THE IMPACTS OF SEA LEVEL RISE ON THE SAN FRANCISCO BAY

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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 along the San Francisco Bay that are 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 but does not reflect the worst-case sea level rise that could occur. 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 San Francisco Bay.

We estimate that a 1.0 meter (m) sea level rise will put 220,000 people at risk of a 100-year flood event, given today's population. With a 1.4 m increase in sea levels, the number of people at risk of a 100-year flood event would rise to 270,000. Among those affected are large numbers of low-income people and communities of color, which are especially vulnerable. Critical infrastructure, such as roads, hospitals, schools, emergency facilities, wastewater treatment plants, power plants, and more will be at increased risk of inundation, as will vast areas of wetlands and other natural ecosystems. In addition, the cost of replacing property at risk of coastal flooding with a 1.0 m rise in sea levels is $49 billion (in year 2000 dollars). A rise of 1.4 m would increase the replacement cost to $62 billion (in year 2000 dollars). Continued development in vulnerable areas will put additional areas at risk and raise protection costs. A number of structural and non-structural policies and actions, which are described qualitatively, could be implemented to reduce these risks.

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

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1. Introduction

The San Francisco Bay, which includes more than 1,000 miles of shoreline, is vulnerable to a range of natural hazards, including storms, extreme high tides, and rising sea levels resulting from global climate change. Development along the San Francisco Bay is extensive. In 2000, 6.8 million Californians lived in counties that border the San Francisco Bay (U.S. Census Bureau 2000), and this number continues to grow. Major transportation corridors and other critical infrastructure are found along the San Francisco Bay, including energy facilities, major ports, harbors, and water and wastewater plants. The San Francisco Bay is also an extraordinary cultural and ecological resource and offers extensive tourism and recreational opportunities.

Flooding already poses a threat to communities along the San Francisco Bay, 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. (2009) 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.

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). 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.

This work was 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 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 California Department of Transportation.

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[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.

2.0 Methods

2.1 Study Area

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

2.2 Sea Level Rise Projections

Sea levels are constantly in flux, subject to the influence of astronomical forces from the Sun, Moon, and Earth, as well as from meteorological effects like El Niño. 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 2.01 millimeters (mm) per year from 1897 to 2006, equivalent to a change of eight inches in the last century.[2]

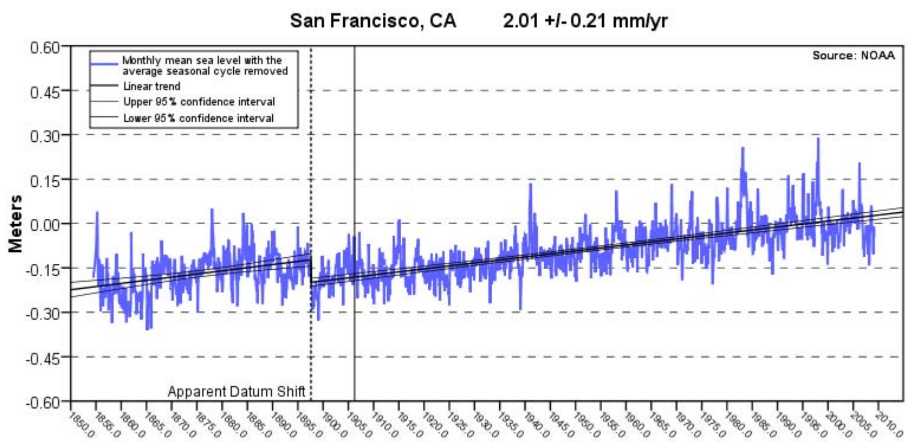

Figure 1. Trend in Monthly Mean Sea Level at the San Francisco Tide Station from 1854–2006

Source: National Oceanic and Atmospheric Administration (NOAA) Sea Levels Online, http://tidesandcurrents.noaa.gov/sltrends/sltrends_station.shtml?stnid=9414290

[2] The solid vertical line shows the earthquake of 1906. NOAA researchers fit separate trendlines before and after an apparent datum shift (vertical movement of the land surface) that occurred in 1897, disrupting consistent measurements.

Sea levels are expected to continue to rise, and the rate of increase will likely accelerate. Based on a set of climate scenarios prepared for the California Energy Commission's PIER Climate Change Research Program, Cayan et al. (2009) 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 as a result of thermal expansion of the oceans and an increase in ocean volume as land ice melts and runs off.

