SEA LEVEL RISE:

PREDICTIONS AND IMPLICATIONS FOR SAN FRANCISCO BAY

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San Francisco Bay Conservation and Development Commission

FUTURE SEA LEVEL RISE: PREDICTIONS AND IMPLICATIONS FOR SAN FRANCISCO BAY

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1. Global Sea Level Rise Increase. Change in global sea level has been gradual and relatively constant over the past 5,000 years. But in the last 100 years, tide gauge measurements have shown that the world's oceans, and San Francisco Bay, have been rising an average of 0.0039 feet/year or approximately 4.68 inches. However, the rate of increase over the last 19-year tidal epoch (the period used to establish tidal datums) is estimated to be 0.0072 feet/year or almost double the 100-year historic average. Thus, as in other areas of the world, the rate of sea level rise in San Francisco Bay may be increasing. The rate of rise for the recent tidal epoch (0.0072 feet/year) used in projecting future sea level in the Bay in this report, results in an estimated rise in sea level of approximately 4.32 inches in the next 50 years.

2. "Greenhouse Effect" Could Lead to Future Accelerated Sea Level Rise. Many scientists believe that over the next century increased concentrations of carbon dioxide, methane, chlorofluorocarbons, and other gases released into the earth's atmosphere will create a "greenhouse effect" that will increase the earth's air temperature by several degrees. This warming would bring about an accelerated rise in sea level worldwide through thermal expansion of the upper layers of the world's oceans and the melting of some of the earth's glaciers and polar ice fields. The warming trend could be exacerbated by the reduction in the earth's vegetative cover, particularly as a result of the clearing of the tropical rain forests. Estimates of the accelerated rise in global sea level over the next century range from one to eleven feet by the year 2100. Although there is a wide divergence in these estimates, all agree that the rate of rise in the next 20 years will be

gradual and close to the historic rate, but the rate may accelerate dramatically in subsequent years.

3. Current Ability to Measure and Relate "Greenhouse Effect" to Accelerated Sea Level is Inadequate. Our current ability to measure and directly relate a possible accelerated rise in sea level to a "greenhouse effect" is inadequate. The effect of global warming on global sea level should be monitored closely, but until there is a direct causal effect established between the two, other methods, principally the historic trend in global sea level change, are a more prudent basis for projecting future sea level. An extrapolation of the historic trend is used in this report to project future relative mean sea level and high water levels in the Bay in the next 20 years (2007) and 50 years (2037), the latter date being the normal engineering design life of a structure constructed today.

4. Future Sea Level Rise Could Adversely Affect Coastal Areas Including San Francisco Bay. Despite the uncertainty regarding the future rate in rise and height of global sea level, there is uniform concern that future sea level rise, particularly an accelerated rise, could cause tidal inundation of unprotected low-lying areas, increased periodic flooding of previously protected low-lying areas, disruption of storm water drainage systems, increased shoreline and beach erosion, and salt water intrusion into estuaries, fresh water tributaries and ground water.

5. Change in Relative Mean Sea Level Takes Into Account the Change in Global Sea Level and Vertical Land Motion. The apparent change in mean sea level at any particular point, referred to as the change in relative mean sea level, is the sum of the change in global sea level and the change in land elevation at that point. Global, or world-wide, mean sea level change is brought about by global climatic occurences. Change in the elevation of the shoreline, or vertical land motion, is the rising or subsidence of the land

mass caused by tectonic (geological) activity, consolidation or compaction of soft soils, or extraction of subsurface ground water, oil, or natural gas deposits. Thus, if global sea level at a point on the shoreline remain constant, but the land mass subsides, the effect is a relative rise in sea level at that point. If the land mass rises at a rate greater than the rise in global sea level, the effect is a lowering in relative sea level.

6. Historical Change in Relative Mean Sea Level in San Francisco Bay. While global sea level rise has been constant in San Francisco Bay, vertical land motion at points around the Bay have varied considerably, from an uplift of 0.0037 feet/year at Sausalito, to a subsidence rate of -0.0920 feet/year at Alviso in San Jose. As a consequence, rates of relative sea level change around the Bay are highly variable, ranging from 0.0002 feet/year at Sausalito to 0.0959 feet/year at Alviso in San Jose. The historical change in relative sea level around San Francisco Bay in the past 100 years (R), the difference between the global change in mean sea level (G), and local vertical land motion (L), is shown in the following table.

Estimated Historical Sea Level Change Around San Francisco Bay

Location	Apparent Global Sea Level Change Rate at the Presidio G (Ft/Yr)	Local Land+ Elevation Change Rate L (Ft/Yr)	Local Relative* Sea Level Change Rate R (Ft/Yr)
Pittsburg	0.0039	-0.0090	0.0129
Benicia	0.0039	-0.0055	0.0094
Sonoma Creek	0.0039	0	0.0039
Point Orient	0.0039	-0.0020	0.0059
Sausalito	0.0039	+0.0037	0.0002
Presidio	0.0039	0	0.0039
Alameda	0.0039	-0.0014	0.0053
Hunters Point	0.0039	0	0.0039
San Mateo Bridge	0.0039	-0.0020	0.0059
Dumbarton Bridge	0.0039	-0.0154	0.0193
Alviso Slough (Coyote Creek)	0.0039	-0.0920	0.0959

+ Positive sign indicates uplift
- Negative sign indicates land subsidence
* G - l = R

7. <u>Future Relative Mean Sea Level in San Francisco Bay</u>. The future rates of change in relative mean sea level, and consequently the change in height of relative mean sea level around the Bay are also highly variable. The projected rates of change and relative mean sea level rise in the next 20 years (2007) and 50 years (2037) around the Bay are shown in the following table.

Future Relative Mean Sea Level Projections

Location	MSL Present (Ft:NGVD)	G Present (Ft/Yr)	L Present (Ft/Yr)	MSL 2007 (Ft:NGVD)	MSL 2037 (Ft:NGVD)
Pittsburg	1.00	0.0072	-0.0090	1.32	1.81
Benicia	0.64	0.0072	-0.0055	0.89	1.28
Sonoma Creek	0.78	0.0072	0	0.92	1.14
Point Orient	0.40	0.0072	-0.0020	0.58	0.86
Sausalito	0.30	0.0072	0.0037	0.37	0.48
Presidio	0.29	0.0072	0	0.43	0.65
Alameda	0.36	0.0072	-0.0014	0.53	0.79
Hunters Point	0.39	0.0072	0	0.53	0.75
San Mateo Bridge	0.39	0.0072	-0.0020	0.57	1.85
Dumbarton Bridge	0.28	0.0072	-0.0154	0.73	1.41
Alviso Slough (Coyote Creek)	0.80	0.0072	-0.0920	2.78	5.76

\- Negative sign indicates land subsidence

8. <u>Need for Bay Shoreline Vertical Land Motion Measurement Program</u>. In order to accurately predict future relative mean sea level around San Francisco Bay, precise vertical land motion data are essential. Currently, vertical land motion data around the Bay shoreline are extremely limited and there is no comprehensive program to establish, relevel, (periodically measure), and maintain benchmarks on the Bay shoreline other than at certain established and tide maintained gauges. It is essential to establish a local and regional Bay vertical land motion measurement program in order to monitor the change in relative sea level around the Bay in a comprehensive manner and

to provide data to predict future Bay relative sea level change. Such a program should be undertaken by bayside local governments in coordination with the U.S. Geological Survey.

9. Procedure for Predicting Extreme High Water Levels. A sound procedure for predicting extreme high water levels that includes the anticipated change in mean relative sea level for the Bay has been developed in this report by extrapolating historical local sea level and vertical land motion data. An assumption has been made that global mean sea level change is uniform throughout the Bay and equal to the relative mean sea level change determined at the Presidio tide gauge for the most recent 19-year tidal period (1984-1982). The procedure requires regular updating of the sea level change rate, at least every ten years, to help assure that any acceleration in sea level change can be accommodated in the process of predicting future relative mean sea level. Local vertical land motions based on long-term benchmark elevation changes are included in the projection. Highest estimated tides are superimposed on the projected mean sea level to obtain the extreme high water levels for use in developing engineering flood protection design criteria. The high water levels represent still water conditions and do not include wave action or impacts due to unique local topography or structures.

10. Future Highest Estimated Tides in San Francisco Bay. The present highest estimated tide (HET) and the projected future highest estimated tides in 20 years (2007) and 50 years (2037) around the Bay are presented in the following table.

High Water Level Projections

Location	HET Present FT:NGVD	HET 2007 FT:NGVD	HET 2037 FT:NGVD
Pittsburg	6.5	6.8	7.3
Benicia	6.5	6.8	7.1
Sonoma Creek	6.5	6.6	6.9
Point Orient	6.4	6.6	6.9
Sausalito	6.1	6.2	6.3
Presidio	6.0	6.1	6.4
Alameda	6.7	6.9	7.1
Hunters Point	6.7	6.8	7.1
San Mateo Bridge	7.1	7.3	7.6
Dumbarton Bridge	7.5	8.0	8.6
Alviso Slough (Coyote Creek)	8.2	10.2	13.2

11. Importance of Sedimentation in Maintaining Tidal Marshes With Rising Sea Level. The key to understanding the effect of rising relative sea level on tidal wetlands is to know the rate of sedimentation for various areas around the Bay. The response of tidal wetlands to a rising relative mean sea level depends upon local rates of sedimentation for which there is very little data in San Francisco Bay. A program to collect this data should be considered by the Commission when it reviews the Bay sediment study it has been tentatively scheduled for its 1988-1989 planning work program. The evolution of tidal marshes in San Francisco Bay has been the result of gradual inudation of low-lying areas balanced by a buildup of sediments. If sedimentation keeps pace with relative sea level change, tidal marshes will maintain equilibrium. However, if relative mean sea level rises at a rate higher than the rate of sedimentation, tidal marsh species more tolerant to submergence, such as cordgrass, will replace high marsh species such as salt grass. If relative mean sea level rises at a much higher rate than the rate of sedimentation, tidal marshes will become submerged and will be converted to deeper water habitat types, such as eel grass beds or mudflats.

12. Importance of Sedimentation in Restoring Diked Historic Baylands to Tidal Marsh With Rising Sea Level. Diked historic baylands which have been restored to tidal action also accumulate sediments in deeper portions of the sites. However, there is probably a threshold size and depth at which tidal sedimentation cannot restore former intertidal elevations in these subsiding diked wetlands. Consequently, if these areas are inundated, they may become open water and mudflats, rather than tidal marshes.

13. Salt Water Intrusion Will Threaten the Suisun Marsh. The most significant biological problem for the Suisun Marsh managed wetlands will be the increase in salinity of the water used in wetland management. The present and planned water control structures in the Suisun Marsh are being constructed under the assumption of stationary or low rates of sea level rise. Salt water intrusion will require additional structures and diversion canals to move fresh water from farther upstream into the marsh. Pumps will be required to drain many of the duck clubs as sea level rises. Moreover, the outboard levees, constructed on compressible peat soils, will be subject to subsidence and overtopping from high water. Although it may be feasible from an engineering standpoint to protect the managed wetlands, the economic cost may be very high.

14. North Bay Marshes May be Submerged by a Rise in Sea Level. A substantial portion of the Bay's mudflats and tidal marshes are located in San Pablo Bay and central San Francisco Bay. This area has experienced a low rate of relative mean sea level change over the past 50 years. Many of the tidal marshes in this area were created by an excessive amount of sediment washed into the Bay during the hydraulic mining in the Sierra Nevada in the 1860's. Much of this sediment has now moved out toward the deeper portions of the

Bay. Upstream fresh water diversions and flood control projects will reduce the amount of sediment naturally transported to this area. Dredging practices in the Bay can also affect the distribution and movement of sediments with the possible redirection of dredged material dispoal to ocean or on-shore locations. Because there is insufficient information regarding sedimentation rates and patterns in this part of the Bay, it is premature to predict the consequence of relative sea level rise on the area's tidal marshes. However, it is likely that there will be a submergence of the tidal marshes. The conversion of tidal marshes to mudflats would significantly impact a number of endangered species in the North Bay. Most of the adjacent diked historic baylands are used for agriculture and do not provide suitable habitat for endangered species such as the clapper rail, black rail and salt marsh harvest mouse. These areas, however, do provide an important location to create tidal marshes and perhaps the last opportunity for extensive tidal marsh restorations.

15. Tidal Marshes in Parts of the South Bay Will be Submerged by a Rise in Sea Level. Tidal marshes in the South Bay, north of the Dumbarton Bridge, are likely to suffer significant losses because of reduced sediment deposition in this area and because the shoreline is eroding in some areas. With a reduction in sedimentation and a relative rise in sea level, tidal marshes will become submerged and will consequently decline. Despite having the most significant rate in relative sea level rise, sediment deposit in the South Bay below the Dumbarton Bridge appears to be occuring quite rapidly and consequently many of the tidal marshes have been maintained. However, the diked wetlands in this area of the Bay have subsided sustantially, consequently if these areas were returned to tidal action, they would revert to open water and mudflats.

16. <u>The Engineering Design for Projects in the Bay and on the Shoreline Should Reflect an Expected Increase in Sea Level</u>. The engineering design for protection of structures such as buildings and piers, proposed to be constructed on the shoreline or in the Bay and shoreline protective devices, such as levees and sea walls, should incorporate the estimates of future relative sea level changes and extreme high water levels as presented in this report.

17. <u>Bay Commission Incorporation of Flood Protection Engineering Design Procedure.</u> Under the McAteer-Petris Act, the Commission has the authority to require that Bay fill be constructed in accordance with sound safety standards which will afford protection to life and property from the hazards of flooding. The Commission does not have the authority to address flood protection in its regulation of shoreline projects that do not involve Bay fill. However, local governments do have the authority to deal with the issue. Consequently, the Commission should:

a. Incorporate the tidal flood protection engineering design review procedure and criteria in Part IV of this report in its permit application review process involving structures and flood protection devices to be constructed on the Bay. Such projects should be reviewed by the staff engineer and where warranted, by the Commission's Engineering Criteria Review Board.

b. Add to the Engineering Criteria Review Board a member(s) with expertise in coastal engineering and tidal hydraulics to assist in the review of the tidal flood control aspects of Bay fill projects.

18. Amendments to the Bay Plan. The Commission should direct the staff to prepare for consideration by the Commission, a Bay Plan amendment to changethe Safety of Fills section of the Plan (pages 13-15) consistent with the information contained in this report. Specifically, the Plan amendment should address a possible change to:

a. Finding "c" to include tidal flooding as a potential safety hazard for Bay fill projects.

b. Finding "d" to state that there are no minimum construction codes for regulating fill projects that take into consideration relative rise in sea level.

c. Finding "f" to include relative change in sea level as a potential cause of flood damage to fill projects and shoreline areas and to state that to prevent flood damage, Commission approved projects should conform to the flood protection design criteria contained in this report.

d. Policy 1 to state that a coastal or hydraulics engineer will be appointed to the Engineering Critiera Review Board.

e. Policy 2 to state that the Commission should not authorize fill projects if the tidal flood hazards associated with the fill cannot be overcome adequately in accordance with the flood protection engineering design criteria contained in this report.

f. Policy 4 to set recommended new minimum heights buildings and levees should be built above mean sea level in the South Bay.

g. Policy 5 to provide that flood damage to structures and protective devices placed in the Bay should be prevented, and to assure prevention of such damage, the flood protection engineering criteria in this report should be followed.

19. Bay Commission Communication With Local Governments Concerning Sea Level Rise. The Commission should directo the staff to communicate with each bayside local government and recommend that each local government:

a. Take into consideration the projected rise in Bay sea level as contained in this report in its land use planning and regulatory process.

b. Undertake a vertical land motion survey program in cooperation with the U. S. Geological Survey; and

c. Incorporate the flood control engineering design procedure and criteria in Part IV of this report in its shoreline project review and authorization procedure.

INTRODUCTION

Over the past 5,000 years, change in the sea level has been gradual and constant. However, recent studies by the U. S. Environmental Protection Agency and scientists worldwide, indicate that global warming resulting from a global "greenhouse effect" will lead to an accelerated rise in sea level over the next century, which will adversely affecting coastal areas. These adverse impacts include innundation of many low-lying coastal areas, increased coastal flooding, shoreline erosion, and saltwater intrusion into estuaries, fresh water tributaries and ground water. In this country, concern about the impact of an accelerated sea level rise has been concentrated on the eastern seaboard and the Gulf Coast where the impacts would be greatest. No comprehensive study regarding the impacts of an accelerated rise in sea level has been conducted on the Pacific Coast.

Projects in the Bay authorized by the San Francisco Bay Conservation and Development Commission must be "constructed in accordance with sound safety standards which will afford reasonable protection to persons and property against the hazards of...flood or storm waters." (California Government Code Section 66605(e).) Typically, the Commission approves residential, commercial, industrial, and recreational projects valued at over $650 million annually, and thus must be concerned whether the projects it authorizes will be adequately protected from possible tidal flooding in the future.

Because a possible accelerated rise in sea level could jeopardize development in San Francisco Bay and along the shoreline, and due to the lack of information to judge the scope and magnitude of such impacts, in 1985 the Commission had its consultant on tidal hydraulics, Dr. Philip Williams, review the existing literature regarding the predicted accelerated sea level rise, indicate the possible implications of this phenomenon for San Francisco Bay, and develop recommendations for its consideration.

In April 1986, Dr. Williams presented his report and recommendations to the Commission ("An Overview of the Impact of Accelerated Sea Level Rise on San Francisco Bay"). Using information developed by the U. S. Environmental Protection Agency, he concluded that mean sea level could rise approximately four feet in San Francisco Bay over the next century. Dr. Williams recommended that, among other things, the physical characteristics of the Bay needed to be analyzed to assess what areas would be at risk from tidal flooding and that flood protection criteria for the Bay should be developed.

The Commission determined that it should undertake such a study and in January 1987 retained Moffatt & Nichol, Engineers to project future mean sea level in San Francisco Bay, identify areas around the Bay at risk of flooding from an increase in tidal level, and prepare practical and specific flood control engineering criteria and procedures for use by the Commission, local governments, and other agencies in setting shoreline tidal flooding protection. The Commission also requested that the study analyze the impacts of a rise in sea level on Bay marshes and adjacent wetlands to assist the Commission and others with natural resource management responsibilities.

Part I of this report, prepared by the Commission's staff, provides an overview of the concept of sea level change, a brief discussion of the "greenhouse effect," and the general strategies available to governments and property owners to cope with a rise in sea level. This part of the report is intended for the nontechnical reader.

Part II, prepared by Moffatt & Nichol, is a technical discussion of sea level change directly related to San Francisco Bay. This part of the report, intended for the reader familiar with technical engineering terms and concepts, includes Moffatt & Nichol's predicted mean sea level at eleven sites around the Bay. To relate to the practical life expectancy of structures, these estimates are for 20 years and 50 years in the future. Moffatt & Nichol also projected the future highest estimated tide level for the eleven sites because this information is essential in developing shoreline flood protection criteria. In this part of the report Moffatt & Nichol also explain how jurisdictions and landowners around the Bay can determine, given adequate data, the historic and future mean sea level on their shoreline.

In Part III, Wetlands Research Associates, consultants specializing in esutarine biological resources, discusses the impacts of a rise in sea level on San Francisco Bay tidal marshes, managed wetlands, and diked historic Baylands. Included are specific recommendations concerning the design of marsh restoration projects and protection and enhancement of Bay wetland resources.

Last, Moffatt & Nichol, in Part IV, recommend specific engineering criteria to be used in designing shoreline structures for protection from tidal flooding and recommend an engineering design review procedure for reviewing the adequacy of a shoreline project design which can be incorporated into the Commission's permit process and local government land use regulatory process to assure protection of the project from tidal flooding.

extend salt water intrusion into the Bay-Delta system and ground water aquifers. Moreover, because of the rise in the Bay water level, drainage systems to the Bay and flood control structures could become dysfunctional.

Relative Sea Level Change

The perceived change in sea level is a product of two factors: the change in the level of the earth's oceans and the rising or subsidence of the earth's land mass at the shoreline. The change in level of the oceans is refered to as "global sea level" change. The rise or subsidence of the shoreline land mass is referred to as "vertical land motion" change. Relative sea level change is the sum of global sea level change and the change in vertical land motion. Thus, if the ocean rises and the shoreline subsides, the relative rise in sea level--the sum of the rise in water level and the amount of land subsidence--will be much greater, and therefore more significant in terms of coastal flooding, than if the shoreline land mass remained at a constant level, or rose. Relative sea level rise is the most important element in determining future coastal flooding potential from a rise in sea level. Therefore, in order to predict future mean sea level at any point around the world, it is necessary to determine whether (1) global sea level may rise in the future and (2) shoreline elevations may change due to vertical land motion at a particular site.

