed: one at the Vincent Thomas Dam and one

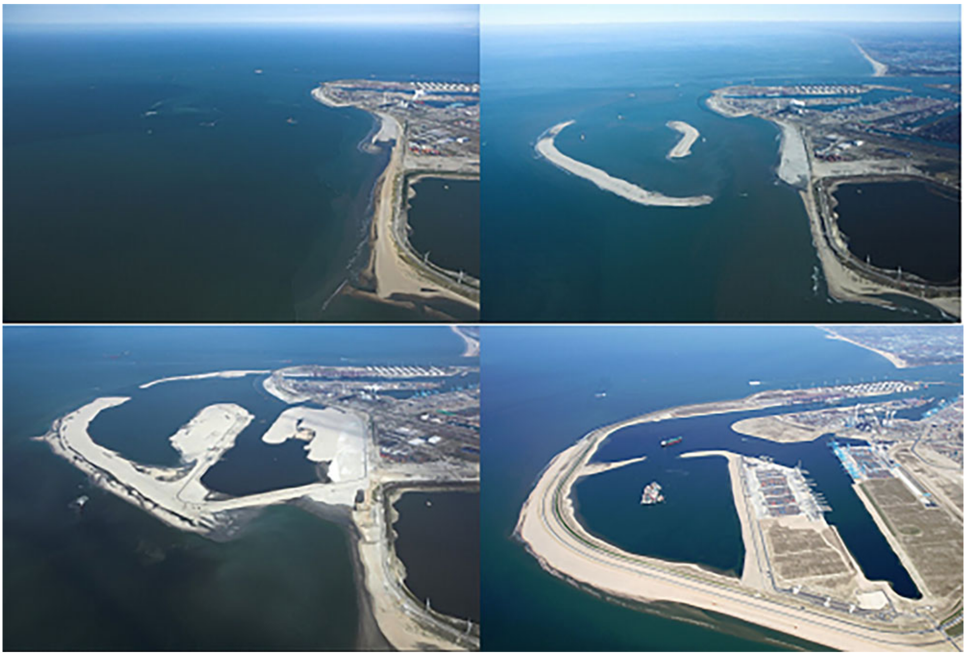


Figure M1. Series of aerial photographs of the new Maasvlakte 2 harbor near Rotterdam that has recently has been completed. Upper left: May 2009; Upper right: October 2009; Lower left: July 2010; Lower right: May 2016. (Source: Port of Rotterdam, 2011–2016).

Figure M2. Example of Hafencity in Hamburg, Germany (Left) and Amsterdam, the Netherlands (right) where an old port area has been transformed into high value residential buildings. (Photos, J. Aerts)

at the rear end of Channel 3, at Pico Ave. These stations pump excessive rainwater and discharge from the Dominguez Channel into the port area and the LA River. The new inland lagoon area would act as a reservoir that can buffer excessive rainwater, similar to the function of existing spreading grounds and other basins in LA County. After the precipitation event, the water can be pumped out of the inland lagoon into the Port and LA River.

Between the port and the new residential areas, green parks and berms would be developed to provide room for recreation and to reduce noise from the port, similar to the function of Wilmington park. This also includes green space along California State Routes 47 and 103 that serve as main transport lines from and to the ports.

Because natural flushing of the water bordering the new residential areas using tidal waters would no longer be possible, assessment studies are needed to ensure water quality will remain at EPA standards. The two pumping stations can support water quality by regularly flushing, where one pumping station pumps water from the ocean into the new closed lagoon area, and the other pumping station pumps water out to the LA river. This creates a current that flushes out contaminated water.

Expanding the ports with elevated, safe facilities also provides opportunities for new business, such as re-location of vulnerable infrastructure (El Segundo, Chevron refinery). Using the cost for Pier 400 as a basis, the estimated cost of new port facilities would be around $3.5 billion. Similar cost are associated with developing the residential area, but those costs will be paid by the new homeowners in the area.

