Climatic Change (2011) 109 (Suppl 1):S229–S249
DOI 10.1007/s10584-011-0308-1

Potential impacts of increased coastal flooding in California due to sea-level rise

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Received: 12 February 2010 / Accepted: 21 September 2011 / Published online: 24 November 2011

Abstract California is likely to experience increased coastal flooding and erosion caused by sea-level rise over the next century, affecting the state's population, infrastructure, and environment. As part of a set of studies on climate change impacts to California, this paper analyzes the potential impacts from projected sea-level rise if no actions are taken to protect the coast (a "no-adaptation scenario"), focusing on impacts to the state's population and infrastructure. Heberger et al. (2009) also covered effects on wetlands, costs of coastal defenses, and social and environmental justice related to sea-level rise. We analyzed the effect of a medium-high greenhouse gas emissions scenario (Special Report on Emissions Scenarios A2 in IPCC 2000) and included updated projections of sea-level rise based on work by Rahmstorf (Science 315(5810): 368, 2007). Under this scenario, sea levels rise by 1.4 m by the year 2100, far exceeding historical observed water level increases. By the end of this century, coastal flooding would, under this scenario, threaten regions that currently are home to approximately 480,000 people and $100 billion worth of property. Among those especially vulnerable are large numbers of low-income people and communities of color. A wide range of critical infrastructure, such as roads, hospitals, schools, emergency facilities, wastewater treatment plants, and power plants will also be at risk. Sea-level rise will inevitably change the character of California's coast; practices and policies should be put in place to mitigate the potentially costly and life-threatening impacts of sea-level rise.

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1 Introduction

The residents of California's coast are already familiar with disaster and live with the risk of flooding from coastal storms and tsunamis, and landslides and property damage due to coastal erosion. In spite of these risks, development along California's coast is extensive. It was estimated that, in 2003, 31 million people lived in the state's 20 coastal counties. In fact, six of the ten fastest growing coastal counties in the United States between 1980 and 2003 were in California (NOAA 2004). Major transportation corridors and other critical infrastructure are also concentrated near California's coast, including oil, natural gas, and nuclear energy facilities, as well as major ports, harbors, and wastewater treatment plants.

In 2008, a set of comprehensive climate scenarios were prepared for the California Energy Commission's Public Interest Energy Research (PIER) Climate Change Research Program, including estimates of future sea-level rise (Cayan et al. 2009). Under medium to medium-high emissions scenarios, researchers estimated that mean sea levels could rise by between 1 m and 1.4 m by the year 2100. Rising sea level, combined with the associated storm surge, wave runup, and related factors will have two important effects: first, it exposes areas that were previously considered safe from flooding to new risks; second, in areas that are already at risk, it will increase the frequency and severity of flooding. In areas where the coast erodes easily, sea-level rise is also likely to accelerate shoreline recession due to erosion. Erosion of some barrier dunes may also expose previously protected areas to flooding. Erosion risks to California's costs are described in detail elsewhere (Heberger et al. 2009; Revell et al. 2011).

National studies on the economic cost of sea-level rise suggest that while adapting to climate change will be expensive, so are the costs of doing nothing (Titus et al. 1992 and Yohe et al. 1996). Flooding in the United States is currently responsible for an average of 140 deaths per year and $6 billion in property losses (USGS 2006). Continued development near coastlines and sea-level rise threaten to worsen vulnerability and increase future losses. Because flood damages and cost are highly site-specific, regional analyses are critical for guiding land-use decisions and evaluating adaptive strategies.

A previous study of the San Francisco Bay area (Gleick and Maurer 1990) concluded that a 1-meter sea-level rise would threaten existing commercial, residential, and industrial structures around San Francisco Bay valued at $48 billion (in year 1990 dollars). Building or strengthening levees and seawalls to protect existing high-value development was estimated to require a capital investment of approximately $1 billion (in year 1990 dollars) and an additional $100 million per year for ongoing maintenance. Gleick and Maurer also noted that substantial areas of the San Francisco Bay, especially wetlands and marshes, could not be protected and would likely be damaged or lost. A more recent analysis by Neumann et al. (2003) found that the economic cost of a 1.0 m sea level rise along the entire California coast would range from $148 million to $635 million (in year 2000 dollars), which includes the cost of protecting existing structures using beach nourishment, levees, and seawalls.

In this study, we analyzed the threats to California's 2,000 miles of coast from increased flooding and erosion caused by climate change induced sea-level rise, together with the associated storm and wave effects. While this article summarizes threats to the state's population and infrastructure from a single scenario of sea-level rise, more detail on the timing and degree of vulnerability for different levels of rise are included in the comprehensive report. The full study also covered erosion impacts, effects on wetlands, costs of coastal defenses, and issues of social and environmental justice related to sea-level rise (Heberger et al. 2009). No reliable estimates of how climate changes would alter El Niño or La Niña events are yet available, and we did not include them here. Future assessments could integrate that information when it becomes available.

2 Methods

Numerous studies have attempted to quantify the cost of sea-level rise and have been based primarily on a framework developed in Yohe (1989) and refined in Yohe et al. (1996) and Yohe and Schlesinger (1998). Yohe used a cost-benefit model to evaluate the property at risk and the cost of protecting or abandoning that property. He assumed that property will be protected if its value exceeds the cost to protect it at the time of flooding. Protection costs were based on the construction cost of a protective structure such as a seawall. If the value of the property does not exceed the cost of protection, Yohe assumed that the property would be abandoned, incurring a cost equal to the value of the land and structure at the time of inundation. The total cost to society of sea-level rise using this approach is the sum of the protection cost plus the value of the lost property.

To determine the value of lost property, the Yohe approach considers land and structure values separately. In most locations, coastal land commands a premium price, with the price declining as one moves inland. With inundation, the Yohe method assumes that land values will simply migrate inland, and thus, the economic value of lost land is equal to the economic value of interior land. The value of structures is calculated under two conditions: with and without foresight. With perfect foresight, the economic value of structures is assumed to depreciate over time as the “impending inundation and abandonment become known” (Yohe and Schlesinger 1998), approaching $0 at the time of inundation. Without foresight, the structure value does not depreciate.

There are several important shortcomings to this approach; the just-in-time approach to coastal protection is unlikely, and prioritizing protection based solely on property value fails to reflect a range of other societal concerns for public access, habitat, scenery, and social justice. This analysis used a different approach to estimate a value of assets potentially at risk from sea-level rise. We performed a planning-level estimate of economic vulnerability by summing the replacement value of property that will be vulnerable to damaging floods in the future, assuming no adaptation mechanisms are undertaken. Actions taken to defend the coast, expand wetland buffers, or floodproof structures, if taken on time, are likely to prevent potential damages. We also note that a number of potential costs of sea-level rise are excluded from this analysis, such as relocation expenses, lost wages and business revenue, and value lost by lost or degraded coastal ecosystems.

