Philip Williams & Associates, Ltd.
Consultants in Hydrology

Pier 35, The Embarcadero
San Francisco, CA 94133
Phone: (415) 981-8363
Fax: (415) 981-5021

ELKHORN SLOUGH TIDAL HYDRAULICS EROSION STUDY

Prepared for:

U.S. Army Corps of Engineers
San Francisco District

Prepared by:

Philip Williams & Associates, Ltd.
and
Moffatt & Nichol Engineers

August 1992

#830

164\SD\830ELKHO.DOC\08-31-92

TABLE OF CONTENTS

LIST OF TABLES

LIST OF FIGURES

I. INTRODUCTION

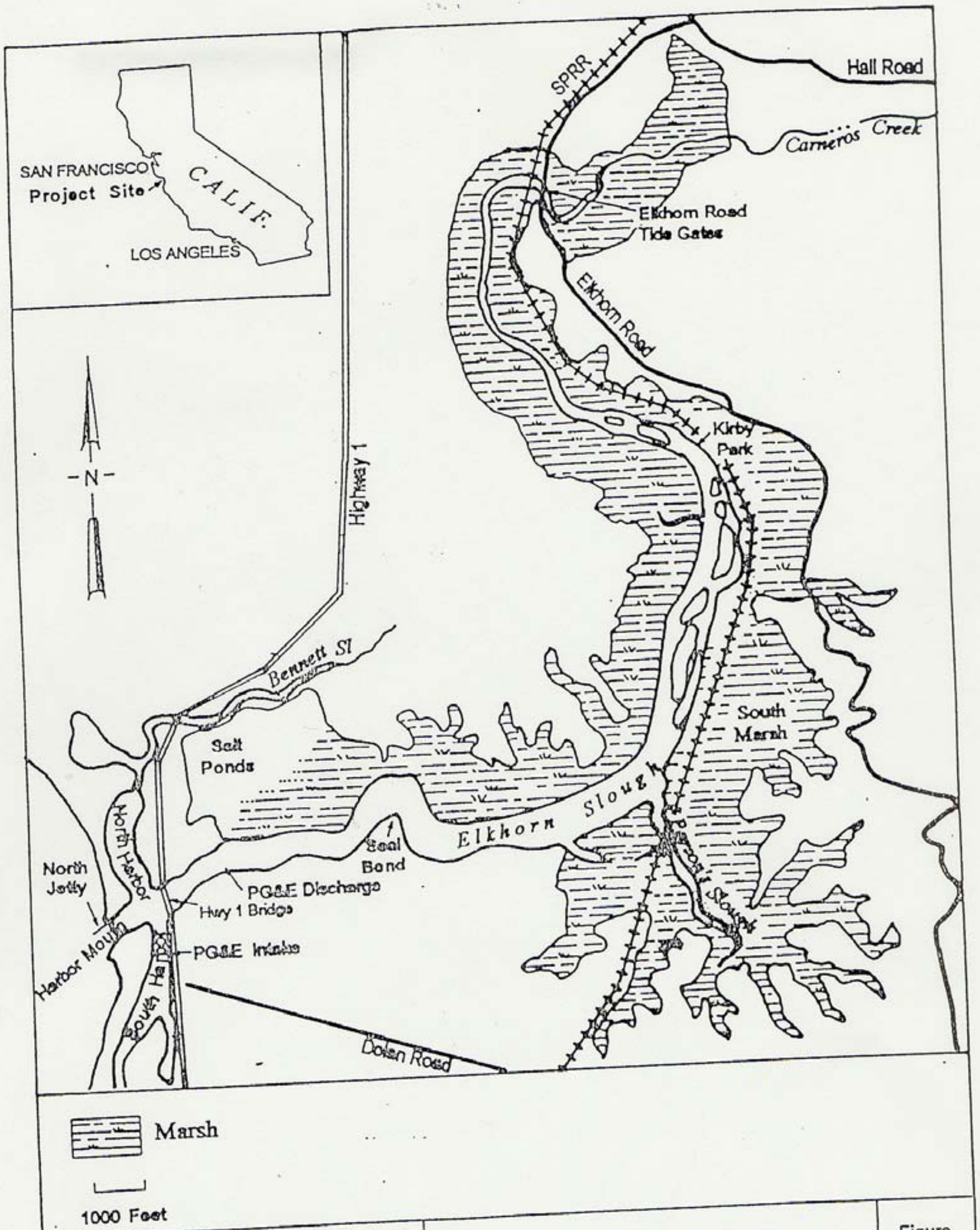
A. OVERVIEW

Elkhorn Slough is a tidal embayment, approximately 7 miles long, located in Central Monterey Bay (Figure 1). The mouth of the slough discharges into the Moss Landing Harbor located immediately to the West. Historically, the slough joined the Salinas River Channel at the Highway 1 Bridge and flowed north about 0.5 miles before discharging to the Pacific Ocean through a small opening in the coastal sand dunes. Moss Landing Harbor was created in 1946 when a new harbor entrance channel was dredged through the sand dunes directly west of the Elkhorn Slough mouth at Highway 1. The 1943 U.S. Army Corps of Engineers (COE) plan for the new entrance called for a dredged entrance channel 200-feet wide and 20-feet deep. The new dredged opening at the mouth of the Monterey Submarine Canyon allowed deep draft vessel access and was also subject to less severe wave action than the previous mouth.

As part of the proposed Harbor improvement project, the original project plans also specified construction of tide gates at the mouth of Elkhorn Slough to prevent tidal influence and damage to low-lying lands up the slough. These tide gates were not constructed. Additional information on the history of the federal project is contained in the Moss Landing Harbor, Monterey County, Section 111 Study Initial Assessment (U.S. Army Corps of Engineers, 1989).

Immediately following the opening of the new harbor entrance, local landowners were aware of the increased tidal currents in the slough. (C.F. accounts in ABA Consultants, 1989 and Oliver, et. al., In Press). As a result of the increased tidal velocity, bank protection was required around the Highway 1 bridge abutments and some local landowners constructed levees to protect adjacent low-lying areas. Erosion resulted in the on-going loss of land adjacent to the channel extending several miles upstream of the slough mouth.

The erosion of the slough has continued during the past 45 years and is currently considered to be the largest problem facing the slough (Oliver et. al., 1989; Silberstein, 1991). As a consequence, the Moss Landing Harbor District in a letter dated April 11, 1988, requested a study of erosion problems and potential solutions under Section 111 of the 1968 River and Harbor Act. In the initial assessment (U.S. Army COE, 1989), the U.S. Army COE concluded that the Harbor opening was largely responsible for the erosion problems and recommended that a reconnaissance level study be initiated to provide additional information on hydrodynamic conditions in the slough, the potential success of the suggested solutions, and the portion of the erosion problem directly attributable to the Federal project.



Philip Williams & Associates, Ltd.
Consultants in Hydrology

Project Location and Study Limits

Figure 1

B. STUDY PURPOSE

In response, the San Francisco District of the Corps of Engineers requested a Tidal Hydraulic Erosion study of Elkhorn Slough, in December, 1991. The purpose of this present study is:

> "...to determine if the Corps' Moss Landing Harbor Navigation Project has caused, or is causing, any erosion of the vegetated marshlands in Elkhorn Slough. The study will also examine other possible causes that may have led to the current erosion condition at Elkhorn Slough. Lastly, the study will evaluate and recommend solutions to the current erosion problems that exist at Elkhorn Slough."

C. STUDY METHODOLOGY

The COE designated approach to the above requested study was to gather available data on historical and existing conditions in the slough and to develop a hydrodynamics model to simulate tidal circulation in the slough for the following conditions:

1. Existing (1991) Conditions (with the Federal Navigation Project, and with upstream levee breaches along Elkhorn Slough);
2. Without-Navigation-Project or Levee Breach Conditions (with pre-1946 conditions at mouth of the slough);
3. Navigation Project Conditions only (without upstream levee breaches); and
4. 1985 Highway 1 Bridge and Levee Breach Conditions only (with pre-1946 conditions at mouth of Slough).

Based on comparison of the designs of the abutments an pilings of the existing (1985) Highway 1 bridge with those of the previous bridge, the COE determined that there was no significant difference in the hydraulic effects of the two bridges. Therefore, all modeling conditions assumed the existing (1985) bridge configuration.

Considering the limited funding available for the study and the significant lack of detailed bathymetric data available to define the slough geometry, it was determined that a one-dimensional, link-node hydrodynamic computer model of the slough would be used in the study. Available (limited) bathymetric data would be used to define the system geometry for each condition, and the flow regime would be estimated under a range of tidal conditions.

It is recognized that a one-dimensional model is only a general approximation of the actual 3-dimensional system. Furthermore, the actual process of slough channel erosion in cohesive sediments has multiple causes and is poorly understood. Finally the lack of detailed historic or current bathymetric data and the lack of available calibration data reduce the level of detail in which the system can be modeled. Thus, the primary value of the modeling results is for intercomparison between the modeled scenarios to compare the relative effects of the various changes which have occurred in the system on the velocity regime. To supplement the modeling results, we have included some field observations in the Elkhorn Slough system, and some comparison data from marsh slough channels at other locations in California.

II. HISTORICAL CHANGES AND PRESENT CONDITIONS

A. HISTORICAL CHANGES IN THE SLOUGH AND ADJACENT AREAS

Elkhorn Slough has been subject to a variety of natural and, during the past 150 years, human induced changes. These have been summarized in the 1989 Slough Master Plan (ABA Consultants, 1989) and by Silberstein (1991). A brief summary of the changes is provided below, and summarized in the sketches in Figure 2 (used by permission from Silberstein, 1991).

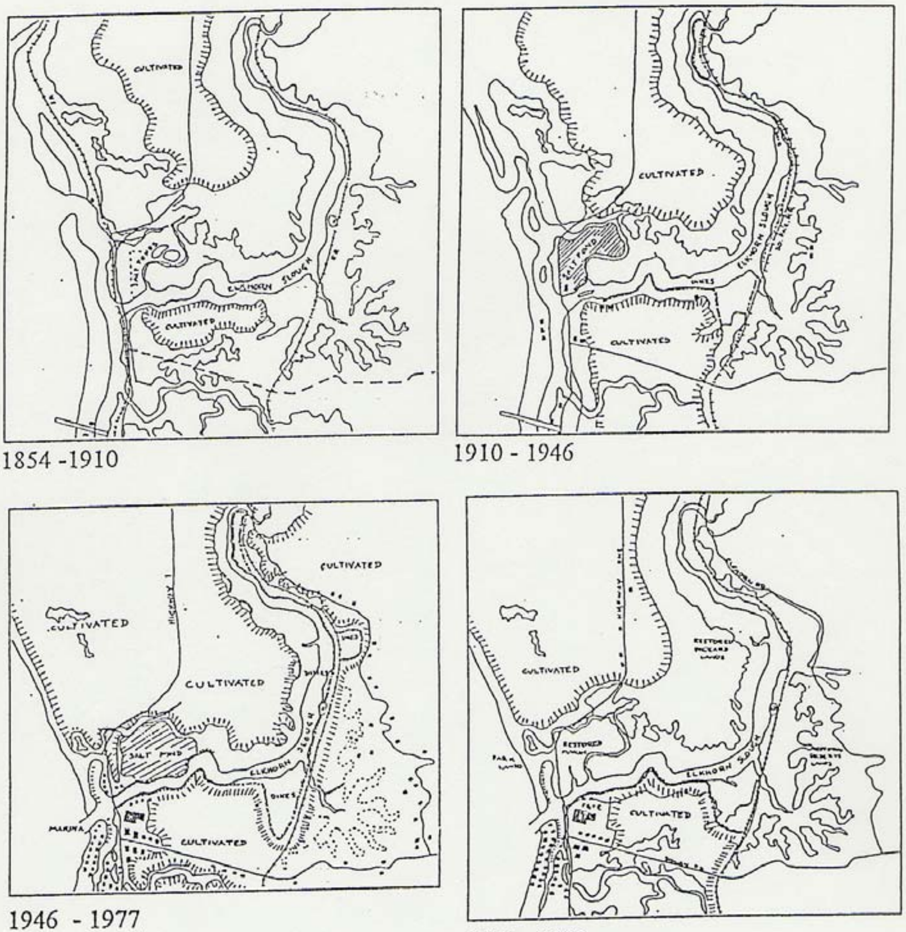
1. 1854-1910 (Figure 2a)

The first map of the system was produced in 1854 by the U.S. Coast and Geodetic Survey (precursor to NOAA). The most significant change to the slough was the construction of the SPRR tracks along the south and east bank of the slough, separating these areas of salt marsh from the main slough channel.

2. 1910-1946 (Figure 2b)

In 1910, a breach was cut in the sand dunes south of Moss Landing to allow the Salinas River to discharge directly to the Ocean. This eliminated both freshwater flow and sediment transport from the historic channel, which paralleled the sand dunes and flowed north to join Elkhorn Slough, then discharged to the ocean 0.5 miles north of the present harbor opening. The loss of freshwater inflow to the slough system is discussed in the Slough Master Plan (1989). However, the overall impacts of the diversion of the Salinas River have not been analyzed in detail; they were likely very significant. In addition to providing a source of freshwater to maintain a fresh and brackish wetland system, the variations in river flow would have created a dynamic hydraulic system in the river adjacent to the slough. Periodic floods conveying 100,000 cfs or more would have dramatically altered the river channel and river mouth morphology. During high flow events, the river mouth would have widened and deepened and the entire system converted to fresh water. As flood flows receded, strong tidal action would have persisted for some period of time before littoral and wave transport of sand recreated the sand sill, reduced the channel opening, and limited tidal circulation. A similar process occurs on approximately an annual basis at the mouth of the Salinas River today.

In addition to fresh water, the large floods conveyed enormous quantities of sediment. McGraph (1987) estimates that the Salinas River conveyed an average of about 1 million cubic yards (cy) of sediment annually; during extreme floods (>80,000 cfs) it was capable of transporting several million cy *daily*. This would have produced a strongly deposited sediment environment. Thus, from a geomorphic perspective, diversion of the Salinas River represented an enormous change to the system.



.1854 -1910

1910 - 1946

1946 - 1977

1980 - 2000

Philip Williams & Associates, Ltd.
Consultants in Hydrology

Historic Changes in the Elkhorn Slough System
(from Silberstein, 1991)

Figure 2

Subsequent to the diversion of the Salinas River, the next major impacts to the slough resulted from the on-going construction of dikes and the draining of the salt marsh areas adjacent to the slough to allow agriculture and ranching. The salt ponds on the north side of the slough near Highway 1 were constructed in this era.

3. 1946-1977 (Figure 2c)

The construction of the Moss Landing Harbor in 1946 represents the most significant change during this period. The opening of the new entrance at the mouth of the submarine canyon and the construction of the jetties allowed the rapid commercial success of the new harbor. The new opening initiated full tidal circulation to the area historically subjected to muted tidal exchange, initiating the erosion in the slough which is the topic of the present study. During this period, major tributary slough channel and marsh systems were cut off from tidal exchange to allow continued or new agricultural use. These areas included the Old Salinas River Channel/Tembladero Slough (south of the Potrero Road tide gates), Moro Coho Slough, and Bennett Slough in the north area of the harbor.

4. 1977-Present (Figure 2d)

The past 15 years have been primarily an era of conservation in the Slough. Major portions of the Slough are managed by public agencies in National Estuarine Reserve Status. The most significant physical change during this period was the reopening of the South Marsh/Parson's Slough and adjacent wetlands to tidal circulation. This has resulted in both positive and negative effects: the area is biologically rich, supporting a diversity of salt marsh and mudflat vegetation and wildlife species. However, shoreline and channel erosion is a severe problem here also. A more detailed discussion of the problems and some potential solutions are discussed in subsequent sections of this report. During the 1980's the problems associated with the ongoing erosion in the slough became more widely publicized following analysis by researchers at the Moss Landing Marine Laboratories. On-going erosion is currently perceived as the major problem causing environmental deterioration in the slough.

B. FIELD OBSERVATIONS OF PRESENT CONDITIONS

Although the study budget did not include collection of detailed new data, several field trips were made to the site to observe existing conditions. Additional information on present conditions is contained in other references (ABA Consultants, 1989; Oliver, et. al., no date).