For this study, we considered coastal flood risks only, e.g., flooding caused by rising seas along the San Francisco Bay. Higher sea levels, however, can also worsen flooding in nearby rivers as higher water surface elevations at the downstream end of a river causes water to back up and increase upstream flooding. These impacts are not evaluated here. For additional discussions on the methods employed in this study, see Heberger et al. 2009.

2.3 Expected Risk to the San Francisco Bay

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. Sea level rise inundation maps were generated from the PIER climate scenarios by the United States Geological Service (Knowles 2009) using a suite of computer models under the CASCaDE (Computational Assessments of Scenarios of Change for the Delta Ecosystem) project that simulate the hydrodynamics of San Francisco Bay under future climate scenarios. To quantify high water levels throughout the Bay, a hydrodynamic model of the San Francisco Estuary was driven by a projection of hourly water levels at the Presidio of San Francisco. This projection was based on a combination of climate model outputs and empirical models and incorporates astronomical, storm surge, El Niño, and long-term sea level rise influences (Knowles 2009). The Bay computer model simulates the water surface elevation for each hour from 2000–2009. Inputs to the model include both upstream inflows and downstream water surface elevations.

Dr. Knowles performed statistical analyses on the Bay model output to determine flood quantiles for various years 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 estimated risks due to inundation with a 0.5 m, 1.0 m, and 1.4 m sea level rise, which for the Intergovernmental Panel on Climate Change's (IPCC) A2 scenario correspond to 2050, 2081, and 2099, respectively. To estimate areas at risk, these inundation layers were overlaid with the highest-resolution elevation data available from various sources and mosaicked to cover the land surfaces of the San Francisco Bay region.

We based our analysis on a 1 percent-annual chance coastal flood, or the so-called 100-year flood. We chose the 100-year flood because it is used as a standard for planning, insurance, and environmental regulations. Results are reported 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 1, 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 (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 1. Year and Estimated Mean Sea Level for Inundation Estimates under the IPCC's 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

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. For this analysis, we overlaid the inundation geodata 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 (Table 2).

For this analysis, we make an assumption common in regional GIS analyses that the population and resources are distributed evenly within a census block's boundaries. So if our mapping shows that 50 percent of a 500-person census block is inundated by a flood, we estimate that 250 people are at risk. This method may underestimate (when the houses are clustered on the coast) or overestimate (when the houses are set back from the coast) the actual risk.

It is critical to understand that these estimates are based on current data on the extent and location of population and resources, not a projection of where they might be in the future. If no policies are put in place to limit new exposure in areas at risk of rising seas, these 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.

Table 2. Data Sources for Human and Natural Systems Affected by Sea Level Rise

Resource	Data Source	Notes
Population and demographics	2000 U.S. Census	Data aggregated at census block group level
Property	Federal Emergency Management Agency's HAZUS database	Based on replacement value of buildings and contents
Roads and railroads	Tele Atlas	
Schools and emergency facilities	Federal Emergency Management Agency's HAZUS database	
Healthcare facilities	California Office of Statewide Health Planning and Development	
Power plants	California Energy Commission	
Hazardous materials sites	U.S. Environmental Protection Agency (U.S. EPA) Geospatial Data Access Project 2008	Includes 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
Wastewater treatment plants	Developed based on data in the U.S. EPA's Permit Compliance System (PCS) database, aerial photo interpretation, and telephone and Internet research	
Wetlands	NOAA's Coastal Change Analysis Program	2001 land cover data

3.0 Results

This section reports on the results of our analyses for the San Francisco Bay. Some counties also have land area along the Pacific Coast, i.e., outside of the Golden Gate Bridge. Impacts on those lands are not included here but are described in Heberger et al. 2009. We report on the population, infrastructure, and property at risk of a 100-year flood event with sea level rise, as well as the impacts on harder-to-quantify coastal ecosystems. All economic values are reported in year 2000 dollars. A number of structural and non-structural policies and actions could be implemented to reduce these risks. The risks reported in this analysis assume that no adaptation efforts are put in place.

A series of maps for the entire coast of California that demonstrate 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. **These maps 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.