We based our analysis on a 1%-annual chance coastal flood, or the so-called 100-year flood. The terminology used to describe the recurrence interval can be misleading and is often misinterpreted. A “100-year flood” does not refer to a flood level that occurs every 100 years. Rather, it refers to a flood that has a 1/100, or 1%, chance of occurring in any year. Over the course of a typical 30-year mortgage a 100-year flood has a 26% chance of occurring one or more times. We used scenarios of sea-level rise and mapped areas likely to be inundated by a 100-year flood under current conditions, and conditions in the year 2100. Additional temporal and spatial estimates and details are provided in Heberger et al. (2009). Geographic layers depicting flood extents were overlaid with geospatial data using GIS software to produce quantitative estimates of the population, infrastructure, and replacement value of property at risk from sea-level rise, as well as the impacts on harder-to-quantify coastal ecosystems. Our estimates of populations at risk are based on current population data, not a projection of populations that might be at risk in the future. If no policies are put in place to limit new exposure in areas at risk of rising seas, our estimates will underestimate impacts following years of population growth and development. If, however, policymakers are proactive about reducing coastal risks in coming decades, the levels of risk could be substantially reduced.

The study area spans approximately 1,800 km (1,100 miles) of California's Pacific coast and 1,600 km (1,000 miles) of shoreline along the inside perimeter of the San Francisco Bay. The San Francisco Bay study area extends from the Golden Gate in the west to Pittsburg, California, in the east and San Jose in the south. The eastern boundary of the San Francisco Bay study was set according to where United States Geological Survey (USGS) researchers were able to accurately model flood elevations in the Bay.

2.1 Sea-level rise projections

Sea levels are constantly in flux, subject to the influence of astronomical forces from the sun, moon, and earth, as well as meteorological effects like El Niño. Measurements at tide gages around the world indicate that the global mean sea level is rising. Water level measurements from the San Francisco gage (NOAA 2009), shown in Fig. 1, indicate that mean sea level rose by an average of 2.01±0.21 mm per year from 1897 to 2006, equivalent to a change of 20 cm (8 inches) in the last century. (The solid vertical line coincides with the San Francisco earthquake of 1906. NOAA researchers have fit separate trendlines before and after an apparent datum shift that occurred in 1897 to account for possible vertical movement of the land surface where the gages is located, disrupting consistent measurements.)

Sea levels are expected to continue to rise, and the rate of increase will likely accelerate. The Intergovernmental Panel on Climate Change (IPCC), in its Fourth Assessment Report (Meehl et al. 2007), estimated that sea levels may rise by 0.2 m to 0.6 m by 2100, relative to a baseline of 1980–1999, in response to changes in oceanic temperature and the exchange of water between oceans and land-based reservoirs, such as glaciers and ice sheets (Meehl et al. 2007). More recent research indicates that sea-level rise from 1993 to 2006 has outpaced the IPCC projections (Rahmstorf 2007; Allison et al. 2009). Previous models failed to include ice-melt contributions from the Greenland and Antarctic ice sheets and may underestimate the change in volume of the world's oceans.

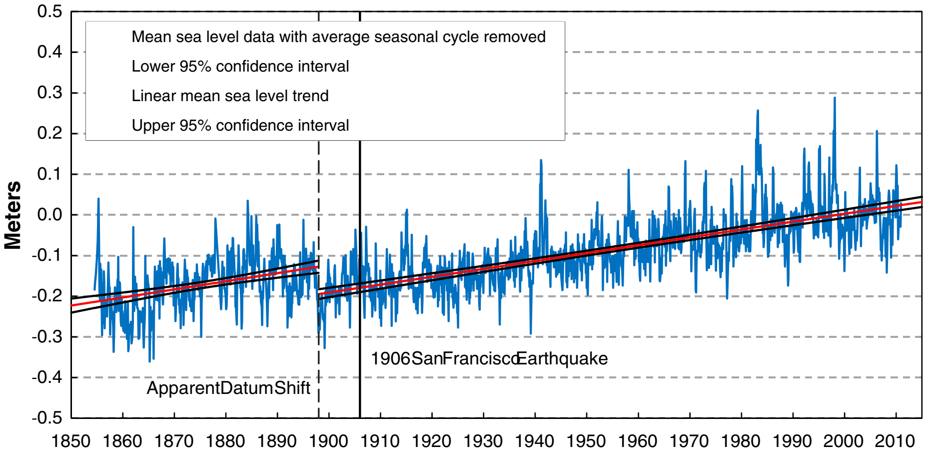

Fig. 1 Trend in monthly mean sea level at the San Francisco tide station from 1897 to 2006 (records begin in 1854; the solid black line represents the major earthquake in 1906). Redrawn from NOAA Sea Levels Online, http://co-ops.nos.noaa.gov/sltrends/sltrends_station.shtml?stnid=9414290

To address these new factors, the California Climate Impacts Study developed sea-level rise forecasts using a methodology developed by Rahmstorf (2007). Cayan et al. (2009) produced global sea-level estimates based on projected surface air temperatures from global climate simulations for both the IPCC A2 and B1 scenarios. The A2 storyline is characterized by “self-reliance and preservation of local identities” (IPCC 2000). Population is expected to continuously increase, but economic growth and technological development are expected to be slow. The B1 storyline has the same population projections as the A1 storyline but “rapid changes in economic structures toward a service and information economy, with reductions in material intensity, and the introduction of clean and resource-efficient technologies.” Additionally, Cayan et al. (2009) modified the sea-level rise estimates to account for water trapped in dams and reservoirs that artificially reduced runoff into the oceans during the 20th century (Chao et al. 2008).

Cayan et al. estimate that mean sea level along the California coast will rise by 1.0 m under the B1 scenario by the year 2100, and 1.4 m under the A2 scenario, as shown in Fig. 2. The highest scenario, A1FI assumes continued high use of fossil fuels; it was not used in this analysis, but is shown for comparative purposes.

2.2 Mapping the Pacific coast

Sea-level rise increases the risk of flooding in low-lying coastal areas. For the California coast, we used GIS software (ESRI’s ArcGIS Desktop 9.2) to produce maps of the areas at risk of inundation from a 1.4 m sea-level rise. For the Pacific coast, we approximate the potential future flood impact by adding projected sea-level rise estimates to water levels associated with a 100-year flood, i.e., current flood elevations for the 100-year flood are increased by 1.4 m, the projected increase in sea level by 2100 under the A2 scenario.

