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June 1, 1989

To: Commissioners

From: Richard McCarthy RJM

Subject: Commission Comments on "Planning for an Accelerated Sea Level Along the California Coast."

Recent scientific studies measure dramatic increases of atmospheric greenhouse gases and predict a rise in temperature or a "global warming." One of the impacts associated with global warming is an accelerated rate of sea level rise. The attached report does not predict a rise in sea level. Rather, the purpose of the report is to inform the Commission of possible consequences to the California coast should the global warming scenarios presented in numerous scientific studies occur.

Representatives of the U.S. Congress, the California Legislature, the media, and local governments, have requested information from Commission staff regarding the impact of an accelerated sea level rise on the California coast. Therefore, Commission review of and comment on this document is important and should generate discussion regarding ways to address this problem.

This study utilizes graphics and tables to explain the manner in which the impacts of a rising sea level are predicted. Predicted erosion rates, estimates of relative severity of impact, and estimates of relative economic loss, are based on the best data available to the Commission. Data in future studies will most likely differ from that presented in this document. However, the report concludes that high rates of sea level rise could dramatically impact the California coast.

Due to the length of this report, it may not be possible to review it in its entirety. Therefore, I suggest that the Commissioners:

- o Review the Executive Summary;
- o review the Table of Contents to become familiar with the subjects covered in the report;
- o skim the report and pay particular attention to data presented in Figures and Tables; and,
- o read Sections 8.0 (Conclusions) and 9.0 (Recommendations).

S.F. CHRONICLE 4/20/89

Scientists Report Sea Rising Faster Than They Thought

Los Angeles Times

Washington

New measurements reveal that the oceans are warming and rising about twice as rapidly as scientists had thought, strongly suggesting that greenhouse warming caused by the burning of fossil fuels has already begun, researchers said yesterday.

Satellite data indicate that the temperature of the Earth's oceans has been rising at a rate of nearly 0.2 degrees Fahrenheit through most of the 1980s, according to a report scheduled for publication today in the journal Nature.

"We may be just beginning to witness the onset of (greenhouse) warming" produced by the accumulation of carbon dioxide in the atmosphere, according to oceanographer Alan Strong of the National Oceanographic and Atmospheric Administration in Suitland, Md.

Coincidentally, Richard Peltier of the University of Toronto reported yesterday at an American Geophysical Union meeting in Snowbird, Utah, that the level of the oceans is rising about one-twelfth of an inch per year — an outcome of greenhouse warming that researchers have long predicted.

Unprecedented Heat

Combined with recently reported data that five of the hottest years in recorded history have occurred during the 1980s — perhaps as a result of the greenhouse effect — the new reports offer evidence that the Earth may already have entered a period of unprecedented heat. The reports seem to add new urgency to predictions that greenhouse warming will lead to widespread coastal flooding and even to the obliteration of some island nations, such as the Maldive Islands.

"This is very important work," said glaciologist Richard Williams of the U.S. Geological Survey. "It has taken a long time to get people's attention, but it is happening now."

Monitoring ocean temperatures has been particularly difficult in the past because of the vastness of the oceans. Such measurements typically are provided by instruments on floating buoys and by ships traversing cargo routes, leaving large areas unmonitored.

In contrast, satellite measurements, which are rapidly becoming the foremost way to monitor global change, cover virtually all areas of the globe and provide as many as 3 million observations per month. The satellite measurements are compared closely with measurements from buoys and ships to ensure accuracy of the data, Strong said.

Caution Urged

Peltier told the geophysical meeting yesterday that his measurements yield an average increase in ocean level of about one-twelfth of an inch each year during the 1980s, about twice the rate scientists had previously estimated. He noted, however, that the measurements must be interpreted cautiously because there are few tidal measurements in the southern hemisphere.

Most oceanographers agree that the level of the oceans has risen as much as two inches over the last century. Various projections of the increase that will result from greenhouse warming range from 10 feet to 25 feet by the end of the next century.

Some of that increase, perhaps as much as a third, is due to expansion of the oceans as they have warmed. Beyond that expansion, however, "the only obvious explanation" is melting of glaciers, Williams said.

So far, he added, most of the Antarctic ice that has disappeared has been floating ice, whose melting will have no effect on ocean levels since the ice was already in the water. But as the fronts of the glaciers retreat, he said, ice resting on land will melt, and that will lead to a much greater increase.

Such increases, experts predict, would cause large-scale flooding along the Eastern Seaboard of the United States, as well as in other low-lying areas.

Taiwanese Boat Suspected of Illegal Fishing

Associated Press

Anchorage

A Taiwanese boat suspected of illegal salmon fishing off the Aleutian Islands steamed home yesterday, trailed by a Coast Guard cutter seeking permission from Taiwan to board the vessel.

"It's going its way, and we're following," said Greg Robinson, a Coast Guard spokesman in Juneau.

Because the boat, the Cyi Yang No. 1, is in international waters, the Coast Guard cannot board it without permission, Robinson said.

The incident began Sunday when the crew of the Cyi Yang warned the Jarvis, a Coast Guard cutter on patrol five miles away, that drift nets were in the water and that it should stay away, said Bill Woolf, an aide to Senator Frank Murkowski, R-Alaska.

2390N

COMMISSION DRAFT:
PLANNING FOR AN ACCELERATED SEA LEVEL RISE ALONG THE CALIFORNIA COAST

Prepared by the California Coastal Commission

Lesley Ewing
Jaime Michaels
Dick McCarthy

TABLE OF CONTENTS

FIGURES AND TABLES

EXECUTIVE SUMMARY

The California coast is an invaluable social, economic and ecological resource. Over 60% of California's population lives within the fifteen coastal counties and this percentage is expected to increase dramatically by the year 2000. Today, approximately 86% of California's 1,100 mile coastline is eroding. Almost 10% of this eroding coastline now requires engineered shoreline protective structures (seawalls, jetties, groins) to prevent the destruction of harbors, ocean front structures, cliffs, highways, beaches and wetlands. Nonstructural shoreline protective methods include beach nourishment programs and setback requirements for shoreline or blufftop development.

GLOBAL SEA LEVEL RISE

Within the last few years, numerous scientists, state and federal agencies, and decision makers have become concerned about the potential impacts of global warming on coastal resources. Early in 1988, AB 4420 (Sher) was enacted calling for the California Energy Commission to study how global warming trends may affect the state's energy supply and demand, economy, environment, agriculture, and water supplies. This report is to be completed by June 1, 1990.

One of the most severe consequences of global warming could be a rise in sea level. Another study, completed by the U.S. Environmental Protection Agency, predicts that sea level could rise 1.5 to 11 feet within the next 100 years (Figure 4-1). A rise in sea level within this range would expose California's coast to flooding and higher wave run-up, reduce the effectiveness of existing shoreline protective works, increase shoreline recession rates, impact wetlands, and alter beach nourishment programs.

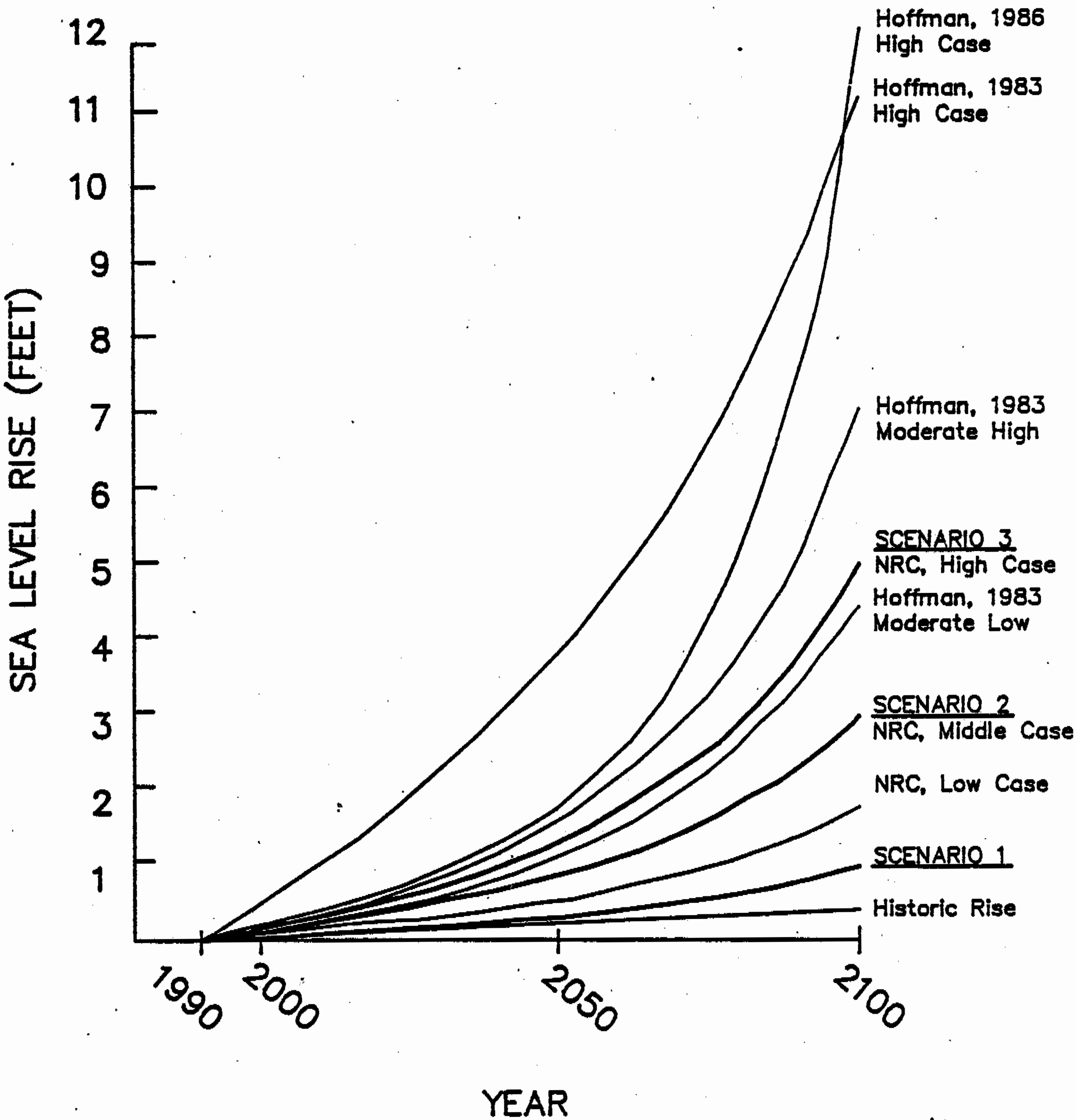
As the earth's temperature increases, the available surface water warms and seas rise due to thermal expansion. Warming also causes glacial recession. This retreat releases water previously bound in glaciers and ice caps increasing the supplies of available surface water

In general, researchers detect a recent global, or eustatic rise in sea level, of about 0.1 to 0.2 cm/yr (0.04 to 0.08 in/yr.) This is an estimate of the rate of global sea level rise due to thermal expansion of the oceans and an ocean volume increase due to the melting of ice sheets.

Changes in sea level tend to lag global climate changes by years or even decades since water has a different thermal capacity than air. The historic rise in sea level reflects a historic rise in mean global temperature, but does not mirror climatic changes on a month to month or year to year basis.

One of the major uncertainties in any scenario of sea level rise is the fate of the West Antarctic Ice Sheet. This sheet may have disappeared during the last interglacial period when average temperatures were 1 to 2 deg. C. warmer than today. This disappearance is believed to be a major cause of the interglacial sea level which was 5 to 7 meters higher than present levels. Unlike gradual sea level rise from expansion of ocean water or increased runoff from land based glaciers, the increase from the West Antarctic Ice Sheet could be rapid and difficult to predict.

FIGURE 4–1
GLOBAL SEA LEVEL RISE SCENARIOS
(using 1990 as the base year)



RELATIVE SEA LEVEL RISE ALONG THE CALIFORNIA COAST

The present day California coast is a tectonic collage of various terraines, formed by millions of years of plate motions. In general, three types of crustal movement occur along the California coast; vertical movement due to normal or reverse faulting, horizontal movement due to strike-slip faulting, and uplift or subsidence due to folding. One problem with determining the rate of uplift or subsidence along the California coast is that in many locations, all three types of movements occur simultaneously. Rates of uplift or subsidence between sites located relatively close together differ greatly.

Since California has an active coastline with significant uplift or subsidence rates through much of the state, any consideration of sea level rise must take this motion into account. The following equation can be used to determine relative sea level, at any location:

$$\text{Relative Sea Level} = \text{Global Sea Level} \pm \text{Change in Land Elevation}$$

EFFECTS OF SEA LEVEL RISE ON COASTAL WETLANDS

A relatively rapid sea level rise may impose extraordinary stress on coastal wetlands which are vitally important ecosystems and perform important recreational and economic functions. Any loss of wetland habitat to sea level rise would result in a loss of spawning and feeding grounds for estuarine and anadromous fish, endangered species and waterfowl, and a loss of a significant economic and social resource.

Most coastal wetlands are located at elevations ranging from mean sea level to approximately 3.5 meters above sea level. In most cases, a sea level rise equivalent in elevation to one single tidal range (the difference between mean high and mean low) would drown many of California's coastal wetlands. Therefore, any permanent rise in sea level will impact wetland areas and could result in an ecological and social loss of these systems which could be irreparable.

California's 145 coastal wetland systems are influenced by continuous sea level change (high tides, storm surge, el Nino) to which they regularly adapt. Regular routes of oxygen transport to plants are interrupted by inundation, but wetland flora undergo structural or chemical transformations to tolerate the excess water.

As a result of prolonged submergence, the normal structural and chemical transformations may be inhibited and ultimately adversely affect plant growth and productivity. In general, a wetland's long term survival is determined by its ability to maintain surface elevations required for continued plant growth, through sediment accumulation, or by the available space on which to migrate both upward and landward.

Unlike the gradual or temporary rises in sea level associated with natural processes, a rapid rise may impose extraordinary stress on coastal wetlands and cause them to react abnormally to a rising sea. With accelerated sea level rise, plants in lower tidal elevations would undergo prolonged submergence ultimately impeding vegetative growth. The most likely effect of prolonged inundation in the lower wetland areas due to the salinity and oxygen changes would be a loss of plant biomass. A reduction in vegetation, in turn, reduces sediment entrapment and adversely affects the mechanism necessary for the wetland to "keep up" with rising sea level. The loss of plants and increased erosion in this area would result in a net loss of wetland habitat in the lower levels. If wetland vertical buildup does not take place relative to sea level, the system could eventually drown.

If sedimentation rates remain high, a wetland may overcome its losses to rising sea levels by migrating upland and thus altering its former pattern by moving into areas previously associated with high or transition wetland zones. However, the degree of slope and the presence of landward obstructions will facilitate or inhibit a wetland's upland shift.

Restricted use of the upland areas could ultimately enable a wetland to migrate upland. Besides abandoning high risk areas and allowing nature to take its course, it is possible to artificially manage the hydrologic cycle or stabilize and defend the areas by employing engineering devices, and thus prevent sea level rise from taking its toll on these areas.

Despite the many uncertainties surrounding possible sea level rise, state agencies, like the Bay Conservation Development Commission, have begun to incorporate the concept of sea level rise into their management plans. The state's other coastal permit authorities and wetland management agencies including the California Coastal Commission, should begin to consider the matter of sea level rise in their land use plans to make future wetland management more effective.

BEACH EROSION AND CLIFF RETREAT

Existing erosion along the California coast is episodic and site specific. It may be due, in part, to existing sea level rise, wave conditions, or insufficient supplies of beach material to develop equilibrium conditions. Along coastal beaches the major effect of sea level rise will be in reducing beach size making summer beaches narrower and entirely submerging winter beaches. Large winter storms could carry beach material too far offshore to be returned to shore by summer waves. Many pocket beaches may undergo areal reduction or total removal.

Along cliffed coasts, the major effect of sea level rise will be the inundation of the talus protection in front of the cliff and cliff undercutting at the new water line. Accelerated cliff retreat could occur since the cliff would be exposed to wave attack more often throughout the year. Beach protection in front of the cliff would be reduced or lost as material moved to deeper water.

If decision makers are convinced that sea level rise is a potential hazard to development, then the impact of sea level rise on a proposed development must be considered during the planning process. Since sea level rise is expected to be gradual, protective steps can be taken as specific problems develop. Beach areas can be nourished, and in some areas perched beaches may be desirable. Solutions available for dealing with sea level rise are numerous and beyond the scope of this initial report. However, fixed, unalterable solutions should be avoided. An inflexible solution based on a single projection of sea level rise could provide only a temporary solution if sea level rises higher than originally projected and an unnecessarily expensive solution if sea level rise is lower than anticipated.

EFFECTS OF SEA LEVEL RISE ON HARBORS AND COASTAL STRUCTURES

Increased water levels and wave heights should have little effect on harbors with entrances uncontolled by jetties or breakwaters. During storm conditions, ingress and egress will be more difficult and there may be days when ships should not leave the protection of the harbor. In harbors with controlled entrances, however, the increased water levels and wave heights could cause overtopping of jetties protecting the harbor. Overtopping could damage the jetty and overtopping waves would make the harbor waters more choppy. Since portions of the harbor must be deep enough for ships, waves which enter the harbor may not be dampened by the harbor topography. Large storm waves could do serious damage to port facilitites and ships in the harbor.

Increased water levels and wave heights can adversely affect piers in several ways. Greater wave heights will exert increased force on the pier supports. Also, higher water levels and wave forces can increase the uplifting forces on horizontal portions of piers and the decks of offshore oil platforms. Another impact of a higher sea level on piers will be on their cargo function. Each foot of sea level rise will raise a ship one foot.

Seawalls and revetments protect inland areas from erosion and wave forces, and their effectiveness is determined by their ability to withstand the force of incoming waves and the effects of overtopping. An increase in sea level will increase forces on the wall and the frequency of overtopping; the seawall or revetment will provide less protection to an inland structure. A second effect of sea level rise may be erosion of the shoreline seaward of the structure. This would reduce the stability of the structure and reduce its resistance to overtopping forces. If sea level rises, the seawall or revetment will require additional height to maintain the same level of design protection and the foundation may require deepening to maintain structural stability.

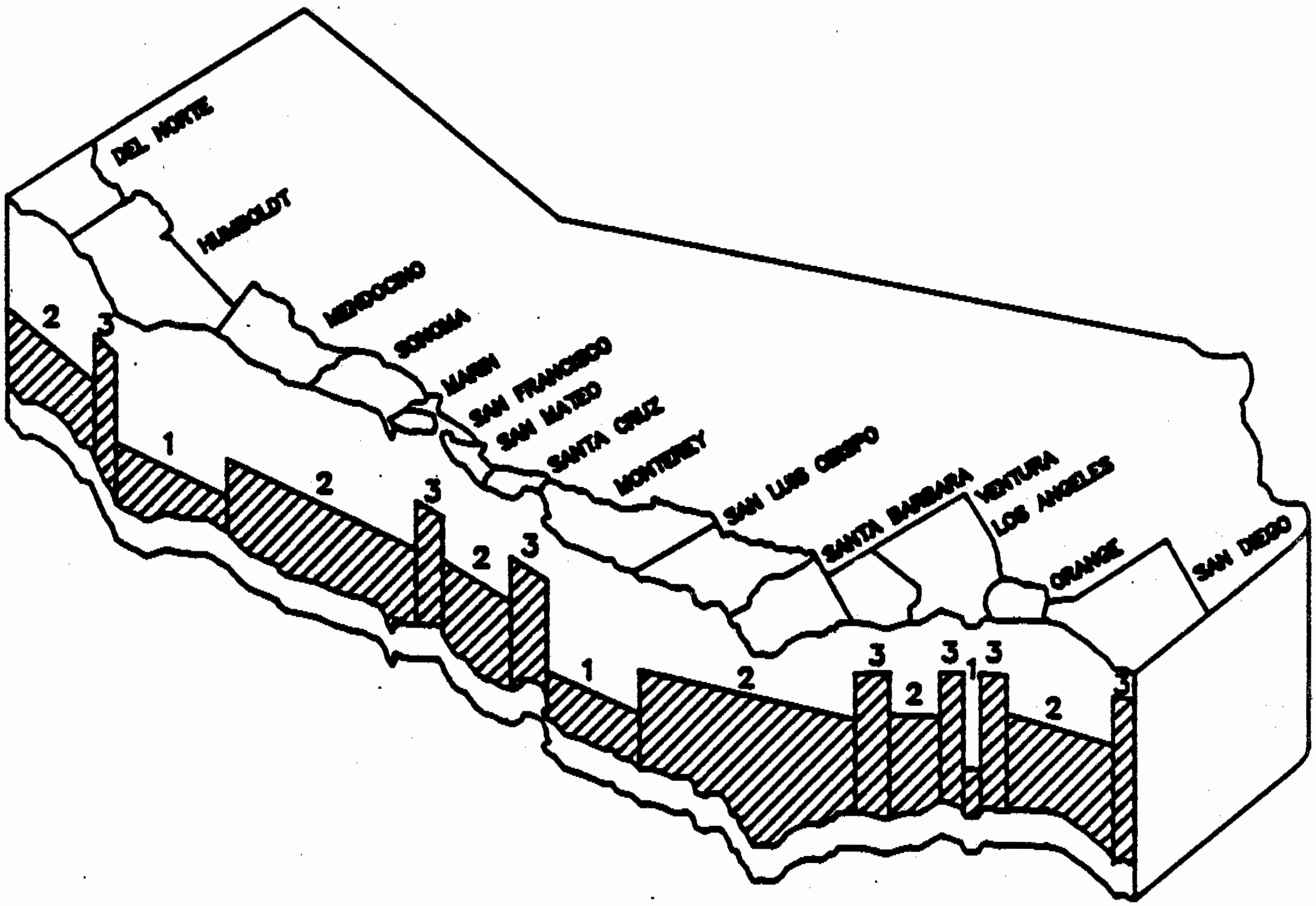
Most structures along the coast have been designed for present-day water levels and wave conditions, but most structures can be modified or rebuilt to maintain acceptable protection in the event of sea level rise. The effects of sea level rise will be most significant during strong storm events. Periodic examination of structures against current sea level conditions may be necessary to assess and develop proper structural reinforcement measures. If structures are not modified, the anticipated level of protection from the structure should be reduced to reflect the current sea level conditions.

RELATIVE SEVERITY OF IMPACT FROM AN ACCELERATED SEA LEVEL RISE

If a substantial rapid rise in sea level occurs due to global warming, much of the California coast will be adversely affected. Even areas undergoing rapid rates of uplift, such as the Santa Barbara to Ventura coast, will experience beach erosion, bluff retreat, and submergence of lowland areas. This report examines the impacts of three accelerated sea level scenarios by the year 2100; 1 foot, three feet, and five feet. Figure 8-1 shows the relative severity of impact from a 5 foot rise (Scenario 3) in sea level by the year 2100. This figure shows the highest impact occurring in low-lying areas undergoing complete inundation, the moderately severe impact at locations where broad beaches or cliffs are protected by talus, and the least impact at locations where steep coastal cliffs consist of resistant rock units. In short, this figure illustrates that a 5 foot rise in sea level occuring by year 2100, would cause extensive localized flooding and erosion.

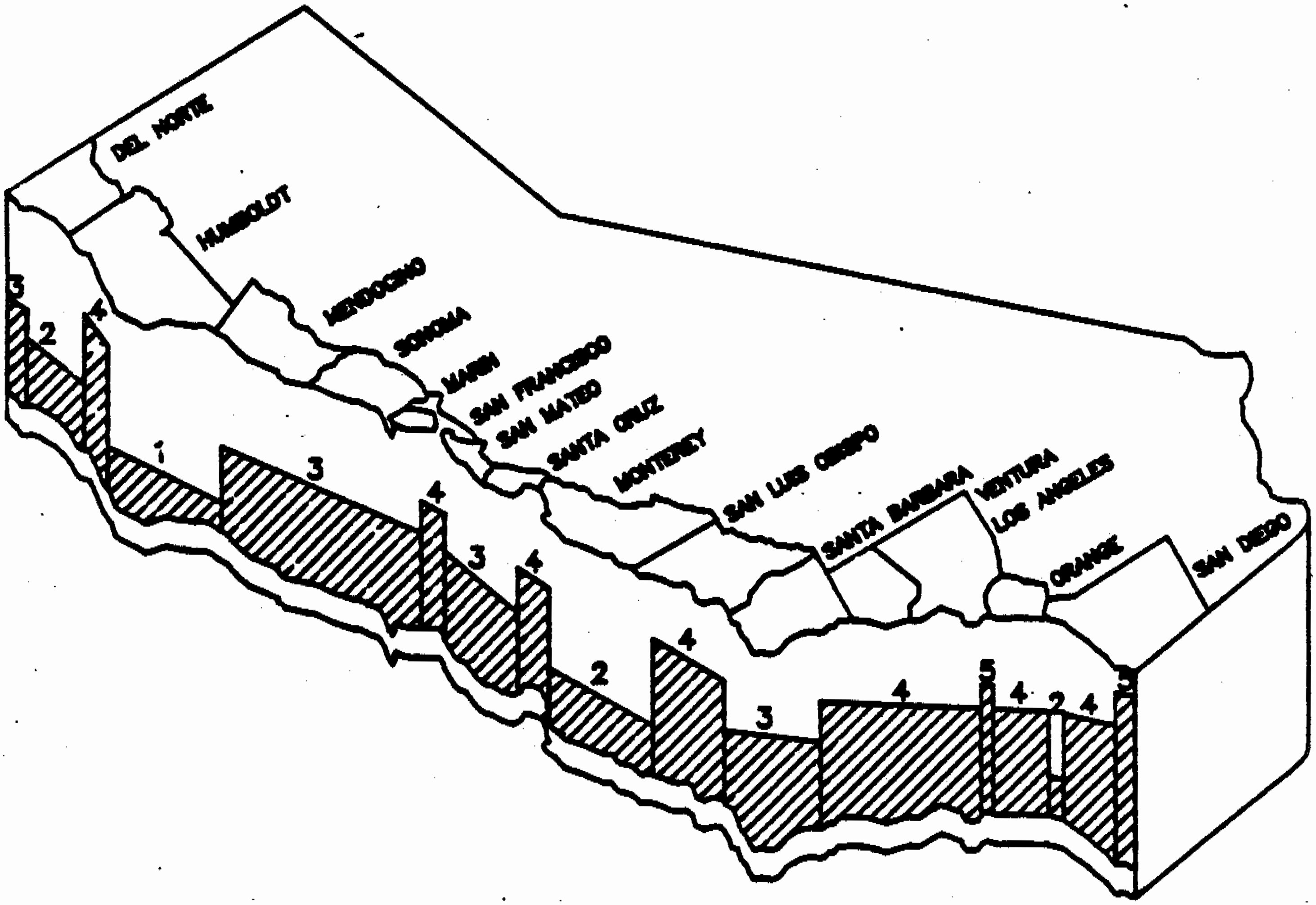
The loss of shoreline due to sea level rise in California will have a profound economic impact on California. Figure 8-2 shows relative economic loss associated with a 5 foot rise in sea level (Scenario 3) by the year 2100. This figure illustrates where a significant loss of buildings, roads, and beaches would take place. The greatest economic loss will occur to structures located on beaches, coastal cliffs, and within or surrounding harbors. The least dollar loss will occur along sections of the coast where the shoreline can migrate landward without impedence by structures. These figures reflect a best guess estimate of the relative amount of erosion,flooding, and economic losses along the California coast should a 5 foot sea level rise occur. They do not predict a sea level rise of 5 feet!

FIGURE 8-1
RELATIVE SEVERITY OF IMPACT FROM SEA LEVEL RISE
5 FOOT RISE BY 2100 (SCENARIO 3)



The relative severity of impact is an estimate of the extent of flooding, erosion and cliff retreat that is likely to occur from a 5 foot rise in sea level by the year 2100. The greatest impact is expected to occur in low lying areas which will be completely inundated, indicated as Impact Level 3. Less impact will occur where there are broad beaches or cliffs protected by talus, indicated as Impact Level 2. The least impact will occur where the shoreline is steeply cliffed and comprised of resistant rock units, indicated as Impact Level 1.

FIGURE 8-2
RELATIVE ECONOMIC LOSS FROM SEA LEVEL RISE
5 FOOT RISE BY 2100 (SCENARIO 3)



Relative economic loss estimates the comparative extent of property damage that is likely to occur from a 5 foot rise in sea level by the year 2100. This assumes that no major shoreline protection projects are undertaken. The greatest loss will occur where extensive urban infrastructure has been located on or near a beach, coastal bluff or harbor, indicated as Impact Level 5 on the Figure. The least impact will occur where landward migration of the coastline can proceed unimpeded by structures or development, indicated as Impact Level 1 on the Figure.

California Coastal Commission
Cartography Section

1.0 INTRODUCTION

California's coastline stretches about 1,800km. (1,100 miles) and serves as an invaluable social, economic and ecological resource. Three of its major metropolitan areas are located on the coast. Over 60% of the State's population lives in the fifteen coastal counties (excluding population centers around San Francisco Bay and the Delta) and benefits from the numerous coastal recreational, residential, industrial and commercial attributes. The coast, a very dynamic area, constantly changes due to tides, waves, seasonal factors and small fluctuations in sea level. If global warming occurs, large increases in sea level may alter significantly the present coastline and impact existing resources.

