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Assessing the Costs of Adapting to Sea Level Rise

A Case Study of San Francisco Bay

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Pacific Institute for Studies in Development, Environment and Security

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ASSESSING THE COSTS OF ADAPTING TO SEA-LEVEL RISE
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EXECUTIVE SUMMARY

Atmospheric concentrations of carbon dioxide (CO_2), methane (CH_4), nitrous oxide (N_2O), tropospheric ozone (O_3), chlorofluorocarbons (CFCs), and other trace gases are growing due to human activities. These trace gases are transparent to incoming solar radiation and trap outgoing infrared (heat) radiation, acting like a blanket to warm the Earth. Without any of these gases in the atmosphere, the surface of the Earth would be about 35 $^{\circ}$C (70 $^{\circ}$F) colder than at present, and life, if any could exist, would be quite different. This natural greenhouse effect is being intensified by human activities that accelerate the emission of these trace gases, such as the combustion of fossil fuels and deforestation.

One of the direct consequences of climatic changes will be a rise in sea level due to the melting of land ice and the expansion of the upper layers of the ocean as they warm. This study presents a method for assessing the costs to society of protecting against an increase in sea level, and applies this method to the San Francisco Bay area -- a region of great ecological diversity, economic importance, and vulnerability. Hydrodynamic effects around the margin of San Francisco Bay are evaluated, structural options for protecting property are identified and chosen for threatened areas, and estimates of costs of protection are determined. For the purposes of this study, a one-meter sea-level rise was assumed, and all development below the future 100-year high tide elevation in San Francisco Bay was considered to be at risk. The types of shoreline protection proposed include constructing new levees and seawalls, raising existing levees and bulkheads, raising buildings, freeways and railroads where necessary, and replenishing beaches. The costs described here are not the total costs of protection -- for example, no estimates are available for evaluating costs of protecting natural ecosystems. Other costs left out are described in detail in the text.

Any economic estimates of the costs to society of the impacts of climatic change or the costs of adapting to such changes must be regarded with caution. The actual costs will depend on the speed and amount of rise, societal choices about what to protect and what to abandon, the form of existing protection, the lifetime of that protection, who will pay (federal, state, or local governments, corporations, private individuals), and a wide range of unquantified or unquantifiable variables -- many impacts can not be compared using standard economic measures.

The risks of global climate change and the impacts faced by society are uncertain. There are uncertainties about future emissions of greenhouse gases, about how the climate will respond to those gases, and about the many impacts to society. These uncertainties will greatly complicate policy responses, but they should not be used as an excuse for inaction. This report tackles one small piece of the problem: how can we evaluate the costs of protecting a particular region against future sea-level rise, and what policy responses might be appropriate. Many uncertainties remain, but the magnitude of the problems of climate change and sea-level rise requires that we begin to understand the threats that we face and the responses available to us.

GENERAL CONCLUSIONS

- Absolute sea level has risen 0.1 to 0.15 meters (4 to 6 inches) in the last century -- an average rate of 1.0 to 1.5 millimeters per year (mm/yr). The local rate of increase in some regions has been greater due to local land subsidence.

- The magnitude of the observed rise is consistent with the changes expected from increases in atmospheric trace gases and the greenhouse effect, but it is not yet possible to unambiguously attribute this rise to the greenhouse effect.

- Plausible projections of the magnitude of future sea-level rise due to the greenhouse effect range from 0.5 meters to over 3.0 meters (20 to 120 inches) by 2100. The frequency of damaging storms will increase long before these much higher levels are reached.

- Projections of the **rate** of future sea-level rise over the next century range from 7 to 50 mm per year (0.3 to 2 inches per year), substantially above the historical rates of the last century. This rate is expected to increase exponentially if no efforts are made to reduce greenhouse gas emissions.

- Such a sea-level rise will inundate developed and natural areas, accelerate coastal erosion, cause salinity contamination of groundwater aquifers and rivers, damage port facilities, erode recreational beaches, and disrupt wetlands and natural habitats.

- The cost of protecting against sea-level rise is large, but often below the value of the property protected. Defensive actions taken today can prevent large damages in the future.

- Many of the economic impacts of sea-level rise are not yet adequately quantified; **some of the impacts of sea-level rise may never be quantifiable.** These include the societal changes needed for coastal response, the social costs of migration away from affected areas, the psychological pressures of living behind coastal protection in threatened areas, the value of lost or altered ecosystem services, and the risks of international or inter-regional conflicts.

- The initially slow rate of increase of sea level will complicate political and economic responses. No advanced planning, or inadequate response, will be followed by a set of severe, damaging flood events.

<u>A CASE STUDY OF SAN FRANCISCO BAY: CONCLUSIONS</u>

- **The value of property threatened by sea-level rise in San Francisco Bay is extremely high because of past development.** Around the perimeter of the Bay, existing commercial, residential, and industrial structures threatened by a one-meter (3.3 foot) sea-level rise is valued at $48 billion.

- **Major damaging storms will occur more frequently in San Francisco Bay due to a sea-level rise.** This increase will occur long before sea level rises one meter. A sea-level rise of only 15 centimeters (5.9 inches) will change the frequency of the 1-in-100 year storm into a 1-in-10 year storm at the entrance to the Bay.

- **The cost of protecting just existing development from a one-meter (3.3 foot) sea-level rise by building new defenses or modifying existing protection around San Francisco Bay**

will exceed $940 million (in 1990 dollars), not including the costs of protecting or restoring wetlands, or the need for any active structures such as pumps, drainage systems, and navigation locks. These costs could exceed an additional one billion dollars. The costs of maintenance for these defenses are also not included and could approach $100 million per year.

- **We think it unlikely that the status quo around the Bay can be maintained under conditions of expected sea-level rise**, even with extensive efforts to build protective structures. Indeed, implementing all of the measures evaluated here would, by themselves, change the character of the Bay.

- **Loss of some of the remaining natural wetlands in San Francisco Bay appears inevitable.** In particular, large tracts of wetlands in the northern stretches of the Bay will be impossible to maintain in their present form, and intertidal wetland habitat in the southern stretches of the Bay may be lost entirely. Options include providing some artificial protection, which converts natural ecosystems into partially managed ecosystems; trying to restore wetlands on adjacent, higher, undeveloped land; or abandoning existing wetlands to try to adapt through natural processes.

- **Deterioration of groundwater quality in some basins around the Bay will accelerate as sea level rises.** No way to prevent this deterioration, other than by preventing sea-level rise, was identified.

- **Given the uncertainties about the magnitude and rate of future sea-level rise, there is a**

value in attempting to slow the rate of rise. The slower the rate of sea-level rise, the more time to plan (and pay for) appropriate responses.

- **Sufficient money or political consensus is unlikely to be made available to protect all resources on the margins of the Bay before damaging storm events occur.** As a result, difficult decisions about what to move or abandon will have to be made, and damages from flooding will increase.

- **Substantial additional -- and unpredictable -- changes in the biological and chemical nature of the Bay region are likely** due to changes in freshwater inflow to the Bay, new development, changes in water and ecosystem management in the Delta, and other effects that cannot now be anticipated. All of these additional effects are beyond the scope of the present study.

RECOMMENDATIONS

1. Future development should be prohibited in waterfront areas likely to be subjected to higher sea level. The cheapest option to protect against future sea-level rise is to prohibit development in regions that are likely to be subjected to the greater future risk of flooding.

2. Future development should be prohibited on natural lands immediately upslope of or adjacent to existing wetlands. These buffer lands may be the only areas to which present wetlands can slowly migrate, and future wetlands restoration projects will require this land.

3. All present activities to construct, maintain, or modify any structure likely to be affected by sea-level rise should assume a future increase in that level. The cost of modifying these structures in the design stage is considerably below the costs of both later reconstruction and flood-damage from unanticipated storm surges. Modification in the design stage can include either the capacity to accommodate higher sea levels or provisions for future retrofitting.

4. Natural ecosystems are undervalued or ignored in traditional economic analyses. A method for incorporating them into future studies is needed. Large tracts of wetlands, such as those in the San Francisco Bay, 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.

5. Detailed surveys of the economic value of land and services at risk in specific regions should be done. The study here provides initial estimates of the costs of adapting to a one-meter sea-level rise, but not the long-term value of property threatened. Such additional information is required for appropriate public policy decisions to be made.

6. Existing flood insurance programs should be modified or phased out in areas likely to be subjected to future flooding caused by sea-level rise.

7. Detailed regional responses are needed. The effects of sea-level rise in one area will have spill-over effects in other areas. Coordinated regional strategies will be necessary to

account for these effects. For example, intrusion of salt water into groundwater aquifers will require the development of alternative fresh water supplies. In regions such as California, alternative fresh water resources may not be readily available at reasonable economic or environmental cost.

8. Additional research on the physical and environmental effects of sea-level rise is needed on a regional basis. More case studies to identify specific effects of a rising sea-level are needed. No general analysis can replace individual regional studies.

PART 1: ASSESSING THE COSTS OF ADAPTING TO SEA-LEVEL RISE

I. INTRODUCTION

Atmospheric concentrations of carbon dioxide (CO_2), methane (CH_4), nitrous oxide (N_2O), tropospheric ozone (O_3), chlorofluorocarbons (CFCs), and other trace gases are growing due to human activities. These trace gases are transparent to incoming solar radiation and trap outgoing infrared (heat) radiation, acting like a blanket to warm the Earth. Without any of these gases in the atmosphere, the surface of the Earth would be about 35 $^{\circ}C$ colder than at present, and life, if any could exist, would be quite different. This natural greenhouse effect is being intensified by human activities that accelerate the emission of these trace gases, such as the combustion of fossil fuels and deforestation.

The growing concern over the societal consequences of large-scale climate changes has led policy-makers to consider two possible responses. The first is to try to reduce the emissions of greenhouse gases. The second is to evaluate the likely impacts to society of possible climate changes and to try to mitigate the worst of them and adapt to the rest.[1] These two responses, often referred to as **prevention** and **adaptation**, are not mutually exclusive. Indeed, it is often argued that "prevention" is a misnomer and that some climate changes are inevitable due to the concentrations of greenhouse gases already emitted and the tremendous inertia in the way society produces and uses energy. As a result, attention is increasingly focusing on evaluating the impacts to society of climate changes and the methods and costs of reducing those impacts.

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[1] The issues raised by these two different responses are discussed in many detailed assessments. Two comprehensive analyses of both greenhouse gas emissions reductions and the impacts of climate change were recently completed by the U.S. Environmental Protection Agency (U.S. EPA 1989a, 1989b). See also Bolin et al. (1986) and Berger et al. (1989).

This study is presented in two sections: in Part 1, a method for assessing the costs to society of protecting against an increase in sea level is developed and presented. Coastal protection strategies and costs are reviewed and the limitations of economic analyses summarized. In Part 2, the method developed in Part 1 is applied to the San Francisco Bay area -- a region of great economic importance and vulnerability.

Any economic estimates of the costs to society of the impacts of climatic change or the costs of adapting to such changes must be regarded with caution. The actual costs will depend on the speed and amount of rise, societal choices about what to protect and what to abandon, the form of existing protection, the lifetime of that protection, who will pay (federal, state, or local governments, corporations, private individuals), and a wide range of unquantified or unquantifiable variables -- many impacts can not be compared using standard economic measures. These problems are discussed in Section V.

II. FUTURE CLIMATE CHANGE AND PROJECTIONS OF SEA-LEVEL RISE

The most widely discussed implication of the greenhouse effect is a rise in the average temperature of the Earth. The best estimates now available suggest that a doubling of the atmospheric concentration of carbon dioxide could lead to an average increase in the Earth's temperature of between 1.5 and 4.5° Celsius (C) (Dickinson 1989). Maximum warming is expected in winter and in the higher latitudes. The precise timing of this warming is uncertain, largely because of the role of the oceans in absorbing trace gases and cycling heat. If only the upper layer of the oceans is affected, global warming will be relatively rapid; if the entire ocean depth is affected, a lag in warming of as much as a century may be possible as much of the additional heat goes into the oceans instead of the atmosphere.

Other uncertainties that can worsen or lessen the magnitude and rate of climate change include the effects of clouds, which are poorly parameterized in the climate models, and other physical feedbacks. Clouds can either slow the warming by reflecting sunlight away from the earth or increase it by trapping additional heat. The net effect of clouds depends on cloud type, location, and behavior. Other feedbacks include the possible sudden release of large volumes of methane frozen in high-latitude regions, changes in ocean circulation patterns and the distribution of heat from one region of the world to another, and chemical interactions within the atmosphere that could alter the sinks for many greenhouse gases.

One of the most widely recognized effects of global climatic changes will be a rise in sea level due to the thermal expansion of the oceans and increased melting from land ice. Heat trapped by greenhouse gases will raise the temperature of the atmosphere and oceans, which in turn will affect sea level. If the oceans absorb the increased heat slowly, higher air temperatures will quickly melt land ice. If the oceans rapidly absorb the excess heat, sea level will rise more rapidly due to thermal expansion. If precipitation in high latitudes increases, snow buildup in Greenland and Antarctica may slow the rate of sea-level rise. At present we cannot accurately determine how the oceans will react, even for well-defined rates of greenhouse gas emissions, and we cannot therefore accurately predict future climate or sea level (Thomas 1986). Nevertheless, we can estimate plausible rates of rise by evaluating a wide range of climate scenarios.

Table I and Figure 1 show some of the most recent projections for sea-level rise. This paper is not the place to resolve the uncertainties in these projections. The assumptions and uncertainties involved in this study are explicitly set out in the methodology section, but it is our belief that the uncertainties about human actions and conditions over the next decade far exceed the uncertainties about future sea level.

Table I Scenarios of Future Sea Level Rise: Magnitude and Rate

Magnitude of Rise
(millimeters above 1980 levels)

Scenario	2000	2025	2050	2075	2100
Conservative	50	130	240	380	560
Mid-Low	90	260	520	910	1440
Mid-High	130	390	790	1370	2170
High	170	550	1170	2130	3450

Rate of rise (mm/year)

Scenario	1980-2000	2000-2025	2025-2050	2050-2075	2075-2100
Conservative	2	3	4	6	7
Mid-Low	4	7	10	16	21
Mid-High	7	10	16	23	32
High	9	15	25	38	53

(All data rounded to integers.)

Source: U.S. EPA (1983).

Local sea-level changes are experienced as a combination of the change in global sea level and any local vertical land movement. A land-subsidence rate combined with a constant sea level results in the appearance of a relative sea-level rise. An increase in absolute sea level combined with an increase in land heights due to isostatic uplift (for example, the slow rising of the earth rebounding from the weight of past glaciers) can lead to the appearance of little or no relative change in sea level. The following paragraphs discuss the global (absolute or "eustatic") rate of sea-level rise. Where specific impacts of sea-level rise are discussed, or where examples of impacts on a particular region are presented (e.g. the case study of San Francisco Bay), "sea-level rise" refers to the locally experienced relative rise.

