THE IMPACTS OF SEA-LEVEL RISE ON THE CALIFORNIA COAST

A Paper From:
California Climate Change Center

Prepared By:
Matthew Heberger, Heather Cooley, Pablo Herrera, Peter H. Gleick, and Eli Moore of the Pacific Institute

DRAFT PAPER

DISCLAIMER

Arnold Schwarzenegger, *Governor*

March 2009
CEC-500-2009-024-D

Acknowledgments

In this report, the Pacific Institute evaluates the areas at risk from sea-level rise on the California coast and San Francisco Bay. We assess the population, infrastructure, and property at risk and provide an estimate of the cost of protecting those areas. We also offer a set of recommendations to inform policy- and decision-makers as they develop land-use plans for coastal regions. A series of maps that demonstrate the areas at risk are available on our website at www.pacinst.org/reports/sea_level_rise. It should be noted that these maps are not the result of detailed site studies and were created to quantify risk over a large geographic area. They are not meant to replace or supplement flood insurance maps from the Federal Emergency Management Agency or flood risk maps from the California Office of Emergency Services.

Major funds for this report were made through the California Energy Commission's Public Interest Energy Research (PIER) Program. Additional support was provided by the Metropolitan Transportation Commission and the Ocean Protection Council. We thank them for their generosity and foresight.

The scientists and engineers at Philip Williams and Associates provided us with information and analysis on coastal flood and erosion hazards. Thanks to Dr. David L. Revell, Robert Battalio, Jeremy Lowe, Justin Vandever, Brian Spear, and Seungjin Baek. For additional information about their work on this project, please see www.pwa-ltd.com/resources/resource_publications.html.

Many individuals, organizations, and agencies helped make this work possible by providing data, information, and input and review of the final report. We owe thanks to Will Travis, director of the Bay Conservation and Development Commission, for initiating the study and suggesting our involvement and to staff members Leslie Lacko, Tim Doherty, Adam Parris, and Steve Goldbeck, who worked closely with us as we prepared this report.

We thank Dr. Noah Knowles, Dr. Dan Cayan, Mary Tyree, and Dr. Peter Bromirski of Scripps Institution of Oceanography for much of the oceanographic data. Dr. Reinhard Flick at Scripps also provided useful data on historical tide trends.

Thanks to Doug Kimsey and his staff at the Metropolitan Transportation Commission for providing accurate transportation data. Thanks to Reza Navai, Vahid Nowshiravan, and Barry Padilla at the California Department of Transportation for many helpful conversations.

Special thanks to the staff at the National Oceanic and Atmospheric Administration's (NOAA) Coastal Services Center, Kirk Waters and Keil Schmid, for helping us obtain several gigabytes of LIDAR data. Abby Sallenger at the United States Geological Survey gave additional advice and insights about the Coastal Change program's LIDAR data. Thanks to Mark Sanchez, geographic information system (GIS) wizard at the State of Oregon, for help in figuring out how to handle all those gigabytes!

Brian Fulfrost at the University of California (UC) Santa Cruz, now at DCE Planning, helped us locate several helpful GIS datasets. We thank Robert Colley, GIS Manager for Santa Clara

County, for providing data and for recognizing that the free and open sharing of public data is so valuable to researchers and the public. Ray McDowell, GIS Data Coordinator at the California Resources Agency, helped locate and obtain still more GIS data. At the Federal Emergency Management Agency (FEMA), Eric Simmons and Ray Lenaburg engaged us in helpful discussion and gave pointers to the spatial data from recent FEMA mapping studies.

Staff at California's Resources Agency engaged us in a number of insightful and provocative discussions. Thanks to Sam Schuchat, Brian Baird, Tony Brunello, John Ellison, and Abe Doherty. Thanks to Christine Blackburn at the Ocean Protection Council for seeing the importance of this issue to the entire state and for many helpful conversations.

Johanna Fenton, formerly head of in the Earthquake and Tsunami Program in Governor's Office of Emergency Services, provided early guidance and advice. Leslie Ewing, Mark Johnsson, and Greg Benoit of the California Coastal Commission provided data or suggestions. We were especially thankful to discover the excellent work of Jennifer Dare, a NOAA Coastal fellow, who compiled the Coastal Armoring Database.

Thanks to Philip Pang in the South Pacific Division of the U.S. Army Corps of Engineers for his work estimating levee construction costs. Thanks to Jos Dijkman, flood management engineer at Detares/Delft Hydraulics in the Netherlands, for a great deal of detailed information on the construction of dikes and flood defenses. Walt Crampton, principal engineer at TerraCosta Consulting Group, also provided seawall construction costs for California.

We wish to thank ESRI. A grant to the Pacific Institute in 2007 through their Conservation Grants program allowed us to expand the range and sophistication of our analysis.

Special thanks go to the leader of the PIER Research Team, Guido Franco, not only for skillfully overseeing this complex set of studies, but also for a number of insightful comments and suggestions. Technical editor Susie Moser provided insightful comments on an early draft. Thanks to editor Mark Wilson for skill and patience in making all of this readable.

Finally, we are especially grateful for our reviewers: Michael Hanemann, Arlene Wong, June Gin, and two anonymous reviewers, who provided thoughtful and insightful comments. All conclusions and errors are, of course, our own.

Preface

The California Energy Commission's Public Interest Energy Research (PIER) Program supports public interest energy research and development that will help improve the quality of life in California by bringing environmentally safe, affordable, and reliable energy services and products to the marketplace.

The PIER Program conducts public interest research, development, and demonstration (RD&D) projects to benefit California's electricity and natural gas ratepayers. The PIER Program strives to conduct the most promising public interest energy research by partnering with RD&D entities, including individuals, businesses, utilities, and public or private research institutions.

PIER funding efforts focus on the following RD&D program areas:

- Buildings End-Use Energy Efficiency
- Energy-Related Environmental Research
- Energy Systems Integration
- Environmentally Preferred Advanced Generation
- Industrial/Agricultural/Water End-Use Energy Efficiency
- Renewable Energy Technologies
- Transportation

In 2003, the California Energy Commission's PIER Program established the **California Climate Change Center** to document climate change research relevant to the states. This center is a virtual organization with core research activities at Scripps Institution of Oceanography and the University of California, Berkeley, complemented by efforts at other research institutions. Priority research areas defined in PIER's five-year Climate Change Research Plan are: monitoring, analysis, and modeling of climate; analysis of options to reduce greenhouse gas emissions; assessment of physical impacts and of adaptation strategies; and analysis of the economic consequences of both climate change impacts and the efforts designed to reduce emissions.

The California Climate Change Center Report Series details ongoing center-sponsored research. As interim project results, the information contained in these reports may change; authors should be contacted for the most recent project results. By providing ready access to this timely research, the center seeks to inform the public and expand dissemination of climate change information, thereby leveraging collaborative efforts and increasing the benefits of this research to California's citizens, environment, and economy.

For more information on the PIER Program, please visit the Energy Commission's website at www.energy.ca.gov/pier/ or contract the Energy Commission at (916) 654-5164.

Table of Contents

Preface.......... iii

Abstract xi

1.0 Introduction.......... 1

1.1. Key Findings..........2

2.0 Methods 4

2.1. Study Area..........5

2.2. Sea-Level Rise Projections..........5

2.2.1. Mean Water Levels and Extreme Events 5

2.3. Expected Risk to the Coast..........8

2.3.1. Coastal Inundation Risk 8

Pacific Coast 9

San Francisco Bay 13

2.3.2. Erosion Risk 15

2.3.3. Limitations of the Analysis 17

2.4. Resources Threatened by Sea-Level Rise..........19

2.4.1. Population 19

2.4.2. Impacts on the Built Environment.......... 22

2.4.3. Natural Resources 26

Spatial Extent of Wetlands 26

Economic Value of Wetlands.......... 27

Impact of Sea-Level Rise on Wetlands 29

2.4.4. Limitations 32

2.5. Determine the Protective Responses Appropriate for the Region 32

2.5.1. Structural Coastal Protection Measures.......... 33

Beach Nourishment.......... 33

Groins 33

Seawalls, Bulkheads, and Revetments 33

Breakwaters 34

Dikes and Levees 34

Raise Existing Structures (Roadways, Railroads, and Other Structures) 34

2.5.2. Cost of Structural Protection Measures 34

2.5.3. Estimating Needed Coastal Defenses 36
3.0 Results 37
3.1. Flood-Related Risks 37
3.1.1. Population at Risk 38
Environmental Justice Concerns 42
3.1.2. Emergency and Healthcare Facilities at Risk 50
3.1.3. Hazardous Materials Sites 51
3.1.4. Infrastructure at Risk 53
Roads and Railways 53
Power Plants 57
Wastewater Treatment Plants 61
Ports 61
Airports 64
3.1.5. Wetlands 64
3.1.6. Property at Risk 73
Pacific Coast 75
San Francisco Bay 77
3.1.7. Cost of Protection 79
3.2. Erosion-Related Risks 80
3.2.1. Population at Risk from Erosion 80
3.2.2. Emergency and Healthcare Facilities at Risk from Erosion 82
3.2.3. Infrastructure at Risk from Erosion 82
Roads and Railways 82
3.2.4. Property at Risk from Erosion 84
4.0 Conclusions and Recommendations 85
4.1. Conclusions 85
4.2. Recommendations 85
4.2.1. Principles for Adaptation 86
4.2.2. Recommended Practices and Policies 86
4.2.3. Additional Research and Analysis 89
5.0 References 90
6.0 Acronyms and Abbreviations 97

List of Figures

Figure 1. Trend in monthly mean sea level at the San Francisco tide station from 1854–2000 6

Figure 2. Scenarios of sea-level rise to 2100 8

Figure 3. Determining future flood elevations 9

Figure 4. Rates of change of tidal datums, San Francisco from 1900–2000 11

Figure 5. Simple schematic of USGS San Francisco Bay hydrodynamic model 13

Figure 6. Historical and projected carbon dioxide emissions scenarios, 1990–2010 14

Figure 7. Comparison of 100-year flood elevations (in meters NAVD88) 17

Figure 8. Limitations of the computer's ability to accurately map coastal flooding in areas protected by seawalls or levees or natural barriers 18

Figure 9. Relationship between demographics and vulnerabilities 22

Figure 10. Distribution of census-block average replacement costs for single-family homes from HAZUS 24

Figure 11. Flooding of a coastal road in Santa Cruz, California 25

Figure 12. National Wetlands Inventory wetlands classified as "coastal" are below or adjacent to the MHHW line 27

Figure 13. Assumed wetland area defined by the intertidal range 30

Figure 14. An example of coastal armoring leading to the disappearance of beach 36

Figure 15. Estimated current and future 100-year coastal flood risk areas around Santa Cruz ... 38

Figure 16. Population vulnerable to a 100-year coastal flood with a 1.4 m sea-level rise, by county 40

Figure 17. Total county population and population vulnerable to a 100-year flood with a 1.4 meter sea-level rise along the Pacific coast, by race 44

Figure 18. Percentages of low-income households among the population vulnerable to a 100-year flood with a 1.4 m sea-level rise compared with the county total 46

Figure 19. Roadways vulnerable to a 100-year coastal flood with a 1.4 m sea-level rise 54

Figure 20. Railroads vulnerable to a 100-year coastal flood with a 1.4 m sea-level rise 55

Figure 21. Power plants vulnerable to a 100-year coastal flood with a 1.4 m sea-level rise 58

Figure 22. San Francisco Bay power plants vulnerable to a 100-year coastal flood with a 1.4 m sea-level rise 59

Figure 23. Southern California power plants vulnerable to a 100-year coastal flood with a 1.4 m sea-level rise 60

Figure 24. Wastewater treatment plants on the Pacific coast vulnerable to a 100-year flood with a 1.4 m sea-level rise 62

Figure 25. Wastewater treatment plants on the San Francisco Bay vulnerable to a 100-year flood with a 1.4 m sea-level rise 63

Figure 26. Existing coastal wetlands 65

Figure 27. Viability of potential wetland migration area in response to a 1.4 m sea-level rise in Northern California 69

Figure 28. Viability of potential wetland migration area in response to a 1.4 m sea-level rise in the San Francisco Bay 70

Figure 29. Viability of potential wetland migration area in response to a 1.4 m sea-level rise in Central California 71

Figure 30. Viability of potential wetland migration area in response to a 1.4 m sea-level rise in Southern California 72

Figure 31. Replacement value of buildings and contents vulnerable to a 100-year coastal flood with a 1.4 m sea-level rise 74

Figure 32. Replacement value (in billions of year 2000 dollars) of buildings and contents at risk of a 100-year flood event with a 1.4 m sea-level rise, by region 75

Figure 33. Value of buildings and contents at risk of 100-year flood event with a 1.4 m sea-level rise along the Pacific coast, by major economic sector 77

Figure 34. Value of buildings and contents at risk of a 100-year flood with a 1.4 m sea-level rise on San Francisco Bay, by major economic sector 79

Figure 35. Road erosion along Highway 1 with deployment of erosion mitigation strategy 83

List of Tables

Table 1. Elevation datasets used for mapping coastal flood risks 12

Table 2. Recurrence intervals of inundation estimates 14

Table 3. Year and estimated mean sea-level for inundation estimates under the A2 and B1 scenarios 14

Table 4. Miles and fraction of coastline studied for the erosion hazard study, by county 19

Table 5. Approaches for estimating ecosystem values 29

Table 6. Mean higher high water (MHWH) for long-term tide stations on California's Pacific coast........31

Table 7. Costs (in year 2000 dollars) for building new levees, raising existing levees, and building new seawalls........35

Table 8. Population vulnerable to a 100-year flood along the Pacific coast, by county........41

Table 9. Population vulnerable to a 100-year flood along the San Francisco Bay, by county........42

Table 10. Total county population and population vulnerable to a 100-year flood with a 1.4-meter sea-level rise along the Pacific coast, by race........43

Table 11. Key demographics of populations vulnerable to a 100-year flood event with a 1.4 m sea-level rise........47

Table 12. Schools and emergency and healthcare facilities along the Pacific coast that are at risk from a 100-year flood event in 2000 and with a 1.4 m sea-level rise........51

Table 13. Schools and emergency and healthcare facilities along San Francisco Bay that are at risk of a 100-year flood event in 2000 and with a 0.5 m, 1.0 m, and 1.4 m sea-level rise. 51

Table 14. U.S. EPA-regulated sites within areas vulnerable to 100-year flood event in 2000 and with a 1.4 m sea-level rise........52

Table 15. Miles of roads and railways vulnerable to a 100-year flood in 2000 and with a 1.4 m sea-level rise along the Pacific coast, by county and type........53

Table 16. Miles of roads vulnerable to a 100-year flood along San Francisco Bay, by county and type........56

Table 17. Miles of railways vulnerable to a 100-year flood along San Francisco Bay, by county 56

Table 18. Existing California coastal wetland area by county........66

Table 19. Wetland migration frontier area classified by land cover type and conversion potential........67

Table 20. Land area available for wetland migration, by county, in square miles, with percent of county total in italics........68

Table 21. Replacement value of buildings and contents (millions of year 2000 dollars) at risk of a 100-year flood event along the Pacific coast, by county........76

Table 22. Value of buildings and contents at risk of a 100-year flood on San Francisco Bay, by county (in millions of year 2000 dollars)........78

Table 23. Estimated length (in miles) and capital cost of required defenses needed to guard against flooding from a 1.4 m sea-level rise, by county........80

Table 24. Erosion with a 1.4 m sea-level rise, by county. 81

Table 25. Average and maximum erosion distance in 2000 for cliffs and dunes, by county. 81

Table 26. Population vulnerable to flood and erosion from a 1.4 m sea-level rise along the Pacific coast, by county 82

Table 27. Miles of roads and railways vulnerable to erosion and flood from a 1.4 m sea-level rise along the Pacific coast, by county and type 83

Table 28. Number of properties within the erosion zone hazard zone with a 1.4 m sea-level rise, by county 84

Abstract

Over the past century, sea level has risen nearly eight inches along the California coast, and general circulation model scenarios suggest very substantial increases in sea level as a significant impact of climate change over the coming century. This study includes a detailed analysis of the current population, infrastructure, and property at risk from 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 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 also evaluate the cost of building structural measures to reduce that risk. If development continues in the areas at risk, all of these estimates will rise. No matter what policies are implemented in the future, sea-level rise will inevitably change the character of the California coast.

We estimate that a 1.4 meter sea-level rise will put 480,000 people at risk of a 100-year flood event, given today's population. Among those affected are large numbers of low-income people and communities of color, which are especially vulnerable. A wide range of critical infrastructure, such as roads, hospitals, schools, emergency facilities, wastewater treatment plants, power plants, and more will also be at increased risk of inundation, as are vast areas of wetlands and other natural ecosystems. In addition, the cost of replacing property at risk of coastal flooding under this sea-level rise scenario is estimated to be nearly $100 billion (in year 2000 dollars). A number of structural and non-structural policies and actions could be implemented to reduce these risks. For example, we estimate that protecting some vulnerable areas from flooding by building seawalls and levees will cost at least $14 billion (in year 2000 dollars), with added maintenance costs of another $1.4 billion per year. Continued development in vulnerable areas will put additional areas at risk and raise protection costs.

Large sections of the Pacific coast are not vulnerable to flooding, but are highly susceptible to erosion. We estimate that a 1.4 meter sea-level rise will accelerate erosion, resulting in a loss of 41 square miles (over 26,000 acres) of California's coast by 2100. A total of 14,000 people currently live in the area at risk of future erosion. Additionally, significant transportation-related infrastructure and property are vulnerable to erosion. Statewide flood risk exceeds erosion risk, but in some counties and localities, coastal erosion poses a greater risk. This report also provides a comprehensive set of recommendations and strategies for adapting to sea-level rise.

Keywords: sea-level rise, climate change, California, San Francisco Bay, flood, erosion, climate adaptation, climate impacts, levees, seawalls, greenhouse effect

1.0 Introduction

California's coastline, which includes more than 2,000 miles of open coast and enclosed bays, is vulnerable to a range of natural hazards, including storms, extreme high tides, and rising sea levels resulting from global climate change. Development along California's coast is extensive. In 2000, 26 million Californians lived in coastal counties, and by 2003, this number had grown to nearly 31 million (U.S. Census Bureau 2000; NOAA 2004). Indeed, 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 found along the California coast, including oil, natural gas, and nuclear energy facilities, as well as major ports, harbors, and water and wastewater plants. The California coast is also an extraordinary cultural and ecological resource and offers extensive tourism and recreational opportunities.

Flooding and erosion pose a threat to communities along the California coast and there is compelling evidence that these risks will increase in the future. Based on a set of climate scenarios prepared for the California Energy Commission's Public Interest Energy Research (PIER) Climate Change Research Program, Cayan et al. (2008) project that, under medium to medium-high emissions scenarios, mean sea level along the California coast will rise from 1.0 to 1.4 meters (m) by the year 2100.[1] Rising seas put new areas at risk of flooding and increase the likelihood and intensity of floods in areas that are already at risk. In areas where the coast erodes easily, sea-level rise will likely accelerate shoreline recession due to erosion. Erosion of some barrier dunes may expose previously protected areas to flooding.

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, as substantial investments are already at risk and vulnerable.[2] Because the economic costs of flooding are highly site-specific, regional analyses are critical for guiding land-use decisions and evaluating adaptive strategies.

The Pacific Institute published one of the earliest comprehensive regional assessments of sea-level rise (Gleick and Maurer 1990), concluding that a one-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 simply to protect existing high-value development was estimated to require an immediate capital investment of approximately $1 billion (in year 1990 dollars) and would require an additional $100 million per year in ongoing maintenance.[3] The report 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.

---

[1] It is important to note that most climate models fail to include ice-melt contributions from the Greenland and Antarctic ice sheets, and as a result, the potential increase in mean sea level may be much higher.

[2] See, for example, Titus et al. (1992) and Yohe et al. (1996).

[3] This estimate does not include the cost of protecting and restoring wetlands, groundwater aquifers, etc.

This assessment updates and expands our 1990 analysis using more comprehensive data, new climate scenarios, and modern computerized analytical tools. We made extensive use of geographic information system (GIS) software and updated sea-level rise scenarios from the Scripps Institution of Oceanography to estimate the population, infrastructure, ecosystems, and property at risk. We also estimate the cost of armoring the coast, one potential adaptation strategy to reduce that risk. This work is part of a larger set of research projects by the California Climate Action Team to understand the impacts of climate change to Californians, funded by the California Energy Commission's Public Interest Energy Research (PIER) program. The Pacific Institute also received significant financial support from two other state agencies: the Ocean Protection Council and the Metropolitan Transportation Commission, part of the Department of Transportation.

1.1. Key Findings

Over the past century, sea level has risen nearly eight inches along the California coast, and general circulation model scenarios suggest very substantial increases in sea level as a significant impact of climate change over the coming century. This study includes a detailed analysis of the current population, infrastructure, and property at risk from projected sea-level rise if no actions are taken to protect the coast, and the cost of building structural measures to reduce that risk. We find the following:

- Under medium to medium-high greenhouse-gas emissions scenarios, mean sea level along the California coast is projected to rise from 1.0 to 1.4 meters (m) by the year 2100. A series of maps for the entire coast of California demonstrating the extent of the areas at risk are posted at www.pacinst.org/reports/sea_level_rise.[4]
- A 1.4 meter sea-level rise will put 480,000 people at risk of a 100-year flood event, given today's population. Populations in San Mateo and Orange Counties are especially vulnerable. In each, an estimated 110,000 people are at risk. Large numbers of residents (66,000) in Alameda County are also at risk.
- A demographic analysis identified large numbers of people at risk with heightened vulnerability, including low-income households and communities of color. Additionally, adapting to sea-level rise will require tremendous financial investment. Given the high cost and the likelihood that we will not protect everything, adaptation raises additional environmental justice concerns.
- A wide range of critical infrastructure, such as roads, hospitals, schools, emergency facilities, wastewater treatment plants, power plants, and more will also be at increased risk of inundation in a 100-year flood event. This infrastructure at risk includes:

[4] These maps are not the result of detailed site studies and were created to quantify risk over a large geographic area. They should not be used to assess actual coastal hazards, insurance requirements or property values, and specifically shall not be used in lieu of Flood insurance Studies and Flood Insurance Rate Maps issued by the Federal Emergency Management Agency (FEMA). Local governments or regional planning agencies should conduct detailed studies to better understand the potential impacts of sea-level rise in their communities.

  - nearly 140 schools;
  - 34 police and fire stations;
  - more than 330 U.S. Environmental Protection Agency (U.S. EPA)-regulated hazardous waste facilities or sites, with large numbers in Alameda, Santa Clara, San Mateo, and Los Angeles counties;
  - 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 megawatts;
  - 29 wastewater treatment plants, 22 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.

- Vast areas of wetlands and other natural ecosystems are vulnerable to sea-level rise. An estimated 670 square miles, or 430,000 acres, of wetlands exist along the California coast, but additional work is needed to evaluate the extent to which these wetlands would be destroyed, degraded, or modified over time. A sea-level rise of 1.4 m would flood approximately 150 square miles of land immediately adjacent to current wetlands, potentially creating new wetland habitat if those lands are protected from further development.

- We estimate that nearly $100 billion (in year 2000 dollars) worth of property, measured as the current replacement value of buildings and contents, is at risk of flooding from a 100-year event with a 1.4 m sea level rise if no adaptation actions are taken. An overwhelming two-thirds of that property is concentrated on San Francisco Bay. The majority of this property is residential.

- Coastal armoring is one potential adaptation strategy. Approximately 1,100 miles of new or modified coastal protection structures are needed on the Pacific Coast and San Francisco Bay to protect against coastal flooding. The total cost of building new or upgrading existing structures is estimated at about $14 billion (in year 2000 dollars). We estimate that operating and maintaining the protection structures would cost approximately 10% of the initial capital investment, or around another $1.4 billion per year (in year 2000 dollars).

- Large sections of the Pacific coast are not vulnerable to flooding, but are highly susceptible to erosion. We estimate that a 1.4 m sea-level rise will accelerate erosion, resulting in a loss of 41 square miles of California's coast by 2100. A total of 14,000 people live in areas at risk of erosion. In addition, significant transportation-related infrastructure and property are also at risk. Throughout most of the state, flood risk exceeds erosion risk, but in some counties, coastal erosion poses a greater risk.

- Continued development in vulnerable areas will put additional areas at risk and raise protection costs.

2.0 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). That framework employs a cost-benefit model to evaluate the property at risk and the cost of protecting or abandoning that property. Property is protected if the value of the property exceeds the protection cost at the time of inundation, and the protection cost is equal to the construction cost of the protective structure. If the value of the property does not exceed the cost of protection, then the property is abandoned, with the cost equal to the value of the land and structure at the time of inundation. The total economic cost is then 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.

Despite its wide application, the Yohe method has a number of limitations, many of which are discussed in Hanemann (2008):

- First, it ignores any transfers among property owners and looks only at the net social cost. In reality, there will be winners (those who had inland property that is now closer to the coast and thus more valuable) and losers (those who have lost their property), and the gross social cost "could be enormous" (Yohe et al. 1996).
- Second, it assumes that coastal protection will be constructed just in time to avoid damage from flooding. This is unlikely. If coastal protection is constructed too late, then the property would incur some damage, thereby increasing the cost. If constructed too early, then the discounted net present value of the cost of building the structure would be higher (Hanemann 2008).
- Third, it only examines changes in mean sea level (eustatic change), thereby ignoring damage from storm surge and extreme events.
- Fourth, by focusing on property values, it ignores other potentially expensive costs. For example, the flooding of transportation infrastructure essential for moving people or goods, e.g., highways and ports, could cause major interruptions to the local economy. Flooding also causes impacts on the health and well-being of the affected individuals and environmental damage, including erosion, oils spills, and discharge of pollution

from coastal industry (Hanemann 2008). Over the long-term, flooding can lead to the loss of wetlands.

- Fifth, prioritization of protection based on property value may directly undermine an environmental justice framework for protection.

This study used a different approach to estimate the economic impact of sea-level rise. We adopted the scenarios developed for the PIER studies and mapped the extent of inundation from a 100-year flood event that is likely to occur with rising sea levels. We also identified areas at increased risk from erosion as a result of rising seas. The inundation and erosion geodata were overlaid with other geospatial data using GIS 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. We also produced an initial estimate of the cost of adaptation measures, specifically building seawalls and levees in high-valued coastal zones to protect against future flooding. Greater detail on the methods is provided below.

2.1. Study Area

The study area spans approximately 1,100 miles of California's Pacific coast and 1,000 miles of shoreline along the 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 extract reliable flood elevations from the Bay hydrodynamic model. We provide a more detailed analysis in the San Francisco Bay due to the extensive, high-valued development in the region and the availability of higher-resolution geographic data.

The study area of the erosion analysis extended from Santa Barbara to the Oregon border, covering about 930 miles (1,450 kilometers, km). Much of the Southern California coast was excluded from the erosion analysis due to the myriad of ongoing initiatives focused on climate change and hazards mapping.

2.2. Sea-Level Rise Projections

2.2.1. Mean Water Levels and Extreme Events

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. A worldwide network of more than 1,750 tidal gages continuously collects data on water levels relative to a nearby geodetic reference, and new satellite-based sensors are extending measurements. Tide gage data indicate that the global mean sea level is rising. Water level measurements from the San Francisco gage (CA Station ID: 9414290), shown in Figure 1, indicate that mean sea level rose by an average of

2.1 millimeters (mm) per year from 1906 to 2001, equivalent to a change of eight inches in the last century.[5]

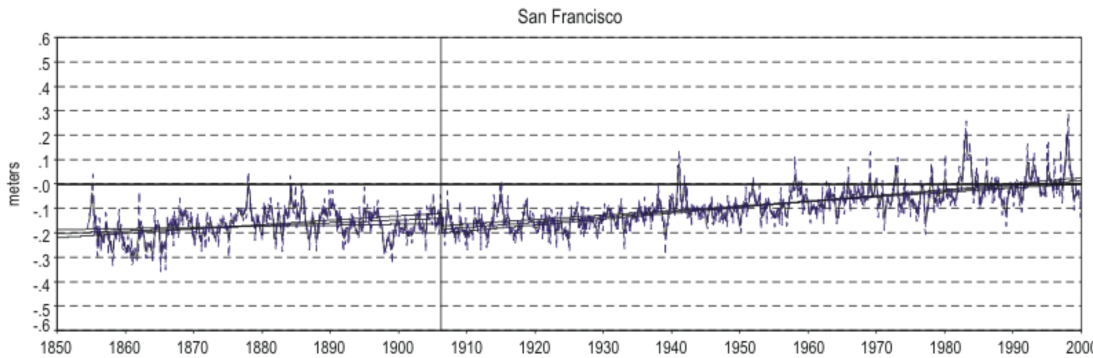


Figure 1. Trend in monthly mean sea level at the San Francisco tide station from 1854–2000

Source: NOAA Sea Levels Online, http://co-ops.nos.noaa.gov/sltrends/sltrends_station.shtml?stnid=9414290

Sea levels are expected to continue to rise, and the rate of increase will likely accelerate. In order to evaluate climate change impacts, the Intergovernmental Panel on Climate Change (IPCC) developed future emission scenarios that differ based on assumptions about economic development, population, regulation, and technology (see Box 1 for a description of the scenarios). Based on these scenarios, mean sea level is projected to 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).

Recent research by leading climate scientists, which includes more accurate sea-level measurements by satellites, indicates that sea-level rise from 1993–2006 has outpaced the IPCC projections (Rahmstorf et al. 2007). The authors suggest that the climate system, particularly sea levels, may be responding to climate changes more quickly than the models predict. Additionally, most climate models fail to include ice-melt contributions from the Greenland and Antarctic ice sheets and may underestimate the change in volume of the world's oceans.

To address these new factors, the PIER projects used sea-level rise forecasts developed by a team at the Scripps Institution of Oceanography led by Dr. Dan Cayan. Using a methodology developed by Rahmstorf (2007), Cayan et al. (2008) produced global sea-level estimates based on projected surface air temperatures from global climate simulations for both the IPCC A2 and B1 scenarios using the output from six global climate models: the National Center for Atmospheric Research (NCAR) Parallel Climate Model (PCM); the National Oceanic and

---

[5] The solid vertical line shows the earthquake of 1906. NOAA researchers fit separate trendlines before and after major seismic events because of the possibility of vertical movement of the land surface where gages are located, disrupting consistent measurements.

Atmospheric Administration (NOAA) Geophysical Fluids Dynamics Laboratory (GFDL) version 2.1; the NCAR Community Climate System Model (CCSM); the Max Planck Institute ECHAM3; the MIROC 3.2 medium-resolution model from the Center for Climate System Research of the University of Tokyo and collaborators; and the French Centre National de Recherches Meteorologiques (CNRM) models.

Box 1: IPCC Climate Change Scenarios

The impacts of climate change will ultimately depend on future greenhouse gas concentrations. Future greenhouse gas emissions remain uncertain and are influenced by a variety of demographic, socio-economic, and technological factors. Scenarios can be a useful tool for examining how changes in these driving factors affect greenhouse gas concentrations. These scenarios can be useful for evaluating impacts associated with climate change as well as assessing adaptation and mitigation activities. The Special Report on Emissions Scenarios (SRES) outlines four storylines that differ according to demographics, social, economic, environmental, and technological factors and lead to different levels of greenhouse gas emissions. Each storyline has a number of different scenarios, referred to as a family. A total of 40 scenarios have been developed.

The four storylines are described below:

The **A1** storyline is characterized by "a future world of very rapid economic growth, global population that peaks in mid-century and declines thereafter, and the rapid introduction of new and more efficient technologies. Major underlying themes are convergence among regions, capacity building, and increased cultural and social interactions, with a substantial reduction in regional differences in per capita income" (IPCC 2000). The A1 family is further divided into three subgroups that are differentiated according to energy source: fossil intensive (**A1FI**), non-fossil sources (**A1T**), and a mix of fossil and non-fossil sources (**A1B**).