APPENDIX N: Adaptation cost per region and per adaptation pathway

All adaptation measures listed below and their costs are addressed in Chapter 5. The table below provides the cost estimate per measure for SLR scenarios of 2.5 ft (75 cm), 3 ft (1m), 5 ft (150 cm), and 7 ft (200 cm), respectively. The numbers in the shaded cells are used for the aggregate cost estimates in Table 6.1:

- All prices are in $2015
- *Groins, revetments, levees, bulkheads, jetties, breakwaters*: The cost number includes a basic investment cost per unit or per mile. Next, an additional fee per 2 ft of SLR is added to the basic investment cost. Hence, we assume that investment upgrades are applied for each expected 2 ft of SLR.
- *Elevation of buildings*: Only the investment costs for elevating an average building in the United States are available. However, significantly higher costs can be expected in LA County, since average building prices in the areas where elevation is an option (Malibu and Naples) are significantly higher than the U.S. average. Therefore, we have used conservative numbers for the cost of elevation and multiplied the numbers provided in Chapter 5 by two. Most likely, the elevation prices will be even higher than our assumptions because in several cases, houses will probably have to be reconstructed. One of the issues for further economic analyses is whether this rebuilding will occur within the lifetime of the building.

- *Dry and wet flood-proofing*: We have used the numbers from the tables in Chapter 5. The unit cost price shown in the tables are the averaged prices per building.
- *Elevation of port facilities*: This measure entails elevating piers with sand. However, the unit cost price is much higher than for beach nourishment, since elevation involves adjusting infrastructure such as roads, cables, and pipes.
- *Maintenance*: These yearly costs are estimated as 0.1–1% of the total investment costs. This estimate matches the range of maintenance costs of flood management addressed in other studies in, for example, NYC (e.g. Aerts *et al.*, 2013).

Area	Strategy	Measure	#	unit	Unit costs [$/unit]	SLR cm	Total costs [$]
Malibu	**Resilience**	Elevation Buildings	582	buildings	$ 140.000,00	75	$ 81.480.000
			762	buildings	$ 160.000,00	100	$ 121.920.000
			987	buildings	$ 180.000,00	150	$ 177.660.000
			1109	buildings	$ 200.000,00	200	$ 221.800.000
		Revetments	5	miles	$ 4.800.000	75	$ 48.000.000
						100	$ 60.000.000
						150	$ 72.000.000
						200	$ 96.000.000
		PCH	6,83	miles	$ 30.000.000	75	$ 204.900.000
					$ 33.000.000	100	$ 225.390.000
					$ 36.000.000	150	$ 245.880.000
					$ 39.000.000	200	$ 266.370.000
		Beach Nourishment	2,71	miles	$15/cy sand	75	$55.220.552
						100	$ 69.307.735
						150	$ 83.394.918
						200	$ 111.400.374
Santa Monica	**Resilience**	Jetties	2	each	$ 800.000	75	$ 4.800.000
						100	$ 6.400.000
						150	$ 8.000.000
						200	$ 11.200.000
		Groins	9	each	$ 800.000	75	$ 21.600.000
						100	$ 28.800.000
						150	$ 36.000.000
						200	$ 50.400.000
		Pumps	3	each	$ 200.000	75	$ 600.000
			4	each	$ 200.000	100	$ 800.000
			5	each	$ 200.000	150	$ 1.000.000
			7	each	$ 200.000	200	$ 1.400.000
		Bulkheads	8,06	miles	$ 7.000.000	75	$ 112.840.000
						100	$ 141.050.000
						150	$ 169.260.000
						200	$ 225.680.000
		Breakwater	2	each	$ 7.200.000	75	$ 14.400.000
						100	$ 18.000.000
						150	$ 21.600.000
						200	$ 28.800.000
		Levees river	2	miles	$ 4.800.000	75	$ 120.000.000
						100	$ 150.000.000
						150	$ 180.000.000
						200	$ 240.000.000