Recently, global warming induced by the greenhouse effect has become a topic of concern. Perhaps the foremost concern is whether global temperatures are rising. If global temperatures increase, many other changes such as sea level rise, and changes in rainfall patterns can be expected. While the timing and magnitude of sea level rise remains uncertain, many of the mechanisms bringing about a change in sea level rise are known. A speculation of the effects of a rise in sea level is possible through the study of previous periods of high water and an examination of existing coastal processes.

Changes in Global Sea Level

Global sea level changes are influenced by the amount of water in the oceans and ocean temperatures. During periods of glaciation, a large quantity of water is present as ice and the amount of fluid water in the oceans is reduced. As glaciers recede, the water previously locked in the glaciers is released and added to the surface water. Periods of glacial growth are marked by cooler temperatures overall, and this cooler temperature causes a further reduction in the volume of surface water due to thermal contraction. Warmer temperatures cause glaciers to recede and also cause an increase in ocean volume due to thermal expansion.

Glaciers can Affect Land Elevation

Water level at a specific location is controlled by sea level and local land elevation. A drop in land elevation has the same local effect as a rise in sea level and a rise in land elevation can counteract the effects of a rise in sea level. If the land rise is greater than sea level rise, the local water level will drop. Many factors change land elevation. As land glaciers grow, the weight depresses the land surface. As the glaciers recede, the weight of the ice mass is reduced and the land rebounds or rises up. This rebound is not an instantaneous event, but rather a slow rise occurring over thousands of years. Other effects to land elevation are plate subduction and abduction, tectonics, and subsidence. These are all localized effects varying from one area to another. One section of a coastline rises while a few miles away, another subsides.

Present Sea Level Rise

The earth is currently in an interglacial period. As the last glacial period ended about 15,000 years ago, there was significant glacial rebound and a rapid rise in sea level of up to 100 to 150 m. (325 to 490 ft) in 10,000 years. This period of rapid rise stopped about 5,000 to 6,000 years ago and over the past 5,000 years, water level rise has been very slight. Current estimates of water level rise from glacial retreat and thermal expansion range from 0.1 to 0.2 cm/yr (0.04 to 0.08 in/yr).

Present Land Subsidence or Uplift

The actual rate of sea level rise observed along the California coastline depends not only on the pace of sea level rise but also the rate at which the coastline rises or falls. Some areas along the California coast are rising at a rate of 1 to 5 mm/yr (0.004 to 0.020 in/yr), but most of the coast is rising less quickly and in some places is actually subsiding. Many locations along the Northern California coast such as Humboldt and San Francisco Bay, and some Southern California basins, are subsiding or maintaining equilibrium. Actual sea level rise augments along subsiding coasts and diminishes along rising coasts.

Future Sea Level Rise

Two recent climatic models predict that global temperatures will increase over the next 50 to 100 years by 2 to 4.5 deg. C. (3.6 to 8.1 deg./F.) due to the "greenhouse effect". This warming is expected to cause an accelerated rise in sea level due to melting of land glaciers and the thermal expansion of sea water. There is great uncertainty in predicting the extent of sea level rise and expected time frames for various sea level events. Since the predictions of sea level rise depend on global warming, all uncertainties of the time and extent of global warming are considered in predictions of sea level rise. There is uncertainty about the quantity and melt rate of continental glaciers and the Antarctic ice sheet. Finally, there is uncertainty in the thermal response of the ocean, such as the rate of heat transfer from the atmosphere to the ocean and from the surface waters to the ocean depths. Due to the many uncertainties in predicting sea level rise, the estimates vary greatly. Using a range of assumptions about the future, Hoffman (1983) developed scenarios for sea level rise, predicting a global rise by 2100 of 56.2 to 345.0 cm (1.8 to 11.3 ft).

Purpose of this Report

This report examines the effects of possible sea level rise along the California coast; to wetlands, structures, and other features. Predictions of future sea level and coastal uplift or subsidence are discussed and several scenarios of sea level rise developed. The remainder of this report discusses the variations in water level along the California coast, coastal uplift and subsidence, predicted future sea level scenarios, and effects of these predicted sea levels on wetlands, shoreline erosion rates, cliff retreat, coastal structures and harbors.

2.0 FACTORS AFFECTING SEA LEVEL CHANGE

2.1 GLOBAL CLIMATE CHANGE

Patterns of Global Temperature and Sea Level

Over the past two million years or more, the earth has undergone periods of warming and cooling; the cooling periods marked by the growth of glaciers and the warm, interglacial periods, marked by the retreat of glaciers. Sea level changed with this cycling of glacial and interglacial periods. During glacial periods continental glaciers and polar ice caps contain large amounts of surface water. Since the total amount of surface water is fairly constant, sea level drops during a glacial period due to the reduction in free flowing surface water. As the earth's temperature increases, an interglacial period begins, the available surface water warms and seas rise due to thermal expansion. Warming causes glacial recession. This retreat releases water previously bound in glaciers and adds to the supplies of ocean water. Over geologic time, eustatic (global) sea level tends to follow the cycle of global climate, rising and falling with temperature.

Previous Temperature and Sea Level Extremes

Global mean temperature has varied by about 5 deg. C. (9 deg. F.) over the past several hundred thousand years. (J./Hansen, et. al., 1984) and sea level is thought to have varied by about 100/m. (328 ft) (Bloom, 1978). According to Hansen, during the previous interglacial period, about 100,000 years ago, sea level may have been 5-7 m. (16 to 23 ft.) higher and global temperatures 1 to 2 deg. C. warmer (1.8 to 3.6 deg. F.). During the Wisconsin ice age, global mean temperatures were probably 3 to 5 deg. C. (5 to 9 deg. F.) cooler than present and sea level was about 40 to 100 meters lower (130 to 330 ft.)(Hansen, et. al., 1984). Small changes in mean global temperatures seem to cause large variations in eustatic sea level. However, temperatures usually change inconsistently around the globe. During the Wisconsin glacial period, for example, the upper latitudes dropped to temperatures that allowed glaciers to extend as far south as New York City and Seattle. Average summer temperatures in the north Atlantic may have been 18 deg. C. (32 deg. F.) cooler than present (Bloom, 1978). In contrast, polar and tropical area temperatures did not vary dramatically from those of the present (Bloom, 1987). Global temperature changes are not always the same as regional temperature changes.

Sea Level Changes in the Recent Interglacial

Following the Wisconcian glacial era, global temperatures began to increase and sea level rose about 10 mm/yr (0.33 in/yr). This rate of rise in sea level tapered off about 5,000 to 6,000 years ago, and temperature and sea level have been relatively constant. Table 2-1 shows several estimates of global sea level rise over the past 50 to 100 years, based on tide gauge readings. These readings are affected not only by sea level rise, but also by the movement of the earth's crust, glacial rebound and other conditions. Each researcher attempted to modify the data to isolate global effects from the local or regional changes in sea level. In his study of sea level change, Barnett (1984) found:

"there is no unique way to average the existing sea level data to obtain an overall measure of RSL (relative sea level) change characteristics of a geographic area represented by the data set. Indeed a number of valid, but subjective, methods could be used. Variations of order 50 % in the estimate of RSL change can be induced simply by use of different averaging methodology.....It is suggested that such a signal, if even moderately strong, will be extremely difficult to detect against a huge low-frequency, natural variability associated with glacial epochs and continental rebound."

TABLE 2-1
RECENT RATES OF GLOBAL SEA LEVEL RISE

Source	Rate of Global Sea Level Rise cm/yr.	ft/yr.	Data Period
BCDC (1987)	0.219	0.0072	Past Tidal Epoch
BCDC (1987)	0.119	0.0039	Past 100 years
Barnett (1983)	0.151 ± .015	0.0049 ± .0039	Past 100 years
Barnett (1984)	0.23	0.0076	Past 50 years
Hicks (1987)	0.15	0.0049	
Gornitz (1987)	0.10 ± 0.12	0.0032 ± 0.0039	Past 100 years
Atwater (1977)	0.10 ± 0.20	0.0033 ± 0.0066	Past 6,000 years
Wigley (1987)	0.10 ± 0.15	0.0033 ± 0.0049	

In general, researchers have found a recent global or eustatic rise in sea level of about 0.1 to 0.2 cm/yr (0.04 to 0.08 in/yr). This is an estimate of the rate of global sea level rise that occurs due to thermal expansion and the melting of ice sheets. Unlike temperature, global sea level increase is expected to be fairly uniform around the globe since it results from increases in the total volume of ocean water.

The Oceans as a Buffer

Changes in sea level tend to lag global climate changes by years or even decades since water has a different thermal capacity than air. The historic rise in sea level reflects a historic rise in mean global temperature, but does not mirror climatic changes on a month to month or year to year basis. If current climatic patterns indicate no increase in temperature, sea level may continue to rise in response to earlier climatic trends. Eventually, global sea level could remain constant if global climate did not change. If global temperatures were to drop or rise, sea level is expected to eventually fall or rise in response to the climate change.

Changes in Solar Insolation and Temperature

Some of the main causes of climatic change are fluctuations in solar insolation, the re-radiation of this energy by the earth, and changes in the tilt of the earth's axis. These factors may be responsible for the cycling of glacial and interglacial periods. Solar radiation passes freely through space. Some solar radiation is reflected or scattered by the earth's atmosphere, while the rest passes through the earth's atmosphere to the earth's surface. The earth's surface may absorb or reflect the radiation. The earth radiates long-wave and infrared radiation in balance with the solar radiation received. Part of the long-wave radiation passes through the atmosphere. The atmosphere absorbs some long-wave radiation and, in turn, warms the earth. The mean temperature of the earth is 33 deg. C. (60 deg. F.) higher than it would be if long-wave radiation were not absorbed (Hansen, et. al., 1984).

Effects of Particulates on Temperature

Changes in the composition of the atmosphere changes the amount of solar radiation reaching the earth's surface and thus alters the amount of absorbed infrared radiation. Airborne particulates, dust and clouds, reflect solar radiation; increases in any one of these could decrease the solar radiation that reaches the earth's surface. The earth would then radiate less long-wave radiation to balance the solar input resulting in a general cooling in response to the drop in radiation. Conversely, decreases in particulates, such as clouds or dust, could increase incoming solar radiation and warm the earth.

Effects of Surface Albedo on Temperature

Earth surfaces differ in albedo: the surface albedo is the percent of incident radiation reflected. For example, snow has an albedo of about 0.4 to 0.95, depending on whether its age; ice albedo ranges from 0.2 to 0.45; soils range from 0.05 to 0.40 (Oke, 1978). Changes in the earth's surface albedo, through changes in the area coverage of fresh snow or ice cover, will alter the amounts of reflected and absorbed solar radiation and alter the mean temperature of the earth.

Effects of Greenhouse Gases on Temperature

Gases such as carbon dioxide, chlorofluorocarbons, methane and others are called greenhouse gases because they absorb long wave radiation (wavelengths from 3 to 100 micrometers) and keep the earth at a habitable temperature. Increases in the concentration of greenhouse gases are expected to increase absorption of long wave radiation and increase the mean temperature of the earth. Decreases in gas concentrations are expected to decrease temperatures. Hansen (1984) believes that the presence or absence of greenhouse gases is partially responsible for the mean temperatures on Mars and Venus, approximately -55 deg. C. and +425 deg. C. (-67 to +797 deg. F.) respectively. Mars has a very transparent atmosphere which absorbs very little long-wave radiation; thus the planet is very cold. Venus, almost completely blanketed in carbon dioxide, has a high mean temperature which is believed to result from the absorption of large amounts of long-wave radiation.

Gases Have Different Warming Effects

Greenhouse gases have distinct bands defining the wavelengths of radiation that they absorb. Figure 2-1 shows the absorptivity of some of the key greenhouse gases and of the whole atmosphere. Some gases such as oxygen and ozone have a very narrow absorption band, from 9.6 to 9.8 micrometers. Carbon dioxide and water vapor have several large absorption bands. Methane (CH4) has two narrow bands. As concentrations of these gases increase, they will absorb more radiation within their absorption bands. At present there is an atmosphere window bewteen 8 to 11 micrometers through which about 5% of all long wave radiation passes unabsorbed (Oke, 1978). Chloroflourocarbons, CFC's, absorb radiation within this atmospheric window and increases in these gases will further reduce the band of radiation that passes unabsorbed through our atmosphere which will both increase warming and alter the radiation spectrum from earth.

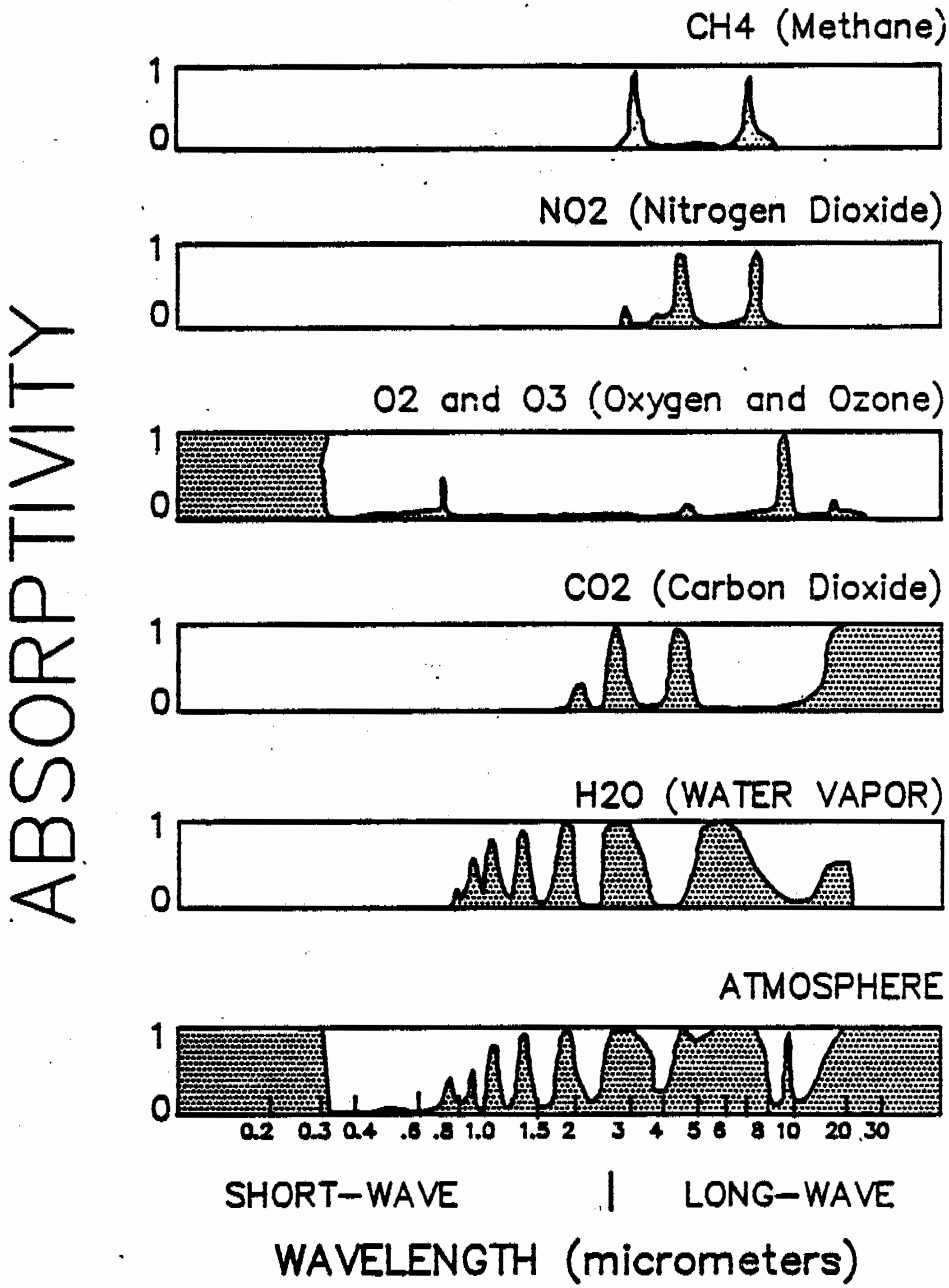
Projected Changes in Temperature from Atmospheric Changes

Future changes in the earth's climate over the next several hundred years are expected to depend on changes in reflection of incoming solar radiation and changes in absorption of long-wave radiation. A major factor affecting both of these will be the concentrations of key atmospheric components - carbon dioxide, methane, chlorofluorocarbons and particulates. Models of future atmospheric concentrations based on population growth, energy demands, fuel choice, etc. project significant increases in greenhouse gases, with a doubling in effective carbon dioxide. Effective carbon dioxide is based on the absorptive capacity of the various greenhouse gases. For example, a projected concentration of methane will absorb a certain amount of radiation. The concentration of carbon dioxide able to absorb the same amount of radiation is effective carbon dioxide.

Projected Time Frame for a Doubling of Carbon Dioxide

The projected time span for a doubling of effective carbon dioxide ranges from 2055 to 2085 depending on high or conservative fuel growth scenarios (Barth and Titus, 1984). Climate models project that a doubling of effective carbon dioxide would obscure any cooling effect of increased particulate emissions and could raise global temperatures by 2 to 4 degrees C. (3.6 to 7 2 deg. F.) (Manabe and Stouffer, 1980; Hansen, et. al., 1984). The increase in temperature is expected to cause a rise in eustatic sea level due to the thermal expansion of sea water and from glacial melting. There will be some lag between increases in carbon dioxide and increases in temperature, and longer lags between temperature changes and sea level response. Table 2-2 shows projections of sea level rise for various scenarios of carbon dioxide concentrations, temperature increases and response time.

FIGURE 2-1
ABSORPTION OF SEVERAL ATMOSPHERIC GASES



SOURCE: T.R. Oke, 1978.

TABLE 2-2
PREDICTIONS OF FUTURE SEA LEVEL RISE

Source	Predicted Future Rise Year 2050, cm (ft)	Predicted Future Rise Year 2100, cm (ft)	Scenario
NRC (1987)	14.9 (0.49)	50 (1.64)	Low case
	29.8 (0.98)	100 (3.28)	Medium case
	44.6 (1.46)	150 (4.92)	High case
Hoffman (1983)	7-12 (0.29-0.39)	12-18 (0.59-0.39)	Historic rise
	23.8 (0.78)	56.2 (1.84)	Conservative
	52.3 (1.72)	144.4 (4.74)	Moderate low
	78.6 (2.58)	216.6 (7.11)	Moderate high
	116.7 (3.82)	345 (11.32)	High rise
Hoffman (1986)	20 (0.66)	57 (1.87)	Low Case
	55 (1.80)	368 (12.08)	High Case
Meier (1985)		50-200 (1.61-6.57)	

The West Antarctic Ice Sheet

One of the major uncertainties in any scenario of sea level rise is the fate of the West Antarctic Ice Sheet, particularly the Ross and Ronne Ice Shelves. Unlike most glaciers, the West Antarctic Ice Sheet is anchored by rock units. A small rise in water temperature could melt the ice shelves and cause them to detach from their base and slide into the ocean. Icebergs and glaciers that are now in the ocean displace a volume of water equal to their melted volume. Should the West Antarctic Ice Shelves slowly slip into the Ross or Weddell Seas as a result of sea level rise, they will displace a volume of water equal to their entire melted volume.

The West Antarctic Ice Sheet may have disappeared during the last interglacial period when temperatures were 1 to 2 deg. C. (1.8 to 3.6 deg. F.) warmer than present temperatures. This disappearance of the West Antarctic Ice Sheet is believed to be the major cause of the interglacial sea level which was 5 to 7 m. (16 to 23 ft.) higher than present sea level (Titus, 1988). Unlike the gradual sea level rise that could occur from expansion of ocean water or increased runoff from land based glaciers, this increase from the West Antarctic Ice Sheet could be very rapid and difficult to predict.

2.2 LOCAL CHANGES IN WATER LEVEL FROM TIDES AND CURRENTS

Tides and Tidal Variations

Tides are driven by the gravitational attraction between the earth and other astronomical bodies, especially the moon and to a lesser extent, the sun. The tides follow a general monthly, lunar cycle of high levels at full and new moons when the earth, moon and sun are aligned, and low levels for the first and third quarter moons when the sun, earth and moon are unalligned. The highness or lowness of these tides varies month-to-month depending upon the distances between the earth, moon, and sun, the declination of the moon and sun, and the gravitational influence of other planets. It is possible to make fairly accurate predictions of future tide levels for specific coastal locations based on knowledge of the sun's and moon's location at a given time, provided there are no major topographical changes.

California Tides and Water Level

The California coast has mixed tides which are dominantly semi-diurnal with two daily high and low tides: a high high, a low high, a high low and a low low tide. Figure 2-2 shows average and maximumm tidal ranges for various locations along the California coast. Table 2-3 shows the predicted highest tides for four coastal location for the years 1983 to 2000. (Zetler and Flick, 1985)

TABLE 2-3
TIDES ALONG THE CALIFORNIA COAST

Location	MHHW (1) or Average Range(2) (ft)	Extreme Range(3) (ft)	Standard Deviation(1) (ft)	Predicted Max. High Water (4) (ft)
San Diego	5.96	11.4	1.81	8.02
Los Angeles	5.45	10.4	1.66	7.28
Malibu (5)	5.2	10.5		
Point San Luis (5)	5.2	8.8		
San Francisco	5.67	10.7	1.75	7.41
Humboldt	6.41		1.93	8.34
Crescent City	6.97	13.0	2.12	

(1) Harris, D.L., 1981. All tide values referenced to Mean Lower Low Water.

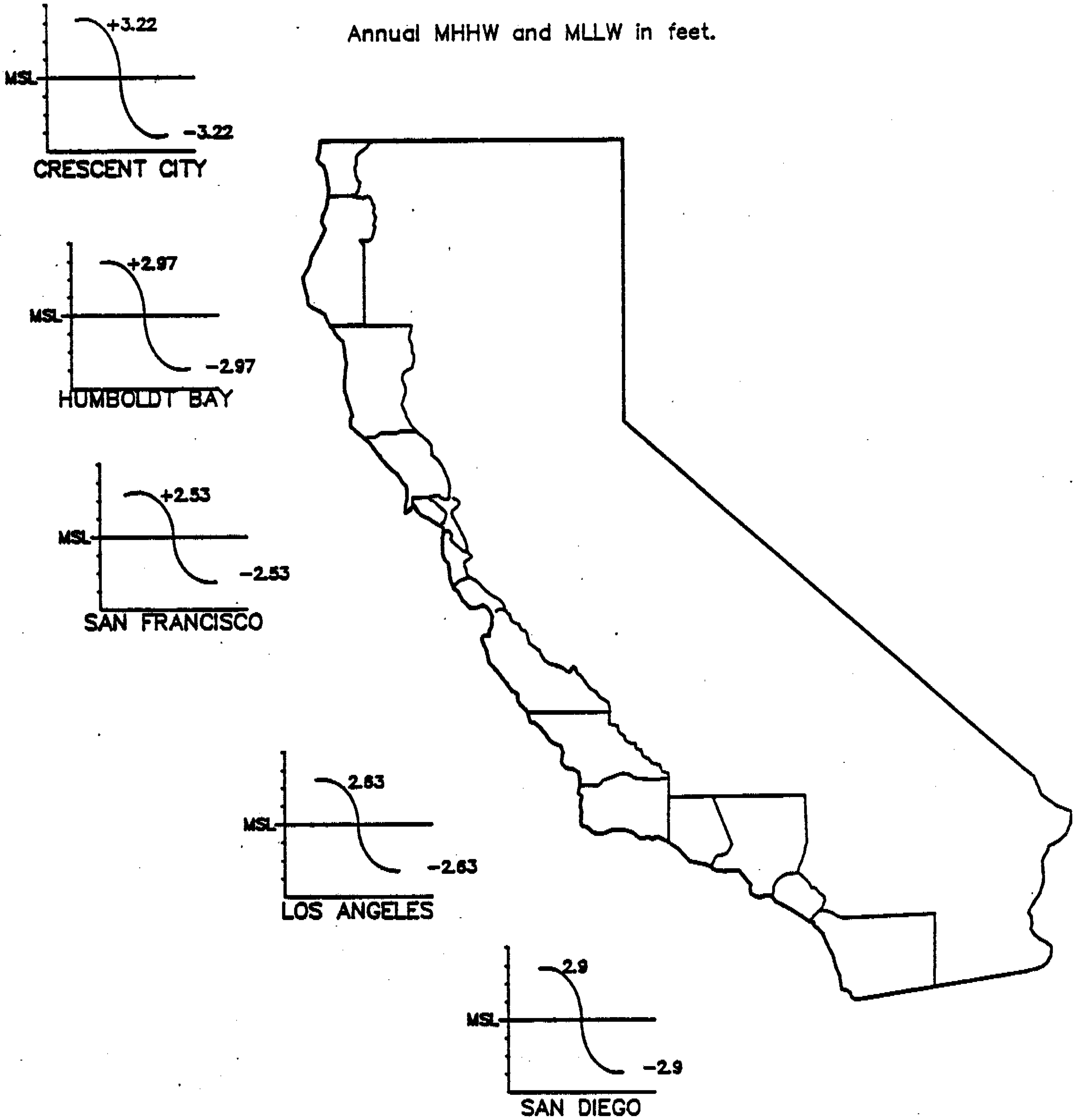
(2) Average range is developed from absolute value (MLLW) + (MHHW), except for Malibu and Point San Luis.

(3) U.S. Army Corps of Engineers, 1973, except values from (5).

(4) Flick, Reinhard and Daniel Cayan, 1984. Predicted Maximum high water levels are through the year 2000.

(5) Griggs, Gary and Lauret Savoy, ed., 1985.

FIGURE 2–2
TIDAL RANGES ALONG THE CALIFORNIA COAST



SOURCE OF TIDAL DATA: D.L. Harris, 1981.

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Currents and Their Effects on Water Level

Current meanders can affect sea level changes. In a study of water levels near Japan, changes in the Kuroshio current caused sea level changes of 3 to 4 cm. (1.2 to 1.6 in.) from the mean. Most currents in the northern hemisphere slope upward to the right when viewed in the direction of current flow (Komar and Enfield, 1987). Increases in discharge and mean velocity increase the cross flow slope and increase the sea level on the right. Figure 2-3 shows this situation for the major currents off the California coast. Due to the current's effect on water level, an increase in the velocity and/or volume of the California current could decrease sea level off the California coast, while a velocity and/or volume increase of the seasonal northerly Davidson current could raise sea level.

2.3 LOCAL CHANGES IN WATER LEVEL FROM METEOROLOGICAL FORCING AND STORMS

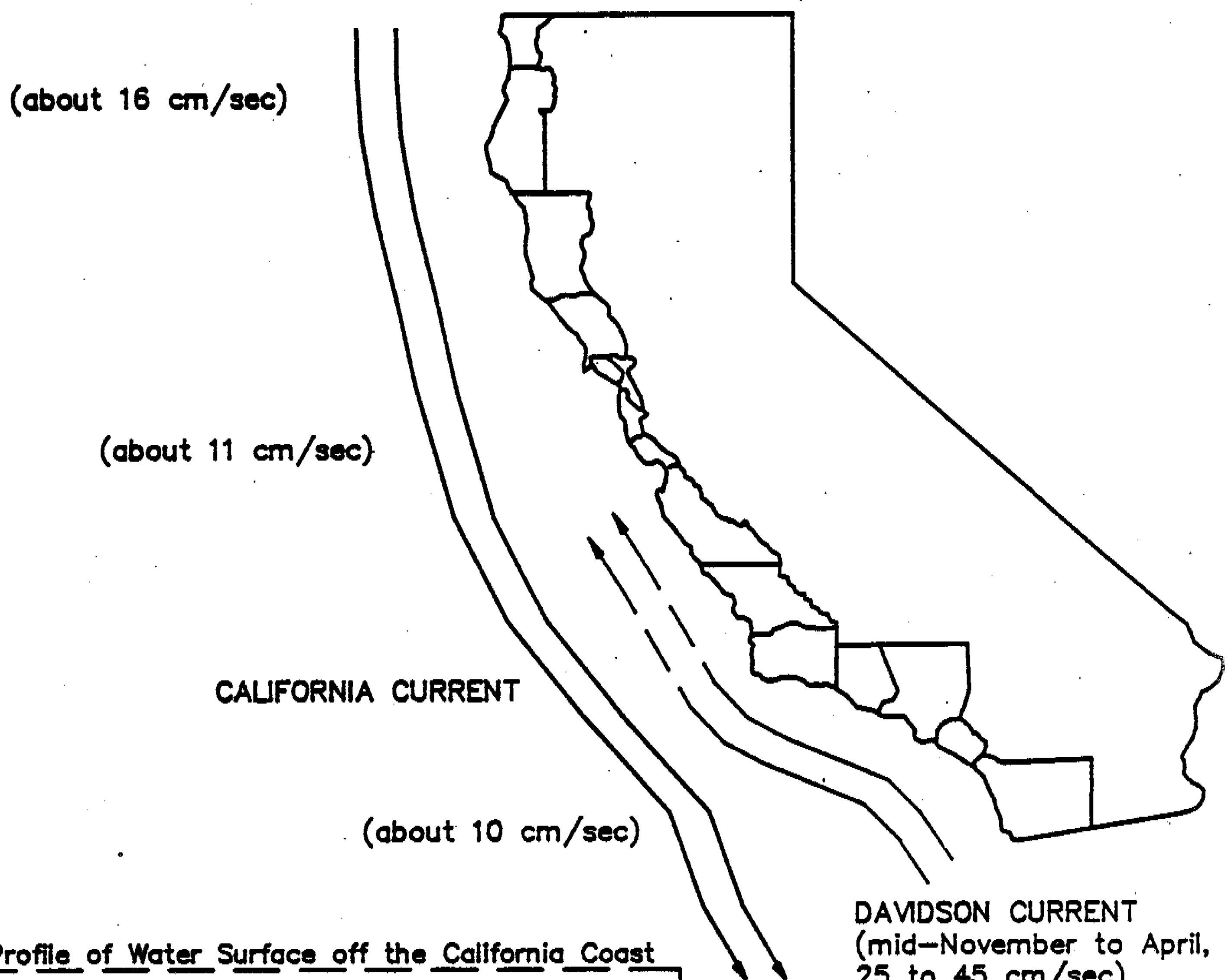
Meteorological Forcing Effects on Water Level

Meteorological forcing can significantly affect local sea surface elevations. During El Nino events, 2 to 3 year-long sea level rises of 6 to 9 cm. (0.2 to 0.3 ft.) along the California coast have occurred (Flick and Cayan, 1984). Often a drop in sea level in the west Pacific of up to 50 cm. (1.6 ft.) lasting for several months, precedes this rise in sea level along the California and Peruvian coasts (Komar and Enfield, 1987). Changes in atmospheric pressure elevate or depress the open ocean, with a depression of approximately 1 cm. (0.39 in.) for each millibar of pressure rise. Along the coast, surface levels have been found to rise or fall one to two times more than accounted for by barometric effects alone (Komar and Enfield, 1987). Some of the extra increase in sea level may be attributed to the presence of southerly winds causing water to pile up along the coast.