Global Sea Level Change

Tide gauges located at established points on the shoreline measure the daily level of the tides in relation to the land mass where the gauge is located. The primary evidence for the recently observed and the predicted accelerated rise in mean sea level comes from the records of these tide gauges. In addition to reflecting the change in sea level, measurements of water levels at a tide gauge station reflect change due to the land movement of the region where the gauge is located. Therefore, it is extremely important to continually measure, or relevel, the tide gauge to determine whether the change in relative sea level is caused by a change in global sea level or by local vertical land motion change.

The levels of the oceans (and San Francisco Bay) are constantly changing in response to many influences; the gravitational attraction of the moon and sun acting upon the rotating earth produces the periodic rise and fall of the tides, while meterological effects, such as winds and changing barometric pressure, further vary water levels. Moreover, global warming effects can cause thermal expansion of the upper layers of the oceans water mass as well as melting of ice fields and glaciers. In addition, periodic climatic effects, such as the El Nino-Southern Oscillation phenomenon, which results in the local warming of the ocean and change in ocean currents, causes oceanic expansion resulting in higher tidal levels during the occurrence.

Over the past century, global sea level has maintained a steady constant rise at most tide gauge stations around the globe. However, some studies, based on tide gauge measurements, show that over the latter part of the century, the rate in the rise in global sea level has increased. Many scientists believe that this increasing rate will accelerate over the next 100 years because of a gradual warming of the earth's air temperature. The increased warming, they believe, will be caused by a "greenhouse effect" in the earth's atmosphere, which will result in an increase in global sea level due to thermal expansion of the upper layers of the oceans and some melting of the earth's glaciers and the polar ice fields.

Light and energy from the sun penetrates the earth's atmosphere and the heat is radiated off the earth's surface as infrared rays. Most of this heat escapes but some is trapped in the lower level of the atmosphere by carbon dioxide and other gases. Much like an ordinary botanical greenhouse, the trapped heat warms the earth's surface. Many scientists are alarmed that with the increased emission of carbon dioxide, chloroflorocarbons, and methane gases into the atmosphere, these heat trapping gases will build up, creating a "greenhouse effect" which will result in a long-term warming of the earth's surface. In addition, because green vegetation absorbs much of the infrared energy waves emmitted from the sun, rapid deforestation, particularly of the earth's tropical rain forests, will contribute to this global warming trend. Without vegetation covering much of the earth's land mass, the energy is reflected off the globe and an increasing amount is trapped in the gas enriched atmosphere.

Many scientists predict that global warming brought on by the greenhouse effect will cause a significant and rapid rise in global sea level over the next century. The U. S. Environmental Protection Agency estimated a rise between two and 11 feet by the year 2100 depending on the magnitude of various contributing factors.

Although many observers believe that the greenhouse effect will lead to an accelerated rise in global mean sea level over the next 100 years, most scientific experts do not believe that we are capable of detecting this possible warming trend until the 1990's (National Research Council, 1987). Because the effect of global climate change is still being studied by the scientific community, the National Research Council believes that planning for the impacts of global sea level rise should be based on the historical trend in global sea level rise for the next 50-year period, the basic design life of a structure. Moffatt & Nichol have similarly concluded that, based on the present uncertainty concerning the future rate in rise of sea level, a 50-year prediction rate based on historical trends is the most prudent course to follow in planning for and designing shoreline flood protection devices. However, both the National Research Council and Moffatt & Nichol emphasize that it is essential to continually monitor the rate in global sea level rise during that 50-year period and adjust the 50-year prediction based on actual measured global sea level change at least every ten years.

Vertical Land Motion Change

All coastal areas around the world are affected by the change in global mean sea level. However, subsidence or uplift of the land mass at the water's edge is uniquely local. Thus to understand how change in mean sea level will affect a particular point on the shoreline, one must determine, in addition to global sea level change, vertical land motion change at the site.

According to the National Research Council (National Research Council, 1987), there are four types of vertical land motion affecting relative change in mean sea level: (1) uplift or subsidence of the earth's surface caused by tectonic activity (geologic changes in the earth's crust caused by shifting surface plates); (2) seismic subsidence caused by sudden and irregular seismic activity [also tectonic activity]; (3) subsidence caused by the consolidation and compaction of soft, compressible muds and peat soils; and (4) subsidence caused by the extraction of groundwater, oil, or natural gas from the ground.

Vertical land motion varies considerably around San Francisco Bay. The topography and soils of the Bay shoreline ranges from steep rocky cliffs to low-lying, gradually sloping soft sediments. Each of the types of vertical land motion affecting relative sea level change is experienced around the

Bay. Much of the Bay shoreline consists of soft compressible Bay muds and peat, the kinds of soils that compact and subside. Moreover, many areas on the Bay shoreline are constructed on fill over soft Bay muds. The weight of the fill on the Bay muds causes the soil to further compact and to subside. Still further, ground water withdrawal in the Santa Clara Valley has caused soils in the south Bay to consolidate and subside considerably. For example, in the Alviso area of San Jose, land has subsided at the shoreline approximately six feet because of ground water withdrawal.

As a general rule, low-lying areas around the Bay, particularly those with sediment-deposited soils, are particularly susceptible to flooding from a relative rise in mean sea level. These low-lying areas are subject not only to global rise in sea level, but more importantly, to subsidence from soil compaction and consolidation in addition to tectonic activity.

Measurements from established reference points, known as benchmarks, are necessary to determine changes in vertical land motion. Monitoring benchmarks can reveal local and regional vertical land motion change. The collection of benchmarks in a region is collectively referred to as a "leveling net." The checking or "releveling" of these nets over time, whether by federal survey or a county or city engineering department, is carried out to determine the change in vertical land motion from the time the benchmark was last releveled.

Around the San Francisco Bay shoreline there are very few releveled benchmarks. Without accurate vertical land motion data for a shoreline area, change in relative mean sea level cannot be determined and an accurate prediction of future relative mean sea level change cannot be made. It is therefore extremely important that communites around the Bay, particularly those built on low-lying areas over sediment soils, establish and maintain a shoreline benchmark leveling system, in order to understand vertical motion change on the shoreline. Currently, the city of Corte Madera in Marin County and Foster City in San Mateo County are instituting such programs as part of each city's tidal flood protection program.

Response to Relative Sea Level Rise

As relative sea level rises around the Bay, unprotected low-lying shoreline areas may be periodically flooded or permanently innundated, depending on a number of factors, such as the magnitude of relative sea level rise and the degree of shoreline protection from tidal flooding. In those low-lying areas with inadequate tidal flooding protection, public policy and economic decisions must be made concerning whether to stabilize and protect the shoreline or abandon waterfront properties. Shoreline stabilization and protection is technically feasible, but it is also costly. If an area such as an urban development or a important natural resource has economic value, it may be inappropriate to allow this to flood. On the other hand, protection of some low-lying areas that have relatively low economic value, such as diked historical baylands used for low-intensity agriculture, may not be justified economically. Such lands may have value as restorable tidal marsh sites or low-intensity recreation uses. To prepare to make these kinds of decisions in the years ahead, shoreline communities and landowners must first determine the future change in relative mean sea level for their shoreline. The next section of this report addresses how this can be accomplished and provides specific predictions of future relative mean sea level for the eleven sites around the Bay where adequate data exist.

PART II: LONG-TERM TREND IN MEAN SEA LEVEL AND ITS IMPACT ON HIGH WATER PREDICTIONS IN SAN FRANCISCO BAY

This part of the report includes a discussion of sea level measurement and an analysis of the historic sea level change and vertical land motion change in and around San Francisco Bay, using available tide gauge and benchmark control data. A procedure is developed for forecasting changes in sea level around the Bay and future relative mean sea level is predicted at 11 sites around the Bay for 20 years (2007) and 50 years (2037) in the future. The forecasting methodology can be used by the Bay Commission and Bay local governments in updating the relative sea level rise forcasts for planning and regulatory purposes.

Mean Sea Level and National Geodetic Vertical Datum

The gravitational attraction of the moon and sun acting upon the rotating earth produce the periodic rise and fall of the water on the shoreline known as the tide. The tide in San Francisco Bay is referred to as a mixed type, that is, there are usually two high and two low waters each day, which are characterized by a relatively large inequality in the successive high- or low-water heights. Sea level is the height that the sea surface would assume if it were undisturbed by tides, waves, or winds. These disturbances do exist, however, and a technique for averaging all possible sea levels has been adopted. Mean Sea Level (MSL) is defined as the average height of the water surface for all stages of the tide over a 19-year period, usually determined from hourly height readings of a tide gauge. The 19-year period is referred to as a tidal epoch, and is used to "smooth out" the long-period tidal fluctuations, as well as those other periodic, or quasiperiodic variations of meteorologic origin that are measured and included in any water level record, such as the recent El Nino warming effect.

Mean Sea Level at a tide station can be computed on the basis of any epoch; however to provide continuity in datums throughout the United States, the National Ocean Survey (NOS) selects a specific epoch for general use. The NOS normally furnishes MSL for the latest tidal epoch, but can provide annual values of MSL by special request. Clearly, MSL is not a fixed reference but fluctuates with the ever-changing stand of sea level.

The National Geodetic Vertical Datum (NGVD) is a fixed reference plane for the National Vertical Control Network and should not be confused with mean sea level. This datum was derived from a 1929 general adjustment of the first order level nets (primary survey benchmark system) of both the United States and Canada in which the sea levels at selected tide stations were held as fixed. The relationship between NGVD and local MSL is not consistent from one location to another nor from one time to another because of the many variables that affect sea level. Nonetheless, NGVD establishes continuity between isolated tide stations, and provides a tool for monitoring geophysical processes of coastal areas. For example, through a system of long-term tide stations and regular releveling (periodic surveys or measuring) between stations, measurement of rates of coastal subsidence or emergence is possible.

Tide stations may be classified as either reference (primary) or subordinate (secondary) stations. Tidal constants (and datums) are determined at reference stations from independent observations at the station. These stations are used as a standard for the comparison of simultaneous observations at subordinate stations. Short series of observations are taken at subordinate stations, which are reduced by comparison with simultaneous observations at a reference station having well-determined tidal constants. While the method allows adequate prediction of daily tides at the subordinate station, the tidal datum planes, including MSL, cannot be determined independently. Although tidal information from such stations cannot be used for the purposes of this study, releveling data from these stations can provide useful information on vertical land motions.

Relative Sea Level Change

Relative sea level change is the difference of two components, the global sea level change and vertical land motions. Tide gauges measure the relative sea level change because they measure the water surface relative to land. As noted previously, the evidence for global sea level rise is largely based on measurements of relative sea level rise determined by tide gauges. The adjustment of the tide gauge measurements to remove the vertical land motions is often necessary, especially when regional land motions are occurring that are significant in comparison with the relatively low rates of global sea level change.

The National Ocean Survey (NOS) maintains a tide gauge at the Presidio, San Francisco, which provides the longest, continuous tide gauge record in the United States. The record starts in 1854 and indicates a relative rate of sea level rise of 0.0039 feet/year (Hicks, et.al. 1983). Published rates for other California locations include 0.0033 feet/year on the south coast and -0.0013 feet/year on the north coast, which illustrates the apparent differences in relative rates, and the difficulty of inferring global rates from a simple comparison of tide gauge records (Hicks, et al., 1983). It also demonstrates the need to consider the sea level change phenomenon in terms of rise or fall, and not just in terms of rise.

The impacts on the Bay that should be of concern to the Bay Commission associated with sea level change are governed by the relative change, rather than the global change. Therefore the development of a meaningful procedure to forecast the change in sea level requires consideration of the relative change in sea level.

Global Sea Level Change

Evidence of global sea level rise is primarily based on tidal gauge records; the average rate of global sea level rise over the last century is about 0.0039 feet/year (1.2 mm/yr)(Dean, 1986). While many experts agree with this historic average rate, they do not agree on estimates of future global sea level rise. Although the estimated rates vary widely, all indicate that sea level over the next 100 years may be expected to continue to rise, and at a rate that is greater than the historic value.

A comparison of several predictions with the historic trend, all relative to the year 1980, is presented on Figure 1 (Dean, 1986). The four EPA estimates are based on multiple regression (a statistical analysis) of sea level on the meteorological and oceanographic parameters that influence the long-term trend in sea level (Hansen, et al, 1981). Although this methodology helps in developing an understanding of the processes involved and may eventually prove to be the best approach, at present the predictions using

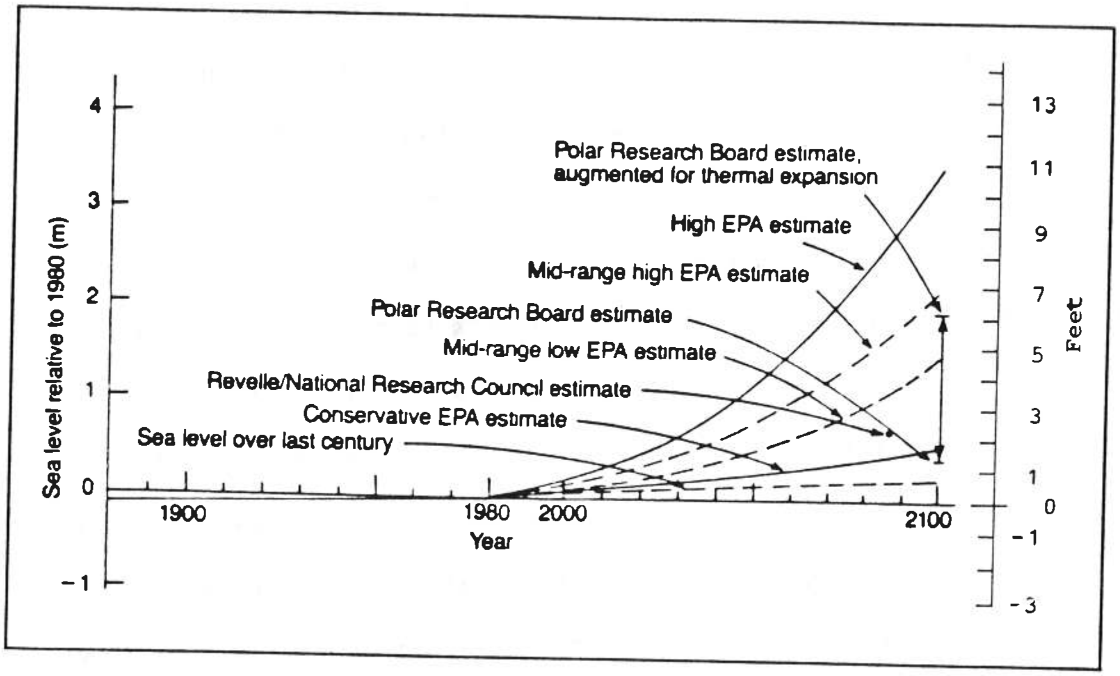


FIGURE 1

Global Sea Level Rise Predictions SOURCE: Dean. 1986

this methodology are questionable, as they rely on uncertain information. Similar comments pertain to the other estimates shown on Figure 1. The projected rise in sea level for the next century ranges from approximately one-foot to 10 feet. The uncertainty associated with this wide range limits the usefulness of these predictions in developing practical planning guidelines for immediate implementation. Therefore the methodology and predictions of future relative sea level change and high water levels in this report are directed to the relatively immediate, and practical time period--the design life of a project, which is 50 years. In addition, estimates for a more immediate, 20-year period are provided.

Vertical Land Motion Change

Vertical land motions result in an apparent change in sea level. An observer on a land mass that was subsiding would experience an apparent rise in sea level, since it was not a true change in sea level that caused the rise, but rather the relative sinking of the land. Vertical land motions on a regional scale result from tilting, folding, or faulting of the earths curst, referred to as tectonic activity. In parts of the Bay Area, this tectonic subsidence amounts to about 2 inches/century or 0.02 centimeters/year (Atwater, Hedel, and Helley, 1977). In contrast to tectonic vertical land motions, which are very difficult to measure because of their regional nature and relatively small rates, subsidence due to consolidation of soils resulting from changes in overburden pressure or withdrawal of ground water are easier to detect and can often exceed the rate of global sea level rise. Severe subsidence has occurred in the southern most reaches of the Bay, as shown on Figure 2, where rates have exceeded 0.024 feet/year measured at San Jose (Poland and Ireland, 1971). According to the Santa Clara Valley Flood Control District, the subsidence has been arrested by reducing the rate of ground water withdrawal in the area. However, no data has been collected to show vertical land motion change in this area in recent years. Subsidence has also been significant in some Bay front developments built on fill placed on compressible bay muds, as well as in the Delta where highly compressible peat soils exist.

Highest Estimated Tide Level

The extreme high tide levels for San Francisco Bay result from the combined occurrence of meteorologic phenomena that can produce superelevation of water level associated with the ordinary astronomical tides. Such meteorologic phenomena include local barometric pressure and winds, as well as large scale atmospheric disturbances such as El Nino. The affects of local wave runup and stream runoff are outside the scope of this report and

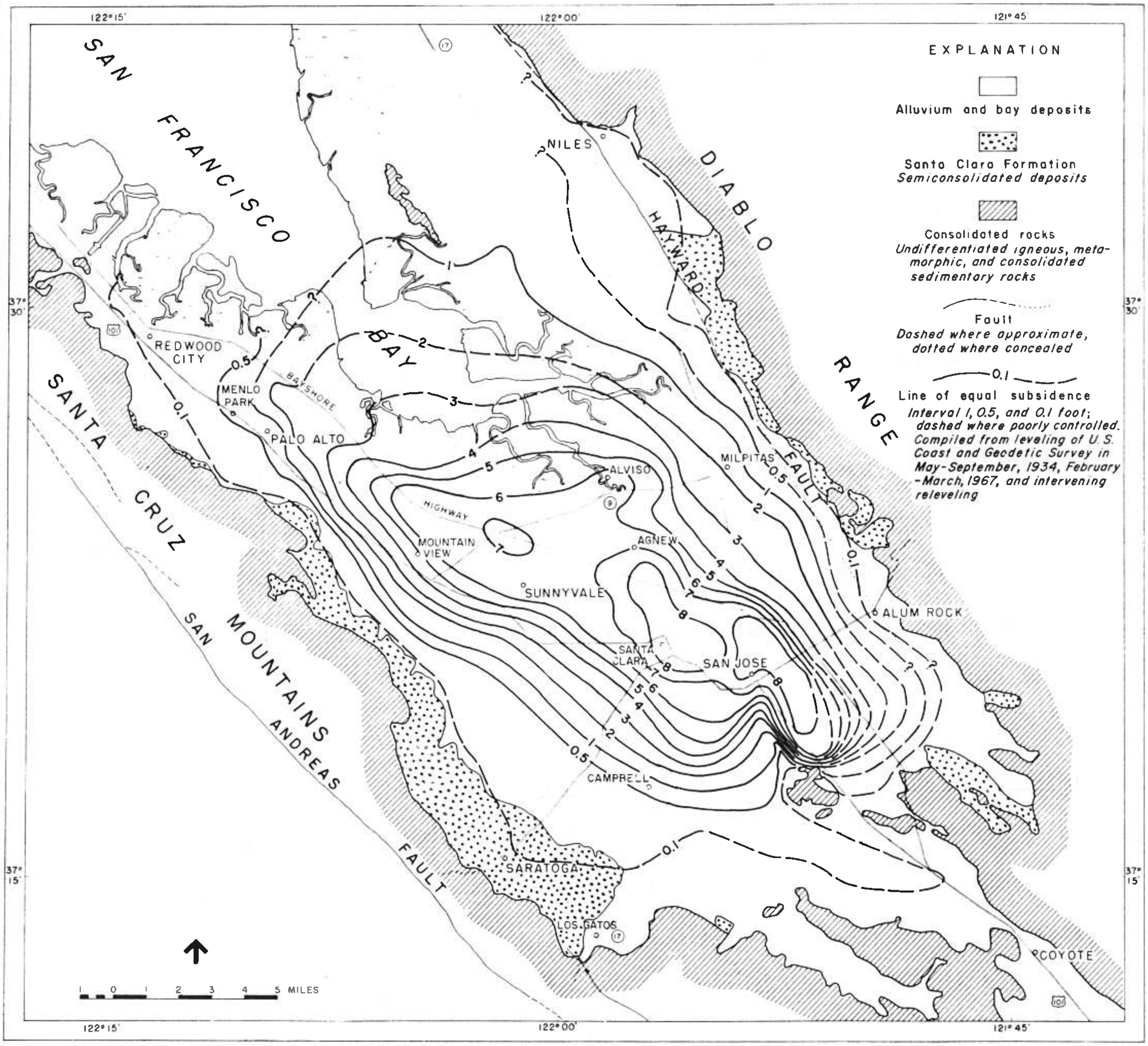


FIGURE 2

Land Subsidence From 1934 to 1967, Santa Clara Valley, California

SOURCE: Poland and Ireland, 1971.

consequently are not considered in this analysis, nor are tsunamis. The U.S. Army Corps of Engineers (San Francisco District, 1984) performed a statistical analysis of the highest yearly tide level observed at the Presidio for the period from 1855 to 1983. The results are presented on Figure 3 in terms of highest estimated tide (HET) level with an expected recurrence interval of 100 years for various Bay locations. The levels generally increase with distance from the Golden Gate, and tend to be larger in the South Bay than the North Bay. Inspection of the data reveals that the highest values for the period occurred in 1983, and are nearly equal to the 100 year highest estimated tide levels.