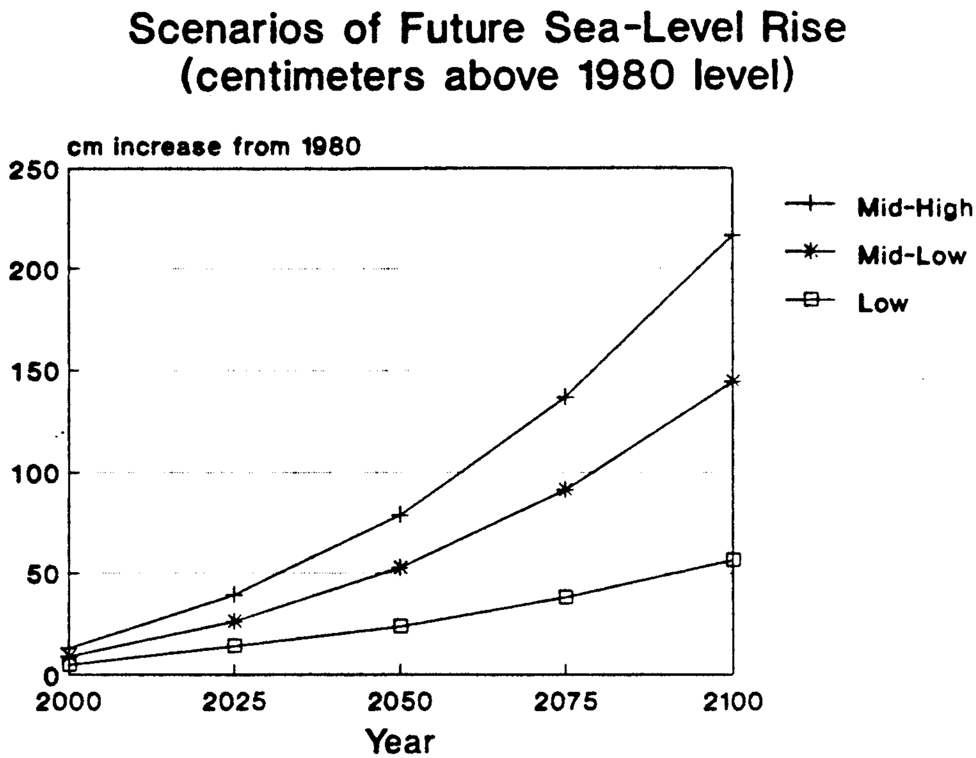
Estimates of rates of change in sea-level over the last century range from 1 to 3 mm/yr, with most recent and detailed evaluations centering on an increase of 1 to 1.2 mm/year (Barnett 1983, Gornitz and Lebedeff 1987, Woodworth 1987). This increase is attributed to thermal expansion of a warming ocean (Gornitz et al. 1982), melting of ice (Etkins and Epstein 1982, Meier 1984), and coastal subsidence (Pirazolli 1986). The current consensus is that this increase can be explained by both melting of land ice and thermal expansion (Thomas 1986, Wind 1987).

There is now some evidence that the rate of sea-level rise is increasing; in the last 50 years, the rate of global sea-level rise has increased by 0.6 mm/year--nearly double the previous rate (Gornitz and Lebedeff 1987). It is tempting to ask whether this recent increase is an indication of global warming, and some analysts have correlated global sea-level rise with global temperature. While this increase is consistent with the projected sea-level rise due to thermal expansion of the surface waters of the oceans and net melting of land ice associated with the greenhouse effect, it is not yet possible to unambiguously attribute the observed sea-level rise with global warming. If climate change projections are correct, this trend can be expected to continue.

The future increase in the rate of sea-level rise is expected to be very slow for the next few decades, contributing to policy confusion over the proper response. This increase will probably not be unambiguously detected until 2020 or later (Thomas 1986). The rate of rise will increase progressively, however, leading to more rapidly rising sea level toward the middle of the 21st century. While this gives us time to develop appropriate policy responses, it also may

permit policy makers to become complacent about the problem, which could lead to extensive and expensive development in coastal regions that should be protected or left undeveloped.

Figure 1 **Projections of Future Sea-Level Rise**



Source: U.S. EPA (1983)

III. PREVIOUS REGIONAL CASE STUDIES

Numerous studies have been done of the impacts of sea-level rise on different regions of the world, and many more are underway. These studies use a variety of approaches and methods for analyzing the regional effects of a range of increases in sea level. Some insights into methods for analysis can be gained by reviewing these approaches. Several general assessments and discussions of impacts also provide good background for this problem (see, especially, Vellinga and Leatherman 1989, Wind 1987, Barth and Titus 1984, National Research Council 1987)

Kyper and Sorensen (1985) look at the physical effects of sea-level rise on a section of shoreline in New Jersey, United States. They limit themselves to evaluating beach erosion rates, shoreline recession, and flooding probabilities under new, higher sea levels. This information is then used to evaluate possible structural responses. No discussion of economic costs is included. Titus (1985) presents a similar study for Ocean City, Maryland that includes a brief discussion of the costs of maintaining the beachfront.

Several detailed studies on the effects of sea-level rise on Bangladesh have been done (see, for example, Broadus et al. 1986, Mahtab 1989), though no economic analyses have yet been done. Mahtab (1989) describes in great detail the physical environment, the agricultural system, and the vulnerability of Bangladesh to climatic changes. Responses to rising sea level include extensive embankments or levees along the coast and rivers, an increase in fresh water releases from reservoirs upstream to reduce the penetration of salt water into the Ganges delta, and the development of disaster response plans.

A similar study was done for the Republic of Maldives -- a chain of coral atolls in the Indian Ocean (Edwards 1989). The study focused on identifying the greatest risks to the Maldives from plausible sea-level rise scenarios. Recommendations for future research are included, but no discussion of economic risks or benefits is presented.

Early efforts to protect populations from coastal flooding can be traced back to the 3rd century B.C. in what is now the Netherlands. At that time, dikes and elevated developments and roads were built (Goemans 1986). By the 1200s, active programs were underway to reclaim land from the sea and defend land from damaging storms. Today, if the country were not protected from the sea, more than 50 percent of the land area would be underwater--a region holding 8 million people.

In response to damaging storms, the Dutch have embarked on a massive program of building sea defenses. In those regions with high economic value, such as the central part of the country with major industrial and agricultural areas and high populations, protection was considered essential. Among the problems the Dutch face is how to choose the level of protection, given storm surges, wave runup, wind effects, sea-level rise, and land subsidence. For example, a dike that has to resist a water level of +5 meters must be much higher than 5 meters. The final report of the Dutch committee to review the 1953 flood disaster concluded that to protect against a 5-meter storm surge would require a dike over 15 meters high (Goemans 1986). The Netherlands presently has about 400 kilometers (km) (250 miles) of sea dikes and 200 km (125 miles) of dunes, which require an annual maintenance cost of approximately $35 million.

All previous protection strategies in the Netherlands have focused on the present threat. To protect against a future sea-level rise will require substantial additional economic outlays. In a simple calculation, Goemans (1986) estimates that a 1.0-meter (3.3 feet) rise would require $4.4 billion over current planned outlays; a 2.0 meter (6.6 feet) rise would require $8.8 billion. About 60% of these expenditures would go to dikes and dunes, 30% for water management, and 10% to rivers and ports.

Perhaps the most detailed attempt to evaluate the costs of protecting against sea-level rise was done by Weggel and others (1988) for the United States Environmental Protection Agency. In this study the effects of sea-level rise were evaluated for six diverse sites in the United States. The costs were determined based on the assumptions that low-lying areas with little development would be abandoned, structures would be raised where appropriate, some structures would be moved to higher elevations, and other economically valuable areas would be protected with dikes, drainage facilities, and pumps. Unit costs for each response were developed using standard engineering designs. After the costs for the six index sites were determined, total costs for protecting the entire U.S. shoreline were calculated by extrapolating.

While this approach has advantages for evaluating regional costs, small errors introduced into calculating the costs at the index sites have the potential to lead to enormous errors during the extrapolation to the entire U.S. coast. Indeed, one of the index sites of this EPA study is within the case study area for the current project, and it appears that Weggel et al. (1988) greatly underestimated the costs of protection by incorrectly measuring the shoreline lengths needing protection.

In another study done for the U.S. EPA (1989a), Yohe (1988) developed a methodology for evaluating the cost of threatened resources. The three areas of focus are: the value of threatened structures; the value of threatened property; and the social value of the threatened coastline. This analysis is limited to developed areas, without consideration of ecosystems, wetlands, and indirect social costs such as the cost of relocation or the risks of environmental refugees -- people forced to flee a country or region for environmental reasons.

Titus et al. (1987) summarize many recent studies on the effects of sea-level rise on coastal drainage systems. Responses include retrofitting existing systems, improving gravity drainage systems to include pumping, and adapting to increased flooding. The specific case studies of LaRoche and Webb (1987) and Waddell and Blaylock (1987) include estimates of costs associated with different scenarios. LaRoche and Webb (1987) conclude that incorporating sea-level rise into current designs is considerably less expensive than retrofitting systems in the future. Waddell and Blaylock (1987) conclude that the appropriate response depends on the watershed of interest, the characteristics and adequacy of the existing systems, and the sea-level rise scenarios assumed.

Day (1987) evaluates the response of the Mississippi Delta to relative sea-level rise -- in this case due to land subsidence rather than a rise in absolute sea level. Several insights are gained into the impacts of sea-level rise on natural and social systems, including details on the deterioration of wetlands, saltwater intrusion, and disruption of sedimentation patterns. Although important implications for institutions are outlined, no evaluation of the costs of responses is included.

The Charleston, South Carolina area is examined by Gibbs (1986). The study evaluates the economic impact of various sea-level rise scenarios depending on when different responses are implemented. Uncertainties in predicting government and individual responses are emphasized. Reducing this uncertainty, as well as uncertainties about the rate and level of sea-level rise, is shown to be crucial to the evaluation of response options. Gibbs' approach is applicable for regions where good estimates of economic activities and values of threatened areas are available.

Several studies have been done for San Francisco Bay area. In one of the earliest studies, Williams (1985) provides a good summary of the types of impacts to expect from sea-level rise. This report outlines areas of vulnerability and issues of critical importance, although no cost analysis is provided. This work was expanded in 1988 to look in detail at the impacts of climate change on the Sacramento/San Joaquin Delta and water quality in San Francisco Bay. Among the most important findings were dramatic effects on the volume and area of the Delta assuming both the protection and loss of the levee system, and the need for large volumes of "carriage water" -- freshwater released from upstream reservoirs -- to maintain water quality in the Bay (Williams 1988).

Also in 1988, the San Francisco BCDC (1988a) summarized the expected impacts of sea-level rise in San Francisco Bay and made recommendations affecting wetlands and general planning along Bay shorelines. Although a summary of predictions of accelerated sea-level rise was provided, no rise over the historical rate was considered and no estimate of the costs to the region was included.

The California Coastal Commission (1989) prepared a comprehensive draft report summarizing possible effects of sea-level rise along the entire California coast. Included are estimates of the magnitudes of various effects for different regions along the coast, as well as the relative economic loss for the regions. No actual dollar figures were provided.

One detailed study for a site in San Francisco Bay was conducted by URS (1988). The town of Corte Madera is presently threatened by storms, and requested a study of alternative flood protection alternatives. Included in the analysis is consideration of a scenario of sea-level rise and the costs associated with incorporating the ability to retrofit protection into designs.

IV. METHODS FOR ANALYZING THE COSTS OF RESPONDING TO SEA-LEVEL RISE

There are four steps to analyzing the costs of protecting against a given sea-level rise for any region:

1. Determine the physical and hydrodynamic effects.

A wide variety of physical and hydrodynamic effects will accompany a rise in sea level, including changes in tidal ranges to which a shore is exposed, changes in currents, changes in wave heights generated by winds, and the rise in water level associated with storm surge. Each of these factors should be considered when evaluating the implications of climate change for coastal developments. Other factors may impact the water quality of estuaries, particularly changes in currents and greater upstream progression of the salt water-fresh water interface.

2. Identify the societal resources threatened by the physical and hydrodynamic effects.

In any given area, many different types of resources would be threatened by rising oceans. There could be transportation facilities such as roadways, bridges, and subways, electric utility systems, storm and sanitary sewers, sewage treatment plants, harbors, groundwater supplies, wetlands, fisheries, species habitats, coastal vegetation, and many other human and natural systems. Evaluating the resources at risk in a region is a prerequisite to choosing the appropriate response and level of protection.

3. Determine the protective responses appropriate for the region.

There are many possible structural responses to sea-level rise, including building or improving coastal defenses such as dikes and dunes, seawalls, bulkheads, beach nourishment, and other structures. Non-structural responses include abandoning property and land and moving to less threatened areas. 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. The costs of different responses can also be determined given local circumstances.

4. **Choose a level of protection for threatened resources given economic and societal values.**

Each of the resources and facilities identified in (3) can be protected by some combination of the alternatives identified in (2). 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 numerous political and societal factors. Physical and hydrodynamic effects may, in turn, change with the level and type of protection chosen. They should be periodically re-evaluated. The effects of sea-level rise, responses, and threatened resources must all be evaluated at a local level, but broader regional effects must be incorporated into final protection strategies.

IV.1. PHYSICAL AND HYDRODYNAMIC EFFECTS OF SEA-LEVEL RISE

Various physical and hydrodynamic effects will accompany a rise in sea level. These include changes in tidal ranges, changes in currents, changes in wind-driven wave heights, and the rise in water level associated with storm surge. Each of these factors plays a role in determining the implications of climate change for coastal developments.

As a first estimate of the impact of sea-level rise on a region, a direct increase in the mean sea level equal to the rise can be assumed. The greater area submerged by the greater depth of water can then be estimated based on the regional topography.

The "drowned-valley" concept may be used to estimate the shoreline profile where the coast can be considered nonerodible or where wave action is limited. The area inundated is estimated using current topographical information with the assumed sea-level rise. Slope is the controlling variable with steep-sloped areas experiencing little horizontal shoreline displacement with water level rise, while gently-sloping shores undergo much greater flooding for a given sea-level rise (National Research Council, 1987).

Where the coast erodes easily, sea-level rise will lead to shoreline recession in addition to general inundation. The amount of erosion can be estimated by several methods. Because of the generally concave-upward slope of a shoreline of sand material, a rise in sea level results in wave energy being dissipated in a smaller area. This causes more turbulence in the surf zone and an increase in the rate of sediment transport. The extent of the shoreline retreat due to this process can be estimated using the so-called Bruun rule, a dynamic-equilibrium model, or a historical-trend analysis.

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 a 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, a rough estimate of the shoreline recession due to readjustment of the beach profile to an equilibrium state is 1.0 to 1.5 meter of shore recession per centimeter of sea-level rise.

Despite its widespread application, many problems exist with the Bruun rule. 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 (a condition difficult to confirm at any site). Another problem is that this approach always predicts shoreline recession with offshore sediment transport as sea level rises. There are several cases cited (National Research Council 1989) where during a rise in sea level shorelines have accreted due to 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 overestimate or underestimate the future recession.

More specific methods are possible for particular sites, and should be conducted to better evaluate the impact of sea-level rise on a region. One possibility is a sediment-budget approach such as that developed by Everts (1985). This extends the Bruun rule to account for changes in sand volume along a shoreline reach. The dynamic-equilibrium model uses a similar concept, but includes a numerical estimate of the dynamic response of the shoreline due to short-term events, such as storms. A historical-trend analysis incorporates the development of a relationship of shoreline response over time based on historical data. These are useful where a local sediment budget is difficult to quantify (U.S. Department of Energy, 1988). Dean (1990) presents a method for evaluating shoreline erosion (and subsequent nourishment requirements) in the presence of onshore sediment transport, and a model is presented that may assist in evaluating the vulnerability of various shoreline systems to increased rates of sea-level rise.

Tidal Ranges

In addition to the rise in mean sea-level discussed above, the tidal range (the difference between mean high and low tides) will be affected by the change in water level. Two different types of systems are discussed here to demonstrate the effects of sea-level rise on tidal ranges: friction-dominated systems and resonance-dominated systems.

For an estuary that can be considered infinitely long (i.e. the amplitude of the incoming tide wave is not significantly affected by wave reflections from a closed end), the system can be considered as friction dominated. In a friction-dominated system, a rise in sea level results in deeper water and a reduction in the effect of bottom friction. When the system is friction dominated, the principal wave form is progressive, and the effect of bottom friction decreases as the tide wave progresses. The ratio of tidal frequency to natural frequency is very small for this type of system. The effect of sea-level rise on the tidal range of a progressive wave is depth dependent, varying with depth to the minus one-third power (U.S. Department of Energy, 1988):

$$Range_{new} = [Depth_{new}/Depth_{old}]^{1/3} * Range_{old}$$

For an estuary that is closed at one end, reflection of the advancing progressive tide wave occurs at the closed end. As the frequency of the tide wave approaches a natural frequency of the system, resonance occurs that amplifies the tidal range toward the closed end, and the system can be considered resonance-dominated. As mentioned by Ippen (1966), of greatest interest in practice are cases of channel length approximating one quarter wavelength.

