



Sea Engineering Incorporated  
Marine Environmental Consultants

# **ELKHORN SLOUGH**

## **A Review of the Geology, Geomorphology, Hydrodynamics and Inlet Stability**



Prepared for:

Elkhorn Slough  
National Estuarine Research Reserve

Prepared by:

Sea Engineering Incorporated  
Ken Israel and Steve Watt

5/31/2006

## PURPOSE

In 1947 the U.S. Army Corps of Engineers completed the installation of two permanent jetties for the construction of Moss Landing Harbor located in the center of the Monterey Bay coastline in California. The jetties provide a permanent waterway connection between the Pacific Ocean, Moss Landing Harbor and Elkhorn Slough. Numerous scientific studies and observations have shown that the construction of the jetties, breaching of Parsons Slough, and changes in land use practices have drastically changed a lower-energy, depositional estuary into a higher-energy, erosional tidal inlet. Since the construction of the harbor, researchers have measured and observed dramatic increases in tidal prism and tidal current velocities which have resulted in extensive erosion in Elkhorn Slough, both vertically in the subtidal channel and laterally into the channel banks and mudflats. The salt marshes bordering Elkhorn Slough have also experienced inundation and increased coverage by tidal waters in the past 50 years, resulting in dramatic changes of vegetation cover.

The purpose of this report is to evaluate and summarize past and present research relating to the erosion problems in Elkhorn Slough such as the geologic history and present substrate conditions; estimates of the changing tidal prism and tidal current velocities over time; locations, rates and volumes of sedimentary erosion and deposition over time; sediment erosion rates with depth (strength of underlying sediments); and how these processes are related to one another in the Elkhorn Slough system. We will also explore the possibility of a positive feedback loop leading to increasing erosion in Elkhorn Slough, and how that may relate to inlet stability at the mouth of Elkhorn and Parsons Sloughs.

By combining relevant scientific literature and the basic mathematical concepts of estuarine processes, evolution, and morphology, a simple sediment transport conceptual site framework will be developed to describe, relate, and where possible, quantify the processes of sediment transport, deposition and erosion in Elkhorn Slough. The Slough will be divided into different sections based on the availability and relevancy of data (such as Parsons Slough, North and South Harbor, etc). This model will be used to develop theories regarding sedimentary processes in the slough if the current situation persists, meaning that nothing is done to alter or prevent tidal erosion from taking place in the foreseeable future.

## **ACKNOWLEDGEMENTS**

This report was prepared by Mr. Ken Israel and Mr. Steve Watt at Sea Engineering, Inc. with assistance from the staff at Elkhorn Slough National Estuarine Research Reserve (ESNERR), Dr. Rikk Kvitek, Pat Iampietro and students of the Seafloor Mapping Lab at California State University Monterey Bay (SFML CSUMB), as well as Dr. John Oliver, Dr. Laurence Breaker, Dr. William Broenkow, Dr. H. Gary Greene, and William C. Seabergh of the U.S. Army Engineer Waterways Experiment Station, Coastal and Hydraulics Laboratory. A summary is presented of observations, interpretations of previously collected data, further analysis of inlet stability, and recommendations developed from information gathered during the project period.

Information about the Elkhorn Slough was provided by both published and, as yet, unpublished data. Recent bathymetric, LIDAR, and sub-bottom survey data, as well as estimates of tidal prism and surface area were provided by NOAA, and SFML CSUMB.

### List of Technical Reviewers:

Larry Breaker, Moss Landing Marine Laboratories (MLML)  
John Callaway, University of San Francisco (USF)  
Lesley Ewing, California Coastal Commission  
Gary Greene, Moss Landing Marine Laboratories (MLML)  
Rikk Kvitek, California State University Monterey Bay (CSUMB)  
Jessie Lacy, U.S. Geological Survey (USGS)  
Bryan Largay, Resource Conservation District Monterey County (RCD)  
Chris Malzone, NortekUSA  
Erika McPhee-Shaw, Moss Landing Marine Laboratories (MLML)  
Doug Smith, California State University Monterey Bay (CSUMB)  
Bill Watson, Moss Landing Marine Laboratories (MLML)

## ELKHORN SLOUGH POINT OF CONTACT

Comments, corrections or inquires should be addressed as follows:

Barb Peichel  
Tidal Wetland Plan Coordinator  
Elkhorn Slough  
National Estuarine Research Reserve  
1700 Elkhorn Road  
Watsonville, CA 95076

Tel: 831-728-2822  
[www.elkhornslough.org](http://www.elkhornslough.org)

Ken Israel  
Vice President  
Sea Engineering, Inc.  
200 Washington Street, Suite 210  
Santa Cruz, CA 95060

Tel: 831-421-0871  
Fax: 831-421-0875  
[www.seaengineering.com](http://www.seaengineering.com)

Steve Watt  
Marine Geologist  
Sea Engineering, Inc.  
200 Washington Street, Suite 210  
Santa Cruz, CA 95060

Tel: 831-421-0871  
Fax: 831-421-0875  
[www.seaengineering.com](http://www.seaengineering.com)

## TABLE OF CONTENTS

<b><u>Section</u></b>	<b><u>Title</u></b>	
<b>1</b>	<b>Introduction</b>	<b>1</b>
<b>2</b>	<b>Geology</b>	<b>3</b>
	▪ <i>Regional geology</i>	<b>3</b>
	▪ <i>Sediment composition</i>	<b>6</b>
	▪ <i>Sediment mobility</i>	<b>10</b>
	▪ <i>Tidal channel geomorphology</i>	<b>10</b>
<b>3</b>	<b>Tides, Tidal Prism, and Tidal Currents</b>	<b>31</b>
<b>4</b>	<b>Inlet Stability</b>	<b>35</b>
	• <i>History of inlets</i>	<b>35</b>
	• <i>Inlet cross-sectional stability and tidal prism</i>	<b>39</b>
	• <i>Inlet model analysis</i>	<b>41</b>
	• <i>Historical note and summary of inlet stability</i>	<b>50</b>
	• <i>Cautionary note</i>	<b>54</b>
<b>5</b>	<b>Conclusions</b>	<b>55</b>
<b>6</b>	<b>Recommendations</b>	<b>57</b>
<b>7</b>	<b>References and Information Considered</b>	<b>58</b>
<b>8</b>	<b>Appendix. Sedflume Analysis</b>	<b>62</b>

**ELKHORN SLOUGH, CALIFORNIA**

**A Review of the Geology, Geomorphology,  
Hydrodynamics and Inlet Stability**

## SECTION 1 - INTRODUCTION

Elkhorn Slough lies in the middle of the crescent shaped Monterey Bay along the central California coast near the Moss Landing Harbor. The harbor is bisected into north and south sections where the Elkhorn Slough mouth connects with the harbor entrance channel at the Highway (HWY) 1 Bridge (Figure 1). Just offshore of the Moss Landing Harbor entrance resides the Monterey Canyon, one of the largest active submarine canyons on the west coast of North America. Elkhorn Slough consists of a subtidal channel, tidal creeks, intertidal mudflats, and salt marshes extending for ~ 10 km northeastward from Moss Landing. The sinuous tidal channel has an average depth of 3 meters (~ 9 m deep at the mouth and ~0.5 m deep near Hudson Landing) and meanders eastward from the Highway 1 Bridge through a tight curve at Seal Bend. Further upslough, the tidal channel bends northward at the intersection with Parsons Slough, ~3.5 km from the HWY 1 Bridge. From Parsons, the northward trend continues for ~2.5 km to Kirby Park where the channel bends northwestward for about 1 km. After the bend, the channel curves to the north again for approximately 1.5 km before hooking eastward near Hudson Landing to the headwaters of the Slough.

Modifications to the Moss Landing and Elkhorn landscape over time have significantly changed the hydrodynamic and geologic evolution of Elkhorn Slough. The most dramatic change happened after construction of the Moss Landing Harbor Inlet was completed in 1947, which established a permanent tidal connection between Elkhorn Slough, Moss Landing Harbor and the open ocean. In addition, the construction of the harbor inlet relocated the mouth of Elkhorn Slough ~600 m directly eastward from the coastal dunes to the location of the HWY 1 Bridge. By shortening, straightening, and deepening the inlet channel, tidal flow became much more hydraulically efficient.

In the past, Elkhorn Slough was part of a broad integrated estuarine system that included other nearby sloughs and the Salinas and Pajaro Rivers. Geologic research indicates that Elkhorn Slough was a depositional environment and experienced weaker tidal currents than the present condition (Schwartz et al., 1986). The location of the Moss Landing Inlet was variable, migrating widely up and down the beach in response to changing environmental conditions. At times, the Moss Landing Inlet may have been temporarily blocked by a seasonal sand bar and was shallower than the current depths maintained at the harbor channel (~7.5 m) or the HWY 1 Bridge (~9 m). Increased rainfall and higher surf in winter produced different slough-mouth morphologies. The inlet was open to tidal flow, deeper than in summer conditions, and breached the coastal dunes in many locations north and south of the current harbor channel. The direct tidal connection established by the jetties exposed a once depositional environment to the daily force of tidal currents and scour. Extensive erosion has been observed in the subtidal channel, mudbanks and salt marshes of Elkhorn Slough since the permanent tidal connection was established in 1947 (Oliver, 1988; Malzone & Kvittek, 1994; Crampton, 1994; Malzone, 1999).

Additional landscape modifications, such as the diversion of the Salinas River in 1908, have altered the hydrodynamic and geologic evolution of Elkhorn Slough. In 1983, the California Department of Fish and Game restored tidal action to 1,800, 000 m<sup>2</sup> in the South Marsh areas (Malzone, 1999). This action, in addition to unintentional levee breaches, was one of the main factors leading to an increase in the mean cross-sectional area of the Elkhorn Slough main tidal channel. The cross-sectional channel area has been calculated to have grown approximately 16% between 1993 and 2001 increasing the tidal volume in the Slough by roughly 30%. Since the slough's main inlet at the Highway 1 Bridge has increased at a slower rate than the tidal volume increase during that time, the result has been a corresponding increase in tidal currents and erosion in the Slough (Dean, 2003; Malzone, 1999).

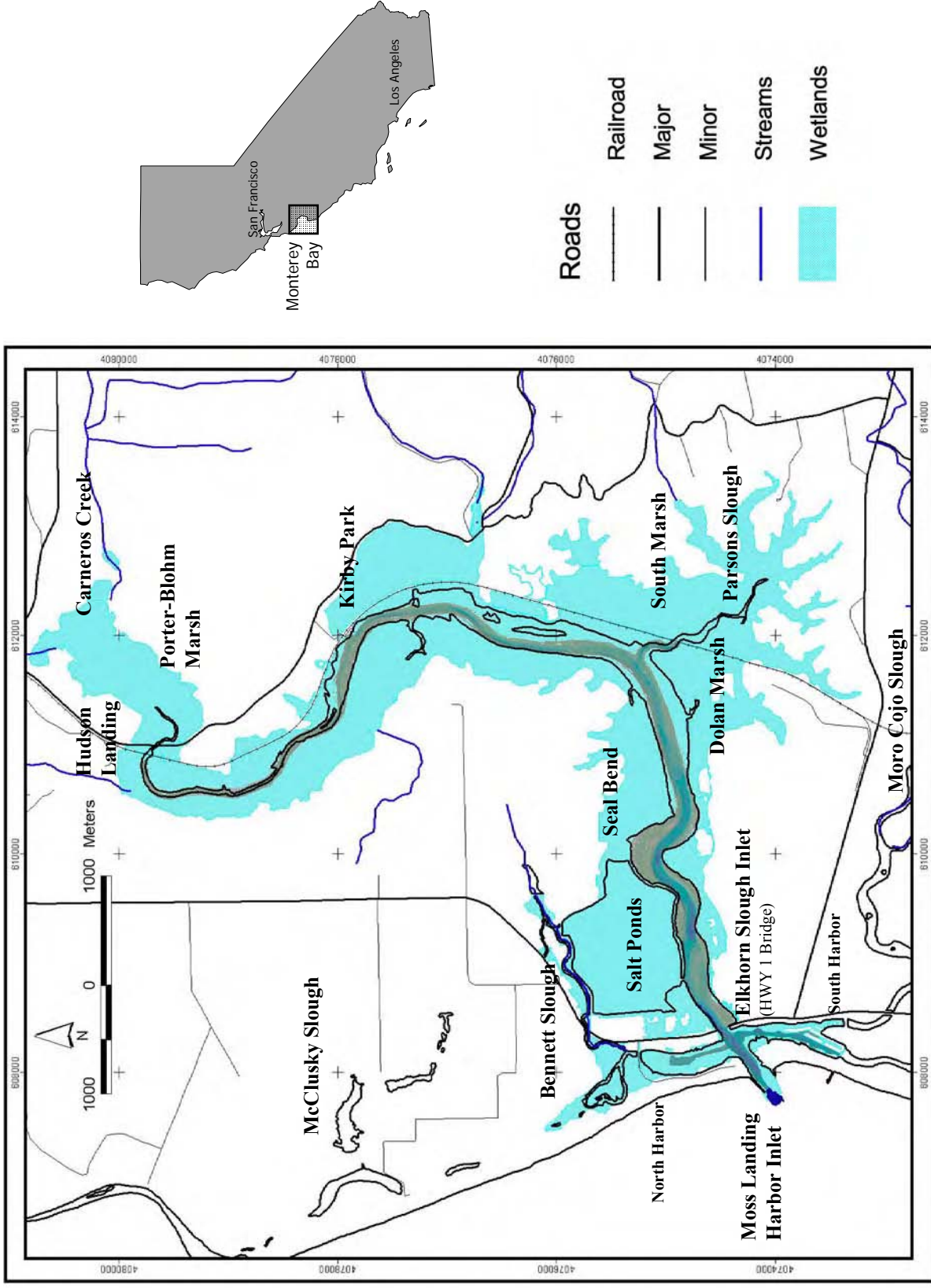


Figure 1. Illustration of Elkhorn Slough and various points of interest including bathymetry collected by CSUMB's Seafloor Mapping Laboratory in 2001/2003. Elkhorn Slough lies in the center of the crescent-shaped Monterey Bay, just east of the Moss Landing Harbor.



## SECTION 2 – GEOLOGY AND GEOMORPHOLOGY

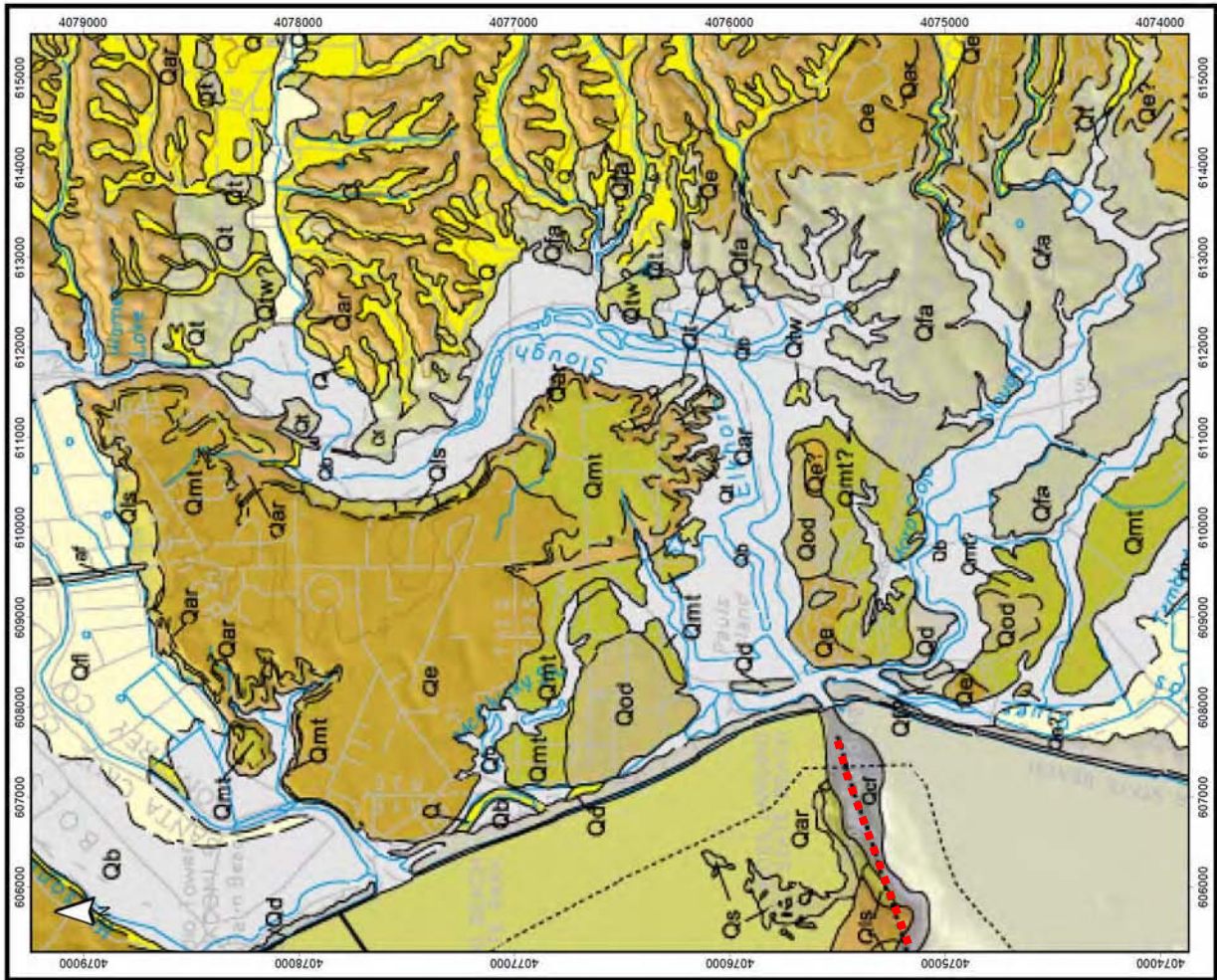
Different substrate types have widely varying potentials for erosion. For example, an unconsolidated silt deposit may be easily eroded, while consolidated clay can be difficult to erode, and a rock exposure may not erode significantly at all when exposed to the same physical forces. Therefore understanding the geology and substrate conditions at the surface and sub-surface in Elkhorn Slough is critical to analyzing the ongoing erosion problem and predicting future erosion. The evolution and processes that have shaped this geographic region in the past provide the framework for the future of Elkhorn Slough.