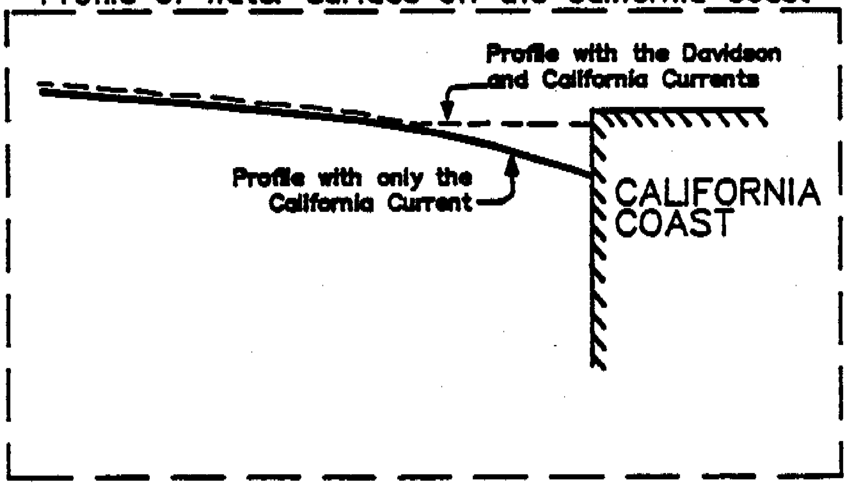
Effects of Barometric Pressure on Water Level

The influence of barometric pressure varies along the California coast. North of San Francisco, about 50 to 60% of the sea level variability is a response to local atmospheric pressure while only 10 to 15% of the variability along the southern coast is due to local barometric changes (Komar and Enfield, 1987). Along southern California, coastal upwelling in the spring and fall brings deep cold water up to the surface, causing a drop in sea level since cold water is denser than the warm water it replaces. A range of 25 cm/yr (9 in/yr) has been detected due to these seasonal changes in water temperature (Komar and Enfield, 1987). The extreme rise in sea level during El Nino events is thus due in part to the absence of cold water upwelling that lower sea level, and to the continued expansion of warm surface waters heated by solar radiation.

FIGURE 2-3
EFFECTS OF CALIFORNIA'S CURRENTS ON WATER LEVEL



Profile of Water Surface off the California Coast



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Influence of Waves on Water Level

When predicting the amount of sea level rise due to tides or barometric effects still water levels are used. Wave effects are not considered. However, water levels along many areas of the coast are modified significantly by wave conditions. Most waves are formed far from shore, generated by storms and wind over the open oceans. The size of the waves depends on the speed and duration of the wind and the extent of the water surface over which it blows. These waves propagate from the generating area as swell, merge with other waves and eventually reach a coastal area. Deep water conditions are such that there will always be some waves reaching coastal areas forming a baseline wave climate. Local winds and storms can generate local waves which combine with the swell to establish the local wave climate. In many parts of southern California local wind conditions are a dominant factor in wave climate. The extreme wave heights from one of the 1983 winter storms along the California coast, for example, were a combination of two deep water swells and a locally generated sea (National Research Council, 1984).

Waves Along the California Coast

In shallow water, waves change their height, length and velocity due to defraction, refraction and shoaling. Local topography strongly modifies waves reaching shore. The waves begin to align with the bottom contours and become directed relatively parallel to shore. The wave heights increase, lengths decrease, and peaks steepen. Normal wave conditions along the Caifornia coast range from about 0.3 to 1.1 m. (1 to 3.5 ft.), but extreme waves from storm conditions can be several times higher. Table 2-4 and Figure 2-4 show average and extreme wave heights for a number of California locations. Since wave heights are measured from peak to trough, only part of the total wave height exceeds the still water level. Approximately two-thirds of total coastal wave height stands above the still water level. For extreme waves, the trough may be limited by bottom depth and most of the total wave height may be above still water level.

2.4 SUMMARY OF WATER LEVEL CHANGES ALONG THE CALIFORNIA COAST

Water levels along the California coast vary due to many factors-- tides, meteorological forcing, currents and waves. Figure 2-5 shows expected high water conditions that could occur due to a combination of a high tide, a low pressure system and high waves. The high tide situation used in Figure 2-5 is mean higher high water. During annual high tide events, water levels can be 0.45 to 0.61 m. (1.5 to 2 ft.) above mean higher high water; extreme high tides can be 0.61 to 0.91 m. (2 to 3 ft.) above the mean. Figure 2-5 does not estimate extreme high water levels; and is a conservative estimate of water levels which could be experienced in serious storm conditions.

FIGURE 2-4
MEAN AND MAXIMUM WAVE HEIGHTS

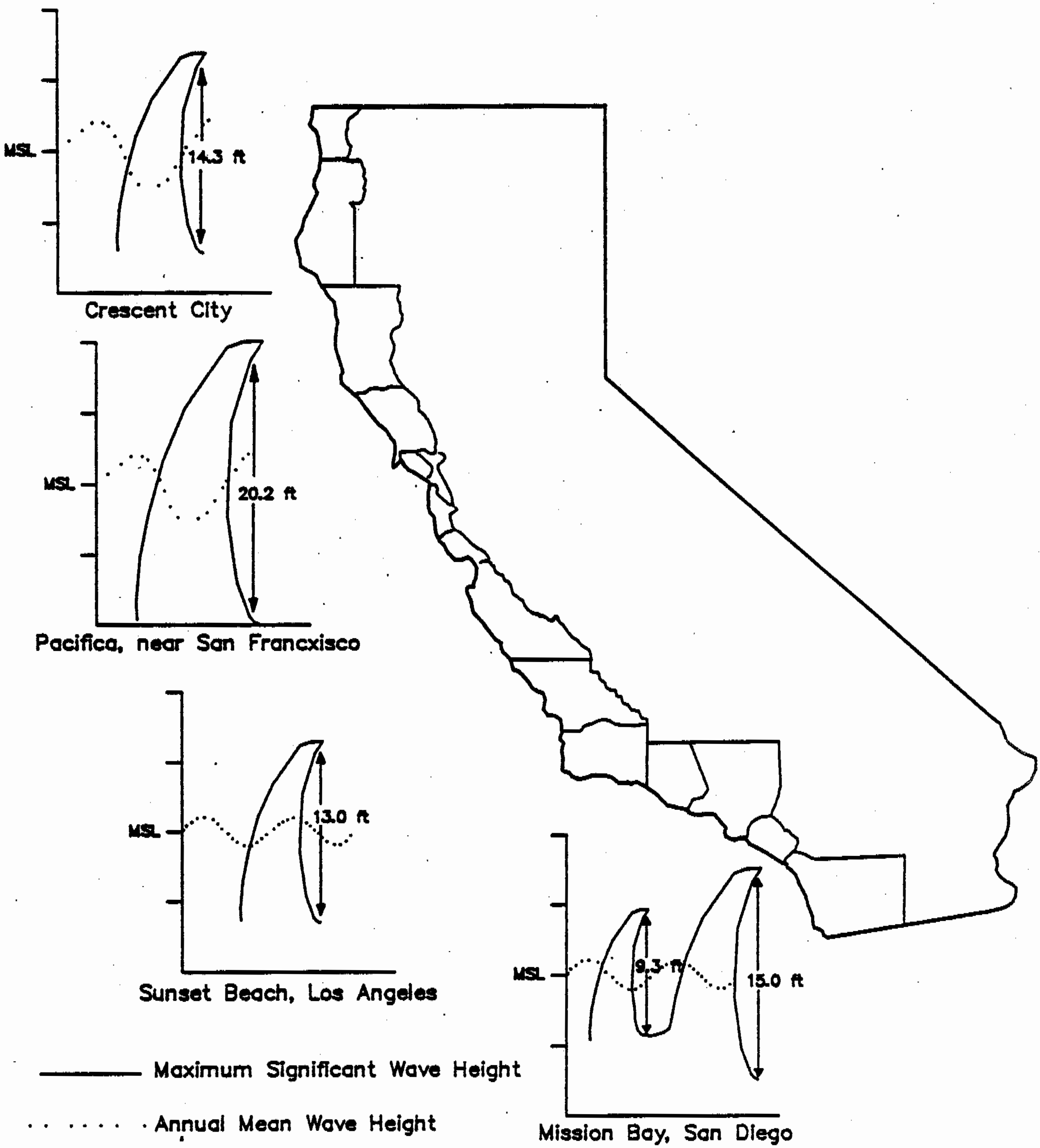

FIGURE 2-5
WATER LEVEL WITH HIGH TIDE AND STORM WAVES

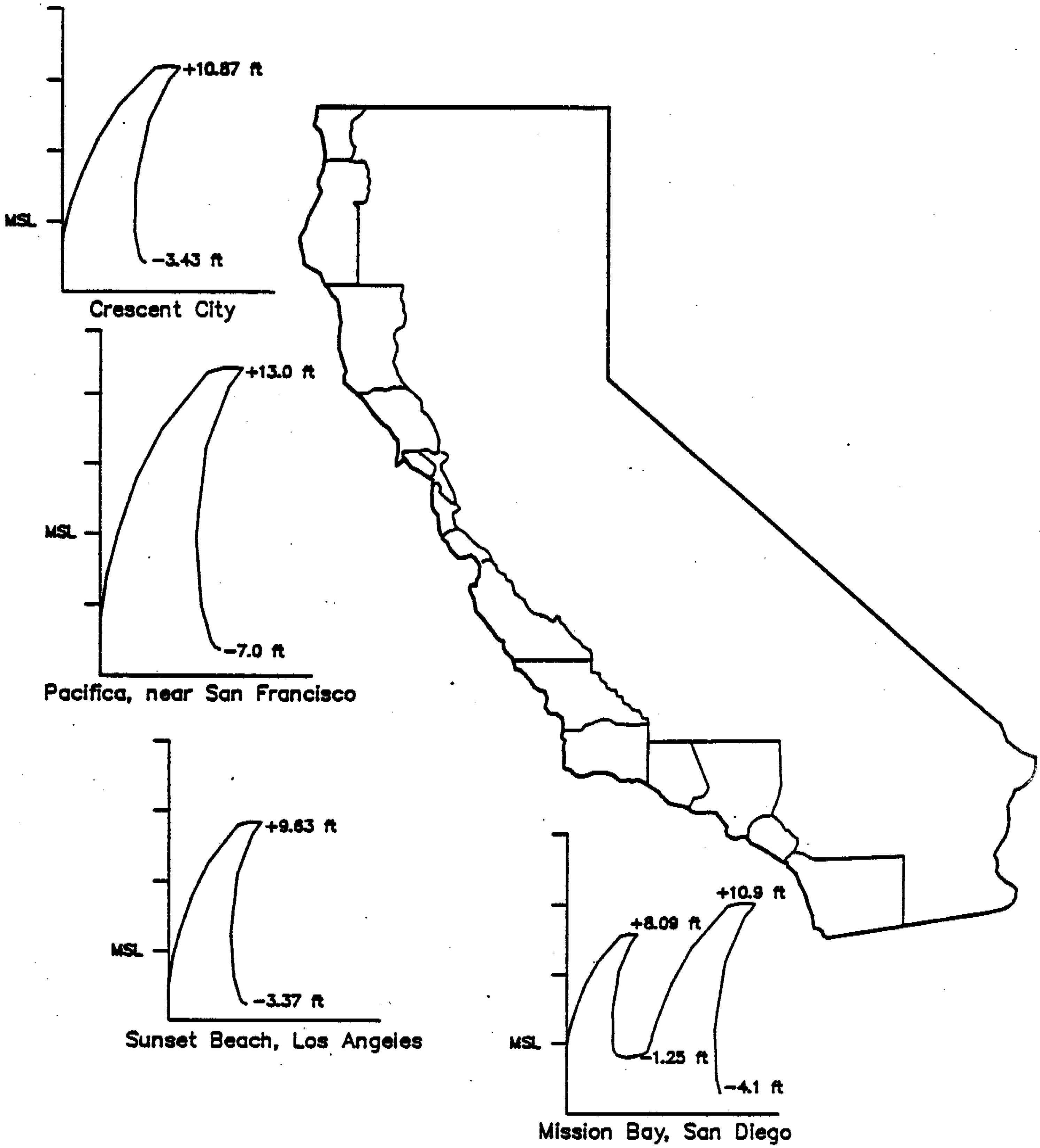

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TABLE 2-4
WAVE HEIGHTS ALONG THE CALIFORNIA COAST

Location	Annual Mean Significant Wave Height m (ft)	Annual Mean Significant Wave Period seconds	Maximum Significant Wave Height (1) m (ft)
Imperial Beach (2)	0.85 (2.8)	13.6	4.57 (15.0) Mission Bay
Torrey Pines (2)	0.91 (3.0)	15.7	2.83 (9.3) Scripps Pier
San Clemente (2)	0.85 (2.8)	14.5	
Huntington Beach (3)	0.73 (2.4)	12.9	3.96 (13.0) Sunset Beach
Venice (3)	0.37 (1.2)	10.5	
PEG at Pt. Magu (2)	0.85 (2.8)	13.4	
Pt. Magu (2)	1.01 (3.3)	10.7	
Channel Ils. Hbr(2)	0.85 (2.8)	11.5	3.17 (10.4)
San Simeon (2)	0.94 (3.1)	12.2	
Natural Bridges (2)	1.01 (3.3)	14.6	3.23 (10.6) Santa Cruz
Santa Barbara	0.97 (3.2)		1.98 (6.5)
Pacifica	1.25 (4.1)		6.16 (20.2)
Crescent City	1.28 (4.2)		4.36 (14.3)

Significant wave height is the average height of the one-third highest waves of a given wave group. Wave height is the vertical distance between a wave crest and the preceding trough. The composition of the highest waves depends on the extent to which the lower waves are considered.

(1) Seymour, Richard J., 1983.

(2) CERC Littoral Cell Observation Program, in U.S. Corps of Engineers, 1984.

(3) CERC Wave Gauge Record, in U.S. Corps of Engineers, 1984.

3.0 FACTORS AFFECTING SHORELINE ELEVATION

3.1 FORMATION OF THE CALIFORNIA COAST

Early Plate Motions

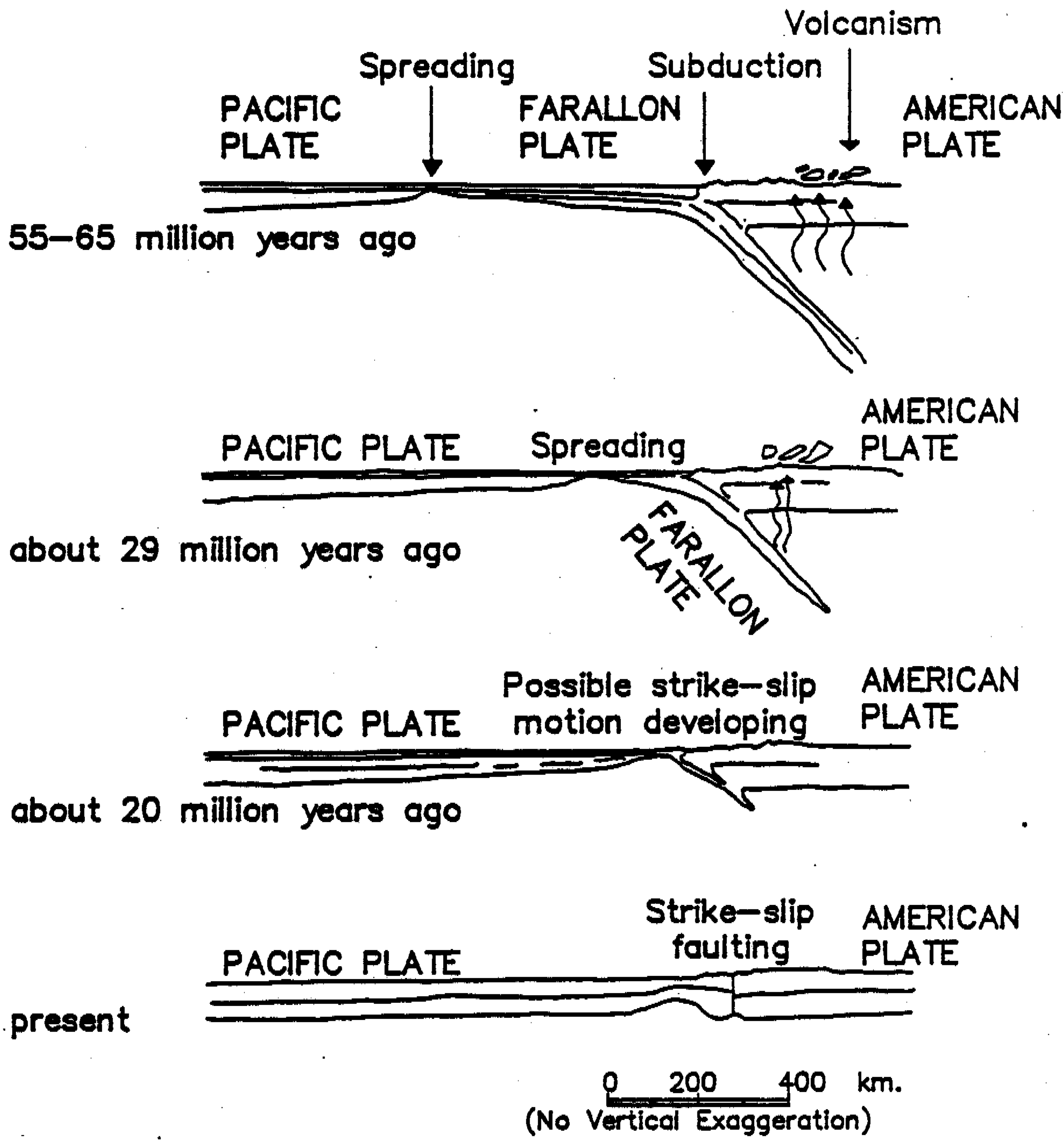
The present day California coast is a tectonic collage of various terraines, formed by millions of years of plate motion. Most of the California coast is on or adjacent to the North American Plate, a westward moving plate. Many millions of years ago, during the Mesozoic era, the Farallon Plate, immediately west of the North American Plate, moved east. The North American Plate overrode the edge of the Farallon Plate, creating a steeply dipping subduction zone, shown in Figure 3-1. Most of the Farallon Plate was forced down into the mantle where eventually it melted and slowly rose as magma. Magma often broke through the continental crust, inland from the subduction zone, as a chain of erupting volcanos. Not all the material from the Farallon Plate was subducted; some of the surface material was scraped off by the overriding plate and piled up against the edge of the North American Plate. The plate scrapings included oceanic basalts and seafloor sediments. This material was deposited mostly underwater, filling in deep offshore trenches, and eventually became the California coast. The trenches formed at the subduction boundary where both plate edges are often forced downward.

Development of the San Andreas Fault System

The Farallon Plate was consumed within the subduction zone more quickly than new plate material could be created. At locations where the Farallon Plate was completely consumed, the Pacific Plate came into direct contact with the North American Plate. Originally, the Pacific Plate had been moving to the northeast. When it came into contact with the North American Plate, rather than subduct, it slipped laterally. Figure 3-2 shows this series of events. This strike-slip boundary started in central California and grew along most of the coast as more of the Farallon plate was consumed. This strike-slip boundary is the well known San Andreas fault system which extends from the Gulf of California to Mendocino. In southern Mexico, the Coco Plate, a remnant of the Farallon Plate separates the North American Plate from the Pacific Plate. North of Mendocino, the Gorda and Juan de Fuca Plates are the Northern remnants of the Farallon Plate. The coast north of Mendicino is still a subduction zone.

The San Andreas fault system, encompassing the San Andreas, Hayward, Calaverdos and other faults, forms by contact between the North American Plate and the Pacific Plate. It is not a single strike-slip boundary, but rather a system of faults consisting of parallel and transform faults. The San Andreas Fault system is a right lateral fault with the Pacific Plate moving north relative to the North American Plate. This northward conveyor system has carried material almost 350 km. (215 mi.) from its original location. Point Reyes is thought to be a slab of granite carried north from about where Santa Barbara is located today. Point Arena is thought to have originated in the same vicinity. (Howard, 1979)

FIGURE 3-1
MODEL OF SUBDUCTION OF FARALLON PLATE



Sequence of cross-sections of California and its offshore, illustrating subduction of the Farallon Plate.
In this model, the Pacific Plate is considered fixed as the spread center (East Pacific Rise) encounters the continental margin

SOURCE: H.L. Levin, 1983.

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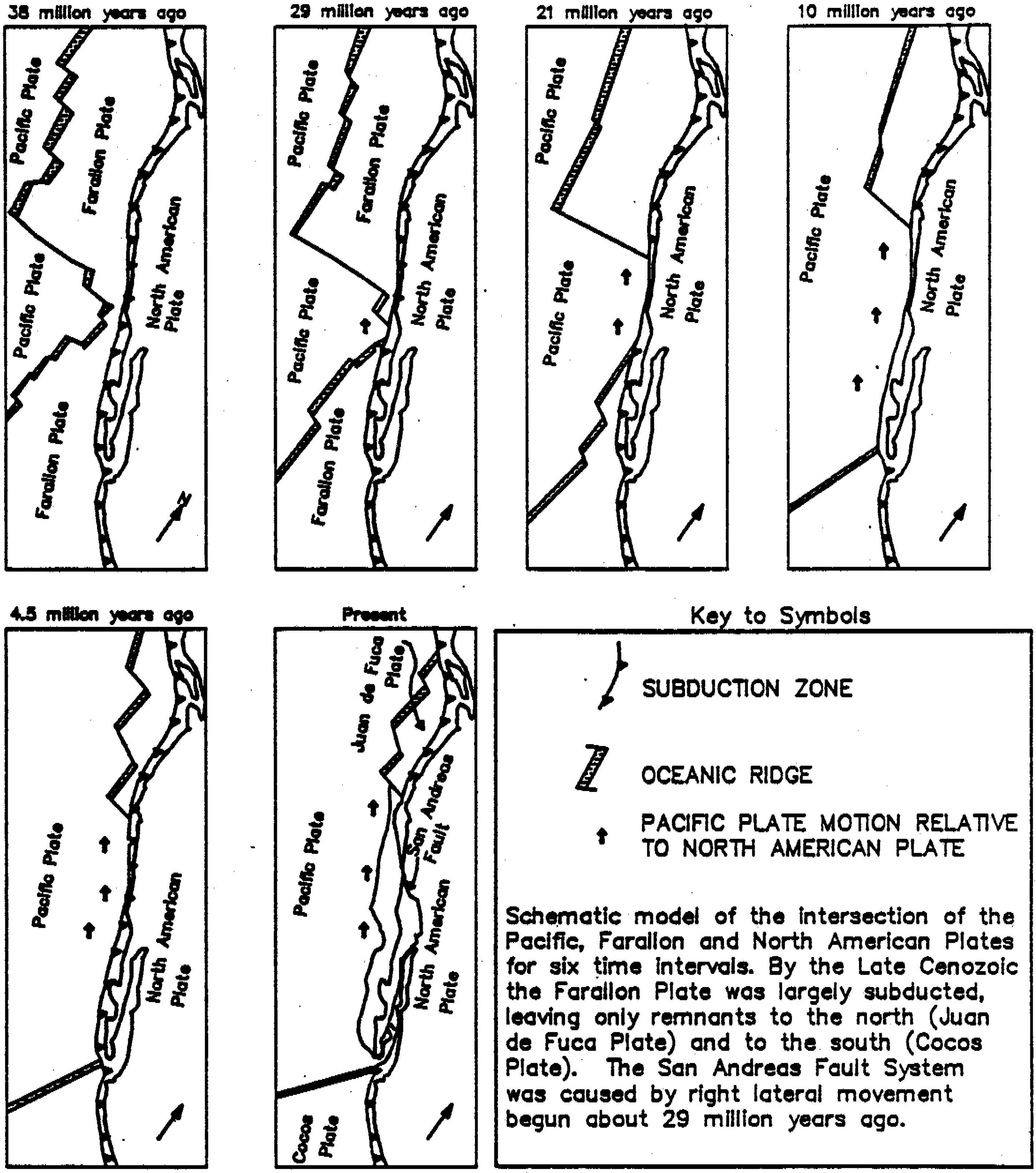
FIGURE 3–2
MODEL OF PLATE INTERACTIONS FORMING THE CALIFORNIA COAST



Schematic model of the intersection of the Pacific, Farallon and North American Plates for six time intervals. By the Late Cenozoic the Farallon Plate was largely subducted, leaving only remnants to the north (Juan de Fuca Plate) and to the south (Cocos Plate). The San Andreas Fault System was caused by right lateral movement begun about 29 million years ago.

SOURCE: H.L. Levin, 1983.

Uplifting of the California Coast

Approximately 4.5 million years ago, subduction ceased along major portions of the California coast and the edge of the North American Plate was no longer being deflected downward. The material scraped off the Farallon Plate was uplifted and initially formed a line of offshore islands separated from the mainland by a large shallow sea. The major forces affecting the coast included rebound from the removal of the subduction force, nearby volcanism due to previously subducted sea plate material, and lateral deformation from the newly created fault system. Eventually the inland sea filled with material eroded from surrounding mountains. The Coastal Range was subjected to continued uplift, subsidence, folding, faulting, erosion, volcanic deposition and sedimentation. These events, sporadic and often localized, did not affect the Coastal Range as a whole. This period of development can be considered one of "chaotic jostling" (Howard, 1979, p. 63). About 2 million years ago, general uplift along most of the coast occurred, with local folding and faulting. This general uplift led to renewed stream erosion and vigorous downcutting of rock units by rivers and streams.

3.2 CURRENT UPLIFT AND SUBSIDENCE OF THE CALIFORNIA COAST

Types of Motion along the California Coast

In general, three types of crustal motions occur along the California coast; vertical motion or warping up and down (as though on a hinge), lateral motion due to a strike-slip faulting, and folding. One of the problems with determining the rate of uplift or subsidence along the California coast is that in many locations all three types of movements occur simultaneously.

Some locations along the coast experience subsidence or uplift due to subduction zone compression or sporadic uplift and lateral movement from faults. Some motion is associated with seismic activity, but much of the vertical motion is aseismic (not related to plate motion). At some locations along the coast, subsidence and uplift have been carefully studied and quantified. Most of the coast however cannot be given a specific rate of vertical movement and can be discussed only generally.