Sea-level rise can result in either an increase or a decrease in tidal range in such resonance-dominated systems. For instance, an increase in water depth can increase the wavelength of the natural frequency, shifting the system to a less resonant condition. This will have the effect of decreasing the tidal range observed at the closed end of the basin. The ratio, R of the amplitude at the closed end to the amplitude at the mouth (for a frictionless channel of length L^*) is:

$$R = 1/[\cos(2\pi L^*/L)].$$

As a ratio of L^*/L approaches 0.25 the above ratio increases, simulating the amplification effect. As the ratio of the length of the channel, L^*, to the length of the tide wave, L, becomes very small, i.e. approaches zero, the ratio approaches unity. The assumptions that bottom friction can be neglected and that complete wave reflection occurs at the closed end interfere with applying this relationship to a natural system. Adapting a relationship given in Ippen (1966), the ratio, R can be expressed:

$$R = 1/[0.5(\cos 2kL^* + \cosh 2\_L^*)]^{0.5}$$

or $$R = 1/[0.5(\cos 4\pi L^*/L + \cosh 2\_L^*)]^{0.5}$$

where k is the wave number = $2\pi/L$, and _ is a damping coefficient. This allows the inclusion of both the damping of the tide wave, and the change in the length of the wave due to the increase in water depth associated with sea-level rise.

Storm Surge

Storm-surge level is the response of mean water level to high winds, pressure differentials, and rainfall associated with storms. Storm surge is a function of water depth; as such it will be affected by a rise in long-term sea level. For the situation where the continental shelf is uniform in depth, the storm-surge level will decrease with an increase in water depth. This is also the case where the shoreline is fixed, since set-up is inversely related to water depth.

For steady-state conditions, the storm-surge height (amplitude) at the shoreline for the case of a uniform depth of the continental shelf is:

$$H = (h_0^2 + 2*B*x)^{0.5} - h_0$$

where h_0 is the original water depth, x is the distance from the shoreline to the edge of the continental shelf, and B is a factor that includes the wind-induced shear stress. The derivative of this with respect to h_0 gives a result that is always negative, indicating that sea-level rise will result in a decreased wind-induced storm-surge height.

For geometries other than a uniform shelf depth, such as a uniform slope of the continental shelf, the descriptive equations for set-up due to storm surge do not yield general conclusions regarding the effect of a rise in mean sea level. To estimate the effect for a particular site, several sophisticated numerical models have been developed. In general, storm surge will be most affected by sea-level rise in areas of mild offshore slopes (U.S. Department of Energy, 1988), for example, the shores of the U.S. along the Atlantic ocean and the Gulf of Mexico.

Wind-Generated Waves

The effect of a sea-level rise on wind-generated waves depends on local geometry. The two effects that a sea-level rise can have on the height of a wave experienced at the shore are: (1) changes in the height of the generated wave; and (2) changes in the damping of the wave as it propagates toward the shore. The cumulative damping due to bottom friction governs whether the result will be an increase or decrease in observed wave heights.

Wind-generated waves in deep water are not expected to change in response to sea-level rise. If the fetch length -- the length of water surface over which the wind acts -- does not change, waves generated over the continental shelf and shallower water will be higher due to reduced effects of bottom friction. This is shown by the relationship given by the National Research Council (1987) for the case of a long fetch and shallow water:

_H/S = 0.75*H/h

where _H is the change in the generated wave height, H is the original wave height, S is the water level increase, and h is the depth. It can be seen from this equation that one can expect a higher wave generation height due to sea-level rise.

Assuming the shelf length does not change significantly with an increase in water depth, the generated waves will decay less, because of decreased damping due to bottom friction. If a wider shelf results from a sea-level rise, wave height may be reduced due to a greater extent of bottom friction (U.S. Department of Energy, 1988). This can be shown by the relationship:

$$H(x) = H(0)/(1+\_)$$

where H(x) is the wave height at a location x, H(0) is the initial wave height, and _ is a relationship defined by:

$$\_ = f\_^{3}H(0)x/[3\pi g C_g \sinh^{3}kh]$$

where f is a coefficient that accounts for bottom stress, _ is wave angular frequency, g is gravitational acceleration, C_g is the wave group velocity, and k is the wave number. For the case of the wide shelf resulting from sea-level rise, _ may increase, resulting in a decreased wave height, H(x) at the shore.

As with storm-surge, detailed numerical models exist that can be used to predict the response of wave height with sea-level rise for a particular geometry.

IV.2. RESOURCES THREATENED BY SEA-LEVEL RISE

The resources at risk from a rise in sea level vary greatly in any area affected by hydrodynamics and physical effects. This area can be below the expected highest tide for the design period or the area within the expected extent of shoreline erosion. Any effects 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 and method of protection.

Residential

Because of the scenic value of coastal and other waterfront property, extensive residential development has occurred in areas already threatened by erosion and storm tides. An increase in sea level will increase the severity of possible damages in threatened areas and will expand the size of flood zones. Many homes in coastal zones are protected by non-engineered levees and revetments, or are not protected at all.

Commercial, Industrial, and Transportation

High-value commercial, industrial, and transportation facilities are also located on waterfront property. Such facilities make use of the waterfront for waste disposal, movement of goods or people, or commercial activities. Among the most common 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.

Natural Resources

The zone between land and water often hosts extremely rich natural ecosystems. The intertidal zone is one of the most diverse and sensitive coastal ecosystems. The brackish water interface between fresh water and salt water in bays and marshes produces special conditions conducive to certain species. Saltwater and freshwater marshes support countless species of invertebrates, fish, and mammals, and provide food and habitat for migrating birds. Many endangered and threatened species are found in these habitats. Little protection is usually provided for these resources; some may have levees.

IV.3. RESPONSES TO SEA-LEVEL RISE

There are three main responses to rising sea levels: (1) reduce or prevent sea-level rise; (2) reduce the impacts of sea-level rise through coastal defenses and remedial measures; and (3) retreat from threatened areas and move or abandon existing developments. Included in the last response is the option of "No Action", where no response is taken to rising sea level and land is eventually inundated, property destroyed, and ecosystems lost. Each of these strategies has advantages and disadvantages. Actual responses to sea-level rise are likely to include combinations of all three options.

In this analysis, no attention is given to methods for reducing or preventing climate-induced sea-level rise. While there is strong support for active measures to reduce the rate of climatic change, there is evidence to suggest that some rise may be unavoidable due to the greenhouse gases already put into the atmosphere. We therefore believe that it is valuable to analyze the costs to society of adaptation measures. For the purpose of this study, we assume that a substantial sea-level rise is plausible (if not inevitable), and we assess strategies for preventing or eliminating the worst negative impacts of that rise.

There are many structural responses to sea-level rise, including building or improving coastal defenses such as dikes and dunes, seawalls, bulkheads, beach nourishment, and other structures. This section briefly reviews the most common physical responses to problems of coastal flooding.

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 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, 1984a). 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.

The use of beach replenishment for shore protection has the advantage of being compatible with the existing processes, and has few negative effects on other areas. The placed sand, however, has a tendency to erode more quickly than the original sand for two reasons. First, by adding sand to the beach and not to offshore areas, beach nourishment throws the slope of the beach out of equilibrium with adjacent underwater areas, steepening the profile of the shoreface. The steeper profile is less stable in storms and the waves move sand offshore to restore the original slope. Second, sand used for beach nourishment often includes many fine particles of silt and clay, which will be washed away by the force of the waves, reducing the net volume of material added to the beach (Lowenstein, 1985).

The addition of sand to an eroding shore is a temporary restoration, and is particularly vulnerable to increased erosion due to sea-level rise. The maintenance costs associated with periodic additions of material determine the cost of this response. A method to roughly approximate increases in beach nourishment volumes due to a sea-level rise is presented by the National Research Council (1987) where the increase is proportional to wave height to the 2.5 power. The increase in wave height for a particular location can be determined using the equations presented in Section IV.1.

Another method for estimating the required increase in sand quantity needed to restore a beach eroding due to sea-level rise is used by Leatherman (1988). This method uses previously established closure depths (the seaward limit of significant offshore sand transport) for regions, and the scaled distance to this depth, to obtain the beach profile to be nourished. The area to be nourished is also obtained from maps and the volume of required material can be calculated.

The costs for beach nourishment are a function of the cost of the material and the availability of local supplies. Costs generally range from $4 to $10 per cubic yard. The higher costs apply where the sand is either pumped from a long distance offshore, or imported from a remote source. These costs are not easily translated to a linear foot basis, but individual cases have yielded costs from $50 (for a beach on a bay) to over $600 per linear foot.

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. 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).

Groins can be classified by permeability, height, and length. Common types are constructed using timber or steel sheet piles, concrete or rubble mounds, or asphalt groins. The selection of the type is based on the quality of the foundation material that will support the groin. A good foundation can accommodate a sheet pile type design; a poor foundation better utilizes a gravity type of structure. As with all of the alternate responses, the availability of materials is an important consideration in the selection of the response (U.S. Army Corps of Engineers, 1984a).

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).

The use of groins together with beach nourishment increases the effectiveness of either technique alone (National Research Council, 1987). An analysis of the cost of beach nourishment projects and an evaluation of the conditions for justification of additional structures to retain the sand are presented by Weggel (1986) and discussed below.

The general costs of groins varies depending on the type of foundation material on the site, the materials used, and the design dimensions and strength. Costs range from under $100 to over $1000 per linear foot. The lower estimates are for minor projects in a relatively mild wave climate, while the higher costs represent extensively engineered groins in a severe wave climate.

Bulkheads, Seawalls, and Revetments

There are three principal forms of vertical shoreline walls used to protect upland areas from storm surges and high tides: bulkheads, seawalls, and revetments. The differences between seawalls, revetments, and bulkheads 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, 1984a).

Bulkheads and seawalls are typically constructed as solid vertical walls above the mean high-water line. These structures can be modified after construction to respond to a sea-level rise. Revetments are either loose or interlocking units laid on a slope, from the upland to some point on the profile. The purpose of revetments is also to protect the upland. Because of the slope of the revetment and the roughness of its surface, erosion at the fronting beach area can be reduced. These can also be modified after construction (National Research Council, 1987).

A wide variety of possible effects and processes relating to the impact of seawalls on a shoreline are summarized by Tait and Griggs (1990). These include erosion of the fronting beach, sand accretion, adjustment of the profile to a steeper or flatter slope, scouring at the end of the wall, and an assortment of other erosion and deposition patterns. There is a wide range of opinion on the processes explaining shore response to the presence of a seawall (or other type of coastal armoring), and due to the lack of field information, many explanations remain speculative. For example, it has been proposed that the loss of a beach in front of a seawall is because, on an open beach, waves expend much of their energy moving across the beach. Structures such as seawalls, revetments, and bulkheads cut the process short, reflecting the wave force seaward, where they can cause significant erosion (Lowenstein 1985). The observed erosion at a beach, however, cannot generally be attributed to the presence of a particular structure without extensive field data.

One of the major observations of Tait and Griggs (1990) is that the most important factor affecting the impact of a seawall on a shoreline is whether there is long-term shoreline retreat. The majority of field studies indicates that most of the direct effects of seawalls on beaches are temporary or seasonal in nature, and that the most prominent lasting impact is sand impoundment at the upshore end of the wall, and erosion at the downshore end. To evaluate the impact of a seawall on a shore, a site-specific assessment of the potential impact should be conducted. This should allow the evaluation of the possible impacts of the structure on upcoast and downcoast areas, and the implications of sediment movement on the functioning of the structure to protect upland areas.

Careful attention must be paid to the details of the structure during design and construction, since rigid structures can fail as a result of many factors including loss of foundation support, inadequate penetration of the structure into the supporting material, scouring at the base, outflanking, inadequate height, and the loss of fill behind the structure (Fulton-Bennett and Griggs, 1986).

Non-rigid structures such as rip-rap revetments can fail for similar reasons, such as scouring at the base of the revetment and outflanking. The typical modes of failure for revetments on sand involve settling of the protective material into the sand due to scouring and fluidization of underlying sand, or collapsing of the revetment into a configuration of a lesser and more stable slope (Fulton-Bennett and Griggs, 1986).

A rise in sea level will have the effect of exacerbating these processes, increasing the possibilities for failure of the structure. For example, increased overtopping will result in greater forces behind the structure and an increased loss of backfill, and increased loss of foundation support and toe scour will result from greater wave energy dissipation at the structure. Sea-level rise can be incorporated into the design of a structure by either constructing it for an anticipated increase in sea level, or by making provisions for future modifications to accommodate the rise.

Typical construction costs for bulkheads and seawalls range from $750 to over $4000 per linear foot. Costs for revetments are similar to those of bulkheads and seawalls where the revetment is engineered. These costs can range from about $750 to $1500 per linear foot. For non-engineered revetments, consisting of concrete or rock rubble simply dumped at a location, the costs of material and construction are very low, consisting primarily of material transportation costs. Very simple rubble-mound walls along a bay shoreline have costs as low as $60 per linear foot (San Francisco BCDC 1988b). The higher costs will be representative of large-scale projects where the wave climate is severe and the intended protection considered essential.

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 father 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).

As with the other structures mentioned previously, to accommodate sea-level rise breakwaters should either be designed with a sea-level rise taken into account or with capabilities for future adaptation. The costs of breakwaters are similar to those of groins, with a high variation in the cost, reflecting the wide variety of materials and construction techniques that can be used. A rough range would cover from under $100 to over $1000 per linear foot, with average costs closer to $750 per foot. The local conditions of both wave climate and foundation material will determine the costs of breakwaters.

Dikes/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 include the above, as well as issues such as land condemnation and interference of the levee with navigation (National Research Council 1987).

Another important factor is the possibility that sea-level rise will lead to additional drainage problems. For existing levees, a higher sea level will result in increased seepage beneath the levees, causing increased drainage and pumping requirements. For both new and existing levees, the drainage of precipitation, flood waters, and water from overtopping of the levees often necessitates a drainage system. As sea level rises, a gravity drainage system will become increasingly less suitable, resulting in the need for either pumping facilities or systems for storing excess water until drainage by gravity is possible. Discussions of these drainage systems is included in Titus et al. (1987) and Weggel et al. (1988). The increased seepage beneath a levee is also of concern where the levee is protecting agricultural land or water-supply areas. In these areas the increase in seepage can cause problems related to an increased salt load on the soil and water quality.

Costs of construction of new levees vary widely, depending on the cost of the material used, the suitability of the foundation soil, and the design standards required for the location. For an engineered levee, costs range from $250 to $800 per linear foot. The lower costs might reflect the cost for a levee along a small slough, while the higher costs could include greater slope protection and greater dimensions. Extensively designed levees in areas where construction is difficult can significantly exceed the upper end of the cost given above.

The costs to raise an existing levee depend on the cost of the material which will be added to the levee. The costs can vary from about $2.50-$5 per cubic yard for material dredged from a channel adjacent to the levee, to more than $10 per cubic yard where material is not available locally. These costs neglect the costs of modifying levees to allow it to be raised. Such costs can be substantial.

Other Structures

A perched beach is a sill constructed offshore of and parallel to the beach to be protected. The function is to collect longshore material being transported offshore, as compared with the function of groins, which attempt to retain a portion of the material being transported along the shore (U.S. Army Corps of Engineers, 1984a). As sea level rises, the sand retention of the sill will become less efficient, and the beach front will be farther from the structure, reducing its overall effectiveness.

Storm-surge barriers are barriers designed with heights to exceed the surge elevations of certain design storms. The factor of safety of these structures will be reduced as sea level rises. (National Research Council, 1987)

Maintenance Considerations

In addition to the costs of construction of the various structures given above, maintenance costs are often significant. In general, the greater the engineering employed in the construction of a shore protection scheme, the lower will be the proportion of maintenance costs. The maintenance cost of engineered riprap-revetment, for example, can amount to 2 to 4 percent 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 to 15 percent of the construction cost per year (Fulton-Bennett and Griggs, 1986). Average maintenance costs for levees are about 10 percent per year of the costs of construction. The estimated maintenance costs for seawalls run from 1 to 4 percent per year, reflecting the higher level of engineering that goes into their construction.

IV.4. SELECTION OF RESPONSE STRATEGIES

In the long run, a comprehensive approach to evaluating the costs of sea-level rise and possible response strategies in a given region needs to be developed. One example of a possible approach is the ISOS (Impact of Sea-Level Rise on Society) framework developed in the Netherlands in 1986. Two versions are discussed by Wind (1987) -- an "ideal" ISOS model, and a simplified ISOS model programmed into a spreadsheet.