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" (IPCC 2000).

The **B2** storyline is characterized by "a world with continuously increasing global population at a rate lower than A2, intermediate levels of economic development, and less rapid and more diverse technological change than in the B1 and A1 storylines" (IPCC 2000).

Additionally, Cayan et al. (2008) modified the sea-level rise estimates to account for water trapped in dams and reservoirs that artificially reduced runoff into the oceans (Chao et al. 2008). Absolute sea-level rise along the California coast was assumed to be the same as the global estimate. Based on these methods, Cayan et al. (2008) estimate an overall projected rise in mean sea level along the California coast for the B1 and A2 scenarios of 1.0 m and 1.4 m, respectively, by 2100 (Figure 2). The more severe A1FI scenario, which assumes a continued high level use of fossil fuels, was not used in this analysis, but is shown for comparative purposes.

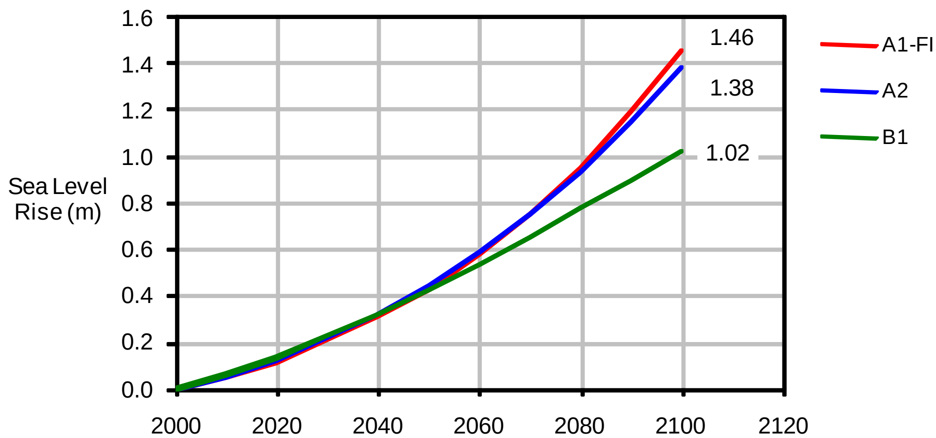


Figure 2. Scenarios of sea-level rise to 2100

Source: Dan Cayan, Scripps Institution of Oceanography, NCAR CCSM3 simulations, Rahmstorf method.

The majority of studies on climate change have emphasized changes in average conditions, yet the greatest socio-economic impacts tend to occur as a result of extreme events. Coastal flooding is often caused by storm surges, which are caused by high winds and pressure differentials associated with storms. Along the California coast, wave-induced storm surge can exceed 1.5 m (Cayan et al. 2006), flooding low-lying areas and eroding coastal bluffs. Increases in mean sea level are expected to increase the frequency and intensity of these extreme events. Although this study does not explicitly account for changes in storm surge, we do account for higher flood elevations associated with extreme events, as described below in Section 2.3.

2.3. Expected Risk to the Coast

2.3.1. Coastal Inundation Risk

Sea-level rise increases the risk of flooding in low-lying areas. For the California coast, we used GIS to produce maps of the areas at risk of inundation from a 1.4 m sea-level rise. For the San Francisco Bay, we produced maps of the areas at risk of inundation under three different sea-level rise scenarios: 0.5 m, 1.0 m, and 1.4 m. Below, we describe the methods used to determine the areas at risk of flooding along the Pacific coast and in the San Francisco Bay. Erosion is discussed in Section 2.3.2.

Pacific Coast

A flood is often described by its recurrence interval, which is the period of time between floods of a particular intensity that is based on historic conditions for a given area. The terminology used to describe the recurrence interval, however, 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. Thus, over a typical 30-year mortgage period, a 100-year flood has a 1-in-4 chance of occurring (see Box 2).

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 event; that is, current flood elevations for the 100-year flood are increased by 1.4 meters, the projected increase in sea level by 2100 under the A2 scenario (Figure 3).

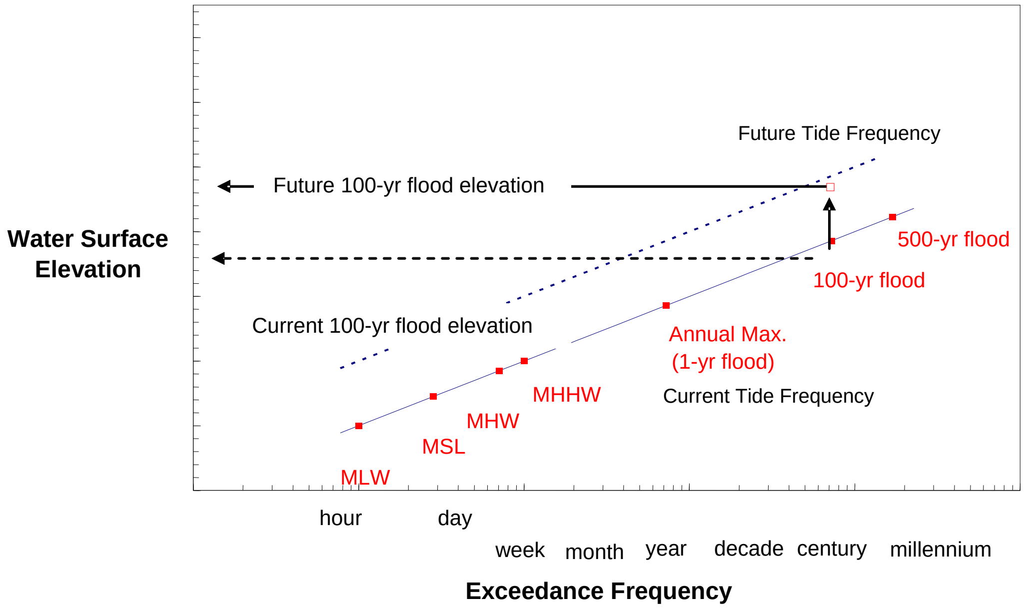


Figure 3. Determining future flood elevations

Note: The solid line represents the current tide frequency. The dotted line represents the future flood frequency. As can be seen, an increase in water surface elevation increases the frequency and intensity of flood events. For example, a 100-year flood event could become an annual flood event. The flood frequency estimates shown are for demonstration purposes only and are not based on actual data. See the Glossary for definitions of the abbreviations MLW, MSL, MHW, and MHHW.

This 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. Flick et al. (1999) found that, in San Francisco, mean higher high water (MHHW) was increasing at a rate of 258 mm per century, while the mean sea level increased at a lower rate of 217 mm per century (Figure 4). Thus, while the overall trend is one of rising seas, the intertidal range, i.e., the difference between MHHW and mean lower low water (MLLW), also seems to be widening. In addition, an increase in storminess due to climate change might cause more frequent storm surges and an increase in the frequency of high water events, although there is not yet consensus among climate scientists on changes in storm intensity or frequency, and such changes are not included here explicitly.

Box 2: Estimating Flood Risk

What are the chances that a 100-year flood will occur during a 30-year period?

To make this determination, we must apply basic probability theory. Flooding is a random event, i.e., the odds of it occurring in any year are independent of past conditions. Thus the odds of a storm not occurring over a 30-year period can be calculated using the following methodology.

If an event has an X percent chance of occurring in a given year, then the odds that the event will **not** occur in a given year are

$$1-X$$

The odds that an event will not occur in two successive years is

$$(1-X)(1-X) = (1-X)^2$$

And the odds of an event not occurring over y number of years is

$$(1-X)^y$$

Let's now calculate the odds that a 100-year flood event will not occur over 30 years.

In this case,

$$X = 1/100 = 0.01 \text{ and } y = 30$$

$$(1-X)^y = (1-0.01)^{30} = 0.74$$

Thus there is a 74% change that a 100-year storm will not occur over a 30-year period; and a 26%, or approximately a 1 in 4 chance that it will occur.

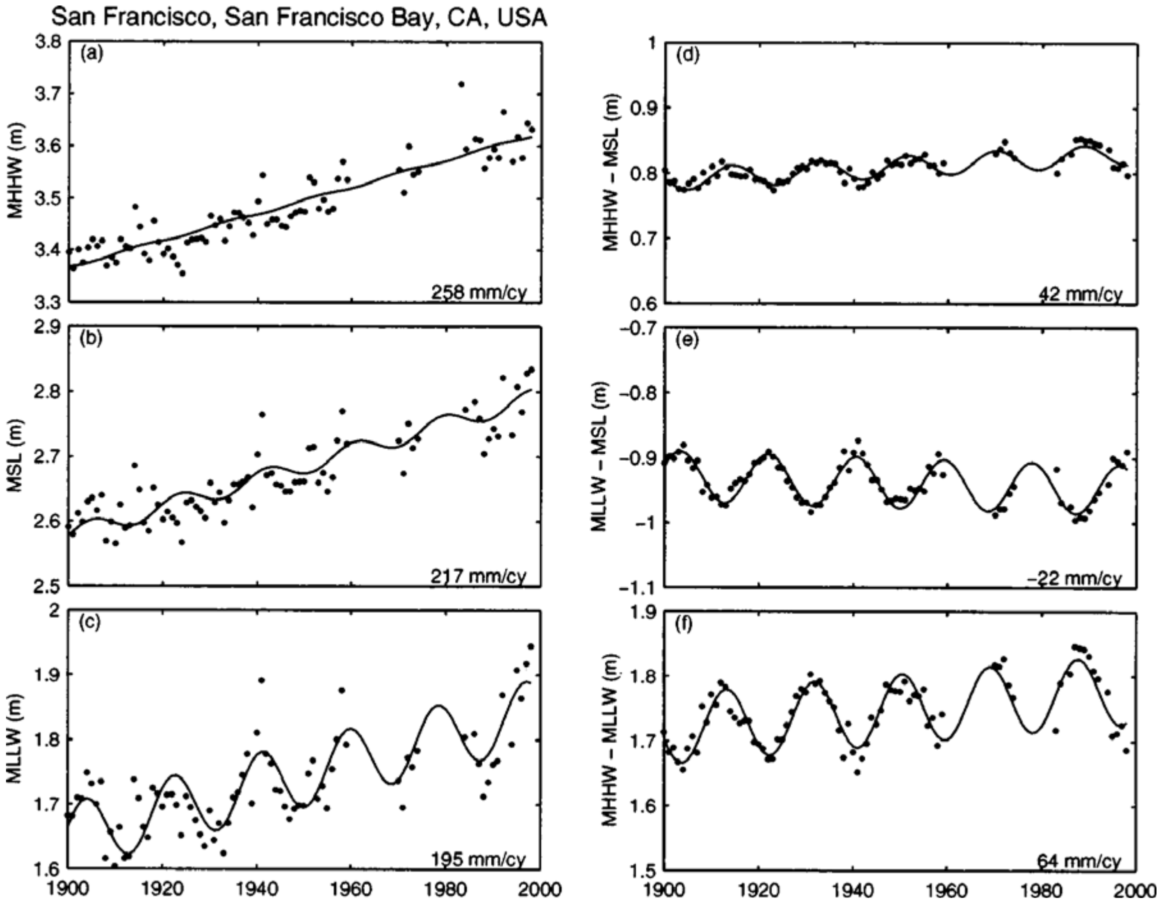


Figure 4. Rates of change of tidal datums, San Francisco from 1900–2000

Source: Flick et al. 1999

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). The Federal Emergency Management Agency BFEs, however, only cover a part of the coast. We contracted with Philip Williams and Associates (PWA) to provide estimates of BFEs where none exist. Their work consisted of the following:

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

Further information on the methods used by PWA is available in a separate technical memorandum (Battalio et al. 2008).

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. For portions of the Central and Northern California coast, Interferometric Synthetic Aperture Radar (IfSAR) data were available from NOAA. NOAA's coastal service center assisted us in processing and obtaining each of these data sets.

For much of the Southern 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 these datasets, and filled in coverage gaps with topographic information from the USGS National Elevation dataset. Although these data are at a much lower resolution and accuracy, they allowed us to map the entire coast. The elevation datasets used for this project are summarized in Table 1.

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
Resolution	10 m	3 m	2 m	3 m
Year Collected	Various	1998	2002	2003
Stated Vertical Accuracy	± 7.5 m	± 0.07 m	± 0.07 m	± 2.2 m

GIS raster math tools were used to compare the elevation of land surfaces with the adjacent flood elevation to determine the extent of flooding. Because of the large file sizes, and the large area being studied, we worked with the terrain datasets in over 600 tiles. Pacific Institute researchers wrote scripts to automate the processing steps on each of these tiles. 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. A separate technical memorandum is available at www.pacinst.org/reports/sea_level_rise that describes the GIS flood delineation methodology in greater detail.

San Francisco Bay

While our study looks at the entire California coastline, we also produced more detailed estimates of coastal flood risk in San Francisco Bay. While the distance from Oregon to Mexico is approximately 1,000 miles, the interior of San Francisco Bay has another 1,000 miles of coastline at risk. Inundation maps generated from the climate scenarios were provided to the Pacific Institute by Dr. Noah Knowles of the United States Geological Survey (Knowles 2008). Dr. Knowles developed a suite of computer models under the CASCADE project that simulate the hydrodynamics of San Francisco Bay under future climate scenarios. The Bay model simulates the water surface elevation for each hour from 2000–2099 and is driven by both upstream and downstream boundary conditions (Figure 5). The upstream boundary condition, inflow from the Sacramento/San Joaquin River Delta, is simulated by a hydrologic model of the upstream watershed and the CALSIM model to simulate the outflow from numerous upstream reservoirs. The downstream boundary condition is the water surface elevation of the ocean at the Golden Gate Bridge, which were provided by Dr. Cayan's group at Scripps.

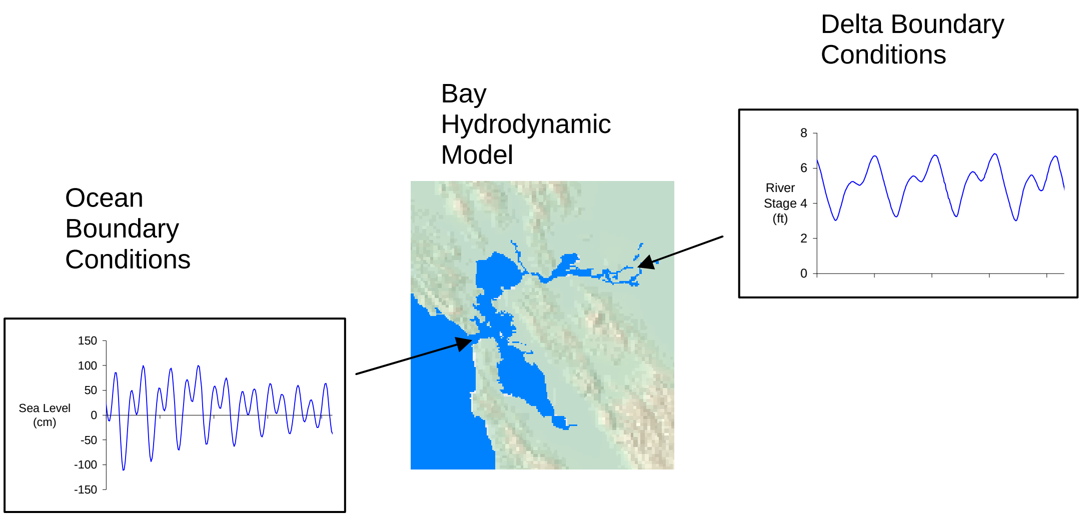


Figure 5. Simple schematic of USGS San Francisco Bay hydrodynamic model

Dr. Knowles performed statistical analyses on the Bay model output to determine flood quantiles at various times and provided outputs in the form of GIS raster files to the Pacific Institute. These files were provided for five flood recurrence intervals (Table 2) for each of four years between 2000 and 2099, for a total of 20 files. Based on this information, we produced GIS layers of the areas at risk of inundation with a 0.5 m, 1.0 m, and 1.4 m sea-level rise, which, for the A2 scenario, correspond to 2050, 2081, and 2099, respectively.

It is important to note that we report results based on the vertical rise in sea level rather than a particular year in which the rise is projected to occur. As shown in Table 3, the year in which a 0.5 m sea-level rise is projected to occur under the A2 and B1 scenarios differs by only three years. Additionally, sea-level rise estimates are continuously updated as climate science advances and greenhouse gas emissions change over time. Indeed, carbon dioxide emissions in 2005 and 2006 were well above even the highest future emissions scenario, as shown in Figure 6 (Raupach et al. 2007). Because the results of this analysis are driven by sea levels and are not directly tied to any set of scenarios, the results of this study will be relevant even when climate projections change.

Table 2. Recurrence intervals of inundation estimates

Flood Interval	Annual probability
1-year	1
10-year	0.1
50-year	0.02
100-year	0.01
500-year	0.002

Table 3. Year and estimated mean sea-level for inundation estimates under the A2 and B1 scenarios

Mean Sea-Level Rise (m)	Year Reached	
	A2	B1
0	2000	2000
0.5	2054	2057
1.0	2083	2098
1.4	2100	2125

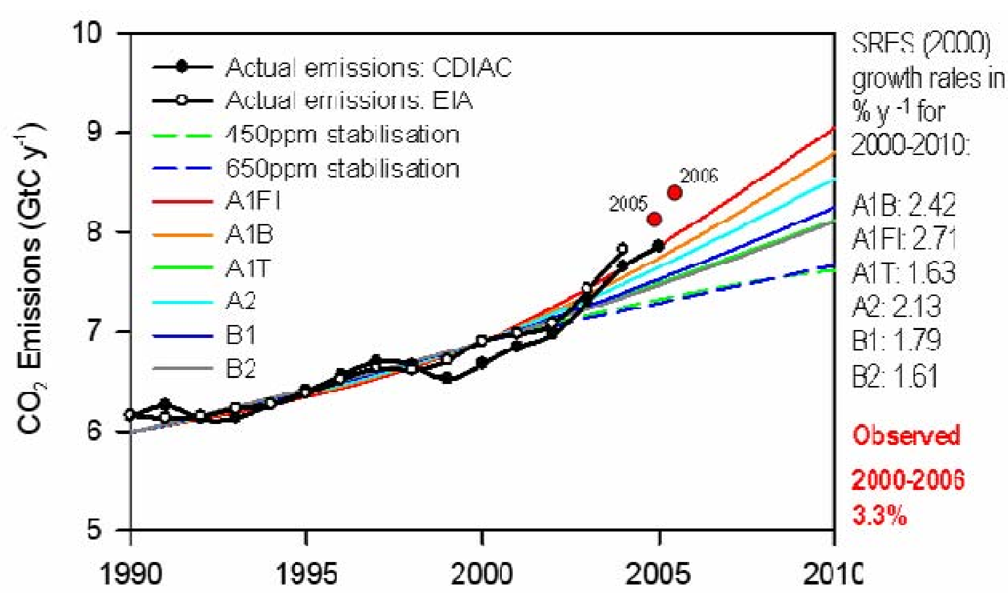


Figure 6. Historical and projected carbon dioxide emissions scenarios, 1990–2010

Note that actual emissions already appear to be exceeding the highest IPCC scenarios.

Source: Raupach et al. 2007

2.3.2. Erosion Risk

Large sections of the Pacific coast, especially those with rocky headlands or sea cliffs, are not vulnerable to flooding, but are highly susceptible to erosion. In areas where the coast erodes easily, higher sea levels are likely to accelerate shoreline erosion due to increased wave attack. In addition, erosion of some sand spits and dunes may expose previously protected areas to flooding.

The amount of erosion can be estimated by several methods. The most widely applied method of predicting shoreline recession based on a sea-level rise was developed by Bruun in 1962. This is based on the concept that the depth of water near the coast remains constant with sea-level rise, that the basic beach profile will remain the same, and that there is a well-defined offshore limit of sediment transport. The sediment required to maintain the beach profile through water-level changes is derived from erosion of the shore material. Based on this, an approximate estimate of the shoreline recession due to readjustment of the beach profile to an equilibrium state is 1.0-to-1.5 meters of shore recession per centimeter of sea-level rise.

Although once widely used, the Bruun rule has been largely abandoned because it makes several assumptions that may not be accurate (Pilkey and Cooper 2004). The formulation is based on a two-dimensional concept, while the sediment transport along a shoreline is a three-dimensional process. The Bruun rule assumes a shoreline profile in equilibrium, which is difficult to confirm at any site. Another problem is that this approach always predicts shoreline recession with offshore sediment transport as sea-level rises, yet there are several cases where shorelines have accreted as a result of sea-level rise due to the movement of sand onshore from offshore deposits. Depending on local sources and sinks of sediment, wave climate, topography, and other conditions governing sediment transport mechanisms, the predictions of shoreline recession obtained using the Bruun rule can significantly over- or underestimate the future recession. More specific methods are needed for particular sites, and should be conducted to better evaluate the impact of sea-level rise on a given region.

A team of scientists and engineers at Philip Williams Associates (PWA) developed an alternative approach to evaluate erosion risk. They evaluated potential future erosion by examining changes to a time series of total-water level (TWL) elevations. TWL is a water elevation determined by the sum of mean sea level, tides, waves and wave run-up, other storm components (including surge), and El Niños (Ruggiero et al. 1996; Ruggiero et al. 2001). Studies suggest that erosion will accelerate as sea levels rise and the coast is exposed to higher waves. Higher water levels result in greater wave energy being dissipated higher up on the shoreline and directly onto the face of cliffs and dunes. The exceedance of TWL above the elevation of the toe junction has been related to erosion (Sallenger et al. 2002; Ruggiero et al. 2001; Hampton and Griggs 2004; FEMA 2005).

To generate the TWL predictions, PWA used a 100-year time series of "measured tides" and deepwater waves from Dr. Dan Cayan and colleagues at Scripps (Cayan et al. 2008). The deepwater wave heights were transformed to 140 nearshore locations by the Coastal Data Information Program to account for differences in wave exposure and shoreline orientation. Finally wave run-up was calculated using the relationship between wave height, wave period, and beach slope (Stockdon et al. 2006). The combination of sea levels and wave run-up were evaluated over time to estimate future elevations of TWL, which were then intersected with the land elevations along 4,100 segments of the coast.

California's coastline is geologically and morphologically complex and each major geologic unit will exhibit differential response to rising sea levels. Philip Williams Associates classified the shoreline based on geologic formations and type, such as sea cliffs and dunes. For each type of coast, slightly different methods were used to project the response to rising seas. For sea cliffs, which accounted for 720 miles of the study area, erosion was estimated based on an acceleration of the historic erosion rate and a percent increase in TWL exceeding the elevation of the toe of the sea cliffs. The historic sea cliff erosion data were obtained from the USGS National Shoreline Change Assessment (Hapke and Reid 2007). The data were averaged by geologic unit with an additional factor of safety (two standard deviations) included to account for subtle changes in geology along the coast.

For the dune classified shorelines, which covered about 170 miles of the study area, erosion rates were based on the following information:

- Recession based on changes in TWL from sea level-rise.
- Historic shoreline change trends from the USGS National Shoreline Change Assessment (Hapke et al. 2006).
- The impact of a "100-year storm event" extracted from the TWL time series and estimated using a storm-response geometric model of dune erosion (Komar et al. 1999).

Based on this approach, PWA developed digital GIS shapefiles representing future coastal erosion hazard zones for cliff-backed and dune-backed coastal areas for 2025, 2050, and 2100 under a low (1.0 m) and a high (1.4 m) sea-level rise scenario. For this analysis, we evaluate the socio-economic impacts of erosion under the 1.4 m sea-level rise scenario for 2100. Note that for erosion, the year is important because it includes a background erosion rate plus accelerated erosion rates resulting from sea-level rise.

The study area of the erosion analysis extended from Santa Barbara to the Oregon border, covering about 930 miles (1,450 km). Much of the Southern California coast was excluded due to the myriad of ongoing initiatives focused on climate change and hazards mapping. Due to insufficient data, however, PWA was only able to include 80% of the 930 mile study area (see Section 2.4 for additional discussion of the limitations).

The erosion analysis represents a first-order evaluation of coastal hazards based on currently available projections of water levels and wave conditions and interpretations of sea-level rise, shoreline change rates, and geomorphic conditions. Available methods and data are not sufficient to model coastal erosion with high confidence. While the methodology used to develop the hazard zones was kept relatively simple and modular to facilitate understanding and future application with minimal effort, it represents one of the most comprehensive erosion hazard assessments under conditions of climate change ever completed for the California coast. For additional information, see PWA (2008).

2.3.3. Limitations of the Analysis

Researchers at Scripps Institution of Oceanography and USGS performed hydrographic modeling of the San Francisco Bay Estuary to determine the flood elevations under climate change scenarios. All models are subject to errors and inaccuracies. It was not possible to directly calibrate or verify a model that predicts flood frequencies. We performed an independent evaluation of USGS-predicted San Francisco Bay flood elevations and found that the model estimates of the 100-year water surface elevation for the year 2000 were generally similar to flood elevations predicted by the U.S. Army Corps of Engineers (1984a). We compared all 52 points on the San Francisco Bay shoreline shown on the 1984 Corps maps and found that 75% of the flood elevations were within 0.25 feet of those predicted by USGS. Most of the new estimates were slightly lower than the heights estimated by the Corps, as shown in Figure 7.

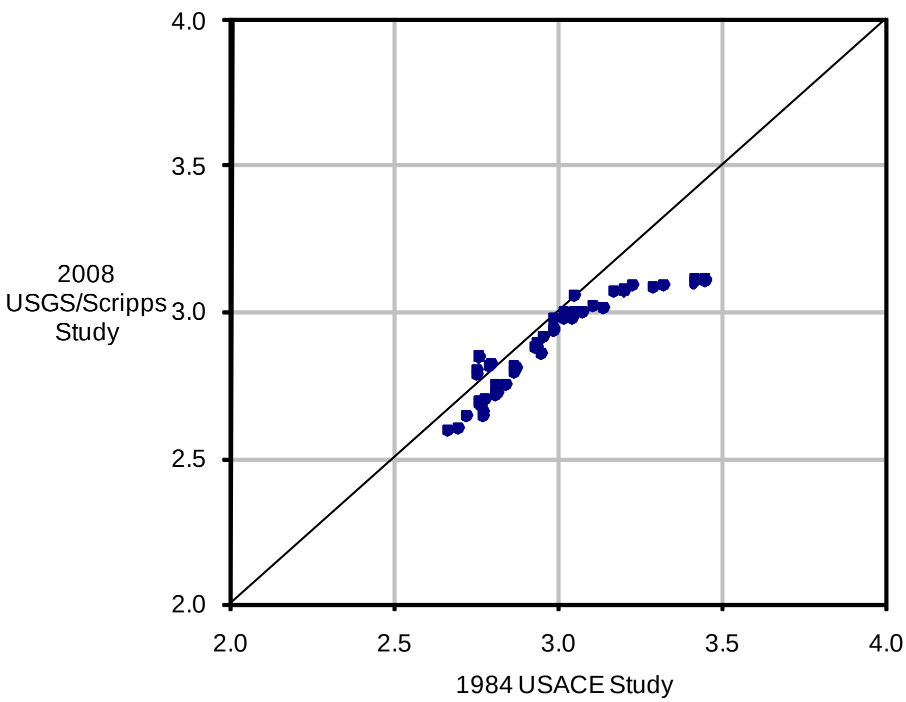


Figure 7. Comparison of 100-year flood elevations (in meters NAVD88)

Furthermore, the location of the shoreline is inexact and probably subjective. Knowles used a "mask" of open water as a filter, so as to report only land areas that are flooded. However, the shoreline is constantly in flux and difficult to map precisely. Further, there are errors and inaccuracies in the terrain data. The digital terrain model creates a smoothed or average surface from the raw elevation data, and it does not accurately depict breaks in elevation that occur at a vertical wall such as a cliff or a curb.

Another limitation is that the automatic, computerized method classifies flooding by depth only. The algorithm using depth alone to determine flooding does not factor in the presence of a flow pathway. In some cases, the high ground may be a levee specifically designed to protect adjacent low-lying areas. In other locations, there are simply depressions, but they are not really at risk because there is no path for seawater to flow into them. This means low-lying objects or features such as ditches, stormwater detention basins, subway tunnels, and empty swimming pools are filled in inappropriately at times, as shown in Figure 8.

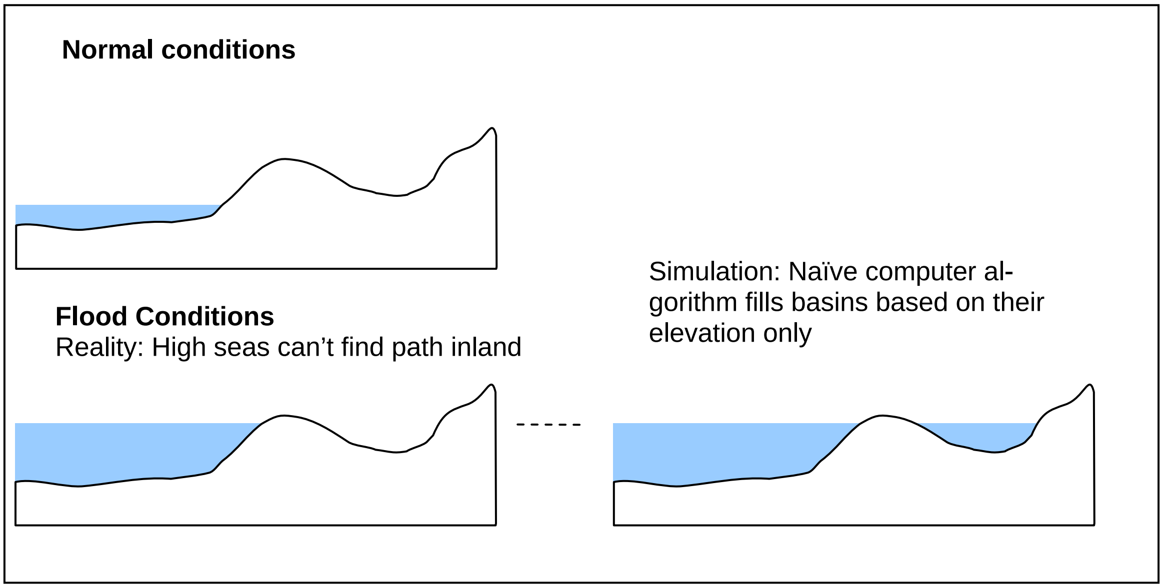


Figure 8. Limitations of the computer's ability to accurately map coastal flooding in areas protected by seawalls or levees or natural barriers

The study area for the erosion analysis was constrained by data availability. The erosion analysis covered only the 11 counties north of Santa Barbara County. Furthermore, data limitations limited the analysis to only 81% of the coast in the 11 counties (Table 4). The three counties with the least coverage include Humboldt County, Monterey, and Santa Barbara. Humboldt County included the Kings Range and the Lost Coast, public lands with no development. The Monterey County analysis was limited along the Big Sur coast where high levels of erosion currently affect the major transportation corridor of Highway 1 and are expected to continue. In Santa Barbara, missing data along the region between Pt. Conception and Goleta and the ending of the erosion analysis south of Santa Barbara harbor explain the missing erosion analysis. As a result, the vulnerability assessments underestimate the actual economic impact from erosion. Note that the flood analysis covered the entire Pacific coast of California and results for the erosion analysis were not adjusted to account for missing segments of the coast.