Continued

Area	Strategy	Measure	#	unit	Unit costs [$/unit]	SLR cm	Total costs [$]
		Culver blvd elevation	1,7187	miles	$ 30.000.000	75	$ 51.561.000
					$ 33.000.000	100	$ 56.717.100
					$ 36.000.000	150	$ 61.873.200
					$ 39.000.000	200	$ 67.029.300
		Bellona levees	0,95	miles	$ 4.800.000	75	$ 9.120.000
						100	$ 11.400.000
						150	$ 13.680.000
						200	$ 18.240.000
		Dry- and wet-proofing	245	buildings	$ 10.320,25	75	$ 2.528.461
			312	buildings	$ 11.031,69	100	$ 3.806.619
			433	buildings	$ 11.743,13	150	$ 5.084.776
			6646	buildings	$ 14.230,00	200	$ 94.572.601
		Beach nourishment	5,43	miles	$15/cy sand	75	$ 110.644.869
						100	$ 138.871.217
						150	$ 167.097.566
						200	$ 223.211.819
Santa Monica	**Protection**	Jetties	2	each	$ 800.000	75	$ 4.800.000
	Resilience					100	$ 6.400.000
	Road					150	$ 8.000.000
						200	$ 11.200.000
		Groins	9	each	$ 800.000	75	$ 21.600.000
						100	$ 28.800.000
						150	$ 36.000.000
						200	$ 50.400.000
		Pumps	3	each	$ 200.000	75	$ 600.000
						100	$ 800.000
			5	each	$ 200.000	150	$ 1.000.000
			7	each	$ 200.000	200	$ 1.400.000
		Bulkheads	8,06	miles	$ 7.000.000	75	$ 112.840.000
						100	$ 141.050.000
						150	$ 169.260.000
						200	$ 225.680.000
		Breakwater	2	each	$ 7.200.000	75	$ 14.400.000
						100	$ 18.000.000
						150	$ 21.600.000
						200	$ 28.800.000
		Levees river	2	miles	$ 4.800.000	75	$ 120.000.000
						100	$ 150.000.000
						150	$ 180.000.000
						200	$ 240.000.000
		Bellona levees	0,95	miles	$ 4.800.000	75	$ 9.120.000
						100	$ 11.400.000
						150	$ 13.680.000
						200	$ 18.240.000
		Wet-proofing	0	buildings		75	$ -
			0	buildings		100	$ -
			427	buildings	$ 25.000,00	200	$ 5.306.825

Continued

Area	Strategy	Measure	#	unit	Unit costs [$/unit]	SLR cm	Total costs [$]
		Road elevation as levee	3,55	miles	$ 30.000.000	75	$ 106.500.000
					$ 33.000.000	100	$ 117.150.000
					$ 36.000.000	150	$ 127.800.000
					$ 39.000.000	200	$ 138.450.000
		Dike under beach	2,5	miles	$ 45.000.000	75	$ 112.500.000
						100	$ 112.500.000
						150	$ 112.500.000
						200	$ 112.500.000
		Beach nourishment	5,43	miles	$15/cy sand	75	$ 110.644.869
						100	$ 138.871.217
						150	$ 167.097.566
						200	$ 223.211.819
Santa Monica	**Protection**	Jetties	2	each	$ 800.000	75	$ 4.800.000
	Sluice					100	$ 6.400.000
						150	$ 8.000.000
						200	$ 11.200.000
		Groins	9	each	$ 800.000	75	$ 21.600.000
						100	$ 28.800.000
						150	$ 36.000.000
						200	$ 50.400.000
		Pumps	3	each	$ 200.000	75	$ 600.000
						100	$ 800.000
			5	each	$ 200.000	150	$ 1.000.000
			7	each	$ 200.000	200	$ 1.400.000
		Breakwater	2	each	$ 7.200.000	75	$ 14.400.000
						100	$ 18.000.000
						150	$ 21.600.000
						200	$ 28.800.000
		Sluice	1	each	$ 250.000.000	75	$ 250.000.000
						100	$ 250.000.000
						150	$ 250.000.000
						200	$ 250.000.000
		Dike under beach	2,5	miles	$ 45.000.000	75	$ 112.500.000
						100	$ 112.500.000
						150	$ 112.500.000
						200	$ 112.500.000
		Beach nourishment	5,43	miles	$15/cy sand	75	$ 110.644.869
						100	$ 138.871.217
						150	$ 167.097.566
						200	$ 223.211.819
Redondo	**Resilience (100 cm)**	Bulkheads	2,65	miles	$ 7.000.000	75	$ 37.100.000
South Bay						100	$ 46.375.000
Resilience-protection (200 cm)						150	$ 55.650.000
						200	$ 74.200.000
		Breakwater	1	each	$ 5.500.000	75	$ 11.000.000
						100	$ 13.750.000
						150	$ 16.500.000
						200	$ 22.000.000