Existing flood levels were based on estimates of the 100-year flood elevation (also called the *base flood elevation* or BFE) from Flood Insurance Studies published by the Federal Emergency Management Agency (FEMA). Flood elevations are a function of a number of local factors, and vary considerably even over a few miles of coast. In California, coastal base flood elevations range from 10.5 m in Mendocino County in the north to 2.3 m in San Diego Harbor in the south (all elevations for the study are reported relative to the North American Vertical Datum of 1988 or NAVD88). As part of this project, we worked with researchers and coastal engineers to develop a GIS layer of approximate 100-year flood elevations for the entire California coast. To develop this new dataset, Battalio et al. (2008) performed the following tasks:

1. Compiled available coastal flood BFEs published by FEMA for the California coast.
2. Estimated BFEs where FEMA estimates are not available using professional judgment.

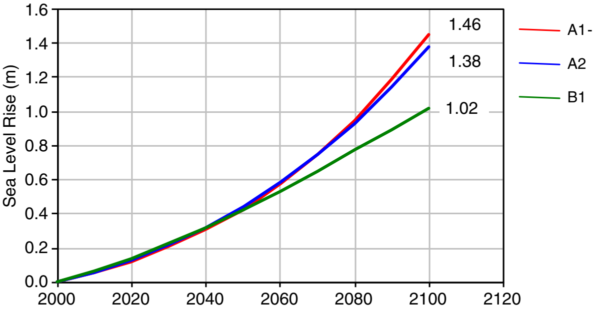

Fig. 2 Scenarios of sea-level rise to 2100. Source: Dan Cayan, Scripps Institution of Oceanography. Based on simulations using the NCAR CCSM3 general circulation model. Sea level changes forecast using the method described in Rahmstorf, 2007

3. Converted elevations to the North American Vertical Datum of 1988 (NAVD88).
4. Adjusted elevations to nearest half foot based on observed sea-level rise to present day.

Our approach assumes that all tide datums, e.g., mean high tide and flood elevations, will increase by the same amount as mean sea level. There is some evidence that this assumption may not always hold true. For example, Flick et al. (1999) found that, in San Francisco, one measure of high tide, mean higher high water (MHHW), was increasing faster than mean sea level.

We used automated mapping methods in GIS to delineate areas inundated by the current and future flood elevations. The key inputs to this analysis are digital elevation models (DEMs), gridded datasets that contain values representing elevations of the earth's surface. We used the most accurate, high-resolution, up-to-date terrain data available.

The elevation datasets used for this project are summarized in Table 1. For much of the Central and Northern California coast, high-accuracy Light Detection and Ranging (LIDAR) data were available from Airborne LIDAR Assessment of Coastal Erosion (ALACE) project, a partnership between NOAA, the National Aeronautics and Space Administration (NASA), and USGS. The ALACE project emphasized shoreline change, and so the data were available for a relatively narrow swath of the coast. The coverage did not always extend inland far enough to fully map the coastal floodplain. In addition, there were several gaps in coverage along the entire coast.

We supplemented the LIDAR data, filling in gaps in coverage with topographic information from the USGS National Elevation dataset. Although these data are at a lower resolution and accuracy, they allowed us to map the entire coast. For portions of the Southern California coast, Interferometric Synthetic Aperture Radar (IfSAR) data were available from NOAA. These data are of coarser resolution than the LIDAR data described above, i.e., 3-meter pixel resolution compared to 2-meter, and have less vertical accuracy, i.e., ±2.2 m for the IFSAR data compared to ±0.07 m for the LIDAR data. Additional details on the GIS data sources and processing steps are summarized in Heberger et al. (2009).

GIS raster math tools were used to compare the elevation of land surfaces with the adjacent flood elevation to determine the extent of flooding. The resulting inundation grids were boundary-smoothed and small isolated ponds and islands were removed. The raster datasets were then converted to vector polygons and merged so they could be used in the social and economic analyses.

Table 1 Elevation datasets used for mapping coastal flood risks

Dataset	National Elevation Dataset	ALACE 1998	ALACE 2002	So. Cal. IFSAR
Source/Mission	USGS	NASA, NOAA, USGS	NASA, NOAA, USGS	NOAA
Geographic coverage	National	Stinson Beach to Santa Barbara	Northern border of California to Stinson Beach	Santa Barbara to Mexican border
Data collection method	Various	LIDAR	LIDAR	IFSAR
Horizontal Resolution	10 m	3 m	2 m	3 m
Year collected	Various	1996-2000	2002	2002-2003
Stated vertical accuracy	±7.5 m	±0.15 m	±0.20 m	±2.2 m

2.3 Mapping San Francisco Bay

Sea-level rise inundation maps were generated from the climate scenarios by the USGS (Knowles 2009) using a suite of computer models under the CASCADE project that simulate the hydrodynamics of San Francisco Bay under future climate scenarios. The CASCADE project allowed us to conduct a more detailed analysis of impacts along the margins of the San Francisco Bay. Similar models have not yet been developed for other sections of the coast.

To estimate inundated areas in the Bay, "the highest resolution elevation data available were assembled from various sources and mosaicked to cover the land surfaces of the San Francisco Bay region. Next, to quantify high water levels throughout the Bay, a hydrodynamic model of the San Francisco Estuary was driven by a projection of hourly water levels at the Presidio. This projection was based on a combination of climate model outputs and empirical models and incorporates astronomical, storm surge, El Niño, and long-term sea level rise influences" (Knowles 2009). The Bay computer model simulates the water surface elevation for each hour from 2000 to 2009. Inputs to the model include both upstream inflows and downstream water surface elevations. The Bay model simulates the water surface elevation for each hour from 2000 to 2099 and is driven by both upstream and downstream boundary conditions. Based a statistical analysis of this output, flood layers of a 0.5 m, 1.0 m, and 1.4 m sea-level rise were produced for five flood recurrence intervals for each of four years between 2000 and 2099. The analysis presented in Heberger et al. (2009) reports results for each sea-level rise scenario. In this paper, we report current risk based on year 2000 conditions, and those in the year 2100, based on a 1.4-meter sea-level rise.

2.4 Estimating population impacts

To determine populations at risk if no adaptation actions are taken, we intersected the inundation layers with the census block boundaries (United States Census Bureau 2000) in GIS. We used year-2000 population data aggregated by census block, the smallest geographic unit for which the Census Bureau reports data collected from all households. We make the assumption common in GIS analyses that the population is distributed evenly within a block's boundaries. So if our mapping shows that 50% of a 500-person census block is inundated by a flood, we estimate that 250 people are at risk. This method may result in an underestimate (where the houses are clustered on the coast) or an overestimate (when the houses are set back from the coast). This is a limitation to many demographic analyses done in a GIS, and despite its lack of accuracy, is suitable for a state-wide planning-level estimate.