Table 4. Miles and fraction of coastline studied for the erosion hazard study, by county

County	Studied	Total	% Studied
Del Norte	42.7	49.7	86
Humboldt	72.9	123.3	59
Marin	69.5	75.2	93
Mendocino	145.5	151.4	96
Monterey	94.4	132.0	71
San Francisco	7.5	8.8	85
San Luis Obispo	77.0	102.6	75
San Mateo	57.8	59.6	97
Santa Barbara	84.4	116.5	72
Santa Cruz	46.0	46.0	100
Sonoma	63.0	68.9	91
Total	**760.7**	**934.1**	**81**

2.4. Resources Threatened by Sea-Level Rise

In any given area, rising seas pose a threat to many different types of resources. Among the vulnerable coastal systems are transportation facilities such as roadways, airports, bridges, and mass transit systems; electric utility systems and power plants; stormwater systems and wastewater treatment plants and outfalls; groundwater aquifers; wetlands and fisheries; and many other human and natural systems from homes to schools, hospitals, and industry. Any impacts on resources within the affected area may lead to secondary impacts elsewhere. Determining the types of resources threatened by sea-level rise is a crucial step toward choosing an appropriate level of response and method of protection.

2.4.1. Population

Sea-level rise and increased coastal flooding will lead to disruption due to evacuations, displacement from destruction of homes and property, and possibly the loss of lives. To determine populations at risk if no adaptation actions are taken, we overlay the inundation and erosion hazard maps with year 2000 census block data. We use current population data aggregated by census block, the highest resolution available for California. We make an assumption common in regional 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 underestimate (where the houses are clustered on the coast) or overestimate (when the houses are set back from the coast) the actual risk.

While disasters do not discriminate, the existing societal and environmental conditions before, during, and after a disaster produce differences in vulnerability among groups within the population affected.

It is critical to understand that 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 be low—perhaps substantially low. If, however, policymakers are proactive about reducing coastal risks in coming decades, the levels of risk could be substantially reduced.

We also evaluate potential environmental justice impacts of sea-level rise.[6] As seen during Hurricane Katrina, flooding and other natural disasters often do the greatest harm to low-income communities and communities of color. Hurricane Audrey, for example, struck the coast of Louisiana in 1957 and had a death rate of 38 per thousand among whites and 322 per thousand among blacks (Bates et al. 1963, cited in Pastor et al. 2006). A study of all U.S. disasters between 1970 and 1980 found that white households had $2,370 less of a financial burden following a disaster than other racial groups (Rossi et al. 1983). One year after Hurricane Katrina, the black population of New Orleans had decreased 57% while the white population had fallen 36% (Frey 2007). Racial disparities are mirrored in economic disparities where low-income communities have shouldered a disproportionate burden of harm resulting from disasters: reports following Hurricanes Hugo and Katrina pointed to a range of problems related to the "invisibility" of low-income communities before the disasters (Pastor et al. 2006).

The uneven distribution of natural disasters' harms mirrors racial and economic inequities in the distribution of other environmental risks and benefits, which in the 1980s catalyzed affected communities to develop the framework of "environmental justice." This framework was ultimately affirmed by the Environmental Protection Agency in its 1992 creation of what is now called the Office of Environmental Justice, which holds that

> "no group of people, including racial, ethnic, or socioeconomic groups, should bear a disproportionate share of the negative environmental consequences resulting from industrial, municipal, and commercial operations or the execution of federal, state, local, and tribal environmental programs" (U.S. EPA).

Presidential Order 12898 of 1994 expanded the application of environmental justice principles in its decree that "each Federal agency shall make achieving environmental justice part of its mission" (Presidential Executive Order 12898).

We use the environmental justice framework in two analyses that are relevant to understanding the full costs of sea-level rise in California. The first is a simple analysis looking for potential inequities in who is likely to be directly exposed to sea-level rise, within the geographic units at which relevant political decisions are made. In this case these geographic units include the state of California as a whole and each county affected by sea-level rise. We urge further studies looking at possible inequities at different spatial scales, e.g., within cities, neighborhoods, and metropolitan regions. Our second environmental justice analysis focuses on the factors of

[6] Here, we evaluate the environmental justice impacts of flooding but not erosion. Additional analysis should examine erosion as well.

vulnerability and the differential vulnerability to the impacts of sea-level rise of people from different demographic groups.

A third analysis, which is beyond the scope of this study, should focus on potential inequities in the distribution of benefits of the resources that are invested in protecting from and adapting to sea-level rise. Here we focus on completing a part of the first and second analyses, and leave the third analysis for future studies.

Any analysis of populations affected by sea-level rise should include a broader discussion of vulnerability to these events. According to the Intergovernmental Panel on Climate Change, "Vulnerability to climate change is the degree to which these systems are susceptible to, and unable to cope with, adverse impacts" (Schneider et al. 2007). Vulnerability is a function of the magnitude of the impact, the sensitivity of the system to that impact, and the system's ability to adapt. Vulnerabilities, like lack of access to a vehicle or other means of transportation, are shaped by "intervening conditions" that are not tied to a specific hazard but will greatly determine the human impact of the disaster and the specific needs for preparedness, response, and recovery (Hewitt 1997).

Here, we report key population characteristics that increase vulnerability to the adverse impacts of flood events and disasters for low-income people and communities of color. We sort the types of vulnerabilities and key demographics correlated with increased vulnerability, according to the three phases of a disaster event: preconditions, disaster, and recovery and reconstruction (Hewitt 1997). Figure 9 offers a conceptual model of the relationship between demographics, vulnerabilities, and human impact. Our analysis is limited to two factors: the distribution of race and income. A more comprehensive analysis of the human impact of sea-level rise is needed for all vulnerable subgroups, including children, elderly, homeless, and incarcerated residents.

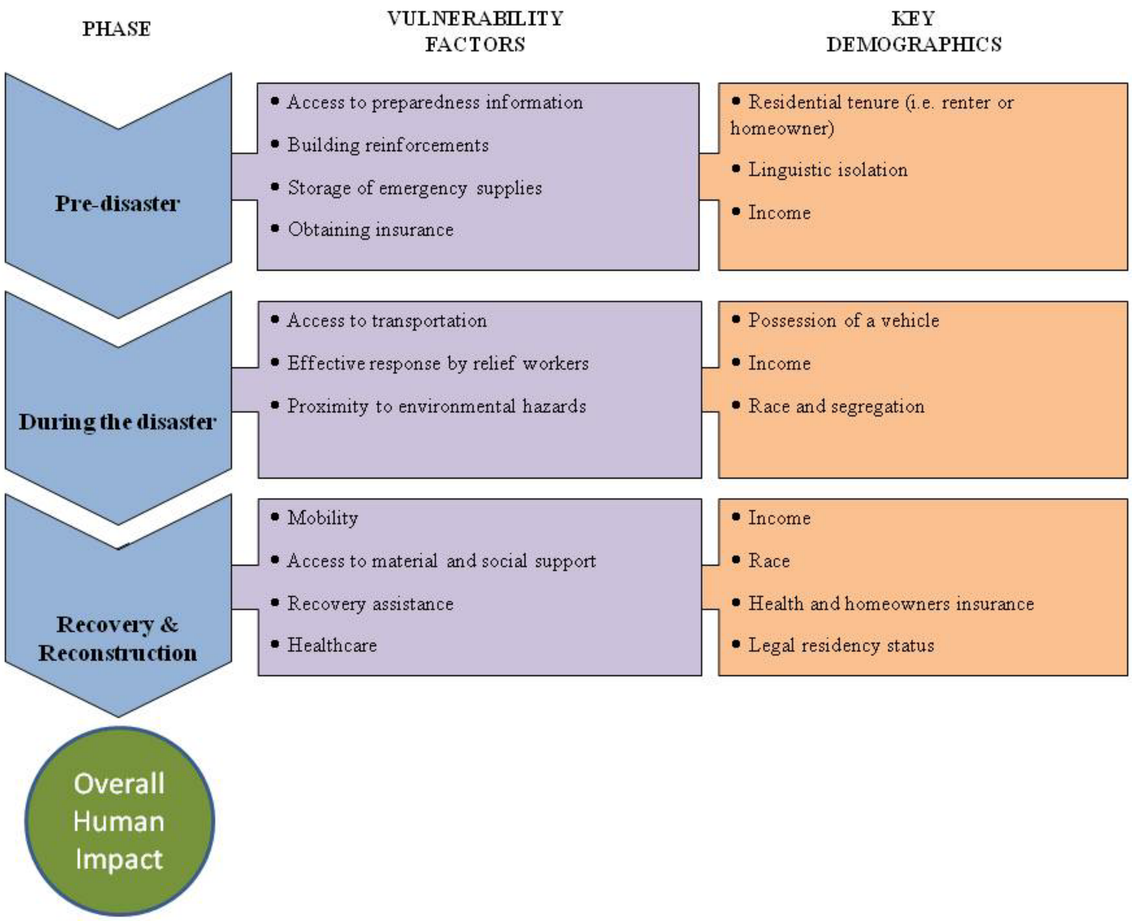


Figure 9. Relationship between demographics and vulnerabilities

2.4.2. Impacts on the Built Environment

Extensive development has occurred in areas already threatened by erosion and floods along the California coast. Residential homes along the California coast often draw a premium price as a result of their location. Some homes in coastal zones are protected by levees and revetments; many are not protected at all. Additionally, high-value commercial, industrial, and transportation facilities are also located along the coast. Such facilities make use of the waterfront for waste disposal, movement of goods or people, or commercial activities. Among the most common coastal facilities are airports, railroad tracks and terminals, highways, power plants, waste-disposal sites, waste-treatment plants, ports and docks, warehouses, salt ponds, and marinas. Existing forms of protection for these facilities vary greatly, from bulkheads and engineered seawalls to riprap and non-engineered levees. An increase in sea level will increase the severity of possible damages in threatened areas and will expand the size of flood and erosion zones.

Data on the replacement value of buildings and contents was taken from datasets supplied with the HAZUS model, which was developed for FEMA's Mitigation Division by the National Institute of Building Sciences. HAZUS was designed to help planners estimate the potential losses from natural disasters such as earthquakes, floods, and hurricane winds. HAZUS uses a database called the “General Building Stock Inventory” that contains the value of buildings and contents 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. HAZUS estimates direct economic losses based on the repair and replacement of damaged or destroyed buildings and their contents, and includes the following:

- Cost of repair and replacement of damaged and destroyed buildings.
- Cost of damage to building contents.
- Losses of building inventory (contents related to business activities).

Replacement values are provided for residential, commercial, industrial, agricultural, religious, governmental, and educational developments and are compiled at the census block level. See Section 14.2 of the HAZUS technical manual for additional detail (FEMA 2006). To determine the replacement value for the areas at risk, we overlay the inundation maps with year 2000 census block data. We assume that if 50% of an area is affected, then 50% of its assets are at risk. For inundation risks, we use replacement value, as described in more detail below, because 1-100 year inundation does not completely destroy property and land value. In contrast, erosion often completely destroys the property. As a result, replacement value is not appropriate for evaluating the economic cost of erosion and was not used for that part of the study.

We compared replacement costs and the market value of homes at a few locations along the California coast and found that the replacement costs in HAZUS can 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 (Figure 10). 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. Of course, homes on the coast are usually much more expensive. For the erosion analysis, we assume that the value of the average coastal property is about $1.4 million (Heinz Center 2000).

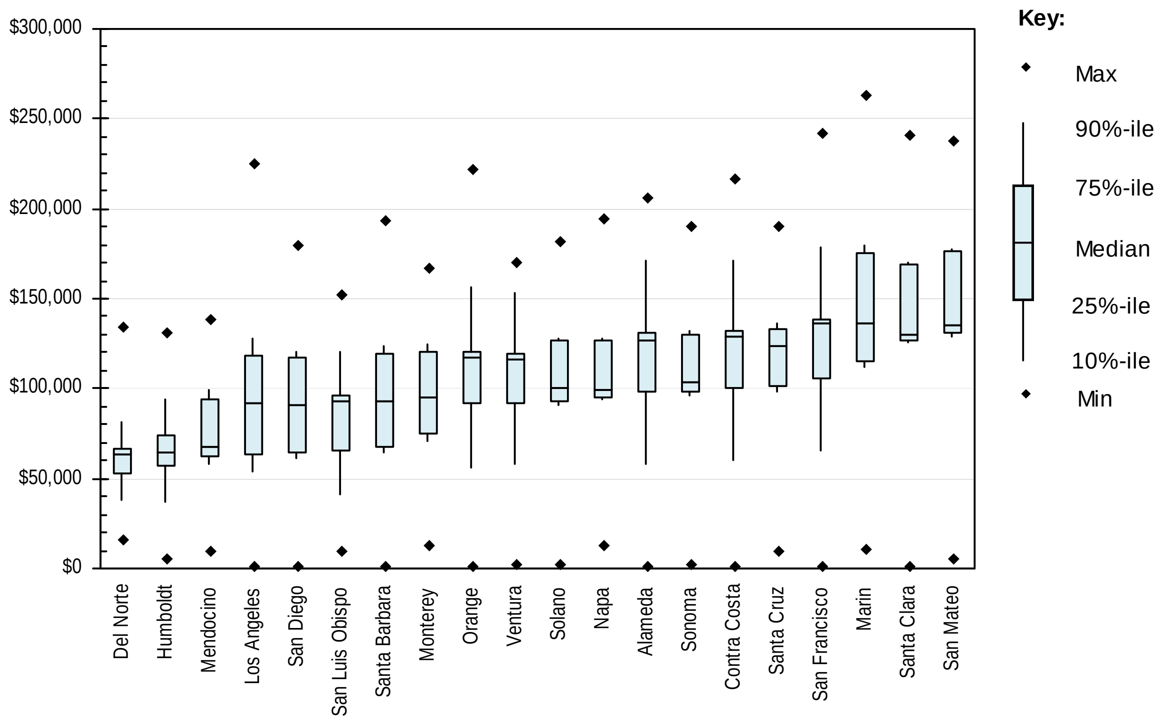


Figure 10. Distribution of census-block average replacement costs for single-family homes from HAZUS

The difference between the replacement value and the market value of a home is likely due to several factors. Home values are determined by more than the cost to build the house, including land value, neighborhood, school district, and dozens of other tangible and intangible factors. In addition, the HAZUS documentation warns that replacement value is based on national-average construction costs, which are much lower than construction costs in California. Future studies should include more detailed estimates of California construction costs.

Parcel data from each county's assessor's office provides higher spatial resolution, but there are some significant limitations to using these data. First, we were unable to obtain a complete coverage for all coastal counties. In some counties, parcel data have not been converted to a digital format, while others claimed that sharing these data was a threat to Homeland Security. Second, even where parcel boundary files are available, these must be linked to the value of the property. While obtaining a list of affected parcels is straightforward, most counties do not readily share their tax rolls or tables with assessed value. This information is part of the public record, and can legally be requested in person or by phone from a county assessor's office, but this approach is not feasible for a regional analysis where hundreds or thousands of parcels are affected. Third, even if assessed value were readily available to us, it often bears little relationship with the actual market value of a property. Finally, assessed value will not include any publicly owned buildings, so it would exclude many police and fire stations, government buildings, park buildings, schools, water treatment plants, and others.

Important transportation infrastructure is also at risk of flooding and erosion from projected increases in sea-level rise (Figure 11). We estimate the miles of roadways and railroads at risk by overlaying the GIS inundation and erosion hazard layers with transportation data from Tele Atlas. We note that because there are not elevations associated with the roadways, it is difficult to infer the extent to which the roadway is at risk from flooding. Additionally, the railroad data does not provide information on the number of tracks, e.g., single, double. We also do not provide estimates of the value of this infrastructure because adequate data are not available. Thus, the information on roads and railways is presented as miles of structures at risk rather than value, but it provides an indication of the areas at risk and those warranting additional analysis.

Figure 11. Flooding of a coastal road in Santa Cruz, California

Photo courtesy of David L. Revell

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

Data on U.S. EPA-monitored hazardous materials sites were from the U.S. EPA Geospatial Data Access Project 2008 and included 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.[7] The Pacific Institute developed a geographic database of wastewater treatment plants based on data in the U.S. EPA's Permit Compliance System (PCS) database, by interpreting aerial photos and by telephone and Internet research.

2.4.3. Natural Resources

Wetlands are among the Earth's most productive ecosystems. Once abundant across the United States, wetlands have been extensively drained and filled to make way for agricultural, industrial, commercial, and residential development. Pollution and invasive species threaten the health of the remaining areas. The U.S. EPA estimates that more than 220 million acres of wetlands existed in the lower 48 states in the 1600s. By 2000, only 100 million acres of wetlands remained (U.S. EPA 2001). In some parts of the United States, wetland loss was even more severe. In California, for example, more than 90% of the historic wetlands have been lost to development. Growing recognition of their importance and concern about their rapid decline has prompted wetland restoration efforts across the United States, including the San Francisco Bay. A recent U.S. Fish and Wildlife Service report suggests that the net wetland acreage actually increased between 1998 and 2004 for the first time as a result of restoration efforts and the construction of engineered wetlands (Dahl 2006).

While legislation has partly protected wetlands from further destruction, rising seas threaten to substantially modify or destroy remaining wetland habitat. Most coastal wetlands in the United States are within one tidal range of mean sea level (Titus 1988), i.e., between mean high tide and mean low tide. Thus, as noted by Titus (1988), if sea levels rose by one tidal range overnight, "then all of the existing wetlands in an area would drown." Rising seas, however, may also inundate land that is now dry, thereby creating new wetlands. Wetlands may also be able to adapt to rising water levels over time by trapping sediment or building on the peat the sediment creates, a process referred to as vertical accretion. These compensatory mechanisms may be hindered by coastal development that limits wetland migration or rates of sea-level rise that exceed natural accretion rates.

Spatial Extent of Wetlands

In this analysis, we use GIS data from the National Wetlands Inventory (NWI) to determine the current spatial extent of wetlands along the California coast and the San Francisco Bay. While there is currently no single source that contains the boundaries of all existing wetlands, the NWI is the best dataset available. It is important to note that all datasets likely underestimate the actual wetland area. Wetland delineation is a time- and labor-intensive task requiring extensive field work by experts; vast areas have never been subject to detailed study.

---

[7] A *brownfield* is an abandoned industrial site available for redevelopment, often with environmental contamination.

The NWI does not make a clear distinction between coastal and upland wetlands. The datasets are distributed in tiles, with each tile containing a mix of marine, estuarine, and freshwater wetlands. We used a simple rule-based approach to decide which wetlands are coastal, or "coast-dependent"" we assume that coastal wetlands are generally limited to within 100 feet (horizontally) of the mean higher-high water line (Figure 12).

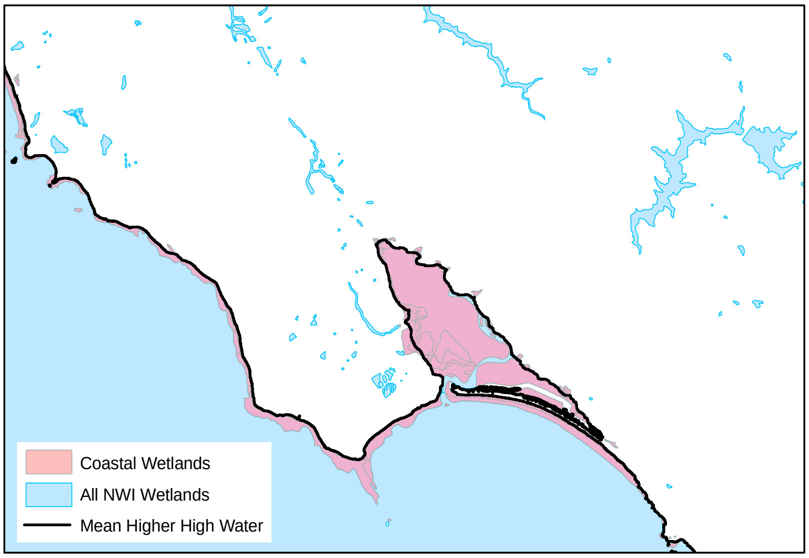


Figure 12. National Wetlands Inventory wetlands classified as "coastal" are below or adjacent to the MHHW line

Economic Value of Wetlands

Wetlands are highly diverse ecosystems that provide a variety of goods and services, including flood protection, water purification, wildlife habitat, recreational opportunities, and carbon sequestration. While there are rarely any direct market values for services provided by wetlands, such as biodiversity and flood control, there is a growing recognition that these services have real economic values and should be included in decision-making processes.

Methods for estimating the economic value of an ecosystem, including wetlands, can be done in one of three ways: direct, indirect, and proxy (Table 5). Each of these methods has strengths and weaknesses; each fails to fully capture the value of ecosystems. The unacceptable alternative, however, is to assign an economic value of $0—clearly acknowledged to be wrong. To put it simply, "we don't protect what we don't value" (Myers and Reichert 1997).

In recent years, a number of studies have attempted to estimate the economic value of wetlands. Based on a literature review and some original calculations, Costanza et al. (1997) estimate that the value of tidal marshes is around $5,700 per acre per year (in year 2007 dollars). In a meta-analysis of 39 wetland valuation studies, Woodward and Wui (2001) found that wetland values varied considerably according to the methods used, the type and location of wetlands evaluated, and the study characteristics. While the valuation method affected the value obtained, the method was not the primary determinant of value. However, study quality was not a strong determinant either; weak studies yielded wetland values similar to strong studies, but with more error, suggesting that the quality of the study affects precision. The authors conclude: "From our analysis it is clear that the prediction of a wetland's value based on previous studies is, at best, an imprecise science. The need for site-specific studies remains" (Woodward and Wui 2001).

For this analysis, we estimate the economic value of wetlands in California using recent cost estimates for restoring wetlands. Numerous wetland restoration projects have been initiated in the San Francisco Bay, with the cost of restoring these tidal marshes ranging from $5,000 to $200,000 per acre (Hutzel 2008). The South Bay wetland restoration project, for example, is estimated to cost about $67,000 per acre (Hutzel 2008). We note that these estimates represent the public's willingness to pay for these ecosystems rather than their actual value, but without a more detailed site-specific analysis, the restoration costs are the best estimates available. We do not evaluate the ability of wetlands to adapt to these changes through vertical accretion or landward migration, but note that these processes could reduce damage to wetlands. We urge more detailed wetland valuation studies be conducted to improve these estimates.

Table 5. Approaches for estimating ecosystem values

Approaches	Description	Example	Weaknesses	Strengths
Direct	Surveys can be used to ascertain people's willingness to pay for benefits provided by the wetland or the level of compensation they would expect for the loss of those benefits. Such surveys measure the value of specific benefits.	A survey that asks users what they would be willing to pay to retain a recreational area.	This approach requires sophisticated survey design, analysis and interpretation.	This approach can measure relatively subtle changes in value and can also be used to calculate the value of non-use benefits.
Indirect	Economists use mathematical models to estimate wetland values based on the market demand for related goods and services.	Expenditures and the distance traveled by people visiting a wetland are used as indicators of the value of the wetland for recreational purposes. Similarly, real-estate price differences could be used to estimate the value of the wetland's aesthetic benefits.	This approach cannot measure non-use benefits (e.g., option or bequest benefits) or benefits that do not currently exist (e.g., the benefits of an enlarged wetland).	This approach is usually faster and less expensive, as it can be based on easily accessible data.
Proxy	The values of other goods and services are used to approximate the values of wetland benefits.	The replacement cost for a wetland benefit (e.g., water filtration), such as the cost of installing a buffer strip or building a water treatment plant, is used as a measure of the value of the benefit.	This approach may confuse costs and benefits. For example, using the cost of a water treatment plant estimates the cost rather than the value of water filtration, (i.e., people's willingness to pay for clean water).	This approach can be more quickly calculated, but the result is only a very rough estimate of value.

Source: Environment Canada 2001

Impact of Sea-Level Rise on Wetlands

Evaluating the impacts of sea-level rise on a particular coastal wetland area requires site-specific data on various physical and biological factors, as described above. While this information is clearly important for developing adaptation strategies, it is beyond the scope of this analysis. A simple method to estimate wetland loss is to compare wetland elevations to future tide elevations. If the areas are permanently inundated in the future, they will be converted to open water and lose their value as wetland habitat. Data limitations, however, prevent us from performing even this simple analysis: the existing digital elevation models (DEMs) do not include data below the shoreline and the modeled mean lower low water mark, even with 1.4 m of sea-level rise, falls below this elevation. This means there are no data in the critical area where the boundary must be drawn. We recommend additional work in this area to create a DEM for the California coast that combines land surface elevations with accurate bathymetry to allow for more detailed study of potential wetland responses to sea-level rise. Given these data limitations, we evaluate the land cover *adjacent* to existing wetlands and the potential for these areas to support suitable wetland habitat. We note that this simplified analysis does not take into account erosion or accretion due to sediment movement, which is difficult to predict with any accuracy.

Wetlands exist in areas that are frequently but not permanently inundated. In *The Effects of Sea Level Rise on US Coastal Wetlands*, Park et al. (1989) assumed that all areas between mean lower water (MLW) and mean higher water springs (MHWS) are tidal wetlands (Figure 13). The MHWS is only a few centimeters from the mean higher high water (MHHW) datum, which is more readily calculated and tabulated in tide reports. We assume that wetlands will migrate to land areas that are below the future MHHW, which we estimate as current MHHW plus the projected 1.4 m sea-level rise.

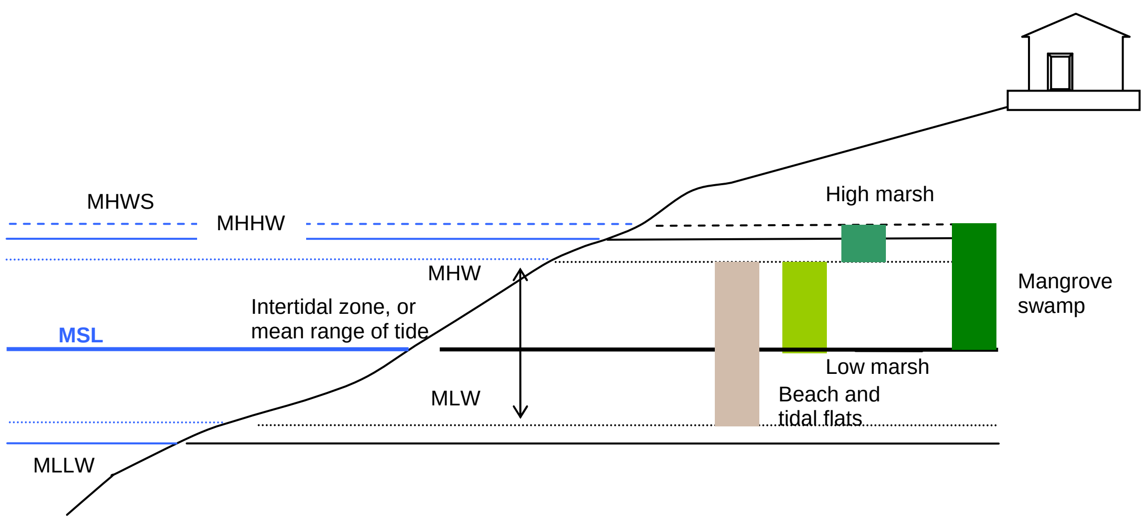


Figure 13. Assumed wetland area defined by the intertidal range

Adapted from Park et al. 1989.

The National Oceanic and Atmospheric Administration maintains tide stations along the California coast that provide measurements of MHHW. We interpolated the high-water elevation for the entire California Pacific coast using data from 12 long-term coastal tide gages. Each of these NOAA tide stations has been in continuous operation for over 25 years. The MHHW elevation for each of these stations is listed in Table 6. Using spatial interpolation tools available in ArcGIS software, we developed a continuous grid or "surface" of MHHW elevations in year 2000.[8] To estimate MHHW elevations with a 1.4 m sea-level rise for the Pacific coast of California, we created a second surface by adding 1.4 m to each pixel in the year 2000 MHHW surface. The difference between the high water lines is the "wetland migration zone": the land into which wetlands must migrate to survive.

Table 6. Mean higher high water (MHWH) for long-term tide stations on California's Pacific coast

NOAA Station ID	Station Name	MHHW
9410170	San Diego, CA	1.61
9410230	La Jolla, CA	1.57
9410660	Los Angeles, CA	1.61
9410840	Santa Monica, CA	1.60
9411340	Santa Barbara, CA	1.61
9412110	Port San Luis, CA	1.60
9413450	Monterey, CA	1.67
9414290	San Francisco, CA	1.80
9415020	Point Reyes, CA	1.75
9416841	Arena Cove, CA	1.76
9418767	North Spit, CA	1.99
9419750	Crescent City, CA	1.98

Note: Elevations in meters above NAVD88 vertical datum. Tide datums calculated by NOAA for the 1983–2001 epoch.

Source: http://tidesandcurrents.noaa.gov/

We analyzed the land cover in the potential wetland migration zone using 2001 land cover data from NOAA's Coastal Change Analysis Program (C-CAP).[9] We rated each land cover type according to its suitability to support wetland habitat in the future. We assume that natural lands such as woodland, grassland, or shrub could provide suitable habitat for wetland plants and animals in the future when they are in the new intertidal zone and are intermittently wetted. Other land cover types may be viable for conversion to wetlands, but at a loss of some direct value to humans, e.g., farmland or parks. The third and final category represents built-up

---

[8] In some areas of Southern California, however, the available digital terrain data was not sufficiently detailed to complete the analysis. The terrain data did not include points below an elevation of 1.5 m NAVD88, and we could not map the current MHHW inundation extent for the entire coast. We mapped about 49% of Santa Barbara County, 23% of Los Angeles County, and 65% of Orange County. The coverage was 100% in the other 11 counties on the Pacific coast.

[9] The C-CAP data layer classifies land cover based on an adapted version of the Anderson et al. (1976) classification scheme and is estimated to have an accuracy of 85% (NOAA Land Cover Analysis website www.csc.noaa.gov/crs/lca/ccap.html).

areas that will likely provide unsuitable habitat for wetlands in the future due to the presence of buildings and other paved areas.

2.4.4. Limitations

Our analysis also has limitations related to the economic valuation methodology. For the flood analysis, we estimate the economic cost of sea-level rise based on estimates of the replacement value of buildings and their contents. We do not include estimates of the property or land value, which are much higher and should be included if inundation is permanent or leads the abandonment of property. Replacement values are also not appropriate for estimating the cost of erosion because it typically results in the total loss of property and land. We make a rough estimate of land values along the coast but note that additional study is needed.

Flooding and erosion can 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. Flooding or erosion of a major highway can prevent people from getting to work. Estimating the replacement value and even some wetland values thus substantially underestimates the total cost of flood impacts and as a result, our results should be considered conservative. A more detailed analysis would include transportation risks, lost work days, health issues, impacts on migratory bird habitat, and others.

We also do 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 regions of future flooding, society could over time reduce the risks. While limiting coastal development (an institutional adaptation) is likely the most effective way to reduce risk, this approach can also incur costs. Development permits designed to provide flexibility for future generations to address sea-level rise (e.g., development permits that allow development but stipulate that the area reverts to nature if seas rise a specified amount) may reduce today's cost. Conversely, if current development in coastal areas continues unchecked, a far larger population and a far larger infrastructure set will be vulnerable than at present. 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 tools developed here.

2.5. Determine the Protective Responses Appropriate for the Region

Each of the resources and facilities described in Section 2.4 can be protected by some combination of structural and non-structural measures. Some of the possible structural measures include building or improving coastal defenses such as dikes and dunes, seawalls, bulkheads, and other structures. Non-structural measures include abandoning property and land and moving to less threatened areas and beach nourishment. Perhaps the most effective non-structural response is to prohibit development in regions likely to be threatened in the future. This choice, however, requires the most forethought and planning. Below, we describe some of the structural measures and their associated costs.