The Federal Emergency Management Agency (FEMA) has also published HET values for locations within the Bay Area. The FEMA flood elevations corresponding to the 100-year event are only used in the portions of the study area where the Corps of Engineers estimates do not apply (i.e., Suisun and Honker Bays).

Diagnosis of Sea Level Change in San Francisco Bay

The components of sea level change are: relative sea level change (R), global change (G), and land elevation change (L). This relationship is expressed by the equation: $R = G - L$.

Land subsidence is given a negative sign. Ground elevation changes are determined by benchmark vertical control data, furnished by the National Geodetic Survey (NGS). Relative sea level changes are determined from tide gauge records supplied by the National Ocean Survey (NOS). These data are summarized in Figures 5 and 6 for selected tide gauge locations around the Bay with adequate data and discussed below.

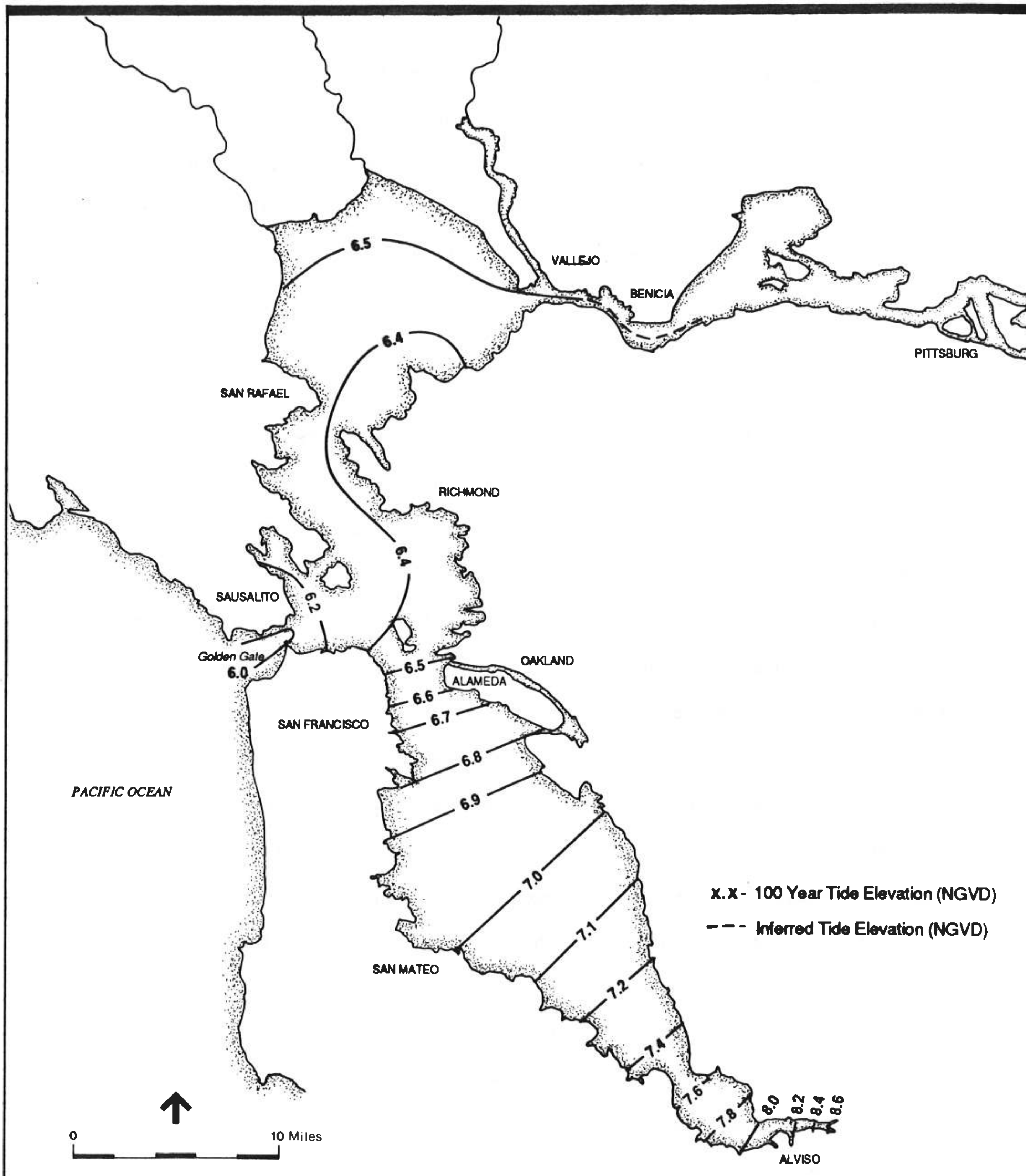


FIGURE 3

100-Year Highest Estimated Tide (HET) Elevation

SOURCE: U.S. Army Corps of Engineers, 1984.

1. Tide Gauge Records. Tide gauge data are available for two primary stations and a number of secondary stations around the Bay (see Figure 4 for location of Bay tide gauges used in this report). The primary stations are at the Presidio in San Francisco for which a 132-year record is available, and at Alameda, for which a 47-year record exists. The Alameda data for the tidal epoch 1924-1942 only is based on an adjustment of the data for the Presidio gauge and is therefore not representative of a primary station. Nonetheless, the data from the Alameda Tide gauge is extremely helpful for this study.

Secondary tide stations are used (occupied) for relatively short periods of time to develop a relationship between the measured water elevations of the secondary station and the primary station. The relationship is used to estimate tidal information for the secondary location based on the more extensive record at the primary location. Analysis of the trend in mean sea level at secondary stations using tide gauge data is not feasible because of the dependence of secondary station data on primary station data. This is clearly illustrated by Figure 5, which shows mean sea level relative to NGVD for nine stations on the Bay. The annual mean sea level at the Presidio is also shown to illustrate the range of sea level fluctuations that occur around the Bay. Secondary stations in the South Bay are controlled by the Alameda station, while secondary stations in the North Bay are controlled by the Presidio station.

2. Vertical Control Data. Vertical ground movements in the vicinity of the tide gauges is determined from tidal benchmark releveling (periodic measuring) data. This data is published by the NGS as Vertical Control Data. Analysis of the trend in vertical ground movements is complicated because:

a. Few tidal benchmarks have releveling data.

b. Those benchmark releveling data that are available extend over a relatively short time span.

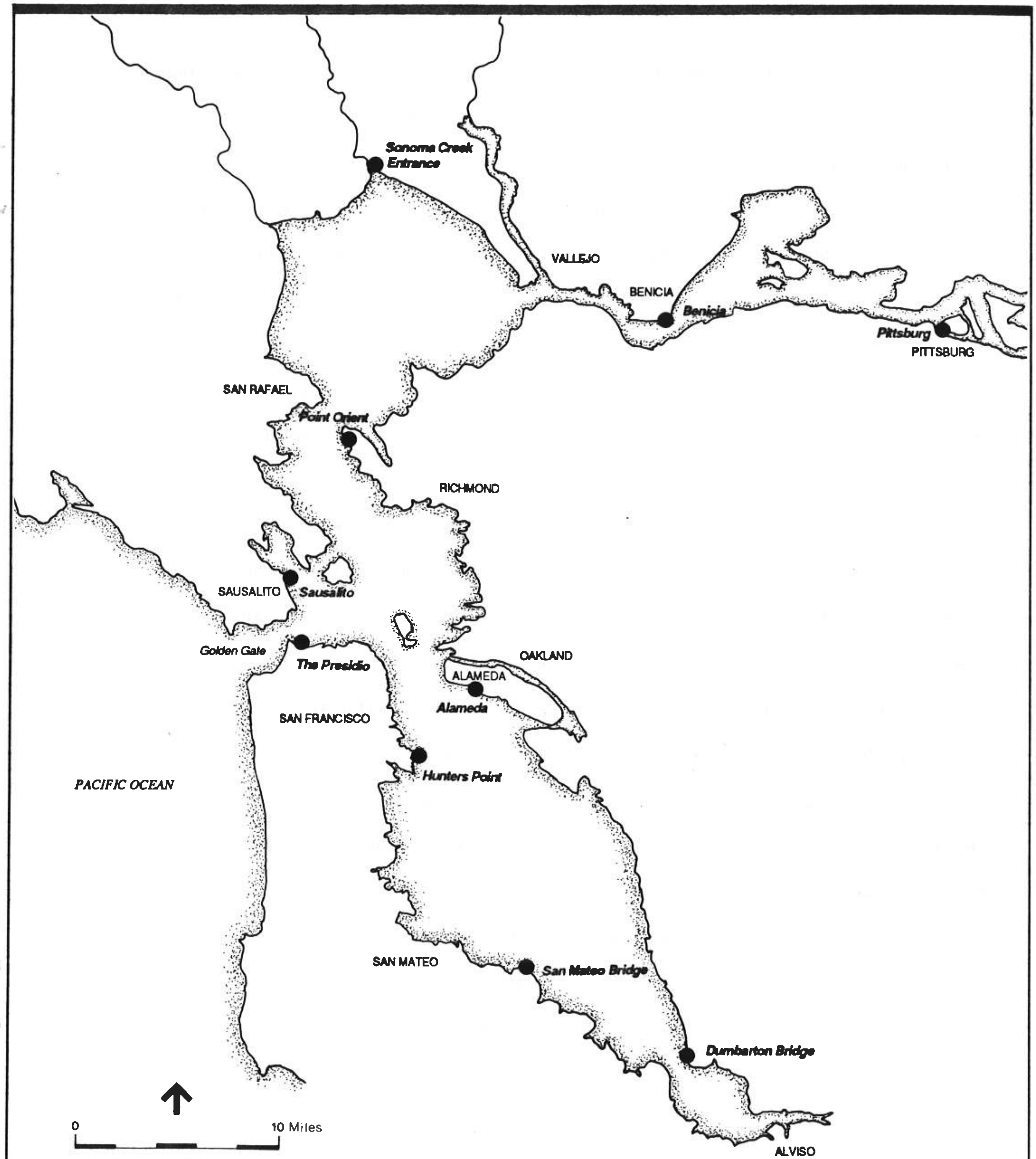


FIGURE 4

Tide Gauge Locations

c. Tidal benchmark releveling data provide ground level changes relative to a leveling net that may in turn be subject to undetected regional ground movements.

d. Little releveling data past the mid-1960's are available around the Bay and hence recent changes in ground level cannot be determined.

These are serious shortcomings that can only be rectified by a data collection program instituted at the local or regional level. Figure 6 displays available vertical control data for the tidal benchmarks at the selected Bay stations used in this report. The elevations are displayed relative to the most recent value. Mean sea level from Figure 5 is reproduced on Figure 6 for each station to facilitate comparison between the data.

The vertical control data indicate subsidence at seven locations, approximately no vertical motion at three locations, and uplift at one location. The severe subsidence identified at the Dumbarton Bridge Station and the Alviso Slough Station was associated with ground water removal, which practice has since been curtailed.

The historic subsidence/uplift rates at the tide stations were determined by fitting a straight line to the limited amount of available data. These rates are given in Table 1.

This data should be updated by means of a regional releveling effort. This is particularly needed in the South Bay, where the past high rate of subsidence may not be representative of present or future conditions due to the reduction in ground water removal.

Historic Sea Level Change

The estimated relative sea level change rates for the 11 tide stations around San Francisco Bay are presented in Table 1. The rates are not based on

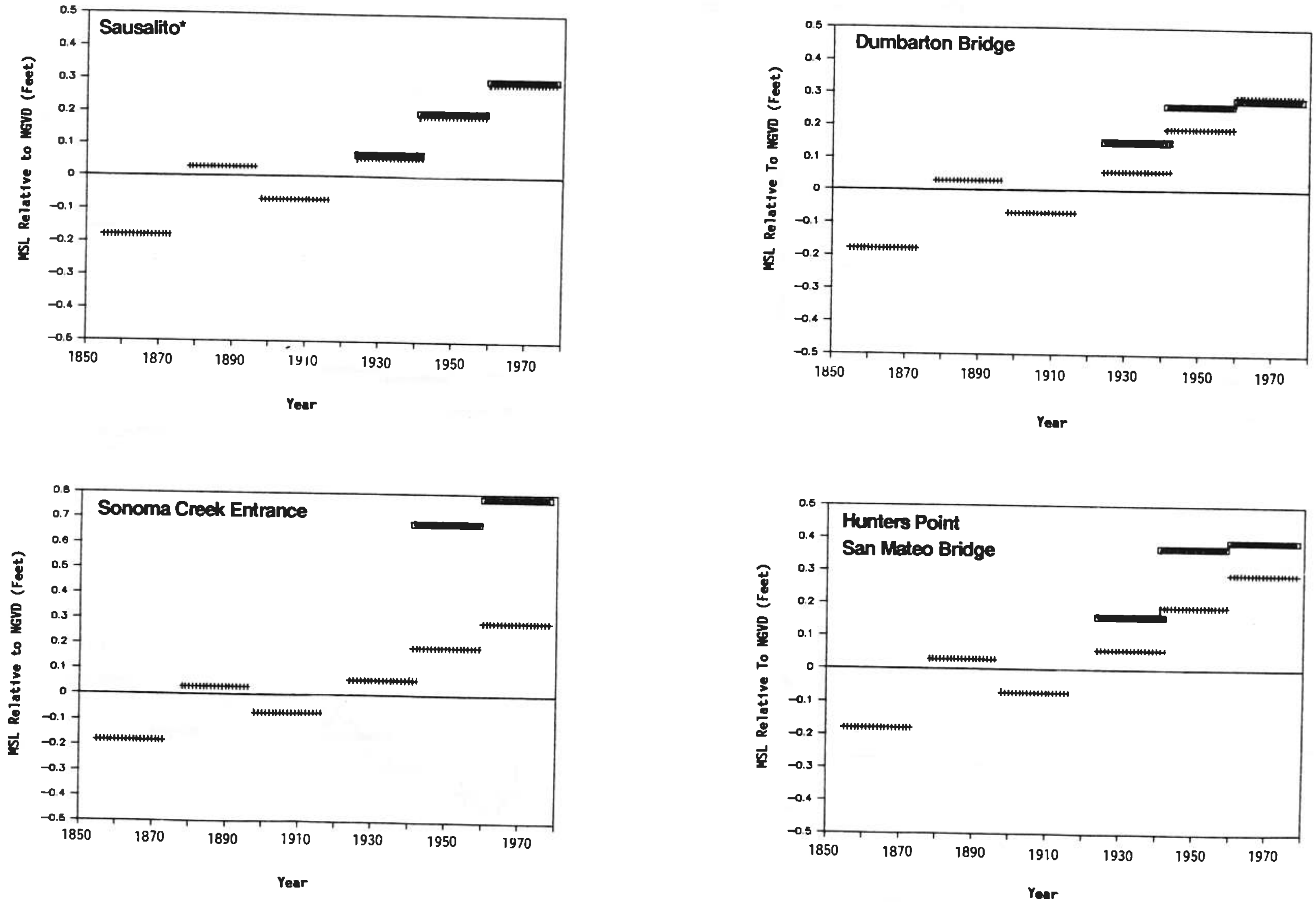
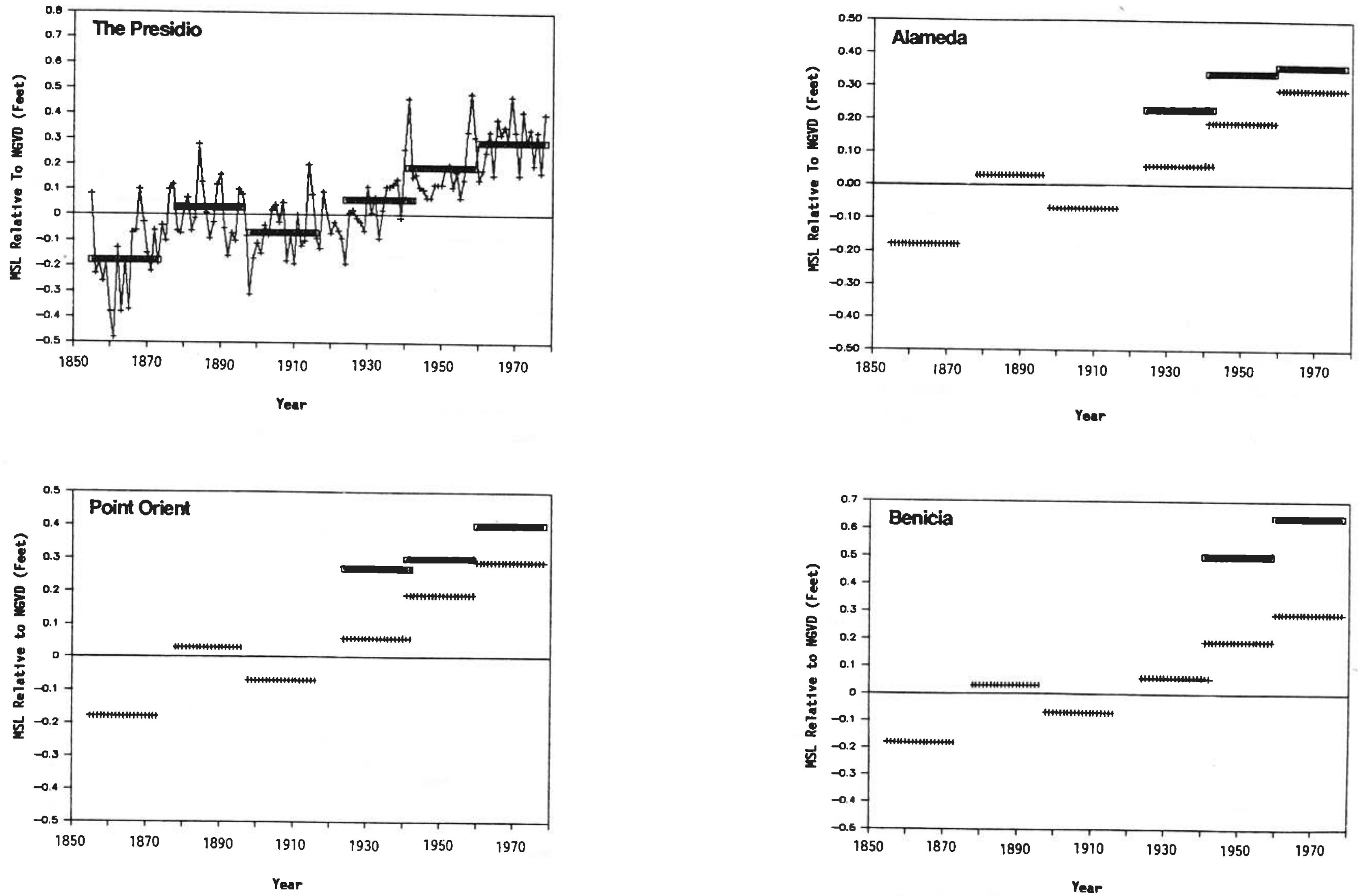


FIGURE 5

Sea Level Change in San Francisco Bay



Display of Dependence of Secondary Station Data on Primary Station Data
Primary Stations are the Presidio and Alameda