We investigated the race, income, and other characteristics of the population vulnerable to current and future coastal flooding through data from the 2000 US Census, also aggregated at the census block level. In the environmental justice literature, "of color" refers to those who reported their race as other than white in the 2000 US Census; this included American Indian or Alaska Native; Asian; Black or African American; Native Hawaiian or Other Pacific Islander.

2.5 Determining infrastructure impacts

Data for the replacement value of buildings and contents was taken from datasets supplied with the HAZUS model. HAZUS is a computer model for conducting standardized, nationally applicable natural hazards loss estimation developed for FEMA's Mitigation Division by the National Institute of Building Sciences (FEMA 2006). HAZUS uses a database called the "General Building Stock Inventory" that contains the replacement value of buildings and contents in each Census block. Replacement values are based on data from a number of sources including the U.S. Census Bureau, Dun & Bradstreet (a business listing service), and the U.S. Department of Energy. The HAZUS model estimates direct economic losses based on the repair and replacement of damaged or destroyed buildings and their contents, and includes: a) cost of repair and replacement of damaged and destroyed buildings, b) cost of damage to building contents, and c) losses of building inventory (contents related to business activities).

To determine the replacement value for structures in the areas at risk, we intersected the inundation layers with year 2000 census block data. As with the demographic analysis, we assumed that the building value is distributed uniformly over a census block's area. It should be noted that replacement value is almost always lower than the actual market value of a building. We compared replacement costs and the market value of one class of building, single-family homes, at a few locations along the California coast and found that the replacement costs in HAZUS may substantially underestimate actual market values for residential properties. According to the HAZUS database, the median home replacement values range from $63,000 in Del Norte County to $135,000 in San Mateo County. In comparison, the median home price in California was $286,000 in November 2008. In Northern California, the median price was $307,000, and in the San Francisco Bay Area, the median price was $474,000. This underscores the fact that a building's market value is usually greater than its replacement cost.

Important transportation infrastructure is also at risk of flooding and erosion from projected increases in sea-level rise. We estimated the miles of roadways and railroads at risk by overlaying the GIS inundation and erosion hazard layers with transportation data published by TeleAtlas (2008). The polylines in the TeleAtlas roads GIS database are two-dimensional; since we do not have any additional information on roadways' elevations, we assume they are clamped to the ground as it is represented by our terrain data. This assumption may be violated for some elevated roadways, as well as bridges and tunnels. Additionally, the railroad file does not provide information on the number of tracks (e.g., single or double), so the miles of railroad affected may underestimate actual miles of track.

We did not attempt to quantify the cost of flooding on roads and railways. In some cases, damages may be minor, resulting in temporary closures and modest repairs. As the frequency and intensity of flooding increases, however, closures may become longer and the cost of repair may rise. Eventually, roads and railways may need to be raised or rerouted. The cost of repairing, moving, or raising roads and railways is highly site-specific and dependent on the level of damage that is sustained. Furthermore, flooding and closure of roads and railways can have significant impacts on the local, state, and national economy. Railways are particularly important for moving goods in and out of California ports. In addition, road closures can prevent people from getting to work, causing major economic disruptions. Thus, the information on roads and railways is presented as miles of structures at risk rather than value.

A number of other facilities along the coast are also at risk of flooding and erosion. We evaluated the sites and facilities at risk by overlaying the GIS inundation layer with the future hazard zones. Data on the locations of schools and emergency facilities come from the HAZUS geographic database (FEMA 2006). Data on licensed healthcare facilities were obtained from the California Office of Statewide Health Planning and Development (2006). Data on coastal power plants were provided by the California Energy Commission.

We obtained data on U.S. EPA-monitored hazardous materials sites from the U.S. EPA Geospatial Data Access Project (US EPA 2008), including Superfund sites, hazardous waste generators, facilities required to report emissions for the Toxics Release Inventory, facilities regulated under the National Pollutant Discharge Elimination System (NPDES), major dischargers of air pollutants with Title V permits, and brownfields (abandoned industrial sites, many of which have polluted soil and groundwater).

We developed a custom GIS layer of wastewater treatment plants based on data in the U. S. EPA's Permit Compliance System (PCS) database. The coordinates were inaccurate, so we adjusted the location of plants based on aerial photos. Also, we noticed that a few facilities were missing, so we added facilities based on telephone and Internet research.

3 Results

In this analysis, we used the extent of the 100-year coastal floodplain to evaluate vulnerability to inundation. Our analysis shows that a significant amount of land, infrastructure, and property are already located in the 100-year floodplain. Under year-2000 conditions, we estimate that 1,200 km^2 (460 square miles) are in the coastal floodplain; with a 1.4-m sea level rise, the floodplain could expand to 1,500 km^2 (570 square miles). The following sections summarize the vulnerable population and infrastructure located in the floodplain areas.

3.1 Population at risk

We estimated 260,000 people, or about 1% of the population of California's coastal counties, live in areas that are currently vulnerable to a 100-year flood event. As sea levels rise, the area and the number of people vulnerable to flooding also rise. We estimate that a 1.4 m sea-level rise will put around 480,000 people at risk from a 100-year flood event. Table 2 reports the population vulnerable to a 100-year flood event along California's coast by county. Populations in San Mateo and Orange Counties are especially vulnerable, accounting for about half of those at risk with a 1.4 m sea-level rise. Large numbers of residents in Alameda, Marin, and Santa Clara counties are also at risk.

An analysis of the vulnerable population's racial makeup revealed that sea-level rise induced flooding disproportionately affects whites in 10 of 20 counties along the coast. In Los Angeles County, for example, 72% of those affected are white, while only 31% of the population in the county is white. Conversely, in 10 of the 20 counties studied, communities of color are disproportionately impacted, including every county around San Francisco Bay. The greater proportion of people of color in areas affected by sea-level rise highlights the need for these counties to take concerted efforts to understand and mitigate potential environmental injustice. A more detailed demographic assessment and discussion of environmental justice is available in Heberger et al. 2009.

3.2 Emergency and healthcare facilities

Table 3 shows the schools and emergency and healthcare facilities that are currently at risk from a 100-year flood event and that will be at risk following a 1.4 m sea-level rise. Numerous schools are vulnerable as well. In 2000, 65 schools were vulnerable to a 100-year flood event. With a 1.4 m sea-level rise, however, the number of schools at risk doubles, rising to 137 schools. Significant numbers of healthcare facilities are also at risk.