3.1 Population at Risk

Major population centers are located all along the San Francisco Bay shoreline. An estimated 140,000 people, or 2 percent of the region's population, live in areas that are currently at risk of being inundated in a 100-year flood event. 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 at risk due to flooding will also rise. Rising sea levels will overwhelm the existing protection structures, putting the 140,000 people currently living in vulnerable areas at increased risk. An increase in sea levels of 1.0 m would put an additional 80,000 people at risk of a 100-year flood event, raising the total number of people at risk to 220,000 (Table 3). With a 1.4 m increase in sea levels, the number of people at risk of a 100-year flood event nearly doubles to 270,000. Populations in San Mateo County are especially vulnerable, accounting for about 40 to 45 percent of those at risk. Large numbers of residents in Alameda, Marin, and Santa Clara counties are also at risk. Continued development in these regions could put additional people at risk.

Table 3. Population Vulnerable to a 100-year Flood along the San Francisco Bay, by County

County	Current Risk (# of people)	Risk with Sea Level Rise 0.5 m	1.0 m	1.4 m
Alameda	12,000	22,000	43,000	66,000
Contra Costa	840	1,600	3,400	5,800
Marin	25,000	29,000	34,000	39,000
Napa	760	830	970	1,500
San Francisco	190	600	1,600	3,800
San Mateo	80,000	88,000	99,000	110,000
Santa Clara	13,000	17,000	24,000	31,000
Solano	3,700	5,500	8,800	12,000
Sonoma	250	300	420	540
Total	**140,000**	**160,000**	**220,000**	**270,000**

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.

Workplaces as well as residences will be vulnerable. We estimate that in the San Francisco Bay Area, 140,000 employees work within the current 100-year flood risk area. An increase in sea levels of 1.0 m would put an additional 110,000 employees at risk, raising the total number of employees at risk to 250,000 (Table 4). With a 1.4 m increase in sea levels, the number of people at risk of a 100-year flood event more than doubles to 320,000. Employees in San Mateo County are especially vulnerable. Large numbers of residents in Alameda, San Francisco, Santa Clara, and Marin counties are also at risk. These estimates do not account for the number of employees that may not be able to get to their jobs due to impacts on transportation infrastructure.

Table 4. Employees 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
Alameda	19,000	27,000	48,000	73,000
Contra Costa	1,500	2,200	3,600	5,200
Marin	20,000	23,000	28,000	33,000
Napa	480	530	690	1,100
San Francisco	1,800	3,500	12,000	41,000
San Mateo	69,000	87,000	105,000	110,000
Santa Clara	30,000	36,000	45,000	53,000
Solano	2,200	3,300	4,600	5,500
Sonoma	300	410	690	870
Total	**140,000**	**180,000**	**250,000**	**320,000**

3.1.1 Vulnerability and Environmental Justice Concerns

Any analysis of populations affected by sea level rise must include a broader discussion of vulnerability to these events. According to the IPCC, 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).

Based upon a literature review of past flood disasters, we developed a set of key population characteristics that increase vulnerability to the adverse impacts of flood events and disasters (Figure 2). Vulnerability factors include access to preparedness information, transportation, healthcare, and insurance. Key demographics associated with these vulnerabilities include income, race, linguistic isolation, and residential tenure. Our analysis is largely centered on 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.

Adaptation also raises environmental justice concerns. Adapting to sea level rise will require tremendous financial investment, and given the high cost, it is likely that we will not protect everything. 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.