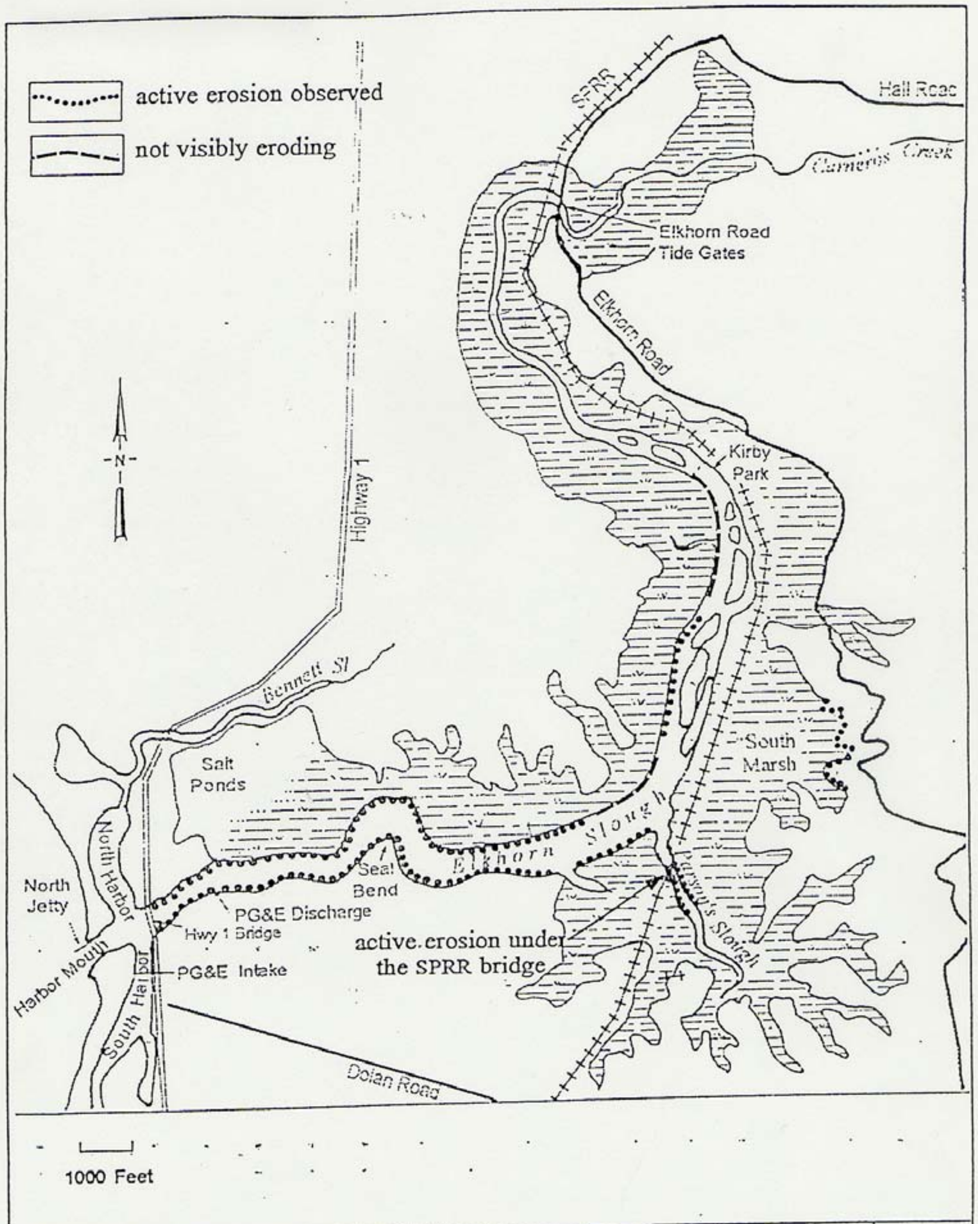
Observations were made along the north bank of the slough for a distance of about two miles upstream of the mouth of the slough at Highway 1. Similar observations were made along the south bank. Field observations were also made in the South Marsh/Parson's Slough area in the company of California Department of Fish and Game and Elkhorn Slough Foundation representatives. Spot observations of slough bank conditions were made further upstream in the system. These site visits consisted primarily of observing bank or channel erosion, and assessing the potential causes. In addition, one set of tidal velocity measurements were collected across the Highway 1 bridge opening during the maximum ebb tide on July 4, 1992 to provide a check on the hydrodynamic model functioning.

The results of our limited field observations are shown in Figure 3. Very active bank erosion is evident along both the north and south banks of the slough upstream of Highway 1. As shown in Photo 1, there is a vertical headwall 5 to 6 feet high along the north bank that is actively retreating. Erosion is breaching levees and eroding into the former salt ponds north of the slough. Active erosion along the south bank is destroying a residual levee on the Vierra property, reintroducing tidal circulation to formerly diked and drained areas. The Vierras have lost a significant amount of property along the south bank to erosion during the past 45 years (David Vierra, personal communication).

Upstream of Seal Bend, active erosion is evident in the salt marshes north of the slough channel. The outer edge of the salt marsh is eroding northward, and the slough channels which provide tidal circulation are deepening and widening (see Oliver et al, no date). This was also evident in the marshes south of the channel except where the channel banks had been protected by riprap.

In the South Marsh, severe erosion is occurring along the marsh margins at the base of the surrounding hillsides. As shown in Photos 2 and 3, base erosion is causing failure of the hillsides and threatening both access routes and upland trees. A more natural hillside-marsh transition occurs along the north shore marshes. As shown in Photos 4 and 5, a stable vegetated marshplain intersects the hillside and no erosion is evident.

In contrast to the extensive salt marsh areas north of the slough channel, the wetlands in the South Marsh consists primarily of intertidal mudflats. It appears that land subsidence has lowered the marshplain surface by about 2.5 feet (from about MHHW to about MSL) during the past century since diking by the SPRR levee. Drying out of the marsh allows an irreversible compaction of the sediment resulting in a lowering of the land surface. As a result of this subsidence, when the marsh was reopened to tidal circulation in 1983-84, the elevation (approximately 0.0 feet NGVD) was appropriate for intertidal mudflats, not salt marsh vegetation. The pre-opening 1983 DFG enhancement plan was clearly a response to the subsidence. The plan attempted to create a more diverse habitat by excavating some areas and mounding the spoils to create vegetated zones at higher elevations. This subsidence may be a major cause of the erosion that is occurring in the South Marsh. The form of the erosion (Photos 2 and 3) is typical of that seen around the periphery of reservoirs (resulting from the presence of ponded water). This would imply that the wetting-drying cycle (which results from tidal exchange), combined with small wind generated waves are major contributors to bank failure. Unlike the slough channel banks near Highway 1, the fingers of the South Marsh are not subject to high velocity tides. Rather, it appears that because of subsidence, when the marsh was reopened to tidal action in 1984, the marsh contained ponded water during approximately half of each tidal cycle. This has allowed



Philip Williams & Associates, Ltd.
Consultants in Hydrology

Areas of Active Erosion Based on Limited Field Observations

Figure 3

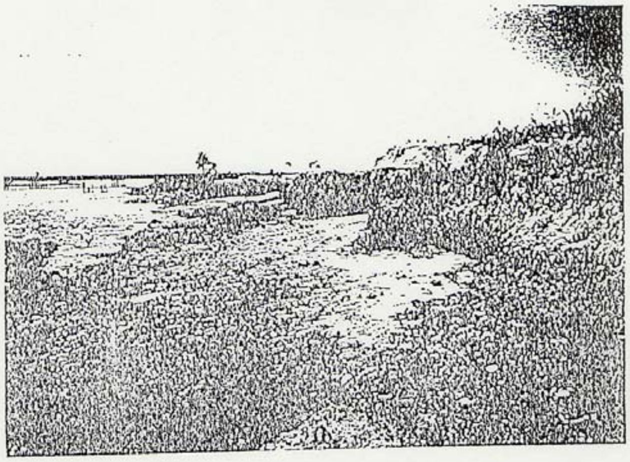
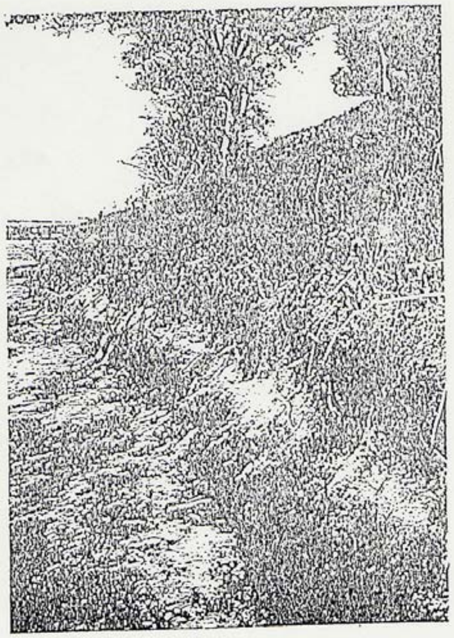
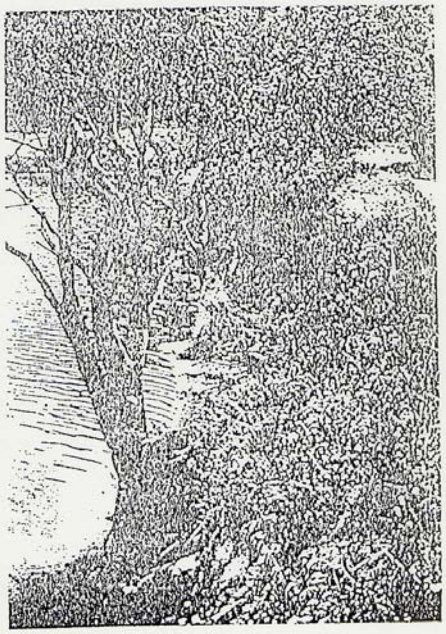


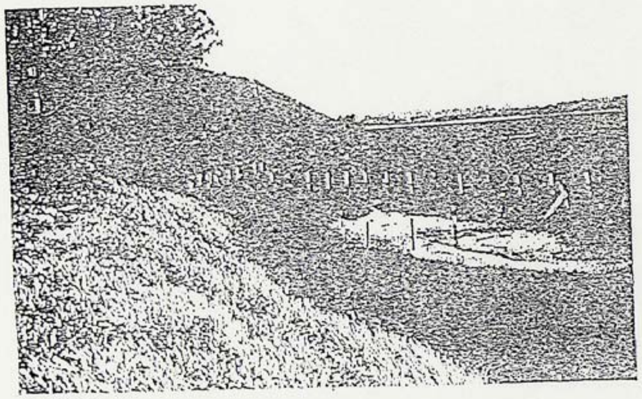
PHOTO 1 ▸
Eroding north bank of Elkhorn Slough just upstream of the Highway 1 Bridge



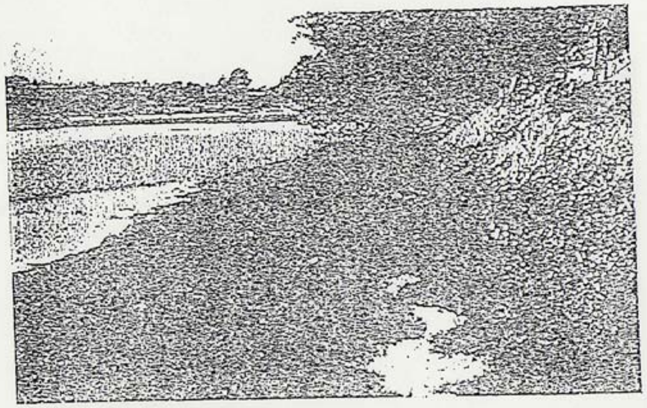
▴ PHOTO 2
Erosion on the shoreline of the South Marsh



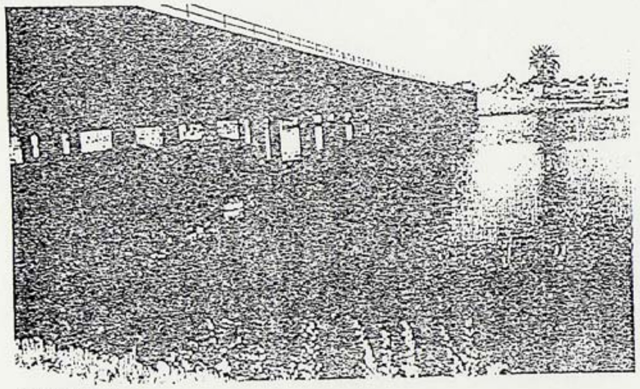
▴ PHOTO 3
Erosion along the shoreline of the South Marsh



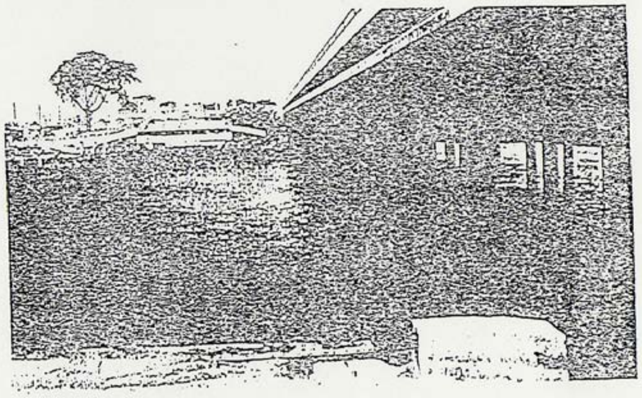
▲ PHOTO 4
Natural marsh-hillside transition in marsh north of Elkhorn Slough Channel



▲ PHOTO 5
Marsh strip stabilizing hillside adjacent to a slough channel in the marsh north of Elkhorn Slough Channel



▲ PHOTO 6
Potential sill location upstream of the Highway 1 Bridge



▲ PHOTO 7
Potential sill location downstream of the Highway 1 Bridge

wave action and bank collapse as a result of regular wetting/drying. The subsidence has created an enormous tidal prism which is exchanged through the SPRR bridge at Parson's Slough. The channel under the bridge is about 125 feet long and reportedly 15 to 20 feet deep. This large volume of tidal exchange (and the increased depth of Elkhorn Slough downstream) is causing tidal erosion in Parson's Slough, which is deepening and extending headward into the South Marsh and the Five-Fingered Marsh area. High velocity flows may also be removing some of the material being eroded from the hillsides, preventing the development of a more stable shoreline around the South Marsh as the hillsides erode and contribute sediment.

The erosion along the main Elkhorn Channel (Figure 3 and Photo 1) is a result of the increased tidal currents associated with the new harbor opening in 1946. This erosion has continued over the past four decades. It will continue to occur at various locations throughout the Slough for decades to come. The rate of erosion was increased by the additional tidal prism resulting from the levee breaches in the South Marsh/Parson's Slough area in the 1980's.

While the causes of the erosion are evident, the actual mechanism of erosion is less clear. This has implications for the type of solution to be recommended and the rate at which erosion might cease following implementation. Channel downcutting is clearly the result of high velocity flow creating bed shear stress. Bank erosion on the outside of bends may also be the result of high velocity flow impinging directly on the banks. However, at other shoreline locations, wave erosion, wetting and drying, and transverse transport of eroded materials may be important components of bank erosion. The channel top width (about 600 feet) is sufficiently large that wind-generated waves and perhaps, small boat wakes have sufficient fetch to attack the bank directly. This, coupled with the wetting-drying as a result of the tidal cycle, can lead to bank collapse. The deepening of the main channel by 15 or 20 feet has created a steeper transverse gradient, and as the material is eroded, it moves down into the deeper portions of the channel where high velocity tidal flows then convey it out through the system. The type of erosion mechanism has some implications for the design of an erosion reduction project. If the actual tidal current velocity is responsible, the sill or constriction at the Highway 1 bridge would have to be sufficiently high to actually reduce tidal exchange and current velocity. If the present extensive depth at the channel center is crucial to the ongoing erosion, it may be possible to reduce erosion with a partial sill, which raises the bed elevation but does not extend vertically into the intertidal zone. This is discussed in greater detail in the section on Erosion Control Alternatives.

C. HYDROGRAPHIC CHANGES

1. Introduction

In this section, an overview of bathymetric changes resulting from erosion in Elkhorn Slough is presented. In addition, some discussion of the changes in wetland areas subject to tidal circulation and changes in the potential and actual tidal prism[1] are discussed. This discussion is important as it quantifies (to the extent possible with limited data) the actual changes which have occurred based on historical records. In addition, it allows some discussion and comparison of the magnitude of change based on hydraulic geometry relations using tidal prism data and comparison with other marsh systems. These simple, geometry-based relationships are based on observations of other natural or altered slough systems. They are useful in that physically-based, hydrodynamic models are still relatively limited in the information they can provide about the actual complex problems of erosion, long-term change, and future equilibrium conditions.

The analyses in this section represent an extension of the study by Oliver, et. al. (no date) which provides the first quantitative assessment of erosion in the slough system.

2. Methods

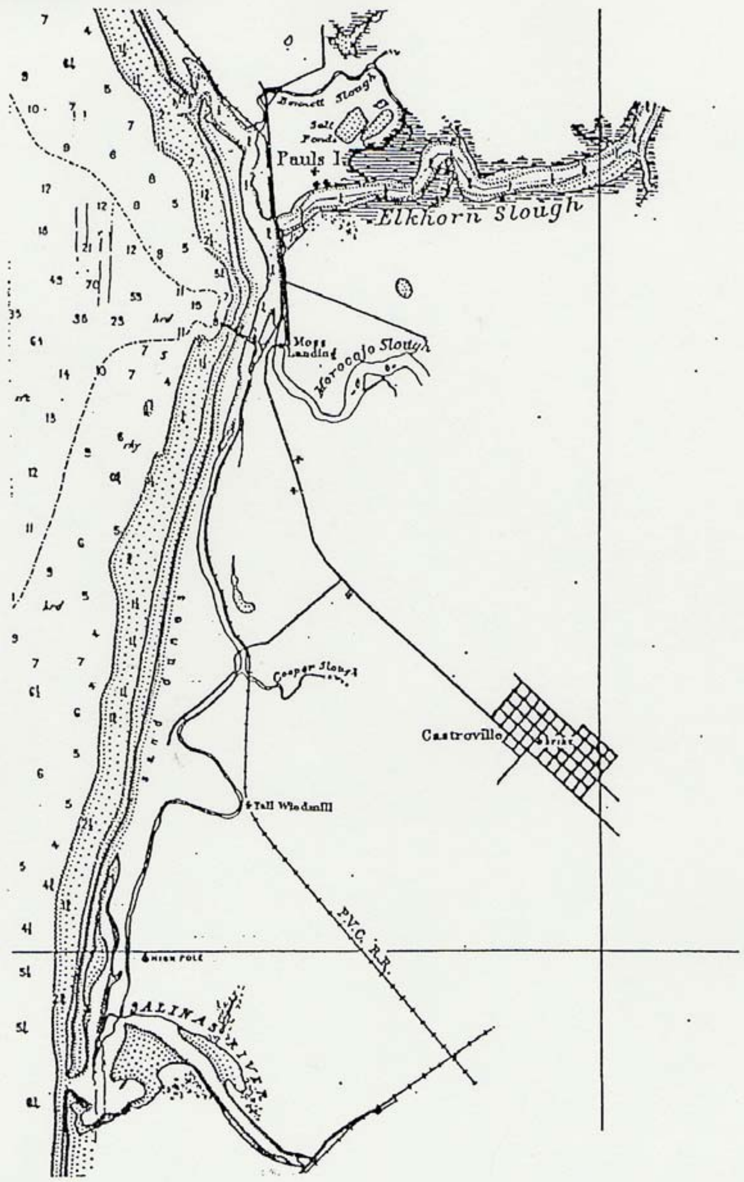
The information used in this study was restricted to data available in the literature. The primary type of information of interest was historical and existing bathymetric data for the main Elkhorn Slough Channel. It should be emphasized that the lack of detailed topographic and bathymetric data for the slough and adjacent wetlands is a serious hindrance to the development of a refined analyses of the historical changes or existing conditions in the system. While representing a costly investment, detailed aerial mapping of the slough (at either 100-scale, 1-foot contours or 200-scale, 2-foot contours) supplemented by bathymetric cross-sections would provide an invaluable benchmark for existing slough conditions and quantifying historic changes and future system evolution.