Table 2 Population vulnerable to a coastal 100-year flood in California, by county (* denotes counties on San Francisco Bay)

County	Currently at risk	At risk with 1.4 m SLR	Percent increase
Alameda*	12,000	66,000	450
Contra Costa*	840	5,800	590
Del Norte	1,700	2,500	47
Humboldt	3,600	7,500	110
Los Angeles	3,600	13,000	260
Marin*	26,000	40,000	54
Mendocino	520	630	21
Monterey	10,000	14,000	40
Napa*	760	1,500	97
Orange	70,000	110,000	57
San Diego	570	690	21
San Francisco*	3,600	10,000	180
San Luis Obispo	4,600	6,300	37
San Mateo*	91,000	130,000	43
Santa Barbara	660	1,300	97
Santa Clara*	13,000	31,000	140
Santa Cruz	4,500	5,600	24
Solano*	3,700	12,000	220
Sonoma*	3,200	9,600	200
Ventura	7,000	16,000	130
State Total	260,000	480,000	85

In 2000, there were 20 healthcare facilities at risk of a 100-year flood. With a 1.4 m sea-level rise, however, the number of healthcare facilities at risk rises to 55.

3.3 Hazardous materials sites

The presence of land or facilities containing hazardous materials in areas at risk of inundation increases the risk of release of these materials into the environment and exposure to toxic chemicals for nearby residents and ecosystems. For example, sediment samples in New Orleans taken 1 month after Hurricane Katrina found excess levels of arsenic, lead, and the gasoline constituent benzene, all considered toxic pollutants by the U. S. EPA (Adams et al. 2007). Those living or working near these facilities may be affected by the potential release and spreading of contamination through floodwaters or through flood-related facility malfunctions.

Table 3 Schools, emergency and healthcare facilities at risk from a 100-year coastal flood following a 1.4 m sea-level rise

Facility	Current risk	Risk with 1.4 m sea-level rise
Schools	65	137
Healthcare facilities	20	55
Fire stations and training facilities	8	17
Police stations	9	17

We evaluated sites containing hazardous materials at risk of flooding along the Pacific coast and San Francisco Bay. Here, we report on a range of sites monitored by the U.S. EPA, including Superfund sites; hazardous waste generators; facilities required to report emissions for the Toxics Release Inventory; facilities regulated under the National Pollutant Discharge Elimination System (NPDES); major dischargers of air pollutants with Title V permits; and brownfield properties. An estimated 130 U.S. EPA-regulated sites are currently vulnerable to a 100-year flood event, reported in Table 4. Nearly 60% of these facilities are located in San Mateo and Santa Clara counties, in the area known as Silicon Valley.

The number of facilities at risk increases by 250% with a 1.4 sea-level rise, with more than 330 facilities at risk of a 100-year flood event. San Mateo, Alameda, and Santa Clara counties have the highest numbers of U.S. EPA-regulated sites within future flood areas.

3.4 Roads and railways

There are many roads and railways that are vulnerable today and with sea-level rise. Under year 2000 conditions, 1,600 miles of roads and highways are at risk from a 100-year flood (of these, 220 miles are highways). With a 1.4 m sea-level rise, the mileage doubles to 3,500 miles, of which 430 miles are highway. The mileage of at-risk railroads increases from 140 under current conditions to 280 miles by 2100. About 50% of the roadways and 60% of the railways at risk are concentrated around the San Francisco Bay. Much of this infrastructure is protected by levees, seawalls, and other structures, which are not likely to provide adequate protection against higher seas unless they are raised and strengthened. Note that we do not provide estimates of the value of the transportation infrastructure at

Table 4 US EPA-regulated sites within areas vulnerable to a 100-year coastal flood event following a 1.4 m sea-level rise

County	Sites currently at risk	At risk with 1.4 m sea-level rise
Alameda	6	63
Contra Costa	4	22
Del Norte	1	3
Humboldt	10	13
Los Angeles	13	26
Marin	1	6
Monterey	1	1
Napa	1	2
Orange	4	16
San Diego	–	13
San Francisco	–	4
San Luis Obispo	–	1
San Mateo	39	78
Santa Barbara	1	5
Santa Clara	41	53
Santa Cruz	5	6
Solano	2	5
Sonoma	–	2
Ventura	5	13
Total	134	332

Data Source: EPA Geospatial Data Access Project 2008 risk. The economic value of roads and railroads is a complicated subject, and reliable information was not readily available for our study.

3.5 Power plants

Many of California's thermoelectric power plants are located on the coast, as they make use of seawater for cooling, and a number of them may be vulnerable to sea-level rise. In some cases, actual power generating infrastructure is at risk; in others, intake or other peripheral structures are vulnerable. Specific site assessments are needed at each coastal plant to determine the actual risk. We identified 30 coastal power plants that are potentially at risk, with a combined capacity of more than 10,000 megawatts (MW), from a 100-year flood with a 1.4 m sea-level rise. The capacities of the vulnerable power plants range from a relatively small 0.2 MW plant to one that is more than 2,000 MW. The majority of vulnerable plants are located in Southern California and along the San Francisco Bay. Figure 3 shows the locations of vulnerable power plants in Southern California.

3.6 Wastewater treatment plants

We identified a total of 28 vulnerable wastewater treatment plants: 21 on the San Francisco Bay and 7 on the Pacific coast. The combined capacity of these plants is 530 million gallons per day (MGD). Figure 4 shows the locations of the plants at risk in the Bay Area. Inundation from floods could damage pumps and other equipment, and lead to untreated sewage discharges. Besides the flood risk to plants, higher water levels could interfere with discharge from outfalls sited on the coast. This could require retrofitting discharge systems with pumps, redesigning outfalls, or other adaptation responses. Cities and sanitation districts should begin to assess how higher water levels will affect plant operations and plan for future conditions.

3.7 Seaports

Goods movement in California, and especially the San Francisco Bay Area, is critically important to the state's economy. A recent report by the Metropolitan Transportation Commission stated that "over 37% of Bay Area economic output is in manufacturing, freight transportation, and warehouse and distribution businesses. Collectively, these goods-movement-dependent businesses spend approximately $6.6 billion [annually] on transportation services. The businesses providing these services also play a critical role as generators of jobs and economic activity in their own right" (Metropolitan Transportation Commission 2004).

Our assessment of future flood risk with sea-level rise show significant flooding is possible at California's major ports in Oakland, Los Angeles, and Long Beach. These ports are important not only to the economy of California, but also to the nation. The Port of Los Angeles-Long Beach, for example, handles 45–50% of the containers shipped into the United States. Of these containers, 77% leave the state; half by train and half by truck (Christensen 2008). Many port managers have already experienced how disasters can affect their operations. Following the Loma Prieta earthquake in 1989, for example, the Port of Oakland sustained damages that interrupted business for 18 months. These disruptions have global economic implications, as evident by a 2002 contract dispute that resulted in a work slowdown at west coast ports and cost the U.S. economy an estimated $1 billion to $2 billion per day. Others speculated that Japan and China would lose several percentage points off their gross domestic product if California's ports closed for longer than a week (Farris 2008).