### *Regional Geology*

The Elkhorn Valley resides upon the Salinian Block, a large “raft” of granitic rocks bound on the east and west between the San Andreas and San Gregorio faults respectively. In the 1940’s exploratory oil and gas wells drilled near the Elkhorn Slough mouth revealed a large erosional canyon or gorge cut into the Salinian granitic rocks 2.5 kilometers below the surface, now referred to as the Pajaro Gorge (Stark and Howard, 1968; Greene, 1977; Schwartz, 1983; Schwartz et al, 1996). Two of the wells were drilled close to the HWY 1 Bridge at the mouth of Elkhorn Slough, penetrating over 500 meters of Quaternary and Pliocene sediment before encountering Miocene sedimentary rock 510 meters below the surface.

The thick sedimentary deposits found onshore probably extend offshore of Elkhorn Slough. In the 1970’s the US Geological Survey collected a series of seismic reflection profiles throughout the waters of the Monterey Bay, two of which are mapped within 1-mile of the Moss Landing Harbor entrance (Greene, 1977). Greene’s interpretation of the offshore seismic lines indicates a deposit approximately 300 meters deep of older sand dune and fluvial sedimentary deposits interspersed with layers of alluvial gravel and sand below the seafloor. These unconsolidated sedimentary deposits overlie the Purisima Formation, a sand-to-siltstone composition that is exposed in some parts of the offshore Monterey Canyon.

A section of a regional geologic map of the Monterey Bay by Wagner et al. (2002) is displayed in Figure 2. A fault is inferred offshore to the west of Elkhorn Slough in the axis of Monterey Canyon but is not mapped onshore. The Zayante-Vergeles Fault and the San Andreas Fault are located directly east of Elkhorn Slough (not shown on map). Rock exposures of Salinian Block granite, Monterey Formation, or Purisima Formation which have been mapped elsewhere onshore and offshore in Monterey Bay, do not crop out in the vicinity of Elkhorn Slough. The surficial sediments in the region are composed of unconsolidated marine and non-marine gravel, sand, silt and clay deposits. Top soils bordering Elkhorn’s salt marshes consist of recently stabilized, coarse-grained sand dunes that are easily penetrated by and drained of water delivered by local storms (Huertos and Shennan, 2002). Storm run-off causes moderate soil erosion potential on slopes less than 15 degrees and high erosion potential on greater slopes. Permeable mixtures of clay, silt, sand, and organic matter found on the surrounding upland areas also have high potentials for erosion from run-off during storm events



Map ID	Geologic description
Q	Alluvium
Qcf	Offshore canyon fill
Qe	Eolian sands
Qfl	Flood plain deposits
Qb	Basin deposits
Qd	Dune sand
Qls	Landslide deposits
Qs	Sand
Qt	Terrace deposits
Qod	Older dune deposits
Qmt	Marine terrace deposits
Qf	Alluvial fan deposits
Qfa	Fan deposits
Qar	Undifferentiated Aromas Sands Formation
Qtw	Terrace deposits

Figure 2. The geology of the Elkhorn Slough region is shown in this modified version of Wagner et al.'s (2002) geologic map of the Monterey Bay. The dashed red line indicates an inferred fault offshore in the Monterey Canyon axis. No other faults or rock outcrops are mapped in the immediate area. In general, the region is composed of differing sedimentary deposits of marine and non-marine gravel, sand, silt and clay that may extend well over 300 meters below the surface.

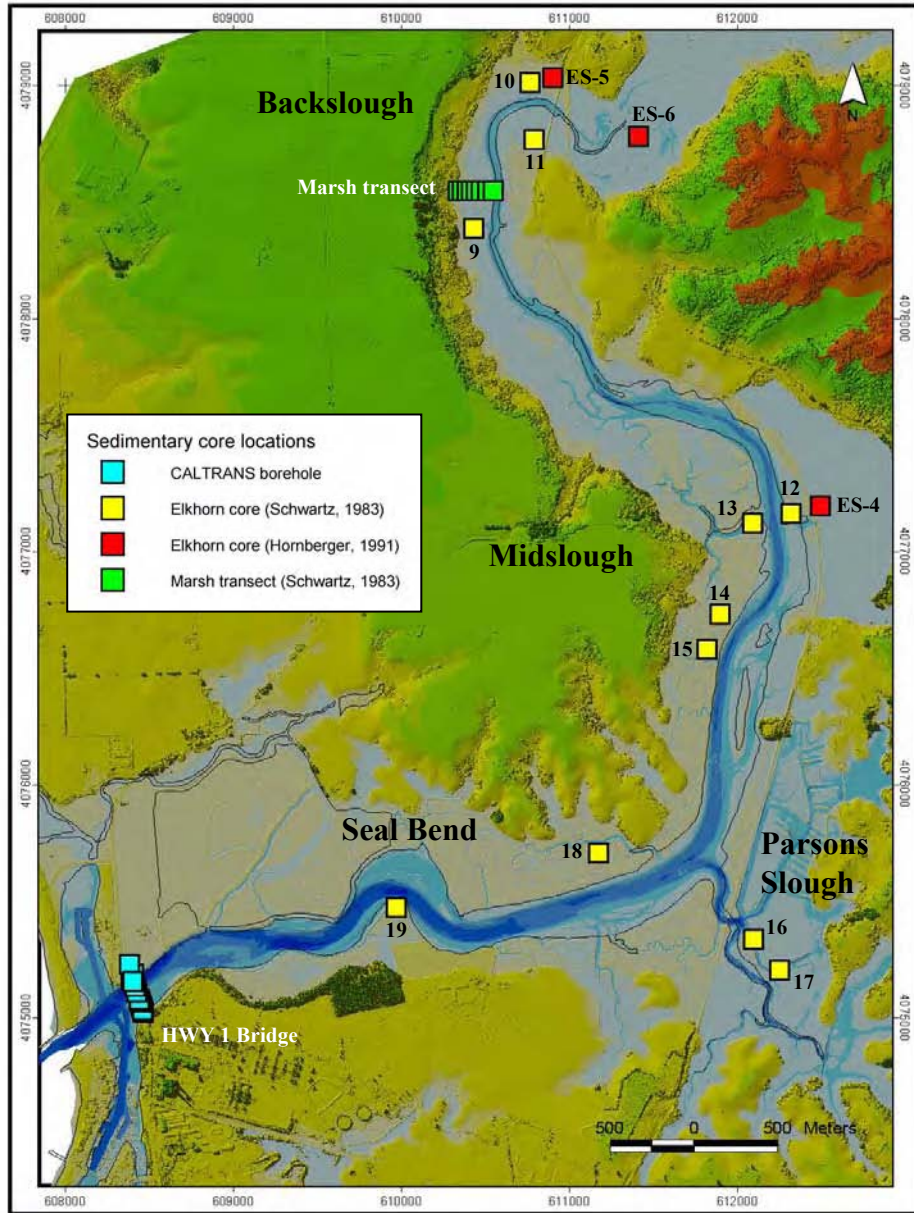


Figure 3. The locations of CALTRANS boreholes (blue squares), the marsh transect hand-driven cores (green squares), and other single Elkhorn cores (yellow squares and red squares) collected by Schwartz (1983) and Hornberger (1991) are depicted above. The cores are displayed over a merge of multibeam bathymetry processed, archived, and distributed by SFML CSUMB and NOAA LIDAR data. Descriptions of the CALTRANS cores are in Figure 4. The marsh transect and other Elkhorn cores are described in Figures 5 and 6.

In 1981, the California Division of Transportation (CALTRANS) collected borehole data prior to the construction of the HWY 1 Bridge at the mouth of Elkhorn Slough (Figure 3). Schwartz (1983) sampled thirteen boreholes from a transect crossing the slough mouth and processed the samples for grain-size and age using radioisotopes and amino acid dating techniques. The analysis of the boreholes revealed the recent geologic evolution of Elkhorn Slough.

Elkhorn Valley formed between 16,000 to 18,000 years ago, eroding into a 500 m thick sequence of alternating marine and non-marine sedimentary deposits that filled in the ancient Pajaro Gorge over time. The channel was inundated by coastal waters as sea level began to rise following the last ice age, creating a high-energy tidal inlet where the Slough met the sea. Continuing sea level rise caused the invaded channel to be filled in by a series of progressively finer sedimentary layers, indicating a shift from a high-energy tidal inlet to a relatively lower-energy estuary over the course of a few thousand years. The construction of the jetties for the Moss Landing Harbor completely changed the system, abruptly replacing a depositional, lower-energy system with an erosional relatively higher-energy system.

### ***Sediment composition***

Surface and sub-surface geologic substrate information including grain size, density, mineralogy, chemistry and others are essential factors for estimating potential erosion from current flow on a particular seafloor, river bed or tidal channel. Because Elkhorn Slough is composed of a wide variety of different substrate types of varying character, it is important to map where sediment composition variations occur and apply this information wherever erosion potentials are estimated.

The borehole data collected at the HWY 1 Bridge in 1983 are positioned at a critical location for this tidal erosion study. The HWY 1 Bridge is considered the mouth of Elkhorn Slough and has experienced significant tidal erosion over time. Other complimentary data sets have been collected near the HWY 1 Bridge over the years, including current measurements and bathymetric surveys, which can be applied with the sedimentary data to predict potential erosion over time.

The boreholes were described qualitatively in six stratigraphic units, five of which describe the distinctive fining upwards sequence of sedimentary layers representing past conditions and a sixth sand deposit which may be a result of more recent changes to Elkhorn Slough. Figure 4 shows the approximate locations and descriptions of the sedimentary layers with the inclusion of probable grain-size diameter ranges (in microns) applied using the Wentworth Scale (Wentworth, 1922). The sedimentary layers extend down 28 meters below Mean Lower Low Water (MLLW) and range from clay (<3.9 microns) to coarse gravel (up to 4000 microns). The clay layer near the surface is expected to be the most resistant strata to tidal erosion because clay tends to consolidate or become cemented over time. While no description is provided for the strength or consolidation of these sediments, bathymetric data indicates that the near surface layers were eroded over time (see section below, *Tidal channel geomorphology*).

Eleven hand-driven cores collected by Schwartz (1983) and three by Hornberger (1991) provide sub-surface sediment data along the flanks of Elkhorn Slough's main tidal channel and in Parsons Slough (Figure 3). A surface elevation in Mean Lower Low Water (MLLW) was applied to the top of each core in GIS using a Digital Elevation Model (DEM) produced from recent multibeam bathymetry and NOAA LIDAR data obtained from SFML CSUMB, permitting comparison of the sedimentary layers down core with bathymetry and sub-bottom profile data.

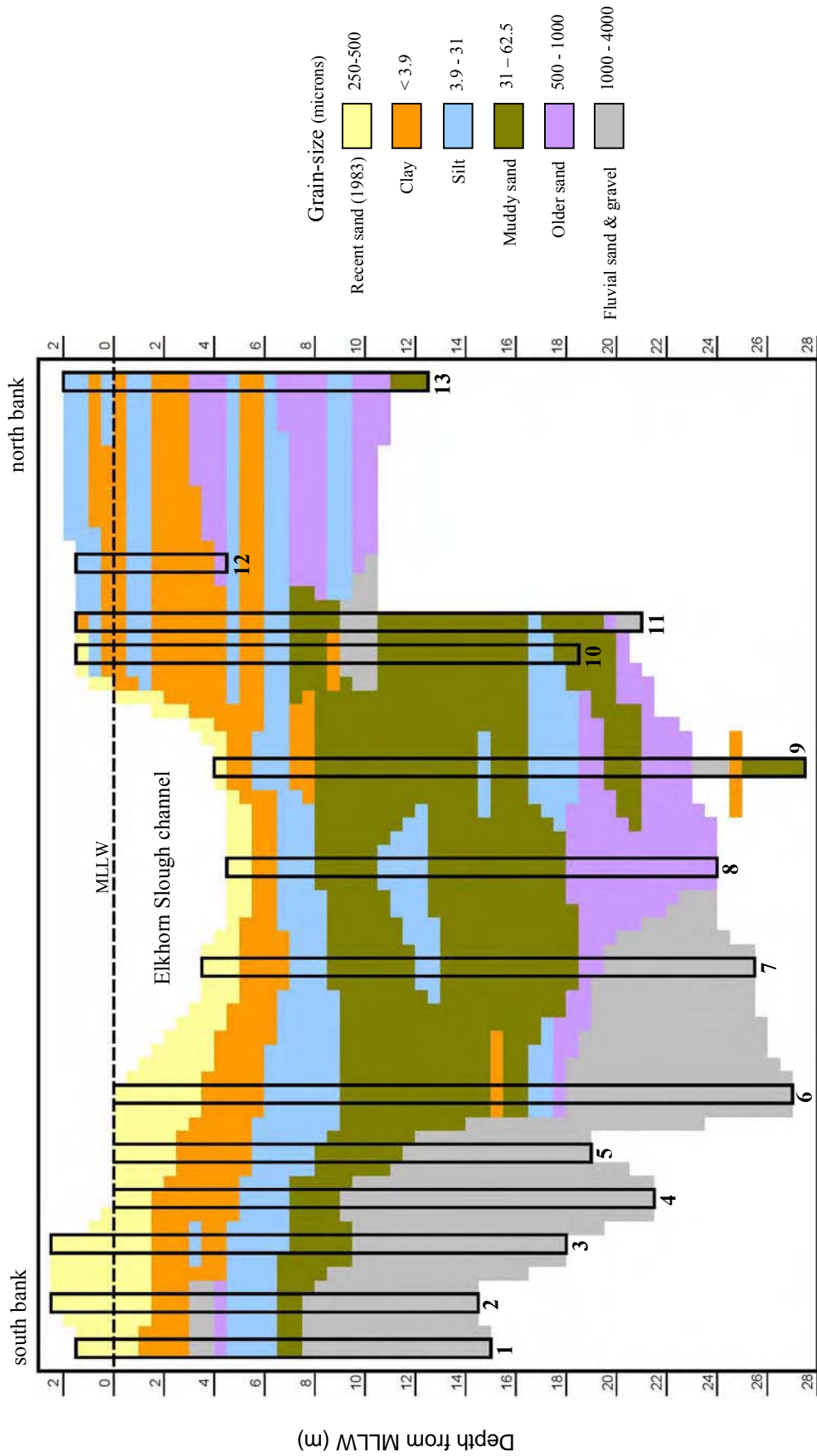


Figure 4. Simplified illustration of Schwartz (1983) descriptions of CALTRANS boreholes collected across HWY 1 Bridge. The cores are shown by depth corresponding to MLLW (dashed line) and color-coded in six different sedimentary layers. The sedimentary layers were inferred by Schwartz (1983) between the outlined and numbered sedimentary cores. The distinct fining upward sequence is illustrated in the bottom five layers with a sixth sand layer at the top, indicating the return to higher-energy conditions after the construction of the Moss Landing Harbor.

*[MLLW is the average height of lower low tides, serving as a reference tidal datum for elevations and water depth.]* Schwartz (1983) collected another transect of eight hand-driven cores in Elkhorn's Backslough extending from the edge of the salt marsh towards the main tidal channel (Figure 3), providing a cross-sectional view of the sedimentary composition between the salt marsh and tidal channel in that area.