2.5.1. Structural Coastal Protection Measures

Beach Nourishment

The addition of beach sand to a shoreline has been used to construct beaches where none had previously existed and to replenish eroded sand. As a response to the expected increase in erosion due to sea-level rise, the purpose of beach nourishment is to restore the width of an eroding beach on a temporary basis, although nourishment can also provide long-term restoration in certain types of areas. The rate at which the replenished beach erodes is a function of wave action, the uniformity of placement of the sand, and the grain size (U.S. Army Corps of Engineers 1984b). The sand used for a beach nourishment project usually comes from offshore dredging and pumping to the desired site; less frequently material is imported from an off-site location. The cost of the material can vary greatly depending on its origin and associated transportation costs.

Groins

One type of structure designed to lessen the impact of coastal processes on a shoreline is a groin—a structure oriented perpendicular to the shore that serves to reduce the flow of sediment along a shore (the local littoral drift rate). Sand collects on the updrift side of the groin until it is filled to capacity, when longshore drift is allowed to pass. Groins are often used in fields (sets of more than one groin) to protect a long section of coastline. The shoreline immediately downfield of the groin field, however, is often subjected to accelerated erosion, especially when the groins are not filled with sand during construction (National Research Council 1987).

Sea-level rise can affect a groin by reducing its effectiveness due to "flanking" or "submergence." A groin typically extends landward to the dune line, and the dune line may retreat due to sea-level rise, leaving the groin susceptible to flanking during high or storm tides, allowing sand to bypass the groin. Submergence of the groin can lead to overtopping by the longshore current, further decreasing the structures' efficiency at stabilizing the area (National Research Council 1987).

Seawalls, Bulkheads, and Revetments

There are three principal forms of vertical shoreline walls used to protect upland areas from storm surges and high tides: seawalls, bulkheads, and revetments. The differences between seawalls, bulkheads, and revetments are in their protective function. Seawalls are designed to resist the forces of storm waves; bulkheads are to retain the fill; and revetments are to protect the shoreline against the erosion associated with light waves (U.S. Army Corps of Engineers 1984b). These structures tend to fix the position of the coast. While this strategy may protect upland development, there are two kinds of adverse consequences of these types of structures. *Placement loss* refers to the loss of beach due to the footprint of the structure. For seawalls this is not as great as a revetment, which is usually built at a 2:1 (horizontal:vertical) slope. The other impact of these structures is called *passive erosion.* As sea level rises, and the structure fixes the position of the shoreline, the beach in front of the structures can be "drowned," resulting in a loss of recreation opportunities and habitat (Griggs 2005).

Breakwaters

Offshore breakwaters are above-water structures parallel to the shore that reduce both wave heights at the shoreline and littoral drift. Sea-level rise will reduce the protective capacities of breakwaters in two ways: rising water levels will effectively move the shoreline farther from the breakwater, increasing the ability of the waves to diffract behind the structure and reducing the sheltering and efficacy of the device; and the increased frequency of overtopping will diminish the ability of the breakwater to reduce the wave energy in the sheltered region (National Research Council 1987).

Dikes and Levees

Dikes or levees are embankments to protect low-lying land. A sea-level rise can result in reduced stability and increased overtopping of existing levees. New levees may be constructed to protect developed areas (National Research Council 1987). Whether existing levees can be modified for a rise in sea level depends on the availability of material for raising the levee, the suitability of the foundation material to support the additional weight of the material, the stability of the levee with the increased water level, and the accessibility of additional area for widening the base of the levee. Considerations for new levees also include issues such as land condemnation and interference of the levee with navigation (National Research Council 1987).

Raise Existing Structures (Roadways, Railroads, and Other Structures)

In some regions, building levees or seawalls to protect a small number of structures may not be cost effective. In these instances, raising the structures may be a better alternative. Roadways, railroads, and other structures may be raised so as to avoid damage from flooding. Over time, for example, we think it likely that important economic assets such as airports, transmission lines, or roadways will be raised rather than protected with levees or seawalls.

2.5.2. Cost of Structural Protection Measures

The cost of flood defenses is site-specific and little reliable information is available to generalize these costs. Gleick and Maurer (1990) developed cost estimates for building new coastal protection structures and raising existing ones, as well as raising roadways, railroads, and individual structures. We update these costs for this analysis based on a literature review (Table 7). Costs are converted to year 2000 dollars. Given the site specificity of construction costs, we relied on cost information from California where possible.

Data suggest that a new levee between 10 and 20 feet in height with a waterside slope of 3:1 would cost about $1,500 per linear foot (in year 2000 dollars). This represents a 320% increase over the 1990 estimate, much higher than the rate of inflation. The increase is likely due to large increases in construction and material costs in recent years. We estimate that raising existing levees would cost about $530 per linear foot (in year 2000 dollars). Seawalls, while providing significant protection, are among the most expensive option, estimated at about $5,300 per linear foot (in year 2000 dollars).

Table 7. Costs (in year 2000 dollars) for building new levees, raising existing levees, and building new seawalls

	Cost ($ per linear foot)	Location	Sources
New Levee	$725–$2,228	San Francisco, CA	Pang (2008)
Average New Levee	**$1,500**		
Raise Levee	$319	Central Valley, CA	Mount and Twiss (2005)
	$223–$1,085	San Francisco, CA	Moffatt and Nichol Engineers (2005)
	$278–$944	Central Valley, CA	Mount and Twiss (2005)
Average Levee Upgrade	**$530**		
New Seawall	$1,292	New England	Kanak (2008)
	$3,828	Southern California	Gustaitis (2002)
	$2,646–$6,173	Northern California	Stamski (2005)
	$5,654–$8,078	Philadelphia	PennPraxis (2008)
	$4,847	California	Crampton (2008)
Average New Seawall	**$5,300**		

Note: All costs are shown in year 2000 dollars. Costs shown for a new levee are based on a U.S. Army Corps of Engineers cost-estimation model, for a levee between 10 and 20 feet in height with a waterside slope of 3:1 and built using local materials.

In addition to the construction costs of the various structures described above, maintenance costs are often significant. In general, the greater the engineering employed in the construction of a shore protection scheme, the lower the proportion of maintenance costs. The maintenance cost of engineered riprap-revetment, for example, can amount to 2%–4% of the construction cost per year over the life of the project. This can be compared with the maintenance cost for a non-engineered revetment of 5%–15% of the construction cost per year (Fulton-Bennett and Griggs 1986). Average maintenance costs for levees are about 10% per year of the costs of construction. The estimated maintenance costs for seawalls run from 1%–4% per year, reflecting the higher level of engineering that goes into their construction. Because the majority of structures in our study are levees, we assume here an annual operation and maintenance cost equal to 10% of the capital cost of construction.

Levees, seawalls, and other structural methods have a number of environmental and social costs that are not reflected in the cost estimates shown in Table 7. Armoring the coast prevents natural movement and migration of the beach and associated ecosystems. In some areas, beaches may disappear completely, as shown in Figure 14. Structural measures can also increase vulnerability by encouraging development in flood-prone areas and giving those who live behind the structure a false sense of security. According to the United Nations, "protective works have a tendency to increase the level of development in floodprone areas, as the assumption is made that it is now safe to build and invest in areas that are protected. However, it must be recognized that at some point in the future the design event will likely be exceeded and catastrophic damages will result" (United Nations 2004).

In addition, structural measures require regular maintenance, a task that is often overlooked due to budgetary constraints. Failure to maintain protective structures can lead to structural failures and catastrophic damage.

Figure 14. An example of coastal armoring leading to the disappearance of beach
Source: David L. Revell

2.5.3. Estimating Needed Coastal Defenses

Details about what level of protection to choose are a function of the perception of the value of the threatened property, the cost of alternative measures, and political and societal factors. In this analysis, we evaluate one scenario: the cost associated with raising the height of existing structures to maintain current flood protection levels and building new structures to protect development that will be at risk of flooding with a 1.4 m sea-level rise. We do not evaluate coastal protection costs for erosion and urge additional studies on this topic.

In order to determine the cost of protecting development along the San Francisco Bay and California coast, we first needed to determine the location and type of existing coastal protection structures. Unfortunately, neither the U.S. Army Corps of Engineers nor any other agency maintains a comprehensive database with this information. The California Coastal Commission, however, recently compiled spatial data on the location and type of protective structure along the Pacific coast, e.g., groins, revetments, levees, and seawalls. Similar data were not available for the San Francisco Bay. Digital Flood Insurance Maps (DFIRMs) that showed the presence of protective structures in the San Francisco Bay, however, were available in some areas. We supplemented the DFIRMS with a visual assessment of aerial imagery of the region. Because the DFIRMs do not distinguish between the types of structure, we assumed that seawalls were located around high-density, highly valued areas and levees were located around all other areas.

Geospatial data on the existing coastal protection structures were overlaid with the inundation maps to determine where existing structures needed to be raised and new structures built. To make this determination, we made the following assumptions:

- Existing coastal protection structures are strengthened and raised by 1.4 m with no change in the type of protection, e.g., levees are raised but are not replaced by a seawall.
- New coastal protection structures are needed wherever built structures are at risk of flooding. Agricultural land was not protected, unless a levee already existed.
- Seawalls are used in areas along the Pacific coast that are currently not protected but will need protection in the future and in areas where space limitations due to development prohibit the construction of new levees.
- Levees are used within enclosed areas, like the San Francisco Bay, that are currently not protected but will need protection in the future. These bays are protected from wave action, and we assume that levees will provide sufficient protection.

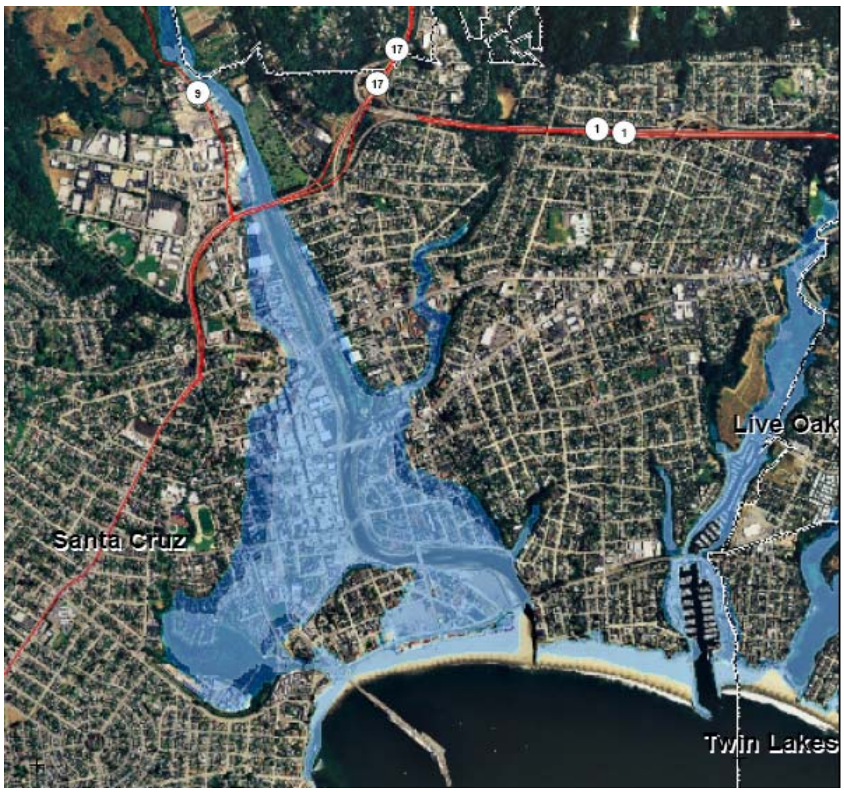
3.0 Results

Here we report on the results of our analyses for San Francisco Bay and the Pacific coast. In particular, we report on the population, infrastructure, and property at risk from sea-level rise, as well as the impacts on harder-to-quantify coastal ecosystems. We also provide an estimate of the economic costs of building coastal protections of different types to protect lives and property from flooding. All economic values are reported in year 2000 dollars. Results are reported separately for the flood and erosion risks.

3.1. Flood-Related Risks

In this analysis, we use the 100-year flood levels to evaluate the vulnerability to inundation. The 100-year flood is used as a standard for planning, insurance, and environmental regulations. It is important to note that people, infrastructure, and property are already located in areas vulnerable to flooding from a 100-year event. Many Californians are already at risk from coastal flooding. Sea-level rise will cause more frequent and more damaging floods to those already at risk and will increase the size of the coastal floodplain, placing new areas at risk where there were none before. In Figure 15, for example, those areas shown in light blue are currently vulnerable to a 100-year flood event in the Santa Cruz area. With a 1.4 m sea-level rise, additional areas (shown in dark blue) will be at risk. Thus, the damage attributed to a 1.4 m sea-level rise is equal to the area currently vulnerable to a 100-year flood event (but now protected by levees, seawalls, etc.) plus new inundated areas, i.e., the areas shown in light blue and dark blue in Figure 15.

A series of maps for the entire coast of California demonstrating the extent of the areas at risk are posted at www.pacinst.org/reports/sea_level_rise. It should be noted again that these maps are not the result of detailed site studies, and were created to quantify risk over a large geographic area. **They should not be used to assess actual coastal hazards, insurance requirements or property values, and specifically shall not be used in lieu of Flood insurance Studies and Flood Insurance Rate Maps issued by the Federal Emergency Management Agency (FEMA). Local governments or regional planning agencies should conduct detailed studies to better understand the potential impacts of sea-level rise in their communities.**



Coastal Flood Risk Area

Current Base Flood
(approximate 100-year flood extent)

Sea Level Rise Scenario
Base Flood + 1.4 meters (55 inches)

Figure 15. Estimated current and future 100-year coastal flood risk areas around Santa Cruz

3.1.1. Population at Risk

Major population centers are located all along California's coast. Nearly 26 million people lived in coastal counties in 2000. Of these, 74% lived along the Pacific coast and the remaining 26% lived along the San Francisco Bay. An estimated 260,000 people, or 1% of California's coastal population, live in areas that are currently vulnerable to a 100-year flood event. As discussed in Section 2.3.3, the inundated area does not adequately take into account existing flood barriers. It is likely that most existing coastal protection structures are sufficient to protect people living in these areas against the present-day flood risk. Most existing defenses, however, will not be adequate to protect inhabitants following significant sea level rise.

As sea levels rise, the area and the number of people vulnerable to flooding will also rise. Rising sea levels will overwhelm the existing protection structures, putting the 260,000 people currently living in vulnerable areas at increased risk. In total, we estimate that a 1.4 m sea-level rise will put around 480,000 people (nearly half a million) at risk from a 100-year flood event (Figure 16). Continued development in these regions could put additional people at risk.

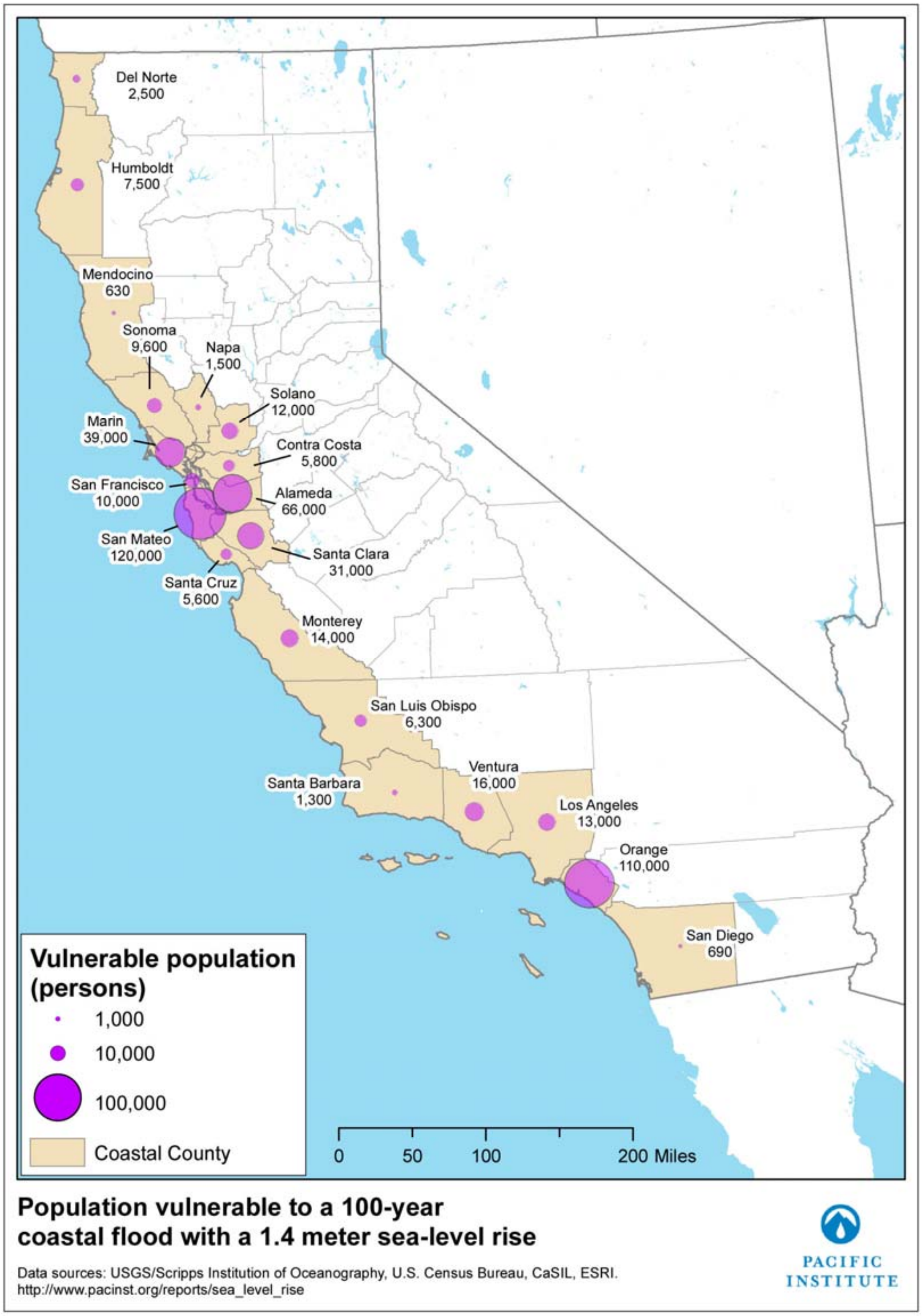


Figure 16. Population vulnerable to a 100-year coastal flood with a 1.4 m sea-level rise, by county

Table 8 shows the population vulnerable to a 100-year flood event along the Pacific coast by county. In 2000, an estimated 120,000 people lived in areas vulnerable to a 100-year flood event. A 1.4 m sea-level rise will increase the number of people vulnerable to a 100-year flood event to 210,000. More than half of these residents live in Orange County, although significant numbers of people are also at risk in Los Angeles, Monterey, San Mateo, Sonoma, and Ventura Counties.

Table 8. Population vulnerable to a 100-year flood along the Pacific coast, by county

County	Current Risk	Risk with 1.4 m sea-level rise	Percent increase
Del Norte	1,700	2,500	47
Humboldt	3,600	7,500	110
Los Angeles	3,600	13,000	270
Marin	520	620	20
Mendocino	520	630	22
Monterey	10,000	14,000	36
Orange	70,000	110,000	55
Sonoma	2,900	9,100	210
San Luis Obispo	4,600	6,300	35
Santa Barbara	660	1,300	98
Santa Cruz	4,500	5,600	24
San Francisco	3,400	6,500	94
San Mateo	11,000	16,000	49
San Diego	570	690	21
Ventura	7,000	16,000	120
Total	**120,000**	**210,000**	68

Note: Counties with borders on the Pacific coast and the San Francisco Bay (e.g., San Mateo) were separated based on the shoreline affected. Numbers may not add up due to rounding.

In San Francisco Bay, the population vulnerable to flooding is even greater. Table 9 shows the population vulnerable to a 100-year flood event in 2000 and with a 0.5 m, 1.0 m, and 1.4 m sea-level rise. In 2000, an estimated 140,000 people lived in areas at risk from a 100-year flood event. An increase in sea levels of 0.5 m has only a modest effect on the number of people at risk. With a 1.4 m increase in sea levels, however, the number of people at risk of a 100-year flood event doubles to 270,000. Populations in San Mateo County are especially vulnerable, accounting for about 40% 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.

Table 9. Population vulnerable to a 100-year flood along the San Francisco Bay, by county

County	Current risk	Risk with sea-level rise 0.5 m	1.0 m	1.4 m	Percent increase (with 1.4 m rise)
Alameda	12,000	22,000	43,000	66,000	470
Contra Costa	840	1,600	3,400	5,800	590
Marin	25,000	29,000	34,000	39,000	55
Napa	760	830	970	1,500	99
San Francisco	190	600	1,600	3,800	1900
San Mateo	80,000	88,000	99,000	110,000	34
Santa Clara	13,000	17,000	24,000	31,000	140
Solano	3,700	5,500	8,800	12,000	230
Sonoma	250	300	420	540	110
Total	**140,000**	**160,000**	**220,000**	**270,000**	**98**

Note: Counties with borders on the Pacific coast and the San Francisco Bay (e.g., San Mateo) were separated based on the shoreline affected. Numbers may not add up due to rounding.

Environmental Justice Concerns

The analysis of the potential environmental justice impacts of sea-level rise considers who currently lives within the areas at risk and the vulnerabilities of this population to the potential adverse impacts. There is little difference between the overall racial and income demographics of Californians affected by a 1.4 m sea-level rise and those of the state as a whole. However, we do find some important differences between the racial and income demographics of those affected and those of the total population of each county.

Table 10 and Figure 17 show a simplified racial breakdown of the flood-affected population and the population of the counties as a whole. Sea-level rise induced flooding may disproportionately affect whites in the majority of counties along the California coast. In Los Angeles County, for example, 73% of those affected are white, while only 31% of the population in the county is white. Conversely, along the San Francisco Bay, however, communities of color are disproportionately impacted by sea-level rise. In total, communities of color are disproportionately impacted in 10 of the 20 counties studied. The greater proportion of people of color in areas affected by a 1.4-meter sea-level rise highlights the need for these counties to take concerted efforts to understand and mitigate potential environmental injustice.

The results presented above highlight the importance of conducting socio-economic analyses and comparisons at various geographic scales. It is significant to note that these numbers only reflect exposure to the hazard. In the next section, we also evaluate other vulnerability factors, such as access to transportation and ability to speak English.

Table 10. Total county population and population vulnerable to a 100-year flood with a 1.4-meter sea-level rise along the Pacific coast, by race

County	White		Asian, Black, Latino, Native American, or Other Race	
	Affected population (%)	County population (%)	Affected population (%)	County population (%)
Alameda	35	41	60	55
Contra Costa	28	58	69	39
Del Norte	75	70	21	26
Humboldt	82	82	15	15
Los Angeles	72	31	26	67
Marin	59	79	38	19
Mendocino	74	75	23	22
Monterey	29	40	69	57
Napa	63	69	35	29
Orange	80	51	18	46
San Diego	73	55	25	42
San Francisco	51	44	46	53
San Luis Obispo	85	76	13	22
San Mateo	46	50	51	47
Santa Barbara	68	57	30	41
Santa Clara	49	44	47	53
Santa Cruz	43	66	54	32
Solano	38	49	58	46
Sonoma	70	75	28	23
Ventura	56	57	41	41
All coastal counties	56	44	41	53

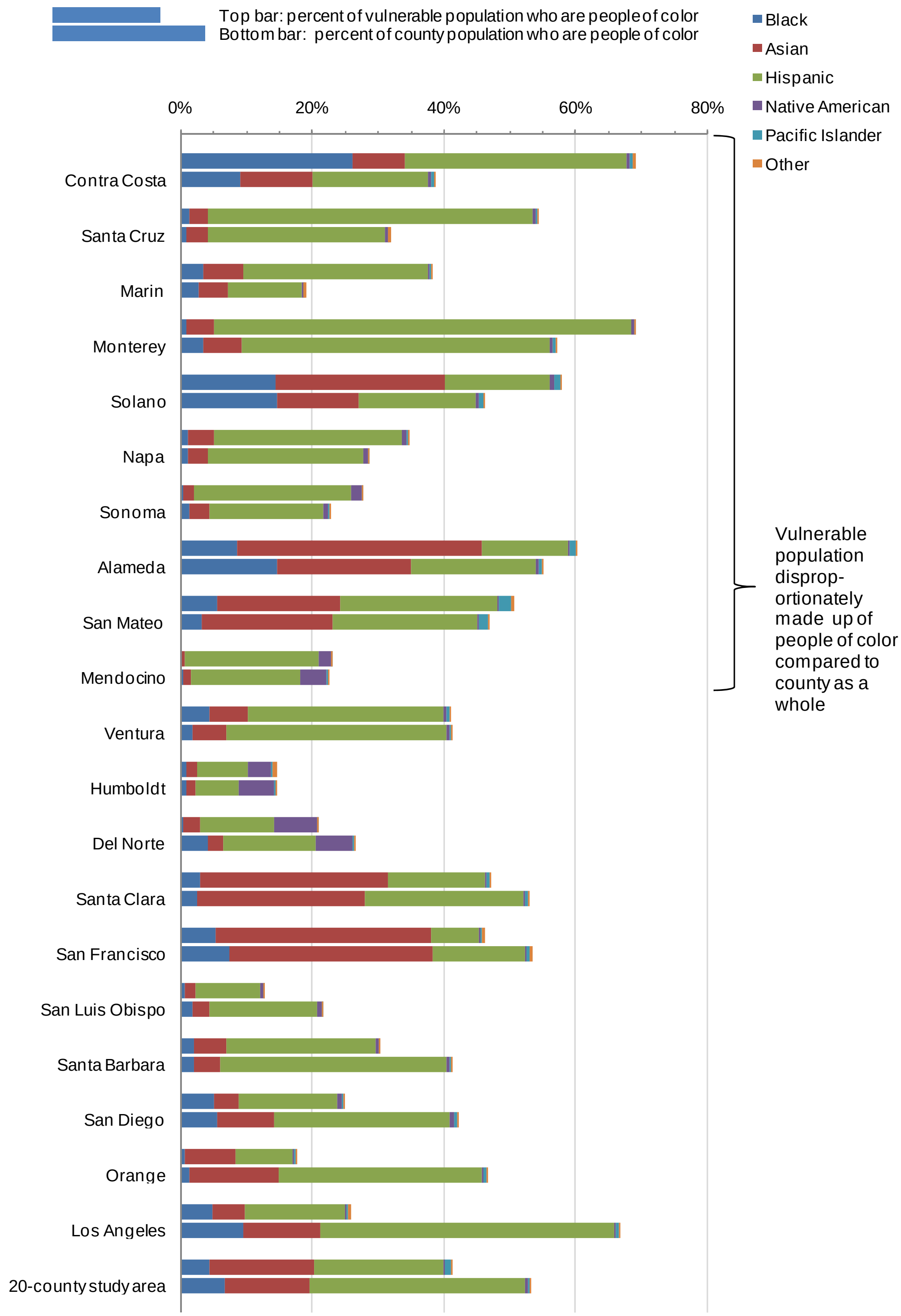


Figure 17. Total county population and population vulnerable to a 100-year flood with a 1.4 meter sea-level rise along the Pacific coast, by race

Note: The lower bar shows the percentage of the county's population that is classified as a person of color, and the top bar shows the percentage of the population at risk of a 100-year flood with a 1.4 m sea-level rise that is classified as a person of color. A county for which the top bar is longer indicates that there is a disproportionate impact on communities of color.

Preconditions

The period preceding a disaster is the key phase for taking action to reduce vulnerabilities and proactively prevent harm. For example, reinforcing residential buildings, obtaining insurance, and storing emergency supplies can reduce injury and loss. Studies show that those who are the most vulnerable are the least likely to adopt these preventive measures. Below, we evaluate key demographic factors affecting vulnerability during the pre-disaster phase, including residential tenure (renter or homeowner), income, and linguistic isolation.

Preventive measures such as reinforcing buildings and buying insurance are adopted at lower rates by people with low income levels (Bolin and Bolton 1986; Blanchard-Boehm 1997). In California, 31% of households earn less than 150% of the federal poverty threshold ($30,000). Low-income households make up 29% of the 20-county study area, slightly less than the statewide total.

An estimated 56,000 households along the Pacific coast, or about 27% of those vulnerable to a 100-year flood with a 1.4 m sea-level rise, earn less than $30,000. Likewise, an estimated 51,000 people along the San Francisco Bay, or about 19% of the affected population, earn less than $30,000 (Table 11). Income demographics vary markedly among the vulnerable populations and counties in this study (Figure 18). Our analysis indicates that there is a disproportionate impact on low-income households in 13 of the 20 coastal counties. These households are less likely than their counterparts to be able to afford emergency preparedness materials, buy insurance policies, and obtain needed building reinforcements.

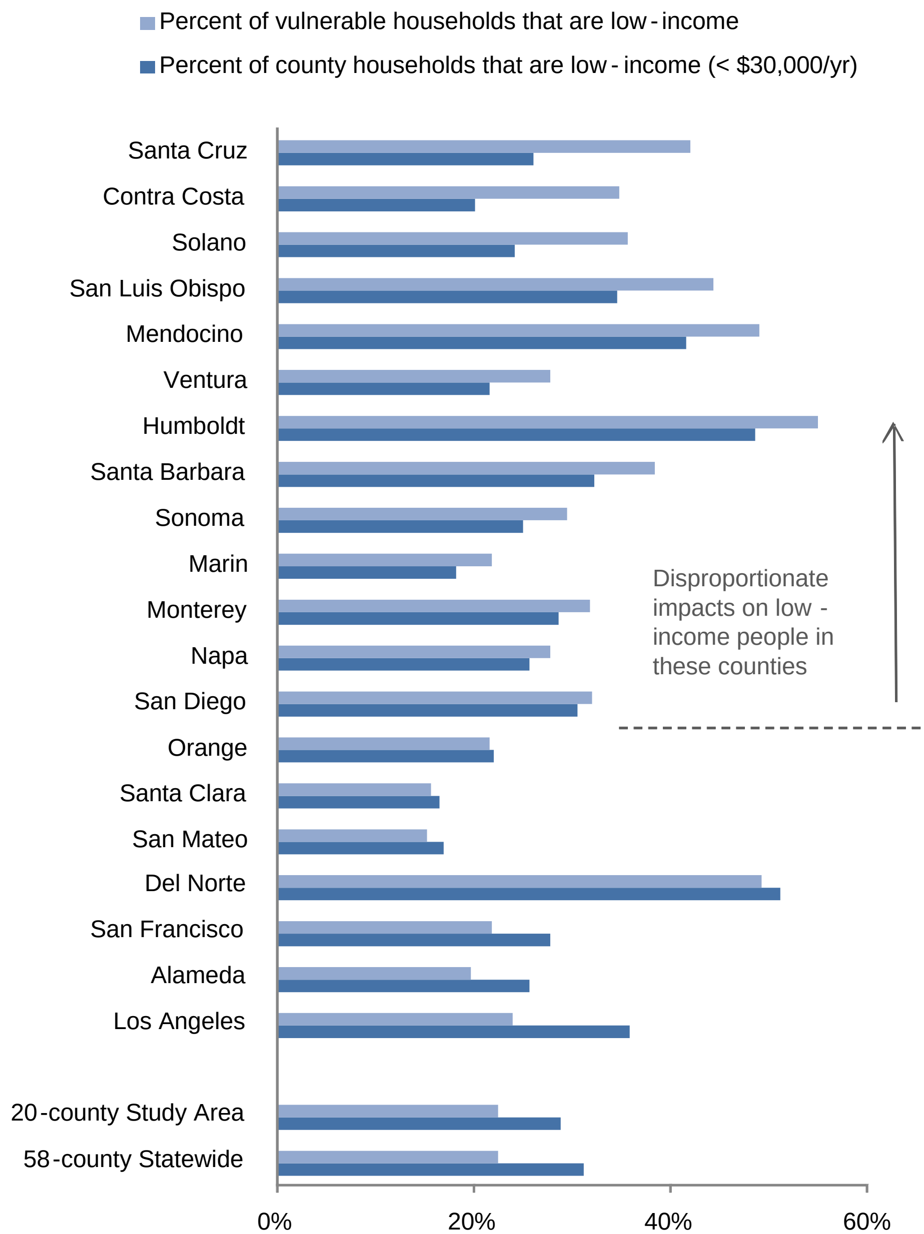


Figure 18. Percentages of low-income households among the population vulnerable to a 100-year flood with a 1.4 m sea-level rise compared with the county total

Note: The lower bar shows the percentage of low-income households in the county, and the top bar shows the percentage of low-income households within the population at risk of a 100-year flood with a 1.4 m sea-level rise. A county for which the top bar is longer indicates that there is a disproportionate impact on low-income households.