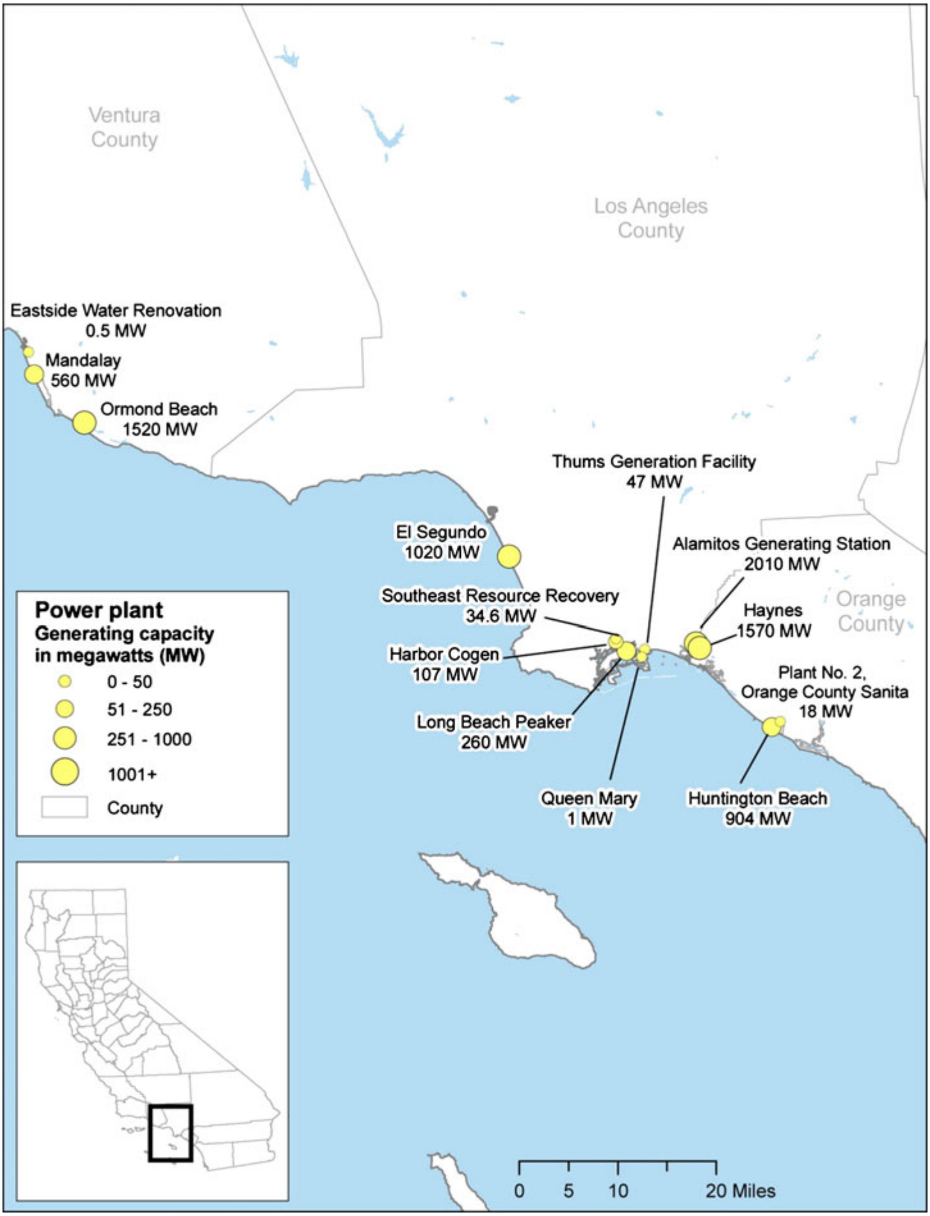

Fig. 3 Southern California power plants vulnerable to a 100-year coastal flood with a 1.4 m sea-level rise

In addition to directly affecting port operations, sea-level rise may cause other interruptions to goods movement at ports. Sea-level rise can reduce bridge clearance, thereby reducing the size of ships able to pass or restricting their movements to times of low tide. Higher seas may cause ships to sit higher in the water, possibly resulting in less efficient port operations (National Research Council 1987). These impacts are highly site specific, and somewhat speculative, requiring detailed local study to verify.

