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

DISCLAIMER

This paper was prepared as the result of work funded by the California Energy Commission, the California Environmental Protection Agency, Metropolitan Transportation Commission, California Department of Transportation, and the California Ocean Protection Council (collectively "the funding agencies"). It does not necessarily represent the views of the funding agencies, their respective officers, agents and employees, or the State of California. The funding agencies, the State of California, and their respective officers, employees, agents, contractors, and subcontractors make no warrant, express or implied, and assume no responsibility or liability for the results of any actions taken or other information developed based on this paper; nor does any party represent that the uses of this information will not infringe upon privately owned rights. This paper is being made available for informational purposes only and has not been approved or disapproved by the funding agencies, nor have the funding agencies passed upon the accuracy, currency, completeness, or adequacy of the information in this paper. Users of this paper agree by their use to hold blameless each of the funding agencies for any liability associated with its use in any form. This work shall 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).



Arnold Schwarzenegger, Governor

Acknowledgments

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. Special thanks to Christine Blackburn at the Ocean Protection Council (OPC) for

seeing the importance of this issue to the entire state, for helping to coordinate OPC's participation in the project, and for many valuable conversations.

Johanna Fenton, formerly head of the Earthquake and Tsunami Program in the 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 Deltares/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. We also received several public comments during the open comment period that helped improve the final report. 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	
2.3.2. Erosion Risk	15
2.3.3. Limitations of the Analysis	
2.4. Resources Threatened by Sea-Level Rise	20
2.4.1. Population	20
2.4.2. Impacts on the Built Environment	23
2.4.3. Natural Resources	27
Spatial Extent of Wetlands	27
Economic Value of Wetlands	
Impact of Sea-Level Rise on Wetlands	
2.4.4. Limitations	33
2.5. Determine the Protective Responses Appropriate for the	
2.5.1. Structural Coastal Protection Measures	34
Beach Nourishment	34
Groins	34
Seawalls, Bulkheads, and Revetments	34
Breakwaters	
Dikes and Levees	
Raise Existing Structures (Roadways, Railroads, and Other	Structures)35
2.5.2 Cost of Structural Protection Measures	35

	2.5.3.	Estimating Needed Coastal Defenses	37
3.0	Resi	ılts	38
3.	.1. F	lood-Related Risks	38
	3.1.1.	Population at Risk	39
	Env	rironmental Justice Concerns	43
	3.1.2.	Emergency and Healthcare Facilities at Risk	51
	3.1.3.	Hazardous Materials Sites	52
	3.1.4.	Infrastructure at Risk	54
	Roa	nds and Railways	54
	Pov	ver Plants	58
	Wa	stewater Treatment Plants	62
	Por	ts	62
	Air	ports	65
	3.1.5.	Wetlands	65
	3.1.6.	Property at Risk	74
	Pac	ific Coast	76
	San	Francisco Bay	78
	3.1.7.	Saltwater Intrusion to Groundwater Aquifers	80
	3.1.8.	Cost of Protection	81
3.	.2. E	rosion-Related Risks	82
	3.2.1.	Population at Risk from Erosion	82
	3.2.2.	Emergency and Healthcare Facilities at Risk from Erosion	84
	3.2.3.	Infrastructure at Risk from Erosion	84
	Roa	ids and Railways	84
	3.2.4.	Property at Risk from Erosion	86
4.0	Con	clusions and Recommendations	87
4.	.1. (Conclusions	87
4.	.2. K	Recommendations	87
	4.2.1.	Principles for Adaptation	88
	4.2.2.	Recommended Practices and Policies	88
	4.2.3.	Additional Research and Analysis	91
5.0	Refe	erences	92
6.0	Acro	onyms and Abbreviations	99