Table 11. Key demographics of populations vulnerable to a 100-year flood event with a 1.4 m sea-level rise

	Pacific Coast		San Francisco Bay	
	Number in 100-year flood zone	**Percent of total in flood zone**	**Number in 100-year flood zone**	**Percent of total in flood zone**
Households				
Linguistically isolated	4,700	4	9,700	9
With no vehicle	7,600	7	8,200	7
People				
Earn less than 150% the federal poverty threshold ($30,000)	56,000	27	51,000	19
People of color	60,000	29	148,000	55
Who rent (not own) their home	45,000	43	47,000	41

Data source: Census 2000

Renters are also less likely to reinforce buildings and buy insurance because the decision to make major improvements and financial gains typically lies with the property owner. Of those vulnerable to a 100-year flood event with a 1.4 m sea-level rise, about 45,000 people along the Pacific coast and 47,000 people along the San Francisco Bay rent their homes. These households comprise 43% and 41%, respectively, of the homes within the areas at risk.

Language ability is also an important factor in assessing vulnerability (Wang and Yasui 2008). Earthquake preparedness materials following the 1987 Whittier-Narrows earthquake in California, for example, were available only in English, despite other language needs of the victims (Tierney 1993, cited in Pastor et al. 2006). Additionally, emergency response crews may be unable to communicate with non-English speakers. A recent study of 148 emergency preparedness and public health entities found that only 72% provided links on their website to translated materials, and only 14% offered courses for service providers that addressed potential language issues and cultural competence (Andrulis et al. 2008). Among the population at risk from a 100-year flood event with a 1.4 m sea-level rise, 9,700 households along the San Francisco Bay and 4,700 households along the Pacific coast are "linguistically isolated," meaning no one over age 14 speaks English well (Table 11). These 14,000 households are the most likely to need preparedness materials and outreach strategies suitable for non-English speakers of various backgrounds.

Even among those for whom language is not a barrier, cultural factors can influence the effectiveness of preparedness outreach. Numerous studies show that black and Latino communities prefer neighborhood meetings as a way of receiving information about hazards (Blanchard-Boehm 1997; Perry and Mushkatel 1986; Phillips and Ephraim 1992, cited in Pastor et al. 2006). The historic role of African-American churches in providing disaster planning and response provides a unique asset and partner to public efforts in these communities (Trader-Leigh 2008).

The representation of low-income and people of color in the groups with heightened vulnerabilities during the pre-disaster phase are higher than these communities' representation in the overall population. In 2000, 65% of white Californian heads of households were homeowners, while 55% of Asian, 46% of Native American, 44% of Latino, and 39% of black heads of household owned their home (U.S. Census Bureau 2000). Eighty-one percent (81%) of Californians who cannot speak English "well" or "well at all" are people of color, while people of color are 31% of the California population (U.S. Census Bureau 2000). Additionally, people of color tend to earn less than white wage earners. The median household income of black, Latino, and Native households in California was $15,000 less than white and Asian households (Census 2000). These factors raise vulnerability to a disaster and increase the likelihood that communities of color and low-income Californians will share a disproportionate burden of harm.

During a disaster

The ability to remain safe and/or evacuate high-risk areas during a flood event is shaped by factors such as quality of residential structures, access to transportation, availability of emergency supplies, effective service by emergency responders, and exposure to environmental hazards. Key demographics associated with these vulnerabilities are income, possession of a vehicle, race, and proximity to environmental hazards that compound health risk, such as toxic waste facilities.

Low-income communities have been unable to evacuate during disasters like Hurricane Andrew due to lack of financial means to buy supplies or transportation (Morrow and Enarson 1996). In a survey after Hurricane Katrina, 55% of respondents who did not evacuate said one of the main reasons was that they did not have a car or other means of transportation (Brodie et al. 2006). Our study shows that nearly 16,000 households in areas vulnerable to a 100-year flood event with a 1.4 m sea-level rise do not have a vehicle (Table 11). Half of these households are located along the San Francisco Bay and the remaining half along the Pacific coast. These households will be more vulnerable to the adverse effects of sea-level rise due to their increased chance of lacking the transportation means necessary to evacuate.

Race has been an important factor influencing the effectiveness of past emergency response efforts. Perceptions of emergency response workers toward neighborhoods that are predominantly people of color can increase the vulnerability of these communities. In a recent report, the International Federation of Red Cross and Red Crescent Societies (IFRCC) found that "stereotypical views of a specific group can overwhelm the scientific methods employed to prioritize the order of relief works, even if some of those involved are professionally trained, such as disaster managers and relief workers" (Klynman 2007). Along the Pacific coast, we estimate that nearly 59,000 Asian, black, and Latino residents live in areas vulnerable to a 100-year flood event with a 1.4 m sea-level rise. The numbers are even higher along the San Francisco Bay, where an estimated 133,000 Asian, black, and Latino residents live in vulnerable areas. The areas with the highest concentrations of people of color are more likely to be subject to problems with stereotypes that may result in less effective emergency services.

Section 3.1.3, below, describes the number of U.S. EPA-regulated facilities that are at risk of flooding. These facilities contain a range of toxic chemicals that result in increased risk during a flood event due to the possibility that environmental hazards could be released and nearby residents exposed. In California as a whole, the population living within 3 kilometers (1.8 miles) of a commercial hazardous waste facility is disproportionately (81%) people of color compared to communities without such facilities (51% people of color) (Bullard et al. 2007). The same national study concluded that "race continues to be an independent predictor of where hazardous wastes are located, and it is a stronger predictor than income, education, and other socioeconomic indicators" (Bullard et al. 2007). The combination of higher concentrations of environmental hazards and higher rates of demographic characteristics that increase vulnerability has been termed "double jeopardy" by the Institute of Medicine (1999).

This disproportionate representation of people of color living near hazardous waste facilities is coupled with an overrepresentation among households with no vehicle. While black and Latino households comprised 7% and 22% of California's households in 2000, respectively, they comprised 13% and 32% of the households with no vehicle (U.S. Census Bureau 2000), and, as noted above, people of color are also over-represented among low-income Californians. Their higher rates of characteristics associated with vulnerabilities during the time of a disaster raise the possibility that communities of color and low-income people will be disproportionately affected.

Recovery and reconstruction

Following a flood event or other disaster, a range of conditions determines the victims' ability to recover and reconstruct their homes and lives. Important vulnerability factors include the ability to move where opportunities arise, obtain insurance compensation for losses, and receive medical care and public services. The demographic characteristics of income, insurance coverage, legal residency status, and race affect the vulnerability of individuals living in potential flood areas.

White and upper middle-class groups have been found to receive more disaster recovery assistance than black and low-income groups (Bolin and Bolton 1986; Fothergill 2004). For example, following the 1995 flooding of New Orleans, low-income elderly women were one-third as likely than other elderly victims to receive FEMA low-interest loans (Childers 1999). Disaster recovery services have often targeted homeowners to the disadvantage of renters and residents of public housing (Pastor et al. 2006). Reconstruction efforts of the past have inadequately rebuilt housing suitable for low-income families. Four years after the Loma Prieta earthquake, half of the affected multifamily units remained uninhabitable (Comerio et al. 1994). Government agencies explicitly denied housing assistance to those who were homeless before the earthquake (Tierney 2007).

The loss of wealth to homeowners resulting from a disaster is greater for those whose home equity comprises a greater proportion of their wealth. This effect is particularly problematic for black homeowners, whose home equity accounts for 20% more of their wealth than white homeowners (Oliver and Shapiro 1995; Gittleman and Wolff 2000).

Legal residency status influences recovery efforts as well. Undocumented residents fear that participating in recovery assistance programs will put them at risk of deportation (Subervi-Velez et al. 1992; Yelvington 1997). Data on the number of undocumented immigrants are elusive, but the Public Policy Institute of California (2008) estimates that 8% of Californians are undocumented. The number and distribution of undocumented immigrants in areas vulnerable to current and future flood events deserves further study.

Recovery for disaster victims suffering adverse health effects is dependent upon their access to health insurance. The uninsured get about half as much medical care as the insured, are less likely to receive preventive screening and care, and overall have worse health outcomes (Bovbjerg and Hadley 2007). Race is a predictor of rates of health insurance coverage in California: 34% of California Latinos did not have health insurance in 2005, while 22% of Native Californians, 18% of Asians, 15% of black Californians, and 13% of whites were not insured, according to the California Health Interview Survey (Brown et al. 2007).

The correlation of lower income and race, and the over-representation of communities of color among those without legal residency and without health insurance, increases these communities' vulnerability to the harms of sea-level rise even in the period following a disaster. The history of disparate treatment of people of color in recovery assistance services suggests another level of increased vulnerability.

Summary of Environmental Justice Concerns

The adverse impacts of sea-level rise on Californians will depend upon the population's vulnerabilities, which are heightened for certain demographic groups. Race and income cut across many of the key vulnerabilities, with low-income and communities of color overly represented in the most vulnerable segments of the population. Additionally, adapting to sea-level rise will require tremendous financial investment. Given the high cost and the likelihood that we will not protect everything, adaptation raises additional environmental justice concerns. Specifically, what we choose to protect and how we pay for it may have a disproportionate impact on low-income neighborhoods and communities of color. Decisions about how to use public funds can lead to inequitable distribution of costs and benefits, whether they are based on economics (protect the most valuable assets) or utility (protect the largest number of people). We urge, therefore, that policy makers planning responses to sea-level rise understand and address environmental justice concerns carefully and proactively.

3.1.2. Emergency and Healthcare Facilities at Risk

Table 12 shows the schools and emergency and healthcare facilities along the Pacific coast that are currently at risk from a 100-year flood event and that will be at risk with a 1.4 m sea-level rise. Numerous schools are vulnerable to flooding along the Pacific coast. In 2000, 30 schools were vulnerable to a 100-year flood event. With a 1.4 m sea-level rise, however, the number of schools at risk nearly doubles, rising to 56 schools. Emergency and healthcare facilities are also at risk.

Table 12. Schools and emergency and healthcare facilities along the Pacific coast that are at risk from a 100-year flood event in 2000 and with a 1.4 m sea-level rise

Facility	Current risk	Risk with 1.4 m sea-level rise
Schools	30	56
Healthcare facilities	5	13
Fire stations and training facilities	2	6
Police stations	4	8

Note: Healthcare facilities include clinics, long-term care facilities, hospitals, and home health agencies/hospices. Counties with borders on the Pacific coast and the San Francisco Bay (e.g., San Mateo) were separated based on the shoreline affected.

Table 13 shows the schools and emergency and healthcare facilities along San Francisco Bay that are currently at risk of a 100-year flood event and that will be at risk with a 0.5, 1.0, and 1.4 m sea-level rise. The risk for each of these facilities is greater than along the remainder of the Pacific coast. Schools in particular are at significant risk. In 2000, 35 schools were at risk of a 100-year flood event. With a 1.4 m sea-level rise, the number of schools at risk more than doubles, to 81. Significant numbers of healthcare facilities are also at risk. In 2000, there were 15 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 42.

Table 13. Schools and emergency and healthcare facilities along San Francisco Bay that are at risk of a 100-year flood event in 2000 and with a 0.5 m, 1.0 m, and 1.4 m sea-level rise.

Facility	Current risk	Risk with sea-level rise		
		0.5 m	1.0 m	1.4 m
Schools	35	41	60	81
Healthcare facilities	15	19	29	42
Fire stations and training facilities	6	7	10	11
Police stations	5	6	8	9

Note: Healthcare facilities include clinics, long-term care facilities, hospitals, and home health agencies/hospices. Counties with borders on the Pacific coast and the San Francisco Bay (e.g., San Mateo) were separated based on the shoreline affected.

3.1.3. Hazardous Materials Sites

The presence of land or facilities containing hazardous materials in areas at risk of inundation increases the risk of exposure to toxic chemicals for nearby residents and ecosystems. For example, sediment samples in New Orleans taken one 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.

We evaluated sites containing hazardous materials at risk of flooding along the Pacific coast and the 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 (Table 14). Nearly 60% of these facilities are located in San Mateo and Santa Clara counties. Sea-level rise will put additional facilities, people, and the environment at risk. 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.

Table 14. U.S. EPA-regulated sites within areas vulnerable to 100-year flood event in 2000 and with a 1.4 m sea-level rise

County	Sites currently at risk	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
Note: Table combines risk for those counties along the San Francisco Bay and Pacific coast.

3.1.4. Infrastructure at Risk

Roads and Railways

Roads and railways are vulnerable to flooding due to a 100-year flood today and with sea-level rise (Tables 15, 16, and 17). In 2000, 300 miles of roads and highways and 70 miles of railways along the Pacific coast were at risk of flooding. With a 1.4 m sea-level rise, an estimated 530 miles of roads and highways and 110 miles of railways are at risk from a 100-year flood event (Figures 19 and 20).

Table 15. Miles of roads and railways vulnerable to a 100-year flood in 2000 and with a 1.4 m sea-level rise along the Pacific coast, by county and type

County	Highways (miles)		Roads (miles)		Railways (miles)	
	Current risk	Risk with 1.4 m sea-level rise	Current risk	Risk with 1.4 m sea-level rise	Current Risk	Risk with 1.4 m sea-level rise
Del Norte	6.6	8.2	59	80	-	-
Humboldt	37	58	120	190	21	28
Los Angeles	14	31	42	140	5.6	14
Marin	1.2	4.1	22	27	-	-
Mendocino	5.6	7.9	28	41	2.7	4.0
Monterey	27	31	85	110	19	23
Orange	32	48	340	490	5.3	6.6
San Diego	0.62	8.0	12	57	3.0	9.8
San Francisco	0.20	0.37	17	22	-	-
San Luis Obispo	5.3	7.4	10	21	0.019	0.31
San Mateo	3.4	5.0	23	30	-	-
Santa Barbara	1.5	8.0	9.1	25	3.4	7.0
Santa Cruz	9.4	11	52	67	4.2	5.5
Sonoma	4.5	5.9	14	20	-	-
Ventura	2.4	11	69	150	3.7	10
Total	150	250	910	1,500	68	110

Note: Counties with borders on the Pacific coast and San Francisco Bay (e.g., San Mateo) were separated based on the shoreline affected. Numbers may not add up due to rounding.

Risks to transportation-related infrastructure are substantially higher along San Francisco Bay (Tables 16 and 17). In 2000, nearly 800 miles of roads and highways and 78 miles of railways were at risk of flooding from a 100-year event. Much of this infrastructure is protected by levees, seawalls, and other structures. Projected sea-level rise estimates increase this risk markedly. Even a relatively modest increase in sea levels of 0.5 m puts 1,130 miles of roads and highways and 94 miles of railways at risk. The projected 1.4 m rise in sea level more than doubles the roads and railways at risk of flooding, placing 1,800 miles of roads and highways and 173 miles of railways at risk of flooding from a 100-year event.

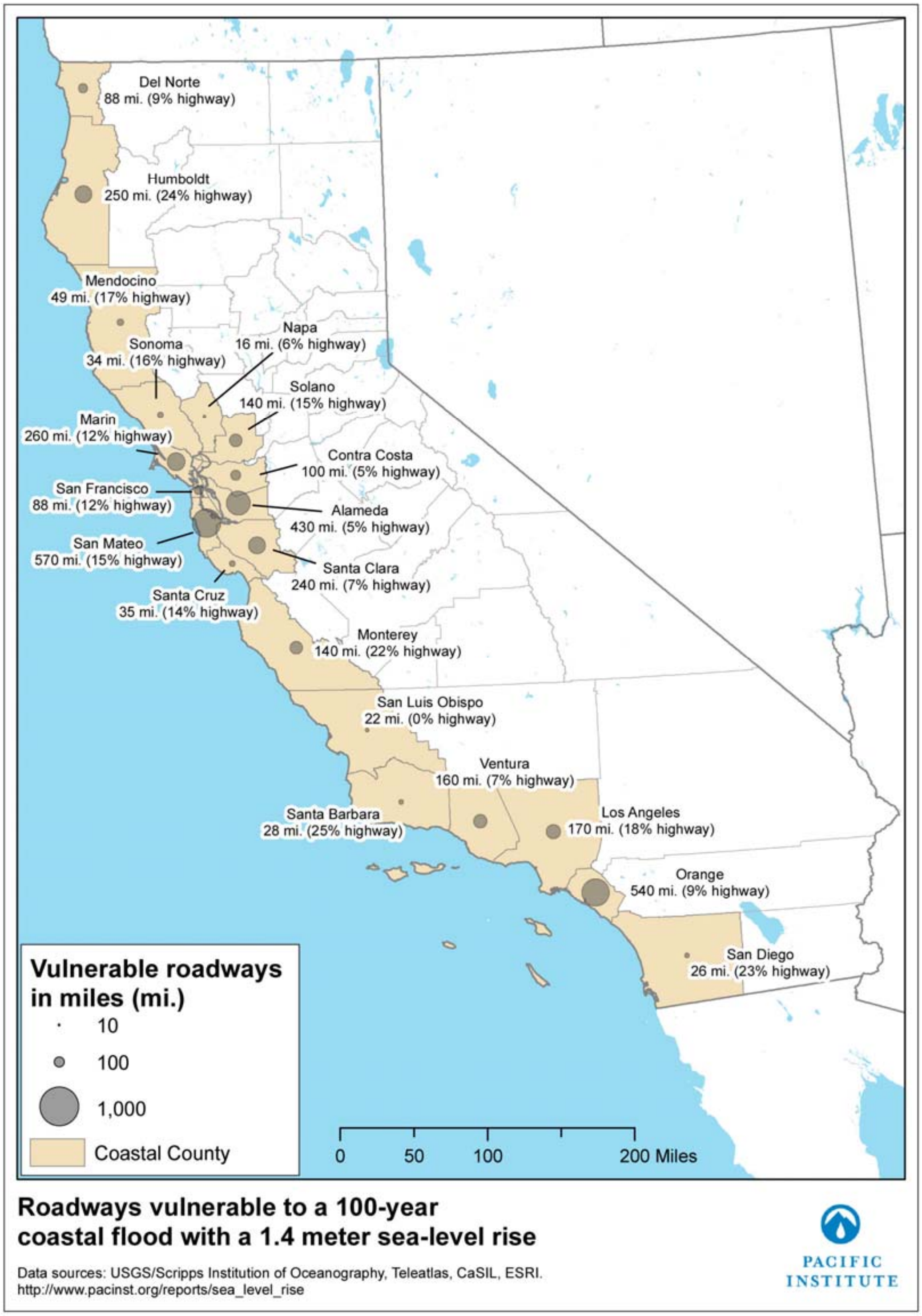


Figure 19. Roadways vulnerable to a 100-year coastal flood with a 1.4 m sea-level rise

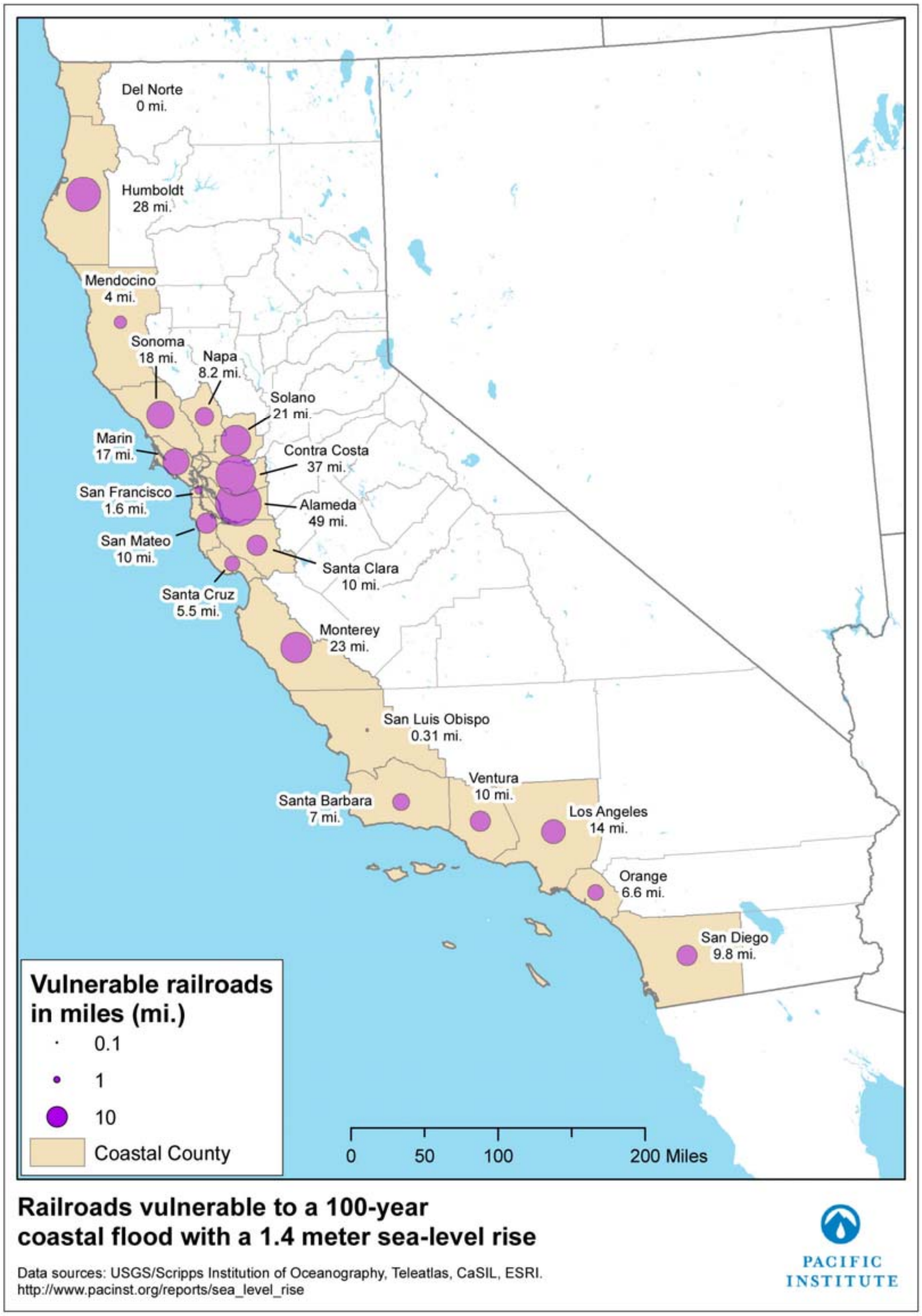


Figure 20. Railroads vulnerable to a 100-year coastal flood with a 1.4 m sea-level rise

Table 16. Miles of roads vulnerable to a 100-year flood along San Francisco Bay, by county and type

County	Current Risk		Risk with sea-level rise					
			0.5 m		1.0 m		1.4 m	
	Highways (miles)	Roads (miles)	Highways (miles)	Roads (miles)	Highways (miles)	Roads (miles)	Highways (miles)	Roads (miles)
Alameda	1.1	76	4.8	160	14	280	23	410
Contra Costa	2.4	20	2.7	42	3.4	67	4.5	96
Marin	16	110	20	150	24	180	28	200
Napa	0.70	7.0	0.70	9.0	0.80	11	1.2	15
San Francisco	0.30	3.4	0.60	11	1.5	29	3.1	53
San Mateo	27	300	49	360	66	390	72	420
Santa Clara	9.4	110	12	150	14	180	15	220
Solano	5.7	53	14	78	19	100	23	120
Sonoma	11	53	12	57	13	59	14	61
Total	**72**	**730**	**120**	**1,000**	**160**	**1,300**	**180**	**1,600**

Note: Counties with borders on the Pacific coast and San Francisco Bay (e.g., San Mateo) were separated based on the shoreline affected. Numbers may not add up due to rounding.

Table 17. Miles of railways vulnerable to a 100-year flood along San Francisco Bay, by county

County	Current risk	Risk with sea-level rise			Percent increase (with 1.4 m rise)
		0.5 m	1.0 m	1.4 m	
Alameda	9.1	17	35	49	81
Contra Costa	10	17	25	37	73
Marin	12	15	16	17	29
Napa	6.0	7.0	7.9	8.2	27
San Francisco	0.26	0.56	0.91	1.6	84
San Mateo	3.7	5.2	7.8	10	65
Santa Clara	5.9	7.2	8.9	10	43
Solano	9.3	12	17	21	56
Sonoma	11	14	17	18	39
Total	**68**	**94**	**140**	**170**	**61**

Note: Counties with borders on the Pacific coast and San Francisco Bay (e.g., San Mateo) were separated based on the shoreline affected. Numbers may not add up due to rounding.

We do 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 the conveyance of goods shipped to and from California ports. In addition, road closures can prevent people from getting to work, causing major economic disruptions. Additional research is needed to improve our understanding of specific transportation risks.

Power Plants

Figures 21, 22, and 23 show California's coastal power plants vulnerable to a 100-year flood event with a 1.4 m 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 for each coastal plant. In total, around 30 coastal power plants, with a combined capacity of more than 10,000 megawatts (MW), are at risk 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.

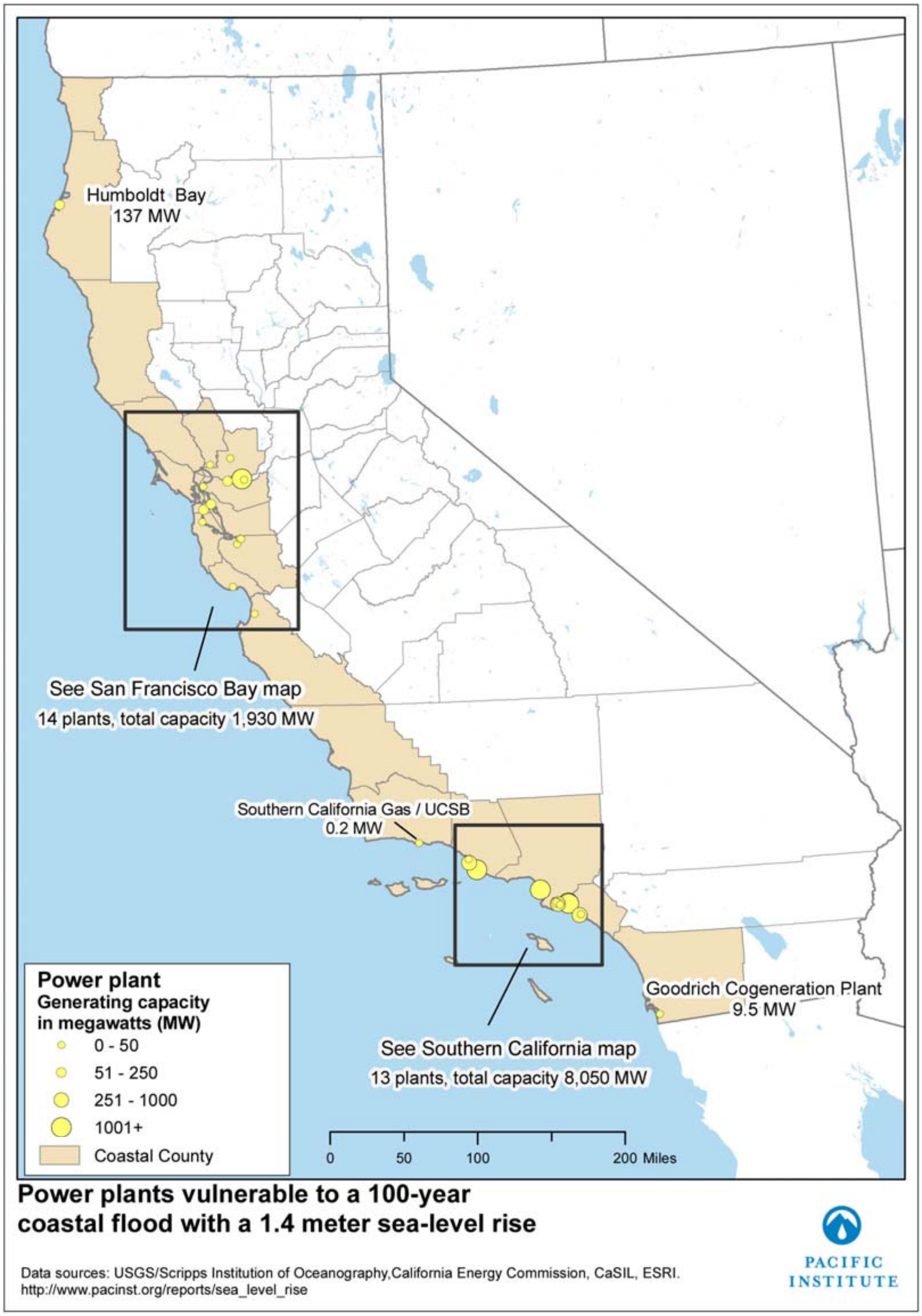


Figure 21. Power plants vulnerable to a 100-year coastal flood with a 1.4 m sea-level rise

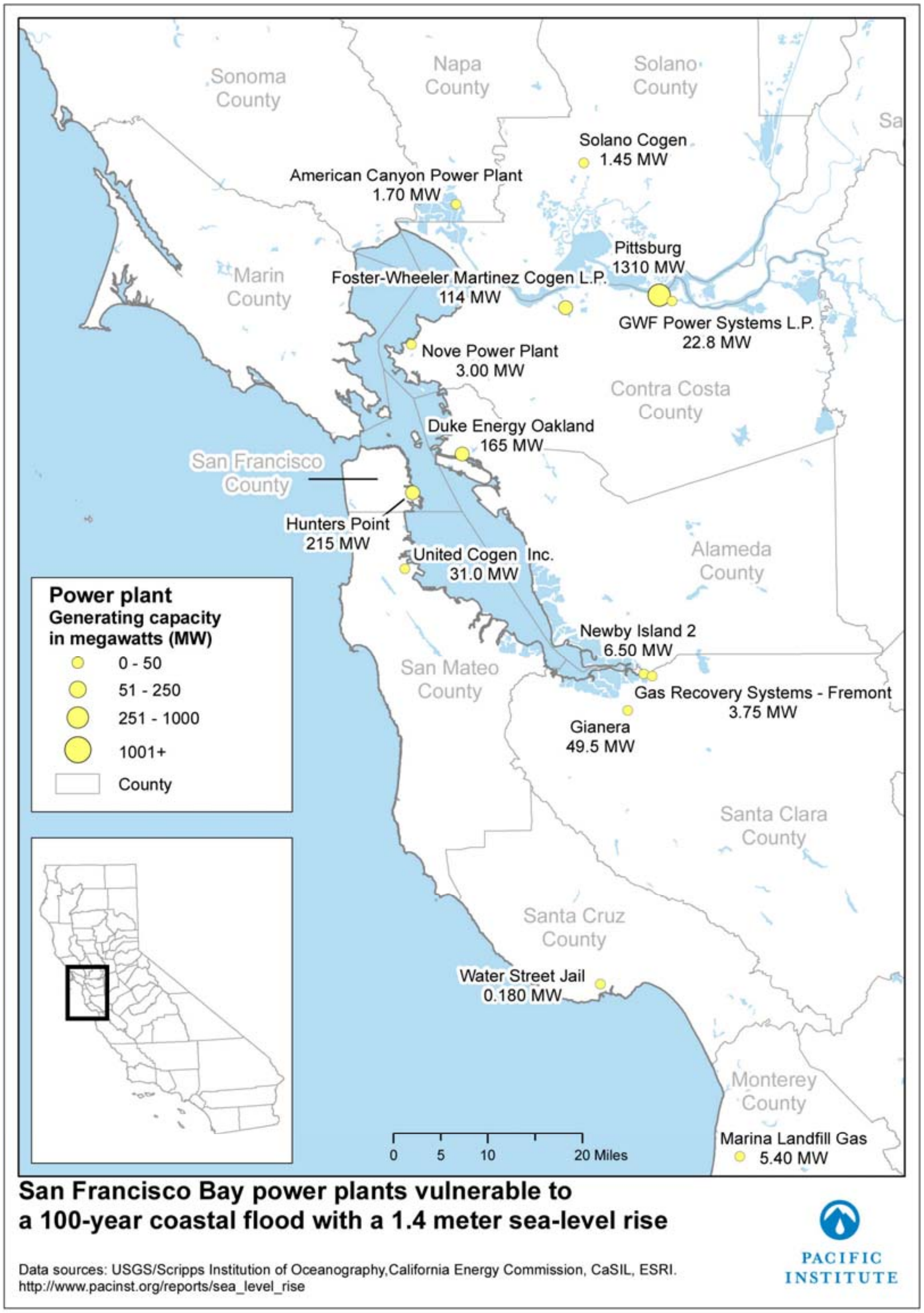


Figure 22. San Francisco Bay power plants vulnerable to a 100-year coastal flood with a 1.4 m sea-level rise