The main components of the "ideal" model are the amount of sea-level rise, details of the impact areas, impact mechanisms, response measures, and societal effects, as discussed earlier in this section. Sea-level rise is considered as a projected rate of rise that can vary over time. The input data for sea-level rise for the working model consists of a current rate of rise plus an acceleration of the rise over the period of interest.

The impact area can be separated into the natural system (including estuaries, lagoons, and wetlands), the existing protection system (both natural and structural), and human activities and facilities (the population and economic activity). The ISOS spreadsheet model allows the division of the region being studied into a maximum of three segments, based on characteristics pertaining to the above area types. The impact characteristics for each segment are described as input to the spreadsheet model and include population, land and capital values, physical characteristics of the land, the flood protection system, the water resources management system, and the shipping and port system.

The impact mechanisms describe the impact of sea-level rise on various components in each area. The most important mechanisms in the model relate to: 1) land losses (area and capital); 2) safety against flooding; 3) salt load (salt-water seepage into water supplies and agricultural areas); and 4) damages related to the water resources management system and the shipping and port system. Land types are divided into intertidal, urban/industrial, agricultural, and environmental, and the area of losses are calculated for each type based on the specified slopes. Also specified as input are monetary values for each land type, which are used to calculate monetary losses. These monetary losses are adjusted based on the capital value growth rate and the social discount rate, both of which are specified as input. Safety against flooding is based on a relationship correlating frequency of overtopping to height above mean sea level, which is specified as input. Likewise, a relationship showing the variation of salt load with sea-level rise, and another showing the damages to the water resources management system (under various investment scenarios) with sea-level rise must be developed for input to the model.

The spreadsheet model produces information on impacts for the population at risk, land loss, safety against flooding, total salt load, damages to the water resources management system and the shipping/port system, and the cost of response measures. Many effects are not shown by the model, such as the effect on ecosystems, administrative costs, social costs, or public health costs. The difficulty in quantifying these makes their incorporation into a model such as the ISOS model unlikely. Despite the weaknesses of this type of model, it can be useful for exploration of involved problems, mechanisms, and trade-offs, and for analysis of actual strategies to determine the relative values of different responses (Hekstra 1988). Extensive research will be required to determine the many values and relationships for input to the model, prior to applying the model to any region.

Another approach for evaluating costs to a region due to sea-level rise is presented by Gibbs (1984). Methods were developed to estimate what may be at stake in decisions of various responses to sea-level rise. Two issues were targeted: the impact on society if no action is taken; and by how much this impact can be reduced through preparation. To address these, two quantities were investigated: the economic impact of a sea-level rise; and the value of anticipating and preparing for it.

As with the ISOS model, the method of analysis outlined by Gibbs (1984) is helpful in understanding some of the potential impacts of sea-level rise, and the effects that different responses might have on these. The inability to quantify certain inputs, and a lack of detailed information about vulnerable regions places significant limitations on the use of the models. Particular regions must base their selection of response strategies on regional characteristics, the availability and types of regional data, and the economic and institutional resources available for responding.

V. LIMITATIONS OF ECONOMIC ANALYSES

The direct physical effects of a rising ocean will have major economic and environmental effects on our coasts, development, and natural ecosystems. Determining what response to make to rising sea level requires evaluating and balancing a wide range of uncertain costs and risks. Many of these costs are not yet quantified; some will be unquantifiable in classic economic terms. This section discusses the difficulties, uncertainties, and limitations of economic assessments of the costs and benefits of adapting to climatic change, specifically protecting against sea-level rise.

Many different "costs" to society from climate change can be assessed. These include:

- The costs of reducing greenhouse gas emissions;
- The costs of increasing the rate of removal of greenhouse gases from the atmosphere;
- The costs of adapting to climate changes, such as building sea walls or developing new crop types; and
- The costs of the impacts of climate changes on society.

Some of these costs are immediate; some are delayed in time. Some can be measured in dollars; some cannot be measured in economic terms. All of these characteristics complicate complete assessments. Given these problems, it is nevertheless important to begin to provide some of this information as long as the limitations and assumptions of any study are clearly stated.

Two important questions can be asked. First, what is the impact to society if we take **no** actions to prepare for sea-level rise? And second, what is the cost and value of taking actions to reduce the impact of sea-level rise? Previous analyses have suggested that the impacts of sea-level rise will be extensive and that there is great value in preparing for that rise (Gibbs 1984, Wind 1987). For example, the U.S. EPA has concluded that in Charleston, South Carolina and Galveston, Texas, the economic consequences of taking no actions could be in the billions of dollars, while preparing for sea-level rise could reduce these impacts by over 60 percent in some cases (Gibbs 1984, U.S. EPA 1989a).

If no actions are taken to prepare for or anticipate future sea-level rise, a variety of unanticipated costs to society will result from inundation of shoreline developments, loss of business activities and property, and wetlands destruction. These costs -- the "no action" alternative -- must be compared with the costs of taking a set of actions that would anticipate sea-level rise.

Sea-level rise will affect both services and structures. Structural costs include the costs of physical property such as building, repairing, or moving a house, dockyard facilities that must be raised, levees that need to be built or strengthened, and industrial, commercial, or residential facilities that need to be protected.

Economic services include the value of land, capital, labor, and non-market amenities. Because land and capital are fixed in location, they can be directly affected by sea-level rise. The supply and productivity of labor can also be directly affected. The problem of non-market amenities is much more difficult to assess and is often ignored in classic economic analyses. Other services include activities in the affected zone, values associated with beachfront property, and so on.

Our goal here is not develop methods to estimate the total value of property in a region at risk from sea-level rise. Such an estimate would require a determination of the net economic services in the regions at risk, the gross services and returns, the value of new investment, the value of the capital stock at the end of the period of analysis, and so forth. For many regions, such data are not available and subject to enormous uncertainties. In addition, we believe that decisions about the appropriate responses to sea-level rise will depend on details about particular sites and societal choices about the value of areas at risk.

We also note that most analyses of the economic activities affected by sea-level rise exclude important costs that are difficult to quantify. These include the loss of recreational activities, distributional or equity effects, the loss of natural ecosystems and the environmental functions and services that they provide, the sometimes severe psychological costs of living behind protective structures (Goemans 1987), losses outside the immediate study area, effects on groundwater quality due to salt-water intrusion, effects on freshwater river quality due to salt-water intrusion.

Costs to protect coastal properties from sea-level rise will not be incurred all at once. Rather they will be imposed over time as decisions are made to reduce the risk of damage; or to prevent additional damages after storm events occur. The values presented in Part 2 for the San Francisco Bay area are the costs that would result from taking actions today to reduce the risk of damages at some unspecifiable future time. An additional problem is that the future rate of sea-level rise is uncertain. A one-meter rise may result by the year 2050 under some scenarios; under others it may be delayed until 2100. If sea-level rise is rapid, the costs described here may be incurred relatively quickly. The slower the rate of sea-level rise, the more time to plan (and pay for) appropriate responses. There is a value, therefore, in slowing the rate of change.

Structural responses can be made relatively insensitive to the rate of sea-level rise by high expenditures at the beginning of the life cycle, or they can be adjusted on an ad-hoc basis during the period of increasing threat.

Unquantified or Unquantifiable Ecological Effects

A change in local sea level will change the environmental conditions of natural ecosystems adapted to a particular region, with particularly profound effects on coastal wetlands, brackish-and freshwater marshes in estuaries, bays, and lagoons. If the change is sufficiently large, the tolerance limits of plant and animal species may be exceeded and dramatic ecosystem shifts may occur, including local extinctions.

Wetlands are important to the ecology and economy of coastal regions; they have extremely high biological productivity, serve as nurseries for commercially significant fish, provide habitat for waterfowl and mammals, remove pollutants from sewage effluent and surface water, and provide protection from coastal storms and high tides (Park et al. 1986). These valuable ecosystems could be lost with accelerating sea-level rise. Wetlands along undeveloped coastlines without protective engineering structures can migrate onto adjacent lowlands only if land is available. Unfortunately, very few regions have undeveloped adjacent land, and the presence of structures will preclude wetlands migration.

Whether or not wetlands are able to adapt to a rising sea level is a function of several variables, including the rates of sedimentation and vegetation growth, changes in salt and freshwater balances, and decisions about how to manage these lands. If mean sea-level rises at a rate faster than the rate of sedimentation, tidal marshes will be submerged and converted to deeper water habitats.

Sedimentation rates are highly sensitive to local conditions. Geologic evidence suggests that wetlands can adapt to low rates of sea-level rise (≈1-2 mm/year) and are inundated at higher rates (≈10 to 20 mm/year). Diked wetlands do not have any sources of sediments and would be particularly vulnerable to inundation from sea-level rise.

Over geologic time, large increases and decreases in sea level have occurred, with maximum rates over the last ten thousand years of 5 to 10 mm/year--about 2 to 5 times larger than present rates of change. During these periods of rapid change, significant modifications of coastal ecosystems have occurred, including inland migration of wetlands and changes from fresh-water systems to salt-water systems. In past periods, however, suitable habitat existed for such shifts; today extensive shoreline and wetland development will directly interfere with the redistribution of coastal ecosystems.

Few good data are available on sedimentation rates within marshes or on mudflats, and much of these data are site specific. Estimates of the normal marsh accretion rate in bay ecosystems range from 1 to 8 mm per year when satisfactory inflow of sediments from rivers is available (Martindale 1987, Josselyn and Callaway 1988), though in some types of rich subtidal waters subject to large sediment inflow from rivers, rates as high as 70 mm/year have been observed (Nolan and Fuller 1986). In deltaic areas with extensive marshes and sediment inflow, more typical accretion rates of 10 mm/year are observed; in areas of moderate wetland extent, 5 mm/year is typical, while under 2 mm/year is average in areas with little wetland extent (Armentano et al. 1988). Under these conditions, adverse effects on coastal marshes would be widely observable by 2050, and would be noticeable in vulnerable ecosystems by the year 2000, even under the low sea-level rise scenario of Table I and Figure 1. Non-linearities and sudden events such as storm surges and a change in storm frequency and intensity could lead to damages even earlier.

PART 2. A CASE STUDY OF THE SAN FRANCISCO BAY REGION

SUMMARY OF RESULTS AND CONCLUSIONS

The San Francisco Bay region, in northern California, is one of the most economically important and ecologically rich bays in the United States (see Figure 2). Future sea-level changes will affect human developments around the Bay and will dramatically alter ecosystem types and functions. For that reason, an analysis of the costs of adapting to an increase in sea level would provide valuable information for policy makers. This section describes the approach taken to determine these costs, the uncertainties involved in making such an assessment, and the results of the study. We also discuss the implications for future policy.

- The value of property threatened by sea-level rise in San Francisco Bay is extremely high because of past development. For San Mateo, Alameda, and Santa Clara counties alone, existing commercial, residential, and industrial structures in the area threatened are valued at nearly $30 billion. For the entire Bay Area, over $48 billion of structures is threatened.

- There is considerable value in incorporating future sea-level rise into planning for new developments.

- The cost of protecting just **existing** development from a one-meter (3.3 foot) sea-level rise by building new defenses or modifying existing protection around San Francisco Bay will exceed $940 million (in 1990 dollars), **not including** the costs of protecting or restoring wetlands, or the need for any active structures such as pumps, drainage systems, and navigation locks. These costs could exceed an additional one billion dollars. The costs of maintenance for these defenses are also not included and could approach $100 million per year.

- We think it unlikely that the status quo around the Bay can be maintained under conditions of expected sea-level rise, even with extensive protective measures. Indeed, implementing all of the protective measures evaluated here would, by themselves, change the character of the Bay.

- Loss of some of the remaining natural wetlands in San Francisco Bay appears inevitable. In particular, large tracts of wetlands in the northern stretches of the Bay will be impossible to maintain in their present form, and intertidal wetland habitat in the southern stretches of the Bay may be lost entirely. Options include providing some artificial protection, which converts natural ecosystems into partially managed ecosystems; trying to restore wetlands on adjacent, higher, undeveloped land; or abandoning existing wetlands to try to adapt through natural processes.

- Deterioration of groundwater quality in some basins around the Bay will accelerate as sea level rises. No way to prevent this deterioration, other than by preventing sea-level rise, was identified.

- We believe it unlikely that sufficient money or political consensus will be available to protect all resources on the margins of the Bay before damaging storm events occur. As a result, difficult decisions about what to move or abandon will have to be made, and damages from flooding will increase.

- Substantial additional -- and unpredictable -- changes in the biological and chemical nature of the Bay region are likely due to changes in freshwater inflow to the Bay, new development, changes in water and ecosystem management in the Delta, and other effects that cannot now be anticipated. All of these additional effects are beyond the scope of the present study.

RECOMMENDATIONS

Future development should be prohibited along the margins of the Bay likely to be subjected to higher sea level.

The cheapest option to protect against future sea-level rise impacts is to prohibit development in regions that are likely to be subjected to the higher future risk of coastal flooding. Some progress in this direction has been made by the San Francisco Bay Conservation and Development Commission, which has recommended that future sea-level be taken into account in future development along Bay margins. This study assumed no increase in the rate of sea-level rise above the current rate of rise. Periodic review of the state of the art estimates on future sea-level rise should be undertaken.

Future development should be prohibited on undeveloped lands immediately upslope of threatened areas or adjacent to existing wetlands.

These lands are the only areas to which present wetlands can slowly migrate, and future wetlands restoration projects will require this land.

Present activities to maintain or modify existing bulkheads and levees around the Bay should assume a future increase in sea level.

The cost of modifying these structures in the design stage is considerably below the cost of later reconstruction or flood-damage from unanticipated storm surges.

Detailed surveys of the economic value of land and services at risk in specific regions should be done.

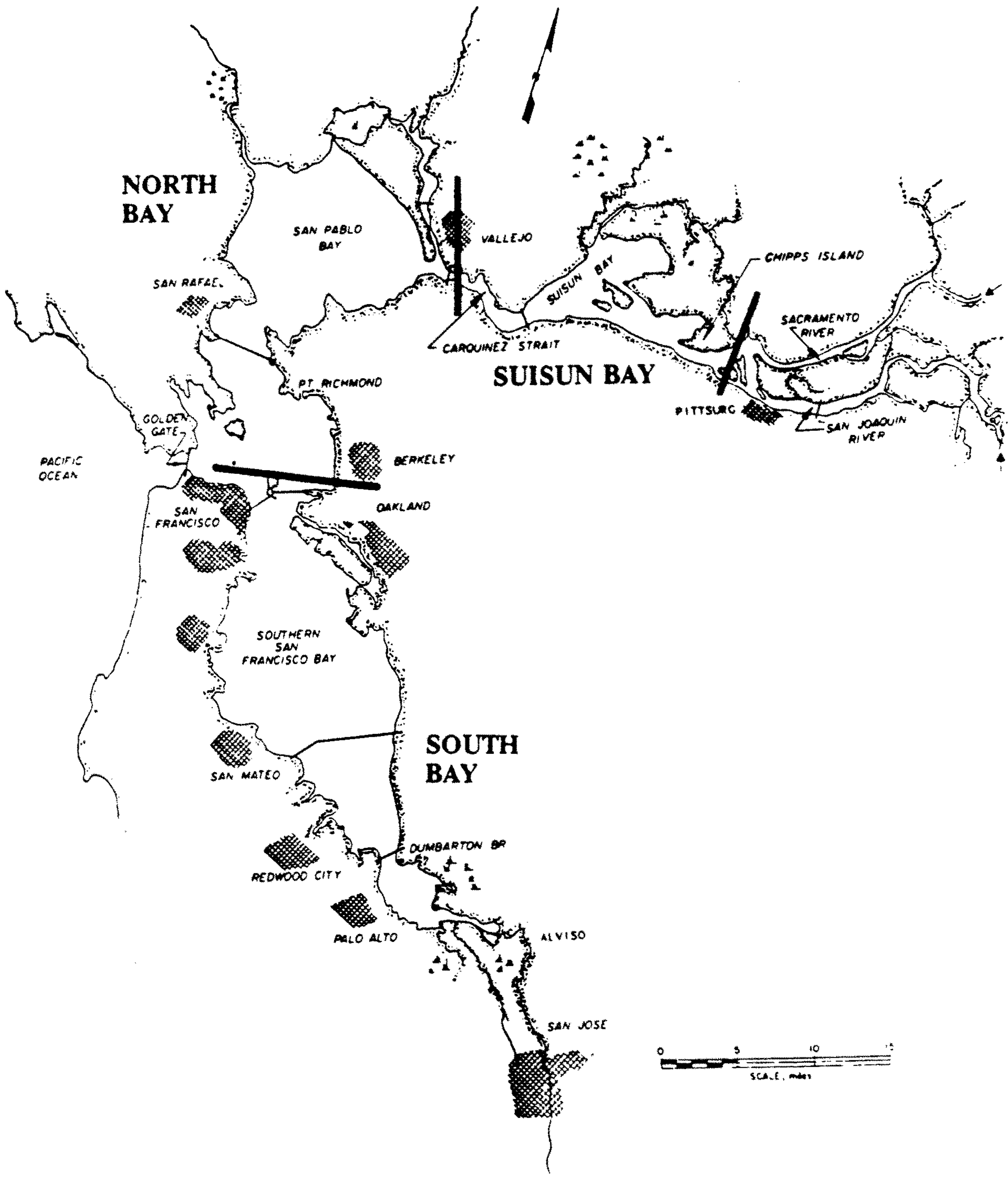
The study here provides initial estimates of the costs of adapting to a one-meter sea-level rise, but not the long-term value of property threatened. Such additional information is required for appropriate public policy decisions to be made.