List of Figures

Figure 1. Trend in monthly mean sea level at the San Francisco tide station from $1854-20066$
Figure 2. Scenarios of sea-level rise to 2100
Figure 3. Determining future flood elevations9
Figure 4. Rates of change of tidal datums, San Francisco from 1900–200011
Figure 5. Simple schematic of USGS San Francisco Bay hydrodynamic model14
Figure 6. Historical and projected carbon dioxide emissions scenarios, 1990–201015
Figure 7. Comparison of 100-year flood elevations (in meters NAVD88)
Figure 8. Limitations of the computer's ability to accurately map coastal flooding in areas protected by seawalls or levees or natural barriers
Figure 9. Relationship between demographics and vulnerabilities
Figure 10. Distribution of census-block average replacement costs for single-family homes from HAZUS
Figure 11. Flooding of a coastal road in Santa Cruz, California
Figure 12. National Wetlands Inventory wetlands classified as "coastal" are below or adjacent to the MHHW line
Figure 13. Assumed wetland area defined by the intertidal range31
Figure 14. An example of coastal armoring leading to the disappearance of beach37
Figure 15. Estimated current and future 100-year coastal flood risk areas around Santa Cruz 39
Figure 16. Population vulnerable to a 100-year coastal flood with a 1.4 m sea-level rise, by county
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
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
Figure 19. Roadways vulnerable to a 100-year coastal flood with a 1.4 m sea-level rise55
Figure 20. Railroads vulnerable to a 100-year coastal flood with a 1.4 m sea-level rise56
Figure 21. Power plants vulnerable to a 100-year coastal flood with a 1.4 m sea-level rise59
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
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
Figure 26. Existing coastal wetlands
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
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
Figure 33. Replacement 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
Figure 34. Replacement 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
Figure 35. Saltwater intrusion
Figure 36. Road erosion along Highway 1 with deployment of erosion mitigation strategy 85
List of Tables
Table 1. Elevation datasets used for mapping coastal flood risks
Table 2. Recurrence intervals of inundation estimates
Table 3. Year and estimated mean sea-level for inundation estimates under the A2 and B1 scenarios
Table 4. Miles and fraction of coastline studied for the erosion hazard study, by county20

Table 5. Approaches for estimating ecosystem values
Table 6. Mean higher high water (MHHW) for long-term tide stations on California's Pacific coast
Table 7. Costs (in year 2000 dollars) for building new levees, raising existing levees, and building new seawalls
Table 8. Population vulnerable to a 100-year flood along the Pacific coast, by county42
Table 9. Population vulnerable to a 100-year flood along the San Francisco Bay, by county 43
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
Table 11. Key demographics of populations vulnerable to a 100-year flood event with a 1.4 n sea-level rise
Table 12. Schools and emergency and healthcare facilities along the Pacific coast that are at risl from a 100-year flood event in 2000 and with a 1.4 m sea-level rise
Table 13. Schools and emergency and healthcare facilities along San Francisco Bay that are a 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 52
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
Table 15. Miles of roads and railways vulnerable to a 100-year flood in 2000 and with a 1.4 n sea-level rise along the Pacific coast, by county and type54
Table 16. Miles of roads vulnerable to a 100-year flood along San Francisco Bay, by county and type
Table 17. Miles of railways vulnerable to a 100-year flood along San Francisco Bay, by county. 57
Table 18. Existing California coastal wetland area by county
Table 19. Wetland migration frontier area classified by land cover type and conversion potentia
Table 20. Land area available for wetland migration, by county, in square miles, with percent o county total in italics
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
Table 22. Replacement value of buildings and contents at risk of a 100-year flood on Sar Francisco Bay, by county (in millions of year 2000 dollars)
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

Γable 24. Erosion with a 1.4 m sea-level rise, by county	83
Γable 25. Average and maximum erosion distance in 2000 for cliffs and dunes, by county	83
Table 26. Population vulnerable to flood and erosion from a 1.4 m sea-level rise along the Pac coast, by county	
Table 27. Miles of roads and railways vulnerable to erosion and flood from a 1.4 m sea-level along the Pacific coast, by county and type	
Table 28. Number of properties within the erosion zone hazard zone with a 1.4 m sea-level r	