The uncertainties of age and sea level at the time when a terrace was formed both introduce significant uncertainty in the rates of coastal uplift. Many of the coastal California emergence rate estimates are based on age dated marine terraces. If the age of the terrace and contemporateous sea level are known, a rate of total uplift can be determined as:

$$\frac{\text{Present Terrace Elevation} - \text{Elevation at Time of Formation}}{\text{Age of Terrace}}$$

Characteristics of the Coast: Oregon Border to Mendocino

The north coast of California, from the Oregon border to Mendocino, is a subduction zone. The Gorda and Juan de Fuca Plates are being slowly overridden by the North American Plate, intersecting a short distance off of the present coastline. The Gorda and Juan de Fuca Plates are pulling down the edge of the North American Plate as it is subducted. The northern California coast is far enough from the subduction zone that it should be uplifted slightly as compensation for subduction of the western edge of the plate. However, the convergence and underthrusting of the Gorda and Juan de Fuca Plates under the North American Plate appear to cause the coast to undergo compression and shortening, resulting in a complex pattern of uplift and subsidence (Vick, 1988). Along sections of the North Coast, coastal lagoons formerly stream mouths are found. As the shore subsided, these stream mouths drowned and then separated from the ocean by wave built sand spits. The coastline is very steep and there is no evidence of level marine terraces. The Late Pleistocene terraces which occur along the coast have all been deformed by recent folding and faulting.

Humboldt Bay is one of the dominant features of this section of coast. This bay is actually three distinct bays each of which lie at the seaward edge of a drowned river valley. The entire bay is a coastal lagoon, separated from the ocean by barrier spits. Several active faults and evidence of crustal folding are common in this area.

Uplift and Subsidence: Oregon Border to Mendocino

Tide gauge records for Humboldt Bay show a steady rise in relative sea level of approximately 10 cm. (4 inches) since 1900. This is similar to the global rate of sea level rise for the same time period, indicating no local uplift or subsidence in the area. Further north along the coast at Crescent City, tide gauge readings show a drop in relative sea level of 5 cm. (2 inches) since 1900. Assuming a global sea level rise of 10 cm. during this period, the Crescent City area rose by about 15 cm (6 inches) since 1900. Study of salt marsh growth and core samples in Northern Humboldt Bay show that the sediment and organic matter in marshes have accumulated quickly enough keeping pace with the rise in sea level. Within the core samples, there is evidence of several rapid inundations which drowned the marshes. These instances of marsh inundation are believed to coincide with slip along the Little Salmon Fault. The most recent movement occurred about 300 years ago, with a maximum subsidence of up to 1.5 m. (4.9 ft.) in Mad River Slough (Carver, Vick, and Burke, 1989). Similar subsidence may have occurred also about 1,000 years ago. The Trinidad and McKinleyville coast shows evidence of possible sudden uplift of 1.5 to 2.5 m. (4.9 to 8.2 ft.) at the same time as the subsidence in northern Humboldt Bay (Carver, Vick and Burke, 1989).

Characteristics of the Coast: Coastal Range South of Mendocino

The Mendocino area is geologically complex; just offshore is a triple junction between the North American, Juan de Fuca, and Pacific Plates. This is an unstable junction with a strong active fracture zone.

Most of the Coastal Range is criss-crossed with local faults, and individual areas are being folded, tilted, uplifted or dropped. Significant marine terraces have been identified in the Russian River area, along the Sonoma coast, and along the coast of Santa Cruz which are remnant beaches. Their existence far above present or historic sea levels indicates that the land has risen relative to sea level.

Uplift and Subsidence of the Coastal Range

The Coastal Range south of Mendocino is slowly uplifting in response to the change from a subduction zone to a strike-slip boundary which removed the downward force on the plate edge and replaced it with a lateral force. This mountain range was formed by warping and faulting with continued deformation occurring due to regional and local influences. Two strong regional influences are the general uplift along the plate edge and movement along the San Andreas fault.

Most motion along the San Andreas fault is lateral, but erratic vertical movement has been observed. Most of the regional vertical movement is due to rebound since subduction ceased, but some faulting along the San Andreas system has led to vertical motion. After the 1906 earthquake, "the western block moved relatively upward a probable 3 feet" and during the 1956 San Miguel earthquake most of the motion was vertical with the east block moving relatively upward (Bailey, 1966, p. 369).

In general, the contours of the Coastal Range south of San Francisco correspond to vertical movements during the past 2 million years but no clear relationship between faults expressing vertical offset and regional strike-slip faults is apparent.

Not all of the central coast is experiencing uplift; San Francisco Bay is subsiding. There is evidence of downwarping in South San Francisco Bay over the past 1.5 million years, and subsidence rates have been estimated from core samples taken along the major bridge locations. An average subsidence rate of 0.2 ± 0.1 mm/yr. (0.008 ± 0.004 in/yr.) was found between San Francisco and Oakland, 0.4 ± 0.1 mm/yr. (0.016 ± 0.004 in/yr.) between San Mateo and Hayward, and 0.4 ± 0.1 mm/yr. (0.016 ± 0.004 in/yr.) between Menlo Park and Fremont (Atwater, 1970). Table 3-1 shows estimated land elevation changes for various sites in San Francisco Bay.

TABLE 3-1

ESTIMATED UPLIFT AND SUBSIDENCE AROUND SAN FRANCISCO BAY

Location	Rate of Land Elevation Change cm/yr (ft/yr)
Pittsburg	-0.0027 (-0.0090)
Benicia	-0.0017 (-0.0055)
Sonoma Creek	0.0 (0.0)
Point Orient	-0.0006 (-0.0020)
Sausalito	+0.0011 (+0.0037)
Presidio	0.0 (0.0)
Alameda	-0.0004 (-0.0014)
Hunters Point	0.0 (0.0)
San Mateo Bridge	-0.0006 (-0.0020)
Dumbarton Bridge	-0.0047 (-0.0154)
Alviso Slough (Coyote Creek)	-0.0280 (-0.0920)

\+ Positive sign indicates uplift
\- Negative sign indicates subsidence

Source: San Francisco Bay Conservation and Development Commission, 1987. Sea Level Rise: Predictions and Implications for San Francisco Bay, prepared by Moffatt and Nichol, Engineers.

Portions of Monterey Bay are also subsiding. Monterey Bay lies on a structural unit known as the Salinian block. It is bounded on the east by the San Andreas Fault and on the west by the San Gregorio-Palo Colorado Fault, was formed as a basin between the Santa Cruz Mountains and the Santa Lucia Range, and was filled with eroding sediments from both basins. During periods of high sea level, marine sediments were deposited in the basin and marine terraces formed. Monterey Basin can be divided into a number of smaller uplifting blocks and basins separated by southeast to northwest tending faults. The Santa Cruz structural block has shown uplift of 0.16 to 0.26 mm/yr. (Bradely and Griggs, 1976). In contrast, central and southern Monterey Bay have continued to subside through the Quaternary (U.S. Army Corps of Engineers, 1985).

Characteristics of the Coast: Transverse Range

The Transverse Range extends from Point Arguello and San Miguel Island south to the Ventura-Los Angeles County line. This range is very distinct in that the mountains are overlapping blocks aligned east west rather than the more common north-south orientation. The San Andreas fault transects the Transverse Range and locally veers east-west, indicating that the factor affecting the alignment of the Transverse Range also influenced the San Andreas fault. The events leading to the dominant east-west orientation in this region has not been unravelled. One theory is that the Sierra and Peninsular Ranges rotated clockwise, causing the San Andreas fault to bend. The Transverse Range, a soft zone caught between these two rotating blocks, deformed to the east-west orientation by the rotation (Castle, et. al., 1976). The area at present is fairly rugged even though maximum elevation is below 2,000 meters (Wehmiller, et. al. 1979).

The Transverse Range is characterized by numerous faults and local deposits of petroleum. The tectonic history of this region is one of episodic activity alternating with periods of relative quiet. The area to the west of the San Andreas fault appears to be moving northward with the Pacific Plate at a rate of approximately 5.6 cm/yr (2.2 in/yr.) (Wood and Elliott, 1979). The area to the west of the San Andreas fault, along the coast, is seismically active with a great deal of recent Quaternary faulting.

The coastal area of the Transverse Range extends from Santa Barbara to Ventura. This segment of coast trends east - west, parallelling the predominantly northward dipping thrust faults of the Transverse Range. Marine terraces are evident, indicating uplift and possibly reflecting a north - south crustal shortening due to right lateral movement of the Pacific Plate.

Characteristics of the Coast: L.A. Basin and Peninsular Range

The Los Angeles Basin, situated between the Transverse and Peninsular Ranges, has been filled by material eroded from these ranges and contains thousands of feet of sediment overlying the crystalline basement rock. Folding is a prominent surface feature and much of the basin is faulted. In general, the center of the basin is subsiding with uplift at the edges.

The Peninsular Range extends south from Los Angeles to the Mexican Border and into Baja. These mountains are northwest-southeast oriented blocks which truncate abruptly in the north at the Transverse Range. The area contains numerous faults which are evidence of active faulting and crustal movement through the Quarternary (Karrow and Bada, 1980). In addition, many of the faults show a strong dip-slip pattern rather than the lateral motion shown to the north.

A significant portion of the southern California coast is cliffed and serious erosion has been noted. Marine terraces are evident along much of this coast, some up to 300 m. (1,000 ft.) above present sea level. Terraces, arching away from the water, warped since their original formation. Parts of the coast consist of thick beds of terrestrial gravels, possibly deposited as alluvial fans. The prominent Malibu cliffs are made of bedded gravels and landslides occur frequently in both the terrace and bedrock units.

Uplift and Subsidence of the Southern California Coast

The southern California coast is made up of several distinct geologic units. Since many of the factors affecting uplift and subsidence are similar throughout southern California, despite geologic differences, it is perhaps clearer to consider all of southern California as a single region rather than as three separate units. Several of the regional effects are the "Southern California Uplift" (also known as the Palmdale Bulge), subsidence caused by withdrawal of subsurface oil, gas and water resources, and longer term geologic uplift or subsidence (tectonics).

Palmdale Bulge

The Palmdale Bulge, a fairly uniform uplift, was observed through much of Southern California from Point Arguello to the Salton Sea. Between 1959 and 1974, at least half of this area showed a height increase of 0.165 m. (0.54 ft.) (Holdahl, 1977) to 0.35 m. (1.15 ft.) (Castle, 1984; 1987). This growth "consisted of two well-defined spasms of positive movement, the second of which was closely followed by partial collapse" (Castle, 1987, p. 1). This uplift was associated with substantial northward to northwestward tilting, where the San Andreas, Garlock, and San Gabriel faults could serve as hingelines (Burford and Gilmore, 1984). Wood and Elliott (1978) theorized that this uplift and collapse are cyclic; similar uplift and collapse were observed between 1897 and 1934. The uplift and collapse may be the product of continuing motion between the marginal plates, but no correlation with seismic events can be made (Castle, 1984).

Land Subsidence Resulting from Fluid Extraction

Significant changes in local land elevation have been induced by changes in subsurface fluids. The pumping of groundwater, oil, or gas can cause local subsidence. Subsidence can be extensive both aerially and vertically when groundwater is withdrawn from sand or gravel aquifers that are interbedded with compressible clays, or when oil and gas are withdrawn from unconsolidated or poorly sorted sands (Castle, 1984). In both cases, the reduction in fluid pressure leads to compaction and surface subsidence. In the L.A. Basin subsidence averaged over 10 mm/yr. (0.39 in/yr.) from the mid-1940's to the mid 1970's, due primarily to groundwater extraction and to a lesser extent to oil and gas extraction and natural sediment compaction (Castle, 1984). The Wilmington oil field located east of San Pedro experienced substantial subsidence during its operation. Recently the field has been waterflooded to counteract the effects of oil withdrawal and elevations have kept constant or risen slightly.

Long Term Subsidence and Uplift

In addition to the cyclic California uplift, and recent subsidence and rebound due to withdrawal and injection of underground fluids, long-term vertical changes occur along the southern California coast. Table 3-2 shows several estimates of current uplift and subsidence for various locations throughout this area.

TABLE 3-2
UPLIFT AND SUBSIDENCE ALONG THE CALIFORNIA COAST

Location	Vertical Rate (mm/yr)	Time Period (B.P.)	Source
Crescent City	+1.7	present	Hicks (1983), in NRC
San Francisco	-0.1	present	Hicks (1983), in NRC
Point Conception	+0.6 to +0.9		Nolan (1979)
Ventura-S.B.	.0 to +6.0	100,000 to 40,000	Wehmiller (1979)
Ventura-S.B.	0	45,000 to present	Yerkes & Lee (1979)
Pitas Point	+3.0 to +10.0	45,000 to present	Sarna-Wojcicki (1979)
Ventura Basin	+10±2	600,000 to present	Yeats (1977)
Point Dume	+0.30 to +0.37	present	Birkeland (1972)
Las Flores	.37 to +0.46	present	Birkeland (1972)
San Pedro	+0.6 to +0.9	present	Wehmiller (1977)
San Pedro	+1.3	present	Balazs & Douglas
San Pedro	+1.2±0.4	since 1853	Wood & Elliott (1979)
Palos Verdes	+0.26 average		Bryant (N.D.)
Palos Verdes	+0.60 maximum		Bryant (N.D.)
Los Angeles	+0.4	present	Hicks (1983), in NRC
Newport Beach	+0.14 to +0.16	present	Wehmiller (1977)
Laguna Beach	+0.14 to +0.19	present	Wehmiller (1977)
Dana Point	+0.26	125,000 to present	Shlemon (1979)
San Onofre	+0.09	125,000 to present	Shlemon (1979)
San Clemente IL.	+0.2	127,000 to present	Muhs & Szabo (1982)
San Diego Area	+0.24 to +0.30	80,000 to present	Kern (1977)
Nestor Platform	+0.45	80,000 to present	Kern (1977)
San Diego	-0.4±0.3	since 1853	Wood & Elliott (1979)
San Diego	+0.4	present	Hicks (1983), in NRC
Point Loma	+0.16	present	Wehmiller (1977)

\+ Positive sign indicates uplift
\- Negative sign indicates subsidence

Santa Barbara and Ventura Area

At one time the area that now extends from Santa Barbara to Ventura was a basin which filled with sediment as it subsided. Yeats (1977; 1978) estimates that this area subsided at rates of 2 to 4 mm/yr (0.08 to 0.16 in/yr.) about 4 million years ago, and from 2,000,000 to 600,000 years ago, it subsided at a rate up to 9.5 mm/yr (0.37 in/yr.). About 600,000 years ago subsidence ceased and uplift began. Recent uplift has been estimated at about 10 mm/yr (0.39 in/yr.) (Yeats, 1979; Yerkes and Lee, 1979). Ventura and Santa Barbara are also affected by the southern California uplift and have gone through short-term cyclic uplift and subsidence in addition to the long term uplift.

Palos Verdes Peninsula

The Palos Verdes Peninsula shows clear signs of uplift. Long term estimates of uplift from marine terraces indicate uplift of 0.26 mm/yr to 0.6 mm/yr (0.01 to 0.02 in/yr.) (Bryant, no date). Recent tide gauge data and geodetic levels indicate uplift rates of 1.2 to 1.3 mm/yr (0.047 to 0.051 in/yr.). This is differential uplift relative to the Los Angeles Basin, based largely on movement along the Palos Verdes Fault (Bryant, no date). In comparison, uplift in the Los Angeles Basin, at Newport and Laguna Beaches is estimated at 0.14 to 0.16 mm/yr (0.0055 to 0.0063 in/yr.), and 0.14 to 0.19 mm/yr (0.0055 to 0.0075 in/yr.) respectively (Wehmiller, et. al., 1977).

Southern California Coast

Along the southernmost part of the California coast, from about Newport Beach to San Diego, emergent marine terraces indicate general uplift and warping. The deformation pattern shows greater uplift to the northwest, in the vicinity of San Onofre; the least uplift is found in central San Diego County (McCrory and LaJoie, 1979). Like the rest of the California coast, this area is geologically complex. Most of the deformation is localized, with uplift and rotation occurring along faults. La Jolla, for example, is rising due to rotation on the Rose Canyon fault (located north of LaJolla), however, Mission Bay and central San Diego have risen little if at all (Kern, 1977). The coast south of the City of San Diego, near the Mexican-United States border, also shows evidence of uplift (Kern, 1977). Uplift in San Diego County ranges from 0.24 to 0.3 mm/yr (0.0094 to 0.012 in/yr.) for the coast from La Jolla to Point Loma up to 0.45 mm/yr (0.017 in/yr.) in northern La Jolla, just south of Rose Canyon fault down to 0.06 mm/yr (0.0024 in/yr.) and 0.01 mm/yr (0.0004 in/yr.) at Del Mar and Scripps, respectively (Kern, 1977; Karrow and Bada, 1980). San Diego Bay has shown recent subsidence of 0.4 ± 0.3 mm/yr (0.016 ± 0.011 in/yr.) since 1853 (Wood and Elliott, 1979).

Summary

The above discussion demonstrates that great variations exist in local uplift and subsidence and, further, that these variations influence the degree of impact at the local level from an accelerated global rise in sea level. In general, subsiding areas will undergo heavier erosion than those locations at which uplift occurs and thus overcomes the rising sea level.

4.0 SCENARIOS FOR SEA LEVEL RISE

4.1 GLOBAL SEA LEVEL CHANGE

As described in Section 2, numerous estimates of future sea level change exist. These projections range significantly due to different estimates of global temperature increase, the lapse time in ocean response, and the extent of glacial melting. The estimates range from about 23 to 117 cm. (9 to 46 in.) for the year 2050, and about 56 to 345 cm. (22 to 136 in.) for the year 2100. The low estimate reflects a small increase in global temperature and a modest increase in sea level. The high estimate assumes significant global warming and extensive melting of glaciers in Greenland and Antarctica. If present sea level rise continues, with no acceleration due to global warming, the rise, by 2050, would be about 10 cm. (3.9 in.) and about 15 cm. (5.9 in.) by 2100.

Estimates of Global Sea Level Rise for Scenarios

For purposes of examining the effects of sea level rise along the coast of California, three different sea level rise scenarios were developed: (1) low; (2) moderate; and (3) high rate of rise. The global levels used for these scenarios are shown in Table 4-1. The estimates for eustatic sea level rise were developed from the formula:

$$\text{Global Sea Level Rise} = bt^2$$

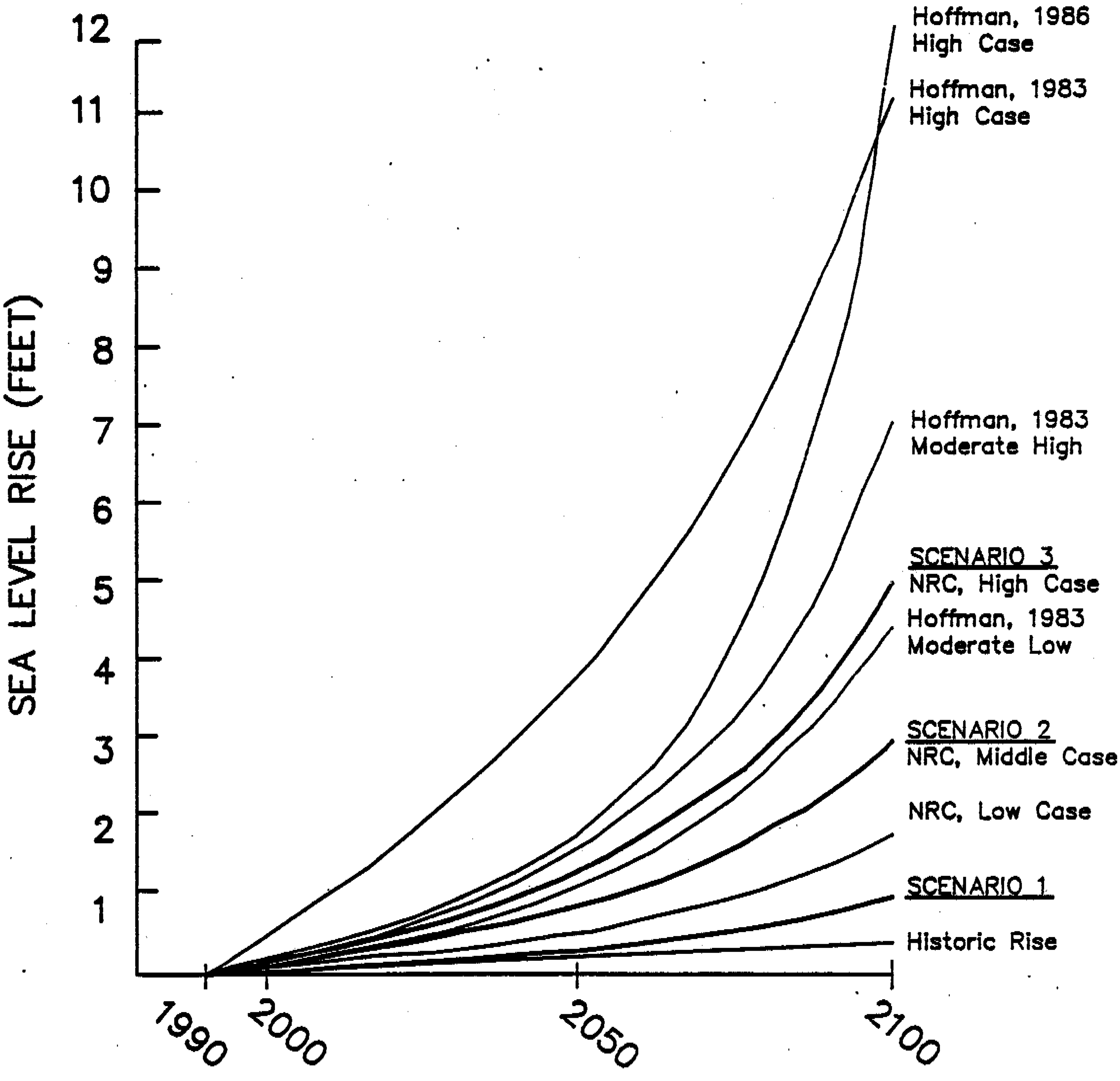
where 't' is time in years and 'b' is a constant having values shown in Table 4-1. When compared with the range of estimated sea levels discussed in Secion 2, these scenarios can be seen to be conservative, as shown in Figure 4-1.

TABLE 4-1
SCENARIOS FOR GLOBAL SEA LEVEL RISE

Scenario	Estimated Rise in Global Sea Level, using 1990 as the Base Year meters (feet) Year 2050	Year 2100
Scenario 1 (Low Rise)	0.091 (0.31)	0.305 (1.0)
Scenario 2 (Moderate Rise)	0.272 (0.89	0.914 (3.0)
Scenario 3 (High Rise)	0.453 (1.49)	1.534 (5.0)

Scenario	Value of b used in Rise = bt^2
Scenario 1	0.0000826
Scenario 2	0.000248
Scenario 3	0.000413

FIGURE 4—1
GLOBAL SEA LEVEL RISE SCENARIOS
(using 1990 as the base year)



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Scenario Objectives

The scenarios are not intended to be predictions of sea level by the years 2050 and 2100. Rather, the scenarios are used to examine what the California coast might be like if global sea level does rise significantly. It is necessary to make some estimates of the occurrence of these sea levels so that the rates of coastal uplift or subsidence can be included with global sea level rise to establish estimates of relative sea level rise. The moderate and high estimates of global sea level rise are similar to those used by the National Research Council (1987). This does not make the scenarios "correct" estimates, but does allow comparison between the scenarios for California and the national scenarios developed by the National Research Council.

4.2 RELATIVE SEA LEVEL RISE

Since California is an active coastline with a significant change in vertical elevation through much of the state, any consideration of sea level rise must take this motion into account. At any location, the relative sea level would be:

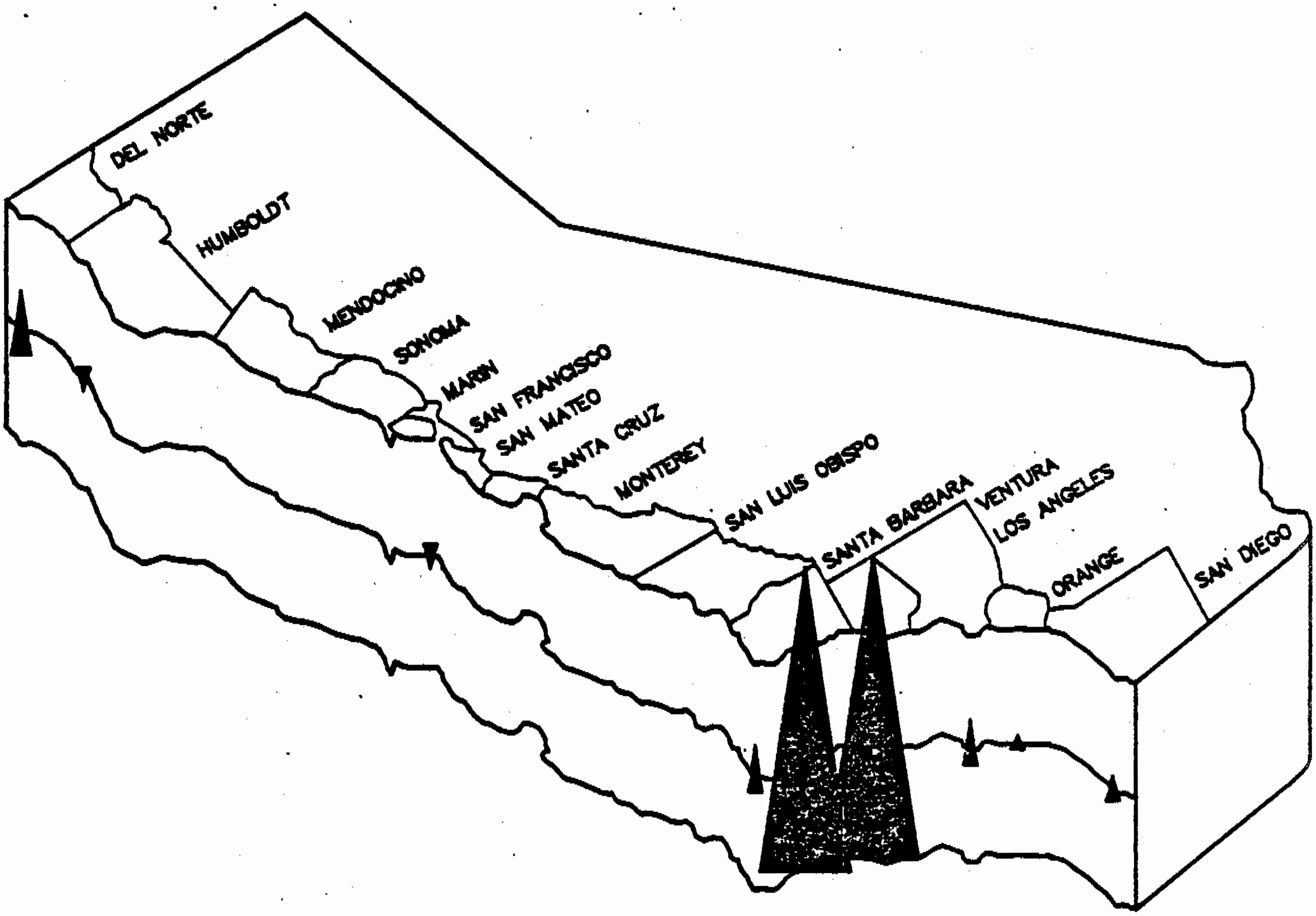
$$\text{Relative Sea Level} = \text{Global Sea Level} \pm \text{Change in Land Elevation}$$

Land subsidence adds to global sea level rise and uplift is subtracted from sea level rise. For example, if the rate of uplift of the coast is greater than the rise in global sea level, the relative sea level rise will be negative.

Three Sea Level Rise Scenarios for the California Coast

Since the rates of uplift or subsidence of the California coast differ along the coast, segments of the coast will be affected to a greater or lesser extent by a rise in sea level. Figure 4-2 shows an overview of uplift and subsidence along the California coast. Unfortunately, detailed leveling and estimates of uplift and subsidence for the entire coast are unavailable. Also, several researchers have studied some regions extensively and have observed different rates of vertical change within a small area. Where regional information is scarce, the available estimates of vertical change have been extrapolated beyond the studied area to estimate regional uplift or subsidence. Where regional data on a detailed scale is abundant, the measurements of uplift or subsidence have been averaged to develop a regional estimate. When Figure 4-2 is combined with estimates of global sea level rise, it provides estimates of relative sea level change along the coast. Estimates of relative sea level rise for various locations along the coast are shown in Tables 4-2 and 4-3. These estimates of relative sea level rise are used in the following sections for examining possible effects of sea level rise to wetlands, beaches and cliffs, coastal structures, and harbors.

FIGURE 4-2
OVERVIEW OF UPLIFT AND SUBSIDENCE
ALONG THE CALIFORNIA COAST



Direction of arrow indicated uplift or subsidence,
size of arrow indicates relative rate of vertical change.

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TABLE 4-2
AVERAGE RELATIVE SEA LEVEL RISE, 2050
meters (ft.)

General Location	Scenario 1	Scenario 2	Scenario 3
Crescent City	-0.012 (-0.04)	+0.171 (+0.56)	+0.354 (+1.16)
Humboldt Bay	+0.098 (+0.32)	+0.277 (+0.91)	+0.460 (+1.51)
San Francisco	+0.098 (+0.32)	+0.277 (+0.91)	+0.460 (+1.51)
Point Conception	+0.046 (+0.15)	+0.226 (+0.74)	+0.408 (+1.34)
Santa Barbara-Ventura	-0.372 (-1.22)	-0.192 (-0.63)	-0.009 (-0.03)
Point Dume-Las Flores	+0.067 (+0.22)	+0.250 (+0.82)	+0.433 (+1.42)
Palos Verdes-San Pedro	+0.037 (+0.12)	+0.216 (+0.71)	+0.399 (+1.31)
L.A.-Newport-Laguna	+0.076 (+0.25)	+0.256 (+0.84)	+0.439 (+1.44)
Dana Point-San Onofre	+0.082 (+0.27)	+0.262 (+0.86)	+0.445 (+1.46)
San Diego	+0.076 (+0.25)	+0.256 (+0.84)	+0.451 (+1.48)

\+ Positive sign indicates a relative sea level rise
\- Negative sign indicates a drop in relative sea level

TABLE 4-3
AVERAGE RELATIVE SEA LEVEL RISE, 2100
meters (ft.)