Natural ecosystems are undervalued or ignored in traditional economic analyses. A method for

incorporating them into future studies is needed.

Large tracts of wetlands in the San Francisco Bay area 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.

**Figure 2	San Francisco Bay Region**



Adapted from: Sanitary Engineering Research Laboratory (1966)

I. INTRODUCTION: THE SAN FRANCISCO BAY REGION

San Francisco Bay is the second largest bay on the Pacific Coast of the United States. Located in central California, San Francisco Bay is home to over 6 million people, extensive industry and commercial development, and the richest bay/delta ecosystem remaining on the west coast. The Bay has a surface area of approximately 450 square miles, 300 miles of shorelines, and 130 square miles of tidal flats and marshes. The counties of San Mateo, Santa Clara, Alameda, Napa, Sonoma, San Francisco, Contra Costa, Marin, and Solano border the Bay. Excluded from this study was the Sacramento–San Joaquin Delta and the coast outside of the Golden Gate.

Freshwater inflow to the Bay comes primarily from the Sacramento and San Joaquin rivers, which drain the Central Valley and part of the Sierra Nevada. Other highly seasonal inflow comes from small streams draining the hills around the perimeter of the Bay itself.

Tidal range in the Bay, measured as the height between high and low tide, seldom exceeds eight feet; the mean range at the entrance of the Bay to the Pacific Ocean (the "Golden Gate") is four feet. In the southern reaches of the Bay, the mean tidal range is amplified to seven and a half feet. In the northern reaches the tidal wave is dampened to just over three feet (Figure 3).

Table II Area and Types of Remaining Wetlands in San Francisco Bay

AREA (acres)	MUDFLAT	TIDAL MARSH	DIKED WETLAND	SALT POND
South Bay below Dumbarton Bridge	6,800	3,000	2,400	13,000
South Bay north of Dumbarton Bridge	24,500	5,600	6,400	15,000
North Bay	27,600	17,000	9,000	9,000
Suisun Bay and Carquinez Straits	5,000	10,500	45,000	<100
TOTAL	63,900	36,100	62,800	37,000

Notes

There are many different categories of wetland habitats. This table breaks down San Francisco habitat types into four: Mudflats, Tidal Marshes, Diked Wetlands, and Salt Ponds. For a more detailed and accurate breakdown and distribution, see Josselyn et al. in press. All figures in this table are rounded.

Mudflats are unvegetated tidal areas.
Tidal Marshes are vegetated tidal areas.
Diked Wetlands are non-tidal wetland areas.
Salt Ponds are commercially developed non-tidal wetland areas.

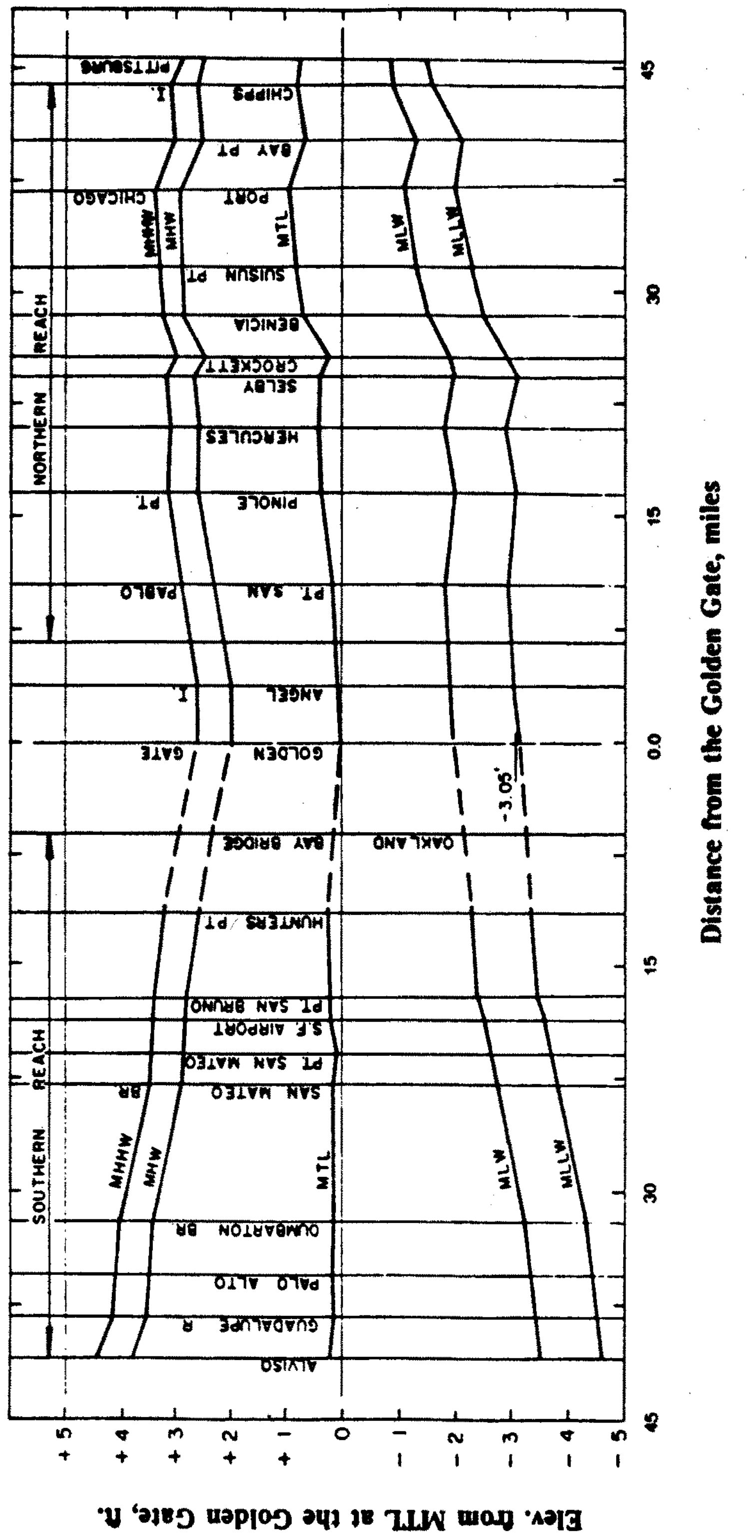
(Sources: San Francisco BCDC 1988; Josselyn et al. (in press).

Diverse natural habitats, flora, and fauna are found in the region. Along the Pacific coast of the United States, only about 10 percent of the coast is suitable for wetlands and less than 10 percent of the total original wetlands in California remain undeveloped or undestroyed

(California Coastal Commission 1989, p.36).[2] A large fraction of the remaining west coast wetlands are in the reaches of San Francisco Bay -- the largest estuary on the west coast of the United States (Josselyn and Callaway 1988). Within San Francisco Bay area only about 20 percent of the original wetlands remain (U.S. Army Corps of Engineers 1981). Table II lists the distribution and type of wetlands in San Francisco Bay Estuary. Despite extensive human modifications, the remaining wetlands of the Bay are vital to migratory birds on the Pacific Flyway and to commercial and recreational striped bass and salmon fisheries. Large numbers of endangered and threatened species are found in these natural ecosystems.

[2] Coastal wetlands are defined by the California Coastal Act of 1976 as "lands within the coastal zone which may be covered periodically or permanently with shallow water and include saltwater marshes, freshwater marshes, open or closed brackish water marshes, swamps, mudflats, and fens."

Figure 3 San Francisco Bay Tidal Ranges



Adapted from: Sanitary Engineering Research Laboratory (1966)

Flooding problems already exist in various locations around the Bay, even without the threat of sea-level rise. Developments around the Napa River are occasionally flooded, portions of Suisun City are vulnerable, the towns of Corte Madera and Foster City are at risk, and many commercial and government facilities are in the 100-year event floodplain (see Table III). Suisun Marsh, in the northern part of the Bay, is of particular concern due to a poor levee system. Significant improvements in the existing levees, or non-structural alternatives, will be needed to maintain this valuable marsh system, even under existing flooding conditions.

In the south Bay, ad-hoc protection is provided by a series of levees built and regularly maintained by the Leslie Salt Company as containment dikes for evaporators. These shoreline levees are not designed to protect other commercial, residential, or industrial developments, and there is no guarantee that the levees will be maintained in the future. Even under existing conditions, these levees are threatened with failure by major storms or extreme high tides.

Table III Major Government, Transportation, and Commercial Facilities in San Francisco Bay Threatened by Sea-Level Rise

Commercial and Private Airports
Oakland International Airport
San Francisco International Airport
Fremont Sky Sailing Field
Palo Alto Airport
Sonoma Valley Airport
San Carlos Airport

Freeways
Highway 880 in south Oakland; north of Albany; south of Fremont; north of Milpitas
Highways 24, 84, and 92, leading to the San Francisco-Oakland bridge, the Dumbarton Bridge, and the San Mateo Bridge
Highway 237 between Alviso and Mountain View
Highway 101 in Palo Alto; and between San Bruno and Redwood City
Highways 37, 29, and 12 in Solano and Sonoma Counties
Highway 121 in Sonoma County
Interstate 680 in Solano County

Railroad Facilities
Southern Pacific Railroad tracks around Bay perimeter
Southern Pacific staging yards, San Mateo County
Northwestern Pacific tracks in Sonoma County

Waste Disposal and Treatment Sites
Major landfill sites in every county
Major sewage treatment and disposal plants in every county

Military and Government Facilities
Oakland Army Terminal
Oakland Naval Supply Center
Alameda Naval Air Station
Alameda Naval Reservation
Alameda Coast Guard Base
U.S. Coast Guard Reservation
Coyote Hills Military Reservation
NASA Ames Research Center
Moffett Field Naval Air Station
Mare Island Naval Base
Skaggs Island Naval Installation
Hunters Point Naval Yard
Concord Naval Weapons Station

Other Facilities
Hetch Hetchy Aqueduct
Numerous yacht clubs and harbors
Municipal golf courses in Alameda, Santa Clara, Marin
Extensive transmission towers

II. FUTURE SEA-LEVEL RISE IN SAN FRANCISCO BAY

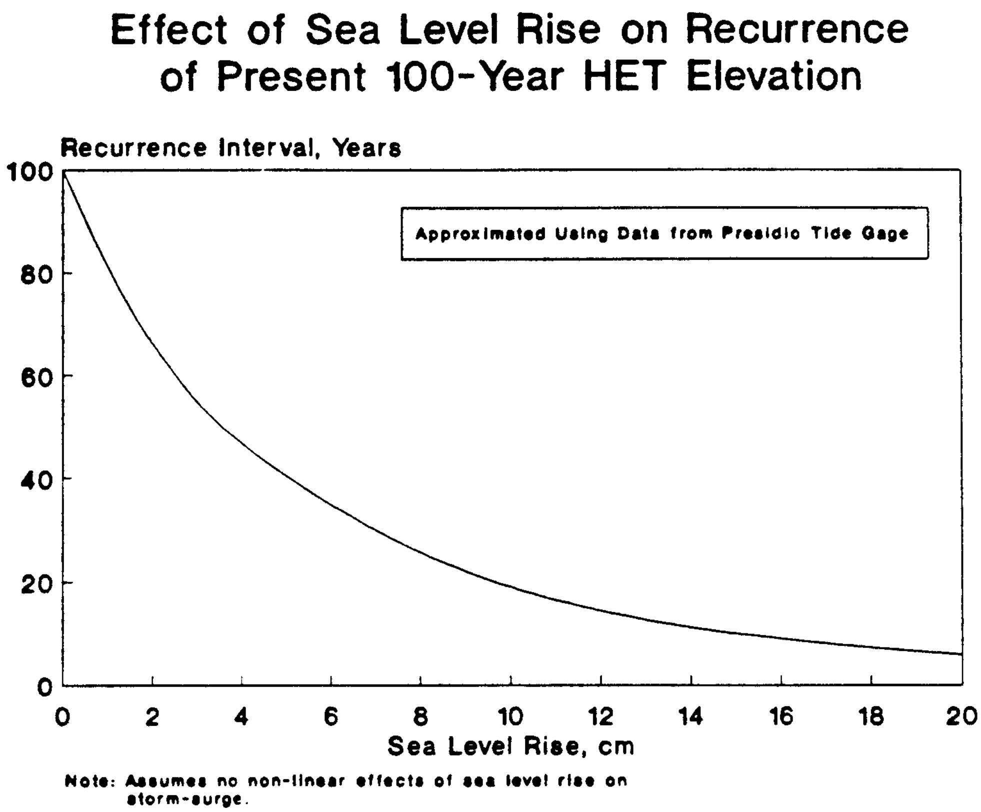
For the purpose of this study, an increase in relative sea level of one meter (3.28 feet) was assumed and the costs of defending against such an increase evaluated. We are not **predicting** that sea level will rise by this amount at any given time; rather we are evaluating the implications of protecting against such an increase in sea level. While there is a wide range in estimates of future sea-level changes because of extensive uncertainties over the physical behavior and dynamics of the oceans, this paper is not the place to resolve these uncertainties. Table I and Figure 1 show some of the most recent sea-level rise scenarios. As these data show, a one-meter rise is a plausible outcome of the greenhouse effect. We also note that the marginal costs of protecting against a sea-level rise of 0.5 meters are likely to be only slightly less than the costs of defending against a one-meter rise because of the large capital and labor expenditures associated with deploying and operating the necessary equipment, and the engineering costs associated with design.

The discussion of sea-level rise in this section refers to a "relative" rise -- that is the combined change in absolute sea-level and the change in level of land due to subsidence and uplift. Williams (1985) notes that "the public's perception of sea level rise will probably only be formed in the aftermath of infrequent but devastating storm-surges rather than as a result of the gradual increase in mean sea level." This point is dramatically illustrated in Figure 4, which shows the increase in frequency of the current 100-year highest estimated tide (HET) elevation with various increases in sea level.[3] For a sea-level rise of only 3.5 centimeters (1.4 inches), the frequency of the current 100-year highest tide doubles -- i.e. the present 100-year storm will now occur once in 50 years, on average. By the time sea level rises 15 centimeters (5.9 inches),

[3] Based on the tide and storm-surge data presented in U.S. Army Corps of Engineers (1984b).

the once-in-100-year storm will have become a once-in-10-year storm. Major disruptive storms will thus occur far more frequently long before sea level actually rises one meter.

Figure 4 Effect of Sea-Level Rise on the Frequency of the 100-Year Highest Estimated Tide



A one-meter sea-level rise will have several hydrodynamic effects such as those described in Part 1, Section IV. Estimates of these effects for San Francisco Bay are described below.