Limited bathymetric data in Elkhorn Slough were available from the 1909 USC & GS map (Figure 4), the 1940 U.S. Army COE map and 1988 cross-sections (Oliver et. al., no date). The 1909 bathymetric data consists solely of a series of 16 thalweg[2] depths extending 2.25 miles up the slough (Figure 3). The 1940 U.S. Army COE maps (which were apparently not available in previous studies) represent a valuable addition to the understanding of the "pre-harbor" slough and Salinas River mouth conditions. The location of some of the available cross-sections are shown in Figure 5; plots of some of the cross-sections are included in Appendix B. Included in the 1940 data are detailed cross-sections of the original river channel mouth, depiction of the Salinas River channel between the mouth and Elkhorn Slough, and cross-sections from the Highway 1 bridge up to Seal Bend. Data on subsequent U.S. Army COE bathymetric maps are confined to the actual harbor entrance channel and do not extend upstream beyond the Highway 1 bridge. These COE surveys are associated with periodic dredging of the Federal Navigation projects (Entrance channel and South Harbor Channel) and are available at about 4-year intervals. Maps from the 1947 survey

---

[1] Tidal prism refers to the volume of water between high and low tides that is exchanged during a given tidal cycle.

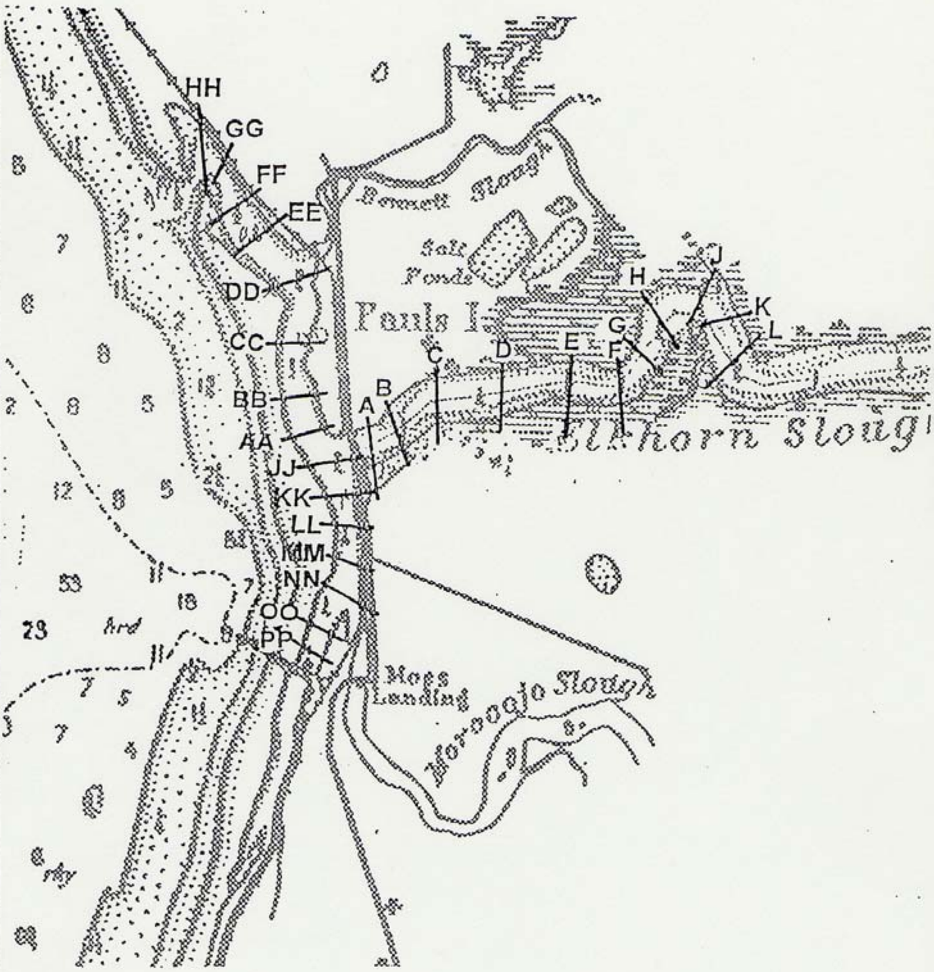
[2] The thalweg represents a line following the deepest portion of the channel.



Philip Williams & Associates, Ltd.
Consultants in Hydrology

1909 USC & GS Map

Figure 4



Philip Williams & Associates, Ltd.
Consultants in Hydrology

1940 U.S. Army Corps of Engineers
Cross-section Locations

Figure
5

were used to model the "post-harbor opening' bathymetry of the new entrance area extending up to Highway 1 bridge. Data from 1984 and 1987 surveys were used to define the current entrance channel bathymetry. Some additional detailed bathymetry in the vicinity of the Highway 1 bridge (extending 30 feet downstream and 120 feet upstream) was collected in 1981 and is available from the 1986 CalTrans Highway 1 Bridge replacement project. The most recent data available is a series of six channel cross-sections collected by Oliver et. al. in 1988 (Figure 6). (For use in this study, cross-sectional data was obtained manually from the figure shown in the paper, as the original data was unavailable). These cross-sections are contained in Appendix B.

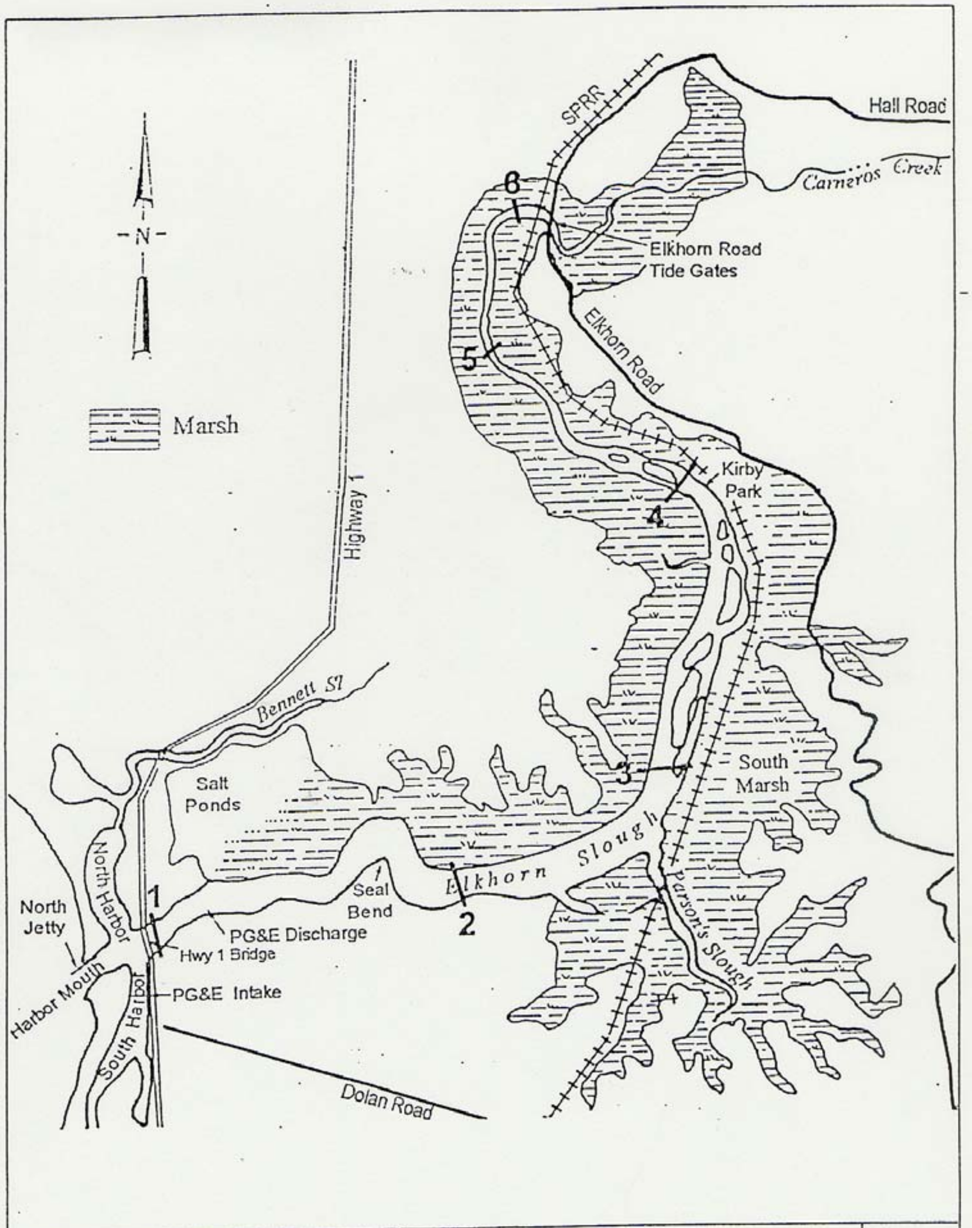
To determine overall slough and wetland areas, an expanded version of the current USGS 7.5 minute map (Elkhorn Slough Quadrangle) was used. Recent changes in levees, etc., were noted based on field observations. Some additional areal determination was made using the 1987 aerial photographs. These are unrectified, so some distortion occurs. A comparison of the estimated area of the South Marsh/Parson's Slough area showed a difference of about 20% using the USGS map and the aerial photo. For consistency, we used the USGS map for all subsequent area calculations, recognizing the limited level of accuracy. In the South Marsh limited topographic data was available from 1983 California Department of Fish and Game Enhancement Plan Map.

A series of historic aerial photographs of the slough, (most focusing on the mouth of the slough) are available. A number of them are organized in a U.S. Army COE sponsored study on coastal processes in Moss Landing (Dames and Moore, 1974). Photos are available for 1940, 1944, 1946, 1950, 1958, 1961, 1962, 1965, 1967, 1970, and 1972. Detailed color-infrared aerial photos were available from 1987. This air photo coverage has recently been reflown (May, 1992).

3. Results

a. Bathymetric Changes

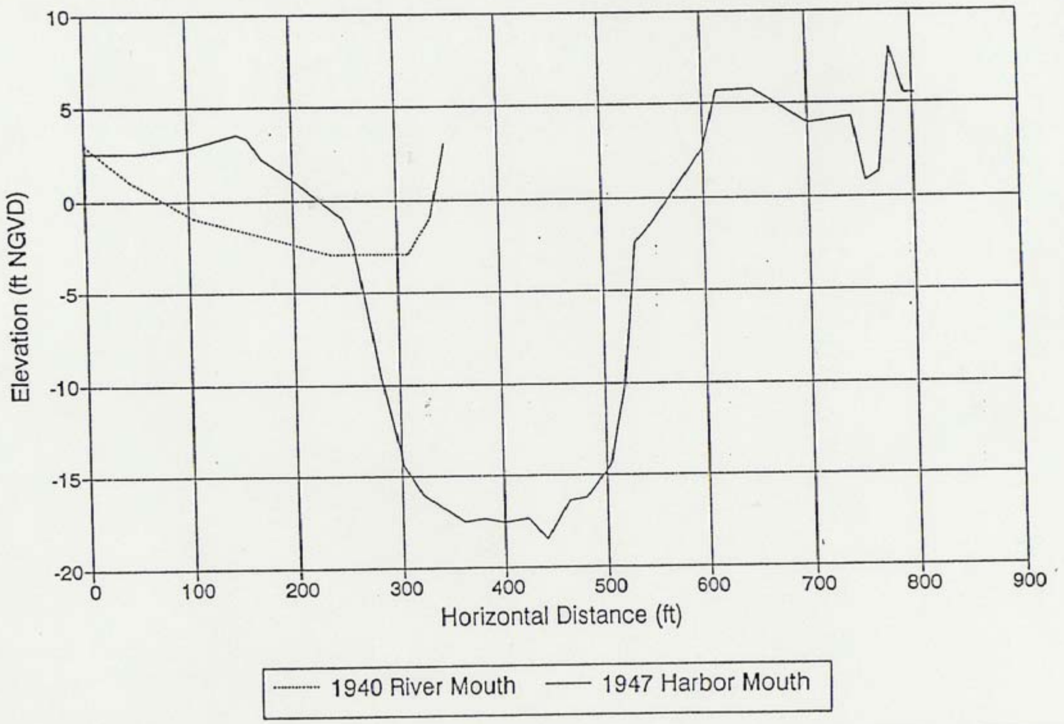
The cross-sectional shape of the mouth of the system at the Pacific Ocean is shown in Figure 7 for 1940 (Salinas River mouth, pre-harbor opening) and 1947 (New harbor entrance). It should be noted that the natural river mouth opening was extremely dynamic and likely varied dramatically in cross-section as a function of flow in the Salinas River, wave climate, and tidal regime. The 1944 photo suggests a river mouth width of about 190 feet, while the 1945 photo indicates a width of 100 feet. Both are significantly narrower than the surveyed 1940 cross-section. The 1909 USC&GS map indicates an opening estimated to be approximately 100-200 feet wide with a maximum depth of about -5 feet NGVD. Based on these data, the 1946 Harbor entrance opening expanded the channel area by approximately 5 times from the 1940-1945 opening area of about 1,000 square feet to about 5,300 square feet.



Philip Williams & Associates, Ltd.
Consultants in Hydrology

1988 Cross-section Locations
(Oliver *et al*, no date)

Figure
6



Philip Williams & Associates, Ltd.
Consultants in Hydrology

Old Salinas River Mouth (1940) and 1947 Harbor Entrance Channel

Figure 7

The changes in channel cross-section at the Highway 1 bridge are depicted in Figure 8. The channel thalweg has deepened by 15 feet, from -7 feet NGVD in the pre-Harbor (1909, 1940) conditions to -23 feet NGVD in the 1980's. Below tide areas have increased from 3,588 square feet in 1940 to 6,359 square feet in 1988, an increase of 2,771 square feet.

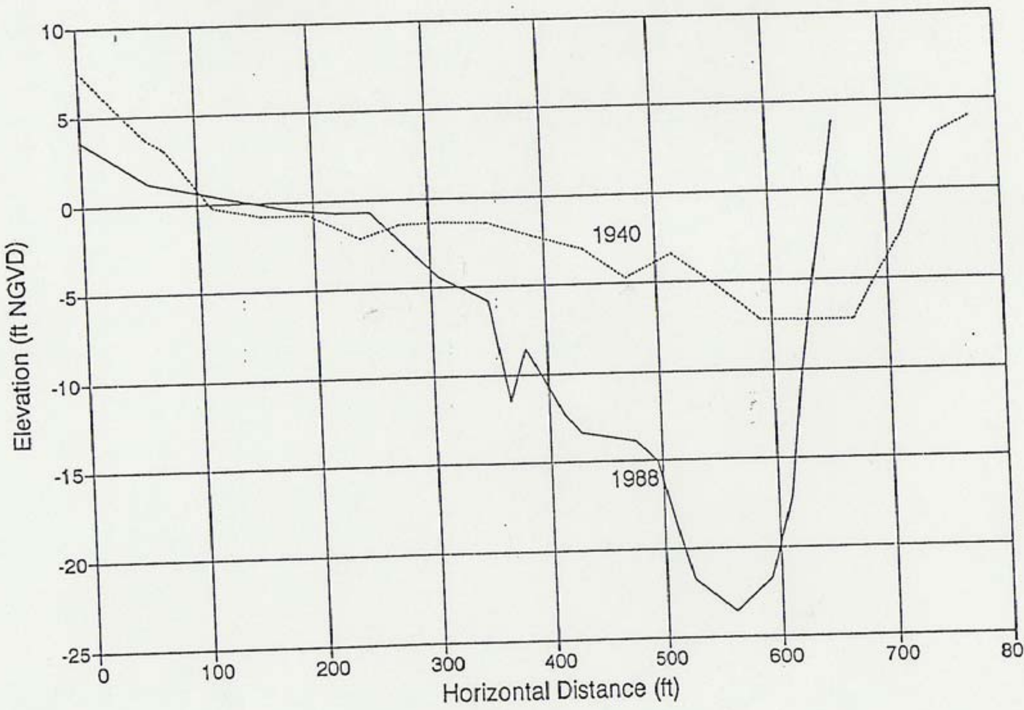
Upstream of the Highway 1 bridge, comparison of historic and current cross-section data becomes more difficult. The detailed 1940's surveys extend only about 1.5 miles beyond the bridge. A comparison of the most upstream 1940 cross-section and the most recent (1988) cross-section is shown in Figure 9. It can be seen that the 1988 channel is considerably deeper at this location. At the most upstream location of the 1909 thalweg data with 1988 data indicates the differences are less significant. This is shown more clearly in Figures 10a and b which depict the longitudinal profile changes in the system. The greatest depth changes (15 to 17 feet) have occurred at the Highway 1 bridge. This results from the Venturi effect of the bridge, resulting in maximum channel velocities. Thalweg depth increases are about 12 feet at Mile 1, 10 feet at mile 2 and 5 feet near mile 3 upstream of Highway 1.

As shown in Figure 10b, the difference between the 1940 (pre-harbor) and 1947 (post-harbor) profile between Highway 1 and the ocean reflect the greatly increased depth (and potential for tidal exchange), the extremely steep channel gradient downstream of the bridge, and the shortened flow distance. The current (1984 and 1988) channel profiles upstream of the bridge reflect a flattening of that initial gradient in response to increased tidal velocity and tidal prism exchange.