A shallow two meter core located on the south side of the curve at Seal Bend (core 19) penetrated sand ~1 m above and 1 m below MLLW. The sandy composition of this core is different from other cores collected in Elkhorn. For the rest of the cores in Elkhorn Slough, the sedimentary composition appears to be related to a core's proximity to the main tidal channel and salt marshes (Figure 5 and Figure 6). Cores located closer to the tidal channel have a high content of clay, while cores further away from the tidal channel (and closer to salt marshes) have a high content of peat. *[Peat has a high potential for erosion by tidal currents and is composed of unconsolidated semi-carbonized plant remains in a water-saturated environment (Bates and Jackson, 1984)].* Most Elkhorn cores are capped by a layer of organic material. Root mat was only penetrated above MLLW, while organic peat layers extend well below MLLW in many locations. In the Midslough, the organic layer(s) are followed by a several meter thick, organically rich, blue to brown clay layer. The clay in most cores extends from ~ MLLW down to the base of each individual core (up to 9.5 meters). In the Backslough, cores are positioned further away from the tidal channel and are composed mostly of peat. In cores ES-5 and ES-6, peat deposits overlay a deposit of fluvially derived sand and gravel ranging in grain diameter from ~1000 to 4000 microns.

The cores collected in Parsons Slough have surficial deposits of coarse-grained fluvial gravel and sand, not organic layers of root mat or peat like the Elkhorn cores. The Parsons cores share the same spatial relationship regarding clay/peat concentration to position between tidal channel and salt marshes as the Elkhorn cores. Core 16 is close to the Parsons Slough tidal channel, penetrating a clay layer down-core of the coarse grained surface deposit. Core 17 is further away from the tidal channel and contains a 2 meter thick layer of peat, before penetrating clay ~ 2 m below MLLW. While no data are presented regarding the consolidation or strength of the sediments sampled in the cores, the ability to retrieve hand-cored sediment up to 7 meters deep through out the Elkhorn Slough suggests that the sediments are poorly consolidated and easily eroded by the tidal currents present in Elkhorn Slough.

Sea Engineering, Inc. collected four sediment cores in February, 2006 from two locations within Elkhorn Slough. Two cores were collected near Seal Bend (one in the mudflat, one in the deeper channel). Two cores were collected near Kirby Park (one in the mudflat, one in a deeper channel). The cores were subjected to a Sedflume analysis with the purpose of determining the sediment shear strength below the bed at the coring locations. Core depths extended approximately 20-50 cm below the bed. Additional descriptions and sediment analyses of the Seal Bend cores are discussed further in Appendix A.

The geologic history and substrate data evaluated above provide an adequate starting point to analyze the ongoing erosion problem in Elkhorn Slough. No rock exposures occur in the region. In fact, the first bedrock layer likely rests over 500 meters below the present surface. The area appears to be composed entirely of alternating layers of unconsolidated marine and non-marine sedimentary deposits consisting of gravel, sand, silt, clay and shell fragments that are easily eroded when compared to bedrock.

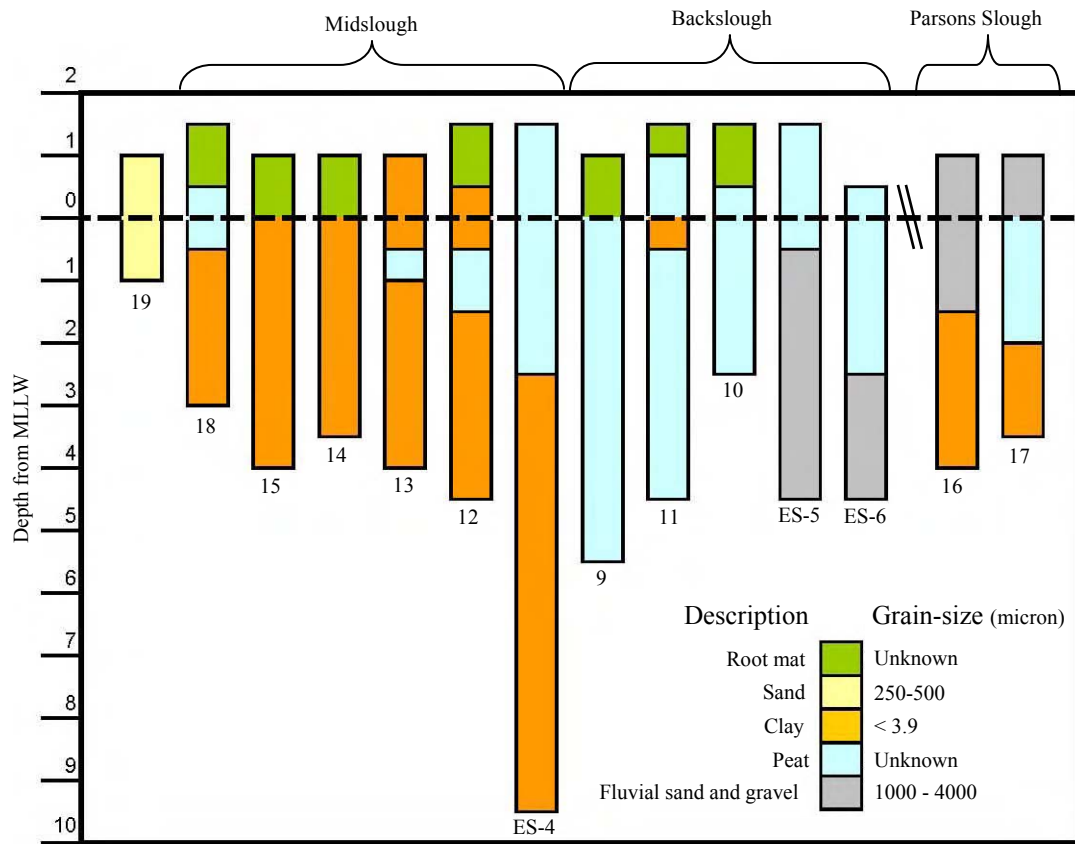


Figure 5. Sediment cores collected by Schwartz (1983) and Hornberger (1991) are ordered from left to right from Seal Bend to Elkhorn's Backslough. Parsons Slough cores are shown on the far right. Descriptions of the cores include a range of possible grain-size diameters in microns. Elevations from the DEM in Figure 3 were applied to the surface of the cores to orient the data in relation to Mean Lower Low Water (MLLW).

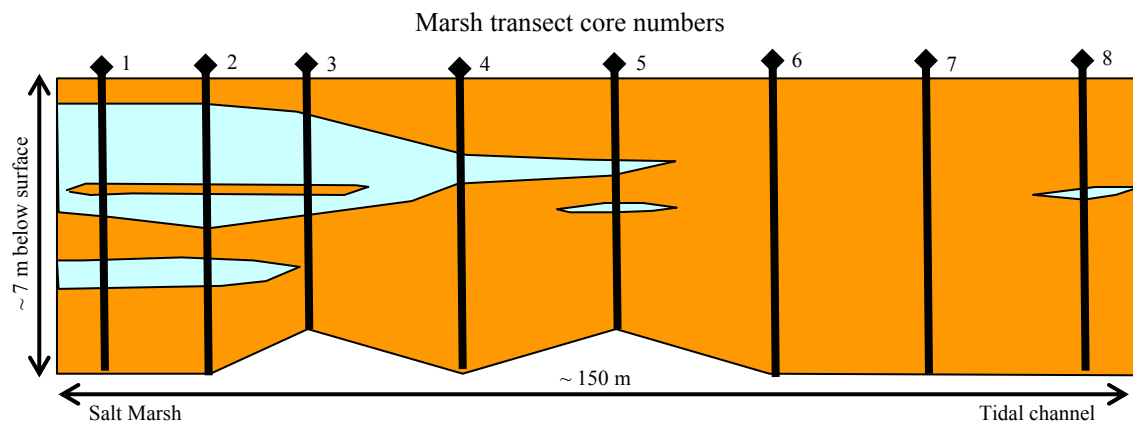


Figure 6. Descriptions of hand-driven cores modified after Schwartz (1983) along a transect between the salt marsh and tidal channel in Elkhorn's Backslough. Clay content is higher in cores closer to the tidal channel (orange), while peat concentration (light blue) is higher in cores closer to the salt marshes (see Figure 3 for core locations).

## ***Sediment Mobility***

The potential sediment mobility in Elkhorn Slough is based on bottom sediment characteristics. Initial estimates of the critical hydraulic condition for mobilization of the sediment were based on available information in the published literature on erosion of estuarine mud, and were computed prior to the recent sediment core collection (February, 2006). Elkhorn Slough is dominated by clay and silt. Cohesion likely plays a role in the mobility of the fine-grained materials (but not in the sandy sediments), and lacking any prior information about geotechnical properties (e.g., yield strength) of Elkhorn Slough sediment samples, we used previous field and laboratory studies of estuarine sediment to estimate erosion potential.

Critical erosion shear velocities were previously computed for contaminated muddy sediment in a shallow section of Buzzards Bay, MA (Onishi, et al., 1993). The sediment had comparable mixtures of grain sizes to those at Elkhorn Slough (dominated by silts and clays), and was cohesive. Other recent studies of critical erosion velocities for cohesive sediment showed similar estimates sediment strength (e.g., Mimura, 1993; Verbeek, et al., 1993).

Estuarine sediments, such as those found throughout Elkhorn Slough that are cohesive and fine grained in character (i.e. mud/clay through silt), typically have a critical shear stress of 3 dynes/m<sup>2</sup>. This critical shear stress would be exceeded if water column current speeds exceeded 30 cm/s, which would cause surficial estuarine sediments to be mobilized, eroded, and transported. At this time we do not have any estimates of critical erosion velocity relevant to peat and unconsolidated organic material.

Fine sand will be eroded or winnowed from the top of the bed at lower stresses or flow velocities than those required for larger sand. However, since mud beds often undergo consolidation during burial over time, the critical condition for entrainment in muddy beds often increases with sediment depth (Mehta, 1986). Therefore, once the surficial material is mobilized and swept away by the ambient flows, the deeper sediment may, or may not, be more resistant to mobilization and erosion. The actual erosive behavior of muddy beds is generally described as a rate process in which the initial mobilization occurs at relatively low bottom stresses (Mehta, 1986). As the top layers of material are stripped away, the exposed sediment may be more difficult to resuspend, and thus erosion rate depends on the strength of sediments exposed. Bioturbation from burrowing organisms, mucous secretions, time for consolidation, and other factors all play a role in the time-dependent erosive behavior of the bed material.

## ***Tidal channel geomorphology***

A multibeam bathymetric data set of the Elkhorn Slough tidal channel was acquired, processed and archived by SFML CSUMB. These data were collected in 2001 (Brantner, 2001) and expanded upon in 2003 (Dean, 2003). The high-resolution one-meter bathymetry grid provides a detailed representation of Elkhorn Slough's diverse tidal channel morphology. The bathymetry data set was merged with a National Oceanic and Atmospheric Administration (NOAA) topographic data set acquired using airborne Light Detection and Ranging (LIDAR) techniques. The compilation of these two data sets provides an invaluable tool for studying the processes that have shaped the geomorphology of Elkhorn Slough.

In spring of 2003 several shallow sub-bottom survey track lines were run up the Elkhorn Slough tidal channel by SFML CSUMB. These data were collected as a preliminary run to test new equipment. As



a result, the quality of the data does not support a rigorous quantitative analysis of sub-surface conditions in the tidal channel. However, when checked and compared with the 2001/2003 multibeam, the images reveal many interesting shallow sub-surface features that significantly add to the understanding of the geology and processes altering the Elkhorn Slough tidal channel.

Survey track lines that produced the highest quality sub-bottom profile images were used to create a single track line along the tidal channel axis from the HWY 1 Bridge to Hudson's Landing (Figure 7). Sub-bottom profile imagery is useful in identifying stratigraphic units with distinct acoustical characteristics. The images were interpreted to the depth of the first water surface multiple, an artifact that appears in some seismic reflection records at approximately twice the water depth (not shown in most records). Tidal channel depths along the track line were calculated by multiplying the speed of sound in sea water (1485 meters/second) by millisecond readings measured from the seismic reflection records. The calculated tidal channel depths were verified by superimposing the sub-bottom track line over the multibeam bathymetry data in GIS. The calculated sub-bottom depth values were comparable to within  $\pm 0.4$  meter of the gridded multibeam bathymetry data in most locations. Because the multibeam data set was collected and processed using more rigorous methods than the sub-bottom data set, depths from the multibeam bathymetry were applied to the sub-bottom track line in GIS to represent the depth to the sea floor in relation to MLLW. The sub-surface depth of sedimentary layers and other features observed in the sub-bottom profile records were calculated by multiplying the speed of sound in sediment (1530 meters/second) by millisecond readings measured from the tidal channel surface to the depth of each particular layer or feature of interest in the seismic reflection records.

A description of the geomorphology of the Elkhorn Slough tidal channel from the HWY 1 Bridge to Hudson's Landing was accomplished using multibeam bathymetry (in map view and 3D-perspective views vertically exaggerated by five times), LIDAR data, sub-bottom profile imagery and sedimentary core data.

These data indicate that Elkhorn Slough changed from a relatively low-energy depositional environment to a high-energy erosional environment. The drastic change most likely occurred after the Slough mouth was engineered to the present configuration at HWY 1 Bridge behind the Moss Landing Harbor Inlet. Distinctive thinly bedded, flat clay layers are deposited in the upper few meters of most seismic reflection records, implying that a low-energy, shallow water depositional environment persisted in the past. The consolidated clay layers are disturbed where past tidal creeks intersected with the main tidal channel, often in the same general locations as present day tidal creeks. Beneath the depositional clay beds, a fragmented, strong reflector discontinuously follows the present Elkhorn Slough tidal channel upslough. This reflector is potentially a consolidated clay layer representing a past tidal channel and possibly the most resistant strata to tidal erosion identified in either the sub-bottom profiles or sedimentary core data.

Following the completion of the harbor, the character of Elkhorn Slough rapidly changed from a relatively low-energy depositional environment to one dominated by tidal erosion. The tidal erosion occurs along a gradient; the most severe erosion occurring near the HWY1 Bridge, gradually decreasing in scale further upslough. Consolidated clay layers, including the potentially erosion resistant past tidal channel deposit, have been entirely eroded through near the HWY 1 Bridge where the longest (300 m) and deepest (+9 m) tidal scour occurs.

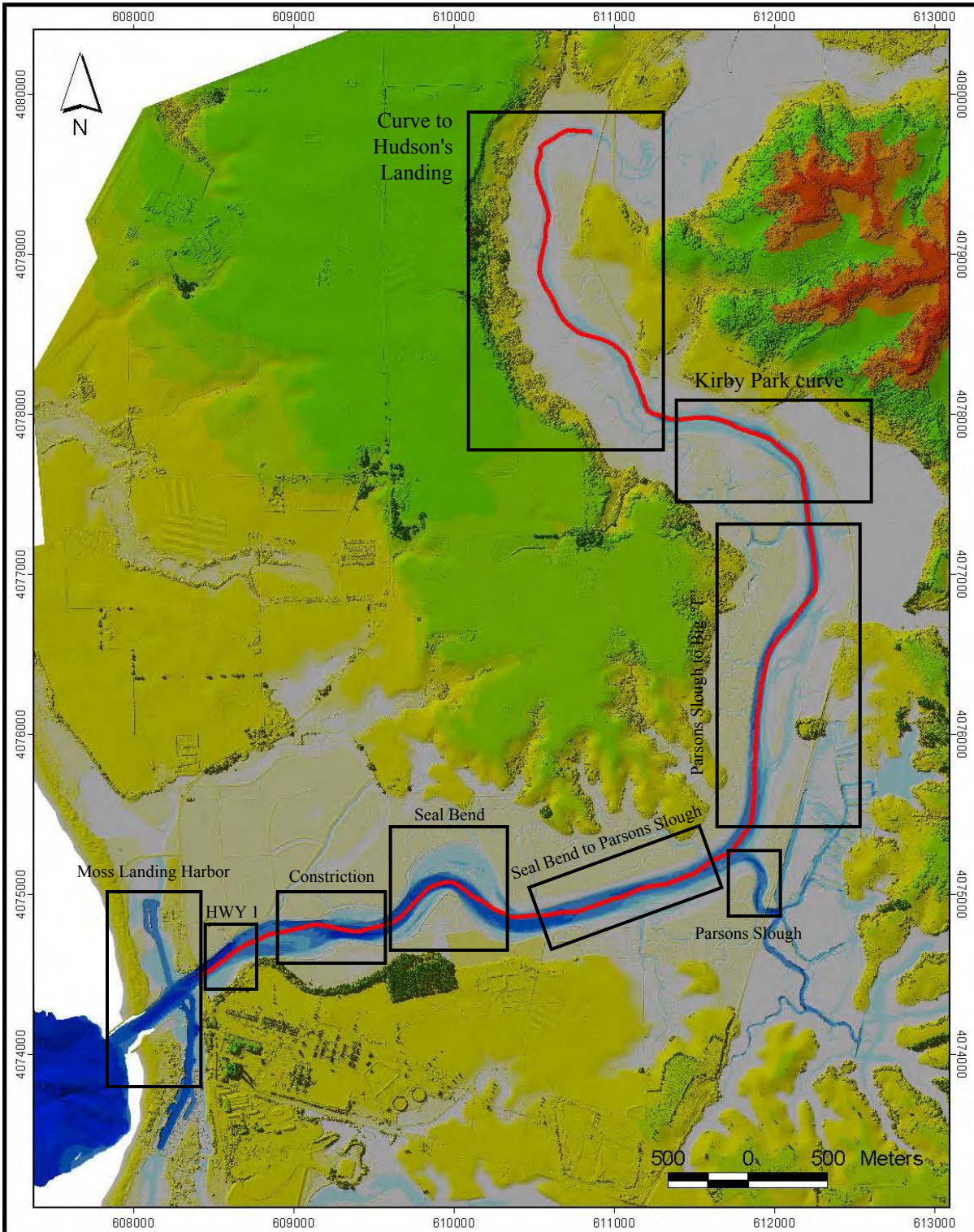


Figure 7. This image is a composite of SFML CSUMB 2001 and 2003 multibeam data merged with a NOAA LIDAR data set. The red line in the image illustrates the path of the sub-bottom profile track line surveyed in Spring of 2003, also by SFML CSUMB. Descriptions of the geomorphology of Elkhorn Slough using multibeam bathymetry, LIDAR, sub-bottom profiles and previously discussed core data are given for each section identified above.