—— Annual MSL at The Presidio

▬ Epoch MSL at Tide Station

++++++ Epoch MSL at The Presidio

FIGURE 5

Sea Level Change in San Francisco Bay

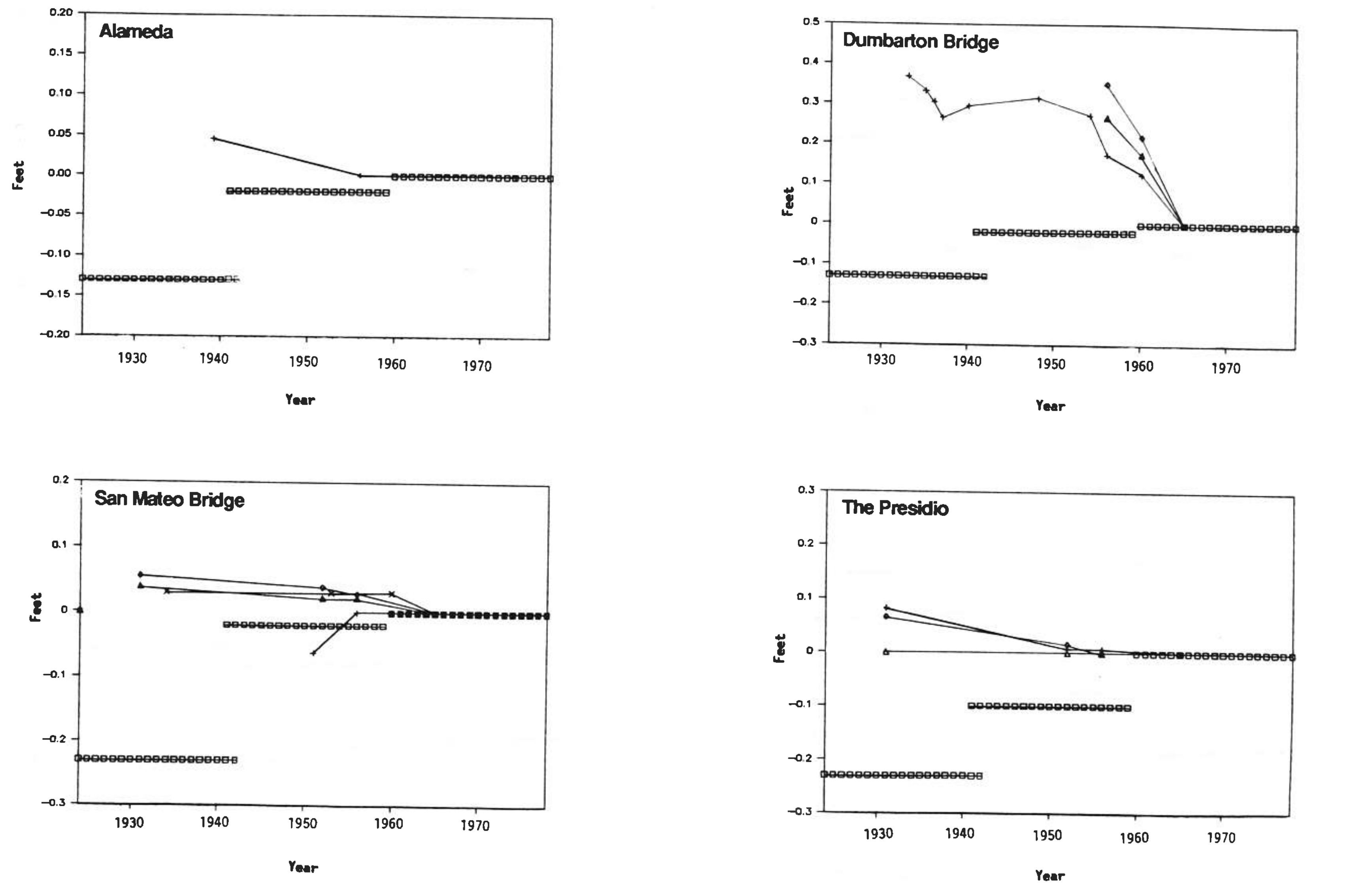
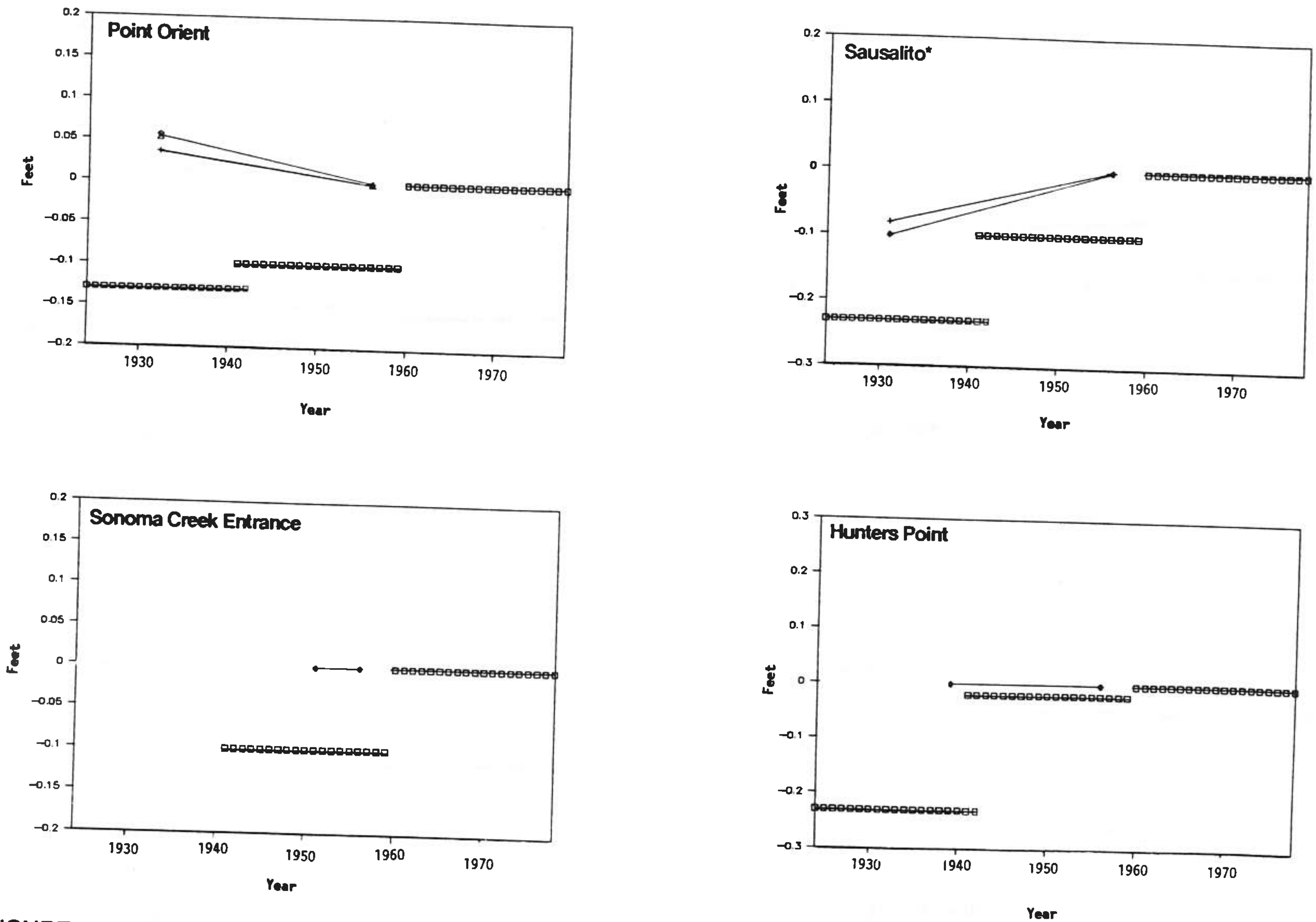


FIGURE 6

Land Elevation and Tide Gauge Data for San Francisco Bay



Elevation changes relative to the most recent value

Land Elevation Data (Source: NGS)
Tide Gage Data (Source: NOS)

*Sausalito ground movement shows uplift, all other stations show subsidence.

□ Global Sea Level Rise
◇ Relative Sea Level Rise
+ Ground Movement

FIGURE 6

Land Elevation and Tide Gauge Data for San Francisco Bay

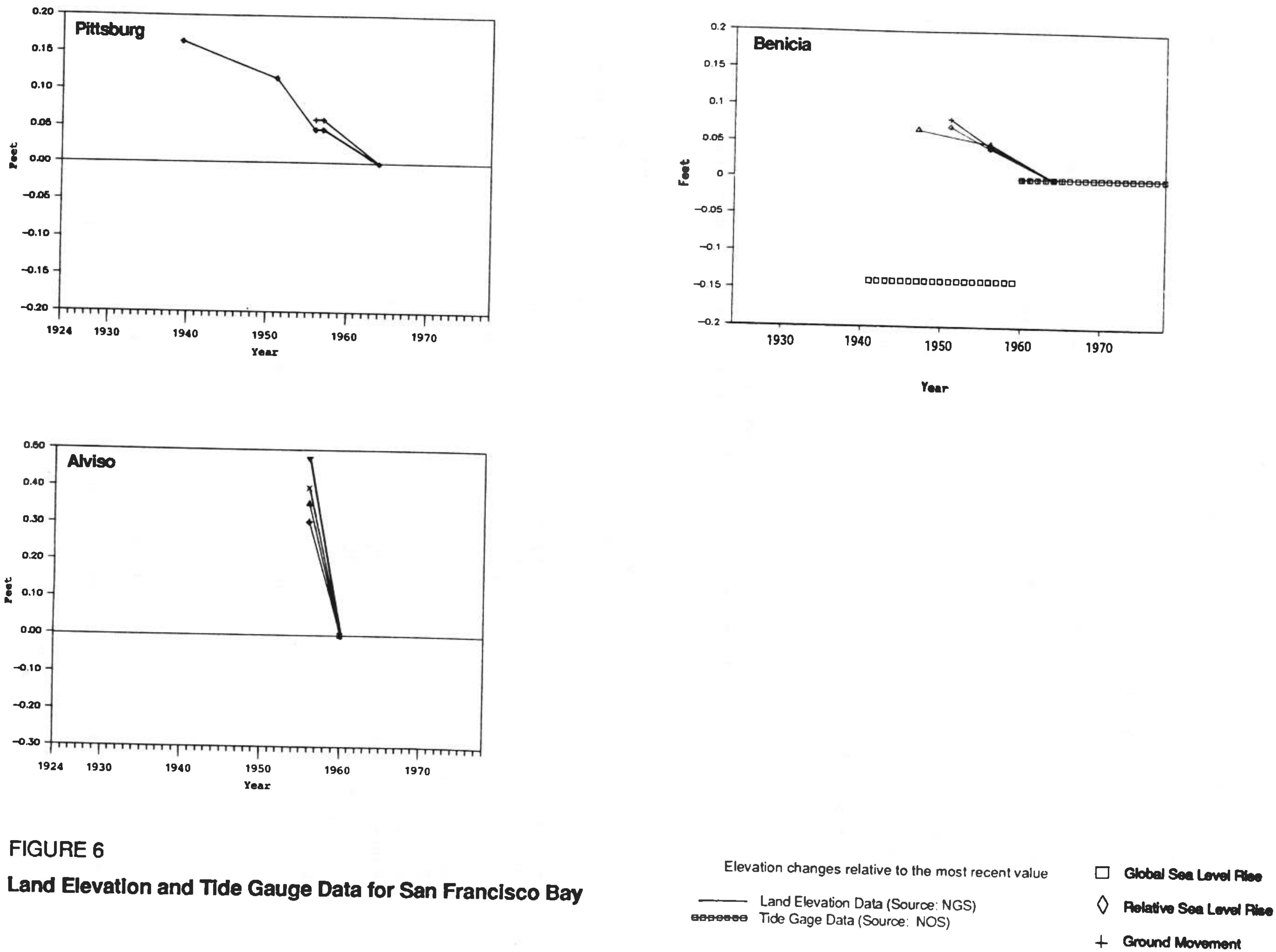


FIGURE 6

Land Elevation and Tide Gauge Data for San Francisco Bay

direct measurement, with the exception of the Presidio. The Presidio is a reference tide station; the measured rate of sea level change is assumed to represent the global sea level change because releveling data for this station reveals no apparent vertical land motions (i.e., the global and relative sea level change rates are equal to the observed value). The relative rates at the remaining stations are computed by algebraic addition of the global sea level change at the Presidio (which is also assumed to be constant throughout the Bay) and the vertical land motions determined from local releveling data available for the respective stations.

Table 1
Estimated Historic Sea Level Change Components

Location	Apparent Global Sea Level Change Rate at the Presidio G (Ft/Yr)	Local Land+ Elevation Change Rate L (Ft/Yr)	Local Relative* Sea Level Change Rate R (Ft/Yr)
Pittsburg	0.0039	-0.0090	0.0129
Benicia	0.0039	-0.0055	0.0094
Sonoma Creek	0.0039	0	0.0039
Point Orient	0.0039	-0.0020	0.0059
Sausalito	0.0039	+0.0037	0.0002
Presidio	0.0039	0	0.0039
Alameda	0.0039	-0.0014	0.0053
Hunters Point	0.0039	0	0.0039
San Mateo Bridge	0.0039	-0.0020	0.0059
Dumbarton Bridge	0.0039	-0.0154	0.0193
Alviso Slough (Coyote Crk)	0.0039	-0.0920	0.0959

+ Positive sign indicates uplift
- Negative sign indicates land subsidence
* G - L = R

The rates of change are based on fitting a straight line by the statistical analysis method of least squares to the available data. Using this method, the global sea level change rate at the Presidio agrees well with generally accepted values of global sea level change. The releveling data that defines the vertical land motions extend over a relatively short time span, utilize local leveling nets (benchmark grid pattern) that may not be able to detect regional ground movements, and provide no information for the most recent period (i.e., past the mid 1960's). However, the relative sea level change rates determined from the questionable releveling data represent the best values that can be provided at this time, or until such time that better data becomes available. Computed relative sea level change for the Bay indicates a rising sea level with a low rate of 0.0002 feet/year at Sausalito and a high rate of 0.0959 feet/year at Alviso Slough.

Projected Future Bay High Water Level

In this section, the methodology used to project future high water levels, and the estimates of high water levels for selected tide stations around the Bay, for the years 2007 and 2037 is presented. This methodology can be utilized by the Bay Commission or local government to determine areas around the Bay that would be at risk of future high water flooding. Much of this discussion is technical because it is intended to be used by engineers or similarly trained individuals who will most likely be carrying out the methodology in determining future shoreline areas at risk from tidal flooding.

A sound procedure for predicting extreme high water levels that includes the anticipated change in mean sea level for the Bay has been developed. The procedure is based on extrapolation of historic water level and vertical land motion data. The assumption is made that the global component of sea level change is uniform throughout the study area and equal to the relative mean sea level change determined at the Presidio tide gauge for the most recent 19-year period. The procedure requires regular updating of the sea level change rate to help insure that acceleration of the sea level change can be accommodated in the planning process as evidence for the acceleration appears in the tide observations. Local vertical land motions based on historic benchmark elevation changes are included in the projection. Highest estimated tides are superimposed on the projected mean sea level to obtain the extreme high water levels used as the planning criteria. The high water levels represent still water conditions and do not include wave action or effects due to unique local topography or structures.

The validity of the planning criteria is largely dependent on the accuracy of the input data on which the extrapolation procedure is based. For the water level data, relatively good information is available; for the vertical land motions, more extensive and up-todate information is needed to fully validate the procedure. The vertical land motions in some locations are the dominant component of the relative sea level change, and in those areas the need for such information is especially important.

1. Projections of Sea Level Change. In a manner analogous to the determination of the historic sea level change rate, the projections are based on extrapolation of the global sea level change at the Presidio, and the vertical land motions at the respective tide stations. Although these time series are not strictly linear, a linear least squares regression analysis (a statistical projection method) has several advantages for this application, including a rate that can be expressed as a single value at each station. Although higher order polynomials (refers to data points plotted on a graph) may provide a better fit, there is no compelling reason to favor the higher order polynomials over the straight line at this time.

Based on a continuous record of mean sea level, the rate of relative sea level rise at the Presidio from 1855 to the present is estimated to be 0.0039 feet/year. During the most recent 19-year period (1967 to 1985) the rate is estimated to be 0.0072 feet/year. The greater rate of rise during the recent period is partially due to unusually high water levels in 1982 and 1983. These high water levels were associated with an extreme climatic event called El Nino. Neglecting the unusual values associated with all El Nino events during the recent period yields a rate of 0.0059 feet/year, which still indicates that the rate of rise is increasing.

The variability in the determination of the sea level change rate is reduced if the fluctuations in annual sea level are dampened using a smoothing function prior to regression analysis. Consequently, the data was smoothed to remove short-term fluctuations caused by the El Nino-Southern Oscillation effect. The periodic rise in sea level associated with El Nino is included, however, in the analysis of highest estimated tides discussed below.

The acceleration in the rate of sea level rise is considered as follows. The projections of sea level rise are based on the most recent 19-year tidal epoch (1964-1982). Ideally, it would be desirable to update the tidal epoch each year, however, this would be impractical. The magnitude of the change in projected sea level resulting from an annual update in tidal epoch is too small to have practical significance at present. An update of the global sea level change rate every 10 years is appropriate. If and when the rate accelerates significantly, more frequent updating should be carried out. When the new rate is computed for the current 19-year epoch (1983-2001), a new mean sea level associated with the same 19-year epoch must also be computed for use in the projection. The present values of MSL and G (0.0072 feet/year) given in Table 2 are based on the 1964-1982 tidal epoch at the Presidio.

Although the method and data for projecting global mean sea level change are sound, application of the results may be limited by problems with the vertical land motion data, as discussed in the previous section. The values of L presented in this report are based on the best data available at present. These values should be updated as soon as better data becomes available to provide a more accurate prediction of relative sea level change. This is particularly true for the South Bay locations (San Mateo Bridge, Dumbarton bridge, and Alviso Slough). It is very likely that the rate of subsidence in the South Bay in the future will not be as severe as the historical rate of subsidence.

The proposed method is not recommended for projections in excess of 50 years. Projections for shorter periods are appropriate if consistent with the expected life of a proposed project. The projected mean sea level for the years 2007 and 2037 at the 11 selected tide stations on the Bay are presented in Table 2, and displayed on Figure 7. The projected relative sea level change to the year 2007 for the Bay indicates a rising sea level, with a low increase of 0.37 feet at Sausalito and a high increase of 2.78 feet at Alviso Slough.