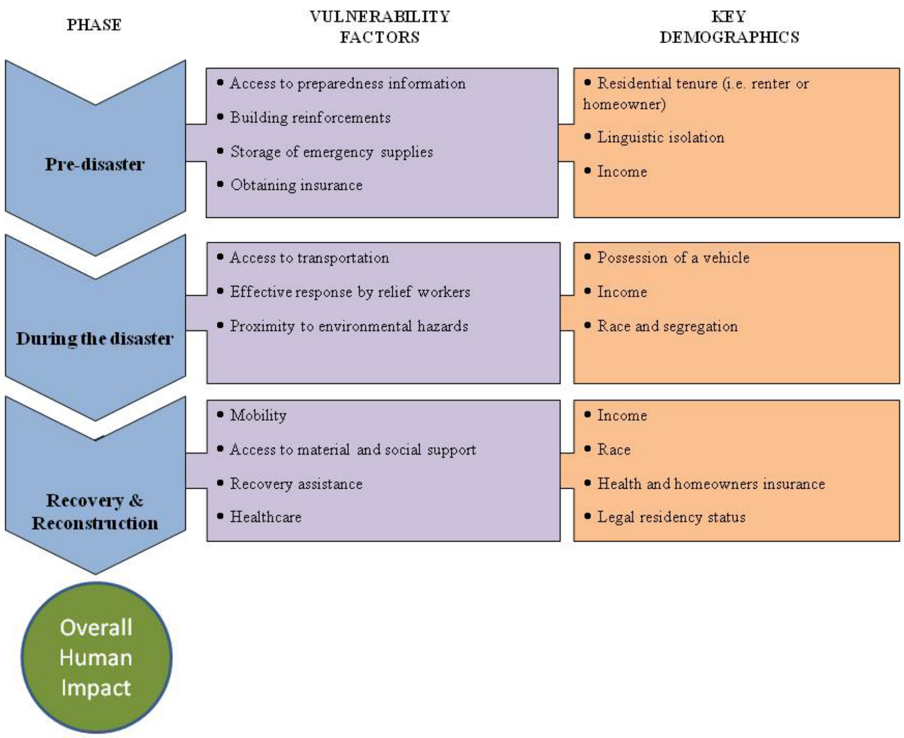

Figure 2. Relationship Between Socio-economic Factors and Vulnerability to Flooding Associated with Sea Level Rise

Table 5 shows the number of people within the areas at risk of a 100-year flood that exhibit vulnerability to these events. Approximately 7,200 people currently at risk of a 100-year flood event live in a household with no vehicle. With projected rise in sea levels of 0.5 m, 1.0 m, and 1.4 m, the population within the areas at risk of flooding with no vehicle increases to 8,500, 9,800, and 10,700, respectively. These individuals 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. In a survey after Hurricane Katrina, 55 percent 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).

Renters are also more vulnerable, as they are less likely to reinforce buildings and buy insurance because the decision to make major home improvements and financial gains typically lies with the property owner. Additionally, disaster recovery services have often targeted homeowners, to the disadvantage of renters and residents of public housing (Pastor et al. 2006). Of the population currently living within the 100-year floodplain, 52,100 (39 percent) live in renter-occupied housing. The renting population at risk increases to 59,400 with 0.5 m rise in sea levels; 67,300 residents with 1.0 m rise; and 72,100 with a 1.4 m rise.

Language ability is 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 percent provided links on their website to translated materials, and only 14 percent 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, 18,000 (7 percent) live in households along the San Francisco Bay that are "linguistically isolated," meaning that no occupant over age 14 speaks English well (Table 11). This represents a 30 percent increase in the population that is currently at risk of a 100-year flood event. These households are the most likely to need preparedness materials and outreach strategies suitable for non-English speakers of various backgrounds.

Table 5. Key Demographics of Populations Vulnerable to a 100-year Flood Event with Sea Level Rise

	Current Risk	Risk with Sea Level Rise		
		0.5 m	1.0 m	1.4 m
Population in linguistically isolated households	13,900 (10%)	15,600 (10%)	17,300 (8%)	18,300 (7%)
Population in households with no vehicle	7,200 (5%)	8,500 (5%)	9,800 (4%)	10,700 (4%)
Population in renter-occupied households	52,100 (39%)	59,400 (37%)	67,300 (31%)	72,100 (27%)
Earn less than 200% of the federal poverty threshold	25,100 (19%)	28,400 (18%)	32,000 (15%)	33,900 (13%)
People of color	66,600 (50%)	75,700 (47%)	85,700 (39%)	91,400 (34%)

Note: Table shows the total number of people within the areas at risk that demonstrate key demographic vulnerabilities, and the percentage these individuals represent of the total population at risk.

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. People of color are less likely to own their homes and less likely to speak English "well" or "well at all" (U.S. Census Bureau 2000). Additionally, the median household income of African American, Latino, and Native households in California was $15,000 less than white and Asian households (U.S. Census Bureau 2000). 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. Along the San Francisco Bay, there are currently 66,600 African-American, Native American, Asian and Pacific Islander, and Latino residents living in areas at risk of a 100-year flood event. With a projected sea level rise of 0.5 m, 1.0 m and 1.4 m, this population at risk increases to 75,700, 85,700, and 91,400, respectively.

3.2 Emergency and Healthcare Facilities at Risk

Table 6 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 m, 1.0 m, and 1.4 m sea level rise. 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 nearly triples, to 42. Flooding at these facilities can be particularly problematic because they often provide emergency response services.