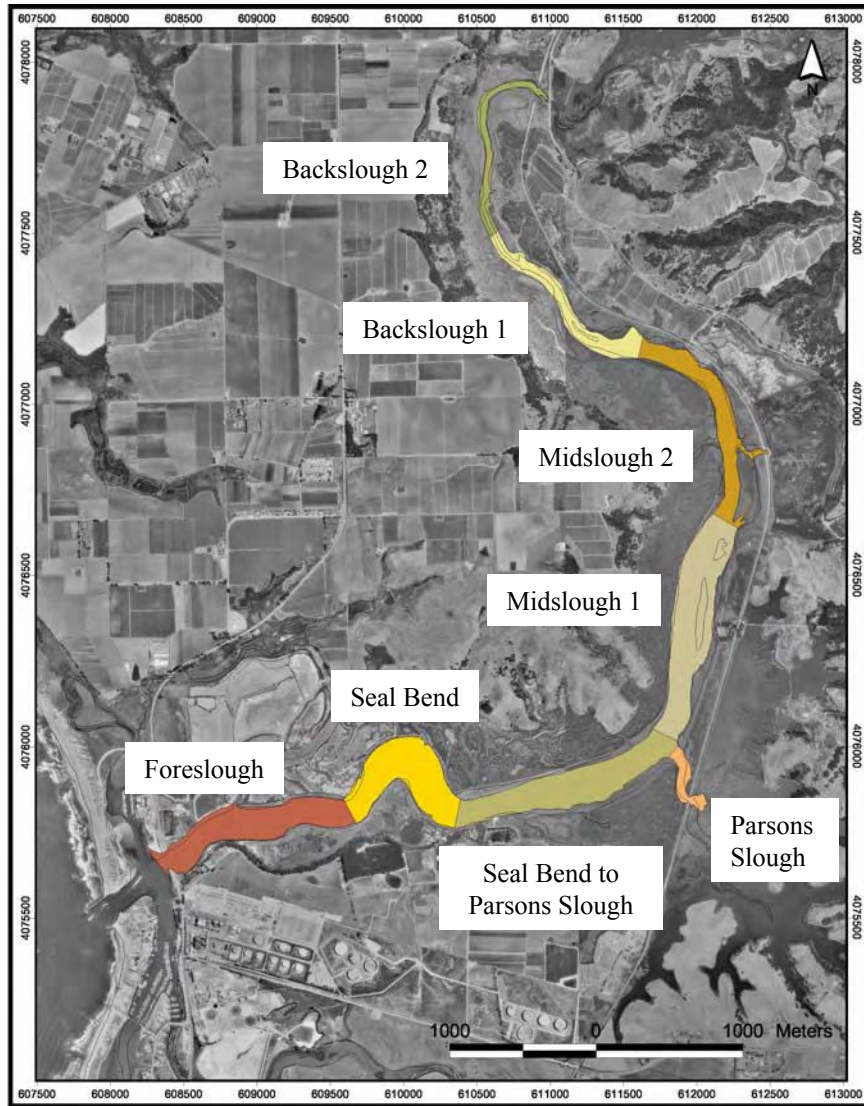
Extensive erosion persists up through Parsons Slough, particularly where the tidal channel width becomes constricted or where the channel curves. The tidal channel floor in this area appears to be swept free of any loose or unconsolidated fine sediment, leaving behind a corrugated irregular surface of differentially eroded clay layers exposed on the tidal channel floor and banks. Following Parsons Slough, tidal scours cut into consolidated clay layers at Kirby Park and at several curves upslough, but at a lesser magnitude than the scours towards the Slough mouth. Approximately 8 km upslough from the mouth, the near surface consolidated clay layers are flat lying and appear intact, not blocky or angular like those noted towards the mouth. Approaching Hudsons Landing, the last remaining accumulations of soft, unconsolidated clay are deposited up to 1.5 m thick over the undisturbed consolidated clay beds. Erosional features in the unconsolidated soft clay deposit are not indicated in the sub-bottom profiles. However, several small-scale scour depressions are visible in the multibeam bathymetry and observations made during scientific dives by local scientists indicate that erosion is occurring in the soft clay to the upper reaches of the Slough.

Other distinctive features occur in Elkhorn Slough including mudflat and salt marsh terraces (near HWY 1 Bridge, Seal Bend, and Kirby Park) that are being undercut and differentially eroded along clay beds. Secondary channels have also developed near curves in the tidal channel (most notably at Seal Bend) and where tidal creeks intersect with and expand into the main tidal channel. The secondary channels divert tidal flow into and out of the adjacent landscape as the tides alternate, eroding sediment between the secondary and main tidal channels. The two channels have the potential to join, expanding the overall size of the main tidal channel. Tidal creeks may also increase erosion in some tidal channel scours such as at Parsons Slough and at a curve west of Kirby Park. A rare depositional feature upslough and west of Kirby Park occurs where a tidal creek has eroded into the main tidal channel. Dean (2003) calculated sediment loss in Elkhorn Slough's tidal channel between 1993 and 2001 by comparing Malzone and Kvitek (1994) 1993 single beam bathymetry with the 2001 multibeam bathymetry in GIS. The results are presented in Figure 8.

#### Moss Landing Harbor channel

The completion of the Moss Landing Harbor Inlet in 1947 displaced the mouth of Elkhorn Slough approximately 2 kilometers south and 600 meters east of the mouth in a 1943 U.S. Army Corps of Engineers Moss Landing Harbor Development plan (Figure 9). In 1943, the Slough flowed northward behind the coastal dunes, in what is now the North Harbor, and the South Harbor resides in what was once an Old Salinas River channel. Depths in the harbor area have increased drastically, in part due to harbor dredging operations and in part due to increases in tidal currents following the completion of the harbor.

A complex interaction between approaching waves, diverse coastline orientations, a harbor channel, and abrupt canyon bathymetry, creates a variety of different sediment transport possibilities at Moss Landing. This coast is particularly exposed to waves approaching from the northwest, although west and southwest swells are also capable of transporting sediment here (Xu, 1999). Sediment traveling in littoral drift along the coastline is derived from many sources, the most important being the Pajaro River approximately 1.5 miles north, and the Salinas River approximately 4 miles to the south (Best and Griggs 1991; Eittreim et al. 2002b). As much as 523,000 yd<sup>3</sup> (400,000 m<sup>3</sup>) of sediment per year is actively transported down the Monterey Canyon (Greene et al. 2002; Mitts, 2003).



Division	1993 (m <sup>3</sup> )	2001 (m <sup>3</sup> )	volume change (m <sup>3</sup> )
Foreslough	560,000	740,000	-180,000
Seal Bend	460,000	520,000	-60,000
Seal Bend to Parson's Slough	440,000	550,000	-110,000
Midslough 1	290,000	310,000	-20,000
Midslough 2	180,000	200,000	-20,000
Back Slough I	110,000	120,000	-10,000
Back Slough II	43,000	42,000	1,000
Parson's Slough	39,000	85,000	-46,000
	<b>2,122,000</b>	<b>2,567,000</b>	<b>-445,000</b>

Figure 8. Dean (2003) estimated the volumes of sediment eroded from each Elkhorn Slough division above between the years of 1993 and 2001 by comparing single beam data collected by Malzone and Kvitck (1994) with multibeam bathymetry collected by Brantner (2001) with additions from Dean (2003).

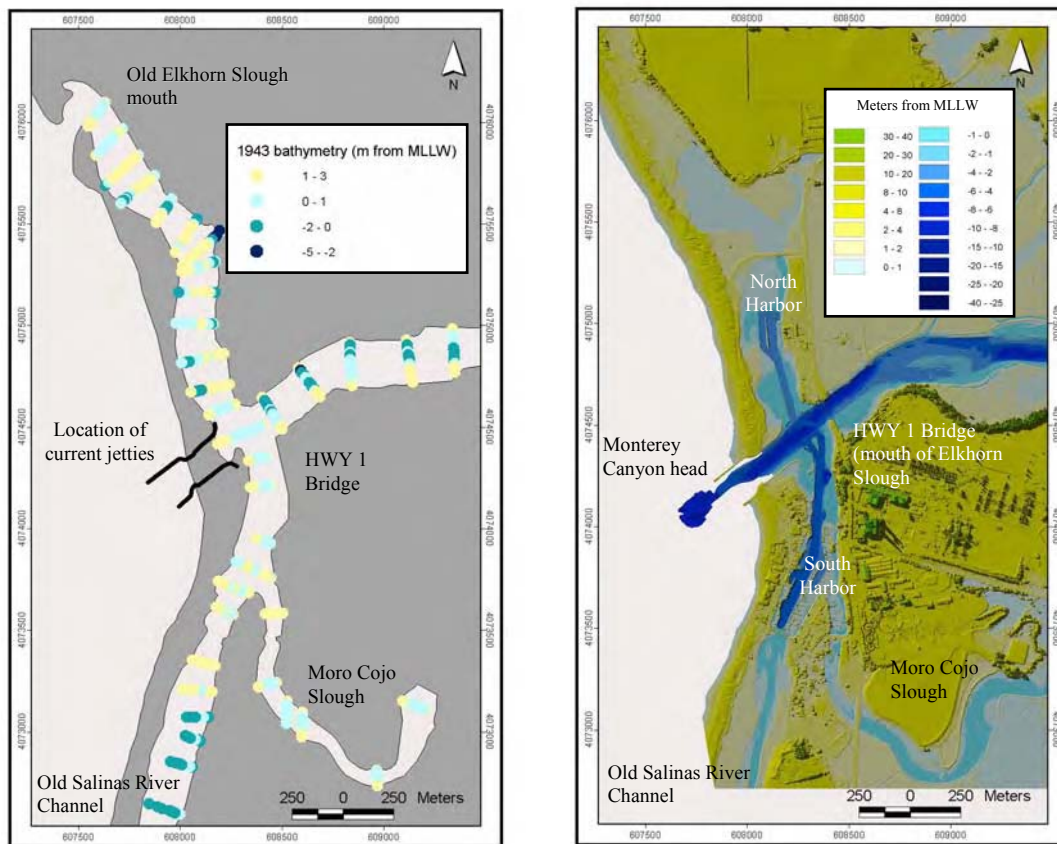


Figure 9. The bathymetry and coastline of the U.S. Army Corps of Engineers 1943 development plans for Moss Landing Harbor were digitized in GIS and are presented on the left in comparison with SFML CSUMB’s 2001/2003 multibeam and NOAA LIDAR data merge on the right. The Elkhorn Slough mouth was ~1.8 km further north than the current location of the Moss Landing harbor jetties and was shifted ~600 meters eastward behind the current locations of the jetties at HWY 1 Bridge. Depths in the harbor and in Elkhorn Slough have more than doubled in many locations following the construction of the harbor in 1947.

The head of Monterey Canyon lies less than 100 meters offshore of the Moss Landing Harbor channel (Figure 10). The canyon head is an active, erosional feature. Slumping events at the canyon head have been observed in the recent past by researchers from Moss Landing Marine Laboratories (MLML), Monterey Bay Aquarium Research Institute (MBARI), United States Geological Survey (USGS), and California State University Monterey Bay (CSUMB); one event taking place during the Loma Prieta earthquake in 1989 (Greene, et al. 1991). If the canyon head continues to erode towards the harbor channel it could cause adverse impacts on both the harbor and Elkhorn Slough by significantly increasing the depth and width of the harbor, possibly increasing tidal currents, and tidal scour.

One hundred meters offshore of the Moss Landing Harbor channel, the water depth is 20 meters in the canyon head. The depth decreases abruptly at the channel entrance to ~5 meters then increases to about 7.5 meters further inside in the harbor. The depth of the entrance channel is variable due to sediment entering the channel from littoral drift and depending on harbor dredging schedules. The width between the jetties is 190 meters wide at the Moss Landing Harbor Inlet and about 130 meters wide inside the harbor.

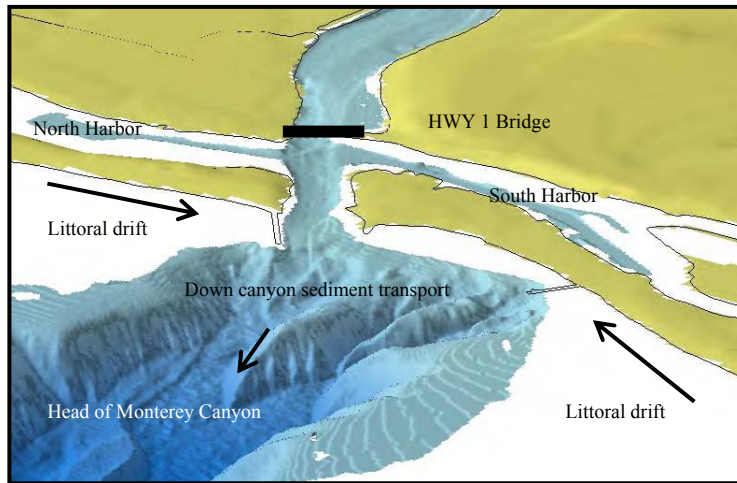


Figure 10. This image is a composite of bathymetry collected by the CSUMB SFML (blue) and a 10-meter USGS DEM (tan) looking over the head of Monterey Canyon and eastward towards Moss Landing Harbor and Elkhorn Slough. Sediment traveling in littoral drift is trapped in the head of Monterey Canyon and transported down the canyon axis. Some sediment from littoral drift enters the harbor where it deposits in the entrance channel.

Observations made by other scientists during scientific research dives indicates that sediment waves ~ 50 cm in height and 2-3 m in wave length composed of gravel, coarse sand, and shell fragments are present on the seafloor, implying high current velocities between the jetties. About 450 meters from the entrance, the harbor splits into north and south sections. Following the split towards the Elkhorn Slough Inlet, a gently sloping 1 meter rise or ridge is indicated on the harbor floor before a set of pilings left over from the previous bridge at HWY 1 are encountered (Figure 11). Depths on the western side of the HWY 1 Bridge are ~ 7 meters, shallower than those immediately on the eastern side of the bridge, which are almost 9 meters deep.

### HWY 1 Bridge

The present HWY 1 Bridge is considered the mouth of Elkhorn Slough (Figure 11). The tidal channel width at the Elkhorn Slough mouth is ~110 meters wide and over 9 meters at the deepest point. Immediately upstream of the bridge, the tidal channel width increases to about 200 meters as the south bank expands into a shallow, gently sloping sub-tidal mud bank terrace for nearly 300 meters up the south side of the tidal channel. On the northern side, a large scour has developed that is over 8 meters deep, 60 meters wide and extends 300 meters up the tidal channel. A pit approximately 10 m deep is located at the eastern end of the scour where the tidal channel width has decreased to 150 meters across. Slump debris undercut from the steeply sloping northern tidal channel bank (>50°) has been deposited in the base of the scour. John Oliver of MLML and Rikk Kvitek of CSUMB have both observed a shell hash deposit on the floor of the scour (possibly armoring the base of the scour against further erosion) where, during past scientific research dives, they had observed only soft unconsolidated clay.