Table 2
Mean Sea Level Projections

Location	MSL Present (Ft;NGVD)	G Present (Ft/Yr)	L Present (Ft/Yr)	MSL 2006 (FT;NGVD)	MSL 2036 (FT;NGVD)
Pittsburg	1.00	0.0072	-0.0090	1.32	1.81
Benicia	0.64	0.0072	-0.0055	0.89	1.28
Sonoma Creek	0.78	0.0072	0	0.92	1.14
Point Orient	0.40	0.0072	-0.0020	0.58	0.86
Sausalito	0.30	0.0072	0.0037	0.37	0.48
Presidio	0.29	0.0072	0	0.43	0.65
Alameda	0.36	0.0072	-0.0014	0.53	0.79
Hunters Point	0.39	0.0072	0	0.53	0.75
San Mateo Bridge	0.39	0.0072	-0.0020	0.57	1.85
Dumbarton Bridge	0.28	0.0072	-0.0154	0.73	1.41
Alviso Slough (Coyote Crk)	0.80	0.0072	-0.0920	2.78	5.76

- Negative sign indicates land subsidence

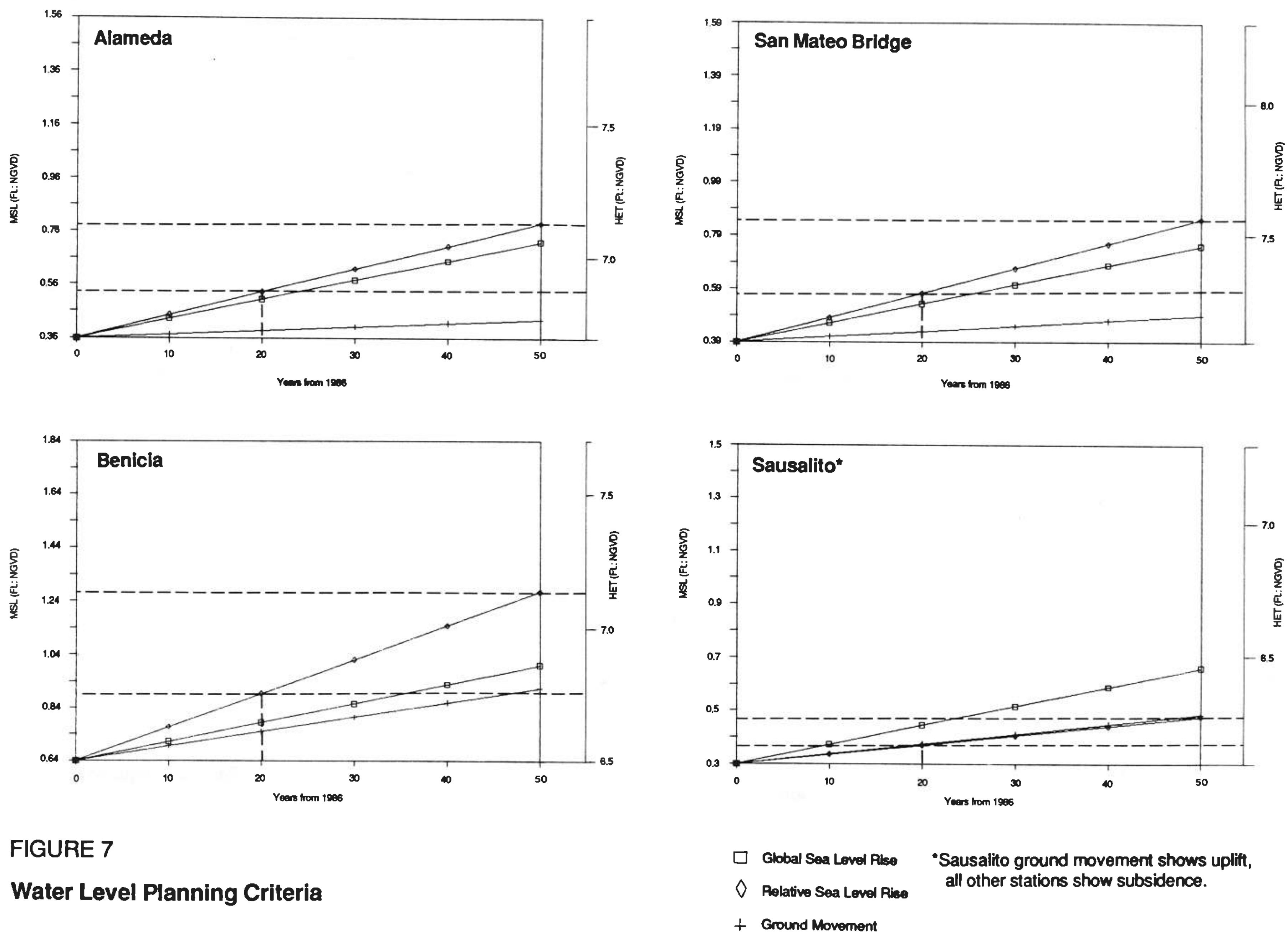


FIGURE 7

Water Level Planning Criteria

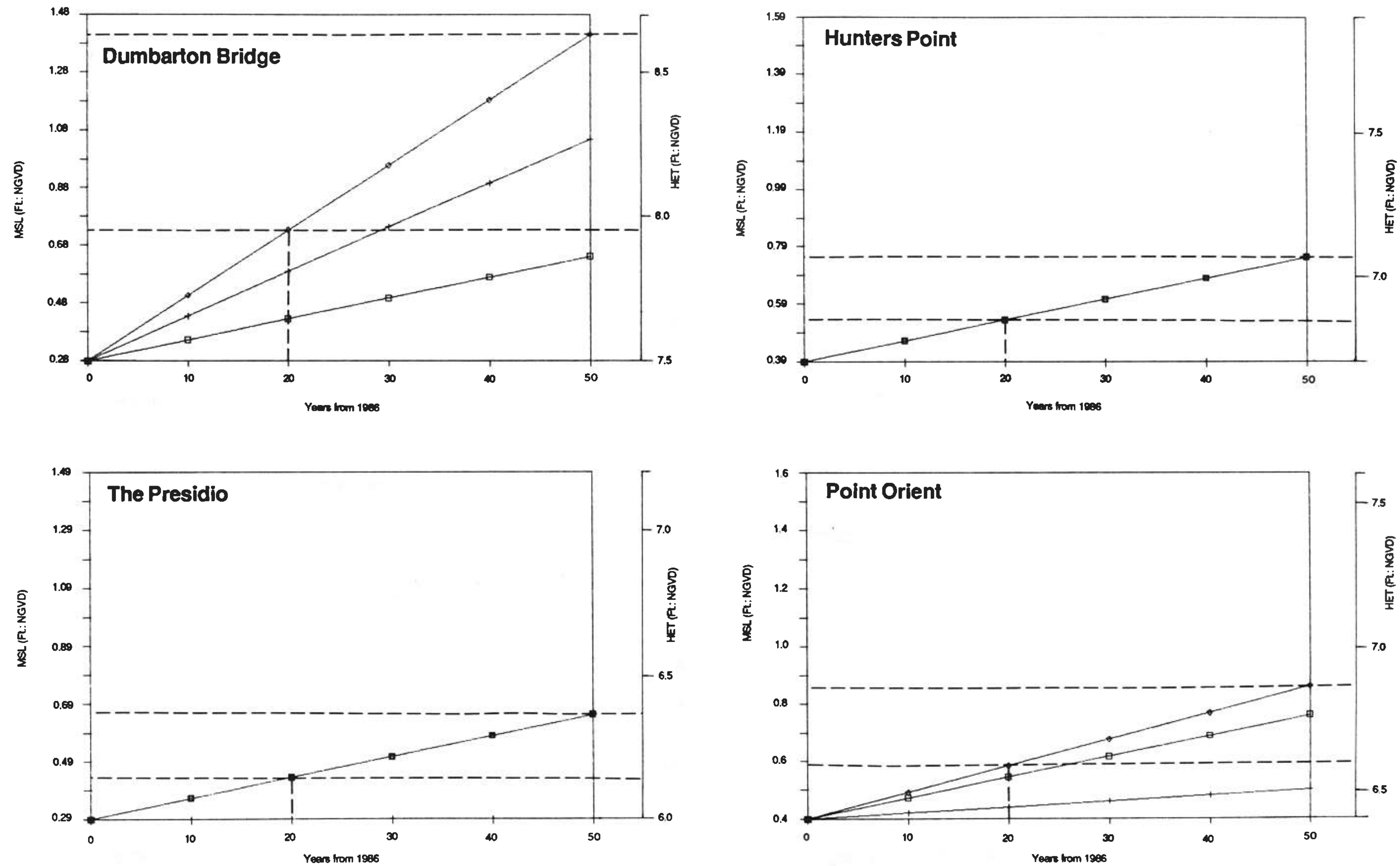


FIGURE 7

Water Level Planning Criteria

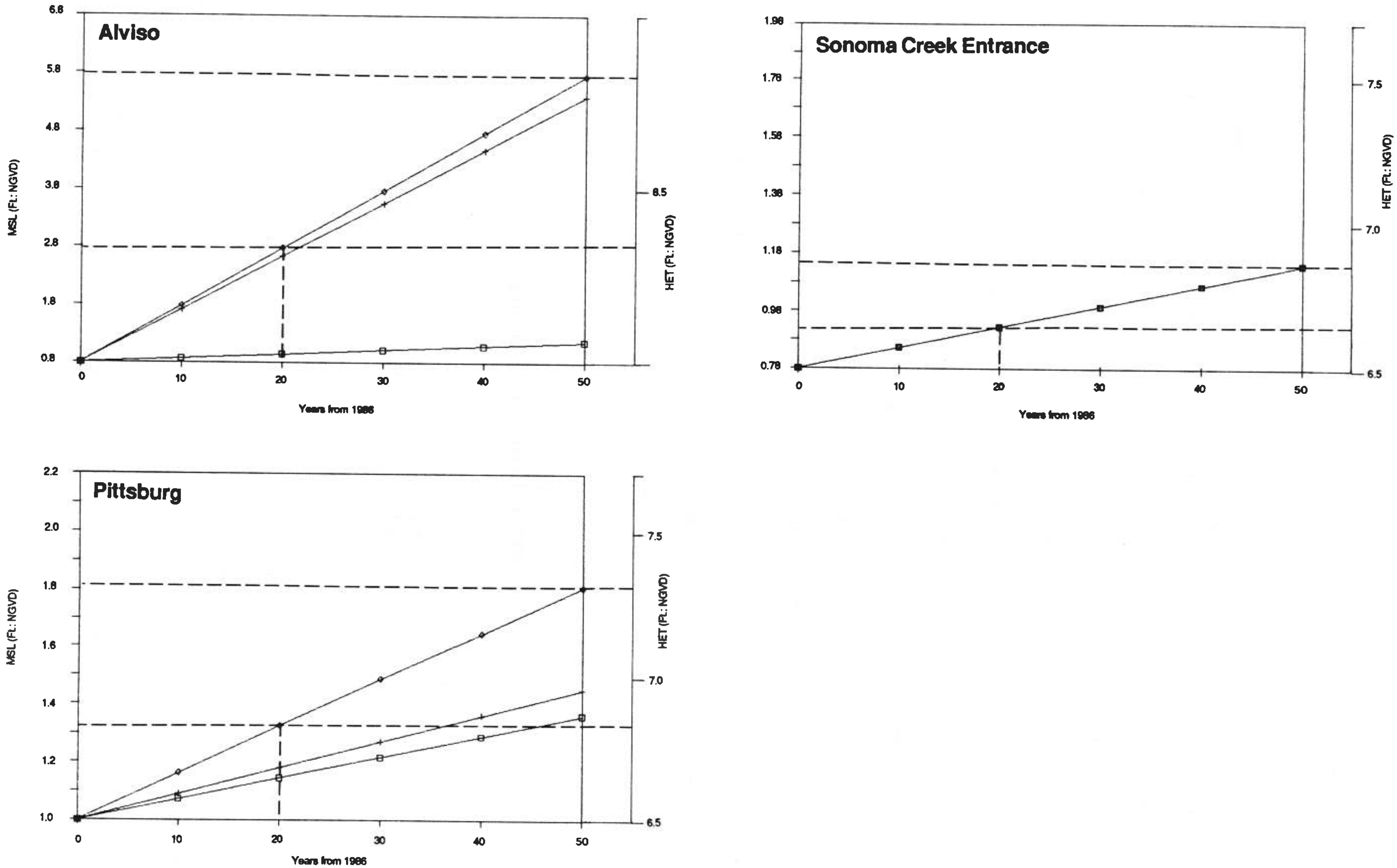


FIGURE 7

Water Level Planning Criteria

2. <u>Projections of High Water Level</u>. The planning criteria for future high water levels on the Bay are obtained by combining the anticipated sea level change with the highest estimated tide (HET). It is recommended that the HET values associated with a recurrence interval of 100 years as proposed by the Corps of Engineers be used in future projections of Bay high water levels. The values of HET presented by the Corps are referenced to NGVD and must be corrected to reference MSL for computation of the criteria. The extreme high water levels for the 11 tide stations around the Bay for the years 2007 and 2037 are presented in Table 3 and displayed on Figure 7.

The extreme high water level is an estimate of the "still water" level; it does not include the effects of wave action, localized topography or structure influence, or stream runoff that could cause superelevation of the water surface. For locations that are between tide stations, linear interpolation may be used. Once again, limitations on the interpretation of the results apply due to questions concerning the vertical land changes.

Table 3
High Water Level Projections

Location	HET Present FT;NGVD	HET Present FT; MSL	HET 2006 FT;NGVD	HET 2036 FT;NGVD
Pittsburg	6.5	5.50	6.8	7.3
Benicia	6.5	5.86	6.8	7.1
Sonoma Creek	6.5	5.72	6.6	6.9
Point Orient	6.4	6.00	6.6	6.9
Sausalito	6.1	5.80	6.2	6.3
Presidio	6.0	5.71	6.1	6.4
Alameda	6.7	6.34	6.9	7.1
Hunters Point	6.7	6.31	6.8	7.1
San Mateo Bridge	7.1	6.71	7.3	7.6
Dumbarton Bridge	7.5	7.22	8.0	8.6
Alviso Slough (Coyote Crk)	8.2	7.40	10.2	13.2

PART III: IMPACTS TO SAN FRANCISCO BAY WETLANDS

Among the various ecosystems affected by global climate change, coastal wetlands and estuaries of the United States will be especially impacted by rising sea level (Titus, 1986). These ecosystems are among the most productive habitats in the world and are responsible for the production of much of the world's coastal fisheries. This part of the report, prepared by Wetlands Reserach Associates, addresses three areas of concern regarding the impact of a rising relative sea level on the tidal marshes and adjacent diked historic Bay wetlands: (1) the current extent of tidal marshes and other wetlands around the San Francisco Bay estuary, (2) the factors which must be considered in assessing impacts to wetlands by rising sea level, and (3) the projected changes likely to occur within various regions of the estuary.

Current Extent of Wetlands in San Francisco Bay

The U. S. Fish and Wildlife Service mapped San Francisco Bay wetlands in its National Wetlands Inventory program (Peters, 1987). These maps, the most detailed analysis of the estuary's tidal and non-tidal wetlands, are based on USGS topographic quadrangles (7.5 minute) and were drawn from aerial infrared photography taken in May 1985. Over 200 different types of wetlands were mapped using the U. S. Fish and Wildlife Service classification system (Cowardin, et al., 1979). The area of each wetland type was determined using computerized methods (Geographic Information System) by the National Wetlands Research Center in Sliddell, LA.

For the purposes of this report, the extent of four general wetland types was analyzed: (1) mudflat (unvegetated tidal areas); (2) tidal marsh (vegetated tidal areas); (3) diked wetlands (non-tidal wetland areas [exclusive of farmed areas] that are generally within the former boundary of historic tidal wetlands); and (4) salt ponds (including crystallizers and bittern ponds). The Bay estuary was further divided into four segments based on the historic rate of relative sea level rise as determined in Part II of this report. These areas are illustrated in Figure 8. The segments selected were based on the close similarity of projected sea level rise at tide gauge stations reported in Part II and shown in Figure 4. The area of each of the wetland types for those segments is given in Table 4.

Table 4
Areal Extent in Acres for Four Generalized Wetland Types Within the San Francisco Bay Estuary

REGION	MUDFLAT	TIDAL MARSH	DIKED WETLAND	SALT POND
Suisun Bay and Carquinez Straits	4,133	10,084	44,132	0
San Pablo and Central Bays	27,397	17,959	9,248	8,687
South Bay (exclusive of area below Dumbarton Br.)	24,488	5,600	6,562	15,271
South Bay below Dumbarton Bridge	6,771	3,081	2,391	13,304
Totals	62,789	35,287	63,770	37,262

Source: Based on U. S. Fish and Wildlife Service National Wetland Inventory maps.

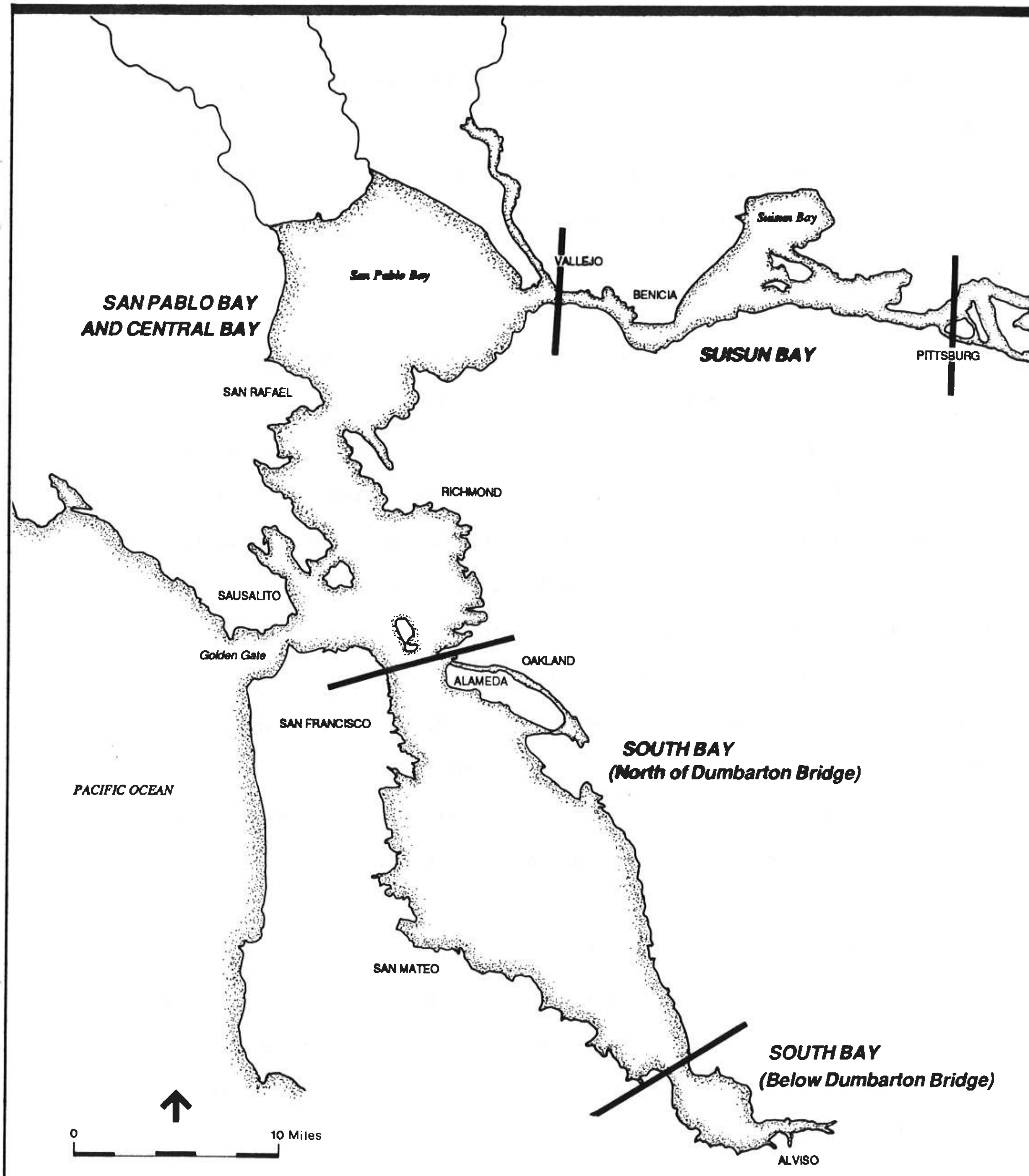


FIGURE 8
Bay Subareas for Wetland Analysis

SOURCE: Wetlands Research Associates, Inc.

For Suisun Bay, the largest component is the diked wetlands which are managed for waterfowl habitat. Nevertheless, there is a substantial amount of tidal marsh, especially along the southern shoreline of the Bay. Many of these wetlands were once diked; however, many of the levees are in disrepair and tidal flows now enter these wetlands.

Mudflats are the most abundant wetland type in the north bay, especially along the northern edge of San Pablo Bay. It is also the location of the highest acreage of tidal marsh, much of it created by hydraulic mining debris in the 1860's. Not clear from the table is the fact that much of the diked historic marshland now farmed, although there is still a substantial amount of diked areas functioning as seasonal wetlands.

In the South Bay, non-vegetated wetland habitats make up the bulk of the acreage. Salt ponds in which water depths are controlled, provide habitat for a number of fish-eating birds, long-legged shorebirds such as avocets and stilts, and migratory waterfowl. Mudflats provide important habitat for short-legged shorebirds such as sandpipers and willets. Vegetated wetlands and diked wetlands each comprise less than 9,000 acres, the smallest acreage of these important habitats for any of the regions in the Bay.

The primary reason for delineating these various regions is that each is subject to varying rates of sea level rise as determined in Part II of this report. The Suisun Bay region is experiencing a local relative change in sea level averaging + 0.01 ft/yr, the north bay and central bay region is +0.004 ft/yr, the South Bay above Dumbarton Bridge is + 0.005 ft/yr, and the area below Dumbarton Bridge is + 0.057 ft/yr. These are average rates and, of course, subject to variability for individual sites. In addition, the rates are averaged over a 50-year period when actually they probably fluctuate, with a relatively stable period up to the 1950's and a more rapid period of relative rise since that time. Nevertheless, the data indicate that historically the South Bay region has experienced the most rapid increase in relative sea level rise in the recent past and the central Bay the least.

Before discussing the implications of sea level rise on wetland habitats, one must first address the factors which affect the response of wetland systems to changing water levels.

Factors Affecting the Maintenance of Tidal Wetland Systems During Sea Level Rise

The evolution of tidal wetlands in San Francisco Bay has been the result of a gradual inundation of low-lying areas balanced by sedimentation. Inundation due to the melting of glaciers has been the major cause for a rise in sea level in the past 10,000 years. There have been two phases in the rate of rise during this period. From approximately 10,000 years before present (YBP) to 7,000 YBP, sea level rose at an estimated rate of 0.06 ft/yr (Atwater, et al., 1977). At this rate, vegetated wetlands were rapidly inundated and converted to mudflats and subtidal areas. Atwater, et al. (ibid) estimated that the sea advanced across the valley floor in the vicinity of South San Francisco Bay at a rate of 100 feet/year. After 7,000 YBP, the rise in sea level slowed to the estimated current rate of 0.006 feet/year. During this phase of sea level rise, extensive marsh development occurred as sedimentation elevated the surface of mudflats. Once above mean sea level, these areas were rapidly colonized by vegetation typical of our present day tidal marshes. In some cases, such as the western Delta, peat over 60 feet thick provides evidence of the ability of marsh plants to maintain intertidal elevations in relation to rising sea level.