Table 6. Schools and Emergency and Healthcare Facilities along San Francisco Bay that Are at Risk of a 100-year Flood Event in 2000 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.

3.3 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 spread of contamination through floodwaters or through flood-related facility malfunctions. These sites also raise environmental justice concerns because the population living within 3 kilometers (1.8 miles) of a commercial hazardous waste facility is disproportionately composed of people of color, compared to communities without such facilities (Bullard et al. 2007).

We evaluated sites containing hazardous materials at risk of flooding along the San Francisco Bay. An estimated 94 U.S. EPA-regulated sites are currently vulnerable to a 100-year coastal flood event (Table 7). More than 85 percent 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. With a 1.0 m sea level rise, 208 hazardous facilities are at risk of flooding from a 100-year flood event. A 1.4 m sea level rise will increase the number of hazardous facilities at risk to 235. San

Mateo and Santa Clara Counties continue to have a large number of U.S. EPA-regulated sites at risk within future flood areas. While Alameda County currently has a relatively small number of facilities at risk of flooding, a large number of facilities will be at risk with sea level rise.

Table 7. U.S. EPA-Regulated Sites Within Areas Vulnerable to 100-year Flood Event in 2000 and with Sea Level Rise

County	Current Risk	Risk with Sea Level Rise		
		0.5 m	1.0 m	1.4 m
Alameda	6	23	49	63
Contra Costa	4	11	19	22
Marin	1	1	4	6
Napa	1	2	2	2
San Francisco	0	0	4	4
San Mateo	39	54	72	78
Santa Clara	41	46	52	53
Solano	2	4	4	5
Sonoma	0	0	2	2
Total	**94**	**141**	**208**	**235**

Data Source: U.S. EPA Geospatial Data Access Project 2008
Note: Table reports risk along the San Francisco Bay.

3.4 Infrastructure at Risk

3.4.1 Transportation

California's transportation infrastructure is vulnerable to flooding under current conditions, and those risks will be greater in the future due to sea level rise (Tables 8 and 9). Under current conditions, we estimate that 800 miles of roadways and nearly 70 miles of railways along the San Francisco Bay are at risk of a 100-year flood event. A 1.0 m sea level rise will increase the risk of flooding dramatically, with 1,460 miles of roadways and 140 miles of railways at risk of flooding. With a 1.4 m sea level rise, 1,780 miles of roadways and 170 miles of railways will be at risk of flooding, more than doubling the current risk.

Table 8. 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. Results are shown for the San Francisco Bay only. Numbers may not add up due to rounding.

Table 9. Miles of Railways Vulnerable to a 100-year Flood along San Francisco Bay, by County

County	Current Risk	Risk with Sea Level Rise		
		0.5 m	1.0 m	1.4 m
Alameda	9.1	17	35	49
Contra Costa	10	17	25	37
Marin	12	15	16	17
Napa	6.0	7.0	7.9	8.2
San Francisco	0.26	0.56	0.91	1.6
San Mateo	3.7	5.2	7.8	10
Santa Clara	5.9	7.2	8.9	10
Solano	9.3	12	17	21
Sonoma	11	14	17	18
Total	**68**	**94**	**140**	**170**

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 quantify these risks.

3.4.2 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 (MTC) stated that "over 37% of Bay Area economic output is in manufacturing, freight transportation, and warehouse and distribution businesses. Collectively, these goods-movement-dependent businesses spend approximately $6.6 billion 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 shows significant flooding is possible at the Port of Oakland. The San Francisco and Oakland airports are also vulnerable to flooding with sea level rise. In addition to directly affecting port operations, sea level rise may cause other interruptions to goods movement at ports. Sea level rise can reduce bridge clearance, thereby reducing the size of ships able to pass or restricting their movements to times of low tide. Higher seas may cause ships to sit higher in the water, possibly resulting in less efficient port operations (National Research Council 1987). These impacts are highly site specific, and somewhat speculative, requiring detailed local study. 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.