The sub-bottom profile track line runs just south of and parallel to the tidal scour (Figures 11). The near surface reflectors of the seismic reflection record are interpreted to be thinly bedded clay laminations (Figure 12). Several differentially eroded clay beds appear to be exposed on the surface of the tidal channel based on the angular, uneven appearance of the channel floor surface.

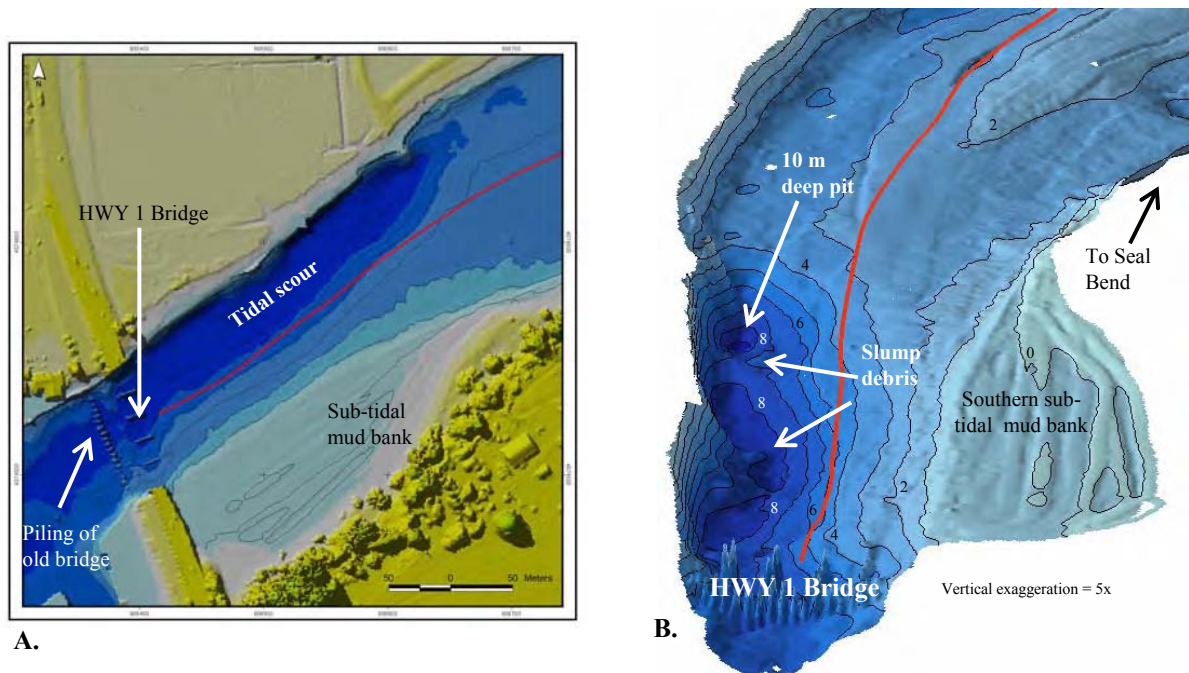


Figure 11. Image A shows the HWY 1 Bridge tidal scour from map view while Image B's point of view is from west to east looking downwards towards the HWY 1 Bridge. The tidal scour is the dark blue area on the left hand side of the tidal channel (north). A 10 m deep scour pit and slump debris have been noted in the image. The red line running just to the right of the scour is the sub-bottom profile track line pictured below. Bathymetry contours are at 1 m intervals

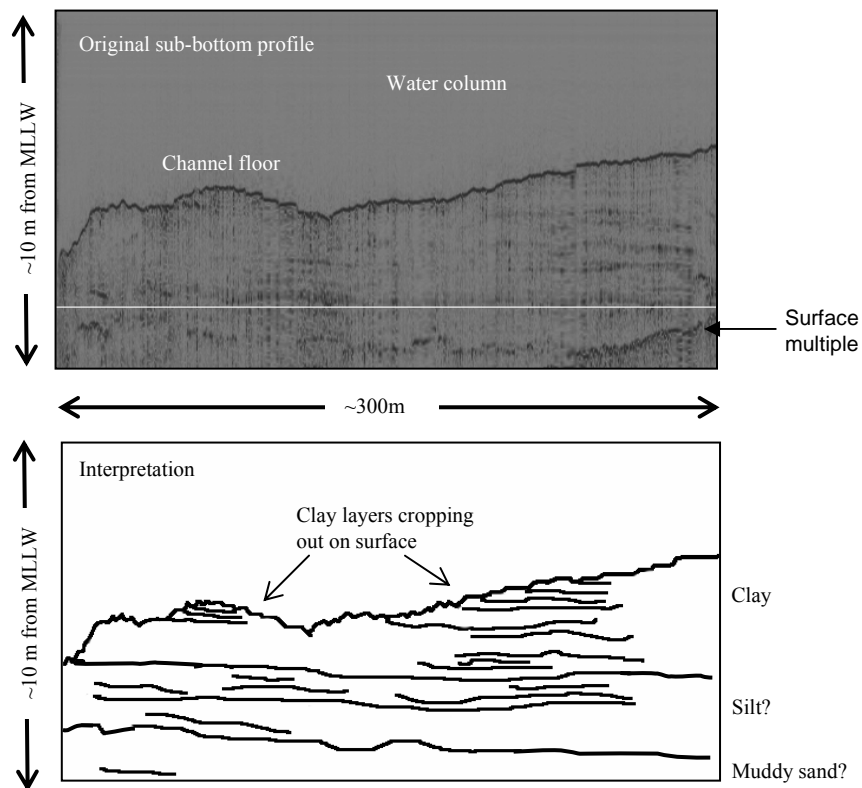


Figure 12. Three different sedimentary layers corresponding to the CALTRANS cores collected by Schwartz (1983) are interpreted in the sub-bottom record collected near the HWY 1 Bridge. The profile runs a few meters south of and parallel to the large tidal scour. Layers identified in the sub-bottom record have been eroded away in the adjacent tidal scour. The clay layers are thinly laminated and exposed on the tidal channel surface. The grainy appearance of the image may indicate the presence of organic detritus or coarse grained sediment mixed within the other layers.

A consistent reflector ~ 6 meters below MLLW probably corresponds to the silt layer sampled in the CALTRANS cores and another relatively strong reflector ~ 8 meters below MLLW may correspond with the muddy sand layer. These layers have been completely eroded through in the scour just a few meters north of the sub-bottom track line.

Dean (2003) compared past bathymetric profiles collected from many locations in Elkhorn Slough to his 2003 multibeam bathymetry data set. The profiles he compared near the HWY 1 Bridge are shown superimposed over Schwartz's (1983) CALTRANS core data in Figure 13. The bathymetric data indicates that the clay layer (the past tidal channel deposit that may represent the most resistant strata to tidal scour) had been entirely eroded through by 1993, and the underlying silt layer by 2003. If we assume that the existing sedimentary layers at HWY 1 Bridge continue in a similar pattern up channel, then the 10 meter pit on the eastern end of the scour has eroded well into the muddy sand layer described by Schwartz (1983).

#### Constriction of tidal channel approaching Seal Bend

Following the tidal scour near HWY 1 Bridge, the tidal channel trends eastward for ~ 500 meters and the channel width increases to about 230 meters across. Depths increase across channel, but the thalweg still favors the north side (~ 4 meters deep) over the south side (~ 3 meters deep). Heading towards the sweeping curve at Seal Bend, the tidal channel constricts to 160 meters across (Figure 14). Depths on the northern side of the channel increase to almost 6 meters approaching the constriction and channel banks slope becomes  $> 45^\circ$ . At the constriction, the thalweg crosses the tidal channel from the north to the south side where another large scour has developed before Seal Bend. The tidal scour is over 7 meters deep, 90 meters wide and about 400 meters long. The slope of the south tidal bank in the scour has increased from less than  $10^\circ$  up to  $45^\circ$ . Opposite of the scour, a shallow mudflat about 70 meters wide and 360 meters long has developed on the northern bank. The mudflat appears to be differentially eroded around outcropping clay strata and dissected by tidal creeks that may be preferential to ebb or flood tide tidal flow. Dean (2003) calculated a loss of  $180,000 \text{ m}^3$  of sediment between the HWY 1 Bridge and Seal Bend (Dean's Foreslough) over 8 years, the highest amount of any location in the tidal channel of Elkhorn Slough.

The sub-bottom track line crosses what appear to be exposed, differentially eroded, consolidated clay layers where the thalweg transitions from the north to the south side of the tidal channel (Figure 15). The sub-bottom seismic reflection record for this area shows a stair-stepping appearance in the channel floor in the both the sub-bottom and multibeam bathymetry, suggesting that clay layers are differentially eroded on the tidal channel floor. An irregular discontinuous reflector ~2 meters beneath the present tidal channel surface may represent the base of a past tidal channel.

#### Seal Bend

Following the constriction, the tidal channel makes a broad sweeping curve over 1000 meters long called Seal Bend (Figure 16). The thalweg takes the shortest possible route through Seal Bend, transitioning to the north shore after the constriction then switching to the south shore at the apex of the curve, and finally following the center of the channel when exiting the eastern end of Seal Bend. The entire curve is another tidal scour feature. The thalweg is well-defined with depths through the curve ranging from approximately 5 to 7.5 meters. Channel bank slopes are steepest at the apex of the curve on both sides of the channel (up to  $40^\circ$ ).



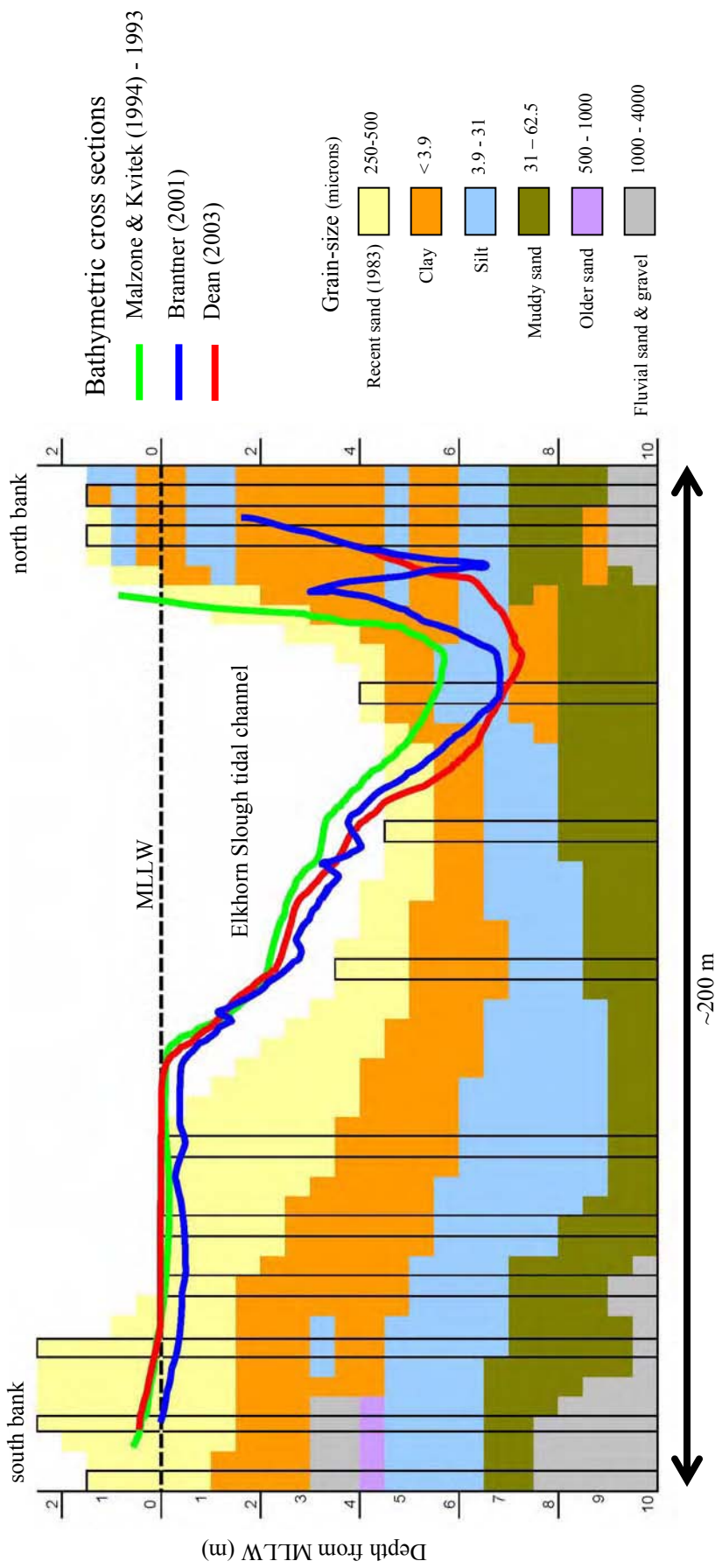


Figure 13. Bathymetric cross sections near the HWY 1 Bridge collected in 1993, 2001, and 2003 are shown superimposed over Schwartz's (1983) description of CALTRANS boreholes (see Figure 4). While this comparison is subject to a degree of positional error, the depth measurements from MLLW are probably accurate. The figure shows that the recent sand layer, clay layer and silt layer have been eroded away. This scour feature is almost 10 meters deep just ~250 m from the bridge, penetrating well into the muddy sand layer.

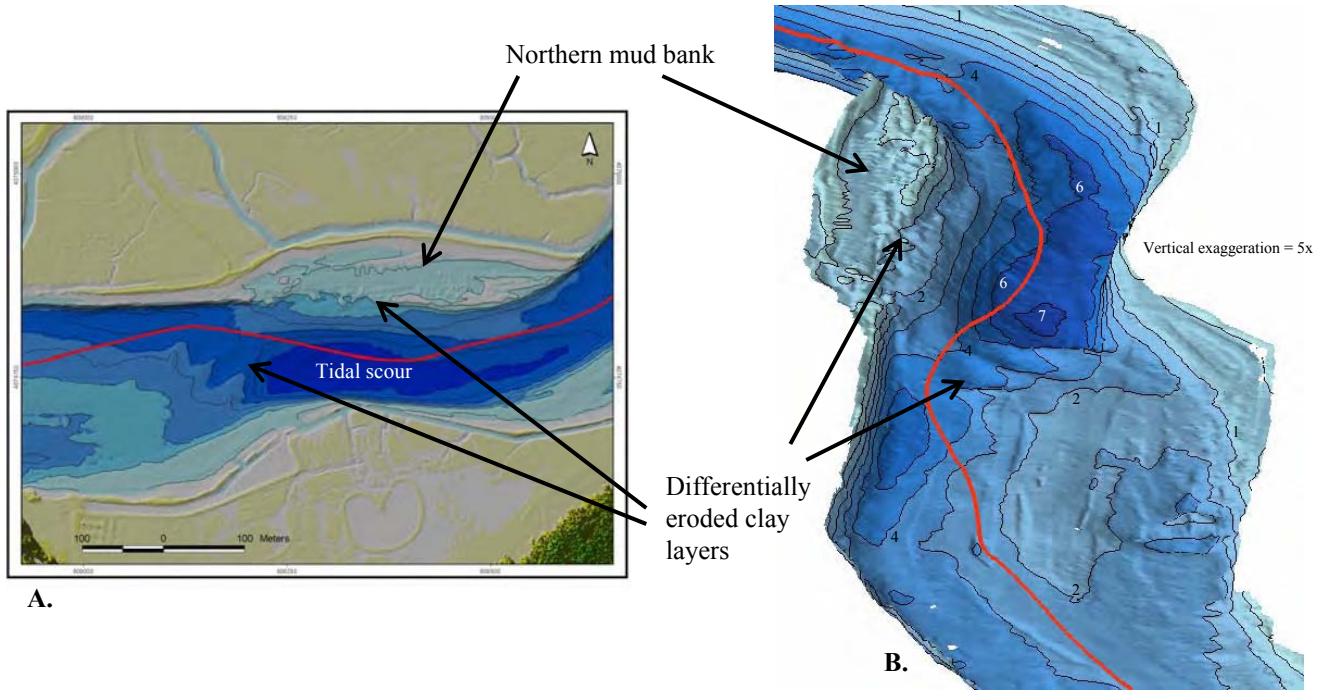


Figure 14. Two images are used to highlight a large tidal scour occurring near a constriction in the width of the Elkhorn Slough tidal channel. The point of view for Image B is down and eastward into the tidal scour (darkest blue). The thalweg crosses the channel from north to south at the constriction. A narrow, sub-tidal mud bank terrace lies opposite the scour and is being undercut and differentially eroded along exposed clay layers. The red line indicates the sub-bottom track line (below), which passes on the north side of the tidal scour. Bathymetry contours are at 1 m intervals.