Current scenarios for global climate change place the average rate of sea level rise at between 0.01 to 0.07 feet/year which would be in the order of magnitude of that experienced 8,000 to 10,000 YBP. However, the rate of sedimentation will be a key factor in determining whether tidal marsh surfaces are maintained or are inundated and converted to deeper water habitats. At present, there is very little information on rates of sedimentation within tidal marshes. Generally, marshes undergo a great deal of seasonal variability dependent upon tidal elevations of the marsh and input from river runoff. Within a cordgrass dominated marsh, Josselyn and Buchholz (1984) observed seasonal changes in elevation due to sedimentation and erosion that exceeded the elevational change observed over the preceding seven years. Lower elevations within tidal marshes exhibit the greatest rates of sedimentation which then decrease rapidly with height above sea level (Krone, 1982).

Areas which are experiencing a rapid rise in relative sea level may actually accumulate more sediment than those undergoing more gradual decline. In an unpublished study by Dr. William Patrick (Louisiana State University, Baton Rouge) within south San Francisco Bay, sedimentation in a tidal marsh near Alviso has been able to counter a 3.0-foot relative rise in sea level caused by groundwater withdrawal over the period of 1955 to 1985. At a tidal marsh near Palo Alto where subsidence is considerably less, sedimentation is less than 0.5 foot during the same time period. Although the vegetation composition at the Alviso site appears to have remained the same, the Palo Alto site has exhibited a shift from pickleweed to cordgrass, the latter species more tolerant of submerged conditions.

Similarly, diked wetlands which have subsided and are subsequently restored to tidal action rapidly accumulate sediment in the deeper portions of the site. In the Hayward Regional Shoreline salt marsh restoration, most of the excavated channels and basins are now filled with sediment to approximately mean sea level. Josselyn and Buchholz (1984) measured sedimentation rates within tidal marsh channels of the Muzzi Marsh ranging between 0.3 to 1.0 feet/year. There is probably a threshold in size and depth in which sedimentation cannot restore former intertidal elevations. A number of Delta wetlands have been submerged (e.g., Sherman and Frank's Tracts) and none have had any substantial spread of tidal marsh vegetation over subsided areas.

The major source of sediment supply to the Bay tidal wetlands is the Sacramento and San Joaquin Rivers. The amount of sediment entering the Bay is directly related to total river discharge (Krone, 1979). Prior to extensive water development in the state, the estimated annual sediment supplied to the Bay via the Delta was 3.3 million tons/year. By 1990, with projected water development, sediment supply will be only 1.8 million tons/year, a 45 percent decrease. Supply from local streams is estimated at 1 million tons/year. At present, we have very little information on how this sediment is distributed throughout the Bay and, therefore no ability to project sedimentation rates in wetlands in various segments.

A number of other factors complicate the issue of sedimentation and sediment supply in the future. Decreases in the tidal prism by the diking of wetlands have caused a number of deep tidal sloughs to be converted to emergent marsh. The decreased flow velocities in the channels allow sedimentation to accelerate. Ravenswood Slough is an excellent example of an open water tidal channel that is now a vegetated wetland. Any future changes in tidal prism due to breaching of levees will modify these local conditions. Land management use can also affect local sediment supplies, especially in areas where residential development occurs in steep terrain. Flood control channels tend to direct these sediments to deeper portions of the Bay rather than spilling over into adjacent wetlands. Dredging practices in the Bay may also change the distribution and movement of sediments in the future with the possible redirection of disposal to off-shore locations.

Sediment supply for diked wetlands depends upon their management. The diked wetlands of Suisun Marsh receive some sediment from the Bay during the fall and spring when tidal flushing is allowed. In addition, the peat produced by the marsh plants themselves contributes to marsh surface elevation. Current elevations within the managed wetlands of Suisun Marsh range between -2 to +5 feet, with the majority of the elevations between 0 and +3 feet. In contrast, lands which are farmed and not subject to tidal flow have undergone substantial subsidence. In Collinsville, adjacent to the Suisun Marsh managed wetlands, surface elevations in diked areas range between -6 to -1 feet. In the Delta, farm lands have subsided as much as 20 feet below sea level.

Similarly, in diked areas around San Francisco Bay, current surface elevations are dependent on the local subsidence of the land surface as well as sediment supply. Many diked historic baylands are completely surrounded by levees and therefore do not receive any sediment from either the watershed or the Bay. For example, the New Chicago diked wetland near Alviso has surface elevations of -4 to -1 feet. Other diked wetlands act as flood control basins and therefore, sediment derived from the watershed accumulates within the wetland. These sites exhibit a smaller degree of subsidence.

In conclusion, the key variable to understanding the effect of rising sea level on tidal wetlands is the rate of sedimentation. Based on geologic evidence, wetlands appear to have flourished under conditions when sea level rose at a rate of 0.006 feet/year. At 10 times that rate, vegetated wetlands were apparently rapidly inundated. Estimates for sea level rise due to global climate warming range between these two values. Some evidence suggests that tidal marshes in south San Francisco Bay do accumulate sediments even under high rates of relative sea level rise. However, diked wetlands do not have a significant sources of sediment to counter any increase in sea level. Nevertheless, the response of tidal marshes and diked wetlands throughout the Bay will depend upon local rates of sedimentation for which there is very little data.

Projected Changes to Wetlands in Various Regions of the Bay

For the purpose of comparative discussion in this report, the Bay has been divided into four subareas: Suisin Bay, San Pablo and Central San Francisco Bay, the South Bay north of the Dumbarton Bridge, and the South Bay below the Dumbarton Bridge. These areas are shown on Figure 8 and discussed below.

1. Suisun Bay. The tidal wetlands of Suisun Bay receive sediment directly from the Sacramento and San Joaquin Rivers. Although this source

is declining, sediment supply to these wetlands is likely to be adequate to maintain their elevations as under the lower scenarios of sea level rise. The current rate of sea level rise is approximately 0.01 feet/year which is at the lower range of the projected increase due to climatic warming. Under these conditions, tidal wetlands have remained essentially stable.

A complicating factor is that as fresh water inflow decreases, the tidal marshes will be converted from tule-dominated systems to cordgrass and pickleweed. Tules grow at lower tidal elevations and their stem density is greater than cordgrass. As a result, tules tend to accumulate and hold sediments better. If these wetlands shift towards salt marsh, it is likely that their ability to trap and hold sediments will be reduced. Under these conditions, erosion and submergence of wetlands will increase under rapid sea level rise.

Unlike the Delta islands, the elevations within the diked managed wetlands of Suisun Marsh are at or above sea level. It is likely that these areas can be protected with higher levees, if individual duck clubs can afford the cost. There is some evidence that duck clubs will abandon areas where levee maintenance cost is too high as has occurred on the islands within Suisun Bay. Some of these areas have reverted to a mixture of open water and tidal marsh which has provided valuable fish and wildlife habitat.

The most significant problem for the managed wetlands will be the penetration of salt water into the marsh. The present and planned water management structures to facilitate the use of fresher brackish water in management of the Marsh are being built under the assumption of static or low rates of sea level rise. Salt water intrusion will require additional structures and diversion canals to move fresh water from further upstream into the marsh. Another problem will be that pumps will be required to drain many of the duck clubs as sea level rises. Thus, although it may be feasible from an engineering standpoint to protect the managed wetlands, the economic cost may be too high.

2. San Pablo and Central San Francisco Bay. A substantial portion of the Bay's mudflats and tidal marshes are located within this segment of the Bay. This region appears to have the lowest rate of relative sea level change over the past 50 years. Many of the tidal marshes were created by excessive sediment deposits caused by the hydraulic mining in the Sierra Nevada Mountains during the 1860's. However, most of the sediment from this source has now moved out towards the deeper portions of the Bay (Krone, 1979). In addition, as fresh water inflow decreases, sediment supply to San Pablo Bay will decrease.

A number of communities along this portion of the Bay were build over historic tidal marsh, e.g., Corte Madera, San Rafael, and Bel Marin Keys in Marin County and Foster City and Redwood Shores in San Mateo County. Subsidence of the land in conjunction with rising sea level will subject these cities and towns to greater flood risk. To protect homes and businesses, levees and flood control basins are proposed or are being constructed. These proposals can have a significant impact on tidal wetlands by eliminating or reducing tidal flows. As a result, they will be cut off from their primary sediment supply, causing further reduction in surface elevations.

The conversion of tidal marshes to mudflats would significantly impact a number of endangered species in the North Bay. Most of the diked areas are used and managed for agriculture and consequently do not provide suitable habitat for endangered species such as the clapper rail, black rail, and salt marsh harvest mouse.

It is premature to predict the consequences of sea level rise for this segment of the Bay as not enough information is available concerning sedimentation in the area.It is likely that resuspension of sediment in the water is a major mechanism for the redistribution between tidal marshes, mudflats, and deeper water. The Central Bay and the Pacific Ocean serve as major sinks for redistributed sediment and should to be considered in this evaluation.

3. South Bay (north of Dumbarton Bridge). The mudflats and salt ponds of the south bay, as with mudflats throughtout the Bay and the salt ponds in the north Bay, provide an important habitat for migratory birds during the fall and spring. Sea level rise is not likely to significantly change the area of these habitats unless levees are abandoned around the salt ponds. Diked, seasonal wetlands are less threatened by sea level rise however tidal marshes are likely to suffer significant loss. Only 5,600 acres of tidal marsh remain in this portion of the Bay.

Krone (1979) determined from bathymetric data that the south Bay was losing sediment. Erosion along the eastern shoreline of the Bay has been noted in a number of areas from Alameda to Newark in Alameda County. In some cases, a substantial amount of tidal marsh has been lost (T. Harvey USFWS, pers. comm.). Cordgrass, the plant species which grows at the lowest elevations in south Bay tidal marshes, does not grow as robust here as in the north Bay. Its ability to trap and hold sediment is therefore reduced and in many areas undergoing rapid erosion, cordgrass is absent and the pickleweed vegetation is being undermined by wave action.

The loss of tidal wetland has occurred despite a relatively low rate of sea level rise this past century. It is likely that with increased rates due to climatic warming, the amount of tidal marsh in this segment will decrease substantially. The consequences will be severe to both endangered wildlife species as well as other birds and mammals that dependant on tidal marshes for their habitat.

4. South Bay (below Dumbarton Bridge). Although small in overall area compared to the other segments of the Bay, this region has a substantial acreage of tidal marsh and diked wetland. Sedimentation appears to be relatively rapid and many of the tidal marshes have been maintained despite the largest increase in relative sea level for any of the Bay segments. In fact, marinas constructed near Alviso and Palo Alto are being closed because silt deposited in the area builds up so rapidly that the cost of maintainence has become prohibitively expensive. [The current elevation in the Alviso marina is +2 feet. It was dredged to over -4 feet less than 10 years ago.] A large portion of the Bay's salt ponds are located in this region. The maintenance of the levees by the Leslie Salt Company has kept the salt ponds functional and they continue to support a large population of waterbirds.

Diked wetlands not used for salt production have undergone substantial subsidence and, consequently, their wildlife habitat value has deminished. For example, the New Chicago marsh in the Alviso area of San Jose is -2 to -3 feet below mean sea level. Rainwater and tidal water introduced via water control structures cannot be pumped out and salt accumulates in the soil. This has lead to degradation of the salt marsh vegetation and loss of wildlife habitat value. If these sites were opened to tidal action, they would revert to open water and mudflat habitats. The importance of diked wetlands for migratory waterfowl and the salt marsh harvest mouse may be reduced if degradation of the habitat is accelerated by sea level rise.

Recommendations

We have two types of recommendations: (1) actions to take in the review of permits dealing with wetland mitigation, and (2) activities to conduct to further refine the impacts of a rapid sea level rise.

Permit applications which either modify existing wetlands (including salt ponds) under the Commission's jurisdiction and/or propose wetland mitigation should include the following:

1. An assessment of how increased sea level will affect the project proposal. It seems prudent to accept a current sea level rise of between 0.005 to .05 ft/yr as a planning range. The exact assessment will depend on the project proposal but may include: .

    a. Current elevations of the project site and recent history, if known, concerning the rate of relative sea level rise.

    b. Current rates of sedimentation, if known, for the project site or sites nearby.

    c. Estimated rate of sea level rise for the project site.

    d. Projected changes in the wetland community due to sea level rise. This should also include information on the surrounding area as well.

    e. Projected hydraulic changes around on the project site that will result in a change in tidal heights, duration of ponding, drainage, erosion, or sedimentation.

f. Levee heights around project site necessary to protect surrounding development from flood tides as estimated for at least a twenty year period.

2. The permit should include design criteria to accommodate an increase in sea level. Such design criteria may include:

a. For projects which modify water regimes on diked wetlands, demonstrate ability to operate system under future estimated sea level over the life of the project.

b. For tidal marsh mitigation projects, include features which will allow natural sedimentation to maintain marsh elevations. For instance, a narrow dike breach instead of completely removing the surrounding dike would be more conducive to sedimentation.

c. Armor critical dikes and levees within a project site to reduce erosion due to high storm waves.

d. Project sites should include a permanently installed bench mark so that elevations can be checked during the project life.

Given the uncertainty over the future rate of sea level rise, the Commission should initiate a number of planning efforts.

1. A study of sedimentation in San Francisco Bay to include information on rates of sedimentation and/or erosion in shallow regions such as mudflats and tidal marshes.

2. Discussions with the Corps of Engineers and Flood Control Districts to determine ways to allow flood overflows into wetlands, particularly diked areas. This would provide some sediment to these areas that are now cut off from their primary supply, the Bay itself. These discussions may also include consideration of dredge spoil disposal within

diked wetlands. Such disposal would have to be considered carefully to avoid or reduce impacts to existing wildlife use. Only diked wetlands in regions of the bay undergoing the most rapid change in sea level, i.e. south bay south of Dumbarton Bridge, should be considered for such action.

3. Undertake of review of potential mitigation sites in the south bay to determine the areas which might be feasibly returned to tidal action to balance losses in tidal marshes anticipated from inundation by rising sea level.

4. Review economic feasibility of maintenance of levees around duck clubs in Suisun Marsh.

5. Regularly review changes in endangered species habitat for various regions of the Bay. In areas undergoing rapid changes in relative sea level rise, monitor habitat loss due to erosion and inundation and consider out-of-kind mitigation to restore these critical habitats. For example, the excavation of mudflat for the construction of a marina might be better mitigated by the creation of intertidal marsh habitat in a region where marsh loss is projected to be high.

In summary, the effect of global climate change will have a myriad of effects on life in the Bay area. The economic cost will be high and there will be considerable pressure to protect human over natural resources. The Commission can play an important role in planning for this change so that the impact to the Bay's critical wetland habitats will be minimized.

PART IV: ENGINEERING DESIGN PROCEDURE FOR PROTECTION OF SHORELINE STRUCTURES FROM HIGH WATER LEVELS AND WAVE ACTION

In order to authorize a project in the Bay, the Bay Commission, must be able to find the proposed project to be safe from the undue risks of flooding in addition to other safety hazards such as earthquakes. This section of the report, prepared by Moffatt & Nichol, Engineers sets out a procedure that the Bay Commission and local governments can use in their permit procedures to assure the reasonable safety of structures and shoreline protective devices build in the Bay or in low-lying shoreline areas from the dangers of tidal flooding including consideration of a rise in relative sea level. It presents a model project review procedure with design criteria for protection of shoreline structures from high water levels and wave action. The process provides the project applicant, the Bay Commission, and local governments a model for use as a basis for evaluating whether a structure or protective device is designed in accordance with sound engineering flood protection principles. This model can be modified to suit the particular needs of individual agencies. Because this section addresses engineering design matters, it is highly technical.

The design review procedure and criteria presented in this section incorporate the estimates of future sea level changes and extreme high water levels around the Bay developed in Part II. Under the proposed process, five kinds of data are required when designing or considering a project: still water level, shoreline erosion, near shore slope, wave characteristics, and wave runup level. Because each site has its own unique characteristics, uniform specific engineering design standards cannot be provided. Each project applicant would be responsible to develop and furnish the required engineering design information as part of the proposed project design and application process.

The design review procedure and applicable criteria for protection from flooding are presented in the following section entitled Design Review Procedure. This recommended step-by-step procedure would assist a project review agency in the analysis of a proposed project for conformance with the flood protection engineering design criteria. The flow diagram used to illustrate this procedure, Figure 10, could be incorporated into the Bay Commission's or a local government's permit and project review procedure.

In reviewing the performance of a proposed structure, two design objectives must be satisfied; acceptable structural behavior and acceptable functional behavior. The performance objectives are usually evaluated with respect to the extreme conditions that may be anticipated. Structural behavior refers to the ability of the structure or protective device (such as a levee or sea wall) to survive extreme conditions such as extreme high tides or strong wave action. Functional behavior refers to the ability of the structure or protective device to produce the desired effects, i.e., to prevent flooding, protect from wave impact, or protect from erosion. The procedure recommended in this report is primarily concerned with functional behavior. Under certain conditions protection for extremely rare events may be compromised when occasional property damage is more acceptable than the construction of a fully resistant structure or protective device. A structure that fails to meet these standards could receive favorable consideration if appropriate justification were provided by the project applicant and the permitting agency agreed that the risk of ocassional damage was minimal.

The recommended design criteria relate to the design of a structure or protective device to withstand high water level and wave action only. All elevations in this report are referenced to the National Geodetic Vertical Datum (NGVD) unless otherwise noted. Aesthetic, ecologic, or geotechnical design standards are not addressed but protection must take into consideration the impact of the design on on nearby property, structures, and Bay resources such as marshes and mudflats. Moreover, with a rising sea level, engineering solutions will likely multiply and waves, currents, and sedimentation and erosion processes may be drastically changed by new structures and protective devices.

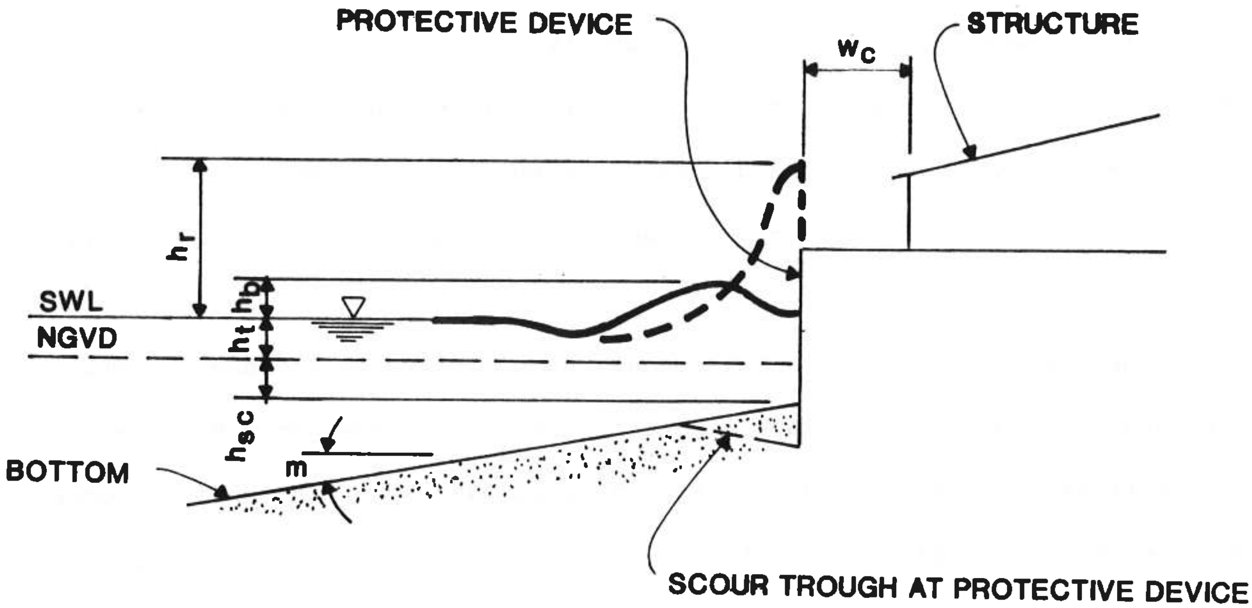
In the event of a conflict between any of the criteria proposed in this report and the standards and regulations of the Federal Emergency Management Agency's (FEMA) National Flood Insurance Program (NFIP), or the building code requirements of a local government, the most stringent requirement should govern.