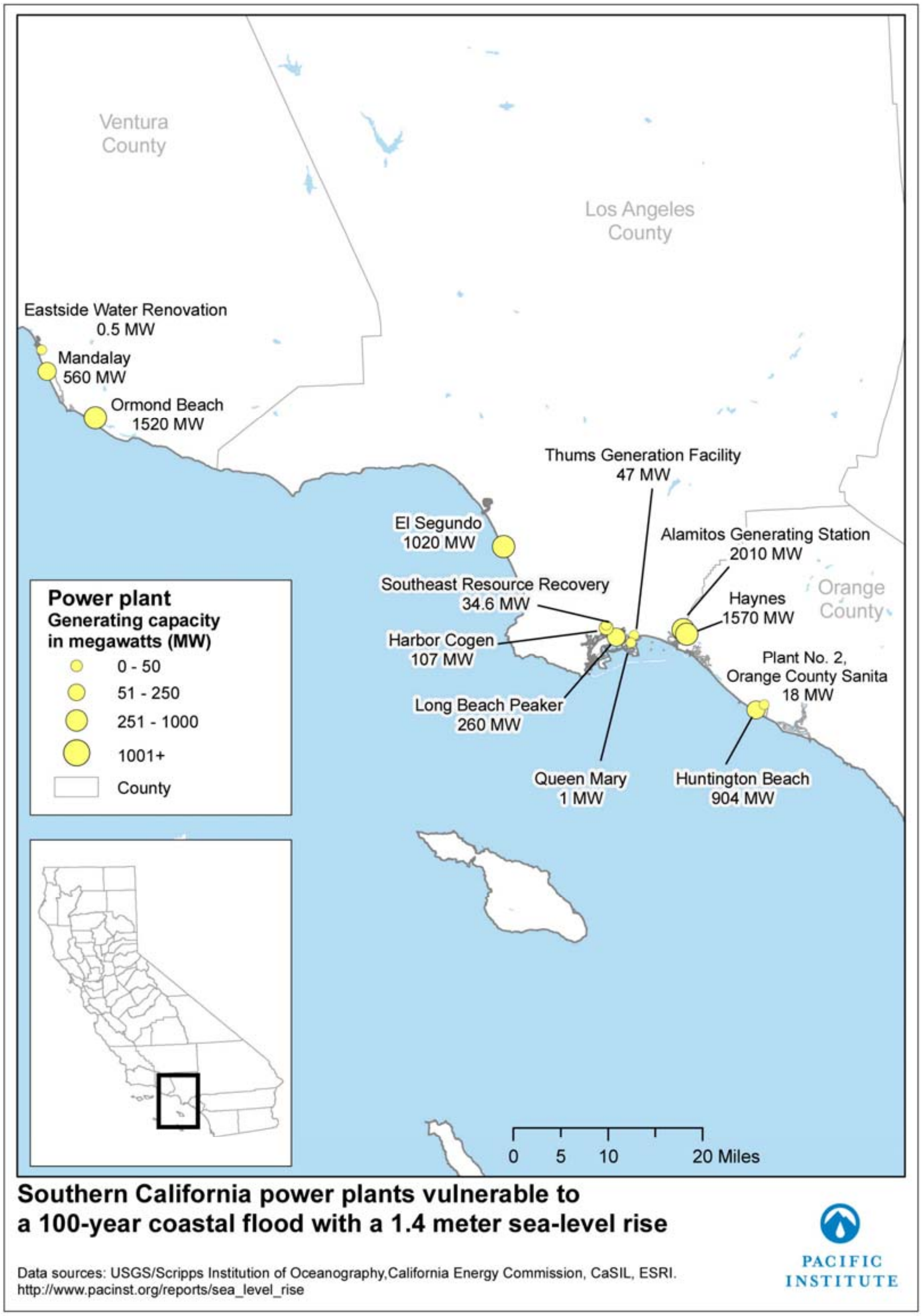


Figure 23. Southern California power plants vulnerable to a 100-year coastal flood with a 1.4 m sea-level rise

Wastewater Treatment Plants

Figures 24 and 25 show the wastewater treatment plants vulnerable to a 100-year flood event with a 1.4 m sea-level rise. We identified a total of 29 vulnerable wastewater treatment plants: 22 on the San Francisco Bay and 7 on the Pacific coast. The combined capacity of these plants is 530 million gallons per day (MGD). 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. Cities and sanitation districts should begin to assess how higher water levels will affect plant operations and plan for future conditions.

Ports

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 percent 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 on transportation services. The businesses providing these services also play a critical role as generators of jobs and economic activity in their own right" (MTC 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 central to the economy of California, the nation, and the world. 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 economic implications for the nation and the world, 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 $1billion to $2 billion per day. Others speculated that Japan and China would lose several percentage points off their gross domestic product if the ports closed for longer than a week (Farris 2008).

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. We also note the connection between possible direct impacts of sea-level rise on the ports themselves and possible flooding of transportation (rail and road) corridors to and from the ports.

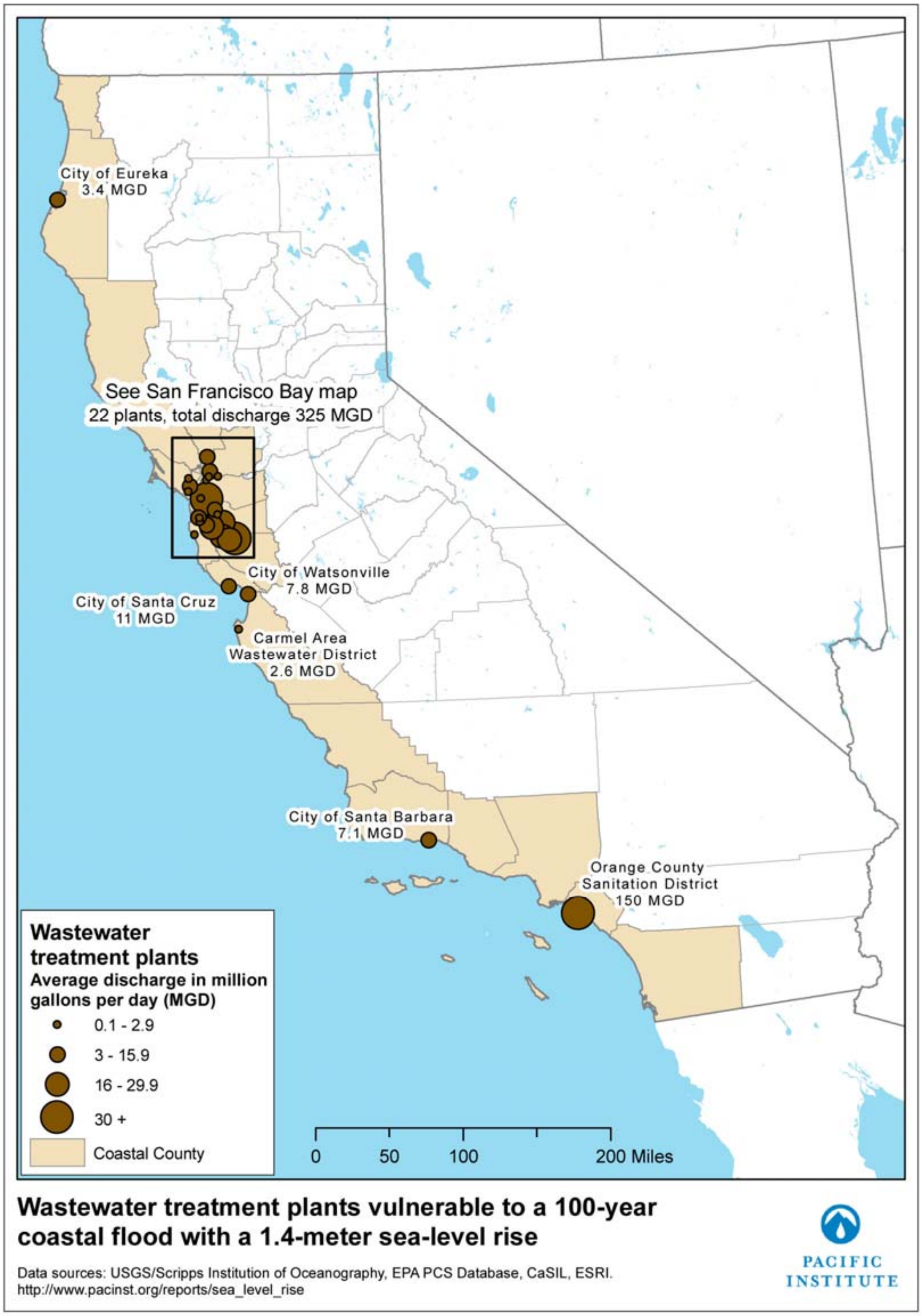


Figure 24. Wastewater treatment plants on the Pacific coast vulnerable to a 100-year flood with a 1.4 m sea-level rise

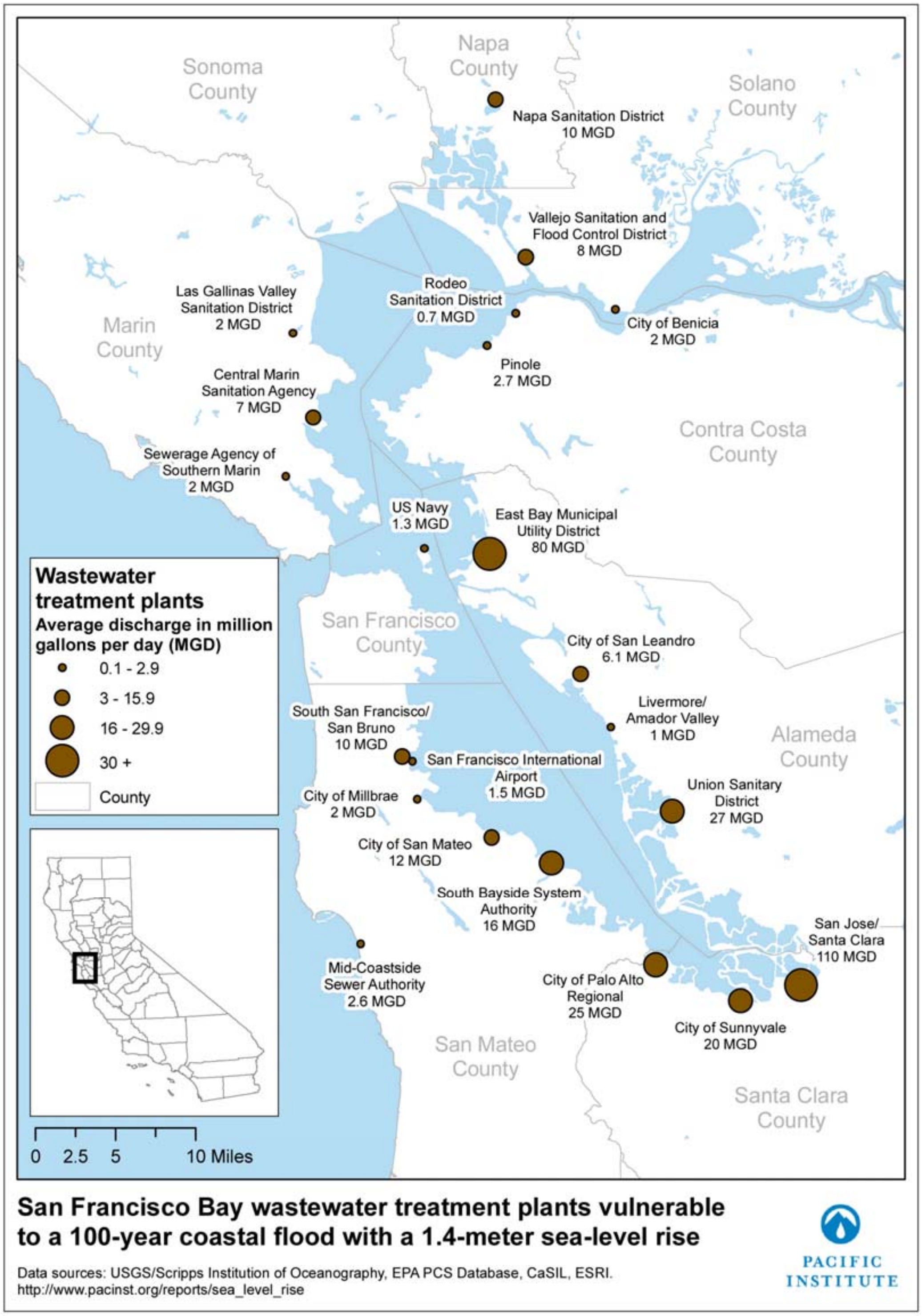


Figure 25. Wastewater treatment plants on the San Francisco Bay vulnerable to a 100-year flood with a 1.4 m sea-level rise

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 2007). 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 (Bureau of Trade Statistics 2006), more than double that of the $23.7 billion handled by vessels at the Port of Oakland.

3.1.5. Wetlands

Today, there are approximately 430,000 acres, or 670 square miles, of coastal wetlands in California (Figure 26). Based on an approximated wetland value of $5,000 to $200,000 per acre, we estimate that California's coastal wetlands are worth from $2.2 billion to $86 billion. Large wetland areas are found in almost every county on the California coast (Table 18). The vast majority of coastal wetlands are in San Francisco Bay and the Sacramento-San Joaquin Delta.

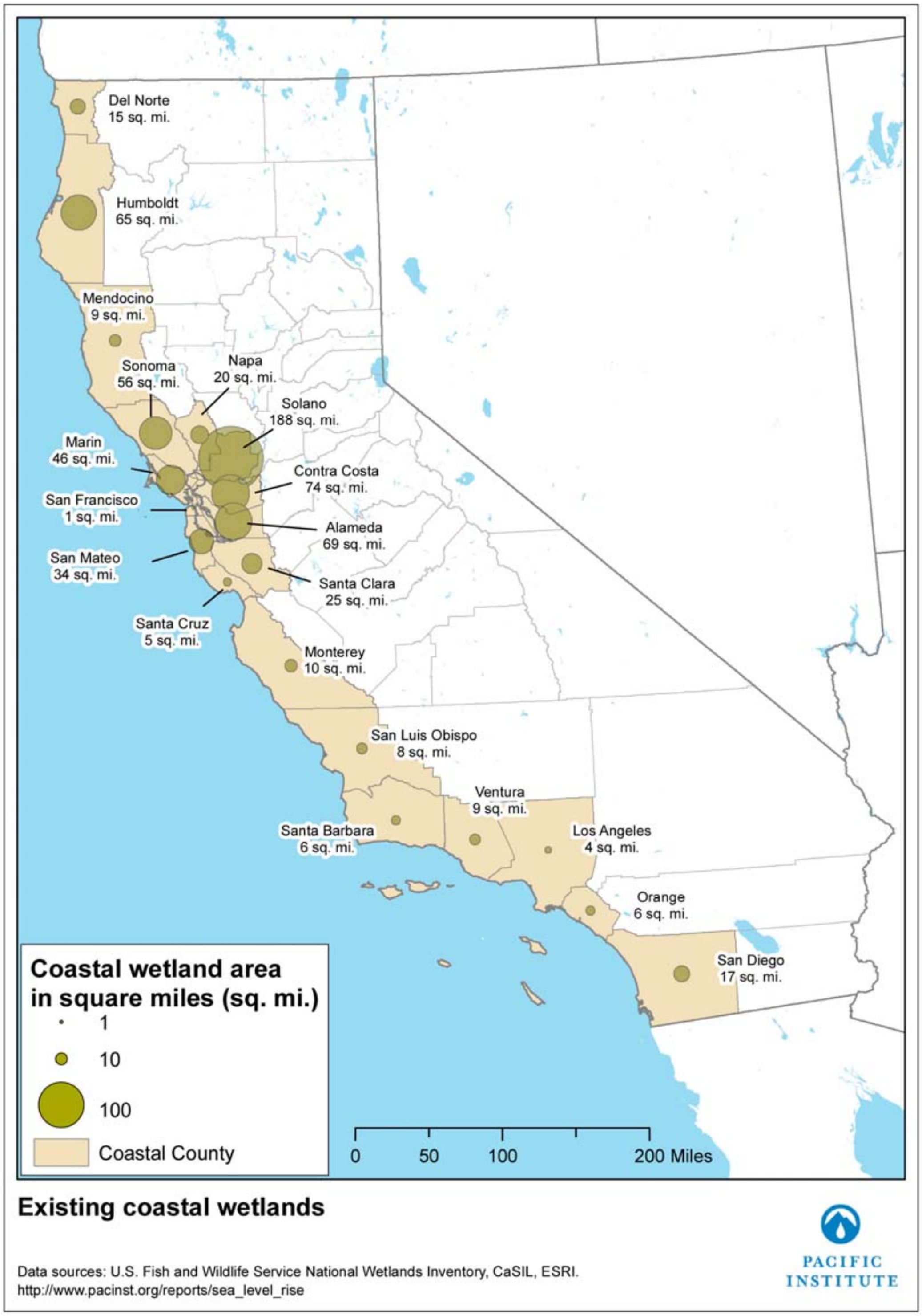


Figure 26. Existing coastal wetlands

There are also significant and important coastal wetlands in Northern California, especially in and around Humboldt and Eureka. Much of the Central California coast, from the Lost Coast in Mendocino County to Big Sur in Monterey, San Luis Obispo, and Santa Barbara counties, is dominated by rugged hills and cliffs plunging into the sea. In these areas, there are very few coastal wetlands. There are critically important wetlands that may be of small size, but that serve vital ecological functions—we understand that size is not the only measure of wetland value. We note that adequate wetland delineation has not been performed on vast areas of California and the actual wetland area may be larger.

Table 18. Existing California coastal wetland area by county

County	Area (acres)	Area (square miles)	Percent of state total
Alameda	44,000	69	10
Contra Costa	47,000	73	11
Del Norte	9,300	15	2.2
Humboldt	42,000	66	10
Los Angeles	2,400	3.8	0.6
Marin	29,000	45	6.8
Mendocino	6,000	9.4	1.4
Monterey	6,600	10	1.6
Napa	13,000	20	3.0
Orange	3,800	5.9	0.9
San Diego	11,000	17	2.6
San Francisco	770	1.2	0.2
San Luis Obispo	5,300	8.3	1.2
San Mateo	22,000	34	5.1
Santa Barbara	4,000	6.3	0.9
Santa Clara	16,000	25	3.7
Santa Cruz	3,400	5.3	0.8
Solano	120,000	190	28
Sonoma	36,000	56	8.4
Ventura	5,700	8.9	1.3
Total	**430,000**	**670**	**100**

Note: Numbers may not add up due to rounding.

Evaluating the impacts of sea-level rise on a particular coastal wetland area requires site-specific data on various physical and biological factors. A simple method to estimate wetland loss is to compare wetland elevations to future tide elevations. Data limitations, however, prevent us from performing even this simple analysis, i.e., there are no data in the critical area where the boundary must be drawn. Given these data limitations, we evaluated the land cover *adjacent* to existing wetlands and the potential for these areas to support suitable wetland habitat. We note that this simplified analysis does not take into account erosion or accretion due to sediment movement, which is difficult to predict with any accuracy.

We estimate that a sea-level rise of 1.4 m provides approximately 150 square miles of potential wetland migration area. Of this amount, 83 square miles, or 55%, would make viable wetland habitat (Table 19). These areas should be protected to ensure their viability as wetland habitat is maintained. Twenty-three square miles, or 15%, is land that is viable for wetland migration but at some loss of value, including parks, orchards, and agricultural land. The remaining 30% of the available accommodation space is unsuitable for wetland migration.

Table 19. Wetland migration frontier area classified by land cover type and conversion potential

Land cover type	Total frontier area (square miles)
Not viable for wetland migration	
High Intensity Developed	12
Medium Intensity Developed	12
Low Intensity Developed	21
Subtotal	**45**
Viable for wetland migration, but will cause property loss	
Developed Open Space	4.7
Pasture/Hay	11
Cultivated	7.0
Subtotal	**23**
Viable for wetland migration	
Evergreen Forest	0.28
Deciduous Forest	0.040
Mixed Forest	0.27
Scrub/Shrub	1.3
Grassland	16
Bare Land	0.89
Palustrine Scrub/Shrub Wetland	0.85
Palustrine Forested Wetland	0.47
Palustrine Emergent Wetland	4.7
Estuarine Scrub/Shrub Wetland	42
Estuarine Forested Wetland	2.4
Estuarine Emergent Wetland	0.11
Estuarine Aquatic Bed	0.046
Unconsolidated Shore	4.0
Water	10
Subtotal	**83**
Total	**150**

Figures 27, 28, 29, and 30 and Table 20 summarize the potential wetland migration area by county. Solano County has the largest wetland migration area, totaling 22 miles, and 85% of that area is currently viable wetland habitat. Of the potential 20 miles of wetland migration area in Humboldt County, only 39% is viable wetland habitat, although an additional 54% is viable but with some economic loss. San Francisco and Los Angeles Counties have only small potential wetland migration areas, in part because there are few wetlands in these counties. Unfortunately, those that do exist are at high risk because 70% and 60% of the potential wetland migration area in San Francisco and Los Angeles Counties, respectively, is not viable wetland habitat.

Table 20. Land area available for wetland migration, by county, in square miles, with percent of county total in italics

County	Wetland migration viable		Migration viable with loss of value		Migration not viable		Total	Percent of State Total
Alameda	8.5	*49%*	0.94	*5%*	8.1	*46%*	17	10%
Contra Costa	8.1	*72%*	0.68	*6%*	2.5	*22%*	11	6.7%
Del Norte	2.1	*81%*	0.39	*15%*	0.13	*5%*	2.6	1.6%
Humboldt	7.7	*39%*	11	*54%*	1.2	*6%*	20	12%
Los Angeles*	0.10	*35%*	0.012	*4%*	0.17	*60%*	0.28	0.17%
Marin	5.7	*54%*	0.29	*3%*	4.7	*44%*	11	6.3%
Mendocino	1.3	*93%*	0.035	*2%*	0.059	*4%*	1.4	0.8%
Monterey	4.1	*56%*	2.6	*36%*	0.60	*8%*	7.3	4.3%
Napa	2.9	*80%*	0.24	*6%*	0.51	*14%*	3.7	2.2%
Orange*	0.72	*22%*	0.20	*6%*	2.4	*72%*	3.3	2.0%
San Diego	3.7	*64%*	0.33	*6%*	1.7	*30%*	5.8	3.4%
San Francisco	0.20	*18%*	0.15	*13%*	0.80	*70%*	1.1	0.7%
San Luis Obispo	0.78	*69%*	0.081	*7%*	0.27	*24%*	1.1	0.7%
San Mateo	2.9	*20%*	0.54	*4%*	11	*76%*	15	8.7%
Santa Barbara*	0.87	*86%*	0.023	*2%*	0.12	*12%*	1.0	0.6%
Santa Clara	2.2	*29%*	0.81	*11%*	4.6	*60%*	7.6	4.5%
Santa Cruz	0.98	*40%*	1.1	*43%*	0.42	*17%*	2.5	1.5%
Solano	19	*85%*	0.87	*4%*	2.5	*11%*	22	13%
Sonoma	7.6	*87%*	0.53	*6%*	0.59	*7%*	8.8	5.2%
Ventura	**3.4**	*45%*	2.2	*29%*	2.0	*26%*	7.6	4.5%
Total	**83**	***55%***	**23**	***15%***	**45**	***30%***	**150**	**100%**

*Given data limitations, we mapped about 49% of Santa Barbara County, 23% of Los Angeles County, and 65% of Orange County. The coverage was 100% in the other 11 counties on the Pacific coast.

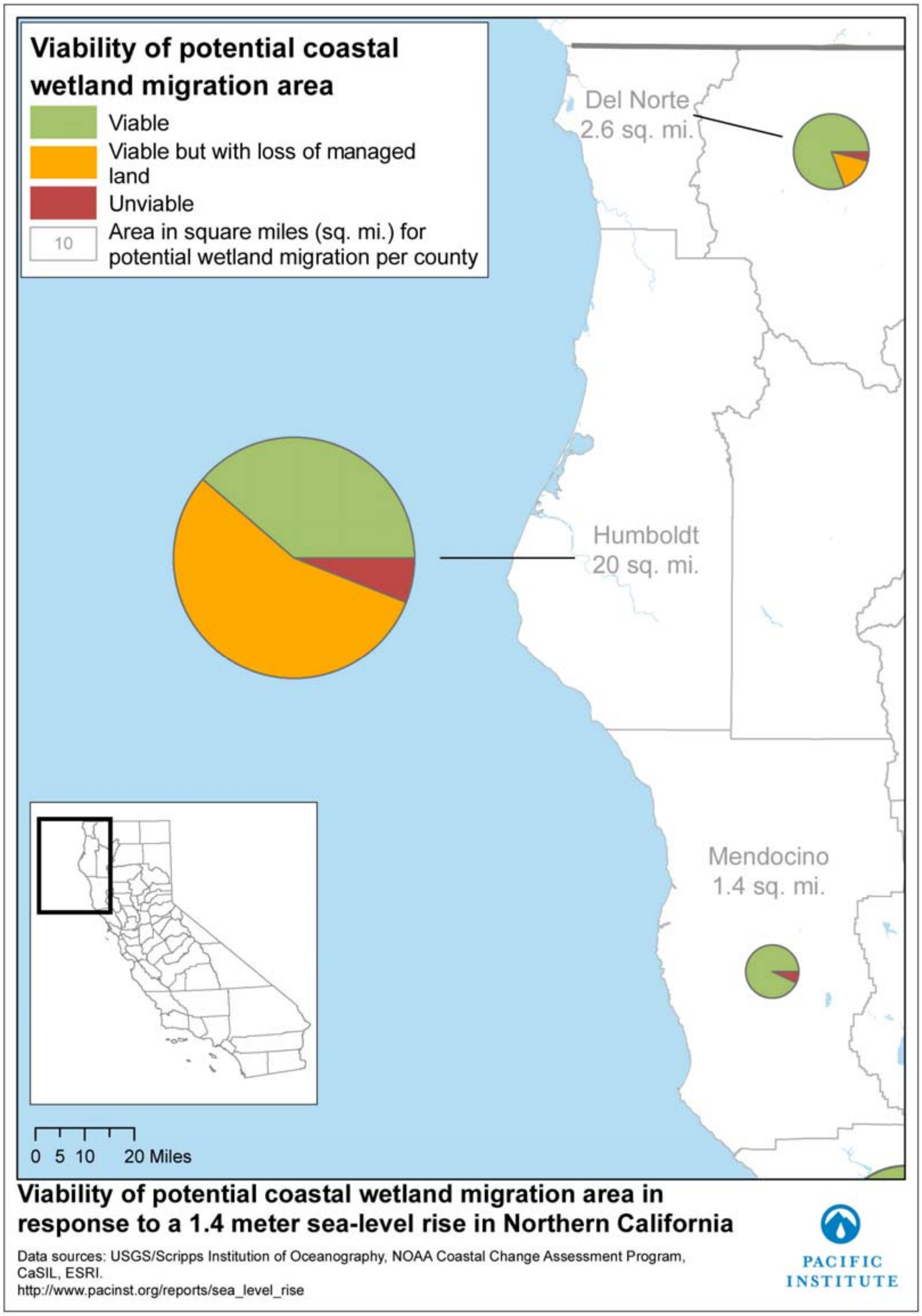


Figure 27. Viability of potential wetland migration area in response to a 1.4 m sea-level rise in Northern California

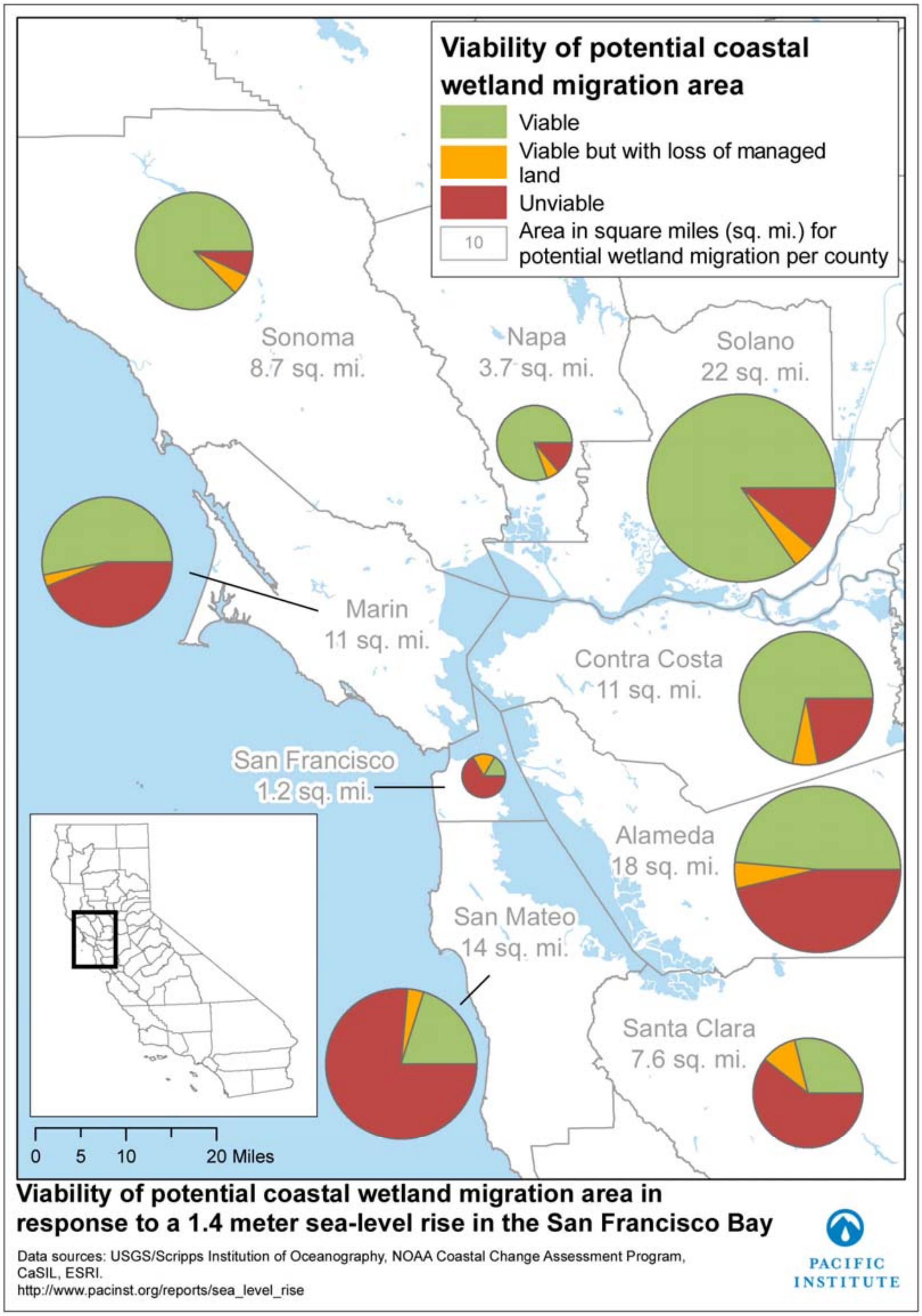


Figure 28. Viability of potential wetland migration area in response to a 1.4 m sea-level rise in the San Francisco Bay