Comparing the 1940 and 1988 cross-sections in the lower system reaches and making some approximations for erosion in the upper slough reaches (relatively small), we estimate that about 1.2 million cubic yards of sediment have been eroded from the channel and banks during the intervening 42 year period. About 60% was eroded between CS-1 and CS-2 (Figure 6).

b. Wetland Areas and Hydraulic Geometry Relationship

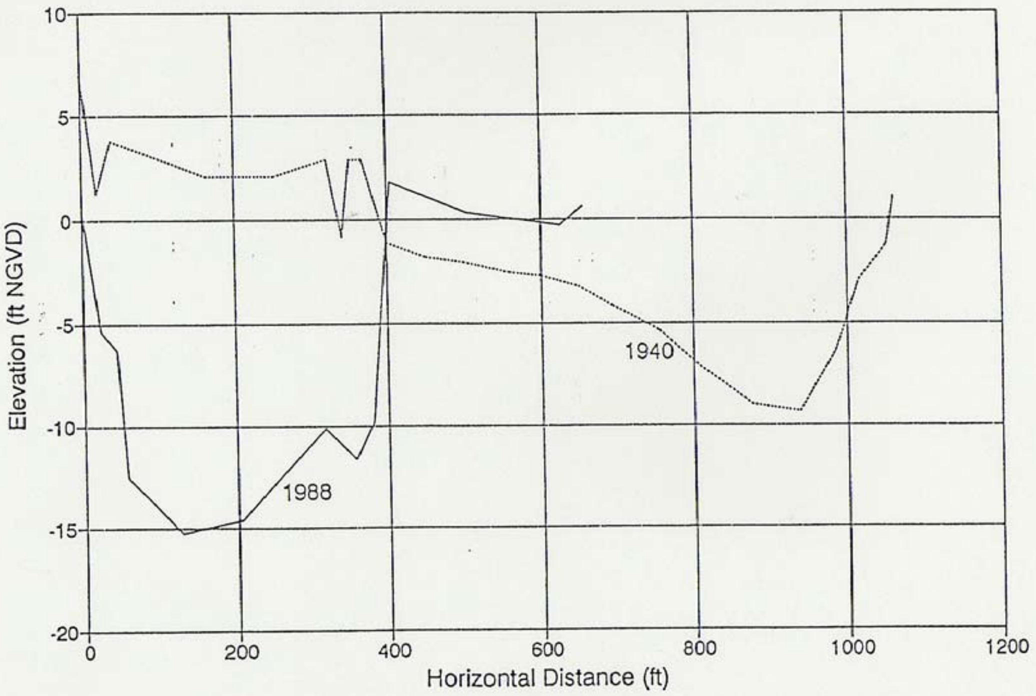
Based on available maps, it appears that presently an area of about 2,641 acres is subject to tidal circulation upstream of the Highway 1 bridge. As summarized in Table 1, it appears that historically about 2,875 acres were tidally influenced area upstream of Highway 1. Of these 404 acres are represented by the open water of the main slough channel and 2,237 acres are tidal wetland or mudflat. An area of 234 acres are currently diked wetlands or salt ponds and are not subject to tidal exchange at this time. Specific interest has been expressed in the National Estuarine Reserve Wetlands both as a result of severe erosion problems at the reserve and because of the potential increased erosion downstream by the reopening of these wetlands to tidal action in 1983-84 For these reasons, the Reserve wetland (referred to as the South Marsh/Parson's Slough areas) are tabulated separately in Table 1. In addition to the Reserve Wetlands, other areas have been restored to tidal action in the past decade. However, the net effect on downstream erosion from these is much less



Philip Williams & Associates, Ltd.
Consultants in Hydrology

1940 and 1988 cross-sections just upstream of the Highway 1 Bridge

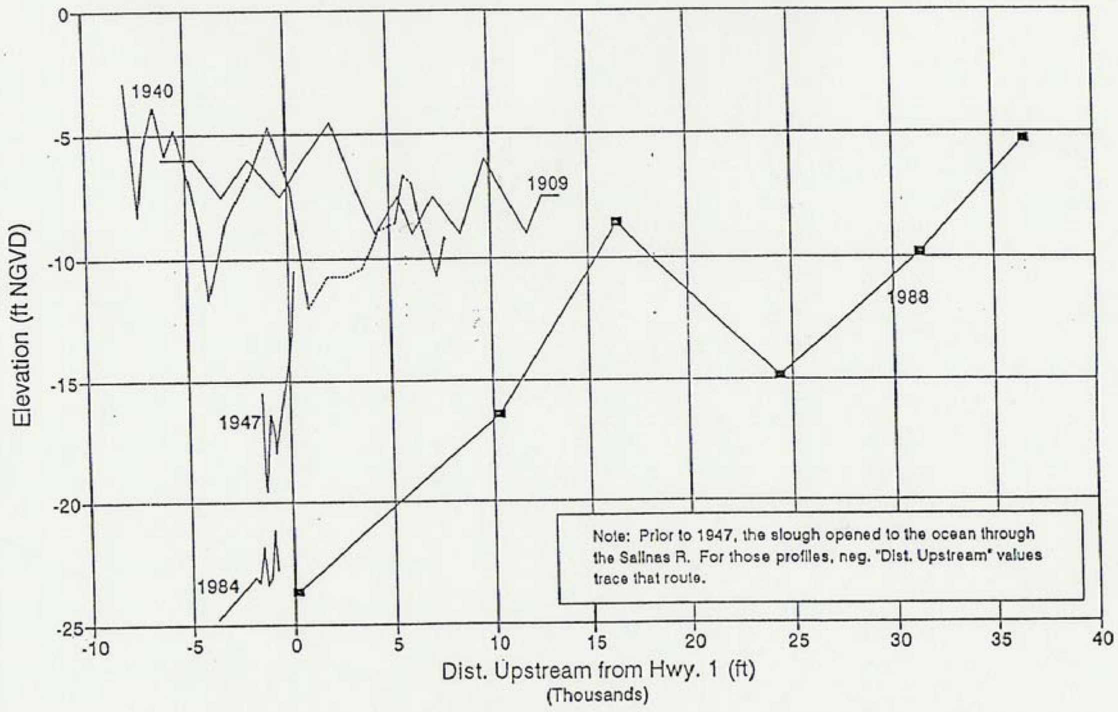
Figure 8



Philip Williams & Associates, Ltd.
Consultants in Hydrology

Comparison of the 1940 and 1988 cross-sections at 1.5 and 1.9 miles respectively upstream of Highway 1

Figure 9

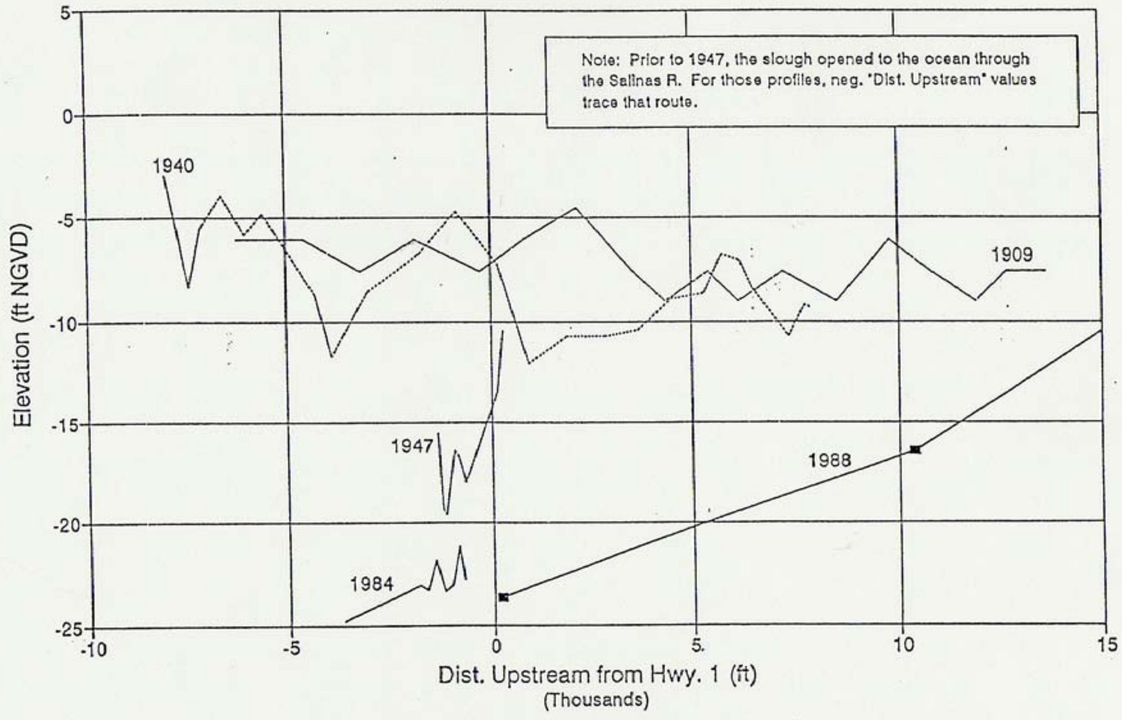


Note: Prior to 1947, the slough opened to the ocean through the Salinas R. For those profiles, neg. "Dist. Upstream" values trace that route.

Philip Williams & Associates, Ltd.
Consultants in Hydrology

Longitudinal Profile of Elkhorn Slough at the Highway 1 Bridge

Figure 10a



Note: Prior to 1947, the slough opened to the ocean through the Salinas R. For those profiles, neg. 'Dist. Upstream' values trace that route.

Philip Williams & Associates, Ltd.
Consultants in Hydrology

Longitudinal Profile of Elkhorn Slough at the Highway 1 Bridge (magnified view)

Figure 10b

than that of Reserve Wetlands. For example, the North Marsh (118 acres) contributes relatively little tidal prism because of controlled tidal exchange, while areas of the former salt ponds (250 acres) have been recently reconfigured to reduce tidal exchange.

An initial estimate of the potential diurnal tidal prism[1] in the system was made as follows: For the main slough open water reaches, the estimated area was multiplied by the diurnal tidal range (5.51 feet). For tidal wetlands, the tidal prism represents the volume of water in the channels and stored on the marshplain areas. Typically, for a given marsh, this is calculated using detailed topographic maps and channel surveys. As these are unavailable for Elkhorn Slough, regression relationships between marsh area and tidal prism measured at other California tidal wetlands were used (Haltiner and Williams, 1987). These may somewhat underpredict the Elkhorn Slough wetlands as a result of the increased erosion of slough channels during recent years.

For the South Marsh/Parson's Slough area, the limited available data indicate that the ground elevation is at about 0.0. feet NGVD. This is well below the typical marshplain elevation, which normally forms at an elevation approximately equal to MHHW (about 2.7 feet NGVD). If correct, this suggests that marshplain has subsided about 2.7 vertical feet from its natural elevation. This amount of subsidence has been observed in other coastal wetlands which have been diked off from tidal circulation for an extended period. The subsequent sediment drying results in a non-reversible compaction of the clay soils and the oxidation of the organic portion of the marsh soil. Subsidence of 3 to 5 feet has been documented in San Francisco Bay marshes. As a result of this subsidence, when the South Marsh and Parson's Slough areas were reopened to tidal circulation, the resulting tidal prism was much greater than is normal for a salt marsh of comparable size. The California Department of Fish and Game 1983 restoration plan for the marsh recognized the problem of subsidence. The plan was an attempt to create a diversity of habitat by excavating portions of the subsided marsh and using the material to create some higher marshplain areas which would support wetland vegetation. While the 1983 Department of Fish and Game plan has been criticized for both aesthetics and performance, these particular concepts appear to have been sound. Without the grading, the area would have all been intertidal mudflat. The grading provided some diversity. However, the plan did not recognize the impacts of the greatly increased tidal prism, which is responsible for the deep scour hole under the SPRR bridge, the deepening of Parson's Slough, perimeter erosion, and the contribution of increased tidal flows to erosion in Elkhorn Slough.

Although the opening of these wetlands added only about 25% of wetland area to the slough system above Highway 1, the addition of tidal prism was about 37 percent (Table 1).

---

[1] "Potential" tidal prism is the volume of water contained between high and low tide. "Actual" tidal prism is the volume of tidal water that flows in and out of the system during a tidal cycle. In areas with full tidal circulation they are identical. Where damped tidal exchange occurs, the actual tidal prism is less than the potential. "Diurnal" tidal prism refers to the tidal prism between MHHW and MLLW based on the most recent 19-year tidal epoch.

TABLE 1

ESTIMATED WETLAND AREA AND POTENTIAL DIURNAL TIDAL PRISM

	Open Water (main slough channel)		Tidal Wetland		Total Tidal Area		Diked Wetland
	Area (acres)	Tidal Prism (acre-feet)	Area (acres)	Tidal Prism (acre-feet)	Area (acres)	Tidal Prism (acre-feet)	Area (acres)
Elkhorn Slough (not including South Marsh)	404	2,226	1,703	1,703	2,107	3,929	234
South Marsh/ Parson's Slough			534[1]	1,465	534	1,464	
Total (Elkhorn Slough at Highway 1 bridge)	404		2,237		2,641	5,393	234

---

[1] Using the 1987 aerial photo, this area was estimated to be about 420 acres.

Some discussion of the post-harbor entrance channel changes can be made based on these tidal prism estimates and "hydraulic geometry" relationships. Hydraulic geometry refers to an analysis in which slough channel characteristics such as depth or cross-section area are related to a "dominant discharge". The approach was originally applied to fluvial systems by Leopold and Maddock (1953) and later applied to a tidal slough in the early 1960's (Myrick and Leopold, 1963). It has been extended to California tidal slough systems for use in designing slough channels in wetland restoration projects (Haltiner and Williams, 1987). The basic concept is that the geometry of tidal slough channels is determined by the tidal prism which they convey. Our observations on a number of marshes indicate that the maximum channel depth and cross-section and area for slough channels evolves to an equilibrium condition based on the tidal prism. These relationships apply to slough channels subject to full tidal circulation, and not affected by wave action, diking, dredging, etc. Clearly Elkhorn Slough in its pristine condition did not function like an estuarine slough; wave action and sand transport at the mouth of the system created a sill which maintained the actual tidal prism below the potential tidal prism. However, the opening and maintenance of the harbor mouth has allowed Elkhorn Slough to evolve in a manner similar to estuarine sloughs, which are typically subject to full tidal circulation.

There are some significant differences: in addition to increasing tidal flow, the harbor mouth dredging represents a form of downstream "base level" lowering. This may increase channel degradation beyond that solely due to tidal scour. In some respects, this is analogous to the "gully" formation which occurs in fluvial systems when downstream base level is lowered. Although the flow volume may remain unchanged, a "knickpoint" or gully headwall moves upstream through the primary and secondary channel in successive phases. Downstream primary channels erode initially, and the erosion process proceeds upstream. Over time, secondary branch channels then respond to the drop in base level of the main channel. In tidal systems, the effect may be increased because as upstream intertidal areas erode, the tidal prism (discharge) actually increases and initiates new erosion downstream in the main channel. However, when the base level decrease is subtidal, the actual fluid turbulence and gully formation process is likely to be less erosive than in a fluvial system.

An example of slough channel erosion resulting from downstream dredging in a system comparable to Elkhorn Slough can be observed in Morro Bay, California; this small central coast harbor was also created by dredging a previously smaller natural entrance channel. The entrance and main harbor channel are now maintained by periodic dredging.. The interior portions of Morro Bay are shallow and subject to full tidal circulation. Studies have shown that the intertidal mudflats and salt marsh areas of Morro Bay are depositional as a result of fluvial sediment transport by creeks, aeolian movement of sand from the dunes, and littoral transport of sand through the harbor mouth (Haltiner and Thor, 1991). However, the main and secondary slough channel systems in the Bay are eroding. Review of historic maps and photos (Asquith, 1991) shows that the channels have deepened and grown in length in response to the main harbor dredging. Thus, the downstream base level lowering by dredging appears to induce additional channel scour beyond that due solely to tidal action.

While the Elkhorn Slough channel erosion is not identical to that observed in estuarine systems, it is similar and the hydraulic geometry of the equilibrium system can be expected to be similar. As discussed earlier, we initially estimated the potential diurnal tidal prism in the Elkhorn Slough system (Table 2).

Extending the hydraulic geometry relations in our 1987 work (which were developed from data on smaller marsh systems), some approximate predictions of channel configurations can be made. These are also summarized in Table 2. At the Highway 1 bridge, based solely on tidal prism, a thalweg depth of about 24 feet and a channel area of 4,200 square feet would be predicted. The actual depth is 25.5 feet; cross-section area is 6,400 square feet. For a natural marsh of this size (2,641 acres), a tidal prism of 2,700 acre-feet would be predicted. Our estimate of the current tidal prism is 5,393 acre-feet.

For the South Marsh, the actual tidal prism is 1,464 acre-feet compared with that predicted for a non-subsided marsh of the same area (534 acres) of 550 acre-feet. Based on the actual tidal prism, a maximum channel depth at the SPRR railroad bridge would be estimated to be about 16 feet and cross-sectional areas of 1800 square feet would be predicted. An approximate depth of 20 feet below MHHW currently occurs. The actual cross-section is about 2,000 square feet at this time. Because the opening is confined to the narrow opening under the bridge, it is deeper than predicted.

Based on these data, some general observations can be made. The 1946 harbor opening allowed Elkhorn Slough to respond as a typical fully-tidal estuarine slough channel. While much greater than the pre-harbor conditions, the channel dimensions are within the general scale of size for a marsh area of this size and tidal prism. However, the cross-sectional area and channel width at Highway 1 exceed predictions substantially. The reason for this may be the overall lack of sediment in the system or the specific effect of dredging in the harbor mouth. The depth of the channel at the Highway 1 bridge is probably not increasing very much at this time. Channel erosion is probably occurring further up the channel, perhaps between miles 2 and 4 (Figure 10a). In the south marsh, the tidal prism greatly exceeds that of a natural marsh due to subsidence. During the past decade, the opening under the SPRR tracks has responded to this large tidal prism. Channel deepening in Parson's Slough has probably slowed at SPRR bridge, but may now be occurring further upstream.