General Location	Scenario 1	Scenario 2	Scenario 3
Crescent City	+0.119 (+0.39)	+0.728 (+2.39)	+1.34 (+4.39)
Humboldt Bay	+0.317 (+1.04)	+0.927 (+3.04)	+1.54 (+5.04)
San Francisco	+0.317 (+1.04)	+0.927 (+3.04)	+1.54 (+5.04)
Point Conception	+0.223 (+0.73)	+0.832 (+2.73)	+1.44 (+4.73)
Santa Barbara-Ventura	-0.543 (-1.78)	-0.067 (-0.22)	+0.677 (+2.22)
Point Dume-Las Flores	+0.262 (+0.86)	+0.872 (+2.86)	+1.48 (+4.86)
Palos Verdes-San Pedro	+0.204 (+0.67)	+0.814 (+2.67)	+1.42 (+4.67)
L.A.-Newport-Laguna	+0.274 (+0.90)	+0.884 (+2.90)	+1.49 (+4.90)
Dana Point-San Onofre	+0.287 (+0.94)	+0.896 (+2.94)	+1.51 (+4.94)
San Diego	+0.277 (+0.91)	+0.887 (+2.91)	+1.50 (+4.91)

\+ Positive sign indicates a relative sea level rise
\- Negative sign indicates a drop in relative sea level

5.0 IMPACTS OF SEA LEVEL RISE ON COASTAL WETLANDS

As discussed in previous sections, the burning of fossil fuels, the production and use of ozone-depleting gases, such as chlorofluorocarbons, and the clearing of forests will continue, and thus possibly induce global atmospheric warming. Rising temperatures could melt polar and land glaciers, warm and expand ocean surface layers, thereby causing a rapid rise in global sea level. Some of the coastal areas affected by the rise would be those hydrologically connected to and thus influenced by the sea, such as coastal wetlands.* This study examines some potential impacts of a rising sea level on coastal wetland areas and some possible approaches to managing those areas affected by an accelerated rise.

An accelerated sea level rise could disrupt the basic structure of existing coastal wetlands, since hydrology plays an important role in designing these areas. To date, an understanding of the impacts of a sea level rise on California's coastal wetlands remains incomplete (Moffat and Nichol Engineers, 1987). However, an examination of data covering the impact of previous inundations indicates that an accelerated rise could threaten the longevity of coastal wetland systems. Precautionary measures could be undertaken to enhance a coastal wetland's ability to adjust to a sea level rise and thus stave off the adverse impacts. However, a number of technological, fiscal, and ecological issues remain unresolved, throwing into question the feasibility of implementing these approaches. Despite the unresolved matters, this study has been undertaken to facilitate preparedness for preserving coastal wetlands when and if an acceleration in the rate of sea level rise occurs.

In its natural state, sea level changes constantly and these periodic shifts influence coastal wetlands. In fact, periodic change in sea level plays a major part in defining the boundaries of coastal wetland systems; the frequency and duration of inundation determines the system's limits, which usually extend seaward to the level flooded at mean sea level and landward to the elevation flooded at spring high tide. The Pacific coast lies on a slowly shifting continental mass and the resultant tectonic instability of this coast causes land elevation to constantly shift relative to adjacent sea levels. Therefore, California's coastal wetlands are influenced by continuous sea level change.

* In this report, coastal wetlands are defined by Section 30121 of 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."

5.1 CALIFORNIA'S COASTAL WETLANDS

The Pacific Coast is characterized by a wide tidal range, which leads to the development of diverse and complex coastal wetlands within a relatively limited area. Only 10 to 20% of California's 1800 km (1100-mile) coast is suitable for wetland development, due to the tectonic instability and the resultant steepness or narrowness of adjacent coastal areas at which wetland formation occurs (Armentano, 1988, p88). Approximately 145 discrete wetland systems totalling 38,445 hectares [ha] (95,000 acres) have developed along the Pacific's almost non-existent coastal plains, at the narrow fringes of relatively straight-cliffed shorelines or in protected areas near river mouths, in bays or in lagoons. Figure 5.1 identifies California's major coastal wetlands.

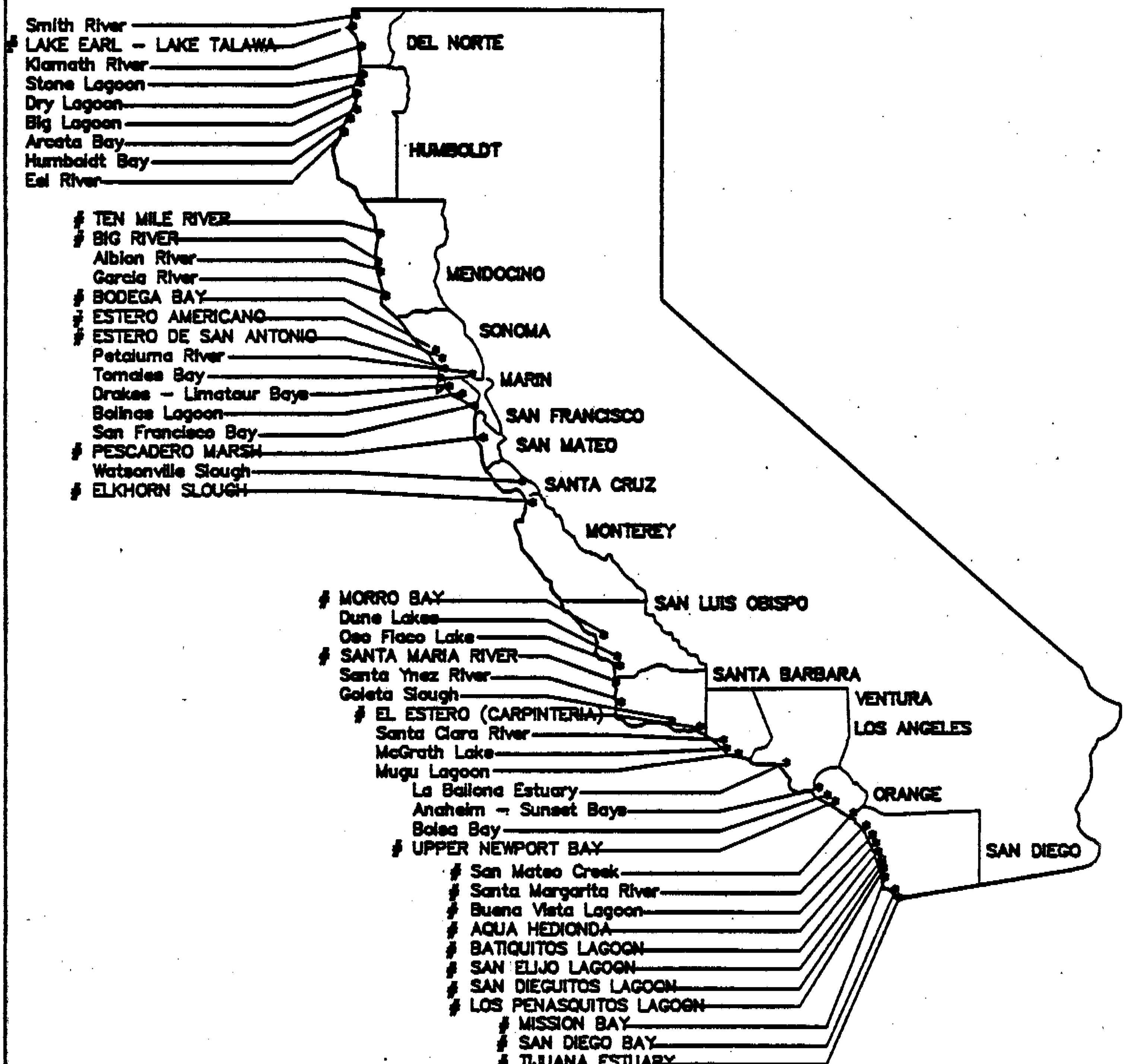
Along California's southern coast, from Mexico to Point Conception, relatively few isolated wetlands remain. About 90 percent of the once extensive wetlands system has been filled or dredged for harbor and port development. The remnant areas have been degraded due to reduced freshwater inflows, contaminated urban inflow, or heavy sedimentation associated with watershed development and subsequent erosion. Despite the tainted quality and declining acreage, many of these wetlands continue to function as migratory bird and endangered species habitat and as urban open space (California Coastal Commission [CCC], 1988).

The central coast comprises a large portion of California's coast from Point Conception to Mendocino County. Many wetlands of this region, such as Bolinas Lagoon or Bodega Harbor, are distinguished by limited freshwater inflow, their intermediate size, and salinity levels approximating that of the nearby ocean. The region's coastal streams terminate in small coastal wetlands and freshwater dune lakes such as the Nipomo dunes of San Luis Obispo County and the Ten Mile and Manchester dunes of Mendocino County; Mendocino County also contains the State's only coastal fen, a relic of the ice age. The coastal terraces of San Luis Obispo and Santa Barbara Counties contain vernal pools, vegetated with plants specially adapted to the pool's freshwater conditions (CCC, 1988).

The north coast wetlands of Del Norte and Humboldt Counties are more estuarine in their composition than other California wetlands due to an almost constant freshwater inflow. The stable freshwater inflow keeps salinity levels relatively low and nutrient content especially rich. The north supports three general wetland types: relatively isolated freshwater and brackish lagoons, such as the Lakes Earl and Talawa or Big Lagoon; estuarine river mouths, such as the Smith River delta; and protected bays or coves with little estuarine area, like Humboldt Bay (CCC, 1988).

In each of these regions, physical environmental forces have confined wetland development to a limited area while anthropogenic forces continue to limit their development (Figure 5.2 estimates California's total wetland loss). Historically, the fertile soils and strategic location of California's coastal wetland areas have led to their drainage and clearance. From 1945 to 1975, California's population tripled to more than 20 million, of which 85% (of the 1975 population) lived within 48 km (30 mi) of the coast. Meeting residential and commercial demands has involved altering the pristine nature of coastal wetlands and their watersheds. Since the turn of the century, California has lost 52% of its original 79,723 ha of coastal wetland (197,000 acres) to filling and dredging activity while 62% of those remaining have been subjected to severe damage and 19% to moderate damage (CCC, 1988). Today, the state supports less than half of its original coastal wetland acreage.

FIGURE 5-1
MAJOR CALIFORNIA COASTAL WETLANDS



WETLANDS CONSIDERED CRITICALLY IMPORTANT BY STATE AND FEDERAL GOVERNMENTS

SOURCE: Sea Grant Report Series, #2, 1979.

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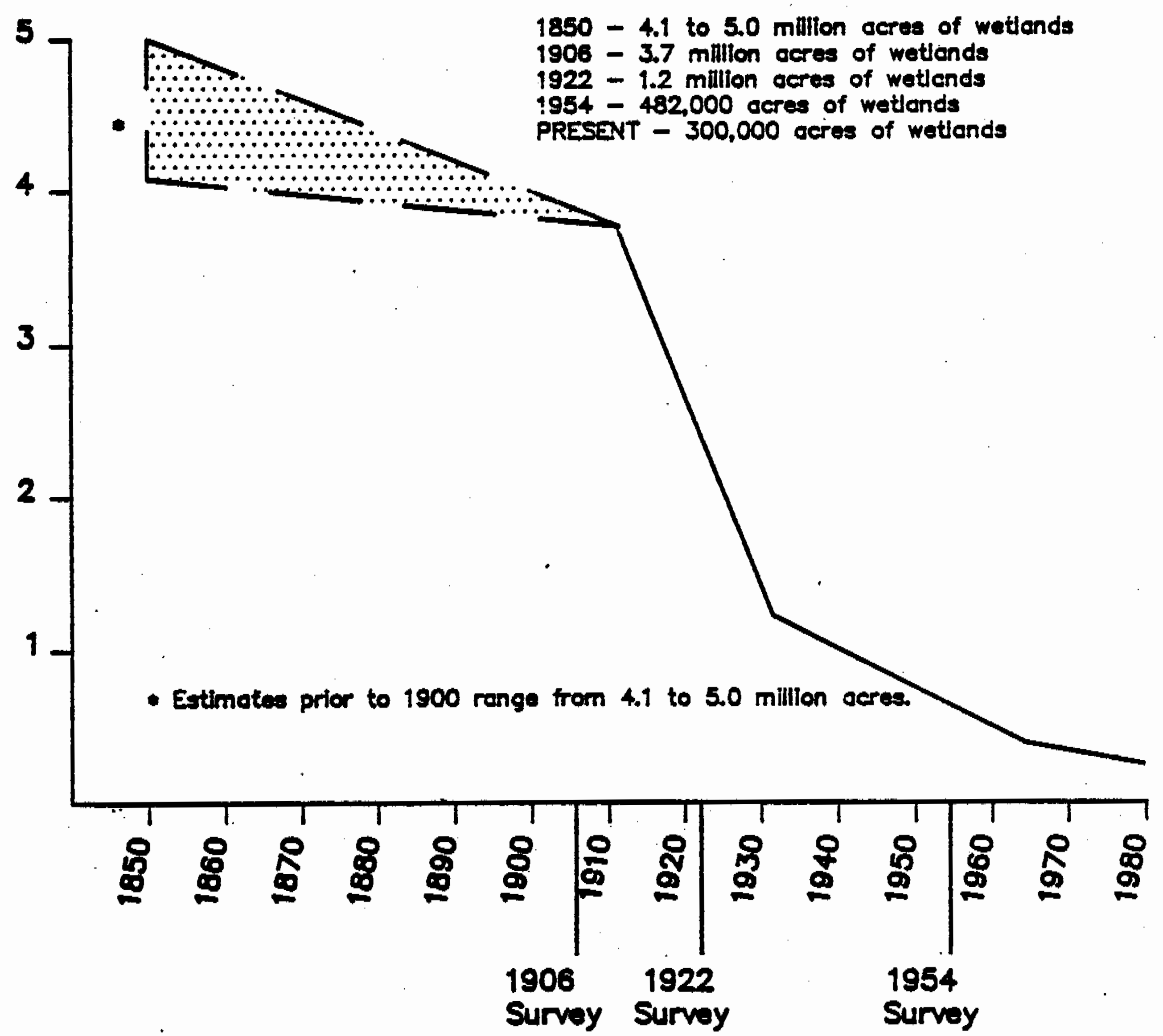
FIGURE 5-2
HISTORIC LOSSES OF WETLANDS IN CALIFORNIA



SOURCE: U.S. Fish and Wildlife Service, 1978.

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Cartography Section

5.2 BIOLOGICAL AND SOCIAL VALUE OF COASTAL WETLANDS

Wetlands are vitally important ecosystems. Any continued loss of wetland habitat would result in a loss of spawning and feeding grounds for estuarine and anadromous fish, endangered species and waterfowl, and a loss of a significant economic and recreational resource.

California's coastal wetlands support plant communities. The tidal action, nutrient import, and moist conditions make coastal wetlands extremely productive. Tidal wetlands are among the most productive ecosystems in the world producing up to 25 metric tons per hectare of plant material annually in the southern coastal plain of North America (Neiring and Warren, 1977).

The abundant food source of coastal wetlands and California's mild Mediterranean climate attracts resident and transient birds to these areas. The U.S. Fish and Wildlife Service designated the California coast as its third highest priority, out of a total of 33 areas nationally, for wintering habitat preservation. In fact, the Pacific Flyway serves as one of the major north-south migratory bird routes in the nation (California Coastal Commission, 1981, p31). California's salt marshes serve as an important habitat for five endangered animal species including the light-footed clapper rail, least tern, Belding's savannah sparrow, and California clapper rail.

King and silver salmon and steelhead trout live much of their lives in the ocean, but return through estuarine wetland areas to spawn. About two-thirds of all commercial fish and shellfish species caught in the U.S. depend on wetlands for part of their life cycle. Many salt water species enter from offshore to spawn, and juveniles remain through the nursery stage and emigrate offshore once reaching maturity (Mitsch and Gosselink, 1986, p396).

In addition to their ecological contribution, wetlands perform important social functions in reducing flood impacts and storing peak flows, improving water quality by temporarily or permanently retaining contaminants, providing food and resting areas for game animals, reducing wave and flood erosion thus stabilizing shorelines, recharging groundwater in areas hydrologically connected to groundwater systems, providing outdoor education laboratories for both students and teachers, and enhancing the aesthetic value of our environment (U.S. Office of Technology Assessment, 1984).

Further losses in wetland acreage could ultimately increase competition for food and reproduction areas, heighten vulnerability of wetland communities to disease and environmental stress, and eventually weaken entire floral and faunal populations. A major reduction of Pacific Flyway migratory waterfowl has already been associated with the conversion of 90% of the State's wetlands (U.S. Office of Technology Assessment, 1984). A continued reduction in coastal wetland area could adversely affect the biological and social landscape of California and, eventually, the nationwide ecosystem.

In general, all ecosystems are interrelated. Wetlands function as habitat for migratory species and thus are interrelated. Therefore, the loss of a coastal wetland area along the Pacific coast indirectly and adversely affect a similar habitat along the Gulf coast. The diminishing number and quality of nationwide wetlands accentuates the importance of preserving California's coastal wetlands.

Legislative Response to Wetland Loss

The European arrival to and resultant steady population and economic growth in the United States created an unprecedented amount of pressure on approximately 9 million ha (215 million acres) of inland and coastal wetlands. Following the Second World War and into the 1970's, annual net wetland loss in the lower 48 states averaged 186,157 ha (460,000 acres)(U.S Office of Technology Assessment, 1984).

In response to the steady decline and degradation of coastal and inland wetlands across the U.S. and along California's Pacific coast, federal and state governments enacted legislation and developed policies to curtail wetland conversion. Their combined efforts in implementing these regulations and policies and orchestrating public and private aquisitions, easements, and restoration projects have helped stave off the careless use and loss of wetland areas. Unlike the federal government's earlier attempts to regulate wetland use through the Swampland Acts of 1849, 1850 and 1860, which permitted state reclamation (ie. draining or filling) of all "swamps" for purposes of flood control and mosquito extermination, the newer laws encouraged wetland preservation instead of elimination. In 1972, Congress passed Section 404 of the Federal Clean Water Act strengthening permit requirements for unnatural disturbances to wetlands. The federal government, through direct ownership, easements, and leases, has participated in protecting approximately 4.5 million ha (ten million acres) in the lower 48 states, while Section 404 itself has been partially responsible for reducing coastal wetland conversion by 70 to 85% (U.S Office of Technology Assessment, 1984).

In 1972, Congress agreed on a major objective to assist coastal zone states in developing and implementing coastal management programs. Also in 1972, California voters adopted a strong, coastal protection initiative which led to the establishment of a permanent Commission to ensure a balance between ecological and human activity along the California Coast. The California Coastal Act (passed in 1976), provides specific protection policies for wetlands and regulates dredging, diking, and filling of these areas. Currently, the Commission's wetland protection policies prohibit development in 19 wetlands identified as critically important and contain strong additional provisions to protect all other wetlands. The Coastal Commission's planning process has assisted local governments in adopting measures to reduce adverse effects on wetlands from surrounding development. The California Environmental Quality Act [CEQA] requires public agencies to prepare reports assessing potential environmental effects of a project and describe mitigation for any adverse impacts associated with the activity.

In the winter of 1988, a bipartisan panel of state and federal officials, business interests and conservationists met to discuss national wetland policy and renewed their commitment to wetland protection; the panel advocated a "no overall net loss" policy of the nation's remaining 40 million ha (99 million wetland acres). A month later, in January 1989, the U.S. Environmental Protection Agency [EPA] announced its new policy to ensure no net loss of remaining U.S. wetlands. With its declaration, the EPA became the first agency overseeing the nation's wetlands to commit itself to the prevention of an overall loss of these areas (Shabecoff, 1989).

The formal approach through enacting laws and aquisition has helped preserve wetland habitat throughout the lower 48 states. However, 40 million ha (99 million acres) or less than half of the original acreage remain, of which only 5% are coastal wetlands (U.S. Office of Technology Assessment, 1984). The dwindling number and quality of wetlands increases the importance of protecting those remaining.

5.3 MECHANISMS PERMITTING AND INHIBITING ADAPTATION TO SEA LEVEL RISE

Wetlands are not static environments. Wetlands adapt regularly to environmental change by developing or using mechanisms designed for adaptation. Coastal wetlands are normally affected by variations in temperature, salinity and oxygen levels as a result of fluctuating tides. Precipitation interacting with a normal tidal cycle, for instance, can change salinity levels by a factor of two; mud surface temperatures can vary 10 deg. C in a single day as the system is alternately exposed to ambient air temperatures and submerged under cooler marine waters. Coastal wetlands are distinguished from other systems by abundant moisture, oxygen deprivation, and saline conditions which result in above-average salinity, and the system's ability to successfully adapt to changing environmental conditions.

Although wetland plants grow in the intertidal zone, the root system of these plants needs oxygen. The hydrological conditions present in coastal wetlands not only shape these wetlands but also determine the degree of oxygen depletion in the soils to which wetland flora adapt. Incoming tides provide plants with moisture, either through direct deposition on leaves and stems or through soil saturation from which plants absorb water. In time, the level of available oxygen in waterlogged soils is reduced, thus limiting the amount useable by plants. Concurrently, as soils become saturated and oxygen availability is reduced, water slowly covers aerial plant parts interfering with the delivery of atmospheric oxygen below-ground. Gradually, inundation cuts off regular routes of oxygen availability to plants, thereby impeding respiration.

Some wetland flora, such as Spartina foliosa (cordgrass), close stomatal openings which normally allow oxygen to enter, at high tide when open air passages may be flooded. Closed stomata allow for the toleration of an overabundance of water (Watts, 1957, p33-34). Other wetland flora adapt more elaborately to regular exposure-inundation tidal cycles, through actual structural changes which facilitate a switch from aerobic to anaerobic respiration. Flooded conditions stimulate the production of ethylene (plant hormone), which in turn stimulate the development of aerenchyma or air spaces. The production of ethylene causes cell walls to collapse and disintegrate (cell separation also takes place during organ maturation); as a result air space is created (Mitsch and Gosselink, 1986, p131). The ability of wetland flora to adapt to waterlogged conditions is enhanced by the development of air space in stems and roots. These air spaces can comprise up to 60% of the body and allow oxygen to move from above-ground photosynthesizing (oxygen producing) tissues to below-ground parts, thus enhancing the diffusion of oxygen from aerial parts to the roots to meet respiratory demands (Mitsch and Gosselink, 1986, p131).

The composition of wetland flora varies according to elevation and is partially attributed to species' salinity tolerance, competition, and inundation tolerance (Purer, 1942). Species equipped with more air spaces are better able to withstand submergence. Spartina foliosa is one of the more water-tolerant wetland plants due to its large, well-developed, air storage tissue; thus it withstands prolonged submergence periods, unlike Salicornia virginica (pickleweed), which lacks arenchyma and thus does not fare well at the lowest wetland elevation (Purer, 1942; Hinde, 1954). Batis maritima (saltwort) and Suaeda californica (sea blyte) withstand only limited periods of submergence due to limited air space.

Wetland plants also adapt to inundated conditions by undergoing chemical transformation. In waterlogged soils, anaerobic respiration brings about the production of nontoxic malate which accumulates and limits the glycolysis rate, thus limiting the production of ethanol (by-product of alcoholic fermentation which occurs during oxygen-deprived conditions). Ethanol is toxic and thus by limiting its production the plant avoids unncessary damage (Crawford, 1978). Sometimes, ethanol is produced under oxygen-deprived conditions but diffusion through plant roots helps prevent morphological damage (Salinas, et al.).

Under periodic and regular tidal inundation, salt marsh plants adapt despite the anaerobic conditions. The degree of anoxia, however, can affect plant growth and interfere with root respiration and plant productivity (Crawford, 1978). Under prolonged submergence, arenchyma lose the ability to compensate for oxygen loss (Mendelssohn, 1981). Waterlogged conditions also enable water to fill soil pore spaces and reduce the rate of oxygen diffusion through soil thus enhancing microbial activity whose consumption of available oxygen decreases the amount available to plants. In waterlogged soils, oxygen solubility is low and oxygen moves less freely. In fact, oxygen diffusion in an aqueous soils is 10,000 times slower than its diffusion through porous, drained soils. Eventually, the lowered oxygen level impairs normal aerobic root respiration, suffocates roots and reduces growth (Mitsch and Gosselink, 1986, p93; Boaden, 1985). Prolonged submergence and anaerobic conditions also impair the availability of soil nitrogen to plants preventing nutrient buildup required for growth and productivity (Mitsch and Gosselink, 1986, p185).

One impact of prolonged anoxic conditions is an increased level of internal toxicity. Under prolonged submergence, organic compounds decompose and form hydrogen sulfide and ethanol (the by-product of reduced oxygen conditions and alcoholic fermentation). One impact of sulfide toxicity is dieback (Mendelssohn, 1987). Under ideal conditions, ethanol diffuses through plant roots but ethanol toxicity reduces carbon production, and carbon deficits can deplete a plant of its energy and ultimately reduce growth (Crawford, 1978).

Another impact of submergence is increased salinity levels which can prove toxic and disruptive to normal osmotic patterns. However, wetland plants develop mechanisms by which to adapt to excessive salt concentrations and reduce levels of salt retention. An overabundance of salt in sap can be highly toxic, so wetland plants dispose salt through small glands at the surface that pick up salt from sap and secrete it through leaf pores; the surface salts are eventually washed away by precipitation or lost as leaves fall and float away with the tide (Mitsch and Gosselink, 1986, p131). Salicornia virginica (pickleweed) tolerates wide salinity variations and, in general, is more tolerant of higher salinities than other wetland plants such as cordgrass (Wilcox and Hein, 1985, p50).

Some halophytes (saltwater-tolerant plants), such as succulents, assimilate salts by diluting them internally with water stored in tissues (Smith, 1986). Glycophytes, salt-intolerant plants, keep salt from the xylem (supporting and water-conducting tissue) by sequestering it in the roots and stems (Salinas et al.). Many plants take up salt but transfer and store it in high concentrations in areas where damage to growing tissues is minimal, but overloading this control mechanism with too much salt increases salt concentration in the leaves and ultimately stunts growth (S.F. Bay Conservation and Development Commission, 1988).

Some mechanisms permit wetland plants to keep salts from disrupting normal osmotic activity. During osmosis, water moves from a less concentrated solution to a more concentrated one in an attempt to make the concentrations on either side equal. In some wetland plants, cells increase the salt concentration of their internal water so it is above the concentration of the seawater surrounding the cell. However, excess salt in a cell can disrupt the osmotic potential surrounding the cell, and a high concentration of inorganic ions in the cytoplasm can be toxic (Watts, 1957, p33-34). Excess salt in a cell environment which exceeds that of the cell cytoplasm causes water to be drawn out of cell as cells will not retain water against an osmotic gradient and thus dehydrates the cell's cytoplasmic content which could be lethal. Under some circumstances, the cytoplasm will rehydrate as salt diffuses through the cell membrane thus raising internal osmotic concentration (the cell also can produce soluble organic compounds in response to the salt stress), but such an adjustment may not occur under prolonged periods of submergence (Mitsch and Gosselink, 1986, p128).

Most flora exclude or excrete toxic ions to prevent damage to growing tissues, but these adaptive mechanisms have their limits (Purer, 1942). Under periods of heavy salinity, root absorption of water continues. The absorbed water, however, contains dissolved salts which enter the roots and cells and the sodium ions interfere with the plant's ability to absorb water. The disruption of water absorption hastens wilting, which further inhibits the plant's absorption ability; an interrupted absorption rate can ultimately hinder the rate of growth (Boaden, 1985).

In hypersaline conditions, plants transfer energy normally targeted for productivity to respond to physiological stress (Coats, et al., 1986, p11). The result leads to smaller plants with less dense canopies. The resultant reduced height and density lead to lower productivity, which has been demonstrated by reduced end-of-the-season biomass in areas subjected to hypersaline conditions; cordgrass, for instance, has been known to exhibit lower productivity level during high salinity periods (Zedler/USFWS, 1982).

Some studies show that a drop in salinity improves growth as demonstrated during winter when precipitation and freshwater runoff are highest (Zedler, 1982). Lower salinity levels stimulate germination as demonstrated during winter storms; biomass appears greater following storms in light of stimulated growth (Onuf, 1987, p43-44). Since salinity is not a requisite for wetland flora productivity and a lack of it stimulates growth, an increase may lead to just the opposite effect. A drop of the salinity level below 5 ppt, however, will create conditions in which reed and rush or brackish water vegetation can survive and bring about their colonization.