3.4.3 Utilities: Power Plants and Wastewater Treatment Plant

Figure 3 shows coastal power plants along the San Francisco Bay that are vulnerable to a 100-year flood event with sea level rise. In total, six small coastal power plants, with a combined capacity of 370 megawatts (MW), are currently at risk from a 100-year flood. A 1.0 m sea level rise would put nine power plants with a combined capacity of 400 MW at risk of flooding. A 1.4-meter rise in sea levels would increase the number of power plants at risk from a 100-year flood to 15. The total generating capacity of these 15 affected plants is 10,000 MW. The capacities of the vulnerable power plants range from a relatively small 3 MW plant to one with a capacity of 1,310 MW. In some cases, actual power generating infrastructure is at risk; in others, intake or other peripheral structures are vulnerable. Using more accurate data, Sathaye et al. (2012) suggest that 13 power plants within the San Francisco Bay Area will be at risk of a 100-year flood event with a 1.4 m rise in sea levels. New, more accurate data are being developed and should be used to produce site-specific assessments for each coastal plant.

In addition to increasing the risk of flooding, climate change is likely to cause other impacts that will threaten California's energy system. Higher temperatures, for example, may alter the thermal performance of power plants, substations, and transmission lines. Wildfire also threatens transmission infrastructure, resulting in increased maintenance costs and reduced line efficiency. See Sathaye et al. (2012) for a detailed discussion of the impacts of climate change on energy infrastructure.

Figure 3 shows the wastewater treatment plants vulnerable to a 100-year flood event with a 1.4 m sea level rise. We identified one wastewater treatment plant along the San Francisco Bay that is currently at risk of a 100-year flood. Rising seas would put 8 and 10 wastewater treatment plants at risk, with a 1.0-m and 1.4-m rise in sea levels, respectively. Inundation from floods could damage pumps and other equipment, and lead to untreated sewage discharges. Beside 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.

Infrastructure vulnerable to a 100-year coastal flood with a 1.4-meter sea-level rise

Data sources: USGS/Scripps Institution of Oceanography, EPA PCS Database, CaSIL, ESRI.
http://www.pacinst.org/reports/sea_level_rise

PACIFIC INSTITUTE

Figure 3. Wastewater Treatment and Power Plants on the San Francisco Bay Vulnerable to a 100-year Flood with a 1.4 m Sea Level Rise

3.5 Wetlands

Large wetland areas are found in almost every county on the California coast. The vast majority of coastal wetlands are in San Francisco Bay and the Sacramento-San Joaquin Delta. 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 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 areas that will likely provide unsuitable habitat for wetlands in the future due to the presence of buildings and other paved areas. 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 wetlands require approximately 93 square miles of accommodation space, or land into which they must migrate to survive a sea level rise of 1.4 m. Of this amount, 53 square miles, or 57 percent, would make viable wetland habitat (Table 10). These areas should be protected to ensure their viability as wetland habitat is maintained. Nearly five square miles, or 5 percent, is land that is viable for wetland migration but at some loss of value, including parks, orchards, and agricultural land. The remaining 38 percent of the available accommodation space is unsuitable for wetland migration because it is built up; covered with roads, buildings, and pavement.

Figure 4 summarizes the potential wetland migration area by county with a 1.4-meter rise in sea levels. Solano County has the largest wetland migration area, totaling 22 square miles. Under current land uses, we estimate that 85 percent of that area may become suitable wetland habitat. San Francisco County has only small potential for wetland migration areas, in part because there are few wetlands in this county. Unfortunately, those that do exist are at high risk because 70 percent of the potential wetland migration area in San Francisco County is not viable wetland habitat.

Although not included here, sea level rise will also affect California's fish species. Moyle et al. (2012) qualitatively describe potential impacts within the Sacramento-San Joaquin Delta, noting that sea level rise will produce dramatic changes in the flood regime and increase the volume of open, brackish water.

Table 10. 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	11
Medium Intensity Developed	8.2
Low Intensity Developed	16
Subtotal	**35**
Viable for wetland migration, but will cause property loss	
Developed Open Space	3.3
Pasture/Hay	<0.1
Cultivated	1.6
Subtotal	**4.9**
Viable for wetland migration	
Evergreen Forest	0.056
Deciduous Forest	0.0015
Mixed Forest	0.043
Scrub/Shrub	0.26
Grassland	12
Bare Land	0.086
Palustrine Scrub/Shrub Wetland	0.096
Palustrine Forested Wetland	0.030
Palustrine Emergent Wetland	2.7
Estuarine Scrub/Shrub Wetland	34
Estuarine Forested Wetland	0.81
Estuarine Emergent Wetland	0.028
Estuarine Aquatic Bed	-
Unconsolidated Shore	0.35
Water	2.6
Subtotal	**53**
Total	**93**

Note: Numbers may not add up due to rounding.