Overall, the lack of sediment in the system as a result of the 1910 diversion of the Salinas River and the ongoing dredging of the harbor entrance have prevented a new stable equilibrium from developing.

TABLE 2

HYDRAULIC GEOMETRY RESULTS[1]

	Tidal Prism (acre-feet)		Maximum Channel Depth (feet)			Cross-Sectional Area (square feet)			Top Width (feet)		
	Actual	Pred. Equil.[2]	Actual	Pred.[3]	Pred. Equil.[2]	Actual	Pred.[3]	Pred Equil.[2]	Actual	Pred.[3]	Pred. Equil[2]
Elkhorn Slough (not including South Marsh)	3,929	2107	NA	21	18	NA	3,300	2,100	NA	360	110
South Marsh	1,464	550	±20	16	11	±2,000	1,800	1,000	125[4]	275	180
Total (Elkhorn Slough at Highway 1 bridge with South Marsh)	5,393	2,700	25.5	24	19	6400	4,200	3,000	650	400	300

---

[1] All depth and areas are measured below MHHW.

[2] Based on the tidal prism considered to represent equilibrium conditions in a tidal marsh of the area.

[3] Based on the actual tidal prism.

[4] Confined by bridge.

III. MODELING STUDY

A. INTRODUCTION

To quantify the effects of the 1946 Harbor opening and the 1983-84 marsh levee breaches (which opened the South Marsh/Parson's Slough to tidal circulation), and to identify potential erosion solutions, a computer modeling study was conducted. A description of the model and the input date are included in the following sections. The following configurations were analyzed:

1. 1940 conditions (pre-harbor): No upstream levee breaches;
2. 1940 conditions with upstream levee breaches (to determine what the effect of the 1983-84 levee breaches would have been without the 1946 harbor opening);
3. 1947 conditions without levee breaches (to determine the effect of the new entrance harbor);
4. Present conditions (with the levee breaches);
5. Present conditions (without the levee breach);
6. Present conditions with the proposed rock sill (elev: -5.0 feet NGVD);
7. Present conditions with the proposed rock sill (elev: -3.0 feet NGVD).

The intent of the model runs was to identify the erosion causes and determine if a rock sill across the channel at the Highway 1 bridge is a feasible erosion solution.

B. MODEL DESCRIPTION AND INPUT DATA

1. Description of ESTFLO

All numerical simulation of the Elkhorn Slough system was conducted using ESTFLO, a one-dimensional hydrodynamic model simulating unsteady, well-mixed, subcritical, gradually varied flow. ESTFLO uses a "three-point" implicit finite difference method to solve the conservation of mass and momentum equations, in the longitudinal direction (Sobey, et. al. 1980). The program uses the Thomas algorithm to solve the matrix resulting from the implicit differencing.

A staggered grid is employed in the finite differencing; at each grid point, head is computed, while in between each grid point, discharge is calculated. The algorithm employed requires a uniform spatial step between grid points. Our model of Elkhorn Slough used a 300 meters (984 feet) space step. All input and output in the model uses SI units. We converted the input and output into English units accordingly.

Friction effects are accounted for through the Darcy-Weisbach friction factor. This factor is calculated using roughness height for each reach. The Colebrook-White formula is used in the conversion, using the assumption that the flow is characterized as "rough."

Version 2B of ESTFLO was developed by Rod Sobey (Department of Civil Engineering, University of California-Berkeley). For the modeling of Elkhorn Slough, we used version 3.0, a version of 2B modified to accommodate non-uniform cross-section geometries.

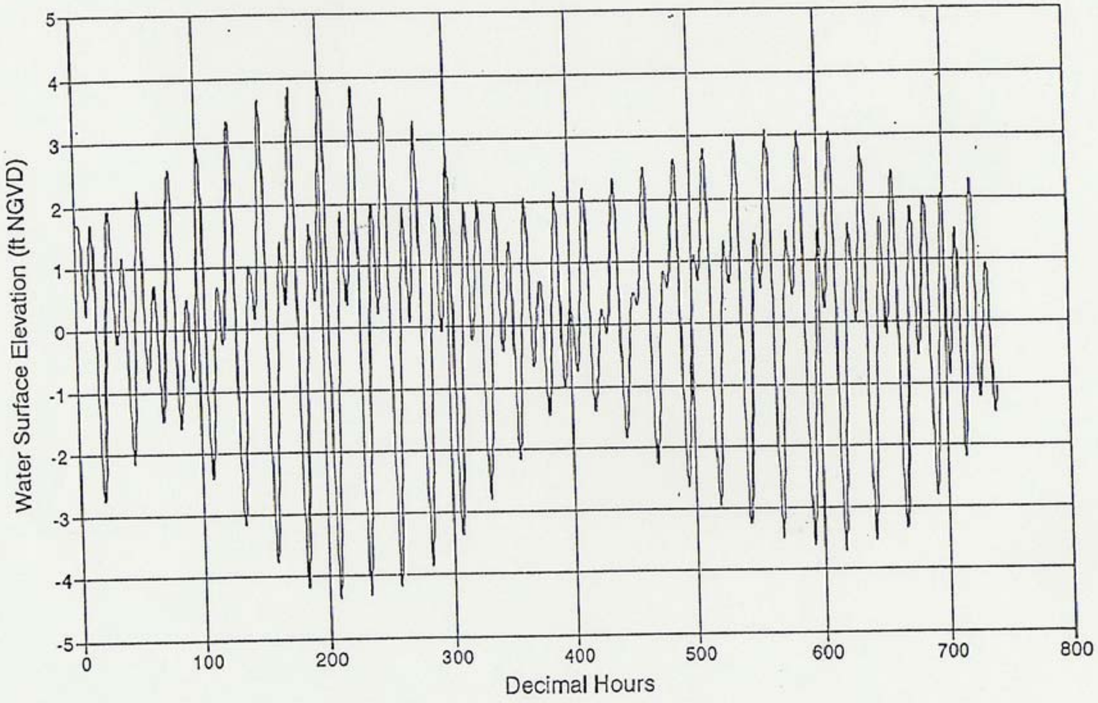
2. Input Data

To model of the Elkhorn Slough system, we specified the following characteristics in ESTFLO:

- Tidal cycle
- Network layout and boundary conditions
- Initial conditions and time step
- System geometry and roughness

a. Tidal Cycle

To simulate the effects of tidal action on the slough system, we calculated a mean monthly tide for the tide station located at the Railroad Bridge at Elkhorn Slough. The mean monthly tide simulates the full range of high and low tides which occur during the entire year. This mean monthly tide was derived from the mean monthly tide for San Francisco, California, as computed by the National Oceanic Atmospheric Administration (NOAA). NOAA obtained this tide by dropping out the long-term constituents of the tidal cycle, leaving a tidal month that closely matches the hourly duration characteristics of a full tidal cycle, including the effects of the spring and neap tides. In all our runs, we used a tidal duration of 742 hours, or approximately 31 days. Figure 11 shows the mean monthly tide used in our simulation.



Philip Williams & Associates, Ltd.
Consultants in Hydrology

Representative tidal month used in simulations

Figure 11

b. Network layout and boundary conditions

In performing calculations, ESTFLO analyzes the system as a network of reaches. Each reach consists of a set of nodes, separated by a uniform distance. We used a 300 meters space step between nodes for all of our simulations.

These reaches are joined together into a system by specifying boundary conditions at the nodes at either ends of the reaches. At the junction of two or more reaches, we defined the head nodes to have identical values (to satisfy conservation of energy). At the ends of the reaches, we either defined the discharge to be zero (i.e. a dead-end reach), or equal to the tidal boundary condition. Figures 12a and 12b show the layout of the link-node models used.

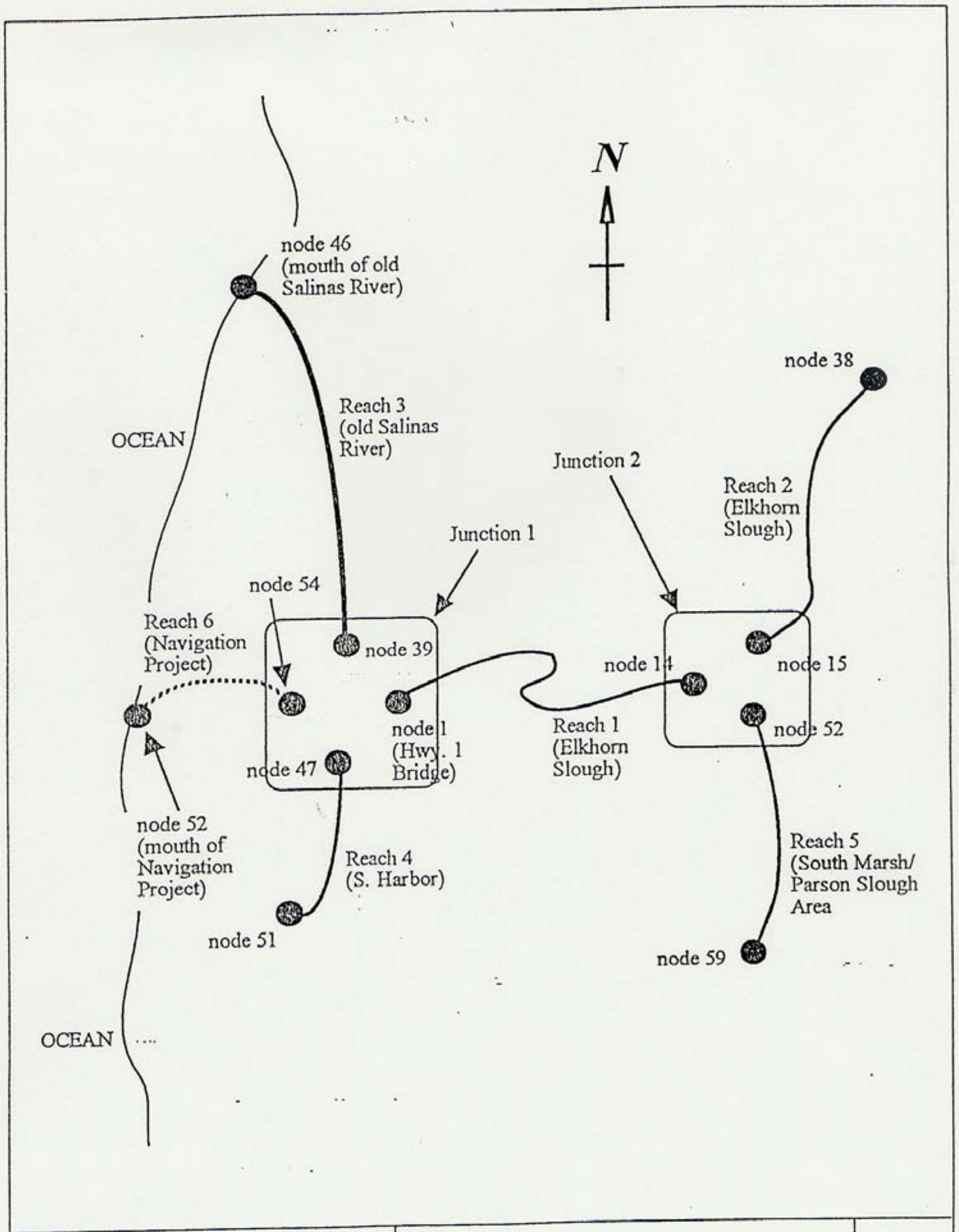
Figure 12b shows the model layout for our simulations of present day conditions. Reach 1 represents the channel and jetty created by the Federal Navigation Project. Reach 4 and 5 represent North and South Harbor, respectively. Reach 6 simulates the South Marsh/Parson Slough Area, and reaches 2 and 3 represent Elkhorn Slough itself. Different conditions were simulated by removing or adding the appropriate reaches. For instance, the 1983 Conditions were described by removing reach 6 from the system in Figure 12b.

In evaluating the effect of a rock sill under the Highway 1 Bridge, we removed the North and South Harbor reaches from the simulation. The inclusion of these reaches in the presence of the sill caused the numerical solution to become unstable. (In this type of numerical modeling, the inclusion of a junction of four channel links [as shown in Figure 12b] occasionally results in a numerical instability in which the finite difference scheme cannot converge to a solution. This may also occur with very shallow channels, which become dry at low tides.) The removal of these arms had a negligible effect on the modeled shear stress distribution in the immediate vicinity of the junction.

The Highway 1 bridge is shown as node 4 in the system (in reach 2). The tidal boundary condition was applied to node 1 in reach 1, which represents the western limit of the Navigation Project jetty.

In our simulation of the 1940 and 1947 conditions, we used the link-node layout shown in Figure 12a. Reaches 1 and 2 represent Elkhorn Slough. Reach 3 represents the old Salinas River north of Elkhorn Slough. Reach 4 represents the Salinas River south of Elkhorn Slough (approximately the same distance the South Harbor is from Elkhorn Slough in the present-day conditions). Reach 6 simulates the South Marsh/Parson Slough Area. Reach 7 describes the Federal Navigation Project immediately after construction in 1947 (and thus was left out in the simulation of the 1940's condition).

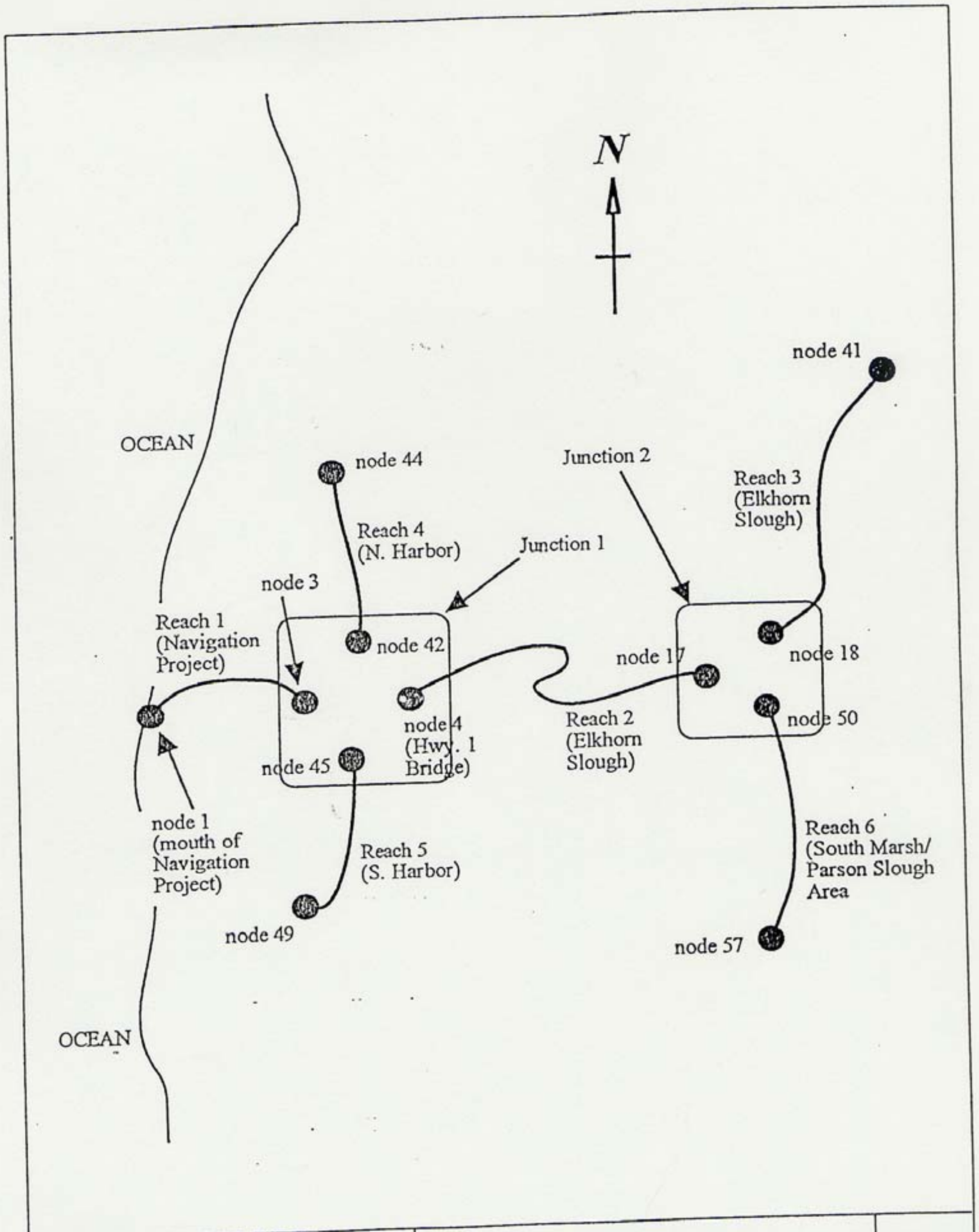
In our simulation of the 1940 conditions, the Highway 1 bridge is node 1 (in reach 1). We applied the tidal boundary at the mouth of the old Salinas River (node 46 in reach 3). To model the 1947 condition (after construction of the Navigation Project), we applied the tidal boundary at both the mouth of the old Salinas River (node 46) and at the mouth of the



Philip Williams & Associates, Ltd.
Consultants in Hydrology

Link Node Configuration
(Pre-harbor Opening)

Figure
12-a



Philip Williams & Associates, Ltd.
Consultants in Hydrology

Link Node Configuration
(Post-harbor Opening)

Figure
12-b

Navigation Project (node 52 in reach 7). Reach 5 was added in later simulations to investigate the effect of the levee breaches had they occurred in 1940.

c. Initial conditions and time step

We started all head nodes in the link-node system at the first high water in the mean monthly tide (1.72 feet NGVD). All discharge nodes were started at zero.