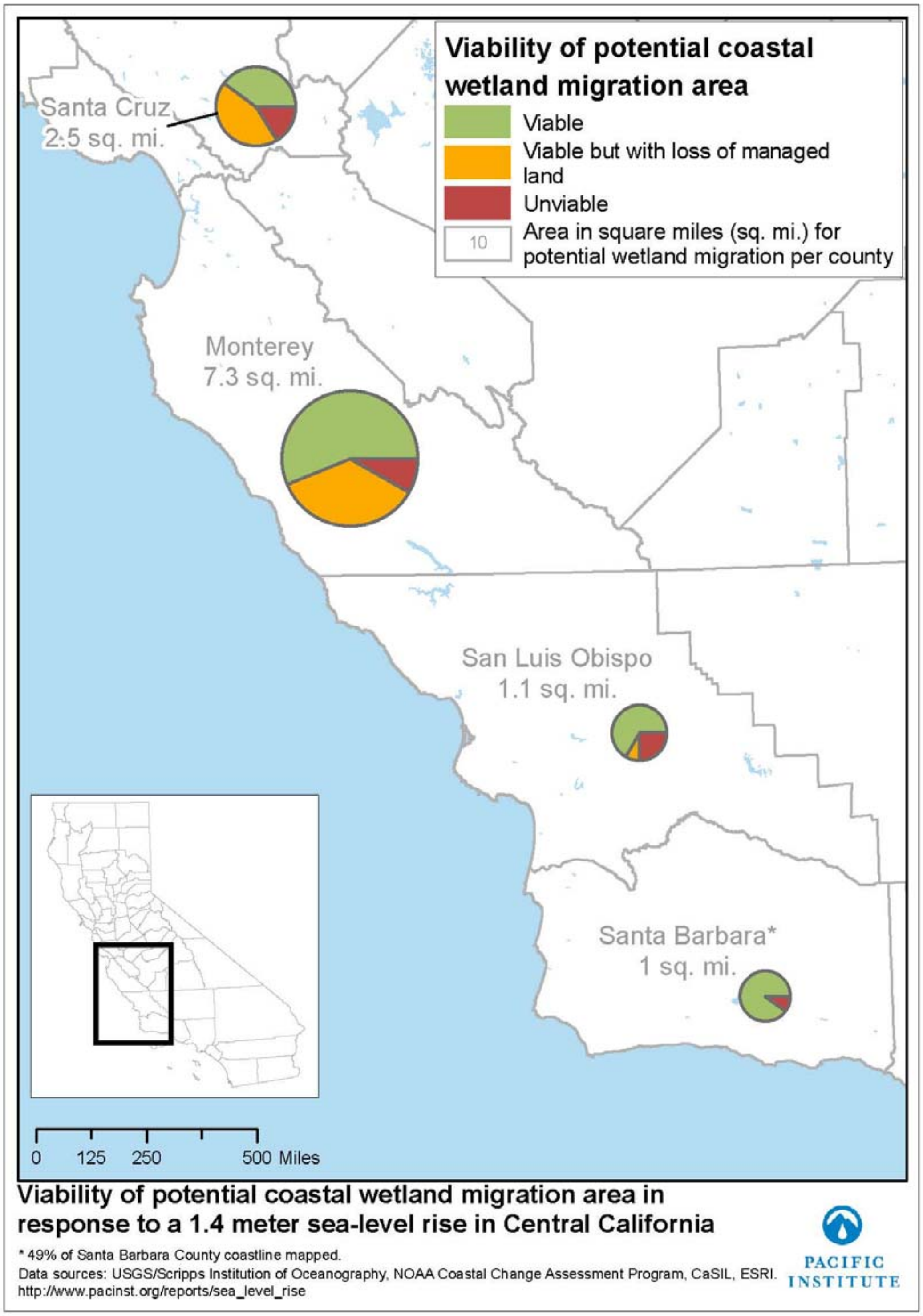


Figure 29. Viability of potential wetland migration area in response to a 1.4 m sea-level rise in Central California

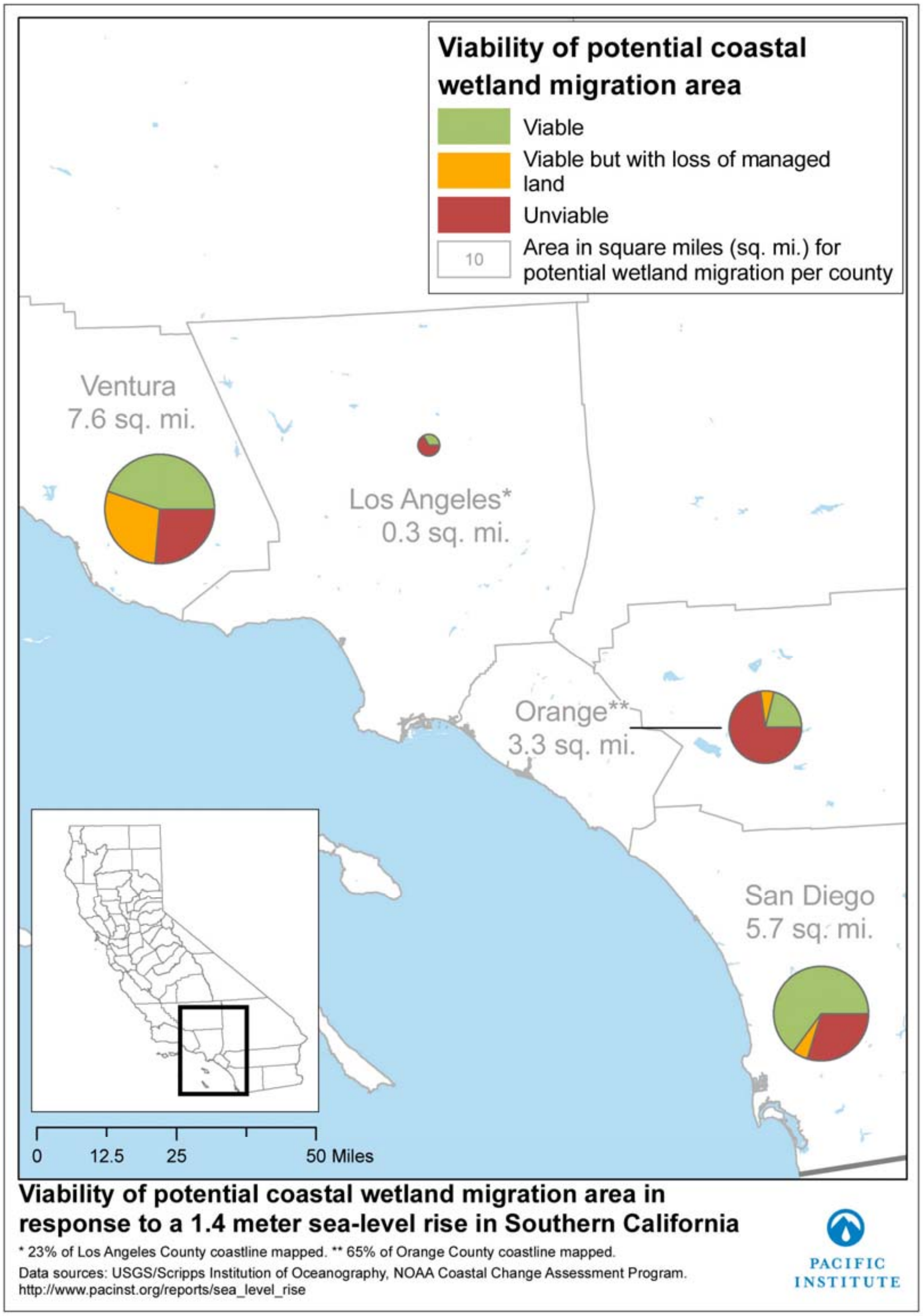


Figure 30. Viability of potential wetland migration area in response to a 1.4 m sea-level rise in Southern California

3.1.6. Property at Risk

Significant property is at risk of flooding from 100-year flood events as a result of a 1.4 m sea-level rise (Cayan et al. 2008). In total, we estimate that the replacement value of this property totals nearly $100 billion (Figure 31). An overwhelming two-thirds of that property is concentrated on San Francisco Bay, indicating that this region is particularly vulnerable to impacts associated with sea-level rise due to extensive development on the margins of the Bay (Figure 32).

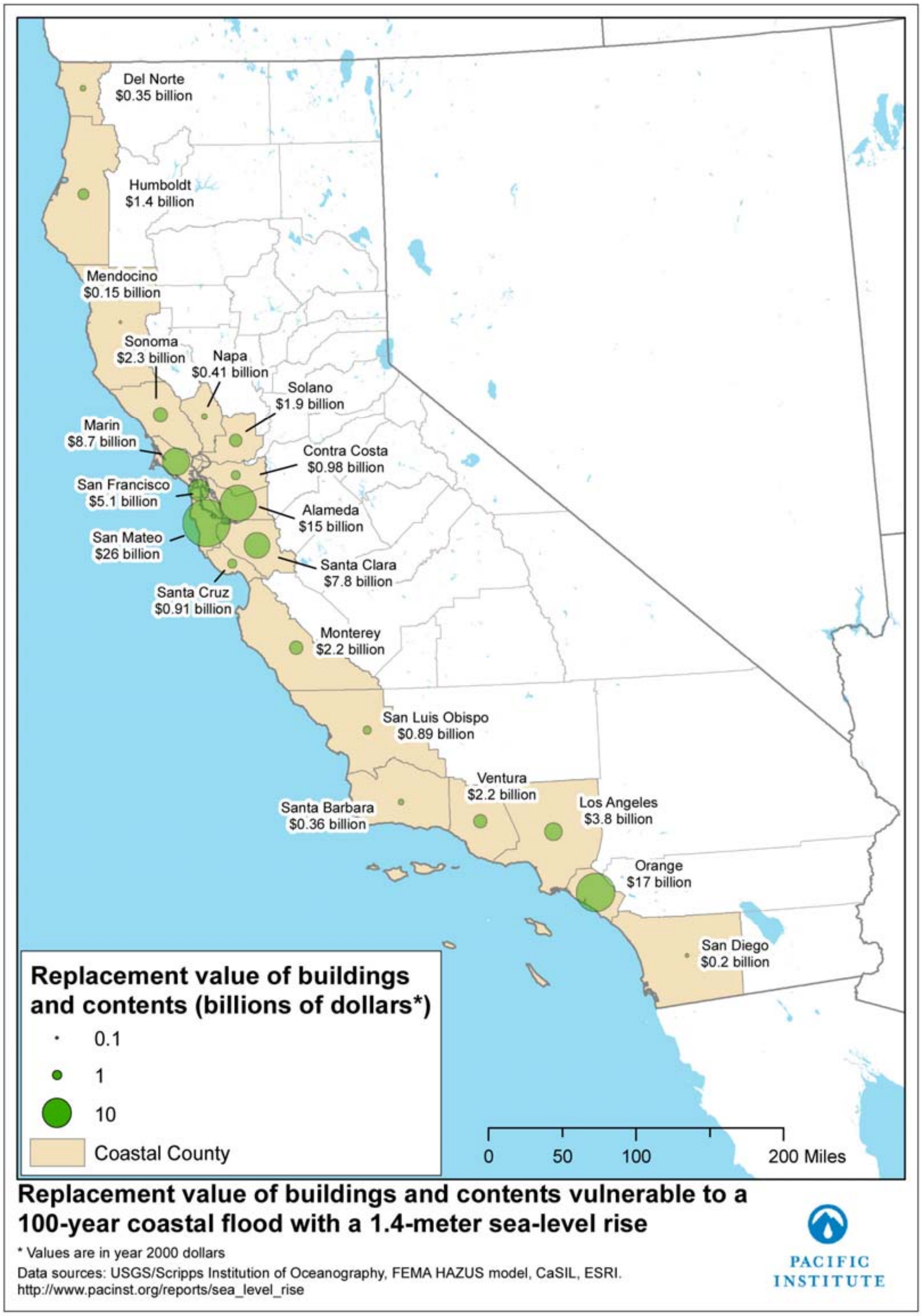


Figure 31. Replacement value of buildings and contents vulnerable to a 100-year coastal flood with a 1.4 m sea-level rise

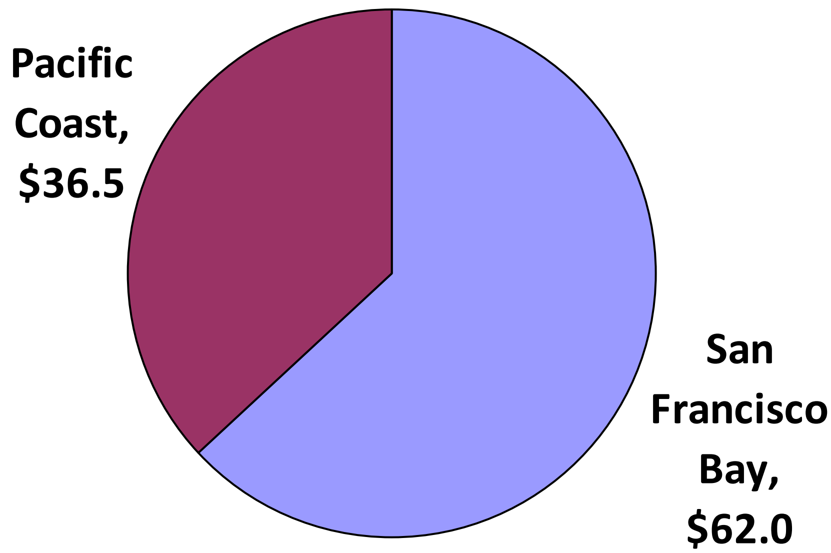


Figure 32. Replacement value (in billions of year 2000 dollars) of buildings and contents at risk of a 100-year flood event with a 1.4 m sea-level rise, by region

Note: Counties with borders on the Pacific coast and San Francisco Bay (e.g., San Mateo) were separated based on the shoreline affected.

Pacific Coast

Within each region, vulnerability to sea-level rise is highly variable. Table 21 shows the replacement value of buildings and their contents at risk of a 100-year flood event with a 1.4 m sea-level rise for the Pacific coast by county. Property at risk during a 100-year flood increases from about $21 billion in 2000 to $37 billion (in year 2000 dollars) with a 1.4 m sea-level rise. About $17 billion of property, or about 50% of the total property at risk, is in Orange County. Los Angeles, Santa Cruz, Monterey, and Ventura Counties also have significant assets at risk, totaling in excess of $2 billion each.

Table 21. Replacement value of buildings and contents (millions of year 2000 dollars) at risk of a 100-year flood event along the Pacific coast, by county

County	Current risk	Risk with 1.4 m sea-level rise	Percent increase
Del Norte	240	350	43
Humboldt	680	1,400	110
Los Angeles	1,400	3,800	180
Marin	220	260	16
Mendocino	120	150	22
Monterey	1,700	2,200	36
Orange	11,000	17,000	63
San Diego	690	2,000	190
San Francisco	670	890	33
San Luis Obispo	220	360	67
San Mateo	730	910	26
Santa Barbara	460	1,100	140
Santa Cruz	2,400	3,300	34
Sonoma	170	200	20
Ventura	980	2,200	120
Total	**21,000**	**37,000**	**71**

Note: All values are shown in millions of year 2000 dollars. Counties with borders on the Pacific coast and San Francisco Bay (e.g., San Mateo) were separated based on the shoreline affected.

All economic sectors are vulnerable to impacts associated with sea-level rise. Figure 33 shows the breakdown of the buildings and contents at risk of 100-year flood by major economic sector for the Pacific coast (specific sectors, such as transportation, are discussed in Section 3.2). More than 70% of the assets at risk are residential. The commercial sector, accounting for nearly 20% of the value at risk, will also likely 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.

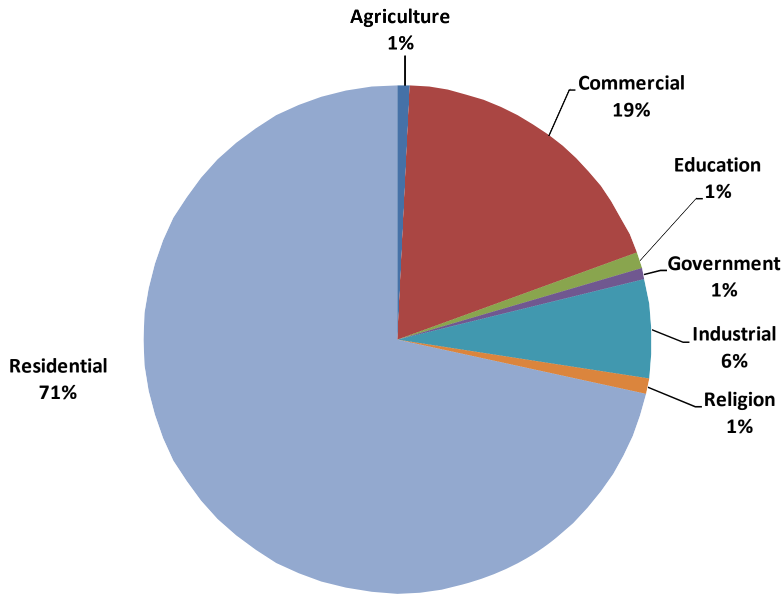


Figure 33. Value of buildings and contents at risk of 100-year flood event with a 1.4 m sea-level rise along the Pacific coast, by major economic sector

San Francisco Bay

The value of assets at risk on San Francisco Bay is substantially higher than along the Pacific coast. Table 22 shows the replacement value of buildings and their contents vulnerable to a 100-year flood event with a 0.5 m, 1.0 m, and 1.4 m sea-level rise. Note that the model used to develop inundation maps for San Francisco Bay allows us to determine the property at risk from any flood intensity. Assets at risk during a 100-year flood increase from about $29 billion in 2000 to $36 billion, $49 billion, and $62 billion (in year 2000 dollars) with a 0.5 m, 1.0 m, and 1.4 m sea-level rise, respectively.

The assets at risk are not evenly distributed among the counties on San Francisco Bay (Table 22). San Mateo and Alameda counties have the greatest assets at risk, accounting for about 60% of the total assets at risk with sea-level rise. Marin, Santa Clara, and San Francisco counties are also exposed to a high degree of risk; exposure to risk in these counties is higher than in all other counties along the Pacific coast, with the exception of Orange County. Exposure to risk in Sonoma and Napa counties is relatively modest.

Table 22. Value of buildings and contents at risk of a 100-year flood on San Francisco Bay, by county (in millions of year 2000 dollars)

County	Risk with sea-level rise			Percent Increase (1.4 m)
	0.5 m	1.0 m	1.4 m	
Alameda	5,300	10,000	15,000	370
Contra Costa	330	620	980	430
Marin	5,900	7,400	8,500	79
Napa	260	320	410	89
San Francisco	370	1,400	4,000	3400
San Mateo	18,000	21,000	23,000	41
Santa Clara	4,700	6,400	7,800	110
Solano	940	1,400	1,900	210
Sonoma	180	240	280	82
Total	**36,000**	**49,000**	**62,000**	**110**

Note: Counties with borders on the Pacific coast and San Francisco Bay (e.g., San Mateo) were separated based on the shoreline affected.

As it is along the Pacific coast, the residential sector on San Francisco Bay faces the greatest risk. Figure 34 shows the buildings and contents at risk of a 100-year flood by major economic sector on San Francisco Bay (specific sectors, such as transportation, are discussed in Section 3.1.4). Of the $62 billion of property at risk with a 1.4 m sea-level rise, about 50% of the assets at risk are residential, substantially smaller than along the Pacific coast. The commercial and industrial sectors face much greater risk on San Francisco Bay than on the Pacific coast. Agriculture, education, religion, and government each account for about 1% of the assets at risk, thus their exposure to risk is fairly small.

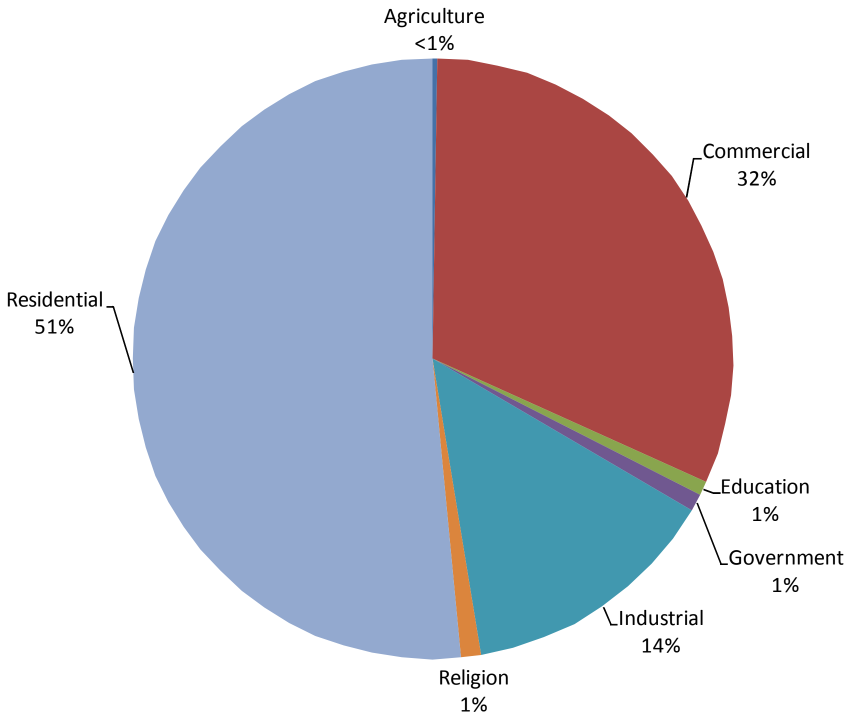


Figure 34. Value of buildings and contents at risk of a 100-year flood with a 1.4 m sea-level rise on San Francisco Bay, by major economic sector

3.1.7. Cost of Protection

Approximately 1,070 miles of new or modified coastal protection structures are needed on the Pacific Coast and San Francisco Bay (Table 23). The total cost of building new or upgrading existing structures is estimated at about $14 billion (in year 2000 dollars). The majority of the investment is needed in Southern California. Nearly 20% of that investment would be needed in Los Angeles County alone. Significant investments would also be needed in Orange and San Diego counties. Mendocino would need the least amount of coastal armoring, although this area is particularly vulnerable to erosion, which is not reflected in this analysis. We estimate that operating and maintaining the protection structures would cost approximately 10 percent of the initial capital investment, or around another $1.5 billion per year.

Table 23. Estimated length (in miles) and capital cost of required defenses needed to guard against flooding from a 1.4 m sea-level rise, by county.

County	Raise levee (miles)	New levee (miles)	New seawall (miles)	Total (miles)	Capital Cost (millions of year 2000 dollars)
Alameda	45	49	16	110	$950
Contra Costa	26	29	8.0	63	$520
Del Norte	-	38	1.0	39	$330
Humboldt	-	36	6.6	42	$460
Los Angeles	0.88	2.5	94	97	$2,600
Marin	43	77	7.7	130	$930
Mendocino	-	0.29	1.2	1.4	$34
Monterey	27	6.4	19	53	$650
Napa	2.8	62	-	64	$490
Orange	-	11	66	77	$1,900
San Diego	-	-	47	47	$1,300
San Francisco	-	10	21	31	$680
San Luis Obispo	-	7.4	5.4	13	$210
San Mateo	35	29	9.2	73	$580
Santa Barbara	2.4	5.6	4.5	13	$180
Santa Clara	47	4.0	-	51	$160
Santa Cruz	3.9	1.6	9.3	15	$280
Solano	2.7	63	8.0	73	$720
Sonoma	30	15	1.3	47	$240
Ventura	-	0.35	28	29	$790
Total	**270**	**450**	**350**	**1,100**	**$14,000**

3.2. Erosion-Related Risks

3.2.1. Population at Risk from Erosion

The erosion hazard zone totals 41 square miles within the 11 coastal counties evaluated in this analysis (Table 24). There is significant variation in the areas at risk of erosion. In Humboldt County, for example, 6.2 square miles of coast would be lost by 2100 under a sea-level rise scenario of 1.4 meters. In San Francisco, however, the erosion-related risk is small.

Table 24. Erosion with a 1.4 m sea-level rise, by county.

County	Dune erosion (sq. miles)	Cliff erosion (sq. miles)	Total erosion (sq. miles)
Del Norte	1.9	2.6	4.5
Humboldt	3.7	2.4	6.1
Marin	1.0	3.7	4.7
Mendocino	0.74	7.5	8.3
Monterey	1.9	2.5	4.4
San Francisco	0.23	0.30	0.53
San Luis Obispo	1.4	1.5	2.9
San Mateo	0.82	2.4	3.2
Santa Barbara	0.62	1.9	2.6
Santa Cruz	0.87	0.9	1.8
Sonoma	0.60	1.6	2.2
Total	**14**	**27**	**41**

As discussed in Section 2.3.2, dunes and cliffs will exhibit differential responses to rising sea levels. Our results indicated that cliffs will erode an average distance of about 66 m by the year 2100 (Table 25). In some areas, however, erosion is projected to be much higher. In Del Norte County, for example, cliffs erode a maximum distance of 520 m. Cliff erosion is much less severe in the other counties along the coast, although still significant. Dunes exhibit much less resistance to erosion. On average, dunes will erode about 170 m by 2100. In Humboldt County, for example, dunes are projected to erode nearly 600 m by 2100.

Table 25. Average and maximum erosion distance in 2000 for cliffs and dunes, by county.

County	Dune erosion		Cliff erosion	
	Average distance (m)	Maximum distance (m)	Average distance (m)	Maximum distance (m)
Del Norte	180	400	160	520
Humboldt	160	600	61	260
Marin	140	270	110	240
Mendocino	190	440	33	160
Monterey	180	400	37	220
San Francisco	150	230	90	220
San Luis Obispo	140	330	78	280
San Mateo	230	430	31	220
Santa Barbara	190	320	54	240
Santa Cruz	170	340	36	130
Sonoma	150	320	41	190
Average	**170**	**370**	**66**	**240**

Table 26 shows the population at risk from erosion with a 1.4 m sea-level rise in 2100. Flood-related risk is shown for comparative purposes. In the 11 coastal counties north of Santa Barbara, a total of 14,000 people live within areas at risk of erosion. In comparison, 69,000 people are vulnerable to a 100-year flood event within these counties. In most counties, the flood-related risk is substantially higher than the erosion-related risk. In Mendocino and Santa Barbara counties, however, erosion poses a greater threat than flooding. In Marin, the flood-related and erosion-related risks are comparable. In addition to those who live in areas vulnerable to erosion, approximately 6,600 people are employed in facilities located there, of which 95% are employed in the commercial sector and the remaining 5% are employed in the industrial sector.

Table 26. Population vulnerable to flood and erosion from a 1.4 m sea-level rise along the Pacific coast, by county

County	Flood-related Risk	Erosion-related Risk
Del Norte	2,500	620
Humboldt	7,400	580
Marin	620	570
Mendocino	630	930
Monterey	14,000	820
San Francisco	6,500	1,200
San Luis Obispo	6,200	1,100
San Mateo	16,000	2,900
Santa Barbara	1,300	2,100
Santa Cruz	5,600	2,600
Sonoma	9,100	300
Total	**69,000**	**14,000**

Note: Numbers may not add up due to rounding.

3.2.2. Emergency and Healthcare Facilities at Risk from Erosion

Emergency and healthcare facilities at risk from erosion along the California coast are limited. The analysis identified a single health care facility near Pacifica that is vulnerable to erosion. There are no schools or fire and police stations within the erosion hazard zone.

3.2.3. Infrastructure at Risk from Erosion

Roads and Railways

Significant transportation-related infrastructure is vulnerable to erosion. Nearly 240 miles of highways and roads and 10 miles of railways are at risk of erosion in the 11 coastal counties north of Santa Barbara (Table 27). This is far fewer than the transportation-related infrastructure at risk from flooding but as mentioned previously, erosion causes far greater and potentially more permanent damage than flooding. In addition, areas such as Big Sur already have significant routine highway maintenance costs due to existing erosion conditions and these costs are likely to increase as erosion rates increase (Figure 35).

Little critical infrastructure is located within the erosion hazard zone. We identified but no wastewater treatment plants within the area at risk of erosion.

Table 27. Miles of roads and railways vulnerable to erosion and flood from a 1.4 m sea-level rise along the Pacific coast, by county and type

County	Highways (miles)		Roads (miles)		Railways (miles)	
	Erosion-risk	Flood-risk	Erosion-risk	Flood-risk	Erosion-risk	Flood-risk
Del Norte	4.3	8.2	14	80	-	-
Humboldt	6.0	58	20	190	-	28
Marin	2.1	4.1	19	27	-	-
Mendocino	13	7.9	25	41	-	4.0
Monterey	11	31	15	110	2.1	23
San Francisco	0	8.0	17	25	-	-
San Luis Obispo	2.5	0.4	18	22	-	0.3
San Mateo	9.8	11	18	67	-	-
Santa Barbara	0.74	7.4	12	21	6.4	7.0
Santa Cruz	2.4	5.0	20	30	1.6	5.5
Sonoma	6.2	8.0	8.4	57	-	-
Total	**58**		**180**		**10**	

Note: Numbers may not add up due to rounding.

Figure 35. Road erosion along Highway 1 with deployment of erosion mitigation strategy

3.2.4. Property at Risk from Erosion

Land on or near the coast is highly desirable and often commands a premium price. Homes lost to erosion cannot be replaced because the land will have disappeared. As a result, the replacement values reported in the HAZUS database cannot be used in evaluate erosion. A detailed estimate of the value of land and homes that would be completely lost was beyond the scope of this analysis. In order to bound the problem, however, we sought to determine the number of parcels at risk by overlaying the erosion hazard zone layer with the available parcel data. Note that the erosion hazard zone was identified for portions of 11 of California's coastal counties. Eight of these 11 counties had parcel data in digital format.

Parcels are used by counties to levy property taxes. Assessor's offices divide entire counties into parcels, which can represent publicly-owned land, roads, lakes, and other features. A single parcel may also contain an apartment building with many hundreds of residences. Thus, this is an imprecise way of estimating how much property may be lost to coastal erosion. This is an area of study that can and should be pursued in more detail by local governments and regional planning agencies.

We estimate that approximately 10,000 parcels lie within the erosion hazard zone, as summarized in Table 28. Of these parcels, 66%, or two-thirds, lie completely in the erosion hazard zone, meaning the property would be lost completely. The remaining third are partially eroded. If we assume that the value of the average coastal parcel is $1.4 million (Heinz Center 2000), then the economic cost to property of erosion from a 1.4 m sea-level rise would total $14 billion. More work on the economic consequences of erosion is needed.