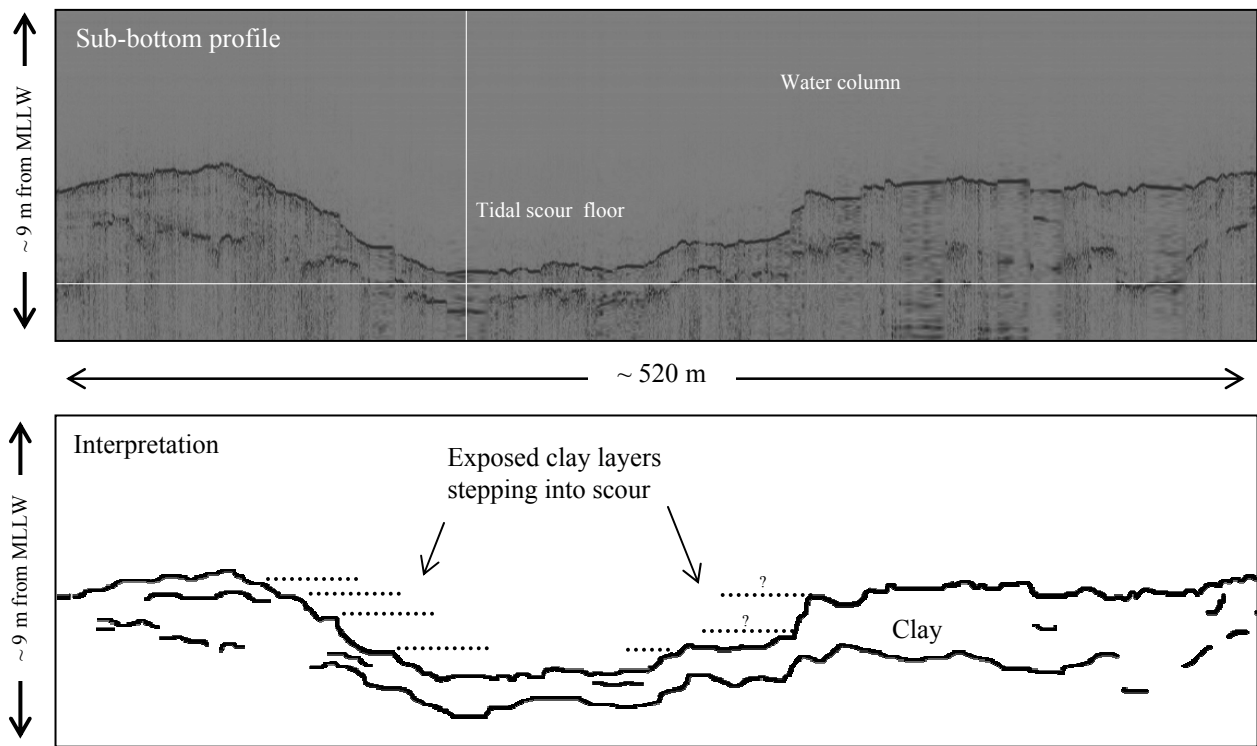


Figure 15. The sub-bottom profile runs along the northern side of the constriction tidal scour, glancing a series of clay layers stepping into the tidal scour (dashed lines). The blocky, uneven surface of the sub-bottom record indicates that clay layers are cropping out on the tidal channel surface, not just within the scour. The hard reflector between 7 and 8 meters below MLLW may be a semi-consolidated clay layer indicating a past tidal channel.

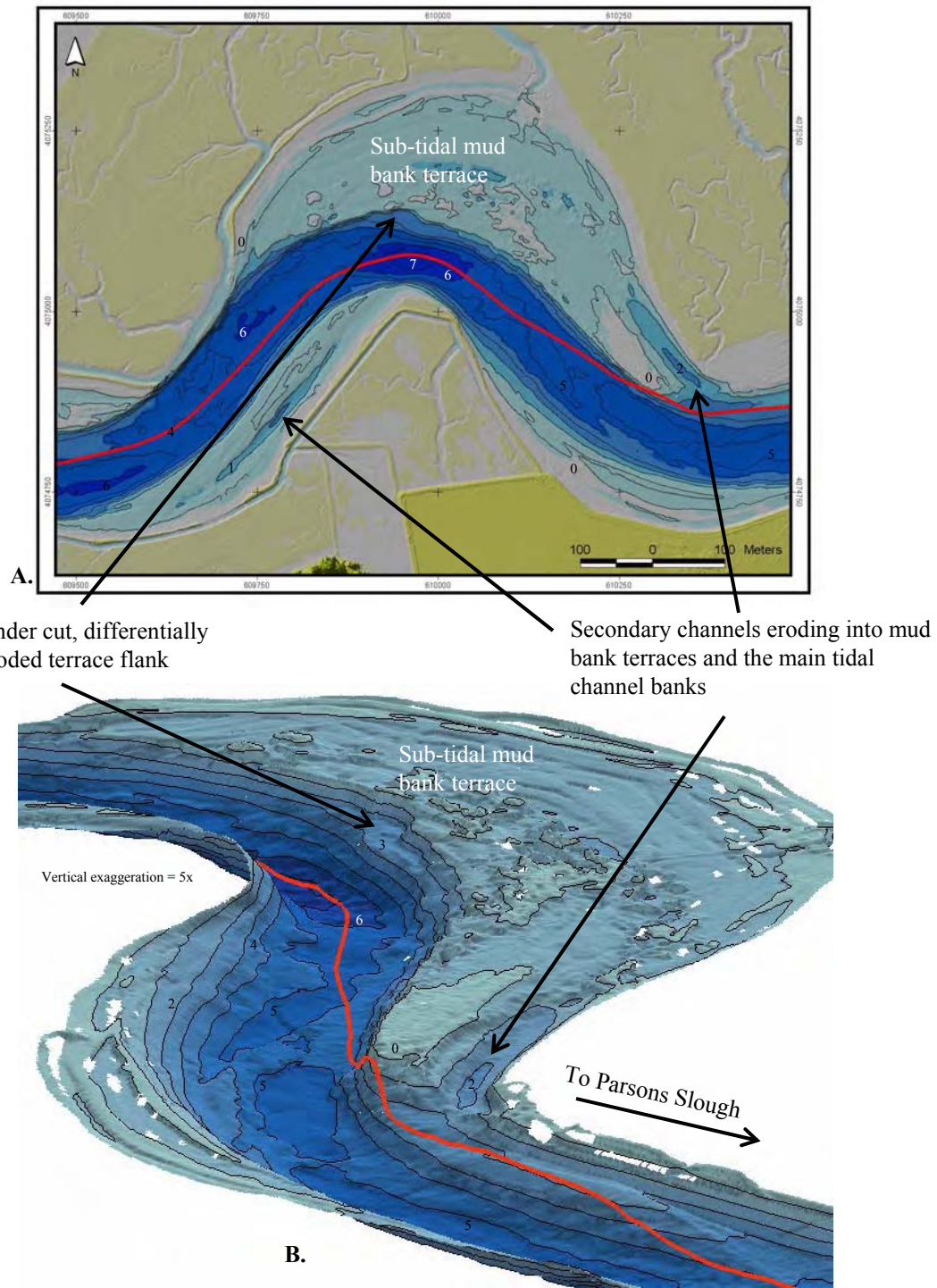


Figure 16. Image A is an overview of Seal Bend, while Image B's point of view looks down and across Seal Bend from the northwest. The entire tidal channel in the curve is a large, well-defined, steeply sloping tidal scour up to 7.5 meters deep at the apex of the curve. The northern mud bank terrace is undercut and differentially eroded along exposed clay layers. Two secondary channels have developed, one along the inside of the southwestern section of the curve and one along the outside of the northeastern section of the curve that connects the main tidal channel and the mud bank terrace. The red line marks the sub-bottom track line through Seal Bend. The sub-bottom record through the curve is not presented.

Expanding from the northern bank at the top of the curve is a crescent-shaped, 600 meter long, 200 meter wide mud bank terrace. Eel grass growing on the terrace has caused some distortion in the multibeam image (Dean, 2003). The surface of the shallow terrace is hummocky, convoluted and eroded by tidal creeks. A secondary channel has eroded into the northeastern side of Seal Bend connecting the mudflat and the main tidal channel. Another secondary channel is developing on the inside of the southwestern portion of the curve above the thalweg. Eventually the secondary channels will join with the main tidal channel, expanding the tidal channel volume. The terrace flanks have been undercut and differentially eroded along sedimentary layers leaving debris in the base of the scour. Dean (2003) calculated 60,000 m<sup>3</sup> of sediment loss from Seal Bend between 1993 and 2003, the third highest in Elkhorn Slough.

The sub-bottom track line runs through the thalweg and up on the bank as it exits Seal Bend. The seismic reflection record (not shown in figures) implies a blocky, angular channel floor surface exists, indicating that clay layers are exposed on the floor of the scour. The past tidal channel reflector is also noted ~2 meters below the tidal channel surface in this seismic reflection record.

### Seal Bend to Parsons Slough

After Seal Bend, the tidal channel takes a fairly straight course in an east-northeasterly direction for 1250 meters to Parsons Slough (Figure 17). Even without a major constriction or curve to increase tidal currents between Seal Bend and Parsons Slough, this section had the second highest amount of sediment loss (110,000 m<sup>3</sup>) between 1993 and 2001 (Dean, 2003). The channel width remains fairly constant at 160 meters. Broad mudflats and significant tidal creeks drain into the main tidal channel from both sides of the channel along this stretch. Tidal channel depths are fairly consistent between Seal Bend and Parsons Slough ranging from about 3 to 4.5 meters, with the deepest sections found on the northern side. Slopes along the channel banks are relatively gentle, ranging between 10° and 20°, and never exceeding 30°.

The multibeam bathymetry and sub-bottom profile records both indicate a channel floor that becomes increasingly rutted and disturbed on the approach to Parsons Slough. What at first appear to be sedimentary waves in the multibeam bathymetry are eroded clay layers exposed on the tidal channel floor (Figures 18). Core 18 located on the north side of the tidal channel (see Figure 3) penetrated clay from 0.5 to at least 3 meters below MLLW (see Figure 5). Parallel sub-surface layers become disturbed, discontinuous and dip as the tidal channel intersects with a significant tidal creek entering from the southern side. Sub-surface layering returns to parallel following the tidal creek for a short stretch, but becomes even more disturbed at the intersection with Parsons Slough. Reflectors near Parsons Slough are dipping, become discontinuous and wash out altogether, including the strong, deep reflector (~6 to 7 MLLW) interpreted in previous seismic reflection records to be a past tidal channel base. Where the reflectors washed out between the dipping beds, a mound appears that could be a deposit of coarse sediment transported down channel or from Parsons Slough. If the sediments came from Parsons, they could consist of fluvially derived coarse-grained gravel and sand indicated in cores 16 and 17. The potentially larger diameter sediment (up to 4000 microns) is more difficult to transport than smaller diameter fine-grained sand, silt, and clay (500 to < 3.0 microns). The mound is most likely a shallow, relatively resistant, differentially eroded ridge due to the high current speeds measured in this location (see Tidal currents section).

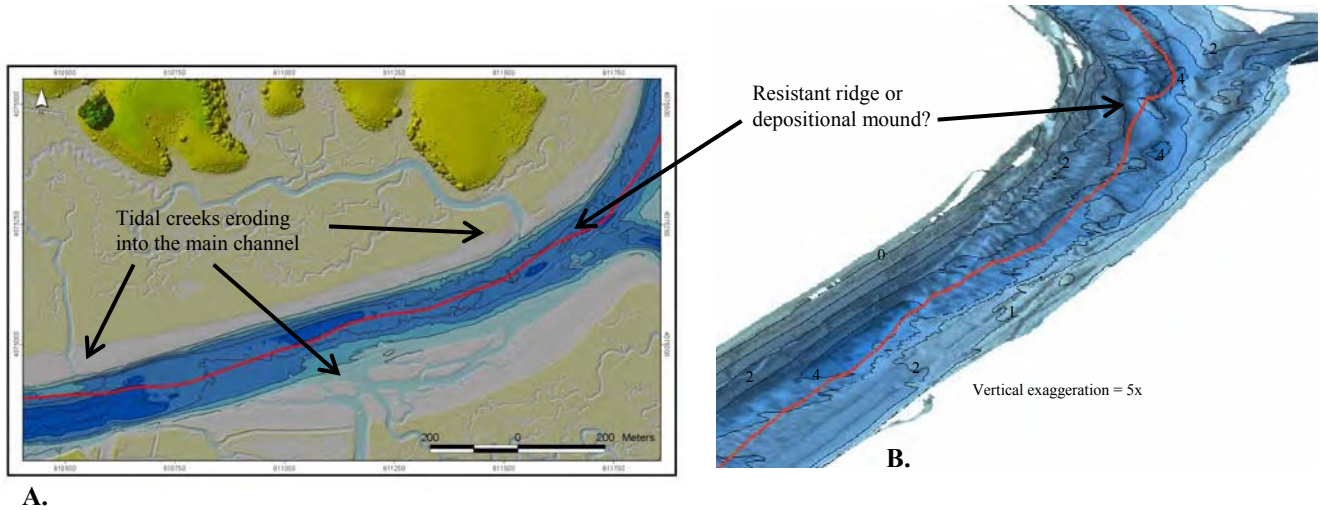


Figure 17. Many tidal creeks drain into and erode the banks of the main tidal channel between Seal Bend and Parsons Slough (Image A). Image B looks eastward up towards Parsons Slough from above. The bumpy channel floor gives the appearance of sediment waves, but the features are exposed consolidated clay layers (see below). The red line illustrates the path of the sub-bottom track line shown below. Bathymetry contours are at 1 m intervals.

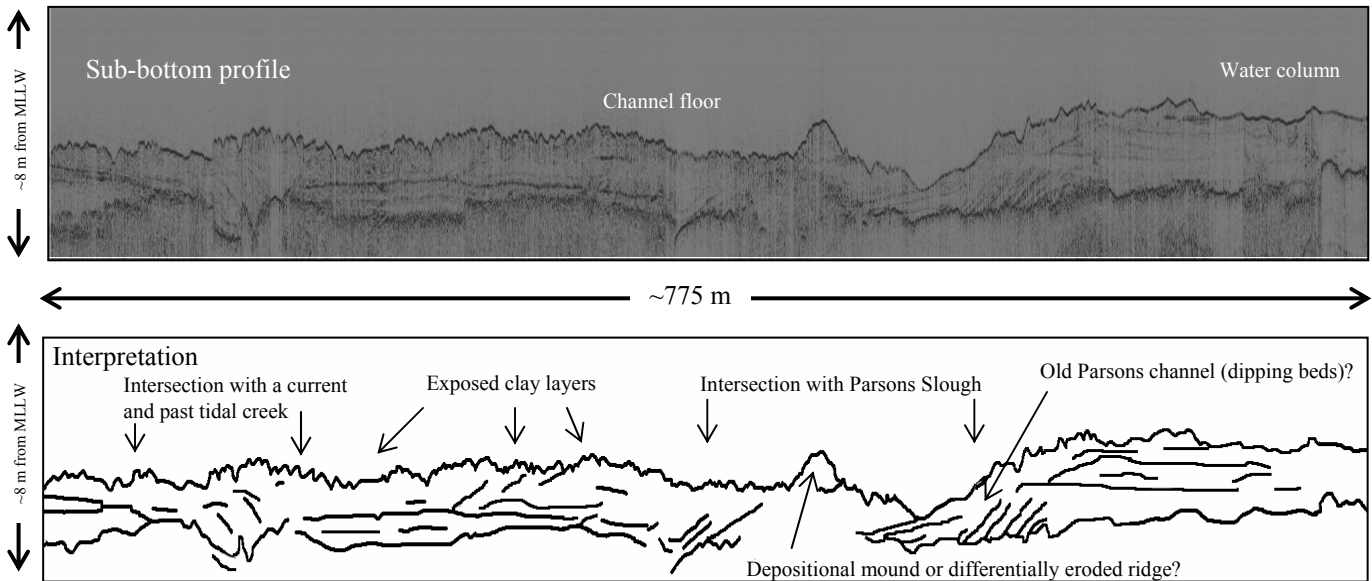


Figure 18. A variety of features are present in the sub-bottom record between Seal Bend and Parsons Slough. Sub-surface layers are disturbed at intersections with past and current tidal creeks and Parsons Slough. The hummocky, angular appearance of the channel floor indicates that clay layers are exposed on the surface with a possible exception near Parsons, where a coarse-grained mound may have been deposited. High current speeds measured in this location suggest that the feature is most likely a differentially eroded clay ridge.