Design Information

The following information is required to evaluate a proposed structure or protective device:

- o Design Still Water Level (h_t), which includes projected change in relative sea level with time;
- o Design Scour Level (h_{sc}), which also includes any anticipated change with time, and Water Depth ($h_t + h_{sc}$);
- o Beach or Near Shore Slope (m);
- o Design Wave Characteristics, which includes Design Wave Height (h_b), Wave Crest Level ($h_b + h_t$) and Wave Period T;
- o Design Wave Runup (h_r) and Wave Runup Level ($h_r + h_t$).

Figure 9 shows the data in schematic form. A brief description of the required information and its use in design follows.



LEGEND

h_r = WAVE RUNUP

h_b = WAVE HEIGHT

h_t = STILL WATER LEVEL (HIGHEST TIDE ELEVATION) -SWL

h_{sc} = SCOUR LEVEL (LOWEST BOTTOM ELEVATION)

m = BOTTOM SLOPE (RISE: RUN)

W_c = STRUCTURE SETBACK

WATER DEPTH AT STRUCTURE = $h_t + h_{sc}$

WAVE CREST LEVEL = $h_t + h_b$

WAVE RUNUP LEVEL = $h_t + h_r$

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FIGURE 9 DEFINITION SKETCH

1. <u>Design Still Water Level</u>. The design still water level is the mean water surface elevation that would exist if waves were absent. It is the base elevation upon which waves and wave runup are superimposed. The design still water elevation is one of the parameters that must be established to determine the design water depth and, under depth-limited wave conditions, the design wave height. Short- and long-term changes in water surface elevation must be considered. Short-term changes are reversible over the life of the structure or protective device. These are gravity effects caused by astronomical factors, i.e. the tides; by weather factors, i.e. storm surge and wind setup; and climatological factors such as the increased sea level caused by the El Nino-Southern Oscillation. Long-term change, which is assumed to be irreversible over the life of the structure or protective device, is the gradual increase (or decrease) in the mean sea level relative to land.

Tsunamis are not considered in the proposed evaluation because the effect of tsunamis during modern times has not been significant in San Francisco Bay. Nonetheless, extreme water level predictions due to tsunamis are available for San Francisco Bay (WES, 1975). The tsunami effect is not additive to the other water level design parameters because the probability of a tsunami occurring coincidentally with extreme still water and wave conditions is considered negligibly small.

In Part II, the matter of short-term and-long term changes in water level was discussed in detail, and the procedure for predicting high water levels on San Francisco Bay was presented. The results are summarized in Table 5, which gives the design still water level associated with an extreme high tide whose recurrence interval is estimated to be once in 100 years. This recurrence interval is frequently adopted for engineering design; however, other levels may be utilized if appropriate justification is furnished by the proposed project engineer. The values are given for nine tide station locations on the Bay, and for project lives of 20 years (2007) and 50 years (2037). The time dependence is necessary because the high water levels include the effect of long-term changes in mean sea level relative to land. Intermediate values (spatial and temporal) may be interpolated.

Table 5
Design Still Water Levels at Selected San Francisco Bay Locations Projected to Years 2007 and 2037

	Still Water Level	
Location	2007 (Ft;NGVD)	2037 (Ft;NGVD)
Pittsburg	6.8	7.3
Benicia	6.8	7.1
Sonoma Creek	6.6	6.9
Point Orient	6.6	6.9
Sausalito	6.2	6.3
Presidio	6.1	6.4
Alameda	6.9	7.1
Hunters Point	6.8	7.1
San Mateo Bridge	7.3	7.6
Dumbarton Bridge	8.0	8.6
Alviso Slough (Coyote Creek)	10.2	13.2

2. Design Scour Level. The design scour level is required to determine the design water depth for a structure or protective device, as shown on Figure 9. The water depth is used to define the depth-limited breaking wave height and hence the wave crest and runup levels on a structure or protective device.

The scour level is also necessary to determine the embedment depth for certain types of structures that cantilever from the bottom, or that are supported on piles. Finally, it is necessary for structures that depend on toe support for stability, or must retain soil behind them without losses under the structure.

Shoreline scour is often reversible in that the sediments lost during a storm may be partially or completely restored after the storm. In the short term, the maximum scour level will usually occur as a result of storm activity. For design in areas where a long term trend in shoreline erosion or accretion is occurring, it is necessary to couple the short term scour estimate with the long term trend in scour level. The scour level determination is therefore analogous to that for the still water level, because it is dependent on both geographic and temporal parameters. Although the sediment transport mechanisms and magnitudes vary depending on whether the shoreline is characterized by fine grained (mud flat and marshland) or coarse grained (beach) materials, the requirement to determine a design scour level remains unchanged.

The design scour level is also dependent upon whether a protective device is located near the shoreline. A trough will usually form at the toe of a protective device during a storm lowering the normal ground level. The dimensions of the trough are governed in a complex way by the type of protective device, the beach material and the storm wave characteristics. General guidance for estimating the depth of scour is provided in the Shore Protection Manual (CERC, 1984). The scour depth, particularly in beach sand, can be significant. Consequently, a rock blanket with adequate bedding material bayward of the toe of the protective device is often provided to prevent this erosion and limit the scour depth.

The scour trough at the toe of a protective device would probably not significantly increase the design wave height. Unless the nearshore slope is very steep, depth limiting conditions bayward of the trough would allow a breaking wave height only slightly higher than that determined without the trough. However, the additional scour depth represented by the trough must be considered when evaluating the structural performance of the protective device.

3. Nearshore Slope. When the water depth is used to determine the depth-limited wave height, it is also necessary to provide the nearshore slope. The slope may be obtained from National Ocean Survey Charts, U.S. Geological Survey "Quad Maps", or survey profiles taken for the specific purpose of the proposed project. The nearshore slope should be defined for a distance of at least seven times the wave height from the toe of the structure or protective device.

4. Design Wave Characteristics. The design wave height, period and direction are used to establish the design wave load on a structure or protective device. They may also be used to calculate the wave runup level, and the quantity of wave overtopping. The determination of the design wave parameters is a complex matter, requiring an understanding of the physics of wave generation, propagation and decay, as well as wave modification due to processes of diffraction, refraction and shoaling. The matter is discussed in detail in the Shore Protection Manual (CERC, 1984). The selection of an appropriate design wave also involves consideration of the recurrence intervals associated with storms of differing intensity levels, and the joint probability of occurrence of the design still water level with the design wave conditions.

The complexity of the wave hindcast analysis, as well as that of the meteorologic and physiographic conditions of San Francisco Bay, suggest that a pre-determined table of design wave characteristics to suit all types of projects is not practical. Each project should be considered on an individual basis with a design wave analysis performed for the specific conditions associated with the project. The following typical, cases may be used to help evaluate the appropriateness of the design wave characteristics developed for a specific project:

a. CASE A. This case assumes that the design wave is a depth-limited breaking wave. The height of the breaking wave can be calculated when the water depth and slope in front of the structure or protective device are known. The design water depth, as shown in Figure 1, is the sum of the design still water level and scour level, both taken for the worst condition anticipated during the design life of the structure or protective device. The wave period to be used for the analysis is dependent upon the wave exposure of the particular site, and will vary from one location to another; use of a longer wave period is justified because as wave period increases, the breaking wave height increases for a given water depth. The resulting breaking wave height represents the extreme condition for design of the structure or protective device. The recurrence interval for this wave condition will exceed that associated with the still water level alone (usually 100 years) because of the combined probability of occurrence of the extreme water level coincident with the storm event capable of producing the extreme wave height. In order to more closely approximate a design event whose combined recurrence interval is about 100 years, the level accepted for design in many applications, additional Cases B and C may be investigated. These cases require probabilistic analysis of extreme wind speeds and hindcast analysis of wind generated waves.

b. CASE B. This case assumes that the design wave is not a depth-limited wave, but is limited by the available fetch for wave generation. The recurrence interval for the storm winds in the fetch direction is about 10 years. The resultant wave condition is superimposed on the still water level whose recurrence interval is 100 years, and the height of the wave at the shoreline is determined by appropriate transformation of the offshore waves. The wave period to be used in the analysis is the peak spectral period determined by the wave hindcast analysis. In the event that the analysis indicates that the design wave is a depth limited breaking wave, this case becomes identical to Case A.

c. CASE C. This case also assumes that the design wave is not a depthlimited wave, but is limited by the available fetch for wave generation. The recurrence interval for the storm winds in the fetch direction is about 100 years. The resultant wave condition is superimposed on a still water level equal to the mean high tide plus an allowance for wind setup. The height and period of the wave at the shoreline is determined as in Case B.

The wave crest level is used to define the elevation below which a structure or protective device is exposed to dynamic wave forces. Using a conservative approach, the design wave crest level is the sum of the design wave height and the design still water level as shown on Figure 8. This approach is appropriate for breaking wave conditions, but may be unduly conservative for non-breaking waves. Other approaches may be utilized if appropriate justification is furnished.

5. <u>Design Wave Runup Level</u>. Wave runup is the rush of water above the still water level on a beach, structure, or protective device after a wave has broken. Flooding of shoreline areas can be caused by a high still water level and only moderate wave action, which often produces extreme runup levels. With reference to the cases discussed in the previous section, although Case C can produce the controlling wave conditions for the determination of wave loading, Case B will typically produce the controlling wave conditions for wave runup (unless the most conservative, Case A, is utilized).

Wave runup is also a function of the wave period, and the characteristics of the shoreline, including the structure or protective device if present. Runup calculations should be performed for a range of wave periods that include the peak spectral period, to help in determining the greatest runup level, which will not necessarily occur for the maximum wave period. Several methods are available to estimate wave runup; the Shore Protection Manual (CERC, 1984) describes the most common methods, which include allowances for wave setup and scale effects, since much of the runup estimation is based on extrapolation of scale model test results. Alternative methods may be utilized if appropriate justification is furnished.

The wave runup level is used to define the elevation below which a structure or protective device is exposed to wave flooding. Although dynamic wave forces are not considered in this case, water velocities may still be significant due to the forward momentum of breaking waves. The runup level is the sum of the wave runup and the design still water level as shown on Figure 9. If a protective device is overtopped by wave runup, a structure may be protected from flooding by providing an adequate distance between the protective device and the structure. The required distance is a function of the type of protective device, and is termed "setback", as shown on Figure 9.

Again, other approaches may be utilized if appropriate justification is furnished.

Design Review Procedure

The design data discussed in the previous section is utilized in the following design review procedure to determine if a proposed structure or protective device conforms to the proposed standards for protection from high water levels and wave action. The procedure would apply to a structure in the Bay, such as a strucure on pilings or on the shoreline and accomplishes the following functional design objectives:

- o Protect structure from wave impact damage;
- o Protect structure from flood damage;
- o Protect structure from erosion of underlying soils;
- o Minimize adverse impacts on adjoining properties/structures resulting from construction of the proposed structure.

The review procedure should be used in the step-by-step order as shown on the Flow Diagram, Figure 10, and discussed in Review Procedure below. The design standards are summarized on Table 2, and discussed in the following Design Standards section. Note that standards related to earth forces are not addressed, and must be covered by a geotechnical investigation. Similarly, standards related to aesthetic and ecologic issues are not addressed, but as with a geotechnical evaluation, must be part of any comprehensive project design and evaluation.

The design review procedure may be applied to all structures and protective devices for which an application may be made to the Bay Commission or a local government. The safety standards for a proposed project for protection from high water levels and wave action apply as well to structures within the Bay Commission's "Bay" jurisdiction as well as upland areas over which local government has additional flooding safety authority.

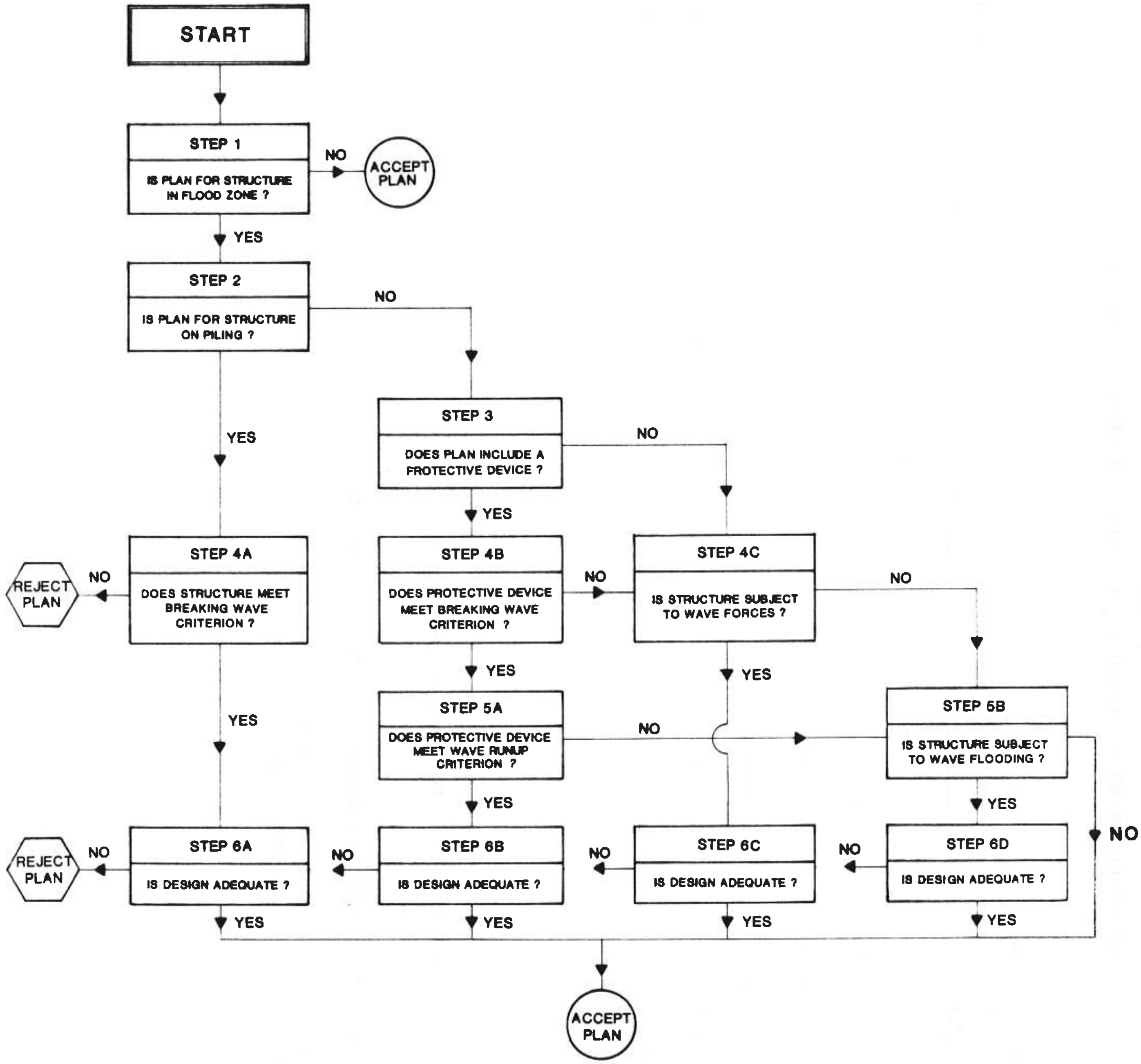

FIGURE 10 PLAN CHECK FLOW DIAGRAM

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Table 6
Recommended Engineering Flood Design Standard Summary[1]

Type	Exposure	Protective Protective Device	Structure Device Crest	Lowest Floor	Structure Setback[6]	Design Requirement for Structure
1	Dynamic Wave Forces on Struct.	None	-	$H_s<h_t+h_b$[4]	-	Unacceptable
		Bulkhead[2]	$H_s<h_t+h_b$	-	-	Elevate
		Revetment[3]	$H_s<h_t+h_b$	-	-	Elevate
2	Flooding W/ Dynamic Ways Forces on Struct.	Bulkhead[2]	$H_s<h_t+h_r$	-	$W_c<h_t+h_r-H_s$	Flood Proof
		Revetment	$H_s<h_t+h_r$	-	$W_c<2.5(h_t+h_r-H_s)$	Flood Proof
		Levee	$H_s<h_t+h_r$	$H_f<h_t$[5]	-	Flood Proof
3	None[7]	All	-	-	-	None

Notes:

[1]See Figure 9 for symbol legend and Figure 2 for review procedure.
[2]Bulkhead with smooth, vertical wall.
[3]Revetment with rough, 1.5:1 slope.
[4]H_s is level of bottom of lowest horizontal member supporting the lowest floor.
[5]H_f is level of lowest floor.
[6]W_c is structure setback; minimum setback is 10 feet.
[7]All exposures that do not meet criteria for Type 1 or Type 2.
h_t Still water level
h_b Wave height
h_r Wave runup

1. Design Standards. The design standards define different levels of protection for a proposed structure, depending on the degree of exposure to high water levels and wave action. The structure exposure (with or without a protective device) is classified in order of decreasing flood risk as one of the following types:

- o Type 1 - Structure exposed to significant dynamic wave forces.
- o Type 2 - Structure exposed to flooding without significant dynamic wave forces.
- o Type 3 - Structure not exposed to flooding or wave forces.

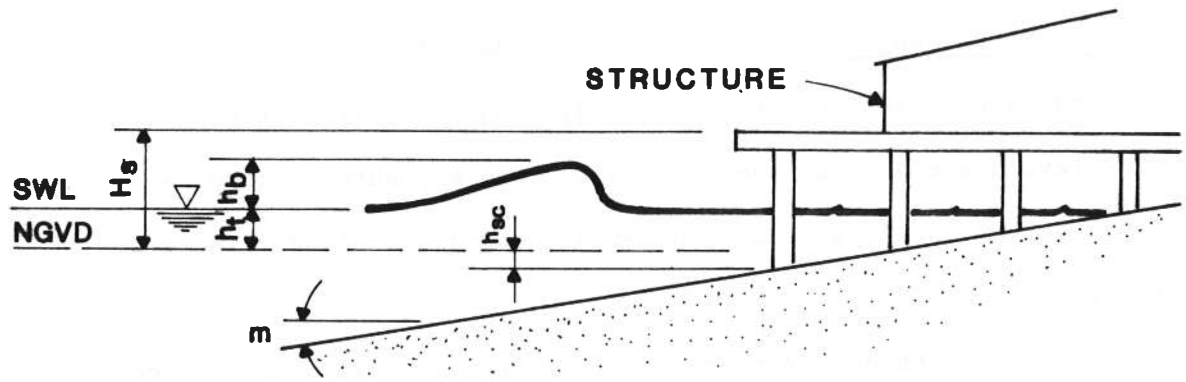
a. Structure Exposure. The criteria that determine structure exposure are:

- o Type 1 - For structures without a protective device, including piers and structures supported on piling, the elevation of the bottom of the lowest horizontal member supporting the lowest floor is below the design wave crest level.

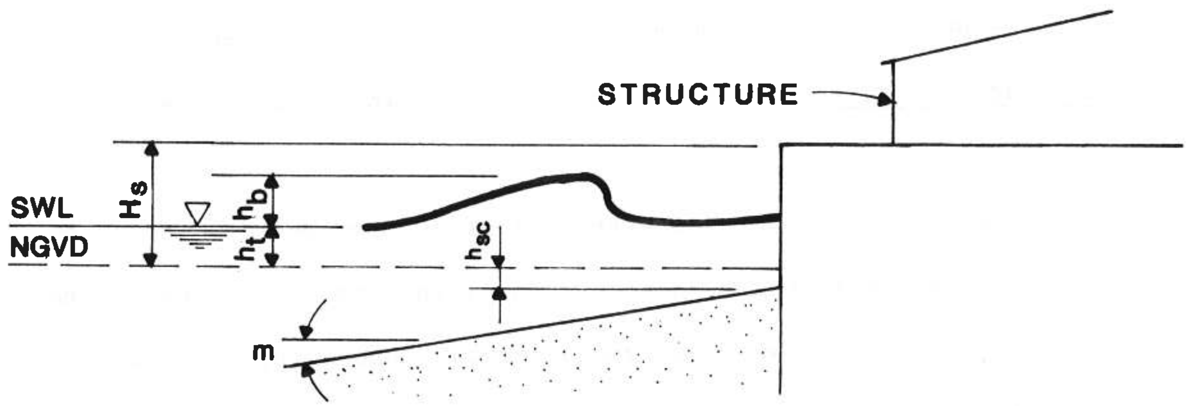
  For structures with a protective bulkhead or revetment, the crest elevation of the protective device is below the design wave crest level.