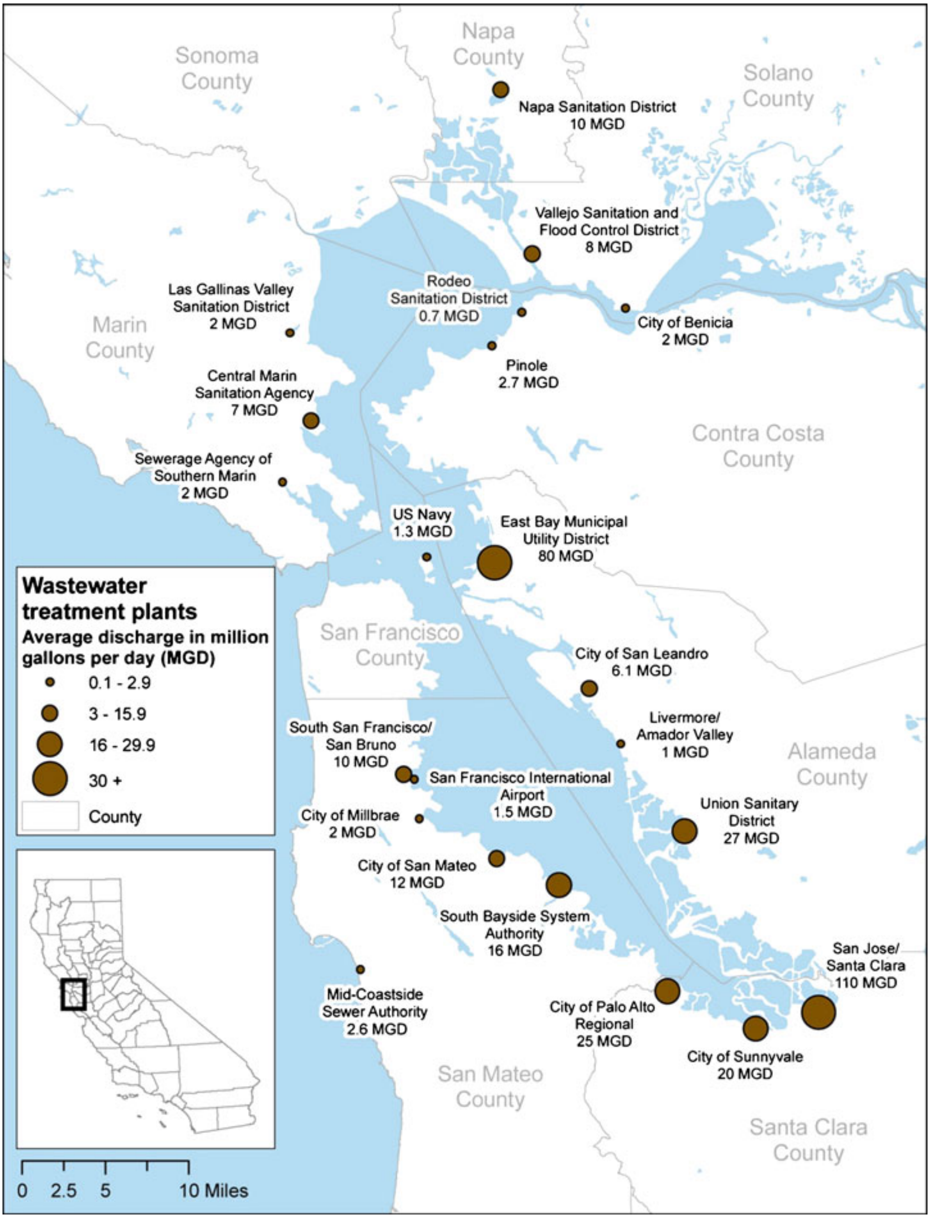

Fig. 4 Wastewater treatment plants on the San Francisco Bay vulnerable to a 100 year flood with a 1.4 m sea-level rise

3.8 Airports

The San Francisco and Oakland airports are vulnerable to flooding with a 1.4-meter sea-level rise. Other major airports near the coast, such as the San Diego, San Jose, and Los Angeles airports, were not identified as vulnerable in our analysis.

The economic impact of a disruption in airport traffic in San Francisco and Oakland is potentially large, and it would have significant effects on the state and regional economy. In 2007, the Oakland International airport transported 15 million passengers and 647,000 metric tons of freight. Activity at the San Francisco International airport is even greater than in Oakland. The San Francisco International Airport is the nation's thirteenth busiest airport, transporting 36 million people in 2007 (Airports Council International 2008). It also plays a significant role in the movement of goods regionally and internationally. In 2007, the San Francisco airport handled 560,000 metric tons of freight. San Francisco Airport ranked twelfth among foreign trade freight gateways by value of shipments in 2005, handling $25 billion in exports and $32 billion in imports (US Department of Transportation 2006), more than double that of the $23.7 billion handled by vessels at the Port of Oakland.

3.9 Property (buildings and contents)

Significant property is at risk of flooding from 100-year flood events as a result of a 1.4 m sea-level rise. Costs cited in the following paragraphs are replacement costs of buildings and contents, and not current market value of the land or buildings. For much of coastal California, market value is significantly greater than construction costs alone. The property at risk from a 100-year flood increases from $51 billion under baseline conditions to $99 billion with a 1.4 m sea-level rise. Two-thirds of the property at risk is concentrated on San Francisco Bay (Table 5) indicating that this region is particularly vulnerable to impacts associated with sea-level rise due to extensive development on the margins of the Bay.

Table 5 Replacement value of buildings and contents (millions of year-2000 dollars) at risk from a 100-year coastal flood, by county

County	Current risk	Risk with 1.4 m SLR
Alameda	3.3	15
Contra Costa	0.19	0.98
Del Norte	0.24	0.35
Humboldt	0.68	1.4
Los Angeles	1.4	3.8
Marin	5	8.7
Mendocino	0.12	0.15
Monterey	1.7	2.2
Napa	0.22	0.41
Orange	11	17
San Diego	0.69	2
San Francisco	0.78	4.9
San Luis Obispo	0.22	0.36
San Mateo	17	24
Santa Barbara	0.46	1.1
Santa Clara	3.7	7.8
Santa Cruz	2.4	3.3
Solano	0.62	1.9
Sonoma	0.32	0.48
Ventura	0.98	2.2
Total	51	99

Figure 5 shows the value of property in each county vulnerable to sea-level rise, with the size of the circle proportional to the value.

Within each region, vulnerability to sea-level rise is highly variable. The risk is greatest in San Mateo County, where $24 billion in property is vulnerable. About $17 billion of property, or about 50% of the total property at risk, is in Orange County. In the San

Fig. 5 Replacement value of buildings and contents vulnerable to a 100-year coastal flood with a 1.4 m sea-level rise

Francisco Bay area, Alameda, Marin, Santa Clara, and San Francisco counties are also exposed to a high degree of risk, with potential damages in the billions.

All economic sectors are vulnerable to impacts associated with sea-level rise. Table 6 reports the value of buildings and contents at risk of flooding by major economic sector. About 59% of the assets at risk are residential. The commercial sector, accounting for 27% of the value at risk, will also encounter significant costs. Agriculture, education, religion, and government each account for about 1% of the assets at risk, thus, their exposure to risk is relatively small.

4 Limitations of the analysis

The study covered a large area using approximate methods, and it is important to keep in mind its limitations when interpreting the results. First, there are uncertainties associated with the level of sea-level rise that will be experienced on the California coast in coming decades. The estimate used in this article comes from one method of predicting sea level rise, given a certain emissions scenario, as described by Cayan et al. (2009). Second, there are a number of uncertainties associated with estimating the current and future flood elevations. We used 100-year coastal flood elevations published by FEMA in flood insurance studies for a number of coastal communities. These estimates were developed by different parties over the past 20 years using a variety of methods that vary in detail and accuracy. Third, our method for using flood elevations to delineate floodplains is subject to further uncertainties. This is due to inaccuracies in the digital elevation data used in the analysis, and the mapping methods. We did not use the detailed methods that would be expected in a site-specific floodplain delineation, for example using a detailed hydrodynamic model to estimate how floodwaters will spread overland. Fourth, we made the simplifying assumption that the shoreline profile is constant, and will not change as a result of sea-level rise, erosion, or flooding. In reality, natural shorelines (and even some protected man-made shorelines) are constantly in flux. However, it remains extremely difficult to accurately predict how shorelines will migrate or change in response to rising sea levels (Pilkey and Cooper 2004).