Continued

Area	**Strategy**	**Measure**	**#**	**unit**	**Unit costs** [$/unit]	**SLR** cm	**Total costs** [$]
		Levees infrastructure	3, 77	miles	$ 4.722.000	75	$ 35.603.880
						100	$ 44.504.850
						150	$ 53.405.820
						200	$ 71.207.760
		Elevation Buildings	20	buildings	$ 140.000,00	75	$ 2.800.000
			291	buildings	$ 160.000,00	100	$ 46.560.000
			734	buildings	$ 180.000,00	150	$ 132.120.000
			1262	buildings	$ 200.000,00	200	$ 252.400.000
		Beach nourishment	10,64	miles	$15/cy sand	75	$ 216.806.889
						100	$ 272.115.977
						150	$ 327.425.064
						200	$ 437.380.065
Redondo South Bay	**Protection**	Bulkheads	2,65	miles	$ 7.000.000	75	$ 37.100.000
						100	$ 46.375.000
						150	$ 55.650.000
						200	$ 74.200.000
		Breakwater	1	each	$ 5.500.000	75	$ 11.000.000
						100	$ 13.750.000
						150	$ 16.500.000
						200	$ 22.000.000
		Levees infrastructure	3,77	miles	$ 4.722.000	75	$ 35.603.880
						100	$ 44.504.850
						150	$ 53.405.820
						200	$ 71.207.760
		Road elevation as levee	4,33	miles	$ 30.000.000	75	$ 129.900.000
					$ 33.000.000	100	$ 142.890.000
					$ 36.000.000	150	$ 155.880.000
					$ 39.000.000	200	$ 168.870.000
		Beach nourishment	10,64	miles	$15/cy sand	75	$ 216.806.889
						100	$ 272.115.977
						150	$ 327.425.064
						200	$ 437.380.065
Ports LA/LB	**Resilience**	Levees infrastructure	1,2		$4.722.000	75	$11.332.800
						100	$14.166.000
						150	$16.999.200
						200	$22.665.600
		Bulkheads	55,8	miles	$7.000.000	75	$781.200.000
						100	$976.500.000
						150	$1.171.800.000
						200	$1.562.400.000
		Elevation port facilities	1366311	cy	$50/cy sand	75	$68.315.566
			1781548	cy	$50/cy sand	100	$102.473.349
			2196785	cy	$50/cy sand	150	$136.631.132
			2688552	cy	$50/cy sand	200	$204.946.699
		Beach nourishment	0,2	miles	$15/cy sand	75	$4.075.317
						100	$5.114.962
						150	$6.154.606
						200	$8.221.430