### Parsons Slough

According to Dean (2003), Parsons Slough lost 46,000 m<sup>3</sup> of sediment between 1993 and 2001. This number only includes the tidal channel area up to the Union Pacific railway bridge where good bathymetric data are available (Figure 19). The Parsons Slough channel is about 460 meters long and 160 meters wide at the intersection with Elkhorn Slough. Parsons Slough tidal channel narrows as it meanders toward the railway bridge to about 60 meters across. Two main scours occur in the tightest sections of the bends and an erosional pit is located at Parsons' intersection with the railway bridge, the extent of the multibeam data. The first tidal scour is up to 5 meters deep and the west bank slopes up to 25°. The second scour is deeper (~6 meters) and steeper (> 35°), perhaps in part due to two different tidal creeks entering Parsons Slough on either side of the second tidal scour. The active creeks may accelerate erosion and deliver coarse-grained sand and gravel down channel to Elkhorn Slough towards the potential depositional mound previously discussed. Across from the second tidal scour on the eastern bank, another secondary channel has developed above the main tidal channel. Up channel after the second scour, a shallow rise occurs before dropping into a 4 meter deep erosional pit near the railway bridge. The railway bridge may constrict tidal flow east and west under the bridge causing an increase in tidal currents and higher potentials for erosion on either side of the bridge.

### Parsons Slough to “Big T” tidal creeks

The main tidal channel trends northward after Parsons Slough for ~1100 meters, flanked on both sides by mudflats and large tidal creeks draining into Elkhorn Slough (Figure 20). The slopes along the channel banks are below 20°. The tidal channel is ~140 meters across after Parsons Slough and the width decreases up channel to about 80 meters. Depths range from about 2 to 3.5 meters but increase when the tidal channel travels through another s-turn for about 700 meters. Two relatively small tidal scours occur in the s-turn, both nearly 5 meters deep and ~350 meters long. About 300 meters after the s-turn, the main tidal channel is crossed in the same place by two tidal creeks running perpendicular to the main tidal channel referred to in Dean (2003) as the “Big T”. The sedimentary cores previously discussed (cores 12, 13, 14, 15, and ES-4, see Figures 3 and 5) indicate that clay is present from ~1.5 m MLLW to at least 9.5 m MLLW.

Following Parsons Slough, near the intersection with a tidal creek on the east side of the channel, the channel floor is blocky, angular and highly disturbed. Again, what at first appear to be sedimentary waves are differentially eroded clay layers. The sub-bottom profile imagery (Figure 21) reveals multiple layers of arcing strata, interpreted to be a past tidal creek intersecting with Elkhorn Slough main tidal channel that has filled in over time. The old tidal creek is being scoured away by tidal currents, exposing the curving clay beds on the tidal channel floor. Further up channel, the sub-bottom track line crosses into the base of the second scour at the northern end of the s-turn. More angular clay layers are exposed and differentially eroded in the scour. Following the scour, the track line runs abruptly up the channel bank (the bump in seismic reflection record B) then another intersection with an old past tidal creek is imaged at the current location of the “Big T” tidal creeks. The sedimentary layers here lay flatter relative to those imaged down channel but the channel floor is still angular and irregular, indicating that the channel floor is exposed clay.

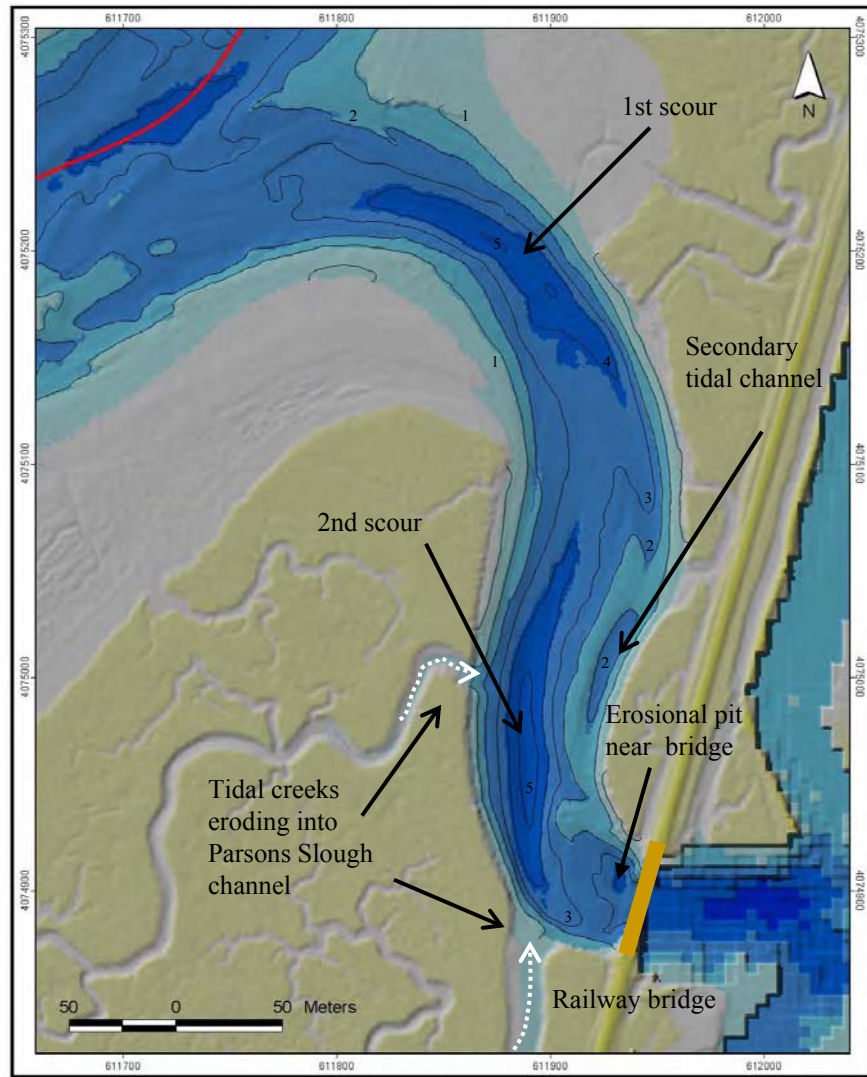


Figure 19. In Parsons Slough, deep tidal scours occur along curving sections of the channel, along an upper branch of the tidal channel and at a pit near the Union Pacific railway bridge. Tidal creeks are eroding into the banks of Parsons Slough and probably contribute to the erosion of the 2<sup>nd</sup> tidal scour. The railway bridge may constrict water flow traveling east and west through the bridge, increasing current velocities and potential erosion. Bathymetry contours are at 1 m intervals. Sub-bottom profiles were not collected in Parsons Slough.

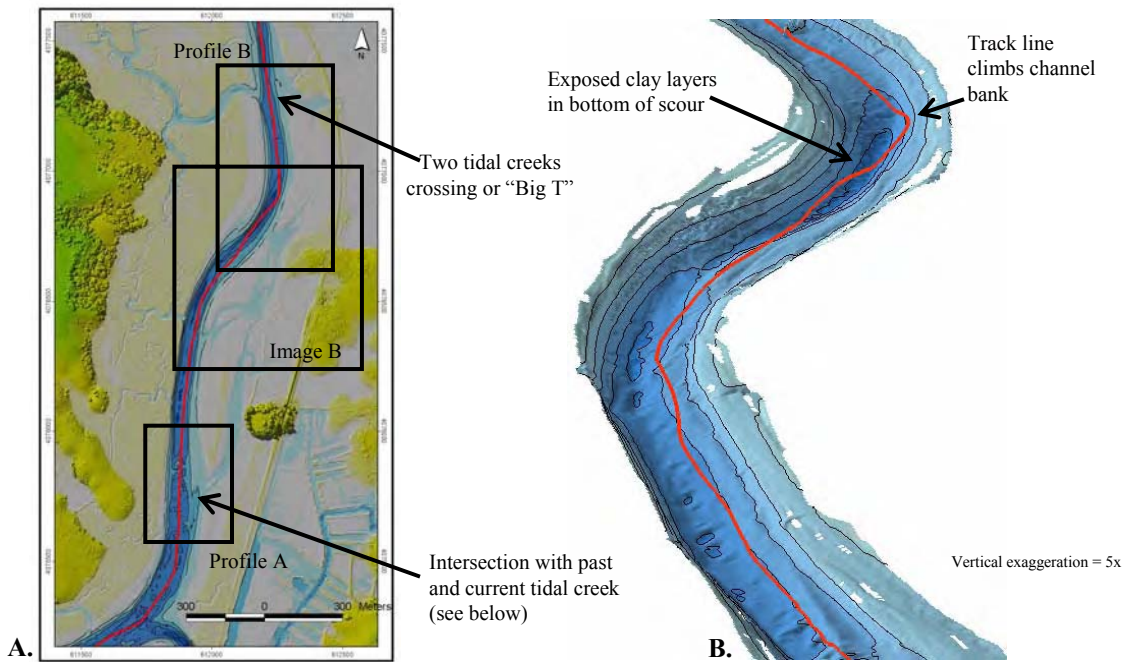


Figure 20. Image A is an overview of the stretch between Parsons Slough and where two tidal creeks perpendicularly intersect Elkhorn Slough in the same place, called the “Big T”. Image B is a perspective view looking northeastward across two tidal scours that occur in an s-turn prior to the “Big T”. The locations of the sonar records are indicated in Image A.

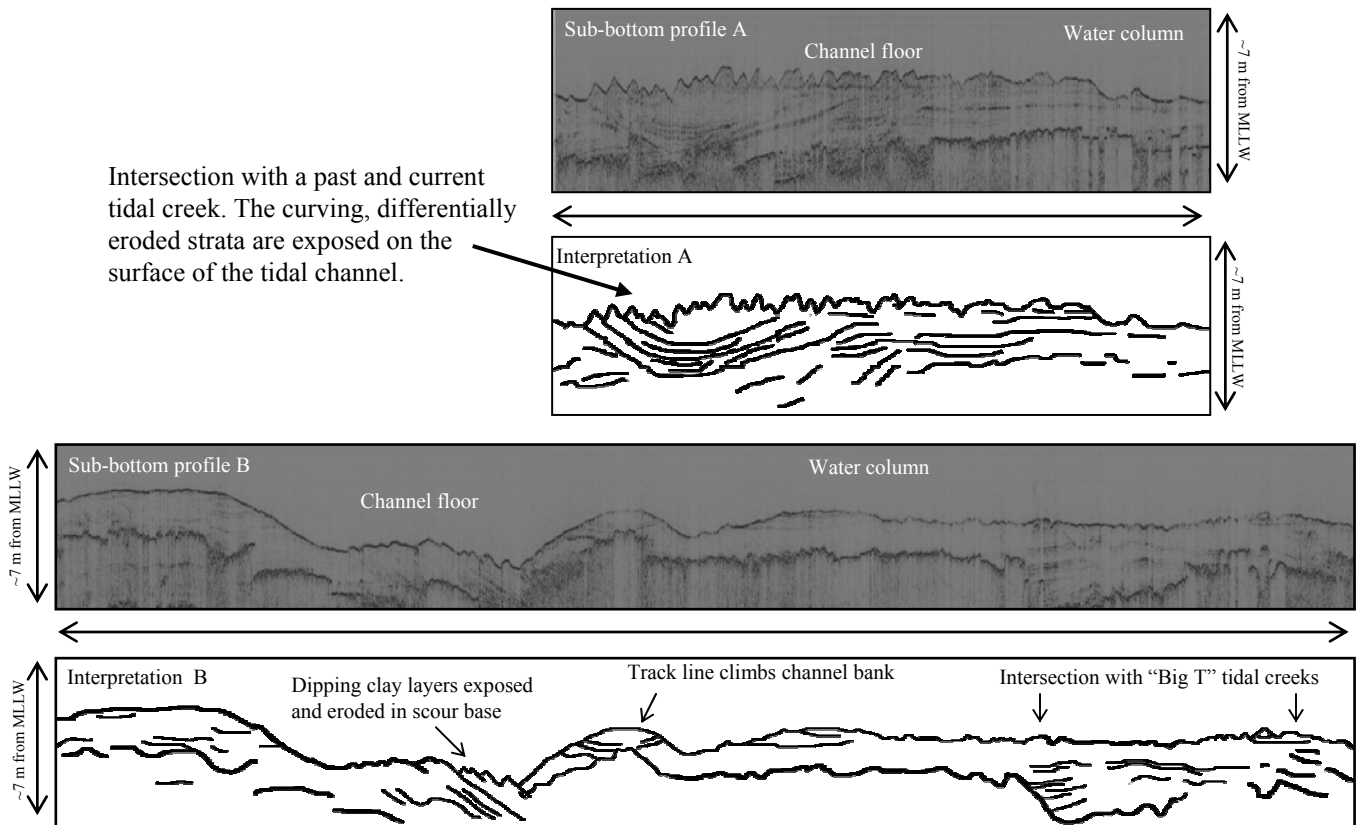


Figure 21. Two sub-bottom records are presented above. In sub-bottom record A, an old tidal creek intersects with the main tidal channel. Eroded clay layers from the tidal creek are exposed on the channel floor, creating the blocky angular appearance. In sub-bottom image B, angular clay layers are exposed in the base of a tidal scour and another old tidal creek is imaged in the same location as the current “Big T” tidal channels.



### Kirby Park curve

The tidal channel curves westwards after the “Big T”, increasing in width throughout the curve, from 80 meters at the “Big T”, to 120 meters at Kirby Park and about 160 meters wide at the end of the curve (Figure 22). Tidal channel depths range from about 2.5 to 3 meters at the “Big T” and increase to over 3.5 meters as the curve begins to tighten near Kirby Park, where another small scour has developed. The scour appears to be undercutting the bank ( $>25^\circ$ ) where the parking lot at Kirby Park extends towards the tidal channel. A large mudflat has formed to the west of the tidal channel opposite of Kirby Park and a large tidal creek enters the main channel on the western side of the curve. The tidal creek runs semi-parallel to the tidal channel along the curve, eventually eroding down into the tidal channel (probably from ebbing tidal currents) as the curve straightens out on the southern end.

The sub-bottom track line runs through the tidal scour near Kirby Park, recording the angular blocky channel floor found at most other locations in the slough (Figure 23). The features are interpreted to be differentially eroded clay layers exposed on the seafloor. Following the scour, a unique feature is encountered, a sedimentary deposit. Approximately 200 meters west of Kirby Park, tidal channel depths decrease to 1.5 meter and the channel floor gradually becomes smoother where sediment has deposited over the clay layers. Clay laminations are not indicated at the peak of the deposit and the semi-consistent hard reflector interpreted to be an old tidal channel base in previous seismic reflection records has also washed out. The sediment was probably delivered by the large tidal creek to the west of the deposit and may be composed primarily of sand due to the hard surface reflection recorded in the seismic reflection image. Immediately west of the deposit, the seafloor abruptly returns to the usual angular, blocky appearance indicating clay layers exposed on the channel floor. The gradual build up of sediment of the eastern side of the deposit, followed by the gradual return to exposed clay layers indicates that the sediment is probably being transported down channel towards Kirby Park, not upstream towards Hudson’s Landing. This indicates that currents in this section are probably stronger on the ebb tide than the flood tide.

### Curve to Hudson’s Landing

After the westward bend beyond Kirby Park, the tidal channel narrows to about 70 meters and another s-turn occurs (Figure 24). In the tightest sections of the curve, two narrow tidal scours have developed. The first scour is just over 4 meters deep and ~ 400 meters long. A tidal creek on the western bank erodes into the tidal channel at the northwestern end of the scour, possibly accelerating erosion in the scour. The second tidal scour is about 4 meters deep and 270 meters long. The scour has under cut the steeply sloping eastern bank ( $45^\circ$ ).

Following the second tidal scour, the tidal channel becomes narrow (~ 50 meters at Hudson’s Landing), shallow (0.5-2 meters) and the channel floor surface appears smooth. The erosional gradient has decreased considerably with relatively small-scale erosional scour depressions appearing near narrow curves and tidal creeks. No other deep scour features were identified in the multibeam imagery. The sub-bottom seismic reflection records recorded a smooth, flat, channel floor, consisting of consolidated laminated clay beds beneath the channel surface (Figure 25).