  These are considered wave crest criteria and are illustrated in Figure 11, (terminal breaking wave criteria in figures), and summarized in Table 6.

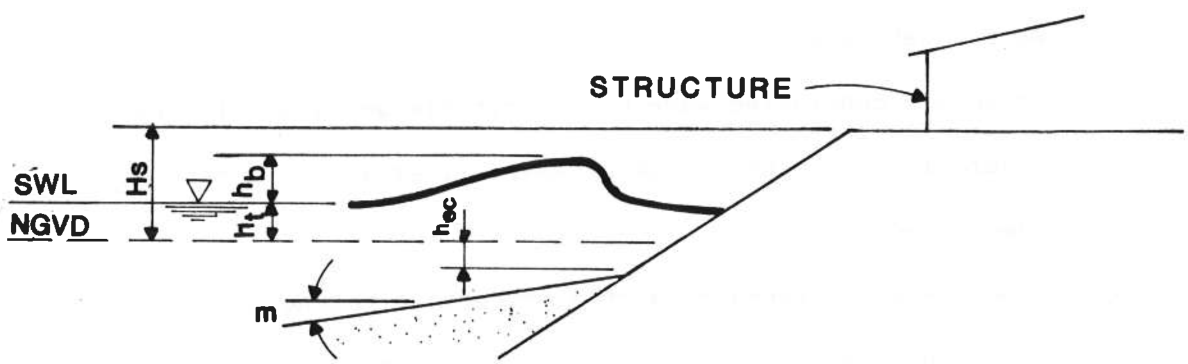
- o Type 2 - For structures with a protective bulkhead or revetment, the crest elevation of the protective device is below the design wave runup level, and the structure setback is less than that required to prevent runup from reaching the structure.



A — STRUCTURE SUPPORTED ON PILING (PIER)



B — PROTECTIVE DEVICE IS A VERTICAL WALL (BULKHEAD)



C — PROTECTIVE DEVICE IS SLOPED (REVETMENT)

LEGEND

H_s = STRUCTURE FLOOR ELEVATION

h_b = WAVE HEIGHT

h_t = HIGEST TIDE ELEVATION

h_{sc} = LOWEST BOTTOM ELEVATION

m = BOTTOM SLOPE

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FIGURE 11 BREAKING WAVE CRITERIA

For structures with a protective levee, the crest elevation of the levee is below the design wave runup level, and the structure's lowest floor elevation is below the design still water level.

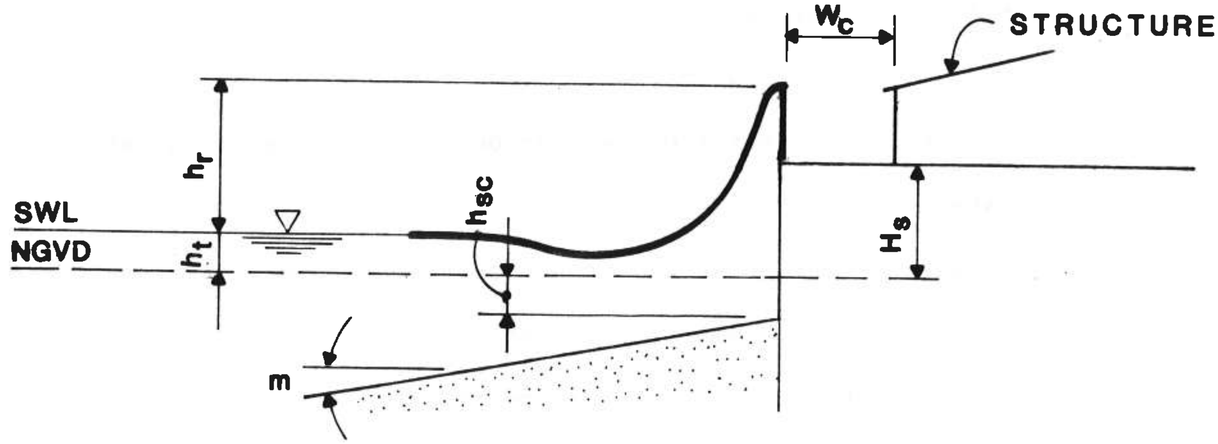
These are considered wave runup criteria and are illustrated in Figure 12, and summarized in Table 6.

- o Type 3 - This includes structure exposures that do not meet the criteria for either Type 1 or Type 2.

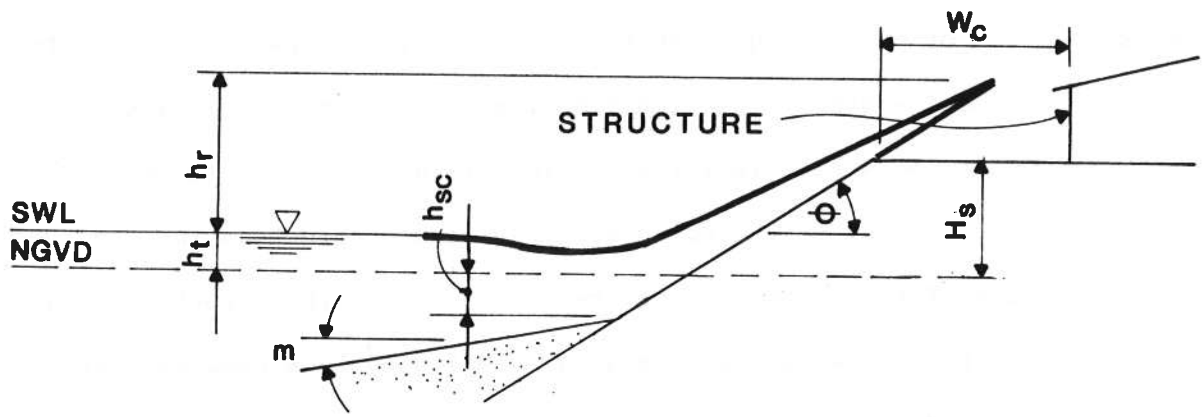
b. Design Requirement Safety Standards. The safety standards, expressed in terms of design requirements for the various exposure types, are:

- o Type 1 - Structures with Type 1 exposure must be elevated so that the structure's lowest floor is above the design wave crest level. Strategies for elevating a structure include the use of fill material, or the use of some form of posts. The use of fill material for elevating a building in a coastal high hazard area is not permitted by the NFIP, but may be appropriate for structures with Type 1 exposure where only moderate wave action is likely. If the structure is raised on fill, design problems that must be addressed include:
  - Type of fill.
  - Compaction and settlement of fill.
  - Protection against erosion of fill.
  - The effect of the fill on flooding of adjacent properties/structures.

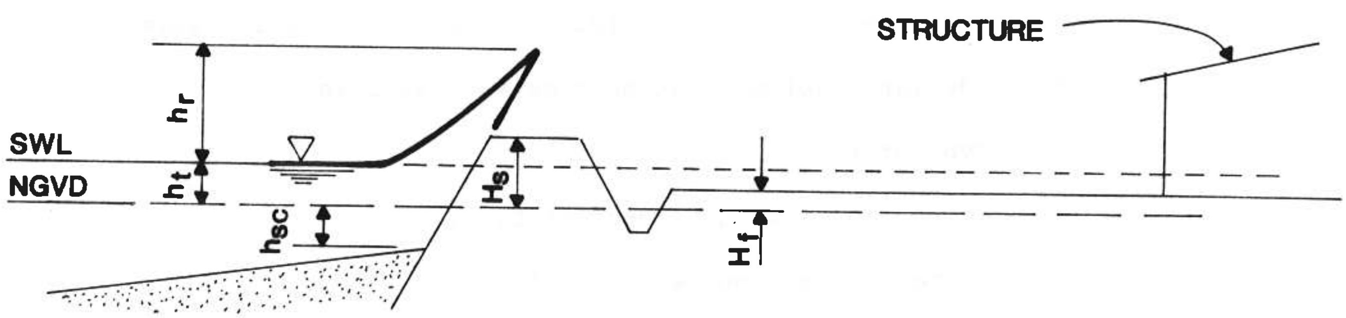
If the structure is raised on posts, piles or columns, which leave the ground level predominantly open, design problems that must be addressed include:



A — PROTECTIVE DEVICE IS A VERTICAL WALL (BULKHEAD)



B — PROTECTIVE DEVICE IS ROUGH SLOPE (REVETMENT)



C — PROTECTIVE DEVICE IS LEVEE

LEGEND

H_s = STRUCTURE FLOOR ELEVATION	h_{sc} = LOWEST BOTTOM ELEVATION
h_r = WAVE RUNUP	m = BOTTOM SLOPE
h_t = HIGHEST TIDE ELEVATION	W_c = STRUCTURE SETBACK

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FIGURE 12 WAVE RUNUP CRITERIA

- Size and spacing of posts to provide adequate support with minimum obstruction.
- Penetration of posts to resist vertical and horizontal water velocity and debris impact loads.

The structure may also be raised on extended foundation walls. However the vertical walls are subject to greater lateral water pressure and must be anchored to prevent displacement. In using any of the methods for elevating a structure, access to and from the building during flooding, and the protection of the building from flooding as described for Type 2 exposure, should be considered. Appropriate design techniques to deal with these problems are available (FEMA, 1981a; FEMA, 1981b; and FEMA, 1986). Specific plans for flood proofing a structure must be certified by a registered professional engineer or architect as meeting the minimum requirement of these standards.

- o Type 2 -Structures with Type 2 exposure must be flood-proofed. Flood proofing consists of methods that make a structure resistant to flood damage. Flood proofing strategies that serve to meet the "dry" flood proofing standards of the NFIP are particularly appropriate for Type 2 exposure where only moderate flooding (i.e., low flood depth, low water velocities and short duration) is likely. The principal approach to meeting this requirement is waterproofing the portions of the structure below the design runup level. Keeping water out of a structure requires special structural support, however. During flooding of the exterior of a waterproof building, water pressure builds up on the exterior that could cause collapse of the building. Building design problems that must be addressed include:

- Entrance of water through building openings.
- Damage to building finishes and contents.
- Seepage through walls, floors and foundations.
- Water pressure on foundations, walls, and floor slabs.
- Backup of water through drain systems.
- Access to and from buildings during floods.

Appropriate design techniques to deal with these problems are readily available (FEMA, 1981). Specific plans for flood proofing a structure must be certified by a registered professional engineer or architect as meeting the minimum requirement of these standards.

- o Type 3 - There are no special design requirements under these standards.

2. Review Procedure. The design review procedure consists of the following steps, which should be applied in the step-by-step order shown on the Flow Diagram, Figure 10:

a. Step 1 - Is Plan for Structure in Flood Zone? This step is used to determine whether a proposed structure is in the flood risk area delineated by the Bay Commission and therefore whether the safety standards in this review procedure apply.

No - Procedure not applicable; accept plan.

Yes - Go to Step 2.

b. Step 2 - Is Plan for Structure on Piling? This step is used to identify whether a proposed structure is supported on piling, including piers and wharves. A structure that uses piles or posts for foundation support in upland areas is not considered "supported on piling" if the structure is protected by a bulkhead, levee or revetment.

No - Go to Step 3

Yes - Go to Step 4A

c. Step 3 - Does Plan include a Protective Device? This step is used to identify whether a plan for a structure includes, or is for, a protective device. The protective devices considered in this procedure are bulkheads (vertical wall), revetments (rough slope) and levees.

A proposed structure does not require a protective device even if it is located in a flood risk area. A plan for a structure may include an existing protective device constructed by others, if it protects the structure, and its proper function can be assured over the structure's life.

No - Go to Step 4C

Yes - Go to Step 4B

d. Step 4A - Does Structure Meet Wave Crest Criterion? This step applies to a structure supported on piling and is used to identify whether the bottom of the lowest horizontal structural member supporting the lowest floor is above the design wave crest level. A structure that does not meet this criterion is conditionally unacceptable. If the structure meets this criterion, then there are no special design requirements for the structure under these standards.

No - Reject Plan

Yes - Go to Step 6A

e. Step 4B - Does Protective Device Meet Wave Crest Criterion? This step applies to a protective device and is used to identify whether the crest of the protective device is above the design wave crest level. If a structure is proposed in conjunction with the protective device that does not meet this criterion, the structure may be exposed to dynamic wave forces. If the protective device meets this criterion, then it must be checked against the wave runup criterion.

No - Go to Step 4C

YES - Go to Step 5A

f. STEP 4C - Is Structure Subject to Wave Forces? This step applies to a structure and is used to identify whether the structure is exposed to dynamic wave forces. The determination requires analysis of wave transmission that includes consideration of structure setback, wave attenuation provided by intervening shoreline features and the relative elevation difference between the structure's lowest floor and the design wave crest level. A criterion based on the setback distance and/or the elevation difference that determines whether a structure is exposed to dynamic wave forces has not been developed, and hence the matter must be analyzed on a case by case basis.

No - Go to Step 5B

Yes - Go to Step 6C

g. Step 5A - Does Protective Device Meet Wave Runup Criterion? This step applies to a protective device and is used to identify whether the crest of the protective device is above the design wave runup level. If a structure is proposed in conjunction with the protective device that does not meet this criterion, the structure may be exposed to flooding caused by wave runup, but not to significant dynamic wave forces. If the protective device meets this criterion, then there are no special design requirements for the structure under these standards.

No - Go to Step 5B

Yes - Go To Step 6B

h. Step 5B - Is Structure Subject to Wave Flooding? This step applies to a structure and is used to identify whether the structure is exposed to flooding due to wave runup. If the protective device is a bulkhead or a revetment, the exposure criterion is based on setback distance. The criterion is based on the assumption that the runup flow, once it reaches the crest of the protective device, will be carried horizontally toward the structure by the horizontal component of flow (for a sloped protective device) and on-shore winds. The horizontal distance traversed by the runup is assumed proportional to the vertical overtopping distance for the protective device. A minimum setback distance of 10 feet is required if overtopping occurs. If the protective device is a levee, the exposure criterion is based on relative elevation difference between the structure's lowest floor and the design still water level. The criterion is based on the assumption that overtopping water could accumulate behind the levee, and reach the design still water level before gravity discharge could occur, preventing further accumulation. If adequate pumping capacity is provided to remove overtopping water, this criterion may be waived. If the structure meets the appropriate criterion for setback distance/lowest floor level, then there are no special design requirements for the structure under these standards.

No - Accept Plan

Yes - Go to Step 6D

i. Step 6A - Is Design Adequate? (Structure on Piling). This step applies to a structure with Type 3 exposure supported on pilings. Design adequacy also depends on degree to which adjoining structures, land, and Bay resources re protected from side effects of the protective structure. There are no special design requirements applicable to the superstructure supported on the piling. However, there are piling design problems that must be addressed to serve the purpose of these standards:

-Lateral wave forces on the piles themselves.

-Lateral wave forces on the pile cross-bracing.

-Uplift forces on the underside of the deck at landward end of pier.

If the design of the support piling conforms to sound engineering practice, the plan is acceptable.

j. Step 6B - Is Design Adequate? (Protective Device). This step applies to a protective device for which there are no flood proofing design requirements. However, there are design problems that must be addressed, depending on the type of protective device, to serve the purpose of these standards. For a bulkhead, these include:

- Dynamic wave forces.
- Protection against loss of backfill.
- Return walls at ends of bulkhead.
- Seaward return at top of bulkhead.
- Alignment of bulkhead with respect to adjacent devices, if any.
- Scour protection at toe of bulkhead.

For a revetment, these include:

- Cover (armor) layer stability.
- Protection against loss of underlayer material and backfill.
- Return walls at ends of revetment.
- Scour protection at toe of revetment.

For a levee, these include:

- Drainage for upland areas.
- Protection against erosion by wave and current forces, or sufficient levee proportions to accommodate erosion without breaching.

If the design of the protective device conforms to sound engineering practice, the plan is acceptable.

k. Step 6C - Is Design Adequate? (Structure Subject to Wave Forces. This step applies to a structure exposed to dynamic wave forces. In this case the plan would be acceptable provided that the structure incorporates the design requirements for Type 1 exposure (See Design Standards section above). Furthermore, if the plan includes a protective device, the design problems presented in Step 6B must also be addressed.

l. Step 6D - Is Design Adequate? (Structure Subject to Wave Flooding). This step applies to a structure exposed to wave flooding, but not to significant dynamic wave forces. In this case the plan would be acceptable provided that the structure incorporates the design requirements for Type 2 exposure (See Design Standards section above). Furthermore, if the plan includes a protective device, the design problems presented in Step 6B must also be addressed.

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APPENDIX A

Definitions

RECURRENCE INTERVAL - Time period during which one design magnitude event can be expected to occur. The 100-year recurrence interval is associated with a design magnitude event that has a one percent probability of occurring in a single year. Recurrence interval should not be confused with design life which references an absolute time interval, not a probabilistic value.

MEAN LOWER LOW WATER (MLLW) - A tidal datum plane which is the average height of the daily lower low waters over a 19-year period. Varies with location and time period.

MEAN SEA LEVEL (MSL) - A tidal datum plane which is the average water level given over a 19-year period. Referenced to a datum such as NGVD. Varies with location and time period.

GLOBAL SEA LEVEL CHANGE - Global, or worldwide, mean sea level change due to global climatic occurances.

RELATIVE SEA LEVEL CHANGE - A local change in mean sea level that combines global sea level change with vertical land motions at specific locations.

HIGHEST ESTIMATED TIDE (HET) - The elevation of extreme high still water level,which includes effects of astronomic tides, climate, wind set up and storm surge. Typically based on historic data and considered a probabilistic event (see recurrence interval). Referenced to a datum such as NGVD.

HIGHEST ESTIMATED TIDE (HT) - The difference between Highest Estimated Tide (HET) and Mean Sea Level (MSL) for a given recurrence interval and location.

NATIONAL GEODETIC VERTICALDATUM (NGVD) - Formerly called SEA LEVEL DATUM OF 1929. A geodetic datum derived from a general adjustment of the first order level nets of both the United States and Canada. In the adjustment, sea levels from selected TIDE stations in both countries were held as fixed. The year indicates the time of the last general adjustment. This datum should not be confused with MEAN SEA LEVEL.

MEAN TIDE LEVEL (MTL) - A tidal datum plane which is plane midway between Mean High Water and Mean Low Water, and usually different from Mean Sea Level.

EPOCH - As used in tidal DATUM PLANE determinations, Epoch is a 19-year PERIOD over which tidal observations are averaged to establish the various tidal datums. The 19-year PERIOD is used since it is the time in years closest to the 18.61-year period (NODE CYCLE) required for the regression of the moon's nodes. The present Epoch is 1960-1978.

PRIMARY TIDE STATION - Tide Station at which continuous tide observations have been taken over a sufficient number of years to obtain basic tidal data for the locality. Such stations are used as a standard for the comparison of simultaneous observations at a secondary station.

SECONDARY (SUBORDINATE STATION) - Tide Station at which a short period of observations has been obtained, which is to be reduced by comparison with simultaneous observations at another station having well determined tidal constants.

BULKHEAD - A protective device consisting of a vertical (or near vertical) wall to retain or prevent sliding of the land. A secondary purpose is to protect the upland against erosion by wave action or currents.

DESIGN STILL WATER LEVEL - Elevation above NGVD that the water would assume if all wave action were absent.

DESIGN WAVE CREST LEVEL - Elevation above NGVD that would be directly exposed to significant dynamic wave forces, usually the crest level of breaking waves. It is based on a design wave height, still water level, and scour level with a specified design recurrence interval.

DESIGN WAVE RUNUP LEVEL - Elevation above NGVD that would be directly exposed to significant wave flooding, usually the limit of up-rush of breaking waves. It is based on a design wave height, still water level, and scour level with a specified design recurrence interval.

LEVEE: - A protective device consisting of a dike or embankment, in order to protect land from inundation.

RECURRENCE INTERVAL - Time period during which one design magnitude event can be expected to occur. The event with a 100-year recurrence interval, which is generally used for the design of structures and protective devices on San Francisco Bay, is based on the statistical probability that one event of such magnitude will occur in 100 years, or that the event has a one percent probability of occurring in any single year. Recurrence interval should not be confused with design life, which references an absolute time interval, not a probabilistic value.

NATIONAL GEODETIC VERTICAL DATUM (NGVD) - A fixed reference datum of elevations derived from a general adjustment of the first order level nets of both the United States and Canada. The last general adjustment occurred in 1929. This datum was formerly referred to as 'Sea Level Datum of 1929'.

PROTECTIVE DEVICE - A seawall, bulkhead, revetment or levee designed to protect a structure from high water levels and from wave action.

REVETMENT - A protective device consisting of a facing of stone, concrete, cast units, etc., placed on a slope to protect the slope and upland against erosion by wave action or currents.

STRUCTURE - Residential or non-residential habitable building.