Unlike flora, fauna are equipped with more complex mechanisms to adjust to periods of prolonged submergence. Many wetland fauna originate from the upland areas enabling them to stress their terrestrial functions during high water levels and thus allow adaptation.

Some insects tolerate salt but are selective in their intake and choose to feed on halophytes with low salt concentrations or feed on plants rinsed of salt by precipitation. Many insects often have water-proof integuments (outer covering) for protection from moisture (Zedler/USFWS, 1982). The salt marsh boatman is one of the few species that tolerates a predominately saline habitat by eating algae and protozoa living in pools and surfacing to renew its oxygen supply (Zedler/USFWS, 1982). Those salt-intolerant insects deliberately avoid total submergence by flying, swimming or walking over water surfaces to drier wetland areas (the less agile insects like large beetles experience more difficulty trying to escape inundation); many insects simply inhabit higher wetland elevations to avoid high water periods altogether (Davis, 1966).

Most birds are highly mobile and thus able to avoid inundation and hypersaline conditions; some actually tolerate salinity by using nasal glands to excrete salt. Belding's savannah sparrow lacks nasal glands by which to excrete salt but tolerates salt with its highly efficient urinary tract which concentrates chlorides allowing the sparrow to drink and process sea water (Zedler/USFWS, 1982).

The meadow mouse adapts to periods of moisture stress by tolerating dehydration. The western harvest mouse tolerates periods of moisture stress by entering torpor or a temporary period of low metabolic rate (Zedler/USFWS, 1982).

Historical Wetland Response to Sea Level Rise

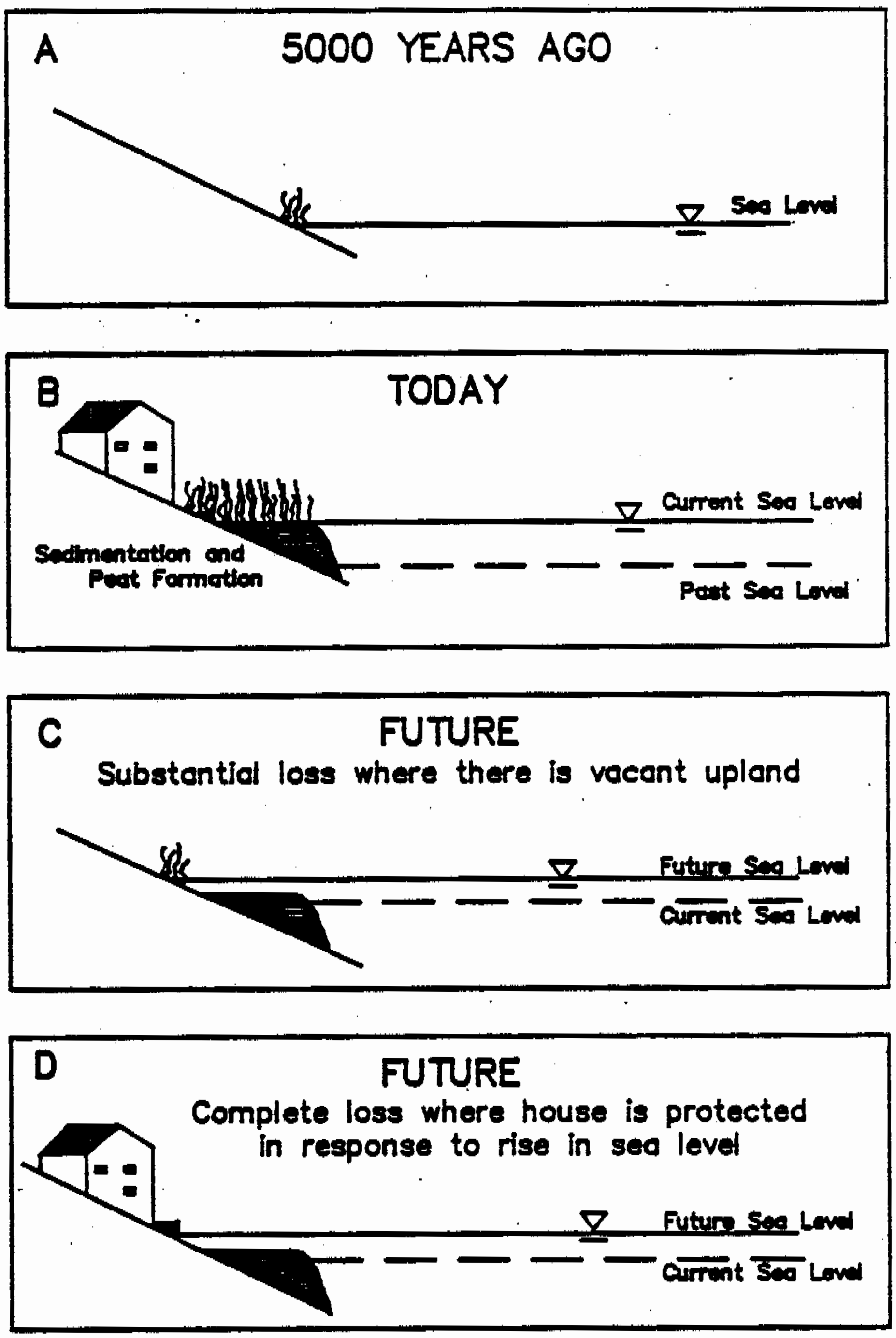
In addition to species adaptation discussed in the previous section, wetland systems themselves hydrologically adapt to sea level changes which occur gradually as a result of natural processes such as diurnal tidal or isostatic changes. In fact, a gradual sea level rise led to the development of our existing coastal wetlands.

Approximately 17,000 years ago, the Pleistocene epoch ice sheets began to melt and water previously stored on land flowed into the sea; since then, sea level has risen between 400 to 450 feet.

Around 4,000 years ago, the sea level rise tapered off, and, in those areas recently cut off from the open ocean, terrestrial plants invaded enabling sediment accumulation or accretion. As accretion rates equalled or exceeded the pace of coastal submergence, our existing estuaries and salt marshes began to take form. The oldest present-day salt marshes formed during the last 3,000 to 4,000 years (Mitsch and Gosselink, 1986, p180).

The environmental conditions associated with the post-glacial sea level rise favored coastal wetland development. In the post-Pleistocene epoch, coastlines adjusted relative to adjoining sea levels due to isostatic changes, seas submerged these coastal areas, vegetation colonized and facilitated gradual sediment accumulation and buildup, and thus wetland development kept pace with changes in sea level, as shown in Figure 5-3(A).

FIGURE 5-3
MARSH EVOLUTION AS SEA LEVEL RISES



Coastal marshes have kept pace with the slow sea level rise characterizing the last several thousand years. The wetlands area expanded as more lands were inundated (A and B). If future sea level rises faster than the ability of the marsh to keep pace, the marsh area will contract (C). Construction of seawalls may prevent new marsh from forming and result in a total loss of marsh in some areas (D).

SOURCE: Titus, 1988.

Under gradual Holocene sea level rise, sedimentation and peat formation kept pace with rising tidal elevations (Orson, et al.; Redfield). Coastal wetlands maintained their substrate and remained stable relative to mean sea level as long as accretion rate kept pace with submergence (Orson, et al., 1985). In time, wetlands reached a stable elevation around mean high water (Mitsch and Gosselink, 1986, p151-67).

Wetland Response to an Accelerated Sea Level Rise

Coastal wetlands accustomed to periodic or slow systemic changes are not necessarily equipped to adjust to a relatively rapid sea level rise associated with global atmospheric warming. Unlike the gradual or temporary rises in sea level, a rapid rise may impose extraordinary stress on coastal wetlands and cause them to react abnormally to a rising sea.

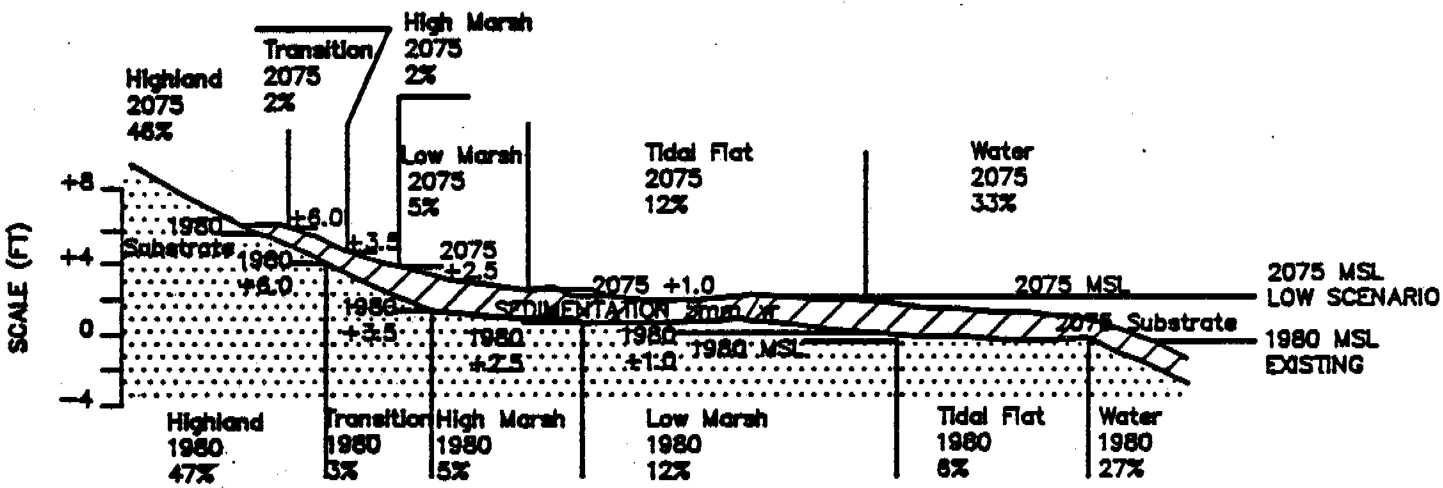
In general, a wetland's long term survival is determined by its ability to maintain surface elevations required for continued plant growth, through sediment accumulation, or by the available space on which to build both upward and landward (Orson, et al., 1985). In undergoing vertical and lateral growth, the substrate remains at a constant elevation relative to sea level, and wetlands continue to move upland to compensate for any loss of lower elevation to submergence. The progressive lateral and vertical movement allows vegetative growth to continue. This promotes sediment accumulation and continued wetland development (Figure 5.3[B])

Under normal rates of sea level rise, wetlands adjust by expanding inland through lateral and vertical growth. The presence of vegetation plays a crucial role in vertical buildup by entrapping sediments and anchoring soils. With accelerated sea level rise, plants in lower tidal elevations may experience prolonged submergence and impede vegetative growth. A reduction in vegetation can, in turn, reduce sediment entrapment and adversely affect the mechanism necessary for the wetland to "keep up" with rising sea level. If wetland vertical buildup does not take place relative to sea level, the system could eventually drown, as shown in Figure 5.3(C). Also, if the rate of sea level rise exceeds the rate of accretion in lower elevations, decreased vertical buildup could exacerbate substrate erosion and lead to a substantial net loss rate in the lower marsh area (DeLaune, 1983; Phillips, 1986).

If sedimentation rates remain high, a wetland may overcome its losses to rising sea levels by migrating upland and thus altering its former pattern by moving into areas previously associated with high or transition wetland zones, as shown in Figure 5.4. However, the degree of slope and the presence of artificial obstructions will determine if a wetland can successfully make the upland shift, as shown in Figure 5.3(D).

The most likely effect of prolonged inundation in the lower wetland areas due to the salinity and oxygen changes would be a loss of plant biomass. Similarly, the loss of vegetation in this area would impede accretion rates, since sediment accumulation is usually greatest where plant cover is densest (Rice, 1977, p. 357). The loss of plants and increased erosion in this area would result in a net loss of wetland habitat in the lower levels, but if sediment inflow remains stable and upland areas remain unobstructed by artificial structures and the configuration of the slope allows, the entire wetland could essentially move upland and alter its former plant zonation patterns and boundaries, as shown in Figure 5.4.

FIGURE 5-4
SHIFT IN WETLANDS ZONATION ALONG A SHORELINE PROFILE



Conceptual model of the shift in wetlands zonation along a shoreline profile if sea level rise exceeds sedimentation by 40 cm. In general, the response will be a landward shift and altered areal distribution of each habitat because of variable slopes at each elevation interval.

SOURCE: Kana, et. al., 1988.

5.4 POSSIBLE REMEDIES AND THEIR LIMITATIONS

Under a prolonged submergence associated with sea level rise, it seems possible that initially flora and fauna could adjust. In time, however, lower wetland flora may experience extreme innundation and be lost. This being the case, the total floral distribution could move upland incrementally according to tidal elevation _if_ the upland area is conducive to the migration by being unobstructed by human-made structures and topographically suitable.

Most coastal wetlands are situated lower than 3.5 meters above sea level yet above mean sea level and are generally less than on e tidal range above mean sea level. Therefore, any sea level rise exceeding 1.5 m (5 feet) would threaten wetland areas (Titus, 1986, p. 155). Further, a sea level rise by a single tidal range (the difference between mean high and mean low) would drown a wetland (Titus, 1988). If upland migration of a wetland system is not possible, legislative and technological steps may be available to enhance upland movement and stabilization of the system.

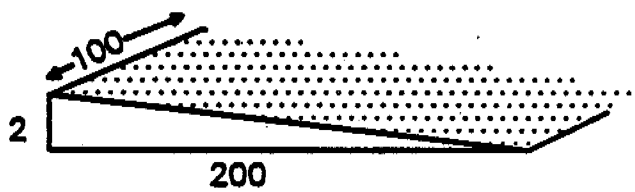
In some areas along the Pacific Coast, wetland upland migration may be inhibited simply due to the nature or degree of the upland slope. Coastal wetlands will only be able to migrate upland if the available area remains uniform above the lower wetland area (Kana, et al., 1988). Wetlands require gentle expansive slopes to expand, as shown in Figure 5.5. The requisite transitional slope between deepwater and the upland environment should be gradual and uniform to allow vegetation to grow and stabilize, yet deep enough to facilitate tidal flushing (U.S. Office of Technology Assessment, 1984). Low slopes without a sharp incline offer broad ranges and thus enhance flora and then fauna species diversity (Titus, 1988). A typical slope at California's Tijuana Estuary is 1% (Zedler, 1984); this degree of slope prevents tidal waters from becoming impounded and drowning the lower wetland. Unfortunately, many of California's wetlands lie at the toe of or are relatively close to the foot of coastal ranges, thus submergence could occur without replacement due to steep upland slopes or landforms (Titus, 1988).

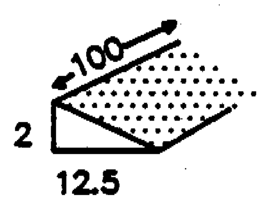
In the event of a sea level rise, at wetlands with an upland slope relatively uniform to that of the lower, the area lost to drowning would equal the area gained by landward encroachment of spring high tides (Titus, 1988). At most coastal wetlands, however, the upland slope is considerably steeper than the wetland itself, and thus a rise in sea level could inevitably bring about a net loss of wetland acreage (Titus, 1984). Along the Pacific Coast south of Los Angeles, gently sloping coastal plains could permit land migration of entire ecosystems, although upland development could impede this migration (Titus, 1984).

Protective structures or residential/commercial development upland of the affected wetland could impede upward migration. Usually land immediately landward of the wetland is unavailable for natural migration due to physical structures or coastal protective devices (in Titus, 1988: Kana, p39). Therefore, if land above the wetland is unavailable, the wetland will eventually be squeezed out between rising sea and upland development (Kana, et al., 1986). Pacific Coast wetlands are as vulnerable to sea level rise as East and Gulf Coast areas of the U.S. and, in some areas of California, 35-100% of existing wetlands could be lost while net loss would be 1-18% if developed areas were abandoned (Titus, 1988, p. 28).

FIGURE 5-5
VARIABILITY OF SLOPE AVAILABLE FOR WETLANDS

PERCENT OF SLOPE	Area in strip 100 yards wide, with 2 yards of vertical drop.
1	20,001 sq. yds.
2	10,002
4	5,004
8	2,508
16	1,266





Comparison of area available for marsh vegetation given different slopes. All figures based on a strip 100 yards long.

SOURCE: J. Zedler, 1984.

California Coastal Commission
Cartography Section

Upland land-use restrictions contained in new legislation could facilitate a wetland's ability to migrate upland. Such legislation could require that development in these areas require a coastal development permit which involves removing the project in a given number of years hence when and if sea level rises a given level. The state of Maine has recently developed policy requiring the construction of mobile houses which can be moved in the event of a sea level rise.

The restriction of development along the landward edge of wetlands can also be achieved through land acquisition. In some cases (funds permitting), the agency issuing the development permit could exercise eminent domain and pay owners full market value for property if sea level rises.

Massachusetts has taken important policy steps to protect their wetlands from sea level rise by establishing construction setback lines and by enacting legislation prohibiting the construction of bulkheads along wetland edges. Maryland now prohibits new devlopment within 304.8 m (1000 ft) of wetland boundaries at Chesapeake Bay. North Carolina, with one of the more effective setback line policies, has altered a key element of its former policy by recalculating the rate of coastal erosion for the entire coast every five years. For every coastal development permit, a setback is established based on the erosion rate for the particular area of development. In general, residential structures require a setback from the vegetation line which is 30 times the annual erosion rate while larger commercial structures require a setback which is 60 times the annual rate of erosion from the vegetation line. Such an approach to moving the setback or construction line allows for preparedness with regard to sea level rise impacts (Brown, 1987).

Besides abandoning high risk areas and allowing nature to take its course, it is possible to artificially manage the hydrologic cycle or stabilize and defend the areas by employing engineering devices, and thus prevent sea level rise from taking its toll on these areas.

California could develop policies to prevent any future disruption of freshwater inflow from coastal watershed areas; incoming freshwater carries upland sediments which could ultimately facilitate substrate build-up. In an effort to save Louisiana's wetlands lost to sea level rise, the state and federal governments joined together to finance the Caenarvon Freshwater diversion project, which will reduce Breton Sound marsh loss by approximately 6500 ha (16,000 acres) in the next 50 years (Louisiana Wetland Protection Panel [LWPP], 1987, p. 39).

Marine sediment inflow could be assured by removing or limiting development of coastal protective devices (such as offshore groins, jetties, revetments) which often interfere with natural sedimentation and wetland development processes. However, such a solution affords minimal flood relief and could exacerbate erosion in wetland areas and eventually create a need to re-construct engineered structures.

Other management techniques may allow wetlands to persist in the event of a rise. Controlling salinity and water levels through the use of artificial devices can maintain stable water depths, thus maximizing diversity and promoting growth of rooted submerged aquatic plants and associated benthic fauna. The use of culverts varying in size restricts incoming waterflow. Water level manipulation can also be achieved through the use of dikes, weirs, control gates and pumps, which control drainage or flooding depth at a desired time. These methods usually maintain normal tidal flushing by incorporating gates which open and close depending upon the height of the tide. Many of these barrier methods, however, tend to block not only the excess water but also organisms. Although periodic opening and fine mesh fences allow flow-through, the obstructed access between wetland and marine systems remains an environmental problem which techonology has yet to remedy. The many organisms, for example, which spend part of their life cycle in wetland areas and part in the ocean would suffer if unable to pass freely between the two ecosystems.

An accelerated sea level rise, however, may preclude the implementation of traditionally-used mechanisms or require the use of several mechanisms at one particular area or bring about the development of new technology or new ways to use old technology to compensate for the rise. Fixed and variable-crested weirs are usually solid structures placed at wetland outflows which maintain minimum water levels. Currently, they provide the poorest control against an accelerated sea level rise since they are useful only in maintaining minimum water levels, rather than maximum levels (LWPP, 1987, p. 47). Tidal gates are useful in holding back a minimal sea level rise but when used with levees and mechanical pumping systems, the gates may be more effective in keeping the wetland water level below that of a rapidly rising sea (Titus, 1988).

Under gradual or periodic sea level rises, mechanisms can be operated passively by simply responding to the force of the incoming or outgoing waterflow, but as sea level rises, passive and other non-manual methods will be more difficult to use and water drainage will require more aggressive manipulation to keep up with the rise (LWPP, 1987, p. 50).

A newer and relatively costly method of ensuring wetland sedimentation involves artificially adding sediment (nourishment) to enhance a wetland's ability to keep pace with the rise. Currently, the system has many techological flaws and thus is used only in existing wetland areas undergoing minor submergence and upstream sediment deficit. At this time, it appears unlikely that this method would be useful in the event of an accelerated sea level rise (LWPP, p. 51).

In the future, new solutions will probably be tested to help defend against sea level rise. New technologies are making this possible today. In Venice, Italy, tides now measure about 23 cm (9 in) higher than those of the early 1900's and projections show tides will rise almost 61 cm (24 in) during the next century. To save their city from periodic floodings and the expected rise related to global warming, the Venetians plan to employ "Moses," a project designed to hold back the threatening tides. Moses is a prototype seagate used to seal off the entire Venice Lagoon from the Adriatic Sea. The system involves flexible walls built at narrow openings; the walls consist of a series of 80 flap gates raised or dropped depending upon tidal height, intended to cause only minimal interference with critical tidal flushing. The system will attempt to protect practically 5 sq km in a 500 sq km (2 sq mi in 212 sq mi) lagoon and will cost five billion dollars (Haberman, 1989).

The cost of adapting to a sea level rise is undoubtedly high. In Charleston, South Carolina, protective devices could cost $1.5 billion. The cost of protecting the entire east coast by building storm gates, pumps and dikes could reach $100 billion (Russell, 1989). Shoreline stabilization is possible from an engineering standpoint but expensive; the decision to commit to such a costly solution must be carefully considered.

Preparing Future Management Plans

Despite the many uncertainties surrounding possible sea level rise , some state agencies have begun to incorporate the concept of sea level rise into their management plans. The San Francisco Bay Conservation and Development Commission (BCDC), which regulates development in and around the state's highest concentration of coastal wetlands, adopted amendments to its Bay management plans requiring that development permit applicants consider sea level rise in the engineering design of projects located on or over the San Francisco Bay. In requiring applicants to consider a potential rise, BCDC will enhance its ability to manage the Bay wetlands if and when a rise occurs.

The state's other coastal permit authorities and wetland management agencies should begin to consider the matter of sea level rise in their land use plans. The probability and magnitude of such a rise in sea level continues to generate discussion, examination, and debate, and yet many questions remain unanswered. In spite of the unanswered questions, California should continue to research and keep abreast of the latest data regarding sea level rise and its impact on wetland areas; future wetland management could be more effective and successful if those participating in project designs, including the California Coastal Commission which indirectly manages wetland enhancement and restoration programs, consider the impact of a rise in sea level on wetlands.

In light of the technological, economic, and scientific uncertainties, California could approach the matter cautiously by waiting for more precise data and act later to plan and prepare for the event. However, waiting to act could result in the State being unprepared to respond if a rise actually occurs or losing the opportunity to invest in technological solutions at a time when costs were lower.

In the event that no steps are taken to enhance a wetland's ability to adjust to the rise, these precious resources could eventually be lost or simply be converted to open water bodies. Any loss of these systems will inevitably be at great cost to California's social and ecological landscape and one that may be irreparable.

6.0 BEACH EROSION AND CLIFF RETREAT

The two dominant features of the California coast are beaches and coastal cliffs; each affected by waves and currents. Some sections of the coast are fairly stable although estimates show that over 86% of the coast is eroding (Griggs, 1985).

6.1 SAND MOVEMENT

General Sand Movement

Most California beaches consist of sand, silt, clay, pebbles or cobbles. This beach material is derived from river deposition and/or cliff erosion. After deposition on a beach, this material can stay in place, move on and off shore, be transported along the coast, or be removed by mining operations. Ignoring mining efforts, beach material is transported by water, waves, currents, and wind action. Waves stir up and suspend beach material and currents transport it. Similarly, winds suspend some of the finer material. The beach material is carried in the direction of the waves or wind and eventually deposited.

Littoral Cells

One useful model of a beach system is the littoral cell. In this model, the coast can be divided into a number of cells; California has been divided into 27 littoral cells. Each cell is an independent system with a source(s) of beach material and a sink(s), with movement of material within the cell. Material can move offshore but there is little if any transport into or out of adjoining cells. The total material in the littoral cell is the sum of material on the beach, in offshore bars, and that provided by rivers or cliff erosion, minus the total amount of material lost to submarine canyons, moved too far offshore to be returned to the beach, and material blown inland off the beach by onshore winds. When the boundaries of a littoral cell are determined, it is possible to determine the amount of sand budget on the sand leaving and entering the system. Beach erosion will occur if more material is leaving the cell than entering, accretion will occur if the volume of the entering material is greater, and stabilization will occur if inflow equals outflow.

Wave Effects on Sand Movement

Sediment carried parallel to the coast is called longshore transport, and sediment carried perpendicular to the beach is called onshore-offshore transport. The specific transport mechanisms differ for both of these, but in general, sediment is suspended by the orbital motion of the waves and moved back and forth. If there is a current superimposed on the wave action or if the wave orbit is stronger in one direction than the other, the sediment can be carried away. The size and amount of sediment that can be suspended by a wave depends on wave energy flux or wave power. Wave power is proportional to wave height squared and to the square root of water depth. A 10 foot high wave contains four times as much energy as does a 5 foot high wave, for example.

When waves approach the coast, they are slowed by the topography of the sea floor and begin to align parallel to the shoreline. This is called wave refraction. Since the offshore topography is irregular, wave refraction is complex. Waves and wave energy diverge over a submarine canyon, with lower wave heights. Waves converge over a rise in bottom topography and wave heights increase. Due to variations in the sea floor, wave energies and wave heights from the same storm system vary substantially along the coast.

Longshore Transport

While waves tend to align along the coast, normally waves are not fully aligned to the shore and usually approach the coast at a non-perpendicular angle. This causes residual water motion along the shore as wave-induced current. In California most winter storms come from Alaska or the northern Pacific and the predominant transport is to the south. In summer, there is some northern transport due to storm waves from the southern hemisphere. Overall southerly transport of sediment is larger than northerly, leading to a net southerly transport. Wave refraction along some coastal segments may develop predominately northerly transport over short segments of the coast.

Seasonal Beach Profiles

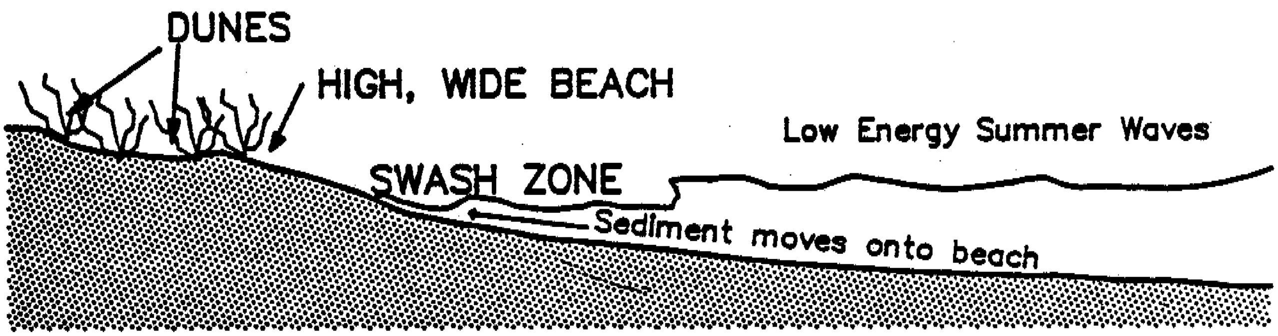
California has seasonal beach profiles, often called summer and winter beaches, as shown in Figure 6-1. The summer beach typically has a wide berm above high water. The winter beach has little if any berm since most of the beach sand has moved offshore onto a series of bars. This shift reduces the profile of the winter beach, making it less steep than the summer beach profile. The switch from a summer to a winter beach is triggered by steeper storm waves where wave steepness is the ratio of wave height to wave length. The critical steepness necessary to move sand offshore appears to depend on the grain size of the sand.

The sand carried offshore accumulates in bars along the breaker zone. The larger the waves, the further offshore the bar is located. These bars reduce the wave energy along the shoreline by causing incoming waves to break on the bar and dissipate some energy offshore. In severe storms, intense wave energy can reach the shoreline despite the presence of the offshore bars and the flatter profile. During periods of calm, the lower, less steep summer waves carry sand from the offshore bars onto shore to build up the steepness of the beach profile and reestablish the berm. Sometimes the winter waves carry sand too far offshore to be picked up by the summer waves and it will be lost from the onshore profile and never return to the beach.