Tidal Ranges

Sea-level rise will affect the tidal range (the range between high and low tides) of San Francisco Bay differently in different areas. The current tidal range at the Golden Gate, the entrance to the Bay, is about 1.2 meters (4 feet). It can be expected that the northern portions of the Bay will experience an increase in tidal range, since the geometry of this portion of the Bay results in a progressive tide wave. The governing formula to estimate this increase is given above in Part 1, Section IV.1.

An application of this formula to the northern reaches of San Francisco Bay can be illustrated using the observed tidal range approximately 2 kilometers (1.25 miles) north of the Richmond-San Rafael Bridge in San Francisco Bay. The present tidal range is 1.2 meters (4 feet) and the average hydraulic depth through the area is about 8.5 meters (28 feet). For a one-meter (3.3 feet) sea-level rise it is estimated that the tidal range will increase by only 4 percent. Another effect produced by the sea-level rise will tend to cancel this predicted increase. The deeper water will result in a greater tidal velocity, causing increased energy losses and a potential decrease in the change. Williams (1988) states that the reaction of the tidal range in the North Bay depends highly on the assumptions regarding failure of levees in the delta.

The southern portion of San Francisco Bay approaches a length equal to approximately one-quarter of the natural wavelength for the tidal oscillation, and is closed at one end. This creates a situation of a resonance-dominated system, described above. An example using this relationship for the southern San Francisco Bay follows. Appendix 1 shows the detailed calculation of the ratio of the length of the estuary to the wavelength of the tidal wave for both the present conditions and the conditions with a one-meter sea-level rise. The method used to calculate this ratio for the South Bay is derived in the report of the Sanitary Engineering Research Laboratory (1966). This ratio is about 0.23 for the present conditions, and it decreases to 0.20 under conditions of a one-meter sea-level rise, assuming that an increase in width or length of the Bay did not accompany the increase in depth. This assumption is consistent with assuming that the shoreline will be protected by some rigid method, e.g. dikes or bulkheads.

The above ratios can be applied to estimate the ratio of the tidal amplitude at the mouth (the Golden Gate) to amplitude at the closed end (southern end of Bay). For the present condition the ratio of amplitudes, R, is approximately 1.85. Using the relationship previously described for tidal range amplitude prediction for a resonance-dominated system with damping, the ratio of amplitudes reduces to 1.64. This is calculated using the assumptions that the length of the estuary and the damping coefficient remain constant with a sea-level rise. This would correspond to an experienced increase in high tide of about 0.88 meter with a rise in sea level of one meter at the Golden Gate, assuming the tidal range at the Golden Gate does not change. It can be expected, however, that damping due to bottom friction will decrease with a rise in sea level. As a result, the decrease in the value of R is likely to be slightly less than predicted above.

Qualitatively, it seems reasonable to expect that a sea-level rise would move the southern San Francisco Bay to a state less resonant than presently occurs. This will result in less tidal range amplification from the present ratio at the southern end of the Bay of approximately twice the range at the Golden Gate.

Wind-Generated Waves and Storm-Surge

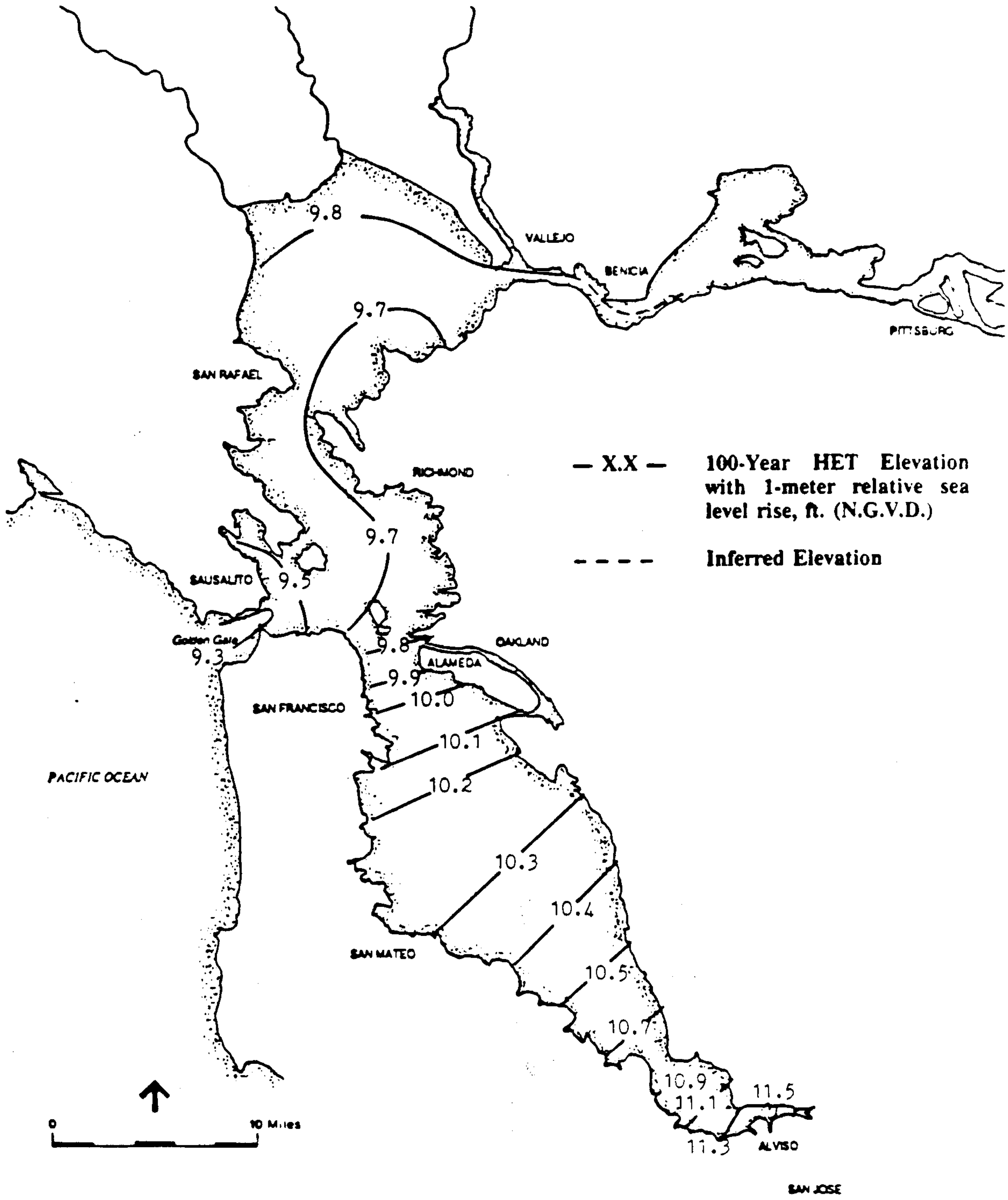
The impact of a sea-level rise on wind waves in San Francisco Bay cannot be determined for general use in this study. It is expected that the effects mentioned above for wind waves will result in increased wave energy along the shore of the Bay. The local conditions will determine the magnitude of the change in wave height and resulting run-up.

As with wind waves, the impact of a sea-level rise on storm-surge in San Francisco Bay is not possible to determine in a general manner for the Bay. As pointed out by Williams (1985), studies have not been carried out on storm surges within the Bay. The possible increase in storm-surge level due to increased fetch length, and potential decrease due to increased shallow water area, have a net effect which is impossible to determine.

Elevations Adopted for This Study

For this study, to determine design water elevations with sea-level rise, we have adopted the approach used by Laroache and Webb (1987), and by Waddell and Blaylock (1987). This approach adds projected sea-level rise to the present design tide elevation for the region of interest. The 100-year Highest Estimated Tide (HET) elevations are used for the present design tide elevations for San Francisco Bay. To these are added the one-meter relative sea-level rise to obtain the future HET elevations. The final design height for a particular site depends on design freeboard, local land subsidence, and wave run-up, which depends on factors such as wave climate, characteristics of the structure, and local bathymetry. For this study, an approximate design elevation is obtained by designing structures to be three feet higher than HET elevations to account for these factors. These design heights are consistent with the assumptions used by the U.S. Army Corps of Engineers (1981) for San Francisco Bay. The future 100-year HET elevations are shown in Figure 5 and these elevations with the design levee heights are listed in Table IV.

Figure 5 New 100-Year Highest Estimated Tides in San Francisco Bay with a One-Meter Sea-Level Rise



HET is the highest estimated tide expected to occur once in the recurrence period.

Adapted from: San Francisco Bay Conservation and Development Commission (1988a)

Table IV 100-Year tide and levee design levels for this study

Location	Present 100-Year Level (ft,NGVD)	Future 100-Year Level (ft,NGVD)	Design Levee Elevation (ft)	Design Height Used (ft)
Pittsburg	6.5	9.8	12.8	13.0
Benecia	6.5	9.8	12.8	13.0
Sonoma Creek	6.5	9.8	12.8	13.0
Point Orient	6.4	9.7	12.7	13.0
Sausalito	6.1	9.4	12.4	13.0
Presidio	6.0	9.3	12.3	13.0
Alameda	6.7	10.0	13.0	13.0
Hunters Point	6.7	10.0	13.0	13.0
San Mateo Bridge	7.1	10.4	13.4	15.0
Dumbarton Bridge	7.5	10.8	13.8	15.0
Alviso Slough	8.2	11.5	14.5	15.0

Notes:

- The 100-Year level is the highest estimated tide level including storm-surge effects.
- Still water levels are obtained from U.S. Army Corps of Engineers (1984b).
- Relative sea level rise at all locations is assumed to be one meter.
- The design levee height is based on the assumption that the new levee is constructed at the margin of the bay.

III. METHODOLOGY FOR ASSESSING THE COSTS OF RESPONDING TO SEA-LEVEL RISE FOR SAN FRANCISCO BAY

This section evaluates the present costs of adapting to a one-meter sea-level rise in San Francisco Bay. Our goal here is not to estimate the total societal costs in a region at risk from sea-level rise. Such an estimate would require a determination of the net economic services in the regions at risk, the gross services and returns, the value of new investment, the value of the capital stock at the end of the period of analysis, ecosystem values, any human health effects, and many other unquantified variables. For the San Francisco Bay as a whole -- indeed for any region of the world -- such data are not available and subject to enormous uncertainties. In addition, we believe that decisions about the appropriate responses to sea-level rise will depend on details about particular sites and societal choices about the value of areas at risk.

In the growing debate over the appropriate response to make today to future climatic changes, the information provided here can help identify some present and future societal costs of relying solely on the option of trying to adapt to future changes.

This study focuses on providing a methodology for evaluating the cost of implementing a set of measures to protect against a rising sea. Methods of protection are described in detail and average costs are presented. Consistent assumptions about how to choose response strategies were made. These are:

- Do not protect low-lying areas with little development.
- Raise existing structures where the cost of raising them is less than the cost of other protection.
- Protect areas with passive structures such as new or improved levees, dikes, seawalls, or bulkheads where appropriate.

- No active measures such as pumps, drainage systems, navigation locks, and so on were assumed. These will raise the overall costs of responding to sea-level rise.

Since the assumed increase in relative sea level is a combination of global change and local land subsidence or rebound, certain assumptions regarding these processes are also implied. No particular time projection is assumed for the one-meter relative sea-level rise, not only due to the uncertainties associated with global rise predictions, but also due to varying land movement rates within the region of interest. The one-meter rise will be experienced at different locations around the Bay at different times, depending on the local land movement. For example, given a one-meter rise in global sea level in 100 years in San Francisco Bay, the experienced rise at Pittsburg, California would be about 1.27 meters, assuming the current rate of land subsidence of -0.0027 meters/year for Pittsburg. This would mean that a one-meter relative rise there would occur in less than 100 years. Most of the shoreline of San Francisco Bay is currently stable or subsiding, although some uplifting, or rebound, has been observed at Sausalito.

The methodology developed here and applied to the San Francisco Bay can be used to evaluate costs of protection elsewhere. We recommend that such studies be done for a diversity of other sites, including regions in less-developed parts of the world, low-lying atolls, particularly valuable ecosystems, and other important ports and cities.

IV. STUDY LIMITATIONS AND UNQUANTIFIED EFFECTS

In analyses such as this one, what has been left out is often as important as what has been included. We have not calculated the costs of protecting the wetlands in the Bay, any costs of sea-level rise in the Sacramento/San Joaquin Delta or outside the Golden Gate along the coasts, the costs of protecting threatened groundwater or freshwater resources, or the costs of "active" protection such as navigation locks, drainage facilities, or pumps. As mentioned earlier, we also find no satisfactory method for evaluating the relative values of different ecosystem types. For example, the 44,000 acres of wetlands of Suisun Bay are presently used for recreational hunting and fishing. One study valued these uses at over $150 million annually (Meyer 1987) -- excluding non-market factors such as wildlife habitat, pollutant filtering, heritage values, and so on. No adequate way was found to incorporate such non-market factors into the present study.

Valuable ecosystems in San Francisco Bay could be lost with accelerating sea-level rise. Wetlands without protective engineering structures can migrate onto adjacent lowlands only if land is available. Unfortunately, very few regions have undeveloped adjacent land, and structures will preclude wetlands migration. In San Francisco Bay, tidal marshes have evolved over time with a gradual inundation of low-lying areas combined with an inflow and buildup of sediments. If mean sea level rises at a rate faster than the rate of sedimentation, tidal marshes will be submerged and converted to deeper water habitats. Because of a reduction in sediment transport due to upstream dams and diversions, it appears likely that a large portion of the area's tidal marshes would be submerged by sea-level rise (San Francisco BCDC 1988a). This would threaten a number of endangered species.

Substantial portions of Bay historic wetlands are presently diked. Over time, these can be restored to tidal action and hence to wetlands, but there is probably a threshold size and depth at which tidal sedimentation cannot restore former marsh elevations. This will limit the areas that can ultimately be restored to marsh. Sedimentation rates are highly sensitive to local conditions. Geologic evidence in San Francisco Bay suggests that wetlands have flourished under low rates of sea-level rise ($\approx$1-2 mm/year) and were inundated at higher rates ($\approx$10 to 20 mm/year).

In addition to the rate of sediment accretion in wetlands, sedimentation patterns throughout the Bay will be affected by a sea-level rise. This can be due to an increase in the tidal prism (the volume of water carried into a bay during a tidal cycle) and changes in currents, sediment inflow, and areas that are inundated. The complexity of the processes of sedimentation causes difficulty in predicting their response to a rise in water level. As recommended by the San Francisco BCDC (1988a), a study of sedimentation in the Bay needs to be conducted, and alternative management of diked wetlands to allow their adaptation to sea-level rise should be investigated.

The region of the Sacramento/San Joaquin River Delta ("the Delta") is also not included in this study. This area is highly susceptible to damages from an increase in mean sea level, and effects in the Delta will be felt throughout the state of California. The major impact of sea-level rise on the Delta would be the inundation of many of the "islands" that are currently protected by levees. According to Williams (1988), the area of the Bay could triple and the volume double if existing levees are not maintained and improved. Such changes in the Delta would dramatically alter the circulation of water in both the Bay and Delta, the movement of sediment, and the level of salinity in the Delta. Since a large portion of California's population receives fresh water from the Delta, this impact would be widely felt.

Water quality in the San Francisco Bay would be affected by the changes in circulation and mixing patterns caused by sea-level rise, and by the flooding of areas around the margin of the Bay containing landfills and sources of toxic wastes. Sea-level rise would increase the risk of these pollutants entering Bay waters. Since the extent of this risk has not been established, no quantitative assessment of water quality degradation is included here.

V. RESULTS FOR SAN FRANCISCO BAY: THE COSTS OF PROTECTION

Options available for protection of coasts, and general ranges of costs have been described in Part 1, Section IV.3., above. For California and San Francisco Bay, costs have been compiled by Fulton-Bennett and Griggs (1986), by the San Francisco Bay Conservation and Development Commission (San Francisco BCDC, 1988b), and by Leatherman (1989) and Weggel, et al. (1988). The specific unit cost assumptions used for this study are based on those in the above references and on costs from local authorities and contractors. These are shown in Table V.