Table 28. Number of properties within the erosion zone hazard zone with a 1.4 m sea-level rise, by county

County	Number of parcels
Del Norte	No data
Humboldt	570
Marin	1,300
Mendocino	No data
Monterey	1,600
San Francisco	850
San Luis Obispo	No data
San Mateo	1,900
Santa Barbara	580
Santa Cruz	3,000
Sonoma	500
Total	**10,000**

Note: Numbers may not add up due to rounding.

4.0 Conclusions and Recommendations

4.1. Conclusions

Rising sea levels 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 eight inches along the California coast and general circulation model scenarios suggest very substantial increases in sea level due to climate change over the coming century. This study evaluates the current population, infrastructure, and property at risk from 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, which are especially vulnerable. A wide range of critical infrastructure, such as roads, hospitals, schools, emergency facilities, wastewater treatment plants, power plants, and wetlands is also vulnerable. In addition, $100 billion (in year 2000 dollars) worth of property is at risk of coastal flooding. A number of structural and non-structural policies and actions could be implemented to reduce these risks. 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. 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.

Large sections of the Pacific coast are not vulnerable to flooding, but are highly susceptible to erosion. We estimate that a 1.4 m sea-level rise will accelerate erosion, resulting in a loss of 41 square miles of California's coast by 2100. A total of 14,000 people live in areas at risk of erosion. In addition, significant transportation-related infrastructure and property are also at risk. Throughout most of the state, flood risk exceeds erosion risk, but in some counties, coastal erosion poses a greater risk. We also provide, below, a set of recommendations for actions and policies that can reduce future risks and vulnerabilities.

4.2. Recommendations

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. Below, we provide a series of recommendations and principles to guide the adaptation process.

4.2.1. Principles for Adaptation

The decisions about what to protect, how to protect it, and who will have to pay will be both challenging and controversial. Given the complexity of these issues, it is important to develop an open and transparent process involving all affected stakeholders. Below, we provide some general principles to guide this process:

- Human life must be protected.
- Critical ecological systems should be preserved.
- Development and protection of the coast should be governed by the principles of sustainability. Simply stated, this means "meeting the needs of the present without compromising the ability of future generations to meet their own needs" (WCED 1987).
- Equal and full participation must be a central element of any decision-making process. No social or economic group should be excluded from decision-making that will affect its well-being.
- Communities must determine the resources and features they value, e.g., beaches, public access, fisheries, etc., and develop plans to protect those resources.
- Consideration should be given to equitable distribution and apportionment of costs and benefits of adaptation measures.
- Adaptation strategies should account for the distinct vulnerabilities of potentially affected subpopulations.
- Local and regional planning processes must begin early to incorporate estimates of sea-level rise and strategies for adaptation.

4.2.2. Recommended Practices and Policies

Climate change must be integrated into the design of all coastal structures.

Current efforts to build, maintain, or modify structures in coastal areas at risk of sea-level rise must now be based on estimates of that rise. The costs of modifying structures in the design phase are often far lower than the costs of later reconstruction or flood damage.

The federal government and the insurance industry should develop and implement a methodology for integrating climate change into insurance policies and strategies.

Properly designed insurance policies are vital for helping landowners choose whether to protect or abandon risky property. The design, availability, and cost of flood insurance will be a key instrument in implementing floodplain policy. For example, the government should not continue to subsidize flood insurance for properties that have suffered repetitive losses. Nor should insurance be available for properties highly likely to be inundated under future conditions.

Federal flood insurance maps should include information on future flood risks due to sea-level rise.

The Federal Emergency Management Agency's official flood insurance studies show hazard zones that reflect past or present flood risks. Because these are the *de facto* planning documents used by most local governments, they should be updated to show the *future* hazard areas and include the current science on climate change and sea-level rise.

Wetlands and the potential migratory paths should be protected.

Development should be prohibited on natural lands that are immediately adjacent to wetlands at risk. These buffer areas may be the only areas suitable for future wetland restorations projects.

Future development should be limited in areas that are at risk from rising seas.

In regions at risk that are not yet heavily developed, local communities and coastal planning agencies have the opportunity to limit development and reduce future threats to life and property. Policies that maintain such low-lying areas will help to accommodate rising seas. In addition to insurance policies, discussed above, such policies may include local ordinances, statewide coastal development policies, and explicit purchases of land for conservation purposes. This is often the least expensive option for currently undeveloped areas.

While limiting coastal development is the most effective way to reduce risk, this approach can incur costs today. Development permits designed to provide flexibility for future generations to address sea-level rise will reduce today's cost. For example, permits might allow development but stipulate that the area reverts to nature if seas rise by a specified amount.

Local planning processes need to involve communities most vulnerable to harm when developing appropriate preparation and adaptation strategies.

The particular needs of vulnerable communities, and appropriate adaptation policies, are best identified and developed through processes in which the affected communities are at the center of decision making. The vulnerabilities to sea-level rise created by access to transportation, legal residency, income, and language abilities can only be fully understood and protected when members of these communities are directly involved in the process.

Consider phased abandonment of low- and medium-density areas at high risk.

In some low- and medium- density areas, the monetary and environmental cost of holding back the sea may become unacceptably high. The lowest-cost option may be to allow natural processes take place. Policies that prevent flood-damaged homes or businesses from rebuilding may help ease this transition.

Protect vital societal resources, especially those that are "coastal-dependent."

In many cases, the value of an area's infrastructure far exceeds the cost to raise structures or build protective barriers. For example, the San Francisco airport and the Port of Long Beach are extremely important to the state and national economy. In choosing what to protect, we should favor infrastructure that necessarily belongs on the coast, such as ports, bridges, and marinas.

Cost-benefit analyses should explicitly evaluate the social and environmental costs of building coastal protection structures.

Armoring the coastline can save lives and property, but it also comes at a cost. The natural dynamics that occur between water and land are disrupted. Beaches and wetlands disappear and habitat is lost. Traditional cost-benefit analyses, such as those required for all US Army Corps of Engineers projects, do not adequately account for these inherent tradeoffs.

Coastal emergencies are inevitable. Coastal communities should improve disaster response and recovery.

In this analysis, we have focused on increased risk of coastal flooding and erosion as a result of sea-level rise. California is also subject to tsunamis, earthquakes, wildfires, terrorist attack, and other hazards. Improving community preparedness provides benefits for responding to any type of emergency. Before a disaster strikes, communities must plan for evacuation routes, emergency action plans, and shelters, and take into account the specific needs of vulnerable populations. In addition, roles and responsibilities must be clearly defined among local, state, and federal agencies.

Coastal managers should consider adopting the principles of "No Adverse Impact" when designing and permitting flood protection, beach nourishment, and other coastal protection projects.

Current coastal protection projects are often done with no regard for how they will affect adjacent portions of the coast. According to the Association of State Floodplain Managers: "Over the past 50 years a system has developed through which local and individual accountability has been supplanted by federal programs for flood control, disaster assistance, and tax incentives that encourage and subsidize floodplain occupation and development." We recommend that coastal managers consider adopting a policy similar to "No Adverse Impact" where the "actions of one property owner are not allowed to adversely affect the rights of other property owners" (ASFM 2008).

4.2.3. Additional Research and Analysis

Local governments or regional planning agencies should conduct detailed studies to better understand the potential impacts of sea-level rise in their communities.

The analysis presented here provides an initial estimate of the impacts of sea-level rise along the California coast. More detailed assessments of local impacts and potential response strategies are needed. While the effects of sea-level rise, responses, and threatened resources must all be evaluated at a local level, broader regional effects must also be incorporated into final protection strategies.

Our analysis was hindered by inadequate data on existing coastal structures. Existing levees and other flood defenses should be surveyed, assessed, and cataloged.

The U.S. Congress passed the Water Resources Development Act of 2007, creating a National Levee Safety. The act requires the establishment and maintenance of an inventory of the nation's levees and inspection of all federally owned, operated, or constructed levees. This program should be fully funded and quickly implemented, and the information it compiles should be made readily available to residents, local government, and others.

Conduct further research focused on all vulnerable subpopulations, including children, elderly, homeless, physically disabled, and people with limited mobility (e.g., incarcerated residents and healthcare facility patients), accurately measuring and analyzing the potential human costs of sea-level rise and adaptation measures.

This analysis does not include various demographic groups that can be expected to have unique vulnerabilities to potential disasters. For pre-disaster, disaster response, and recovery efforts to effectively safeguard all Californians, further study is needed to identify all vulnerable populations and assess the unique vulnerabilities of each group.

Assess the environmental justice implications of potential mitigation measures, and develop strategies to effectively safeguard all communities.

The measures taken to adapt to sea-level rise must not distribute costs and benefits of protection in ways that place a disproportionate burden on the low-income households and communities of color who are most vulnerable to a potential disaster. The means of prioritizing protection measures must be analyzed with and held to the principles of environmental justice.

Natural ecosystems are at serious risk from sea-level rise, but are undervalued or ignored in traditional economic analyses. Improved methods for incorporating them into future studies are needed.

Wetlands are highly diverse ecosystems that provide a variety of goods and services, including flood protection, water purification, wildlife habitat, recreational opportunities, and carbon sequestration. Large tracts of wetlands along the California coast are vulnerable to sea-level rise. No satisfactory method for incorporating their environmental values has been developed, and we thus risk ignoring them when we make policy decisions. This would be a serious mistake. Additional work is needed to evaluate the costs and values of natural ecosystems.

5.0 References

Adams, C., E. Witt, J. Wang, D. Shaver, D. Summers, Y. Filali-Meknassi, H. Shi, R. Luna, and N. Anderson. 2007. "Chemical Quality of Depositional Sediments and Associated Soils in New Orleans and the Louisiana Peninsula Following Hurricane Katrina." *Environmental Science and Technology* 41(10): 3437–3443.

Airports Council International. 2008. Airport Traffic Reports. Microsoft Excel spreadsheet document at www.aci-na.org/stats/stats_traffic.

Andrulis, D. P. and N. Siddiqui, and J. Purtle. 2008. "A Background Paper: Snapshot of California's Emergency Preparedness Efforts for Culturally Diverse Communities." Philadelphia, Pennsylvania: Center for Health Equality, Drexel University School of Public Health.

Association of State Floodplain Managers (ASFM). 2008. NAI – No Adverse Impact Floodplain Management. White Paper. Accessed on January 29, 2009 from www.floods.org/NoAdverseImpact/NAI_White_Paper.pdf.

Bates, Frederick, C. W. Fogleman, B. Parenton, R. Pittman, and G. Tracy. 1963. "The Social and Psychological Consequences of a Natural Disaster." NRC Disaster Study 18. Washington D.C.: National Academy of Sciences.

Battalio, R., S. Baek, and D. Revell. 2008. California Coastal Response to Sea Level Rise: Coastal Base Flood Elevation Estimates. Technical Memorandum to the Pacific Institute. San Francisco, California.

Blanchard-Boehm, D. 1997. "Risk Communication in Southern California: Ethnic and Gender Response to 1995 Revised, Upgraded Earthquake Probabilities." Research Report. Bolder, Colorado: Natural Hazards Research and Applications Information Center.

Bolin, R., and P. Bolton. 1986. *Race Religion and Ethnicity in Disaster Recovery*. Monograph No. 42. Boulder: University of Colorado, Institute of Behavioral Science.

Bovbjerg, R., and J. Hadley. 2007. Why Health Insurance is Important. Health Policy Briefs. The Urban Institute. Washington, D.C.

Brodie, M., E. Weltzien, D. Altman, R. Benson, and J. Benson. 2006. "Experiences of Hurricane Katrina Evacuees in Houston Shelters: Implications for Future Planning." *American Journal of Public Health* 95(5): 1402–1408.

Brown, E. Richard, Shana Alex Lavarreda, Ninez Ponce, Jean Yoon, Janet Cummings, Thomas Rice. 2007. The *State of Health Insurance in California; Findings from the 2005 Health Interview Survey.* Los Angeles, California: UCLA Center for Health Policy Research.

Bullard, R., P. Mohai, R. Saha, and B. Wright. 2007. *Toxic Waste and Race at Twenty: 1987–2007.* Prepared for the United Church of Christ Justice and Witness Ministries.

Silicon Valley Daily. 2009. "Median California Home Price $285,680 in November." January 9, 2009. www.svdaily.com/realestateprices.html.

California Office of Statewide Health Planning and Development. 2006. Digital data files of California licensed health care facilities. Downloaded from California Spatial Information Library. http://casil.ucdavis.edu/casil/.

Cayan, D., M. Tyree, M. Dettinger, H. Hidalgo, T. Das, E. Maurer, P. Bromirski, N. Graham, and R. Flick. 2009. Climate Change Scenarios and Sea Level Rise Estimates for California 2008 Climate Change Scenarios Assessment. California Climate Change Center. In preparation.

Cayan, D., P. Bromirski, K. Hayhoe, M. Tyree, M. Dettinger, and R. Flick. 2006. Projecting Future Sea Level. California Climate Change Center. California Energy Commission, Public Interest Energy Research Program. CEC-500-2005-202-SF. 64 pages.

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

Childers, C. D. 1999. "Elderly Female-headed Households in the Disaster Loan Process." *International Journal of Mass Emergencies and Disasters* 17(1): 99–110.

Christensen, M. "Protecting America's Busiest Port From Seismic Impacts." Presentation at University of Southern California's Megacities Workshop. Los Angeles, California. November 10, 2008. http://mededonline.hsc.usc.edu/research/workshop-2008/session-5-christensen.htm.

Comerio, M., J. Landis, and Y. Rofe. 1994. "Post-Disaster Residential Rebuilding." Institute of Urban and Regional Development Working Paper 608. Berkeley: University of California.

Costanza, R., R. d'Arge, R. de Groot, S. Farber, M. Grasso, B. Hannon, K. Limburg, S. Naeem, R. V. O'Neill, J. Paruelo, R. G. Raskin, P. Sutton, and M. van den Belt. 1997. "The value of the world's ecosystem services and natural capital." *Nature*. 387: 253–260. 15 May.

Crampton, W. 2008. Principal Engineer, TerraCosta Consulting Group, Inc. Personal communication. November 24, 2008.

Dahl, T. E. 2006. Status and trends of wetlands in the conterminous United States 1998 to 2004. U.S. Department of the Interior; Fish and Wildlife Service, Washington, D.C.

Environment Canada. 2001. Putting an Economic Value on Wetlands – Concepts, Methods, and Considerations. Downsview, Ontario. Canada. Accessed on 9/26/08 from www.on.ec.gc.ca/wildlife/factsheets/fs_wetlands-e.html.

Executive Order No. 12898: Environmental Justice in Minority Populations. February 11, 1994.

Farris, M. T, II. 2008. "Are you prepared for a devastating port strike in 2008?" *Transportation Journal* Winter 2008. www.entrepreneur.com/tradejournals/article/176689816.html.

Federal Emergency Management Agency (FEMA). 2005. Final Draft Guidelines, Coastal Flood Hazard Analysis and Mapping for the Pacific Coast of the United States. Prepared for the U.S. Department of Homeland Security. Washington, D.C.

Federal Emergency Management Agency (FEMA). 2006. Hazards U.S. Multi-Hazard (HAZUS-MH). Computer application and digital data files on 2 CD-ROMs. Jessup, Maryland. www.fema.gov/plan/prevent/hazus/.

Flick, R. E., J. F. Murray, and L. Ewing. 1999. Trends in U.S. tidal datum statistics and tide range: A data report atlas. Scripps Institution of Oceanography. San Diego, California.

Fothergill, A. 2004. Head Above Water: Gender, Class, and Family in the Grand Forks Flood. Albany, New York: State University of New York Press.

Frey, W., A. Singer, and D. Park. 2007. Resettling New Orleans: The First Full Picture from the Census. The Brookings Institution. Washington, D.C.

Fulton-Bennett, K., and G. B. Griggs. 1986. Coastal Protection Structures and their Effectiveness. Marine Sciences Institute, University of California at Santa Cruz and State of California Department of Boating and Waterways, Sacramento, California. 48pp.

Gittleman, M., and E. N. Wolff. 2000. Racial Wealth Disparities: Is the Gap Closing? Levy Economics Working Paper No. 311. New York: The Levy Economics Institute of Bard College.

Gleick, P. H., and E. P. Maurer. 1990. Assessing the Costs of Adapting to Sea-Level Rise: A Case Study of San Francisco Bay. Pacific Institute, Oakland, California. 97 pages with two maps. www.pacinst.org/reports/sea_level_rise/.

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

Gustaitis, R. 2002. New Sand – and New Seawalls on San Diego County Beaches. *California Coast and Ocean* 17(3): Article 2.

Hampton, M. A., and G. Griggs. 2004. Formation, Evolution, and Stability of Coastal Cliffs - Status and Trends. U.S. Geological Survey (USGS) Professional Paper 1693. http://pubs.usgs.gov/pp/pp1693.

Hanemann, M. 2008. What is the Economic Cost of Climate Change?

Hapke, C., and D. Reid. 2007. National Assessment of Shoreline Change Part 4: Historical Coastal Cliff Retreat along the California Coast. U.S. Geological Survey (USGS) Open File Report 2007-1133.

Hapke, C. J., D. Reid, B. M. Richmond, P. Ruggiero, and J. List. 2006. *National assessment of shoreline change Part 3: Historical shoreline change and associated coastal land loss along sandy shorelines of the California Coast.* U.S. Geological Survey Open File Report 2006-1219.

Heinz Center. 2000. Evaluation of erosion hazards. Report prepared for the Federal Emergency Management Agency. Contract EMW-97-CO-0375. Washington, D.C.

Hewitt, K. 1997. *Regions of Risk: A Geographical Introduction to Disasters.* London: Addison Wesley Longman.

Hutzel, A. 2008. Personal communication. Coastal Conservancy. October 7, 2008.

Institute of Medicine. 1999. *Towards Environmental Justice: Research, Education, and Health Policy Needs.* Washington, D.C.: National Academy of Press.

Intergovernmental Panel on Climate Change. 2000. *Special Report on Emissions Scenarios.* Cambridge University Press, UK. 570 pp.

Kanak, J. 2008. "Repair of Entire Wells Seawall to be Completed." *Seacoast Online* October 23, 2008.

Knowles, N. 2008. Inundation data provided by Dr. Noah Knowles, U.S. Geological Survey, with funding from the California Energy Commission's Public Interest Energy Research (PIER) Program through the California Climate Change Center at Scripps Institution of Oceanography, and from the CALFED Science Program CASCaDE Project.

Komar, P. D., W. G. McDougal, J. J. Marra, and P. Ruggiero. 1999. "The rational analysis of setback distances: Applications to the Oregon Coast." *Shore and Beach* 67(1): 41–49.

Klynman, Y., N. Kouppari, and M. Mukhier. 2007. *World Disasters Report: Focus on Discrimination*. International Federation of Red Cross and Red Crescent Societies. Switzerland.

Meehl, G. A., T. F. Stocker, W. D. Collins, P. Friedlingstein, A. T. Gaye, J. M. Gregory, A. Kitoh, R. Knutti, J. M. Murphy, A. Noda, S. C. B. Raper, I. G. Watterson, A. J. Weaver, and Z.-C. Zhao. 2007. Global Climate Projections. In: *Climate Change 2007: The Physical Science Basis. Contribution of Working Group I to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change.* Solomon, S., D. Qin, M. Manning, Z. Chen, M. Marquis, K. B. Averyt, M. Tignor, and H. L. Miller (eds.). Cambridge, United Kingdom and New York, New York, USA: Cambridge University Press.

Metropolitan Transportation Commission. 2004. *Regional Goods Movement Study for the San Francisco Bay Area.* Oakland, California. 26 pages. www.mtc.ca.gov/pdf/rgm.pdf.

Moffatt & Nichol Engineers. 2005. "Urban Levee Flood Management Requirements. South Bay Salt Pont Restoration Project." Prepared for the California State Coastal Conservancy.

Morrow, B., and E. Enarson. 1996. "Hurricane Andrew through Women's Eyes: Issues and Recommendations." *International Journal f Mass Emergencies and Disasters* 14(1): 5–22.

Mount, J., and R. Twiss. 2005. "Subsidence, Sea Level Rise, Seismicity in the Sacramento-San Joaquin Delta." *San Francisco Estuary and Watershed Science* 3(1): Article 5.

Myers, J. P., and J. S. Reichert. 1997. Perspectives on Nature's Services. In G. C. Daily, *Nature's Services: Societal Dependence on Natural Ecosystems.* Island Press, Washington, D.C.

National Oceanic and Atmospheric Administration (NOAA). 2004. *Population Trends Along the Coastal United States: 1980–2008.* Washington, D.C.

National Research Council. 1987. Responding to Changes in Sea Level: Engineering Implications. Washington, D.C.: National Academies Press. www.nap.edu/openbook/0309037816/html/.

Oliver, M. L., and T. M. Shapiro. 1995. *Black Wealth, White Wealth: A New Perspective on Racial Inequality.* New York: Routledge Press.

Pang, P. G. 2008. U.S. Army Corps of Engineers. Personal communication.

Park, R. A., P. W. Mausel, and R. C. Howe. 1989. The Effects of Sea Level Rise on U.S. Coastal Wetlands. Appendix B in *The Potential Effects of Global Climate Change on the United States.* Report to Congress. U.S. Environmental Protection Agency. EPA 230-05-89-052. Washington, D.C.

Pastor, M., R. Bullard, J. Boyce, A. Fothergill, R. Morello-Frosch, and B. Wright. 2006. *In the Wake of the Storm: Environment, Disaster and Race After Katrina.* New York: Russell Sage Foundation.

PennPraxis. 2008. *An Action Plan for the Central Delaware: 2008 – 2018.* PlanPhilly.com, School of Design of University of Pennsylvania.

Perry, R., and A. H. Mushkatel. 1986. *Minority Citizens in Disasters.* Athens: University of Georgia Press.

Philip Williams & Associates, Ltd. 2008. Sea-Level Rise Coastal Erosion Mapping. San Francisco, California.

Phillips, B., and M. Ephraim. 1992. "Living in the Aftermath: Blaming Processes in the Loma Prieta Earthquake." Working Paper No. 80. IBS. Boulder: University of Colorado, Natural Hazards Research and Applications Information Center.

Pilkey, O. H., and J. A. G. Cooper. 2004. "Climate: Society and Sea Level Rise." *Science* 19 March 2004: 303(5665): 1781–1782.

Public Policy Institute of California. 2008. Just the Facts: Illegal Immigrants.

Rahmstorf, S., A. Cazenave, J. A. Church, J. E. Hansen, R. F. Keeling, D. E. Parker, and R. C. J. Somerville. 2007. "Recent Climate Observations Compared to Projections." *Science* 316(5825): 709.

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

Raupach, M. R., G. Marland, P. Ciais, C. Le Quere, J. G. Canadell, G. Klepper, and C. B. Field. 2007. Global and regional drivers of accelerating CO_2 emissions. Proceedings of the National Academy of Sciences 104(24): 10288–1029.

Rossi, P. H., J. Wright, E. Weber-Burdin, and J. Pereira. 1983. *Victims of the Environment: Loss from Natural Hazards in the United State, 1970–1980.* New York: Plenum Press.

Ruggiero, P., P. D. Komar, W. G. McDougal, and R. A. Beach. 1996. Extreme water levels, wave runup and coastal erosion. Proceedings of the 25th International Conference on Coastal Engineering. ASCE. 2793–2805.

Ruggiero, P., P. D. Komar, W. G. McDougal, J. J. Marra, and R. A. Beach. 2001. "Wave run-up, extreme water levels, and the erosion of properties backing beaches." *Journal of Coastal Research* 17(2): 401–419.

Sallenger, A. H., W. Krabill, J. Brock, R. Swift, S. Manizade, and H. Stockdon. 2002. "Sea cliff erosion as a function of beach changes and extreme wave run-up during the 1997–1998 El Niño." *Marine Geology* 187:279–297.

Schneider, S. H., S. Semenov, A. Patwardhan, I. Burton, C. H. D. Magadza, M. Oppenheimer, A. B. Pittock, A. Rahman, J. B. Smith, A. Suarez, and F. Yamin. 2007. Assessing key vulnerabilities and the risk from climate change. Climate Change 2007: Impacts, Adaptation and Vulnerability. Contribution of Working Group II to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change. M. L. Parry, O. F. Canziani, J. P. Palutikof, P. J. van der Linden, and C. E. Hanson, Eds. Cambridge, UK: University Press. 779–810.

Stamski, R. 2005. The Impacts of Coastal Protection Structures in California's Monterey Bay National Marine Sanctuary. Marine Sanctuaries Conservation Series MSD-05-03. U.S. Department of Commerce, National Oceanic and Atmospheric Administration, Marine Sanctuaries Division. Silver Springs, Maryland.

Stockdon, H., R. Holman, P. Howd, and A. H. Sallenger. 2006. "Empirical parameterization of setup, swash, and run-up." *Coastal Engineering* 53:573–588.

Subervi-Velez, F. A., M. Denney, A. Ozuna, and C. Quintero. 1992. *Communicating with California's Spanish-Speaking Populations: Assessing the Role of the Spanish-Language Broadcast Media and Selected Agencies in Providing Emergency Services.* Berkeley: California Policy Seminar.

Tierney, K. 2007. "From the Margins to the Mainstream? Disaster Research at the Crossroads." *Annual Review of Sociology* 33:503–25.

Tierney, K. 1993. "Socio-Economic Aspects of Hazard Mitigation." Preliminary Paper No. 190. Newark: University of Delaware, Disaster Research Center.

Titus, J. G. 1988. Sea Level Rise and Wetland Loss: An Overview. In Titus, J. G. *Greenhouse Effect, Sea Level Rise, and Coastal Wetlands.* U.S. Environmental Protection Agency. Washington, D.C. 186.

Titus, J., R. Park, S. Leatherman, J. Weggle, M. Greene, S. Brown, C. Gaunt, M. Trehan, and G. Yohe. 1992. "Greenhouse effect and sea level rise: The cost of holding back the sea." *Coastal Management* 19: 219–233.

Trader-Leigh, K. 2008. "Understanding the Role of African-American Churches in Community Crisis Response." Washington, D.C.: Joint Center for Political and Economic Studies, Health Policy Institute.

United Nations. 2004. Guidelines for Reducing Flood Losses. United Nations. Accessed April 2006. www.unisdr.org/eng/library/isdr-publication/flood-guidelines/Guidelines-for-reducing-floods-losses.pdf.

United States Army Corps of Engineers. 1984a. San Francisco Bay Tidal Stage vs. Frequency Study. San Francisco, California. October.

United States Army Corps of Engineers. 1984b. Shore Protection Manual, Volumes 1 & 2. Waterways Experiment Station, Coastal Engineering Research Center, Vicksburg, Mississippi.

United States Census Bureau. 2000. Census 2000 Summary File 3 (SF3). Retrieved from U.S. Census http://factfinder.census.gov.

United States Department of Transportation. 2006. Top 50 U.S. Foreign Trade Freight Gateways by Value of Shipments: 2005. Bureau of Transportation Statistics. Washington, D.C. www.bts.gov/programs/international/.

United States Environmental Protection Agency – Office of Enforcement and Compliance Assurance (U.S. EPA-OECA). 2000. Retrieved December 2008 from www.epa.gov/Compliance/environmentaljustice/.

United States Environmental Protection Agency. 2001. Threats to Wetlands. Office of Water and Office of Wetlands, Oceans, and Watersheds. Washington, D.C.

Wang, T., and L. Yasui. 2008. "Integrating Immigrant Families in Emergency Response, Relief, and Rebuilding Efforts." Baltimore, Maryland: Annie E. Casey Foundation.

Woodward, R. T., and Y. Wui. 2001. "The economic value of wetland services: a meta-analysis." *Ecological Economics* 37: 257–270.

World Commission on Environment and Development (WCED). 1987. Our Common Future, Report of the World Commission on Environment and Development. Published as Annex to General Assembly document A/42/427, Development and International Co-operation: Environment August 2, 1987. www.un-documents.net/wced-ocf.htm.

Yelvington, K. A. 1997. "Coping in a Temporary Way: The Tent Cities." In Hurricane Andrew: *Ethnicity, Gender and the Sociology of Disasters,* edited by Walter G. Peacock, Betsy H. Morrow, and Hugh Gladwin. New York: Routledge.

Yohe, G. 1989. "The Cost of Not Holding Back the Sea: Phase 1 Economic Vulnerability" In *The Potential Effects of Global Climate Change on the United States. Report to Congress. Appendix B*: Sea Level Rise. Washington, D.C.: U.S. Environmental Protection Agency. EPA 230-05-89-052.

Yohe, G., J. Neumann, P. Marshall, and H. Ameden. 1996. "The Economic Cost of Greenhouse-Induced Sea-Level Rise for Developed Property in the United States." *Climatic Change* 32(4): 387–410.

Yohe, G. W., and M. E. Schlesinger. 1998. "Sea-Level Change: The Expected Economic Cost of Protection or Abandonment in the United States." *Climatic Change* 38: 447–472.

United States Department of Transportation, Bureau of Transportation Statistics. 2006. Top 50 U.S. Foreign Trade Freight Gateways by Value of Shipments: 2005. www.bts.gov/programs/international/.

6.0 Acronyms and Abbreviations

ALACE	Airborne LIDAR Assessment of Coastal Erosion
ASFM	Association of State Floodplain Managers
BFE	Base flood elevation; elevation of floodwaters with an annual probability of 1%. Also referred to as the 100-year flood.
CALSIM	A computer simulation model of river basins developed by California's Department of Water Resources
CASCADE	Computational Assessments of Scenarios of Climate Change in the Delta Ecosystem; a suite of computer models of the hydrology and biology of California's Sacramento/San Joaquin river delta developed by the US Geological Survey
C-CAP	Coastal Change Analysis Program, a NOAA initiative
CCC	California Coastal Commission
CCSM	Community Climate System Model

CNRM	Centre National de Recherches Meteorologiques (France's National Center for Meteorological Research)
DEM	Digital Elevation Model, a digital database of land surface elevations
DFIRM	Digital Flood Insurance Map, electronic maps and databases published by FEMA
EPA	US Environmental Protection Agency
FEMA	Federal Emergency Management Agency
GFDL	Geophysical Fluids Dynamics Laboratory
GIS	Geographic Information System
HAZUS	Hazards U.S. Multi-Hazard, a computer model for estimating damages from natural disasters
IFRCC	International Federation of Red Cross and Red Crescent Societies
IfSAR	Interferometric Synthetic Aperture Radar
IPCC	Intergovernmental Panel on Climate Change
LIDAR	Light Detection and Ranging, a remote sensing technology used to collect terrain elevation data
MGD	million gallons per day
MHHW	Mean higher-high water
MHW	Mean high water
MHWS	Mean high water springs
MIROC	The Model for Interdisciplinary Research on Climate
MLLW	Mean lower-low water
MLW	Mean low water
MSL	Mean sea level
NASA	National Aeronautics and Space Administration
NAVD88	North American Vertical Datum of 1988; modern reference system for measuring heights above the earth's surface
NCAR	National Center for Atmospheric Research
NPDES	National Pollutant Discharge Elimination System
NGVD29	National Geodetic Vertical Datum of 1929; a reference system for

measuring heights above the earth's surface, superseded by NAVD88

NOAA	National Oceanic and Atmospheric Administration
NPDES	National Pollutant Discharge Elimination System; an EPA program to track and regulate pollutants discharged to surface waters of the United States
NRC	National Research Council
NWI	National Wetlands Inventory, a geographic database of US wetlands published by the US Fish and Wildlife Service
OPC	Ocean Protection Council
PCM	Parallel Climate Model
PCS	Permit Compliance System; an EPA database of licensed discharges to the surface waters of the United States
PIER	Public Interest Energy Research
PWA	Philip Williams and Associates
SLR	Sea level rise
TWL	Total water level
USACE	US Army Corps of Engineers
USFWS	US Fish and Wildlife Service
USGS	US Geological Survey