Further uncertainty is introduced by the approximate methods for translating floodplain extents into physical impacts. A well-established method to estimate flood damages to buildings is the use of "depth-damage curves" that relate the depth of flooding to the percentage of a structure's value that is lost in a flood (FEMA 2006). The depth-damage curve method was inappropriate for our analysis for two reasons. First, we are not aware of

Table 6 Value of buildings and contents at risk from a 100-year flood after a 1.4 m sea-level rise, by economic sector (millions of year-2000 dollars)

Sector	Current risk	Risk + 1.4 m SLR	% of total value at risk in future
Residential	43	58	59%
Commercial	15	27	27%
Industrial	5.8	11.0	11%
Religion	0.61	1.00	1.0%
Government	0.44	0.86	0.9%
Education	0.57	0.85	0.9%
Agriculture	0.34	0.42	0.4%
Total	66	99	100%

existing datasets giving the first-floor elevation for buildings near California's coast. While we could have assumed that structures were built "at grade" (e.g. clamped to the earth's surface) or at a constant elevation, there was insufficient data to support this or a similar assumption. Second, the magnitude of damages caused by flooding are affected by factors other than the depth of flooding, such as the velocity of floodwaters, duration of flooding, and whether there is floating debris that can act as a "battering ram." As our study was meant to broadly identify risk over a large area, we did not perform the detailed modeling to quantify these parameters.

For the flood analysis, we estimated the economic cost of varying levels of sea-level rise (and associated storm surge and flooding) based on estimates of the replacement value of buildings and their contents. Only a single scenario is summarized here, though more detailed results can be found in Heberger et al. (2009). We did not include the value of lost land, which should be included if inundation is permanent or leads the abandonment of property. Flooding can also cause serious economic and social disruptions that are not captured in estimates of the buildings and infrastructure. For example, flooding events can cause deaths and injuries. When roadways are flooded or eroded, it can cause a cascade of impacts, such as preventing people from driving to work, blocking evacuation routes, or interfering with the movement of emergency vehicles. It is difficult to put a price tag on any one of these impacts. A more detailed economic analysis could include transportation risks, lost work days, health issues, or impacts on migratory bird habitat.

We also did not factor in any expected changes in population density or the level of development in the regions at risk over the next century; these are largely unknown and will be determined by future policies. If policies are put in place to reduce development in flood-prone regions, society could reduce future risks, and future costs. While limiting coastal development (an institutional adaptation) is likely the most effective way to reduce risk, this approach can also incur costs. If current population trends continue, many more people and places will be affected. We make no estimates of these changes, but future research could look at different scenarios for growth and coastal development and integrate them into the assessment framework similar to the one developed here.

Lastly, we note that we analyzed only a "do nothing" scenario which does not take into account potential adaptation mechanisms. In this regard, the study presents the maximum vulnerability under the climate change scenarios we considered. Future damages from coastal flooding can be lessened by taking appropriate actions; these may include coastal defenses, wetland buffers, and floodproofing buildings. Future research should better characterize and if possible quantify how various programs and policies may change the risk California coastal communities may face.

5 Conclusions

Rising sea levels and associated coastal flooding and damage will be among the most significant impacts of climate change to California. Sea level will rise as a result of thermal expansion of the oceans and an increase in ocean volume as land ice melts and runs off. Over the past century, sea level has risen nearly 20 cm (8 inches) along the California coast and climate models suggest substantial increases in sea level due to climate change over the coming century and beyond. This study evaluates the current population, infrastructure, and property threatened by projected sea-level rise if no actions are taken to protect the coast. The sea-level rise scenario was developed by the State of California from medium to medium-high greenhouse gas emissions scenarios from the Intergovernmental Panel on Climate Change (IPCC) but does not reflect the worst case sea-level rise that could occur.

We estimate that a 1.4 m sea-level rise will put 480,000 people at risk of a 100-year flood event. Among those affected are large numbers of low-income people and communities of color. Populations in San Mateo and Orange Counties are especially vulnerable, with an estimated 130,000 and 110,000 people are at risk in each, respectively. Large numbers of residents (66,000) in Alameda County are also at risk.

A wide range of critical infrastructure is vulnerable to sea-level rise. This includes: nearly 140 schools; 34 police and fire stations; more than 330 U.S. Environmental Protection Agency (EPA)-regulated hazardous waste facilities or sites; an estimated 3,500 miles of roads and highways and 280 miles of railways; 30 coastal power plants, with a combined capacity of more than 10,000 MW; 28 wastewater treatment plants, 21 on the San Francisco Bay and 7 on the Pacific coast, with a combined capacity of 530 million gallons per day; and the San Francisco and Oakland airports. In addition, $100 billion (in year 2000 dollars) worth of property is threatened by increased probability of coastal flooding.

Climate changes are inevitable, and adaptation to unavoidable impacts must be evaluated, tested, and implemented. Sea levels have risen observably in the past century, and scientists forecast that sea-level rise will continue for centuries, even if we stop emitting greenhouse gases immediately. As a result, coastal areas will be subject to increasing risk of inundation and erosion. A number of structural and non-structural policies and actions could be implemented to reduce these risks. While this paper does not include a discussion of explicit adaptation options and costs, Heberger et al. (2009) do include some initial estimates of physical adaptation options, including building or strengthening seawalls and levees. For example, we estimate that protecting vulnerable areas from flooding by building seawalls and levees will cost $14 billion (in year 2000 dollars), along with an additional $1.4 billion per year (in year 2000 dollars) in maintenance costs (Heberger et al. 2009), and may also incur a range of environmental costs such as loss of beaches, wetlands, and wildlife habitat. Continued development in vulnerable areas will put additional assets at risk and raise protection costs. Determining what to protect, how to pay for it, and how those choices are made raises concerns over equity and environmental justice.

The study, conducted for the 2009 California Climate Impacts Assessment, resulted in more information than can be presented here. There are additional figures, GIS data downloads, and color maps in PDF format at the Pacific Institute website at www.pacinst.org. In addition, an interactive map lets the user zoom to anywhere on the coast and get more information on the geographic data layers discussed in this paper.

Acknowledgments Major funds were provided by the California Energy Commission's Public Interest Energy Research (PIER) Program. Additional support came from the Metropolitan Transportation Commission and the California Ocean Protection Council.

The authors wish to thank the scientists and engineers at Philip Williams and Associates for their analysis on coastal flood and erosion hazards. Thanks to Dr. David L. Revell, Robert Battalio, Jeremy Lowe, Justin Vandever, Brian Spear, and Seungjin Baek.

Thanks also go to Noah Knowles, Dan Cayan, Mary Tyree, and Peter Bromirski, and Reinhard Flick of Scripps Institution of Oceanography for much of the oceanographic data.

We owe thanks to a number of agencies and organizations for sharing data and expertise: Philip Pang at the Army Corps of Engineers, Eric Simmons and Ray Lenaburg at FEMA, Reza Navai, Vahid Nowshiravan, and Barry Padilla at the California Department of Transportation, Jennifer Dare at NOAA, and a number of others.

Finally, we are especially grateful for our reviewers: Michael Hanemann, Arlene Wong, June Gin, and several anonymous reviewers who helped to improve the report on which this paper is based.

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