All conditions simulated, except for the 1947 conditions (without levee breaches), used a time step of 120 seconds. For that exception, we used a time step of 180 seconds, because the shorter time step caused the solution to become unstable. (The 120 second time step may have been too small, permitting numerical reflections off of the reach junctions to propagate through the solution, eventually resulting in an indeterminate solution.)

d. System geometry and roughness height

Bathymetric data used in defining the system geometry was obtained from historical maps and recent studies of the area. To describe the Present Conditions in Elkhorn Slough, we used cross-sections from 1988. The location of six cross-sections available from this study are marked in Figure 6.

Present conditions in the North and South Harbor were taken from surveys done on July 5 and 24, 1984, by Towill, Inc. for the U.S. Army COE. The 1984 bathymetry under the old Highway 1 bridge was obtained from As Built drawings from the State of California Department of Transportation (Caltrans) dated December 5, 1985.

Conditions in 1940 and 1947 were obtained from COE cross-sections made in 1940 and 1947. The 1940 soundings included Elkhorn Slough up to 14,000 feet upstream from the Highway 1 bridge, and the Old Salinas River from approximately Moss Landing to the mouth of the River.

In the upper reaches of Elkhorn Slough, we used the 1988 upstream cross-sections to simulate early conditions (1940). Channel degradation in the upper reaches of Elkhorn Slough appears to be relatively small.

The geography of the South Marsh/Parson Slough Area was obtained from enlargements of U.S. Geological Survey (USGS) 7.5 minute Quad maps. We characterized this area as a basin with a bottom elevation of 0 feet NGVD. A channel extended through the basin, starting with an invert elevation of -20 feet (-6.10 meters) NGVD at the junction with Elkhorn Slough, and rising to an elevation of -6.56 feet (-2 meters) NGVD at the end of the marsh reach.

The historical maps used in obtaining cross-sections for 1940 and 1947 (as well as thalweg elevations for 1909) were all referenced to the local mean lower low water (MLLW) at that time. To enable us to make comparisons across time, we referenced all elevations to the National Geodetic Vertical Datum (NGVD), also known as the Mean Sea Level of 1929.

The 1909, 1940, and 1947 data were corrected by using information provided by NOAA/National Ocean Service (NOS) for the Elkhorn Slough Railroad Bridge at Moss Landing (Station 941 3663), and by assuming MLLW increases approximately 5 inches every century. The NOS figures specified the value of different tidal datums with respect to MLLW, for the period of July 1976 to September 1977.

To account for friction effects in the system, we set roughness height to 5 cm for all reaches.

3. Model Output

ESTFLO computes the head and discharge at all nodes in the system. We present the output and analysis at the Highway 1 Bridge, cross-section CS-2, and cross-section CS-3, with output every half-hour at those sections.

Using the discharge and head information, we computed mean velocity over each cross-section, and plotted the shear stress distribution, as a function of percent of time of exceedence. Mean wall shear stress at the above sections was calculated using the following equation (Fischer, et al 1979):

$$\tau_0 = \rho g R_h S$$

where:

τ_0	is mean wall shear stress
ρ	is density of water
g	is gravitational constant
R_h	is hydraulic radius
S	is energy slope

Energy slope is computed using a forward-differencing scheme. Hydraulic radius is calculated as the mean of the hydraulic radii at the section and the section one node upstream.

While it is clear that erosion results from increased shear stress, the actual onset and rate of erosion is difficult to predict. Channel bed erosion begins when the bed shear stress exceeds a critical threshold value. This threshold is a function of the bed material density and cohesiveness, and varies. In general, the critical shear stress threshold ranges from about 0.5 to 2.0 pascals (Pa) (Nicholson and O'Connor, 1986). In the following model studies, the change in a bed shear stress between 0.0 and 2.0 pascals is analyzed.

C. MODELING RESULTS

As described previously, the model was run in different configurations to evaluate historical changes and evaluate a preliminary solution. The modeled runs were:

Run #1	1940 conditions (pre-harbor): No upstream levee breaches
Run #2	1940 conditions with upstream levee breaches (to determine what the effect of the 1983-84 levee breaches would have been without the 1946 harbor opening)
Run #3	1947 conditions without levee breaches (to determine the effect of the new entrance harbor)
Run #4	Present conditions (with the levee breaches)
Run #5	Present conditions (without the levee breach)
Runs #6-9	Present conditions with a level rock sill (elevs: -5.0, -3.0, -2.0 feet NGVD at Highway 1)
Runs #10-11	Present conditions with a notched rock sill (elevs: -5.0 and -3.3 feet NGVD at Highway 1)
Run #12	Present conditions with a rock sill (elev -2.0 feet NGVD at Highway 1) and a rock sill at the SPRR tracks in Parson's Slough (-3.0 feet NGVD).

As described in section B, the output for each model run consists of discharge and water elevation at each cross-section throughout the representative tidal month. For use in erosion analysis, discharge and elevation were converted to an average cross-section velocity and shear stress. These result in an enormous amount of data output which is not feasible to include directly in the report. Since most of the historic changes of interest have been in the lower reaches of the slough, we present the results primarily for the reach at the Highway 1 bridge and the next reach upstream (CS-2). For these two locations, plots of the velocity and the shear stress distribution during the tidal month are included in Appendix C. For comparative evaluation, the estimated shear stress distributions for various combinations of the runs are presented in Figures 13 through 19.

Figure 13 presents the shear stress distribution for the pre- and post-harbor entrance conditions at the Highway 1 bridge. The enormous increase in the frequency of higher shear stress during both ebb and flood tides is evident. Figure 14 represents the same comparison further upstream (CS-3). The increased shear stress is evident, although not as great as at Highway 1. Greater influence of the ebb tide on shear stress is evident.

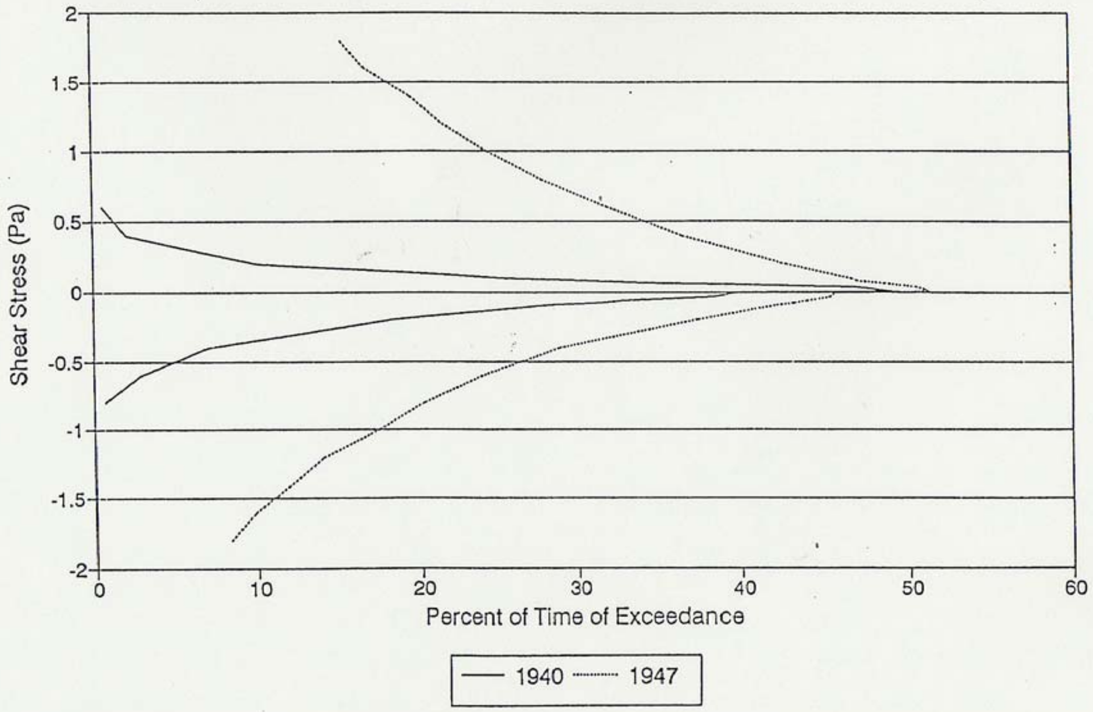
Figure 15 represents a hypothetical comparison, showing the shear stress at Highway 1 prior to the new harbor opening with and without the upstream levee breach. The results indicate a somewhat increased shear. However, the constricted Salinas River mouth still precludes full tidal circulation and high shear.

Figure 16 depicts model results for the present bathymetry at Highway 1 with and without the upstream levee breaches. These indicate a significant increase in shear stress associated with the additional tidal prism added by the 1983-84 levee breaches. While an increase is expected, the magnitude of the increase is surprising. Our hydraulic geometry results indicate that the levee breaches increased tidal prism by about 37 percent, yet the shear stress increase are much greater.

Figures 17, 18, and 19 show the effects of our initial sill configuration. Our initial runs used a level sill with elevation of -5.0 feet NGVD. When this did not markedly reduce the velocity distribution, we raised the sill elevation to -3.0 feet NGVD. This results in an enormous increase in the shear stress at the sill (Figure 17) and a reduced shear stress upstream at CS-2. However, the CS-2 shear stress distribution was still substantially higher that the 1940 condition at this location. Therefore, we made a series of additional runs to test various solution scenarios. Figure 18 shows the stress results at CS-2 with a Highway 1 rock sill at elevation -2.0 feet, and a run with a rock sill at the SPRR tracks (-3.0 feet) at the Highway 1 rock sill (-2.0 feet). These show a substantial reduction of the CS-2 shown to about one-third of its present value. While neither of these provides the level of shear shown for the 1940 conditions, based on typical critical threshold shear values, they would be adequate to prevent further erosion of the slough and initiate deposition.

Figure 19 depicts the CS-2 shear stress values for a notched rock sill at Highway 1. This sill opening would have bottom elevations of either -5.0 or -3.3 feet. The 5.0 feet opening reduces the CS-2 shear by half, while the -3.3 feet opening reduced the shear to one-third of its present level. Although more detailed modeling is required to design the structure, it is likely that a notched weir with these configurations would adequately reduce erosions rates.

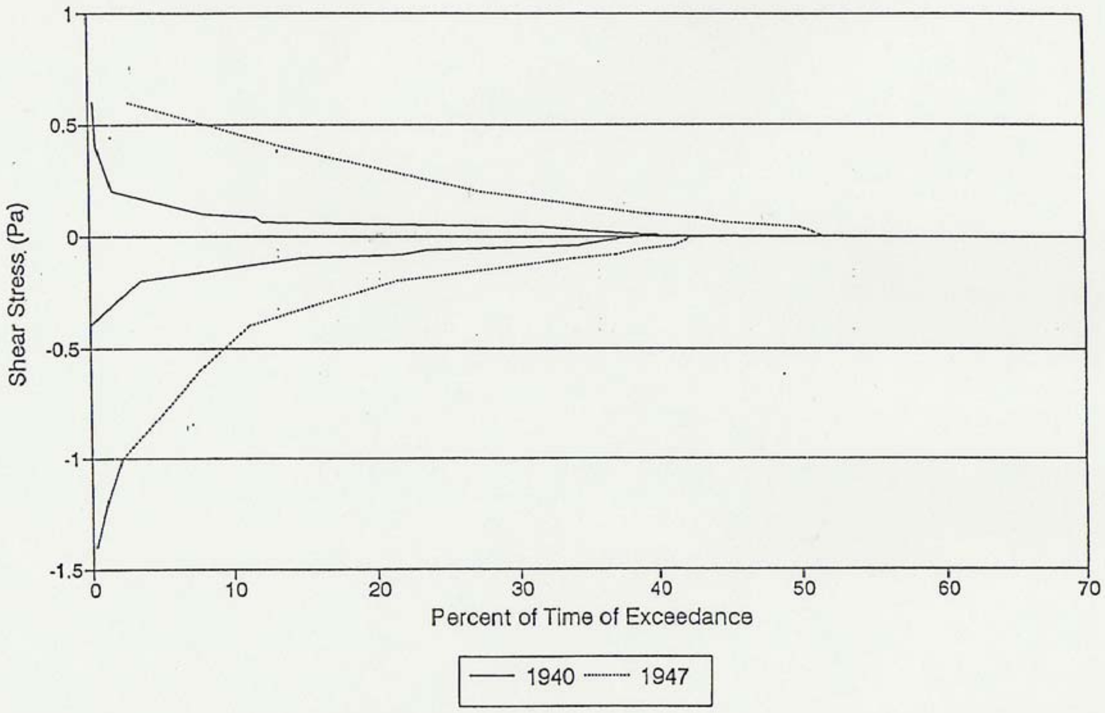
The implication of the modeling results are described in the following sections, and some conceptual level designs are presented in Section V.



Philip Williams & Associates, Ltd.
Consultants in Hydrology

Shear stress distribution at the Highway 1 Bridge for 1940 and 1947 Conditions

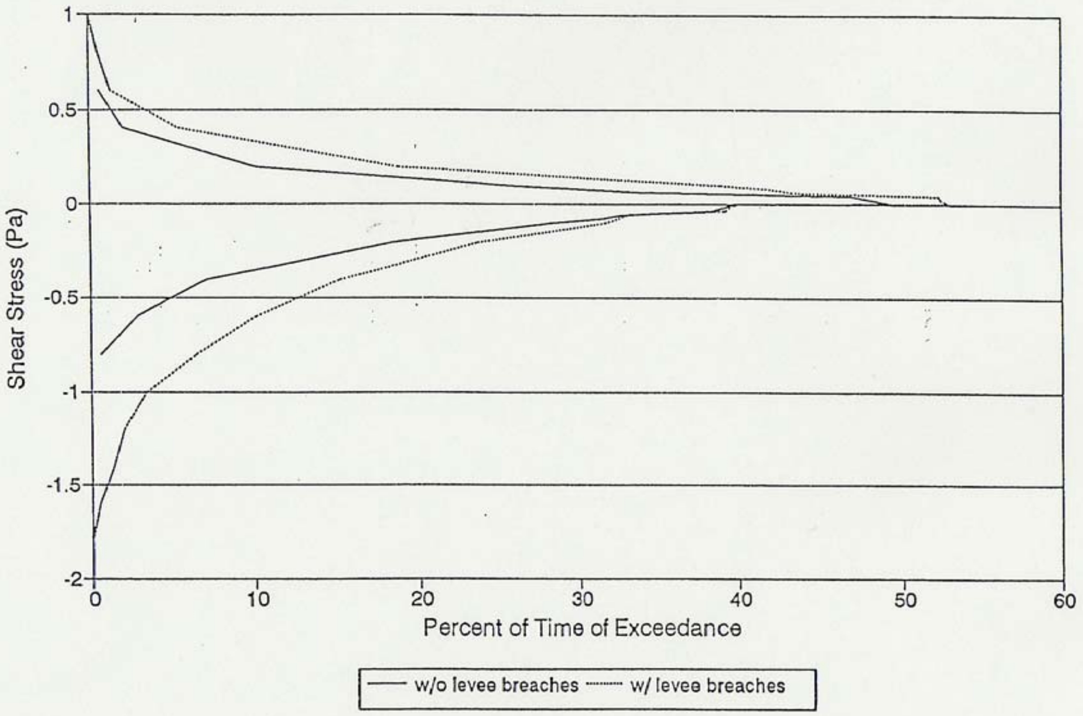
Figure 13



Philip Williams & Associates, Ltd.
Consultants in Hydrology

Shear stress distribution at CS-3 for the 1940 and 1947 Conditions

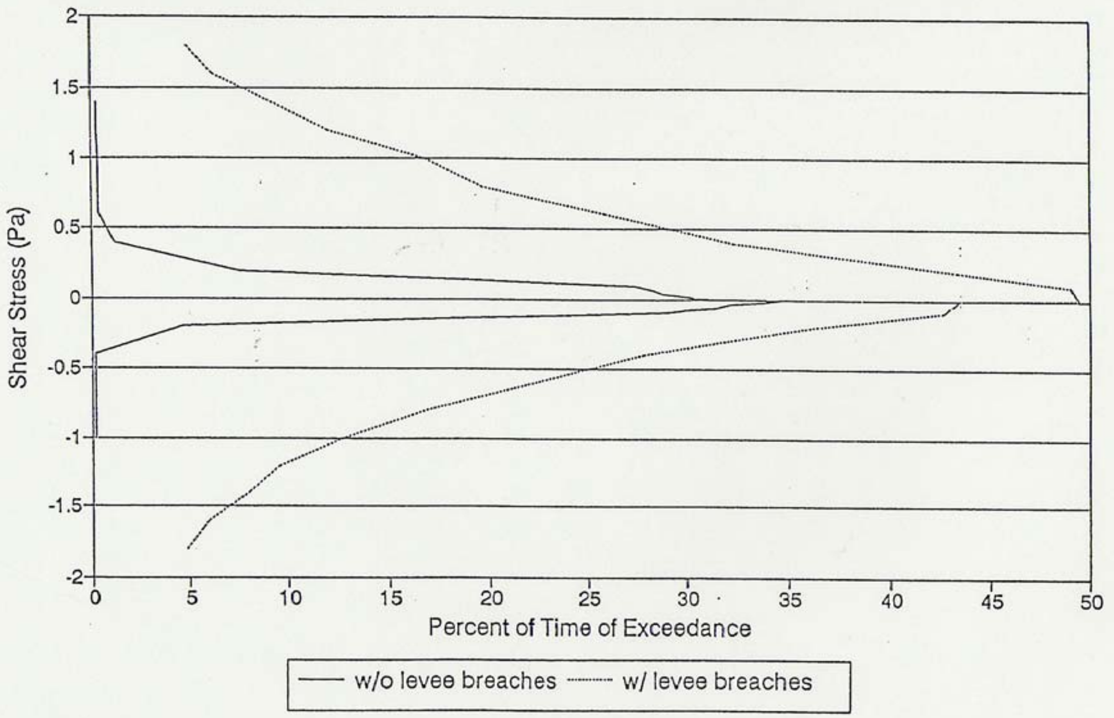
Figure 14



Philip Williams & Associates, Ltd.
Consultants in Hydrology

Shear stress distribution at the Highway 1 Bridge with 1940 bathymetry with & without the levee breaches