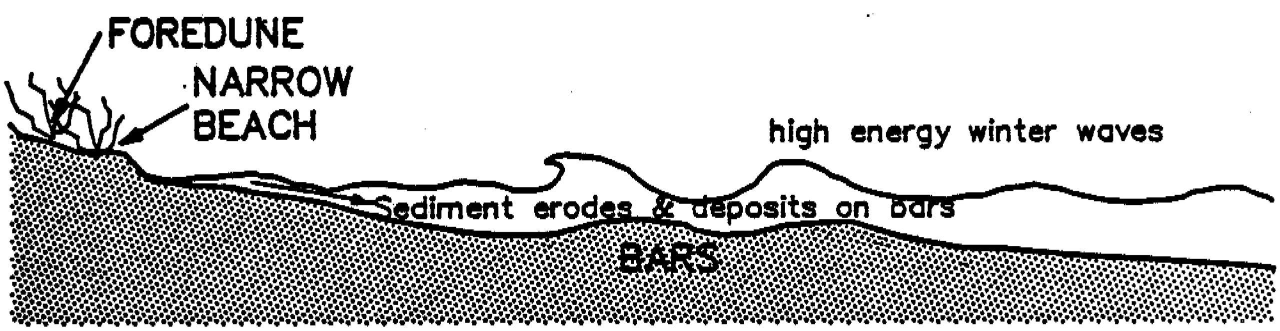
Changes in Beach Profiles with Wave Height

Beach profiles reflect the amount and size of beach material and the height and direction of wave attack. Normally low sloped beaches are characterized by fine sand and wide surf zones. Steep-sloped beaches generally are made of cobble or shingle with waves breaking close to shore (Dean, 1976). For a given size of beach material, an increase in wave height leads to a flattening of the beach profile, usually by carrying material offshore. The higher the waves, the flatter the profile and deeper the offshore transport of sand.

FIGURE 6–1
SEASONAL PROFILES OF A SANDY BEACH



SUMMER BEACH PROFILE



WINTER BEACH PROFILE

SOURCE: G. Griggs, 1976.

6.2 CLIFF RETREAT

Cliffs along the California coast vary in height, composition, wave exposure and erosion rates. Many cliffs are formed of highly resistant material that stand up to wave attack. If local weaknesses exist, waves may excavate these areas to form caves or sea stacks. Cliffs composed of sedimentary rock may erode so that ledges or shelves form.

Cliffs, just as beaches, often have a summer and winter profile, as shown in Figure 6-2. In calm weather, cliffs are often protected by beaches. If the beach material moves offshore during storms, the cliffs are without storm protection. Cliffs along Mendocino and Big Sur do not develop protective beaches and are under attack by waves year-round.

Cliff erosion by waves occurs primarily from pressure exerted by wave impact and by abrasion of the sand and gravel carried by the waves. Wave erosion undercuts the cliff, leaving it unsupported. The cliff may erode, shedding small layers of material to keep pace with the undercutting, or remain unchanged during the undercutting and eventually collapse as large sections of cliff slide off the cliff face; slumps and rotational slides can occur or the cliff can retreat through a series of mudflows.

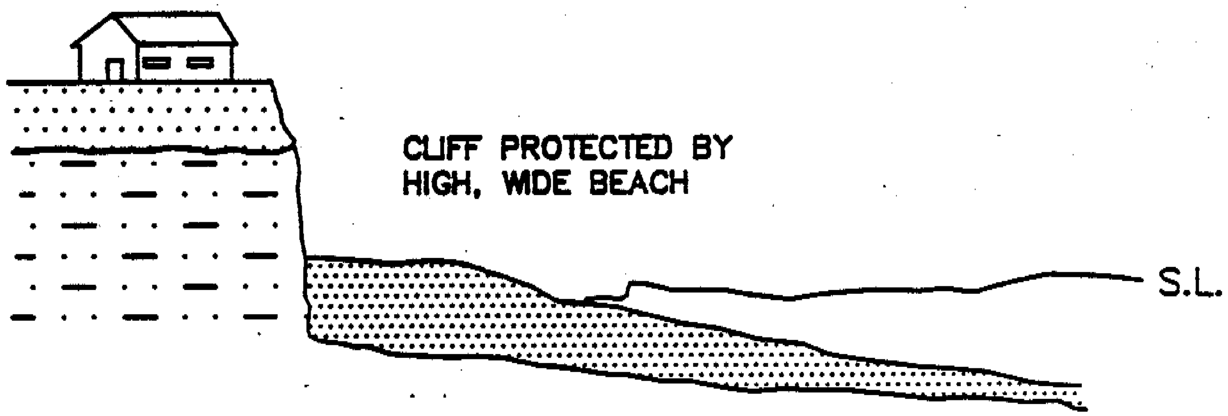
A second form of cliff retreat can be caused by increased load on top of the cliff--from a heightened water table and increased weight of saturated soil; from construction of buildings, roads or parking lots; or even from the storage of material on the cliff. Cliffs with significant erosion from non-marine factors tend to be convex upward at the top of the cliff.

A final assault of the cliff is erosion of the face. Sheet flow over the face of the cliff can cause erosion, as can ice wedges from freezing of water trapped in cracks on the cliff face which expands and separates material from the cliff. Ocean spray on the cliff face leaves behind salt which can chemically weaken the cliff material, also causing erosion.

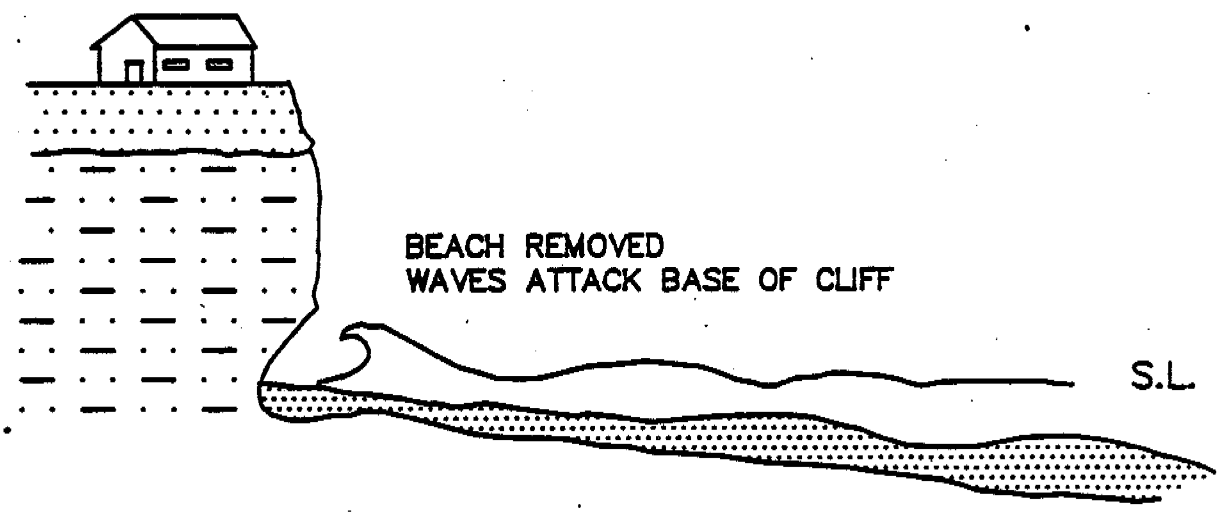
During periods of ocean calm, the eroded material can form a beach area fronting the cliff and protect it from undercutting. This material, often referred to as talus, can build up for long periods and is often a source of beach material to nearby shores, being moved by littoral transport or onshore-offshore transport. While there is talus fronting the cliff, the wave pressure against the cliff face is reduced and little if any undercutting occurs. Most cliff erosion in these situations will result from loads at the top of the cliff or erosion of the exposed cliff face.

Cliff erosion by wave action is often episodic, with many years of very low rates of erosion followed by sudden erosion of several feet to tens of feet. Often dramatic losses of coastal cliffs occcur during periods of high tide and high storm waves. Under these conditions, the soil is often saturated creating loading forces on the cliff, the face is eroded by rainwash, and usually the talus protection at the front of the cliff has been washed away so that the cliff is exposed to full wave attack. This combination of events may not occur annually or even every 5 years, but when it does, significant cliff retreat can result.

FIGURE 6-2
SEASONAL PROFILE OF A CLIFFED SHORE



SUMMER SHORE PROFILE



WINTER SHORE PROFILE

SOURCE: G. Griggs, 1976.

6.3 EFFECTS OF SEA LEVEL RISE ON BEACHES AND CLIFFS

Sea level rise can affect beach erosion and cliff retreat in a number of ways. In most cases sea level rise will exacerbate existing erosion problems and cause erosion and cliff retreat in areas where the coastline has been historically stable. Some effects will be due directly to increased sea level and other effects may result from the general climatic changes expected to accompany the greenhouse effect.

Direct Effects of Sea Level Rise

As sea level rises, more areas of the coast can be expected to be below sea level. This effect was seen in Tables 3-2 and 3-3 on relative sea level rise. For a small increment of sea level rise, many parts of the California coast will experience little if any increased inundation since much of the California coast is rising. If sea level rise is high (1 to 1.5m. by 2100), the rise of the coastline will have little effect on reducing the relative sea level rise impact. If sea level were to rise 1.52m. (5ft.) by 2100, most of the California coast will experience a relative rise of 1.43 to 1.49m. (4.7 to 4.9 ft.). Mean sea level would be 1.43 to 1.49m. higher than present, as would high and low tide levels. On a gentle beach with a 20 on 1 slope (horizontal to vertical) this rise moves the high tide line landward about 29m. (95 ft.), assuming no modification to the beach. The water level of river mouths, discharging along the coast, will increase by the amount of sea level rise. This rise in water level will work upriver, increasing water depths until the river adjusts to the new water level. The amount of sediment carried by the rivers will change as will the location of the river-ocean interface.

A second direct effect of sea level rise will be increased wave heights. There will be less wave dampening and bottom friction so more wave energy will reach the shoreline. Since wave energy increases with the square of the wave height, a small increase in wave height could have a noticeable effect on shoreline processes. The increase in wave height would be greatest for waves forming over a wide continental shelf. With a 10 kilometer (6.2 mi.) wide shelf and 10 meter water depth, a 1 m. (3.3 ft.) rise in water level could increase a 2 m. (6.6) high wave by 3 to 7.5% (National Research Council, 1987). The narrow shelf off the coast of California does little to dampen or reduce wave height and energy. An increase in sea level would decrease the dampening effect of the shelf, but this would only have a small effect on wave heights and energy.

Waves approaching the coast are affected by bottom topography. As sea level rises, existing topographic features will be located in deeper water and will have a different effect on wave trains approaching the coast. Features landward of the breaker zone will be in deeper water and will have greater effect on the wave climate than at present. Deep water features may deepen to the degree that their effect on wave climate is negligible. This deepening will change the local wave climate. The points of energy convergence and divergence will change. The new locations of energy convergence would be expected to experience an increase in erosion. Changes in wave approach would change longshore currents and longshore transport. Specific changes could only be determined through detailed modelling and are beyond the scope of this report. Nevertheless, the probability of such changes should be recognized.

Possible Changes from the Greenhouse Effect

The greenhouse effect is expected to cause a number of climatic changes along with increased global warming. Changes in the duration, location and severity of storms may occur as well as changes in global wind patterns. Ocean waves are generated by winds, and major storms over the ocean create the high waves which reach the coast. Wave height is a factor of the size of the area over which the wind is blowing (fetch), the strength of the wind and its duration. An increase in any of these factors can increase the resulting wave heights.

Some predictions indicate that hurricanes will be stronger and more frequent due to a temperature increase (Titus, 1984). Currently, California is affected rarely by hurricanes. An increase in wind strength may enable hurricanes to cross from the Gulf of Mexico to the Pacific more often. This would expose the California coast to southerly storms. Areas protected, due to coastal alignment, from the usual northern storms may experience very high wave conditions from a southerly storm. Also, since hurricanes occur in the late summer and fall, these storms could remove the summer beach earlier than occurs now. The shoreline could be exposed to the full strength of wave attack for a longer time each year than it is at present.

Changes in storm patterns and wave climate along the California coast are likely outcomes of the greenhouse effect. The specific types of changes cannot be predicted at this time. It is reasonable to expect that in some areas wave effects will worsen, causing beach erosion and cliff retreat to accelerate. In other areas, the wave attack may be reduced, causing cliffs and beaches to stabilize, or some beach accretion. The local changes in wave climate are some of the many unknowns in the concern about greenhouse effects.

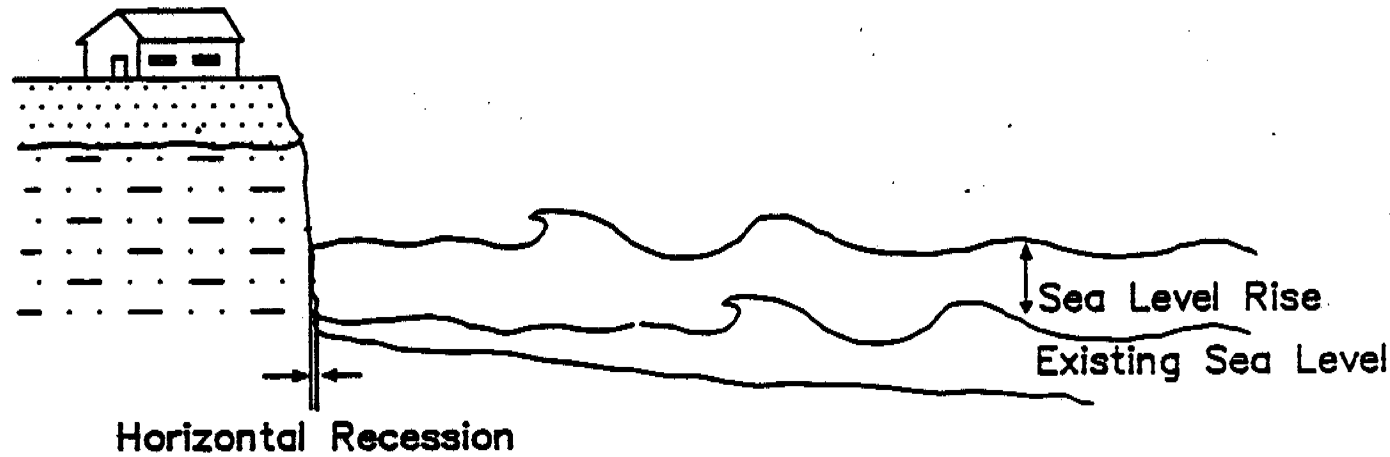
6.4 TECHNIQUES FOR PREDICTING EROSION AND CLIFF RETREAT

As sea level rises relative to the shoreline, land along the shoreline will be inundated. There are a variety of methods for predicting how much shoreline will be inundated and how the shoreline will change with rising sea levels. These methods vary from marking off contour lines on a topographic map to detailed computer models.

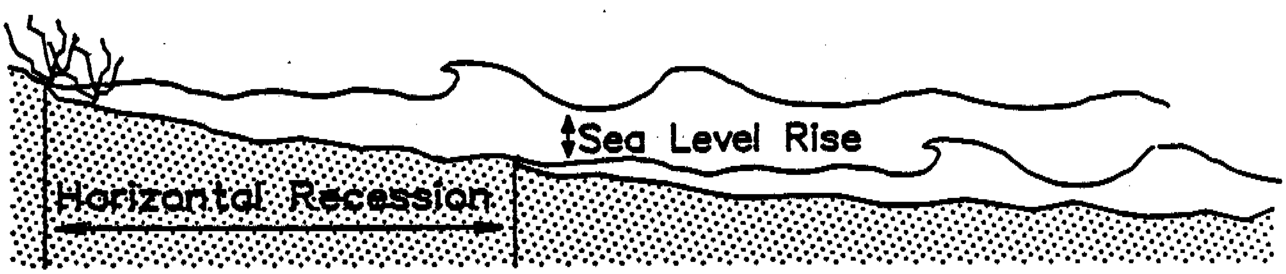
Drowned Valley Method

The drowned valley method is the simplest approach to sea level rise. It assumes that the shoreline slope will remain constant and the shoreline will be flooded up to the level of water rise. In this method, a sea level rise of 1 meter, relative to the land, would flood all land to an elevation of 1 meter above the present water level. Mean sea level would rise 1 meter as would all tide levels and waves. All coastal activity would adjust upward 1 meter. The horizontal extent of this shift would depend on the shoreline slope. On a cliffed or very steep shoreline, the vertical shift may have only a small horizontal effect. On a gradual beach slope, this rise may have a large horizontal effect. Figure 6-3 shows two drowned shorelines. Along coasts with existing erosion or cliff retreat, historic rates of erosion or retreat would be added to the drowned shorelines for complete shoreline change.

FIGURE 6-3
EXAMPLES OF DROWNED VALLEY COASTS



CLIFFED SHORELINE



SANDY BEACH SHORELINE

Several problems with this approach are the assumption that changes in sea level will not modify the existing beach profile and that historic trends can be used to predict future erosion rates. One of the theories of coastal engineering is the "equilibrium beach profile", where the shoreline is adjusted so that the wave energy impinging on the beach is exactly enough to transport the sediment supplied to the beach. With this balance of sediment, wave energy and beach profile, a rise in sea level would result in an adjustment to the shoreline until the equilibrium profile is regained. This adjusted shoreline concept is shown in Figure 6-4 and discussed more in the following section.

Coastal erosion depends greatly on wave action and the size and density of coastal material. Historic rates of erosion can be good estimates of future erosion. This theory holds true only if future wave conditions and coastal material are similar to existing conditions and material. If future wave heights increase, erosion rates may increase above historic rates. A change in wave direction could totally change the response of the shoreline. And if the shoreline is made up of different rock strata, a rise in sea level may expose a weak stratum to direct wave attack, or may submerge a weak layer and expose a more resistant layer to wave attack. Any of these changes would reduce the applicability of historic trends to future erosion rates. Despite these concerns, historic trends are often used to indicate the future. It is important to recognize that significant changes in wave climate or coastal geology will change the erosion rates.

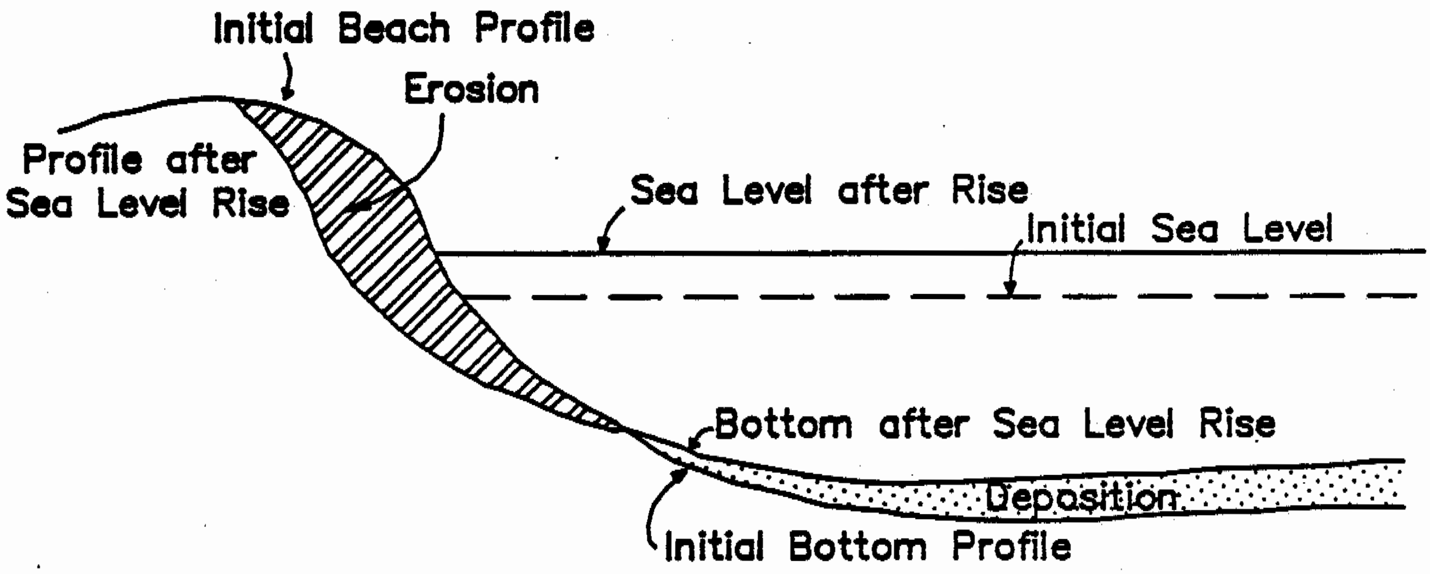
Equilibrium Beach Profile Method

Figure 6-4 shows the change in an equilibrium shoreline resulting from sea level rise. This equilibrium beach is not an instantaneous response, but rather a long term modification of the shoreline to the new water level conditions. In this method, first developed to address sea level rise by Per Bruun and often called the Bruun Rule, the water depth and beach profile would stay constant. As sea level rises, material would be carried from the beach to raise the offshore area so that water depths in the surf zone would also remain constant. The vertical change onshore will be the relative rise in sea level. The horizontal change will be the horizontal change seem in the drowned valley method plus the horizontal change necessary to provide material to raise the offshore bottom. This volume varies with the size of the surf zone and the beach profile. Mild slopes will retreat more rapidly than steep beaches for each unit of sea level rise.

The Bruun Rule can be expressed as: $R = SWG/h$

where R = Horizontal recession
S = Vertical sea level rise
W = Width of the active profile, from the beach to offshore limit of transport
h = water depth at the offshore limit of the profile
G = an overflow factor to account for beach material too fine to be offshore bed material.

FIGURE 6-4
EQUILIBRIUM BEACH PROFILES WITH SEA LEVEL RISE



Effects of a rise in sea level on coastal erosion and offshore deposition as envisioned by Bruun (1962).

SOURCE: National Research Council, 1987.

California Coastal Commission
Cartography Section

As a rough estimate, sea level recession, not including the horizontal shift from the inundation aspect of sea level rise, is about 100 times the amount of sea level rise (NRC, 1987, p. 54). Horizontal recesssions for various levels of sea rise are shown in Table 6-1, for a 20 to 1 beach slope (horizontal to vertical).

TABLE 6-1
ESTIMATES OF RECESSION FROM SEA LEVEL RISE,
on a 20 to 1 slope beach

	LEVELS OF SEA RISE, feet				
	1	2	3	4	5
Drowned Valley Component	20	40	60	80	100
Equilibrium Profile	100	200	300	400	500
Total Horizontal Recession	120	240	360	480	600

The equilibrium profile method has been evaluated along the Florida coast and the Great Lakes. The long term profiles adjusted to rises in sea level as predicted by the Bruun Rule. Shoreline adjustments were not immediate and often occurred in conjunction with storm wave conditions which could transport beach material offshore.

This method assumes that the beach area considered has been in equilibrium and that net longshore transports in and out of the area are about equal. On an actively eroding or accreting beach, it is difficult to develop equilibrium conditions. Also, if the wave climate changed with a rise in sea level, the equilibrium profile would change. This method is useful for studying specific beach areas where wave conditions and beach profiles are known. It can be applied very generally to the entire California coast.

Dynamic Equilibrium Models

Dynamic equilibrium models attempt to account for short-term beach profile changes due to changes in wave conditions and water level. When longshore transport is included, these models can provide detailed estimates of profile changes. These models, however, require information on beach and wave conditions. Once developed, the models are only as good as the input. They are useful for studying individual beaches but not the entire coast.

6.5 FUTURE EROSION AND CLIFF RETREAT ALONG THE CALIFORNIA COAST

Future beach erosion and cliff retreat can be estimated in a number of ways. In estimating changes for the entire coast, the most reasonable approach is to use the drowned valley method along with a predicted erosion rate. There is reason to believe that historic trends may underestimate future erosion rates if there is a significant rise in sea level. In a study of coastal erosion along Galveston Bay, historic erosion was related to historic sea level rise and future erosion was projected to increase in proportion with sea level rise (Leatherman, 1984). Since wave conditions are the major factors affecting erosion along the California coast, there may not be a direct correlation between accelerated sea level rise and accelerated erosion.

Existing erosion along the California coast may be due to existing sea level rise, wave conditions, and insufficient supplies of beach material to develop equilibrium with the waves; it is unclear what percentage of existing erosion is due to each factor. A change in the rate of sea level rise should change the rate of existing erosion that is only due to sea level rise while rates due to wave conditions and sediment supplies would not necessarily change. Some increase in the rate of erosion is expected from a rise on sea level, but the increase itself is not clear. For this report, unaltered historic rates will be used to estimate future erosion.

Along coastal beaches the major effect of sea level rise will be a reduction in beach size. The summer beach will be much narrower and the winter beach may be entirely submerged. Material carried offshore by winter storms may be in water too deep to be returned to shore by summer waves. Also due to a continued rise in sea level, material carried offshore by winter waves will be in slightly deeper water by summertime, and possibly beyond the reach of summer waves. Many small pocket beaches will be reduced in area or removed completely. Tables 6-2, 6-3 and 6-4 show estimated beach losses for the three sea level rise scenarios for the years 2050 and 2100.

Along cliffed coasts the major effect of sea level rise will be the inundation of the talus protection in front of the cliff and cliff undercutting at the new water line. Accelerated cliff retreat could occur since the cliff would be exposed to wave attack more of the year. Beach protection in front of the cliff would be reduced incrementally as material is lost on offshore bars which are beyond reach of summer waves. Table 6-5 shows estimates of cliff retreat by 2050 and 2100, based on historic rates of cliff retreat and any available protection from talus or beaches. Since these estimates are conservative for future conditions, coastal uplift will not be included. Erosion tends to be episodic and site specific; these average rates may greatly misrepresent retreat at specific sites.

Future development along any section of coast where extensive shoreline loss is anticipated should take this possible impact into consideration during the planning process. Since sea level rise is expected to be gradual, if it does occur, protective steps can be taken as specific problems develop. Beach areas can be nourished, and in some areas perched beaches may be desirable. Solutions available for dealing with sea level rise are numerous, and beyond the scope of this initial report. However, fixed, unalterable solutions should be avoided however are . It is uncertain what erosion and cliff retreat will result from possible sea level rise. An inflexible solution based on one projection of sea level rise can provide a worthless solution if sea level is higher than projected and can provide a very expensive solution if sea level is lower than projected.

TABLE 6-2
ESTIMATED BEACH RECESSION FOR A SEA LEVEL RISE OF 1 FOOT BY THE YEAR 2100 (SCENARIO 1)

	Estimated Total Horizontal Recession, meters (ft)	
	2050	2100
Crescent City		
20 to 1 slope	N.A.	14.3 (46.8)
30 to 1 slope	N.A.	15.5 (50.7)
40 to 1 slope	N.A.	16.6 (54.6)
Humboldt Bay and San Francisco Bay		
20 to 1 slope	11.7 (38.4)	38.0 (124.8)
30 to 1 slope	12.7 (41.6)	41.2 (135.2)
40 to 1 slope	13.7 (44.8)	44.4 (145.6)
Point Conception		
20 to 1 slope	5.4 (18.0)	26.7 (87.6)
30 to 1 slope	5.9 (19.5)	28.9 (94.9)
40 to 1 slope	6.4 (21.0)	31.2 (102.2)
Santa Barbara		
20 to 1 slope	N.A.	N.A.
30 to 1 slope	N.A.	N.A.
40 to 1 slope	N.A.	N.A.
Point Dume, Las Flores		
20 to 1 slope	8.05 (26.4)	31.5 (103.2)
30 to 1 slope	8.72 (28.6)	34.1 (111.8)
40 to 1 slope	9.39 (30.6)	36.1 (120.4)
L.A., Newport, Laguna		
20 to 1 slope	9.14 (30)	32.9 (108)
30 to 1 slope	9.91 (32.5)	35.7 (117)
40 to 1 slope	10.78 (35.0)	38.4 (126)
Dana Point, San Onofre		
20 to 1 slope	9.88 (32.4)	34.4 (112.8)
30 to 1 slope	10.70 (35.1)	37.2 (122.2)
40 to 1 slope	11.52 (37.8)	40.1 (131.6)
San Diego		
20 to 1 slope	9.14 (30)	33.2 (109.2)
30 to 1 slope	9.91 (32.5)	36.1 (118.3)
40 to 1 slope	10.68 (35)	38.8 (127.4)

All estimates of beach recession are using a base year of 1990.

N.A. For these areas the shoreline is expected to rise more quickly than the sea level and there should not be any beach recession due to the change in sea level used in this scenario.

TABLE 6-3
ESTIMATED BEACH RECESSION FOR A SEA LEVEL RISE OF
3 FOOT BY THE YEAR 2100 (Scenario 2)
using a base year of 1990

	Estimated Total Horizontal Recession, meters (ft)	
	2050	2100
Crescent City		
20 to 1 slope	20.5 (67.2)	87.4 (286.8)
30 to 1 slope	22.2 (72.8)	94.7 (310.7)
40 to 1 slope	23.9 (78.4)	102.0 (334.6)
Humboldt Bay and San Francisco Bay		
20 to 1 slope	33.2 (109.2)	111.2 (364.8)
30 to 1 slope	36.1 (118.3)	120.5 (395.2)
40 to 1 slope	38.8 (127.4)	129.7 (425.6)
Point Conception		
20 to 1 slope	27.1 (88.8)	99.9 (327.6)
30 to 1 slope	29.3 (96.2)	108.2 (354.9)
40 to 1 slope	31.6 (103.6)	116.5 (382.2)
Santa Barbara		
20 to 1 slope	N.A.	N.A.
30 to 1 slope	N.A.	N.A.
40 to 1 slope	N.A.	N.A.
Point Dume, Las Flores		
20 to 1 slope	30.05 (98.4)	104.6 (343.2)
30 to 1 slope	32.5 (106.6)	113.3 (371.8)
40 to 1 slope	35.0 (114.8)	122.0 (400.4)
L.A., Newport, Laguna		
20 to 1 slope	30.7 (100.8)	106.1 (348)
30 to 1 slope	33.3 (109.2)	114.9 (377)
40 to 1 slope	35.8 (117.6)	123.7 (406)
Dana Point, San Onofre		
20 to 1 slope	31.5 (103.2)	107.5 (352.8)
30 to 1 slope	34.10 (111.8)	116.5 (382.2)
40 to 1 slope	36.1 (120.4)	125.4 (411.6)
San Diego		
20 to 1 slope	30.7 (100.8)	106.4 (349.2)
30 to 1 slope	33.3 (109.2)	115.3 (378.3)
40 to 1 slope	35.8 (117.6)	124.2 (407.4)

All estimates of beach recession are using a base year of 1990.