Continued

Area	**Strategy**	**Measure**	**#**	**unit**	**Unit costs** [$/unit]	**SLR** cm	**Total costs** [$]
		Breakwater	3	each	$16.666.667	75	$100.000.000
						100	$125.000.000
						150	$150.000.000
						200	$200.000.000
		Levees river	10,54	miles	$4.800.000	75	$101.184.000
						100	$126.480.000
						150	$151.776.000
						200	$202.368.000
		Dry-proofing	656	buildings	$3.258,16	75	$2.137.355
			1276	buildings	$9.493,00	100	$12.113.179
			2086	buildings	$10.589,17	150	$22.089.003
			3035	buildings	$9.766,23	200	$29.640.498
Ports LA/LB	**Resilience**	Levees infrastructure	1,2		$4.722.000	75	$11.332.800
	Protection					100	$14.166.000
	Road					150	$16.999.200
						200	$22.665.600
		Bulkheads	55,8	miles	$7.000.000	75	$781.200.000
						100	$976.500.000
						150	$1.171.800.000
						200	$1.562.400.000
		Elevation port facilities	1366311	cy	$50/cy sand	75	$68.315.566
			1781548	cy	$50/cy sand	100	$102.473.349
			2196785	cy	$50/cy sand	150	$136.631.132
			2688552	cy	$50/cy sand	200	$204.946.699
		Beach nourishment	0,2	miles	$15/cy sand	75	$4.075.317
						100	$5.114.962
						150	$6.154.606
						200	$8.221.430
		Breakwater	3	each	$16.666.667	75	$100.000.000
						100	$125.000.000
						150	$150.000.000
						200	$200.000.000
		Pumps	15	each	$200.000	75	$3.000.000
						100	$4.000.000
			25	each	$200.000	150	$5.000.000
			35	each	$200.000	200	$7.000.000
		Levees river	10,54	miles	$4.800.000	75	$101.184.000
						100	$126.480.000
						150	$151.776.000
						200	$202.368.000
		Road elevation as levee	3,1	miles	$30.000.000	75	$93.000.000
					$33.000.000	100	$102.300.000
					$36.000.000	150	$111.600.000
					$39.000.000	200	$120.900.000
Ports LA/LB	**Seaward**	Pumps	15	each	$200.000	75	$3.000.000
						100	$4.000.000
			25	each	$200.000	150	$5.000.000
			35	each	$200.000	200	$7.000.000

Continued

Area	**Strategy**	**Measure**	**#**	**unit**	**Unit costs** [$/unit]	**SLR** cm	**Total costs** [$]
		Levees	12.4	miles	$15.000.000	75	$186.000.000
						100	$186.000.000
						150	$186.000.000
						200	$186.000.000
		Sluice	1	each	$250.000.000	75	$250.000.000
						100	$250.000.000
						150	$250.000.000
						200	$250.000.000
		Dam	1	each	$30.000.000	75	$30.000.000
						100	$30.000.000
						150	$30.000.000
						200	$30.000.000
		Bulkheads	38,5	miles	$7.000.000	75	$539.000.000
						100	$673.750.000
						150	$808.500.000
						200	$1.078.000.000
		New Piers	100	mln cy sand	$20/cy		$2.000.000.000
Naples	**Resilience**	Jetties	2	each	$ 800.000	75	$ 4.800.000
						100	$ 6.400.000
						150	$ 8.000.000
						200	$ 11.200.000
		Elevation buildings	5659	buildings	$ 140.000,00	75	$ 792.260.000
			6373	buildings	$ 160.000,00	100	$ 1.019.680.000
			7055	buildings	$ 180.000,00	150	
			9161	buildings	$ 200.000,00	200	$ 1.832.200.000
		Pumps	6	each	$ 200.000	75	$ 1.200.000
			8	each	$ 200.000	100	$ 1.600.000
			10	each	$ 200.000	150	$ 2.000.000
			14	each	$ 200.000	200	$ 2.800.000
		Bulkheads	8,89	miles	$ 7.000.000	75	$ 124.460.000
						100	$ 155.575.000
						150	$ 186.690.000
						200	$ 248.920.000
		Levees river	4,02	miles	$ 4.800.000	75	$ 38.592.000
						100	$ 48.240.000
						150	$ 57.888.000
						200	$ 77.184.000
		Levees infrastructure	4,37	miles	$ 4.722.000	75	$ 41.270.280
						100	$ 51.587.850
						150	$ 61.905.420
						200	$ 82.540.560
		Beach nourishment	4,03	miles	$15/cy sand	75	$ 82.117.647
						100	$ 103.066.484
						150	$ 124.015.320
						200	$ 165.661.811