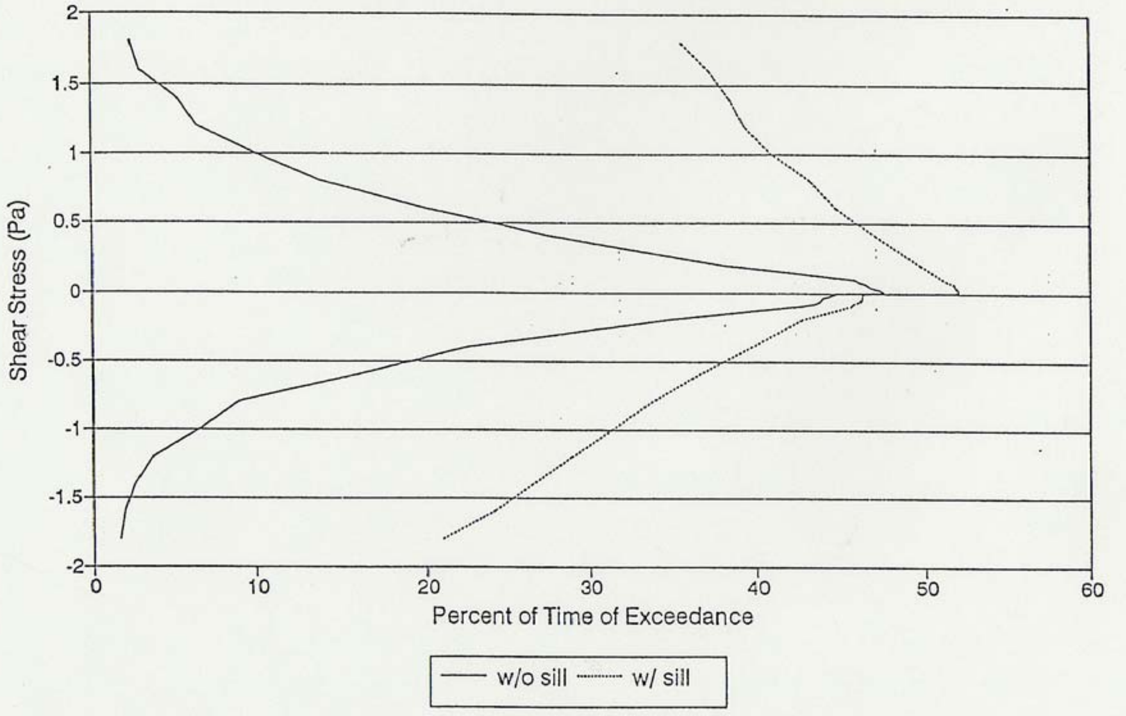
Figure 15



Philip Williams & Associates, Ltd.
Consultants in Hydrology

Shear stress distribution at Highway 1 Bridge with
Present bathymetry with & without the levee breaches

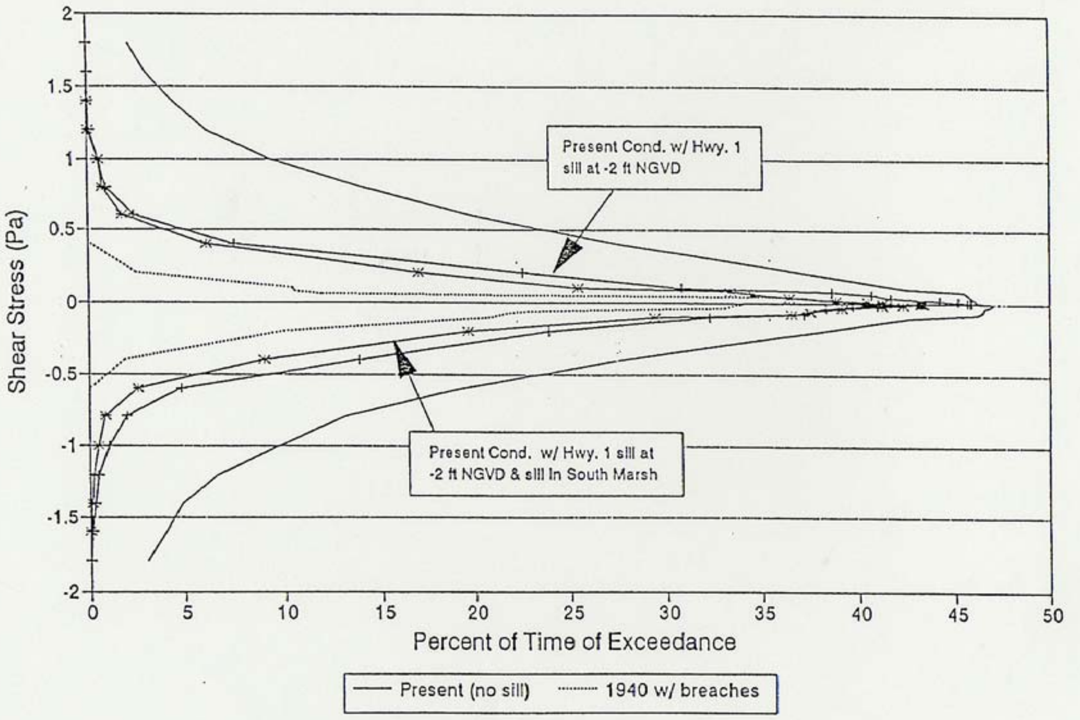
Figure 16



Philip Williams & Associates, Ltd.
Consultants in Hydrology

Shear stress distribution at Highway 1 Bridge with Present bathymetry with & without the sill (-3 ft NGVD)

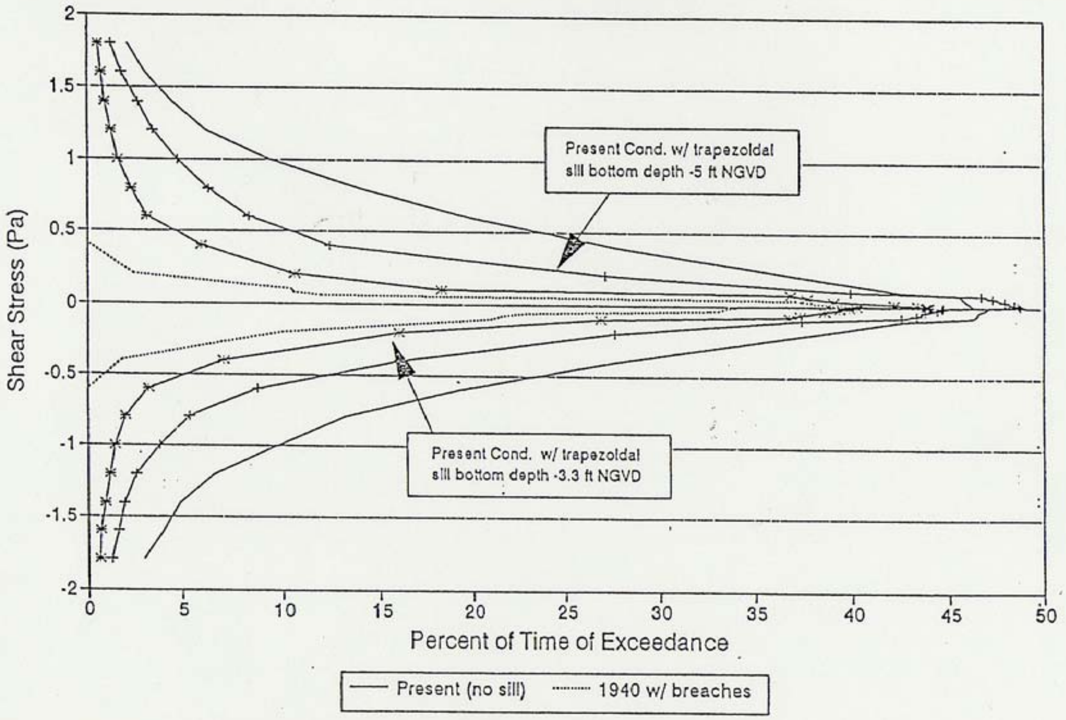
Figure 17



Philip Williams & Associates, Ltd.
Consultants in Hydrology

Shear stress distribution at CS-2 for different Present Conditions and 1940 Conditions with levee breaches

Figure 18



Philip Williams & Associates, Ltd.
Consultants in Hydrology

Shear stress distribution at CS-2 for different Present Conditions (e.g. trapezoidal sill at Hwy. 1) and 1940 Conditions with levee breaches

Figure 19

IV. OBSERVATIONS AND CONCLUSIONS

Based on the results of the field observations, the hydraulic geometry analyses and the hydrodynamic modeling, some reconnaissance-level observations and conclusions can be made:

1. The pre-1946 slough system had undergone significant alterations from a pristine condition. The most important of these were the 1910 diversion of the Salinas River and the diking and draining of various wetland areas. The loss of Salinas River inflow reduced freshwater inflow and most importantly, eliminated the major sediment supply to the entire system.

   The diking eliminated circulation from major wetland areas. It appears to have resulted in large scale subsidence of several feet over a large area; subsidence in the South Marsh/Parson's Slough area was especially important.

   Prior to 1946, the actual tidal exchange in the Elkhorn Slough, Salinas River, and other sloughs was relatively small in comparison to the enormous potential tidal prism because of the restricted exchange through the Salinas River Mouth.

2. The 1946 opening of the new harbor entrance and maintenance of the dredged entrance channel allowed full tidal exchange. The resulting higher tidal velocities initiated rapid erosion in the downstream reaches of Elkhorn Slough. A maximum degradation of about 15 vertical feet has occurred. The amount of channel degradation which has occurred since 1946 decreases further upstream. However, it appears that the channel and bank erosion is proceeding upstream and over time, more active erosion in the upper slough reaches may occur. The rate of channel deepening in the most downstream reaches has likely decreased. However, the channel is very actively widening in response to the increased channel depths. To date, an estimated 1.2 million cy of material have been eroded from the system. The erosion is causing significant loss of salt marsh and intertidal wetland habitat throughout the lower reaches of the system, converting these areas to subtidal habitat. Without the subsequent levee breaches, extensive erosion would still be occurring as a result of the 1946 harbor opening. Rapid erosion adjacent to the Highway 1 bridge would likely have slowed, but

active erosion would be occurring in the channel and wetlands further inland.

3. The levee breaches of 1983-84 significantly increased the tidal prism (estimate to be about 37 percent) to downstream reaches. The additional tidal prism has definitely increased erosion in the downstream reaches. The hydrodynamic model indicates a large increase in shear stress in these downstream reaches. The actual increase in erosion potential is difficult to quantify. The 1981 Caltrans bridge survey seems to indicate that most of the channel downcutting at Highway 1 had occurred prior to the levee breaches. Since then, bank erosion and channel widening have been the dominant erosion process. Our hydraulic geometry concepts would suggest that the additional tidal prism from the levee breaches is responsible for a depth increase of about 3 feet and an increase in channel cross-section of about 33% in the reaches below the Parson's Slough-Elkhorn Slough junction. The levee breaches would not have greatly increased erosion upstream of the junction.

4. Based on limited topographic data, it appears that prior subsidence had lowered the South Marsh and Parson's Slough area by 2 to 3 feet. When opened to tidal action in 1983-84 these areas contributed a large increase (37%) to the total tidal prism causing erosion downstream. Had these areas been opened to Elkhorn Slough without 1946 Harbor opening, they would have had little effect on the system. The sill at the mouth of the Salinas River would have continued to limit tidal exchange. However, because the main slough was subject to full tidal exchange, the 1983-84 opening allowed full tidal circulation into these areas.

   Because of the subsided nature of the South Marsh, the margins of South Marsh were subject to erosion and forces which did not exist prior to the diking off of these areas. In its pristine (pre-diked) condition, the margins of the marsh were protected by tidal marsh, just as the hillside-marsh interfaces are in marsh areas of the slough which were never diked.

5. A sill across the channel at the Highway 1 bridge can be designed to reduce tidal circulation and associated erosion. To replicate pre-harbor entrance channel conditions, it will have to substantially reduce the channel width and depth. A notched sill appears to be the preferable design to allow continued navigation between the slough and harbor. A sill across Parson's Slough at the SPRR bridge in the Reserve also appears desirable. In addition to reducing erosion in the South Marsh,

the reduction in tidal prism will reduce the size of the structure required at Highway 1.

6. The geomorphic response of the system to these structures will be gradual. Erosion will continue to occur until the slough invert is raised by subsequent deposition. The rate of restoration of the channel toward the pre-harbor conditions could be increased by addition of sediment to the channel or South Marsh. While this has significant regulatory and environmental implications, there are clear benefits from this considering the sediment-poor regime which currently exists. This could involve placement of dredge spoils upstream of the proposed sill or in the South Marsh area. The South Marsh would particularly benefit by the placement of sediment to recreate the historic marshplain. This would improve habitat, reduce internal erosion and reduce the downstream erosion by reducing tidal prism.

V. EROSION CONTROL ALTERNATIVES

A. NO PROJECT

The "no project" scenario considers the condition that no Federal action would be taken, and the present conditions of a dredged harbor entrance would be continued. Under this alternative, erosion of the channel bottom and banks and subsequent erosion of the marsh lands would continue to occur. The erosion damage, which has so far occurred primarily in the downstream half of the slough system, would gradually extend upstream. Over an extended period of time (50 to 100 years) the system would evolve until the channel and marsh system is in equilibrium with the tidal scour and sediment regime. Based on available data, it is not possible to predict the final configuration of the system in detail. Clearly, it would involve wider and deeper channels and reduced areas of marshplain and intertidal mudflats. The hydraulic geometry and modeling results suggest that the rate of channel deepening in the slough near Highway 1 has likely decreased. However, widening is still actively occurring, and erosion of marshes upstream is evident.

Based on available estimated habitat damage, the "no project" scenario does not represent a practical solution to the problems which are occurring. If a major erosion control project is not implemented in the short-term, we would recommend additional data collection to monitor the current rate of erosion and prediction of the equilibrium conditions and the time frame over which these might develop.

B. SHORELINE PROTECTION

Limited reaches of shoreline are currently protected by revetment. These include the Highway 1 bridge approaches, SPRR levee and structures, and some reaches of private property. However, the cost of providing continuous shoreline protection along the slough would be prohibitive and the ecological consequences unacceptable.

C. TIDAL BARRIER NEAR THE HIGHWAY 1 BRIDGE

1. Introduction

The concept of some type of tidal barrier at the Highway 1 bridge was contained in the original U.S. Army COE Harbor design guidelines in the early 1940's. The intent at this time was to prevent salt water intrusion problems to agricultural areas up the slough. This project was never implemented, though similar structures were built on the Old Salinas River Channel (the Potrero Road tidegates) and at Moro Coho Slough by local interests. While preventing upstream tidal circulation, these have had severe adverse ecological impacts.

The Elkhorn Slough Master Plan (ABA Consultants, 1989) recommends investigation of a submerged sill across the main channel of Elkhorn Slough at Highway 1. The intent would be to replicate the effect of the natural sill at the mouth of the Salinas River that existed prior to the harbor construction. The most likely location for the sill would be immediately upstream or downstream of the Highway 1 bridge, (see photos 6 and 7) with a number of different possible configurations.

A second constriction could be constructed at the SPRR bridge where Parson's Slough drains the South Marsh and adjacent wetlands.

These appear to be the most feasible approaches to arresting the erosion which has been ongoing for the past 45 years. In addition, they offer the potential for gradual future restoration of the pre-1946 bathymetry if this is desirable. This project would represent a major engineering structure, with significant environmental ramifications. The analysis, environmental review and compliance would represent a major percentage of the actual cost of constructing the project. However, in the absence of less structural solutions, this appears to be the preferred option.

The following sections describe the preliminary hydraulic modeling results, design concepts, and concept-level costs. A brief discussion of the environmental considerations is also included.

2. Model Results

The computer model was initially run with a uniform sill elevation at -5.0 feet NGVD for the cross-section at the Highway 1 bridge opening. A second run was made with a higher sill elevations of -3.0 and -2.0 feet NGVD. The resulting velocity regimes are contained in Appendix C.1, while the shear stress distributions were presented in Figures 17, 18 and 19. These suggest that to substantially reduce tidal velocity at various upstream cross-sections, the sill must extend nearly into the intertidal zone. However, a number of different sill configurations could achieve similar results. For example, a notched sill, with higher elevation on the sides and a deeper center opening could be constructed. The depth of this notch could extend from as little as -3.0 to as much as -10.0 feet NGVD in depth to allow navigation and/or more complete water circulation. A deeper notch would require a more constricted opening to achieve the same level of flow reduction. The model output indicates that maximum ebb and flow tide velocities and associated shear stress would increase greatly at the sill, creating significant forces on the structure and possible navigation hazards.

A shallow sill could also be constructed, with sill top elevation of -10 to -15 feet NGVD. This type of sill would reduce the effect of the downstream dredging on upstream erosion but not greatly affect tidal circulation. It would allow deposition of sediment behind it, somewhat in the same manner as a grade control structure in a river. Over time, deposition would raise the channel bed. However, its effect would diminish upstream in the system.

The detailed hydraulic effects of a specific structure are beyond the capability of a 1-dimensional model to simulate. However, the model results clearly show that a structure can be constructed to reduce upstream erosion.