N.A. For these areas the shoreline is expected to rise more quickly than the sea level and there should not be any beach recession due to the change in sea level used in this scenario.

TABLE 6-4
ESTIMATED BEACH RECESSION FOR A SEA LEVEL RISE OF 5 FEET BY THE YEAR 2100 (SCENARIO 3)

	Estimated Total Horizontal Recession, meters (ft)	
	2050	2100
Crescent City		
20 to 1 slope	42.4 (139.2)	160.6 (526.8)
30 to 1 slope	46.0 (150.8)	173.9 (570.7)
40 to 1 slope	49.5 (162.4)	187.3 (514.6)
Humboldt Bay and San Francisco Bay		
20 to 1 slope	55.2 (181.2)	184.0 (604.8)
30 to 1 slope	59.8 (196.3)	200 (655.2)
40 to 1 slope	64.4 (211.4)	215 (705.6)
Point Conception		
20 to 1 slope	49.0 (160.8)	173.0 (567.6)
30 to 1 slope	53.1 (174.2)	187.4 (614.9)
40 to 1 slope	57.2 (187.6)	201.8 (662.2)
Santa Barbara		
20 to 1 slope	N.A.	81.2 (266.4)
30 to 1 slope	N.A.	88.0 (288.6)
40 to 1 slope	N.A.	94.7 (310.8)
Point Dume, Las Flores		
20 to 1 slope	51.9 (170.4)	177.6 (583.2)
30 to 1 slope	56.3 (184.6)	192.6 (631.8)
40 to 1 slope	60.6 (198.8)	207.4 (680.4)
L.A., Newport, Laguna		
20 to 1 slope	52.6 (172.8)	179.2 (588)
30 to 1 slope	57.1 (187.2)	194.2 (637)
40 to 1 slope	61.5 (201.6)	209.1 (686)
Dana Point, San Onofre		
20 to 1 slope	53.4 (175.2)	180.7 (592.8)
30 to 1 slope	57.9 (189.8)	195.7 (642.2)
40 to 1 slope	62.3 (204.4)	210.8 (691.6)
San Diego		
20 to 1 slope	54.1 (177.6)	179.6 (589.2)
30 to 1 slope	58.6 (192.4)	194.6 (638.3)
40 to 1 slope	63.2 (207.2)	209.5 (687.4)

All estimates of beach recession are using a base year of 1990.

N.A. For these areas the shoreline is expected to rise more quickly than the sea level and there should not be any beach recession due to the change in sea level used in this scenario.

TABLE 6-5
Estimated Regional Cliff Retreat,
using a Base Year of 1990

	Historic Retreat (in/yr)		Estimated Total Retreat (ft.)	
	Range	Average	2050	2100
State-wide		4 ± 51	20	36.7
Del Norte	6-22	12	60	110
North Humboldt	+8-30	9	45	82.5
San Francisco (Landslide area)	0-49	14	70	128.3
Half Moon Bay to S.C. (Landslide area)	4-92	15	75	137.5
Monterey Bay	0-115	38	190	348.3
Monterey to S.B. (Landslide area)	2-12	2	10	18.3
S.B. to Oxnard	6-12	8	40	73.3
Los Angeles (Landslide area)	2-12	3	15	27.5
San Diego (Landslide area)	0.5-96	30	150	275

\+ Positive sign indicates accretion
No sign indicates retreat

Developed from data in Griggs and Johnson (1979), Griggs and Savoy (1985), Kennedy (1973), National Research Council (1987), Sunamura (1983) and U.S. Corps of Engineers (1984;1985). These erosion rates do not show retreat for the entire coastline. Many sections of the coast are stable and there are even portions of stable shoreline within long stretches of eroding shoreline.

The erosion rates used in this table were developed from site specific studies which show an initial bias toward eroding areas; the areas which are not eroding are often omitted since they are not problem areas. The values in this table should be considered average erosion rates for areas which historically have experienced erosion.

7.0 EFFECTS OF SEA LEVEL RISE ON HARBORS AND COASTAL STRUCTURES

Many miles of California coast are undeveloped, with spectacular cliffs and broad beaches. Large sections of coast, too, have been developed; over 20 harbors and bays, numerous piers and wharfs, and almost 100 miles of shoreline protective structures exist (Griggs, 1985). A rise in sea level can affect all of these facilities.

7.1 HARBORS

A harbor is any protected water area which provides boats a safe place to anchor. Many California harbors are or contain ports where ships receive or discharge cargo (often the terms "harbor" and "port" are interchangeable, however this report will use "harbor" to mean the protected water area only). Several harbors are located in northern California but most lie south of Point Conception. The northern harbors are mostly openings along rocky coast, some with breakwaters or jetties to provide safer ingress and egress to ships during rough seas. Along the southern coast, harbor openings can be blocked or reduced by deposition of sediment, so harbor entrances are often kept open by jetties or groins which trap sand upcurrent of the harbor entrance.

Changes in Tidal Prism with Sea Level Rise

The tidal prism of a harbor or bay is the total volume of water carried by tidal currents into the harbor or bay between low and high tide. On a sandy coast an equilibrium exists between the area of the harbor entrance and its tidal prism (O'Brien, 1969). A rise in sea level will increase the tidal prism of a harbor and thus increase the equilibrium area of its entrance. Uncontrolled entrances may deepen or widen, or new entrances may develop to provide this extra area. The response will depend on the erosion resistance of material at the harbor entrance. Controlled entrances will be able only to deepen their channels since resistant structures will limit entrance widening. The deepening may reduce the stability of the jetties or other structures at the harbor entrance by undermining the foundations. Concurrent with entrance deepening, greater water levels and wave heights will increase forces on the structures. These structures should be checked periodically for stability.

Effects of Increased Water Levels and Wave Heights

Increased water levels and wave heights should have little effect on uncontrolled harbors. During storm conditions ingress and egress will be more difficult and some days ships should not leave the protection of the harbor. In controlled harbors, however, the increased water levels and wave heights could cause overtopping of the jetties protecting the harbor. Overtopping could damage the jetty while overtopping waves would make the harbor waters more choppy. Since portions of the harbor must be deep enough for ships, waves which enter the harbor may not be dampened by the harbor topography. Large storm waves entering the harbor can do serious damage to port facilities and ships in the harbor.

Effects of Sea Level Rise on Piers and Port Facilities

Increased water levels and wave heights affect piers in several adverse ways. Greater wave heights will exert increased force on the pier supports. Also, when waves break under a horizontal platform such as a pier, they exert large compressive, or uplifting forces on the platform. Higher water levels and wave forces can increase the likelihood of these uplifting forces on piers. During the 1982-1983 winter storms, high waves and their associated impacts such as floating debris, erosion of foundation support and sand abrasion caused substantial damage to piers along the California coast (National Research Council, 1984).

The second effect of higher sea level on piers will be on their cargo function. Some piers are used for fishing or recreation; many piers however, are used for loading and unloading cargo. As water level rises, ships will rise relative to the pier. The unloading facilities are often designed for a functional ship deck elevation, with cranes, for example, designed to hoist cargo from the ship's hold. A fully loaded ship can be accessed but as the ship lightens and floats higher, it may rise out of reach of the cargo equipment. Each foot of sea level rise will raise a ship one foot. If cargo handling equipment is not designed to keep pace with sea level rise, loading and unloading may be scheduled only for low tide periods.

7.2 EFFECTS OF SEA LEVEL RISE ON COASTAL PROTECTION

Numerous protective structures are used along the California coast--breakwaters to reduce incoming wave forces and seawalls and revetments to reduce erosion and wave forces directly onshore. A rise in sea level will expose these structures to higher water levels and increased wave heights.

Breakwaters

Breakwaters often are designed for depth-limited waves (the highest wave possible for the water depth where the breakwater is located). An increase in water level will increase the height of the possible depth-limited waves. As sea level rises, breakwaters will be exposed to higher waves and experience overtopping. This can damage the integrity of the breakwater. In addition, areas behind the breakwater will experience increased water levels and wave forces and be improperly protected from wave damage.

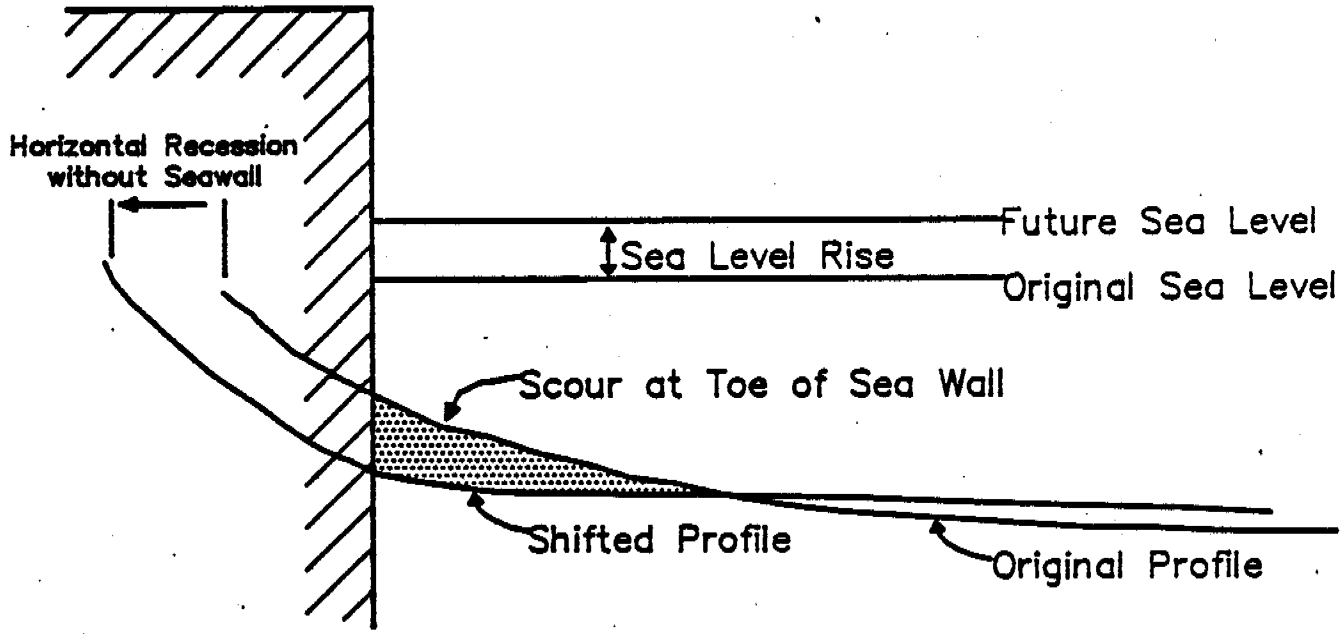
Breakwaters consist of an inner core, a filter layer and a top armor layer; each layer sized for design wave conditions. If sea level rise accelerates, existing breakwaters could require thorough modification of each layer to provide the level of protection for which they were designed. Future breakwaters could be designed initially for a range of sea levels, built for the existing water level but easily modified for possible rises in sea level by adding more armor units. Overtopping could also be included in the breakwater design.

Seawalls and Revetments

An increase in sea level would expose seawalls and revetments to higher water levels and wave forces. In addition, the base of these structures is likely to experience greater scour due to increased erosion (See Section 6 for detail on coastal erosion and cliff retreat). Seawalls and revetments protect inland areas from erosion and wave forces, and their effectiveness is determined by their ability to withstand the force of incoming waves and the effects of overtopping. An increase in sea level will increase forces on the wall and the frequency of overtopping; the seawall or revetment will provide less protection to an inland structure. A second effect of sea level rise may be the erosion of the shoreline seaward of the structure to develop an equilibrium beach profile (Dean and Maurmeyer, 1983) This is shown in Figure 7-1. Erosion in front of the structure will reduce the stability of the structure and reduce its resistance to overtopping forces. If sea level rises, the sea wall or revetment will need to be raised to maintain the same level of design protection. The foundation may also require deepening to maintain structural stability.

Most structures along the coast have been designed for water levels and wave conditions similar to present conditions, but most structures can be modified or rebuilt to maintain acceptable protection in the event of sea level rise. The effects of sea level rise will be most significant during strong storm events. This is not the time to recognize that protective structures were designed for lower sea levels than those being experienced. Design conditions should be checked periodically against current sea level conditions, structures can be modified to keep pace with sea level rise. If structures are not modified, the anticipated level of protection from the structure should be reduced to reflect the current sea level effects. Finally, since sea level rise may cause increased scour and erosion, the stability of the structures should be monitored occasionally and reinforced if necessary.

FIGURE 7-1
SCOUR AT SEAWALL TOE



SOURCE: Dean and Maurmeyer, 1983.

8.0 CONCLUSIONS

1. Greenhouse gases, such as carbon dioxide, chloroflurocarbons, methane, and others, absorb long wave solar radiation and keep the earth at a habitable temperature. An increase in concentration of greenhouse gases due to man's activities could increase absorption of long wave radiation and cause mean global temperature to rise by 2 to 4 degrees C. One impact of global warming would be an increase in ocean volume due to thermal expansion and the melting of glaciers and polar ice caps resulting in a rise in eustatic sea level.

2. Any rise in sea level, including one occuring at the historical rate, will decrease recreational potential of coastal beaches and increase erosion hazard to adjacent upland development. California is particularly susceptible to beach retreat as a result of sea level rise since most of California's coastal streams are already dammed and small rises in sea level will further slow the transport of sand to the coast. Coastal beach retreat between 30 and 200 feet, can be expected by the year 2050.

3. A rise in sea level is expected to exacerbate coastal erosion and cliff retreat as beach material and coastal bluffs are lost to the offshore area during winter wave conditions.

4. Harbors may experience greater wave action and may have to limit or prohibit ingress and egress during storm periods.

5. An increased water level may increase the tidal prism of harbors and bays, and result in a widening or deepening of the harbor entrance. If the harbor entrance is controlled by breakwaters or jetties, the harbor may deepen, possibly undermining the stability of structures located at the harbor entrance.

6. An increase in water level may increase water forces on coastal structures such as piers, jetties, breakwaters, and seawalls. Structures designed for current sea level conditions may be unable to provide their current level of protection. Overtopping of these structures by storm waves may occur more frequently. Design conditions for a structure can be assessed periodically against current water levels and most structures can be modified to maintain acceptable levels of protection in the event of sea level rise.

7. A relatively rapid sea level rise may impose extraordinary stress on coastal wetlands. Any continued loss of wetland habitat to sea level rise would result in a loss of spawning and feeding grounds for estuarine and anadromous fish, endangered species and waterfowl, and a loss of a significant economic and recreational resource. Flora and fauna could initally adjust to a prolonged submergence associated with sea level rise, but lower wetland flora may ultimately be lost. This being the case, the total floral distribution could move upland incrementally according to tidal elevation <u>if</u> the upland area is conducive to the migration by being unobstructed by human-made structures and topographically suitable.

8. The Pacific Coast wetlands are as vulnerable to sea level rise as East and Gulf Coast areas of the U.S. and, in some areas of California, 35-100% of existing wetlands could be lost while net loss would be 1-18% if developed areas were abandoned and wetlands migrated upland..

9. If upland migration of the wetland system is not possible, costly structural solutions may enable wetlands to adjust to a rising sea level.

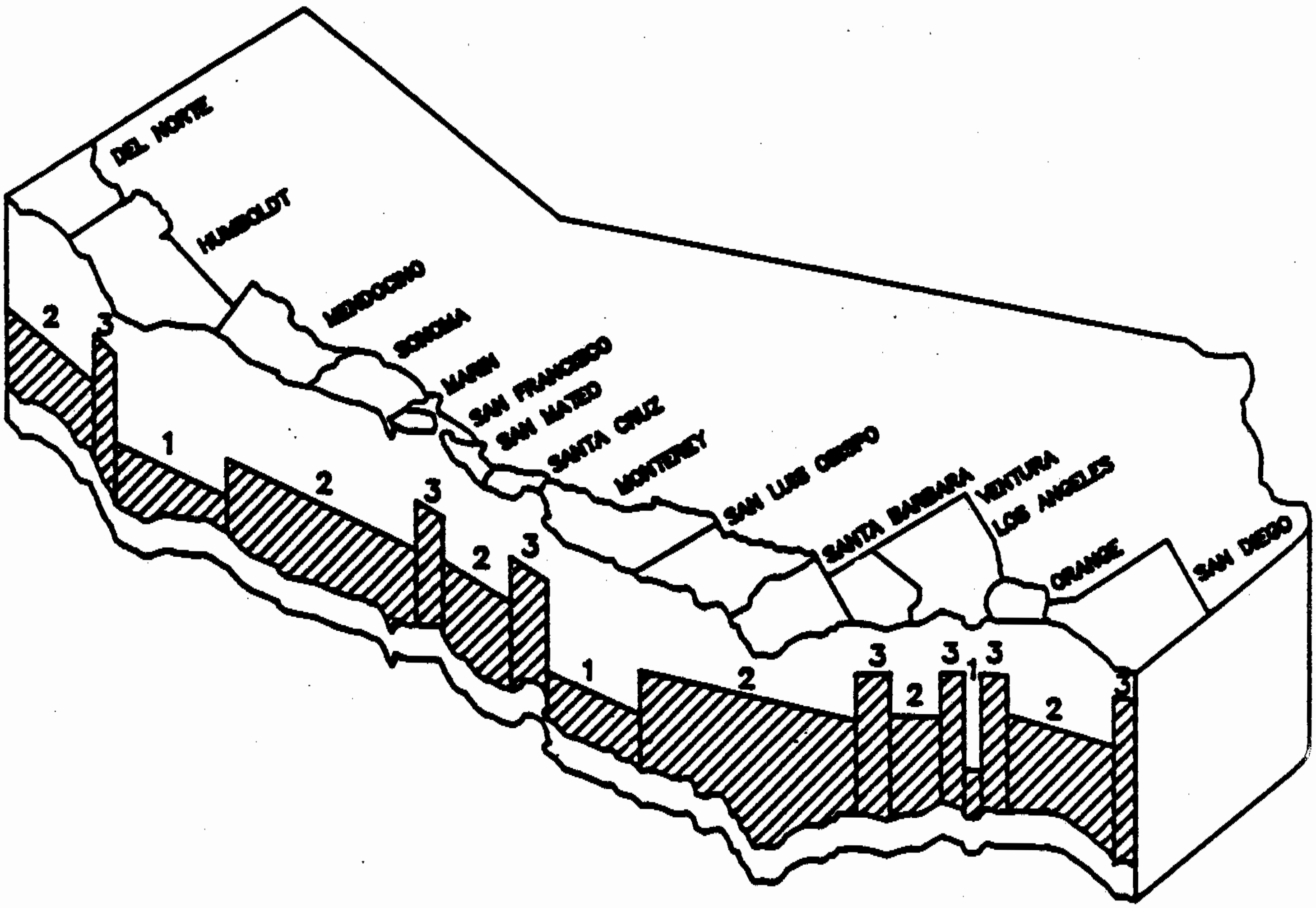
10. A better understanding of the impacts of an accelerated sea level rise on low-lying coastal wetlands is necessary in formulating forthcoming coastal management plans and policies. The probability and magnitude of such a rise in sea level continues to generate discussion, examination, and debate, and many questions remain unanswered. The lack of conclusive evidence, however, should not interfere with efforts to preserve the ecological and economic value of coastal wetlands. The State of California should continue to research and keep abreast of the latest data regarding the sea level rise impact on coastal areas. In addition, the state's coastal management agencies should begin to consider the matter of sea level rise in their land use and wetland enhancement and restoration plans.

11. If a rapid rise in sea level occurs due to global warming, much of the California coast will be adversely affected. Even areas undergoing rapid rates of coastal uplift, such as that section of the coast from Santa Barbara to Ventura, will experience beach erosion, bluff retreat, and submergence of lowland areas. Figure 8-1 shows the relative severity of impact from a 5 foot rise (Scenario 3) in sea level by the year 2100. This figure shows the highest impact occurring in low-lying areas which would be completely inundated, a moderately severe impact at locations with broad beaches or fragile coastal bluffs protected by talus, and the least impact at locations where steep coastal cliffs consist of resistant rock units.

12. The loss of shoreline due to sea level rise will have a profound economic impact. Figure 8-2 shows relative economic loss associated with a 5 foot rise in sea level (Scenario 3) by the year 2100. This figure illustrates where there would be significant loss of buildings, roads, beaches, wetlands and urban infrastructure, if no protective measures are taken. The greatest economic loss will occur to structures located on beaches, coastal cliffs, and within or surrounding harbors. Coastlines with structures located landward of the the shoreline will experience less loss. The least amount of loss will occur along sections of the coast where the shoreline can migrate landward without impedence.

FIGURE 8-1

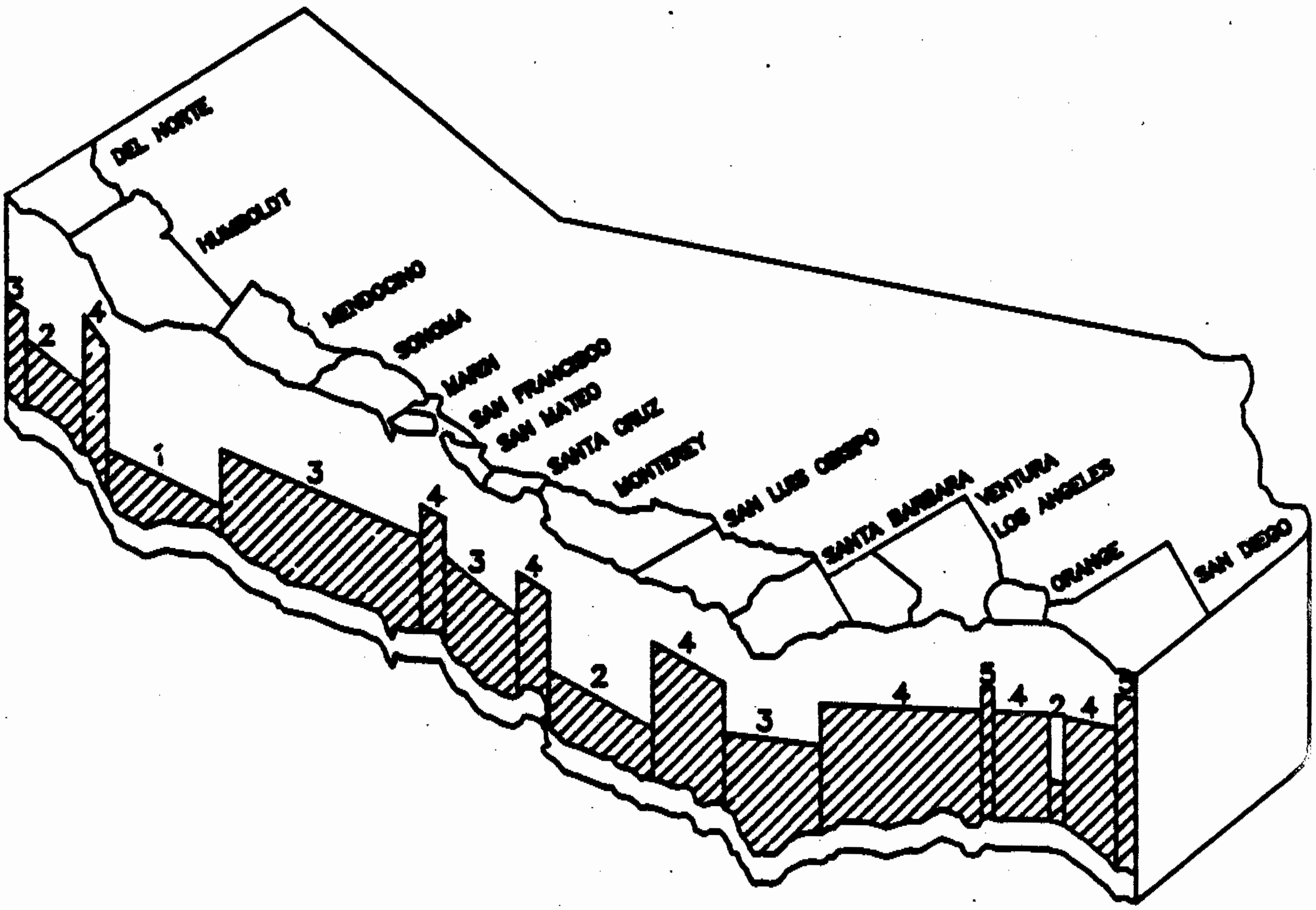
RELATIVE SEVERITY OF IMPACT FROM SEA LEVEL RISE
5 FOOT RISE BY 2100 (SCENARIO 3)



The relative severity of impact is an estimate of the extent of flooding, erosion and cliff retreat that is likely to occur from a 5 foot rise in sea level by the year 2100. The greatest impact is expected to occur in low lying areas which will be completely inundated, indicated as Impact Level 3. Less impact will occur where there are broad beaches or cliffs protected by talus, indicated as Impact Level 2. The least impact will occur where the shoreline is steeply cliffed and comprised of resistant rock units, indicated as Impact Level 1.

California Coastal Commission
Cartography Section

FIGURE 8–2
RELATIVE ECONOMIC LOSS FROM SEA LEVEL RISE
5 FOOT RISE BY 2100 (SCENARIO 3)



Relative economic loss estimates the comparative extent of property damage that is likely to occur from a 5 foot rise in sea level by the year 2100. This assumes that no major shoreline protection projects are undertaken. The greatest loss will occur where extensive urban infrastructure has been located on or near a beach, coastal bluff or harbor, indicated as Impact Level 5 on the Figure. The least impact will occur where landward migration of the coastline can proceed unimpeded by structures or development, indicated as Impact Level 1 on the Figure.

9.0 RECOMMENDATIONS

1. California's state and local coastal management agencies should begin to factor sea level rise into their land use plans, wetland enhancement and restoration management programs. The Commission and local governments, in conjunction with efforts undertaken by other agencies and other coastal states, should begin to formulate a plan to identify and implement appropriate policy to respond to an accelerated sea level rise.

2. A rise in sea level will affect the shoreline and shoreline boundaries in California. The State should inventory the coastline of California in order to identify those areas most susceptible to loss of natural and economic resources from sea level rise. Such an inventory should include analysis of relative sea level rise, shoreline morphology, recreational and natural values of the shoreline, economic values of adjacent uplands including port facilities, beaches, and coastal protection structures.

3. The development of rational responses to sea level rise which do not result in severe economic losses should be undertaken. The Commission should undertake or assist in developing: a) more accurate measurements of sea level at more locations, which allow greater precision in identifying trends and possible accleration; and b) more accurate measurement of actual shoreline response that allows correlation of shoreline retreat and sea level rise. The information gathered should be used to develop a data base that narrows the uncertainty range in forecasting the rate and effects of sea level rise.

4. Local governments, as part of Local Coastal Planning processes, should evaluate land use plans and zoning ordinances which regulate uses within areas subject to accelerated sea level rise impacts; land use plans could be revised to reflect potential impacts and thus minimize adverse effects to resources and structures. The Commission should assist local governments by identifying policy and regulatory mechanisms appropriate to specific resource areas and constraints, and suggest policy and zoning ordinance language to implement the regulatory mechanisms.

5. Legislation should be enacted which both restricts use and provides for purchase of coastal wetland upland areas to enable wetland upland migration. Innovative techniques should be developed to allow the removal of upland structures if and when needed for landward migration of wetlands.

6. Many coastal areas throughout the world are now experiencing noticeable relative rise in sea level due to a combination of global sea level rise and local subsidence (for example, Great Lakes; the Netherlands; Venice, Italy; Louisiana; and others). California should examine what has been done in these areas to protect against rising sea level and consider applying selective successful techniques along the California coast.

7. Since many of the jetties and breakwaters protecting California's harbors were built during conditions of lower sea level than today, the rise in sea level could increase scour at their foundations and undermine the stability of the structure. Maintenance programs should reflect the potential impact from a sea level rise on shoreline protective works, piers, offshore platforms, and others. The Commission should also assess the cost of upgrading or replacing existing coastal protective devices to keep pace with a rising sea level.

8. California should continue to support research on the effects of near shore wave climate on sediment transport and keep abreast of the latest data regarding sea level rise impacts on coastal areas.

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