Continued

Area	**Strategy**	**Measure**	**#**	**unit**	**Unit costs** [$/unit]	**SLR** cm	**Total costs** [$]
Naples	**Protection 2**	Pumps	6	each	$ 200.000	75	$ 1.200.000
			8	each	$ 200.000	100	$ 1.600.000
			10	each	$ 200.000	150	$ 2.000.000
			14	each	$ 200.000	200	$ 2.800.000
		Levees river	4,02	miles	$ 4.800.000	75	$ 38.592.000
						100	$ 48.240.000
						150	$ 57.888.000
						200	$ 77.184.000
		Levees infrastructure	4,37	miles	$ 4.722.000	75	$ 41.270.280
						100	$ 51.587.850
						150	$ 61.905.420
						200	$ 82.540.560
		Road elevation as levee	1,2	miles	$ 30.000.000	75	$ 36.000.000
					$ 33.000.000	100	$ 39.600.000
					$ 36.000.000	150	$ 43.200.000
					$ 39.000.000	200	$ 46.800.000
		Sluice	1	each	$ 250.000.000	75	$ 250.000.000
						100	$ 250.000.000
						150	$ 250.000.000
						200	$ 250.000.000
		Elevation buildings	242	buildings	$ 140.000,00	75	$ 33.880.000
			242		$ 160.000,00	100	$ 38.720.000
			242	buildings	$ 180.000,00	150	$ 43.560.000
			242	buildings	$ 200.000,00	200	$ 48.400.000
		Beach nourishment	4,03	miles	$15/cy sand	75	$ 82.117.647
						100	$ 103.066.484
						150	$ 124.015.320
						200	$ 165.661.811

APPENDIX O: Experts involved

Name	Organization	Department/role
Ted Johnson	Water repl. Distr. Southern Ca.	Chief Hydrologist
Lesley Ewing	California Coastal Commission	Senior Coastal Engineer
Laura MacPherson	City of LA	Policy Planning
Shahen Akelyan	City of LA	Department of Buildings and Safety (DBS)
Susan Shu	City of LA	Permit and Engineering Bureau (BOE)
Garett Wong	City of Santa Monica	Office of Sustainability
Casey Zweig	Malibu	Environmental Program Specialist
Jennifer Voccola Brown	Malibu	Senior Environmental Programs Coordinator
Jessica Colvard	Malibu	Associate Planner
Mike Phipps	Malibu	Contract Geologist/Coastal Consultant
Ismael Lopez	Los Angeles County	Beaches and Harbors Planner, Planning Division
Michael Tripp	Los Angeles County	Beaches and Harbors, Chief of Planning
Cesar Espinosa	Los Angeles County	Beaches and Harbors Planning Specialist, Planning Division
Fern Nueno	Long Beach	Planner
Ted Semaan	Redondo Beach	Department of Public Works, Director
Bradley J. Lindahl	Redondo Beach	Public Works Department, Capital Projects Program Manager
Andrew S. Winje, P.E.	Redondo Beach	Public Works Department, City Engineer
Aaron S. Jones	Redondo Beach	Community Development, Director
Alison Spindler	Long Beach	Department of Development Services, Planner
Christopher Koontz	Long Beach	Department of Development Services, Advanced Planning Officer
Christian J. Perez	Long Beach	Engineering Bureau, Civil Engineer
Joshua Hickman	Long Beach	Department of Public Works, Program Manager
George C. Ker	Long Beach	Department of Public Works, Senior Civil Engineer
Justin Luedy	Port of Long Beach	Environmental Specialist
Justin Vandever	AECOM	Coastal Engineer