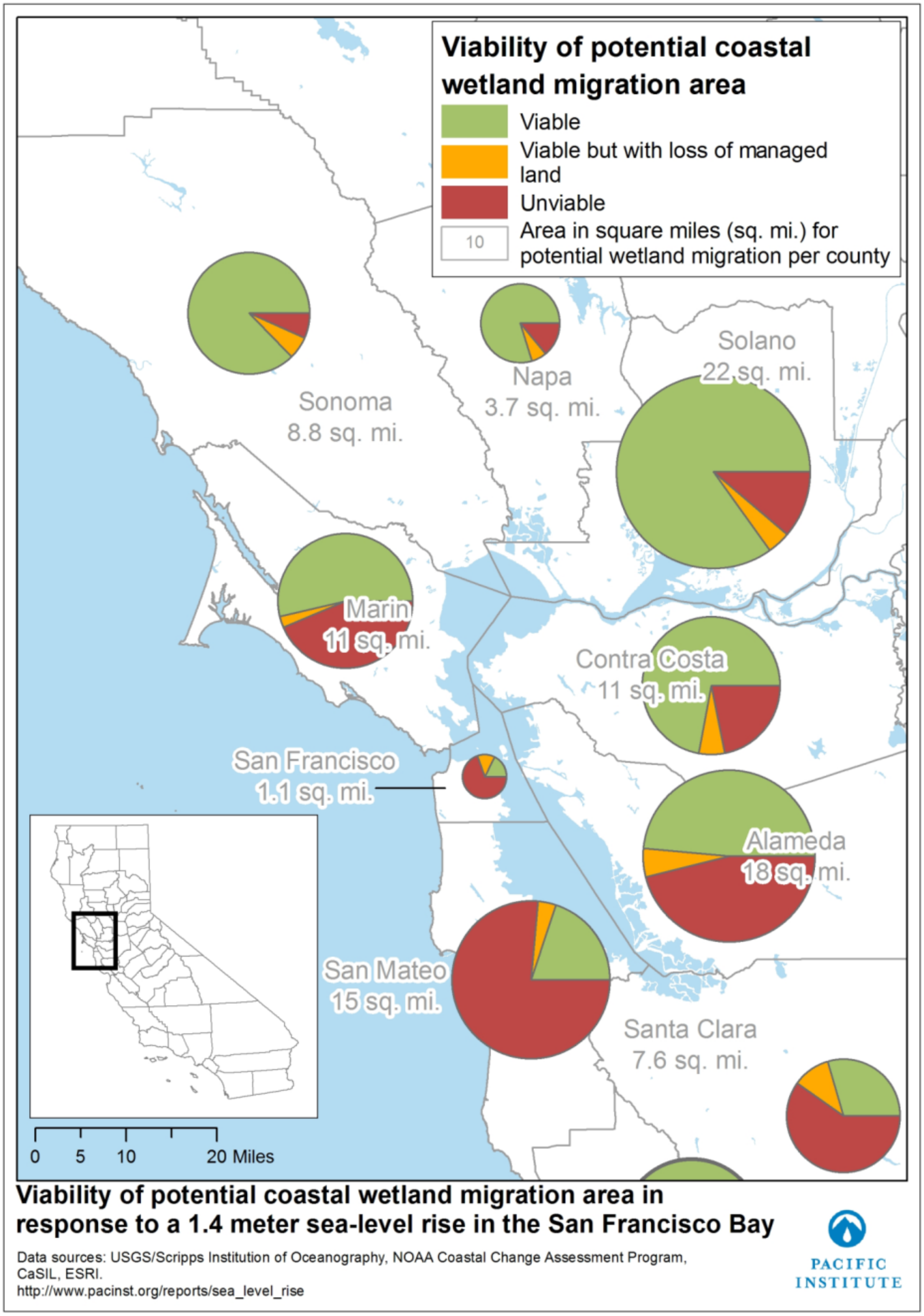

Figure 4. Viability of Potential Coastal Wetland Migration Area in Response to a 1.4 m Sea Level Rise in the San Francisco Bay