3. Preliminary Design Concepts

One preliminary concept developed for the rock sill consists of a notched berm constructed of quarry stone (Figure 20). The berm would be about 360 feet long oriented perpendicular to the channel axis. Flow would occur over the lower crest constructed at about elevation -5 feet NGVD, with a width of about 150 feet. The crest elevation for the remainder of the berm would be above the typical tide range, and as shown at elevation +3 feet NGVD. The structure cross-section would be trapezoidal in shape (Figure 21). Armor stone would consist of graded rip rap with a median weight of about 500 pounds. The remainder of the rock (core rock) would be smaller stone with a wide gradation.

In the preliminary concept we show the structure located on the ocean side of the existing State Highway 1 Bridge, roughly along the old highway bridge alignment. This location is preferable because

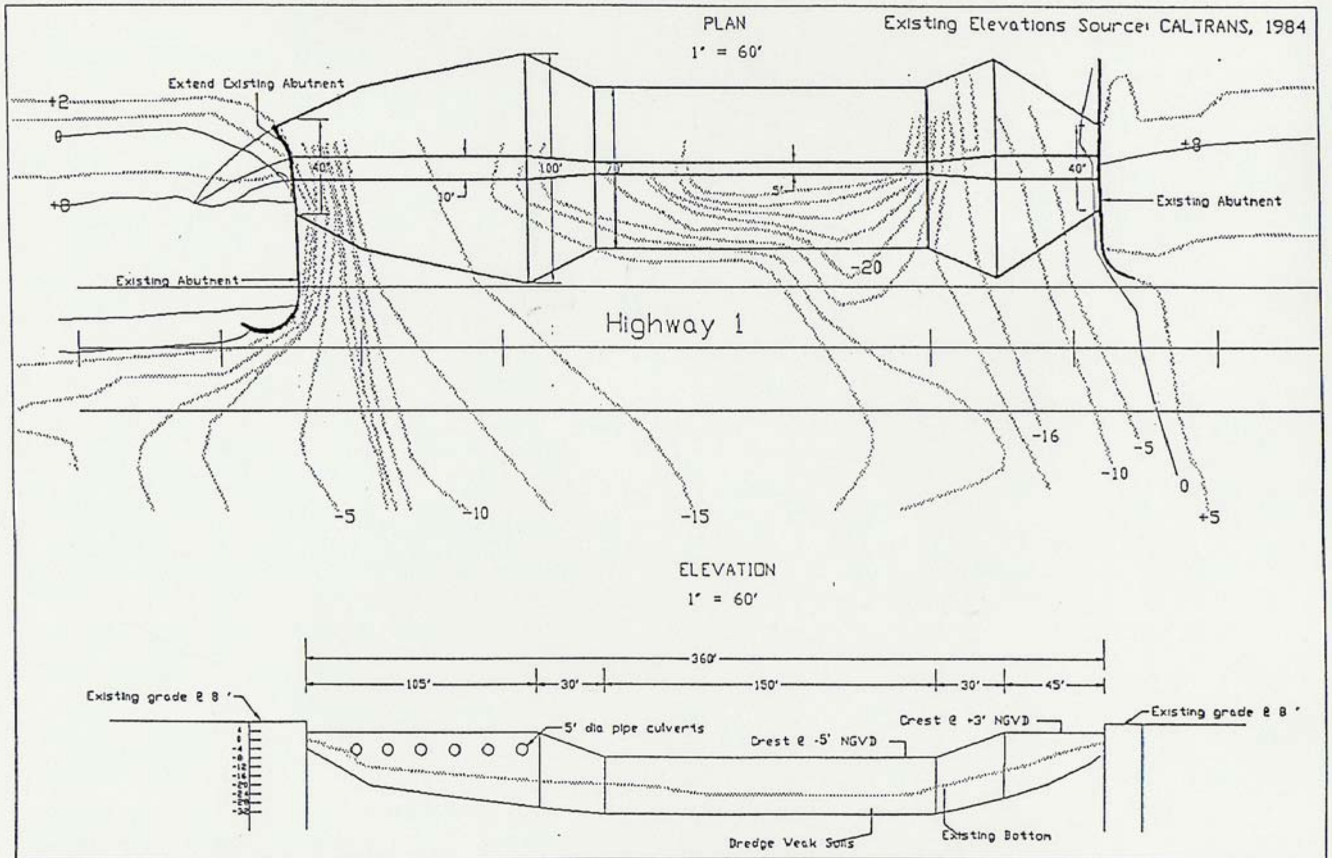
1. it is the narrowest part of the channel;
2. sheet pile abutments exist; and
3. vehicular access exists.

Additional issues of property ownership, impacts to the bridge, etc. would have to be considered in the final location selection.

The sill was notched to minimize impacts to navigation. The sill elevation of -5 feet NGVD would provide approximately three feet of draft at Mean Lower Low Water (MLLW). The remainder of the structure would be above water at most tides. It must be stressed that this concept is shown for illustration purposes only. The final sill cross-section would require detailed hydraulic analysis.

Soil boring logs in the Highway 1 Bridge construction plans were reviewed. Very weak, compressible soils (soft organic clay and peat) were identified, primarily above -30 feet NGVD. Consequently, the concept includes dredging the upper layer of soil to provide a better foundation for the sill. Subsequent analyses should include settlement potential and bearing capacity under static and earthquake loads.

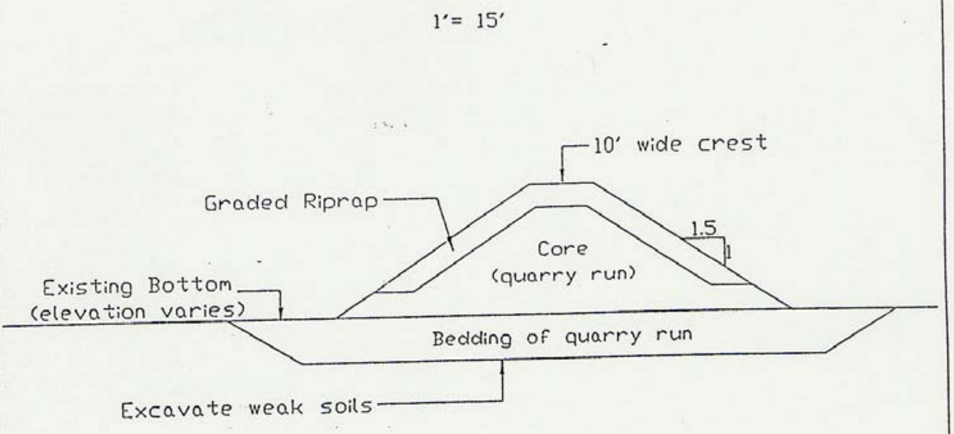
A crest width of 10 feet was selected for the higher portion of the berm so that land-based construction equipment could be used. Water based equipment could also be used.



Philip Williams & Associates, Ltd.
Consultants in Hydrology

Conceptual Drawing of Rock Sill at Highway 1
(From Moffatt & Nichol, Engineers)

Figure
20



Philip Williams & Associates, Ltd.
Consultants in Hydrology

Cross-section View of the Rock Sill
(From Moffatt & Nichol, Engineers)

Figure 21

The concept includes horizontal culverts through the berm to allow adjustment of flow rates with gates. These were included to stress the importance of providing some flexibility in the design, and providing some flexibility in the system performance. This would accommodate both uncertainty in the design and future changes in the system.

Other structures may be possible alternatives to the rock sill. A cellular coffer dam structure constructed with interlocking steel sheet piles is one potential alternative. A reinforced concrete baffle wall supported on piles is another alternative. Both alternative structures would replace the high-crest portion of the rock berm. A rubble berm would still be used for the low crest portion of the sill. These alternatives may involve fewer foundation problems and could possibly lower costs.

4. Construction Cost Estimate

The following table provides the concept-level estimate of construction cost. A large contingency was applied to reflect the preliminary nature of the estimate. Costs are at summer, 1992 levels. Engineering design drawing and specifications, and construction management allowances are provided. This estimate does not include feasibility studies, detailed modeling or environmental review costs.

TABLE 3

CONCEPT-LEVEL CONSTRUCTION COST ESTIMATE
ELKHORN SLOUGH SILL
RUBBLE ALTERNATIVE
1992

BID ITEM	DESCRIPTION	QUANT.	UNIT	UNIT PRICE	TOTAL PRICE
1.	Mobilization	1	LS		$ 200,000
2.	Dredging	8,000	CY	$30.00	240,000
3.	Core Rock	33,000	TON	$50.00	1,650,000
4.	Armor Rock	6,000	TON	$85.00	510,000
5.	Culverts	6	EA	$20,000.00	120,000
6.	Navigation Aids	1	LS		10,000
SUB TOTAL					$2,730,000
CONTINGENCY (25%)					680,000
TOTAL CONSTRUCTION					$3,410,000
Engineering and Design (Plans and Specifications)					170,000
Construction Management					70,000
TOTAL PROFESSIONAL SERVICES					$240,000
TOTAL PROJECT COST					$3,650,000

5. Environmental Considerations

Construction of a channel sill, and/or a sill at the SPRR Bridge/Parson's Slough Channel would have enormous implications for the slough ecology and hydraulics. Resolution of these would require detailed environmental analysis and coordination with local, state and federal resource agencies. In anticipation of this, the U.S. Army COE requested initial review by the U.S. Fish and Wildlife Service. The Planning Aid Letter (U.S. Fish and Wildlife Service, 1992) provides a brief overview of the resources of the Slough, possible effects and recommended studies. It is likely that these future studies would be undertaken both as part of a feasibility level study and in conjunction with the NEPA/CEQA process. Significant changes to water quality, impacts to vegetation, fish and wildlife, and navigation issues would require analysis. It is possible that the cost of pre-project monitoring, environmental studies, compliance, and post-project monitoring could represent a major portion of the actual construction costs of this project.

In addition to the effects in the Slough, modification of hydrodynamic and sediment regime in the Slough would have significant effects in Moss Landing Harbor. Our data suggest that erosion of the Elkhorn Channel has generated a large volume of sediment that has been conveyed out of the Slough and into the Harbor. How much material is deposited in the Harbor channel and must be dredged is unclear. Reduction of erosion would represent the beneficial reduction of deposited material downstream. However, the reduction of tidal exchange from the Slough by a sill at the Highway 1 bridge or SPRR bridge at Parson's Slough would also represent a large decrease in the tidal exchange through the entrance channel, leading to a decrease in ebb tide scour.

D. SOUTH MARSH/PARSON'S SLOUGH

1. Overview

Based on the limited available data, it appears that the erosion in the South Marsh/Parson's Slough area is a complex response to a number of factors: the diking of the area which resulted in significant subsidence; the 1946 opening of the new Harbor entrance, which created full tidal action and resulted in a deep main Elkhorn Slough channel immediately adjacent to the SPRR bridge; the 1983-84 opening of the area to tidal circulation for restoration.

The resulting erosion appears to be of two forms: (1) channel deepening and widening at the SPRR bridge which is extending headward and over the next few decades, will lead to a more extensive system of entrenched channels; (2) erosion at the system margins due to a lower base (marsh) level and subsequent wave action and wetting-drying cycles. It is unclear whether the eroded material is being removed from the system or being deposited on the marsh surface. However, there is no indication that the erosion of the hillsides around the marsh perimeter is slowing, or allowing development of a stable slope.

2. Potential Solutions

In the San Francisco Estuary where subsidence has lowered marsh elevations, a number of different restoration approaches have been used.

a. Where a depositional sediment environment exists, some areas have been allowed to evolve without interference. In these areas, natural sedimentation gradually raises the marshplain (over 30 to 60 years) and the area gradually reverts to a natural condition of marshplain (near MHHW elevation) and appropriately-sized slough channels.

b. In other locations where a more rapid reversion to appropriate marshplain elevation is desired, dredge spoils are proposed for use in raising marshplain elevations.

c. A third approach has been to constrict the tidal opening and reduce the tidal prism exchange.

For the South Marsh, it does not appear that the first approach (no action) is acceptable. There does not appear to be an available sediment source other than the eroding hillsides. Since the erosion is causing damage to the adjacent trails, at roads, and ecosystems, a more active approach seems warranted.

We would recommend a combination of approaches (b) and (c). Constriction of the SPRR bridge opening would reduce the rate of erosion and headward extension of the Parson's Slough Channel system. This is a smaller version of the same solution represented by the sill at Highway 1. For that reason, it may be appropriate to construct the Parson's Slough Project initially and monitor the results prior to undertaking the larger Highway 1 project. The degree of constriction necessary is not immediately evident. Excess constriction may result in water quality problems as a result of stagnation. Underconstriction may not halt erosion. If the long-term goal is to restore the South Marsh/Parson's Slough area as a natural tidal marsh, the opening under the SPRR bridge should be sized to that appropriate for a natural slough channel draining a marsh of this size (534 acres). Based on our hydraulic geometry data, this would require an opening with a channel invert elevation of about -7.0 feet NGVD and a cross-sectional area of about 1,000 square feet (below MHHW). If a channel were designed to actively restrict tidal circulation, it would have to be much smaller, with a sill elevation of about -3.0 feet NGVD. Cost and design data were not part of this study. They would depend on site specific issues such as access, substrate conditions and design criteria. As a rough estimate, the rock sill would be about 25-percent the size of the Highway 1 sill, and the cost may be proportional.

If a natural salt marsh habitat is desired in this area, it would require importing sediment to recreate the appropriate natural elevations. If the entire area (400-500 acres) has actually subsided to about 0.0 feet NGVD, an enormous amount of fill (about 1.5 million cubic yards) would be required to recreate the natural topography (see Photo 5). Clearly this is not feasible at this time. A more manageable approach may be to create a fringing marsh terrace around the system margins to retard erosion. This would have a form similar to the shown in Photo 5 which occurs in the unsubsided wetlands north of the slough. If fetch distances are not excessive, this could prevent wave action and allow for eventual stabilization of the hillsides.

Even this alternative would be a substantial undertaking considering the length of shoreline affected. The terrace would be at elevations of +2.0 to +2.5 feet NGVD, with a width of about 50 feet and a gradual slope to the existing bottom. This may require about 4 to 6 cy of fine-grained material per linear foot of bank protected. Active planting of pickleweed and some vegetation protection during the establishment stage may be required.

We would recommend a pilot project involving several hundred linear feet of protection to determine if the approach is feasible. Clearly, a detailed topographic map of this area and more specific study of the area is needed to accurately quantify past changes and plan solutions. On an interim basis, a number of surveyed shoreline cross-sections, monitoring the SPRR bridge opening, and establishment and monitoring of a number of sedimentation plates in the South Marsh would provide valuable data regarding the ongoing evolution of the system.

REFERENCES

ABA Consultants. 1989. Elkhorn Slough Wetlands Management Plan. Prepared for The Monterey County Planning and The California Coastal Conservancy Department. Capitola, CA 174p.

Asquith, D.K., 1991. Evaluation of Morro Bay Tidal Channels, 1884 to Present. Proceedings of the State of Morro Bay Conference, Oct. 4-12, 1991, Morro Bay, California.

California Coastal Conservancy, 1991. Elkhorn Slough. In Coast and Ocean Magazine. Fall, 1991.

Dames and Moore, Inc. 1974. Coastal processes study of Moss Landing Harbor, California: Survey Report no. 0086-32. U.S. Army Corps of Engineers, San Francisco District. 69p.

Dickert, T., and A. Tuttle. 1980. Elkhorn Slough watershed: Linking the cumulative impacts of watershed development to coastal wetlands. Institute of Urban and Regional Development, University of California, Berkeley.

Fischer, Hugo B., E. John List, Robert C.Y. Koh, Jörg Imberger, Norman H. Brooks, 1979. Mixing In Inland and Coastal Waters. San Diego. Academic Press, Inc. 483 pp.

Haltiner, J.P. and P.B. Williams, 1987. Slough Channel Design for Salt Marsh Restoration. Proceedings of the 8th annual meeting of the Society of Wetland Scientists, Seattle, Washington, May 1987.

Haltiner, J.P. and D. Thor, 1991. Sedimentation processes in Morro Bay, California. Proceedings of the Coastal Sediments '91 Conference, Seattle, Washington, June 25-27. Sponsored by the ASCE Waterway, Port, Coastal and Ocean Division.

Leopold, L.B. and T. Maddock. 1953. The hydraulic geometry of stream channels and some physiographic implications. U.S. Geological Survey Professional Paper 252.

McGrath, J. 1987. Sediment discharge from the Salinas River and the effects of upstream reservoirs. U.C. Berkeley. Term paper for Dr. H. Shen, CE Class 299.

Myrick, R.M. and L.B. Leopold. 1963. Hydraulic geometry of a small tidal estuary. Geological Survey Professional paper 422-B.

Nicholson, J. and B.A. O'Connor. 1986. Cohesive Sediment Transport Model. ASCE J. of Hyd. Eng. Vol 112, No. 7. July.

Oliver, J.S., J.A. King, M. Hornberger and D.L. Schwartz. (no date, in review). Extensive salt marsh erosion caused by human activities in Elkhorn Slough, California. Wetlands.

Silberstein, M. 1991. A cartoon history of Elkhorn Slough. Proceedings of the State of the Bay: Morro Bay Conference. October 4-12, 1991. Produced by the Morro Bay Task Force.

Smith, R.E. 1974. The hydrography of Elkhorn Slough, a shallow California coastal embayment. M.A. Thesis. San Jose State University.

Sobey, R.J., T.S. Adil, and P.F. Vidler., 1980. User's Guide to ESTFLO/Version 2B. (James Cook University of North Queenlsland, Department of Civil and Systems Engineering), Research Bulletin No. CS22, February, 1980.

U.S. Army COE. 1989. Moss Landing Harbor, Monterey County, Section III Study: Initial Assessment. Memorandum dated August 25, 1989.

Water Resources Engineers. 1969. Evaluation of alternative water quality control plans for Elkhorn Slough and Moss Landing Harbor; presented to the California State Water Resources Control Board and the Central Coastal Regional Water Quality Control Board.

Wong, C.R. 1989. Observations of tides and tidal currents in Elkhorn Slough. M.S. Thesis. San Jose State University.