Table V Unit Costs Used in this Study

Item	Unit	Cost per Unit
New Levee - 15 feet high	linear foot (l.f.)	$500
New Levee - 13 feet high	l.f.	$450
Raised Levee	l.f./ft.of height	$25
New Seawall - 13 feet high	l.f.	$1,500
Raise Freeway - 1 meter vert.	l.f./lane	$100
Raise Railroad - 1 meter vert.	l.f./track	$100
Raise Structure	each	$20,000
Beach Nourishment	l.f.	$50
Raise Bulkhead - 1 meter vert.	l.f.	$150

Note:

- The above costs were determined based on cost information pertaining to the San Francisco Bay region. Costs for other areas can vary depending on local conditions and available materials.

Topography around the case study region was analyzed using United States Geological Survey 7.5 minute series quadrangle maps at 1:24,000 scale. Twenty-four maps cover the region between the south Bay and the city of Pittsburg in the north Bay. Shoreline lengths were measured, and present levels and types of shoreline protection were determined by site visits, map analysis, and existing surveys. It was assumed that existing protection, such as levees and bulkheads, could be raised to meet the 100-year high tide under conditions of higher sea level. In regions with extensive bayside levees, and interior levees protecting developments, all levees were assumed to be raised. In regions where bayside levees were able to protect interior developments, only the outer levees were assumed to be raised.

The majority of the Bay shoreline and its tidal sloughs are protected against flooding by some form of levee. Many of these levees are privately managed and owned, and the flood protection benefits provided are incidental. For the purposes of this study, all existing levees are assumed to be structurally sound enough to be raised. In fact, according to the U.S. Army Corps of Engineers (1988), 33 percent of the levees in the South Bay are in poor condition; only 28 percent are in good condition. Many levees may, therefore, have to be completely rebuilt to provide adequate protection under future conditions. Such additional costs are not included here.[4] All costs in this study are treated without consideration for whether incurred costs are public or private.

For each USGS map, the length of levees to be raised is divided into three categories of existing heights based on percentages of these categories established from detailed maps of levee elevations in the region. The new heights for the levees are determined from Table IV, and the total quantities of length of levee, multiplied by height to be raised, are calculated for each map. Areas not presently protected are given protection determined to be appropriate, generally new levees, or if the region has little development, no protection is allotted and any

[4] In one study (URS 1988), new levees designed with the capacity to be raised 2.5 feet cost about 20 percent more than levees without this feature. The costs for later modifying levees to accommodate the added height would, however, be substantially greater than this.

small structures are raised.

Where a bulkhead or seawall presently exists, it is assumed to be raised by one meter. Any railroads or freeways within the future 100-Year HET elevation contour line are assumed to be raised by one meter, unless they can be protected by a less-expensive levee system.

Table VI Quantities and Costs for Protection of the Shoreline of San Francisco Bay

Item	South Bay Golden Gate to Alviso (feet)	North Bay Golden Gate to Vallejo (feet)	Suisun Bay Vallejo to Pittsburg (feet)
New Levee – 15 feet high	198,900	0	0
New Levee – 13 feet high	65,000	111,700	63,000
New Seawall – 13 feet high	23,400	0	0
Raise Roadway – 1 meter vert.	107,600	78,200	93,400
Raise Railroad – 1 meter vert.	103,500	151,300	174,700
Beach Nourishment	10,200	0	0
Raise Bulkhead – 1 meter vert.	515,800	311,700	116,800
Raise Levee – varying heights	1,586,000	568,700	409,200
Raise Structure (no. of structures)	66	69	179

Notes:

- All units are in linear feet, except raising of structures, which are numbers of structures affected. Values are rounded.
- The units presented in this table are not in the form of the unit costs presented separately. For example, the linear footage of raised roadway shown above includes 2 through 8 lane roads, while the unit cost used varies for each width.

REGION OF BAY	TOTAL COST
South Bay – Golden Gate to Alviso	$564,400,000
North Bay – Golden Gate to Vallejo	$219,100,000
Suisun Bay – Vallejo to Pittsburg	$158,800,000
Total Cost of Protection for San Francisco Bay:	**$942,300,000**

Using this approach, we estimate the cost of protecting existing development in San Francisco Bay from a one-meter sea-level rise to exceed $940 million. The costs for the three sections of the Bay are listed in Table VI. We also reiterate that these costs do not include any costs for protecting wetlands, active structures such as navigation locks, pumps, and drainage systems, or periodic costs of maintaining protective structures.

In order to check our approach, we compared our method of determining costs of protection with detailed studies of two regions within the Bay -- the towns of Corte Madera and Foster City. Engineering studies have already been completed for these towns because of their locations in low-lying, vulnerable Bay lands (URS 1988, Valkenaar, personal communication). Table VII shows the results of comparing the general method used in the present study with the more accurate engineering approach required for any particular site. Given the uncertainties and simplifying assumptions described in Part 1, Section V, these methods give quite similar answers.

Table VII Comparison of Assessment Methods: This Study and Two Detailed Case Studies in San Francisco Bay

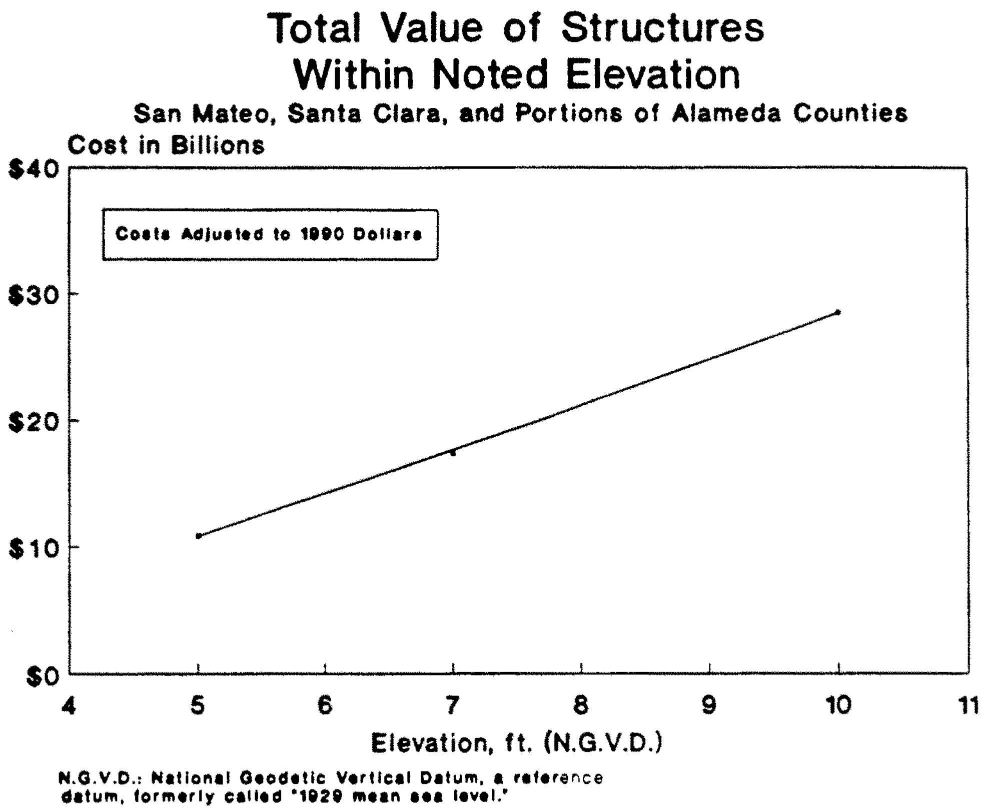
Site	This Study	Detailed Engineering Study
Foster City, San Mateo Co.	$12,300,000 (raise existing levees, some new levees)	$12,000,000 – $14,000,000 (raise levees, or add walls where space is limited)
Corte Madera, Marin Co.	$5,800,000 (raise existing levees, some new levees)	$6,500,000 (levee improvements, navigation lock, offshore tidal barrier

Note:

- Each study uses different assumptions and approaches. For Corte Madera details, see URS (1988); Foster City details provided by Valkenaar (personal communication).

To compare the above costs for improving the existing shore protection with some measure of the value of property threatened for the San Francisco Bay shoreline, we include Figure 6. This shows the approximate value of structures within certain elevations around the south Bay. It can be seen that about $29 billion (1990 dollars) worth of structures lie below the 10-foot N.G.V.D. (National Geodetic Vertical Datum) contour in three counties around the Bay. The area within this contour represents the approximate area at risk from flooding from the 100-year high tide with a one-meter sea-level rise. This area is illustrated on Figures 7 and 8. The data used to derive these values were obtained from file reports of the U.S. Army Corps of Engineers for the economic inventory of the San Francisco Bay Shoreline Study and brought to current 1990 values. These figures were then extrapolated using the cost per unit area for developed portions of the South Bay for which data were available and applying this to developed areas in the entire Bay within the 10-foot N.G.V.D. contour. We estimate that structures valued at $48 billion (1990 dollars) are at risk of flooding.

Figure 6 Value of Structures versus Elevation in South San Francisco Bay



It should be noted that these values are total values of threatened structures, not the actual value of that portion of property that would be damaged by a flood to the shown elevation. The U.S. Army Corps correlates the amount of damage to a structure with its level of inundation, which is based on a first-floor elevation of an individual structure, the ground elevation in the area, the flood elevation, and an estimate of contents. This type of calculation produces an estimated value of damaged property from a certain flood elevation less than the total value of the property.

Despite the difficulty of determining the economic value of ecosystem functions, one estimate suggests that marshes provide an annual return equivalent to $5500 per acre (1983 dollars) (Thurman 1983). Another estimate is that the cost of "restoring" marsh in San Francisco Bay on suitable land averages about $15,000 per acre (1984 dollars) (Barth and Titus 1984), but costs can be as high as $100,000 per acre where extensive work is required (Haltiner, personal communication). We note that restored wetlands rarely replace all of the natural functions of natural ecosystems; nevertheless, marsh restoration is increasingly seen as a possible response to development. A massive effort to protect or restore half of the present amount of wetlands in the Bay could easily cost one billion dollars, assuming adequate methods and land was available.

Other costs not included above are the costs of maintaining protective measures. Assuming an average figure of 10 percent per year of the construction costs -- as described in Part 1 -- could add around $100 million per year to the total costs.

Figure 7 Area of San Francisco Bay Threatened by a 1-meter Sea-Level Rise: Southern Portion

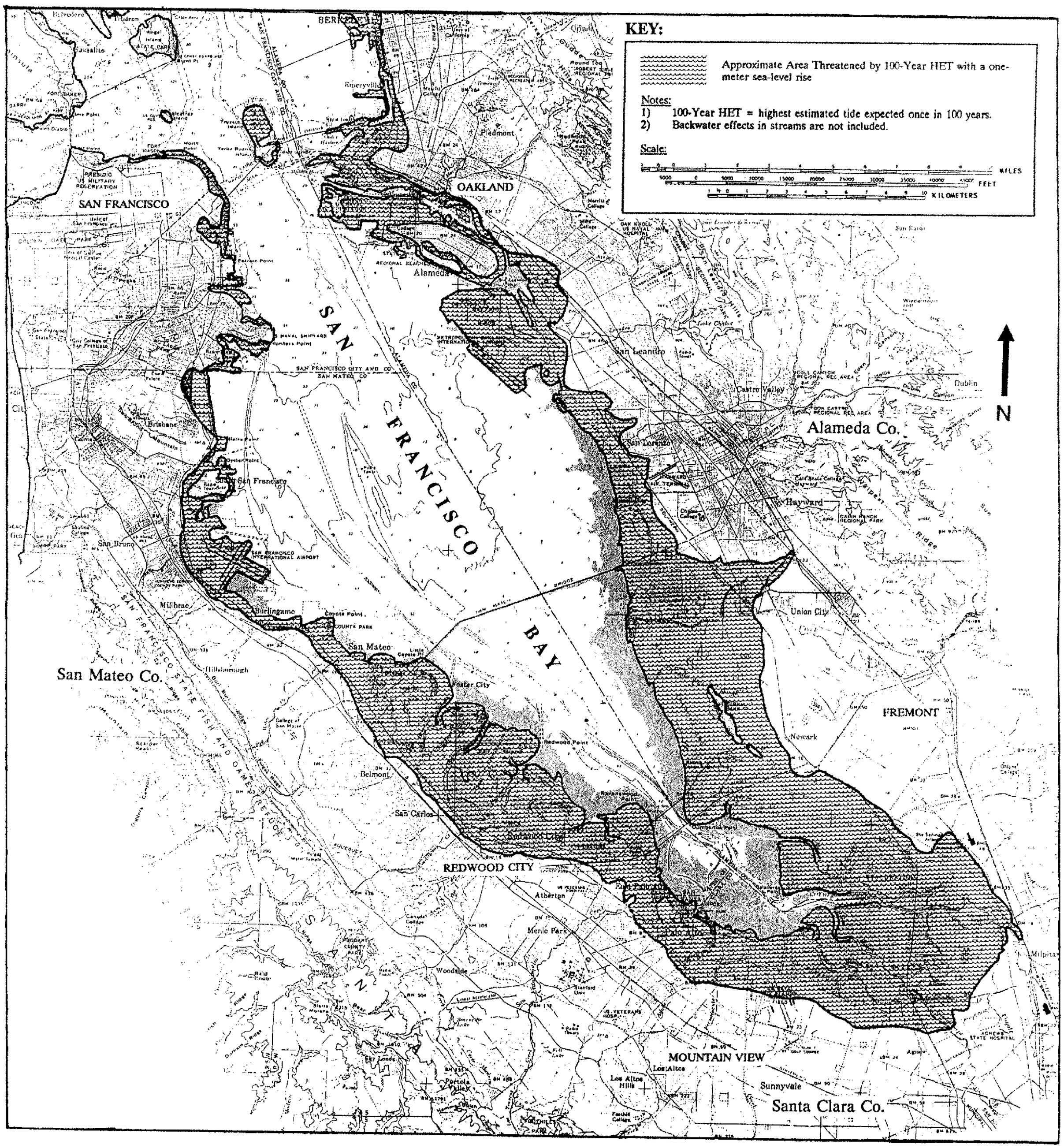
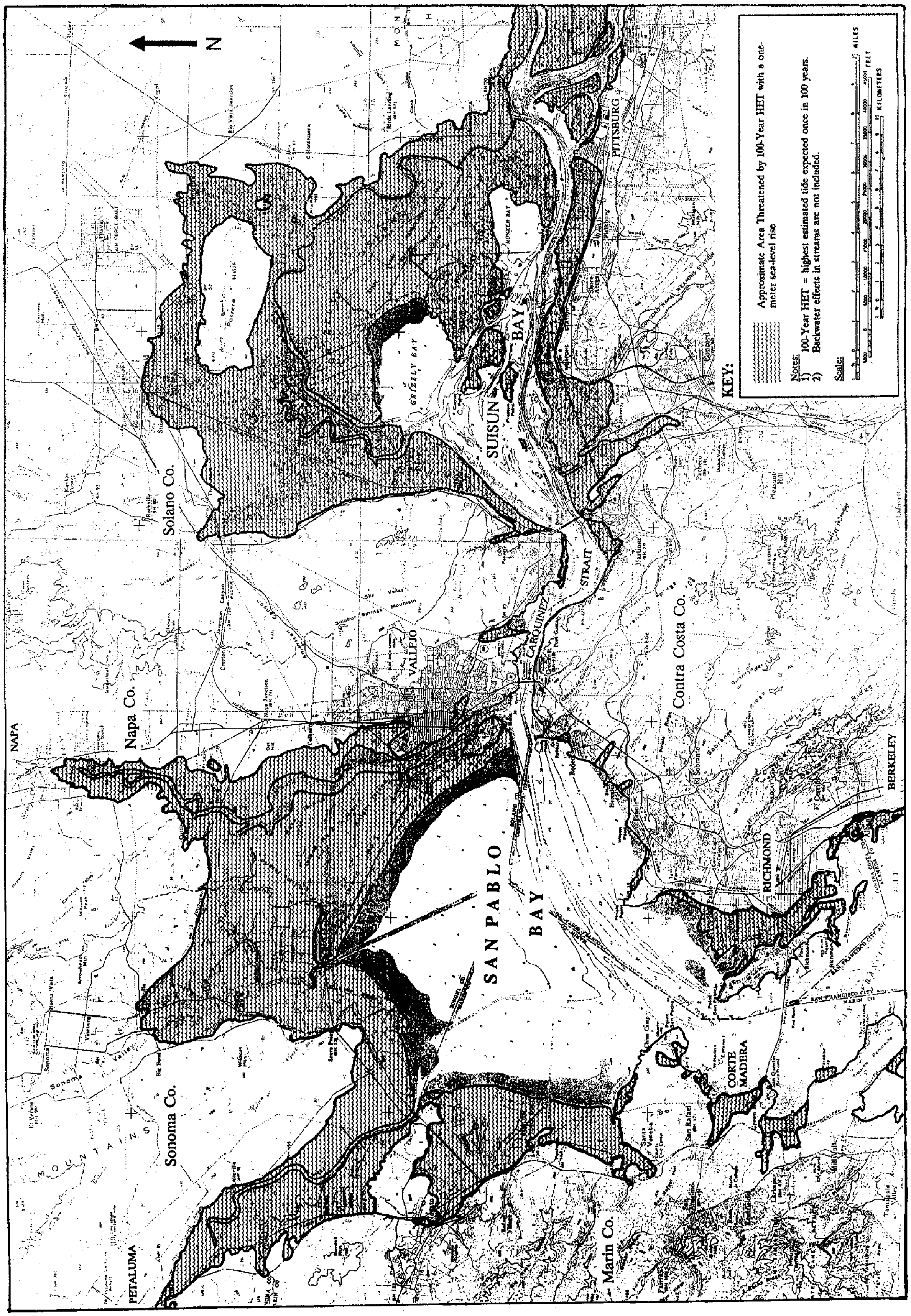


Figure 8 Area of San Francisco Bay Threatened by a 1-meter Sea-Level Rise: Northern Portion



VI. CONCLUSIONS

Coasts have always been threatened by severe storms, which lead to loss of life, destruction of property, and the construction of expensive coastal protection measures. Many coastal regions have high economic real estate value, and hence justify expensive engineering solutions. But now, a new threat to waterfront property is emerging -- global climate change and sea-level rise. Global climatic changes will increase the risks to society by raising sea level and changing the frequency and intensity of storms.