3.6 Property at Risk

The value of assets at risk on San Francisco Bay is substantially higher than along the Pacific coast. Table 11 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. Assets at risk during a 100-year flood increase from about $29 billion under current conditions 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 along the San Francisco Bay. San Mateo and Alameda Counties have the greatest assets at risk, accounting for 60 percent to 65 percent 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 11. Replacement 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	Current Risk	Risk with Sea Level Rise		
		0.5 m	**1.0 m**	**1.4 m**
Alameda	3,300	5,300	10,000	15,000
Contra Costa	190	330	620	980
Marin	4,700	5,900	7,400	8,500
Napa	220	260	320	410
San Francisco	110	370	1,400	4,000
San Mateo	16,000	18,000	21,000	23,000
Santa Clara	3,700	4,700	6,400	7,800
Solano	620	940	1,400	1,900
Sonoma	150	180	240	280
Total	**29,000**	**36,000**	**49,000**	**62,000**

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

The residential sector on San Francisco Bay faces the greatest risk. Figure 5 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 3.4). Of the $62 billion of property at risk with a 1.4 m sea level rise, about 50 percent of the assets at risk are residential. Risk for the commercial and industrial sectors is also high. Agriculture, education, religion, and government each account for about 1 percent of the assets at risk, thus their exposure to risk is fairly small.

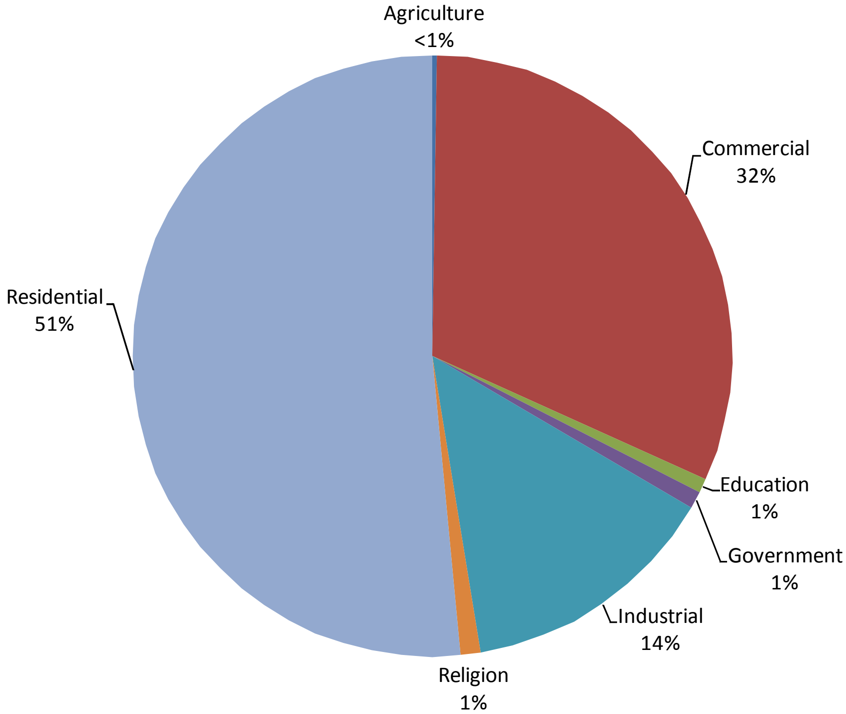

Figure 5. Percent Replacement Value of Buildings and Contents at Risk of a 100-year Flood with a 1.4 m Sea Level Rise on San Francisco Bay, by Major Economic Sector

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 into the ocean. 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.

We estimate that sea level rise will put 220,000 and 270,000 people at risk of a 100-year flood event with a 1.0 m and 1.4 m rise in sea levels, respectively. 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, $49 billion to $62 billion (in year 2000 dollars) worth of property is at risk of coastal flooding with a 1.0 and 1.4 m rise in sea levels, respectively. A number of structural and non-structural policies and actions could be implemented to reduce these risks. Continued development in vulnerable areas will put additional people and 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.

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 is 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) 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.

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Glossary

CASCaDE	Computational Assessments of Scenarios of Change for the Delta Ecosystem
FEMA	Federal Emergency Management Agency
GIS	geographic information system
IPCC	Intergovernmental Panel on Climate Change
LIDAR	Light Detection And Ranging
MTC	Metropolitan Transportation Commission
MW	megawatts
NOAA	National Oceanic and Atmospheric Administration
NPDES	National Pollutant Discharge Elimination System
PCS	Permit Compliance System
PIER	Public Interest Energy Research
UC	University of California
USGS	United States Geological Survey
U.S. EPA	United States Environmental Protection Agency
WCED	World Commission on Environment and Development