Despite scientific and social uncertainties, public agencies responsible for coastal protection and development must begin now to consider the effects of future sea level in current planning. Even under a scenario of slow rise in sea level, the damaging effects of storms will increase rapidly, and one-meter rise could erode coastal shorelines by over 100 meters. In San Francisco Bay, a sea-level rise of only 15 centimeters (5.9 inches) would change a 1-in-100 year storm into a 1-in-10 year storm.

A one-meter sea-level rise in San Francisco Bay would threaten a wide area with commercial, industrial, and residential development, valued at nearly $48 billion for just existing buildings. The resources at risk include ports and docks, factories, residential sub-divisions, transportation facilities such as airports, freeways, and railroads, wastewater treatment plants and waste disposal sites, military facilities, and a wide variety of natural ecosystems. Possible responses include constructing new levees, bulkheads, or seawalls in unprotected areas, raising and improving levees and bulkheads where they already exist, raising or moving other structures, freeways, and railroads where necessary, replenishing beaches with sand, and protecting or restoring wetlands.

For the San Francisco Bay, the costs of protecting just existing developments would exceed $940 million (1990 dollars), excluding the costs of protecting natural ecosystems, active structures such as drainage systems and navigation locks, and hard-to-quantify social costs. Such costs could easily exceed an additional $1 billion. Also not included are any costs of regularly maintaining protective structures, which could run to $100 million per year. No attempt was made here to evaluate the costs of protecting the Sacramento/San Joaquin Delta or the coast outside of the Golden Gate.

Despite the limitations to this type of economic analysis and the many things that are poorly quantified or unquantifiable, we conclude that sea-level rise will pose great economic and environmental threats to San Francisco Bay. Taking no actions runs the risk of loss of life, increased property damage, and wetlands loss due to more frequent, damaging storms. Selective protection could somewhat reduce, but not eliminate, the greater risks of damage. Extensive protection would have high immediate costs, but would significantly reduce the long-term economic risks to developed areas. Complete protection is not possible, particularly for the valuable remaining natural ecosystems of San Francisco Bay. The magnitude of the problem of sea-level rise requires that we begin to understand the threats that we face and the responses available to us.

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APPENDIX 1

CALCULATION OF SOUTH BAY RESONANCE

The following calculations are based on the assumptions described in Sanitary Engineering Research Laboratory (1966) used in developing the relationships. The theoretical propogation of a frictionless long-wave in a channel of constant cross section is equal to $(gD)^{1/2}$, where g is gravitational acceleration, and D is water depth. The length of the tidal wave is then $T(gD)^{1/2}$, where T is the wave period.

The time that it takes for the wave to travel the length of the reach (i.e. the distance from the Golden Gate to the south end of the Bay at Alviso) is $L^*/(gD)^{1/2}$, where L^* is the length of the reach. The ratio of the length of the reach to the wave length is then:

$$L^*/L = t^*/T = L^*/T(gD)^{1/2}$$

The time of travel of the frictionless tidal wave through each of the sections shown in the following calculations is then:

$$t^* \approx \_\ \_x_i/(gD_i)^{1/2}$$

where $\_x_i$ is the incremental length of the section, D_i is the average hydraulic depth of the section, and the sum is taken over all sections in the reach.

The calculations for the present and for the scenario of a one-meter water level rise are shown on the attached spreadsheet. The attached figures show the locations of the stations and sections.

Figure 9 South Bay Tidal Resonance Calculations

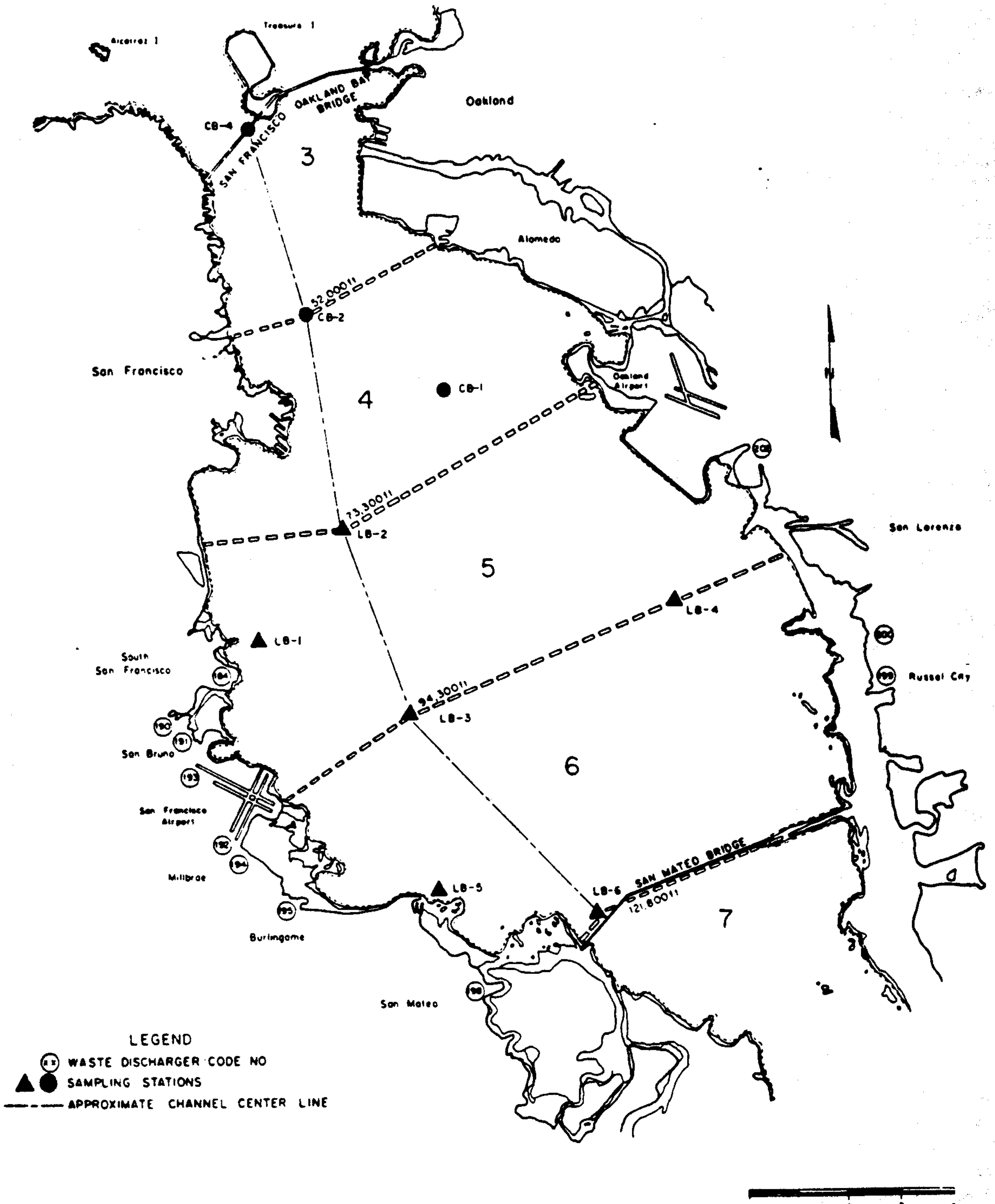
Resonance Calculation for the Southern Reach of San Francisco Bay with a one meter, or 3.28 feet depth increase

				at old depth					at new depth		
Station	Section	Dist from Gold Gate ft	Length of Sect ft	X-Sect area ft^2	Hydr. Depth ft	Mean Tide Range ft	(gD(i))^.5 ft/sec	dx(i)/ (gdi)^.5 hour	Depth (old+incr) ft	(gD(i))^.5 ft/sec	dx(i)/ (gdi)^.5 hour
cb-6		0		938,000	177.0	4.0					
cb-5		16,510				4.1					
	2										
cb-4		32,320		825,000		4.3					
	3	42,160	19,680	850,000	38.7		35.30	.15	41.98	36.77	.15
cb-2		52,000		915,000		4.5					
	4	62,650	21,300	890,000	24.4		28.03	.21	27.68	29.86	.20
lb-2		73,500		920,000		4.8					
	5	83,800	21,000	1,030,000	16.9		23.33	.25	20.18	25.49	.23
lb-3		94,300		820,000		5.2					
	6	108,100	27,600	653,000	12.2		19.82	.39	15.48	22.33	.34
lb-6		121,900		333,000		5.6					
	7	129,700	15,600	359,000	14.0		21.23	.20	17.28	23.59	.18
sb-3a		137,500		292,000		5.9					
	8	143,350	11,700	286,300	13.7		21.00	.15	16.98	23.38	.14
sb-1		149,200		232,000		6.1					
	9	159,475	20,550	165,500	11.4		19.16	.30	14.68	21.74	.26
sb-4		169,750		101,000		6.4					
	10	177,775	16,050	126,200	11.2		18.99	.23	14.48	21.59	.21
sb-5		185,800		92,000		6.7					
	11	191,050	10,500	65,710	6.8		14.80	.20	10.08	18.02	.16
sb-6		196,300		3,700		6.9					
	12	200,050	7,500	33,070	6.8		14.80	.14	10.08	18.02	.12
sb-7		203,800		19,400		7.1					
	13	208,450	9,300	19,350	7.6		15.64	.17	10.88	18.72	.14
sb-8		213,100		10,300		7.3					
	14	215,800	5,400	8,240	5.1		12.81	.12	8.38	16.43	.09
sb-9		218,500		6,900		7.4					
	15	226,750	16,500	3,200	4.5		12.04	.38	7.78	15.83	.29
								=========			=========
						t* =		2.90			2.51
					L*/L =	t*/T =		.23			.20

Notes:

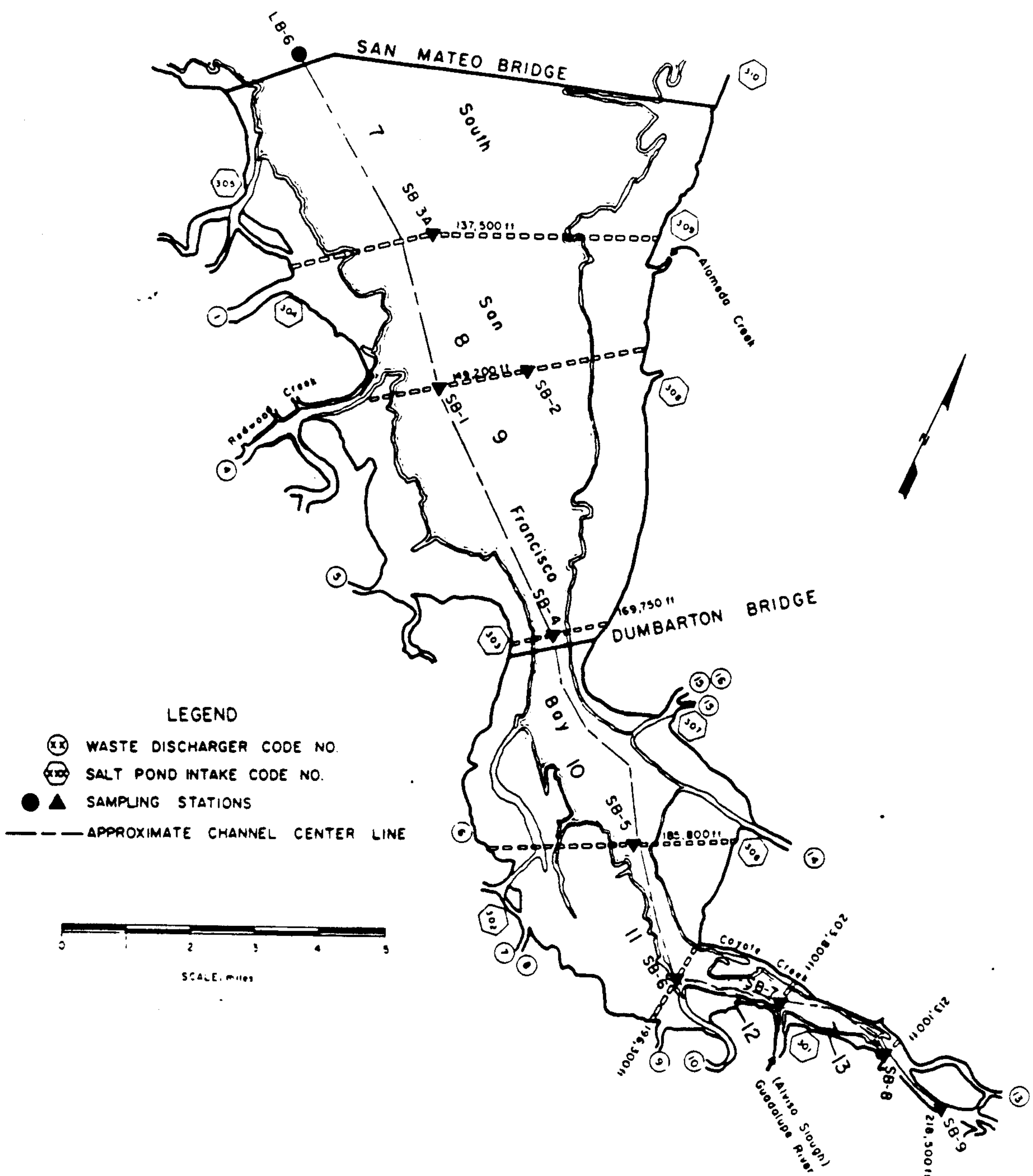
1) The period, T, of the tide wave is 12.42 hours.
2) Physical data for the Bay, and the calculation method, is taken from Sanitary Engineering Research Laboratory (1966).
3) The increase in depth of 3.28 feet (one meter) is assumed to occur without a significant increase in the width or length of the portion of the Bay being considered.
4) The L*/L ratio is the ratio of the effective length of the bay to the natural wavelength of the tide wave.

Figure 10 San Francisco Bay Sections: Above San Mateo Bridge



Adapted from: Sanitary Engineering Research Laboratory (1966)

Figure 11 San Francisco Bay Sections: Below San Mateo Bridge



Adapted from: Sanitary Engineering Research Laboratory (1966)