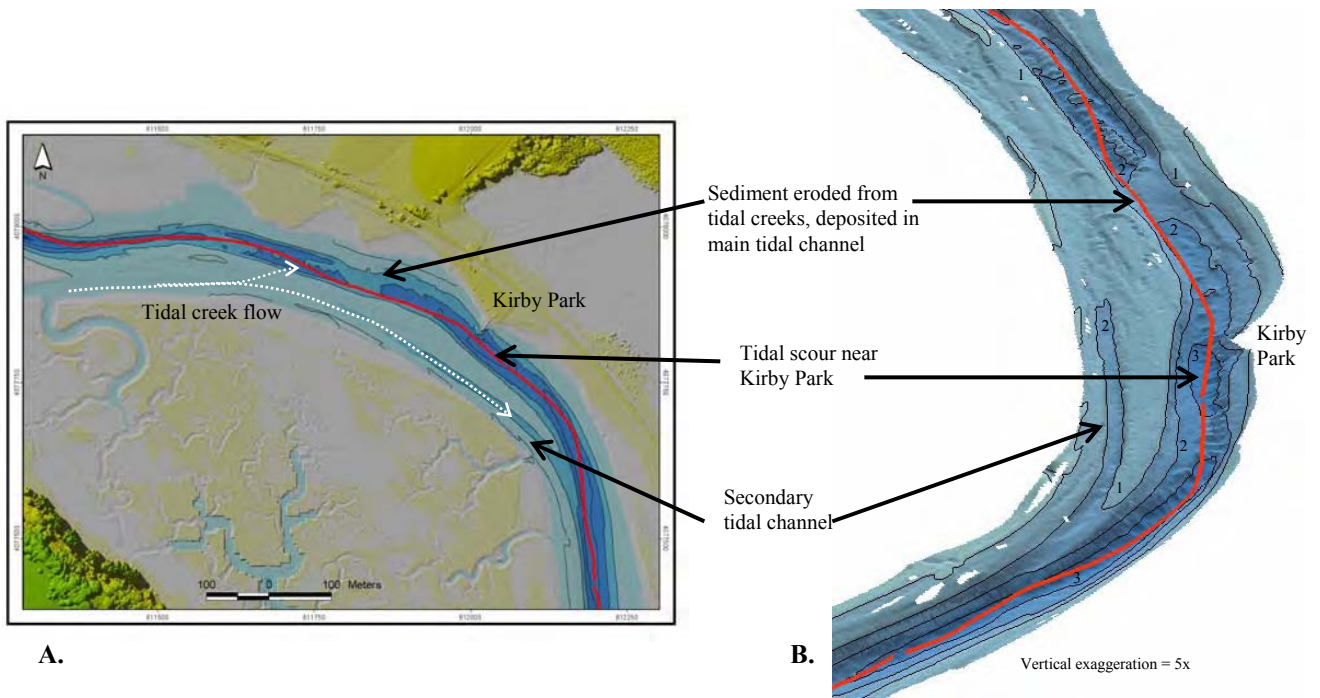


Figure 22. Image A is an overview of the curve near Kirby Park and Image B lends a different perspective on some interesting features looking westward towards Kirby park from above. The images highlight a tidal scour near Kirby Park, an erosional tidal creek and a unique sedimentary deposit.

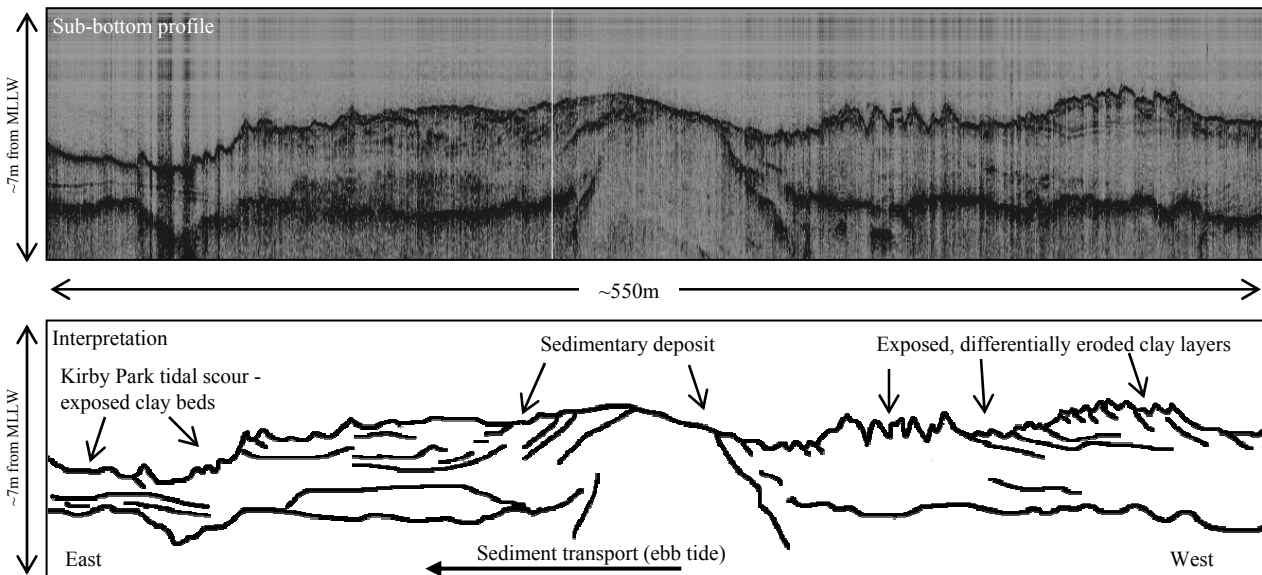


Figure 23. Exposed differentially eroded clay layers in the tidal scour near Kirby Park become gradually deposited over by sediments entering up channel from a tidal creek. The immediate return of the channel floor to exposed angular clay layers west of the deposit indicates that the sediments are being transported down channel towards Kirby Park on ebbing tides.

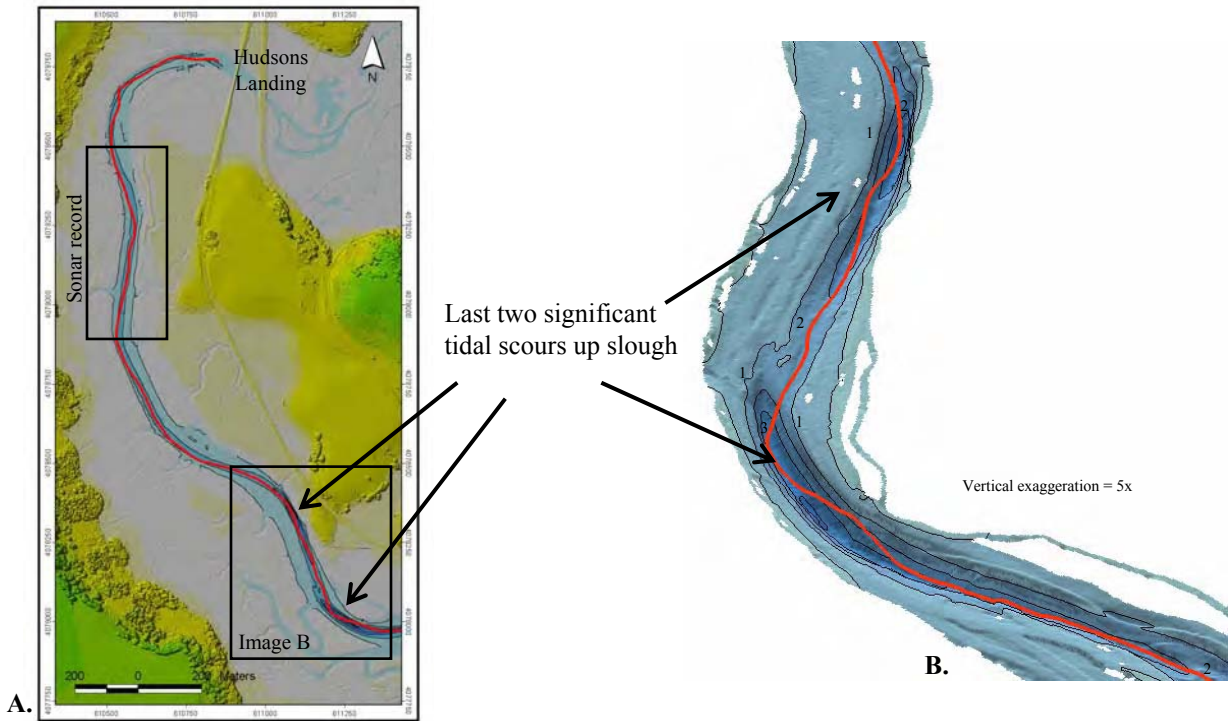


Figure 24. The two images provide different perspectives of the last two deep tidal scours up the Elkhorn Slough tidal channel. The magnitude of tidal erosion drops off considerably following the two scours.

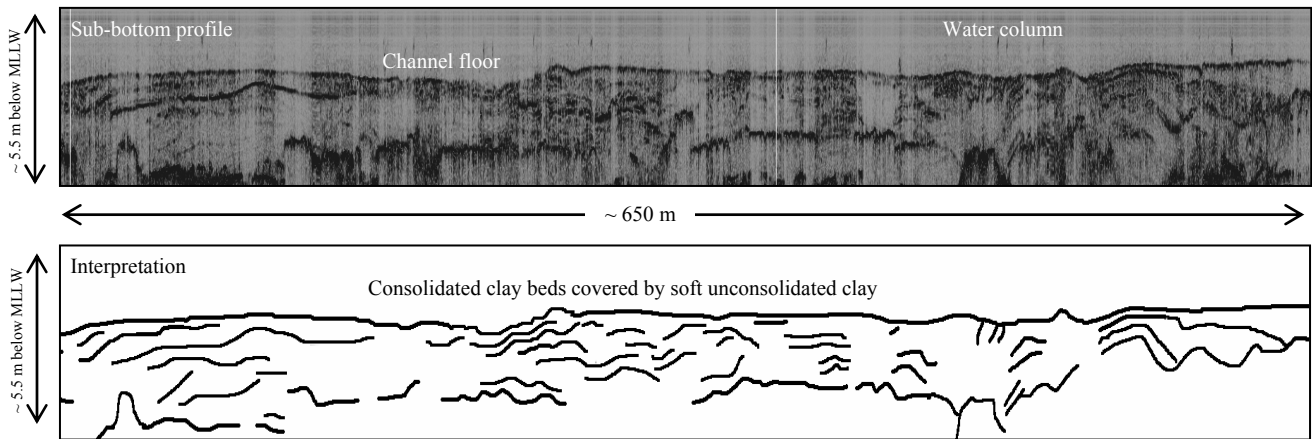


Figure 25. The sub-bottom record after the two tidal scours illustrates the decreased magnitude of the erosional gradient upslough. The channel floor is smooth indicating that near surface clay beds are undisturbed and covered by up to 1.5 m of soft unconsolidated clay. While the sub-bottom images do not indicate that erosion is taking place, observational evidence indicates that the soft clay deposit is eroding in many places in the upper reaches of the Slough.

The appearance of the sub-bottom image does not indicate that the channel floor is being eroded to any significant extent. The core data shows that the channel banks are composed of clay (see Figures 3 and 6) while cores further away from the tidal channel (see Figures 3 and 5) identify peat, fluvial gravel and sand deposits. The grainy appearance of the seismic reflection record may indicate the presence of organic debris and coarse-grained fluvially derived sediment mixed in with the clay beds.

## SECTION 3 – TIDES, TIDAL PRISM, AND TIDAL CURRENTS

### *Tides*

The tides in Elkhorn Slough are mixed semi-diurnal with a mean range of 1.2 m and a mean diurnal range of 1.7 m (Broenkow & Breaker, in press). The spring tidal range is about 2.5 m while the neap tidal range is about 0.9 m. The greatest tidal exchange, or range, in Elkhorn Slough occurs on the ebb tide, during the transition from Mean Higher High Water (MHHW) to Mean Lower Low Water (MLLW). Reported current measurements have shown that ebbing tidal currents are stronger than flooding tidal currents. From a tidal erosion perspective, this implies that sediment will most likely be mobilized during ebb currents. The tide is not equal at any given moment throughout the Elkhorn Slough. For example, high tide occurs at the Slough mouth 25 minutes earlier than it does at Kirby Park (Caffrey and Broenkow, 2002). Locations in the Slough have different lag times based on environmental factors such as tidal channel slope, geometry, and friction along the channel floor or with estuarine flora such as the pickleweed common in Elkhorn Slough.

### *Tidal Prism*

The tidal prism is defined as the volume of water that passes from the ocean into an embayment over a tidal cycle and is the primary factor that determines tidal currents (Caffrey and Broenkow, 2002; Broenkow & Breaker, in press). Dramatic increases in Elkhorn Slough’s tidal prism have been estimated by a variety of researchers using two primary methods: 1) estimating the surface area of water levels at various tidal stages in the Slough and multiplying by different tidal heights and 2) recording continuous currents measurements through a vertical cross section over tidal cycles to calculate a volume transport. Table 1 documents the increase in tidal prism over time.

Source	Date collected	Tidal Prism (m <sup>3</sup> )
<b>Elkhorn Slough</b>		
Johnson (1973)	1956	2,650,000
Smith (1973)	1970-1972	4,700,000
Wong (1989)	1986	5,700,000
Broenkow & Breaker (in press)	1992	6,000,000
Broenkow & Breaker (in press)	2003	6,400,000
<b>Parsons Slough / South Marsh</b>		
Philip Williams & Associates (1992)	1987?	1,400,000
Broenkow & Breaker (in press)	2003	1,840,000

Table 1. Tidal prism estimates in Elkhorn Slough over time. Tidal prism estimates are relative to MLLW.

Using an unknown method, Johnson calculated a tidal prism of 2,650,000 m<sup>3</sup> based on a survey of tidal inlets from 1956 (Broenkow and Breaker, in press). Using the first method above, Smith (1973) estimated tidal prism to be 4,700,000 m<sup>3</sup>. Fifteen years later in 1986 Wong (1989) used a similar method and estimated the tidal prism to be 5,700,000 m<sup>3</sup>. Phillip Williams and Associates (1992) also produced tidal prism estimates for the entire Slough and the Parsons Slough/South Marsh using method one and regression relationships between marsh

area and tidal prism's of other California tidal wetlands for a tidal prism estimate of 6,600,000 m<sup>3</sup>. An estimate of tidal prism for Parsons Slough/South Marsh was reported at 1,800,000 m<sup>3</sup>. These estimates are difficult to assign to any specific time period since a variety of map sources were used (a 1987 aerial photo, a USGS quadrangle map of unknown publication date, and field observations) and may have a higher degree of error as a result. Broenkow and Breaker (in press) used the same method as Smith (1973) but with an updated aerial photo taken in 1992 that included the reclaimed Parsons Slough/South Marsh that did not exist in Smith's (1973) estimate. The tidal prism estimated from this work is 6,000,000 m<sup>3</sup>.

The most recent data is from 2003, when Broenkow and Breaker (in press) used method two to compute tidal prism volume transport through a tidal cycles. They measured current speeds 250 m east of the HWY 1 Bridge in a vertical cross-section over a ~7 hour flood tide (Figure 26). The data were integrated over the duration of the flood cycle to produce an integrated volume transport estimate of 6,400,000 m<sup>3</sup> (personal communication, Larry Breaker). A similar method was used at the mouth of Parsons Slough/South Marsh areas in 2002 to produce a tidal prism estimate for that location of 2,400,000 m<sup>3</sup>. Recent estimates of tidal prism using method one for Parsons Slough is 1,700,000 m<sup>3</sup>.

### *Tidal currents*

Tidal currents are subject to many different factors such as channel morphology, tidal forcing and freshwater river input. The most important factors, however, are tidal prism and effective surface area (Broenkow and Breaker, in press). As tidal prism and surface area increase so do tidal currents if a tidal inlet does not grow enough in area to accommodate these increases. In order to accommodate an increase in tidal prism, more water must enter and leave an estuary over the same amount of time (a tidal cycle), increasing tidal current velocity. The Elkhorn Slough may compound this problem by retaining a permanent fixed-width entrance at the HWY 1 Bridge, and only varying the depth. The effect of an increased volume of the tidal prism and surface area being forced through a fixed-width inlet increases measured tidal currents over time.

In 1970, Clark (1972) made the first measurements of tidal currents in the main channel of Elkhorn Slough on the harbor side of the HWY 1 Bridge (Figure 26 and Table 2). He measured a maximum average velocity on the flood tide of 0.48 m/sec and 0.61 m/sec on the ebb tide. Sixteen years later, in 1986, Wong (1989) collected current measurements near the HWY 1 Bridge at ~ 1.6 m above the channel floor and at the entrance of Parsons Slough/South Marsh. At the HWY 1 Bridge inlet he predicted current velocities on the flood tide to be 0.75 m/sec and on the ebb tide to be 1.13 m/sec. At the Parsons Slough inlet he found even higher current velocities of 1.50 m/sec on the flood tide and 1.70 m/sec on the ebb tide. Wong attributed this higher speed to the narrow constrictive entrance at the Parsons Slough inlet and the fact that they were collected in 1986, just two years after the Parsons area was reclaimed by the California Department of Fish and Game.

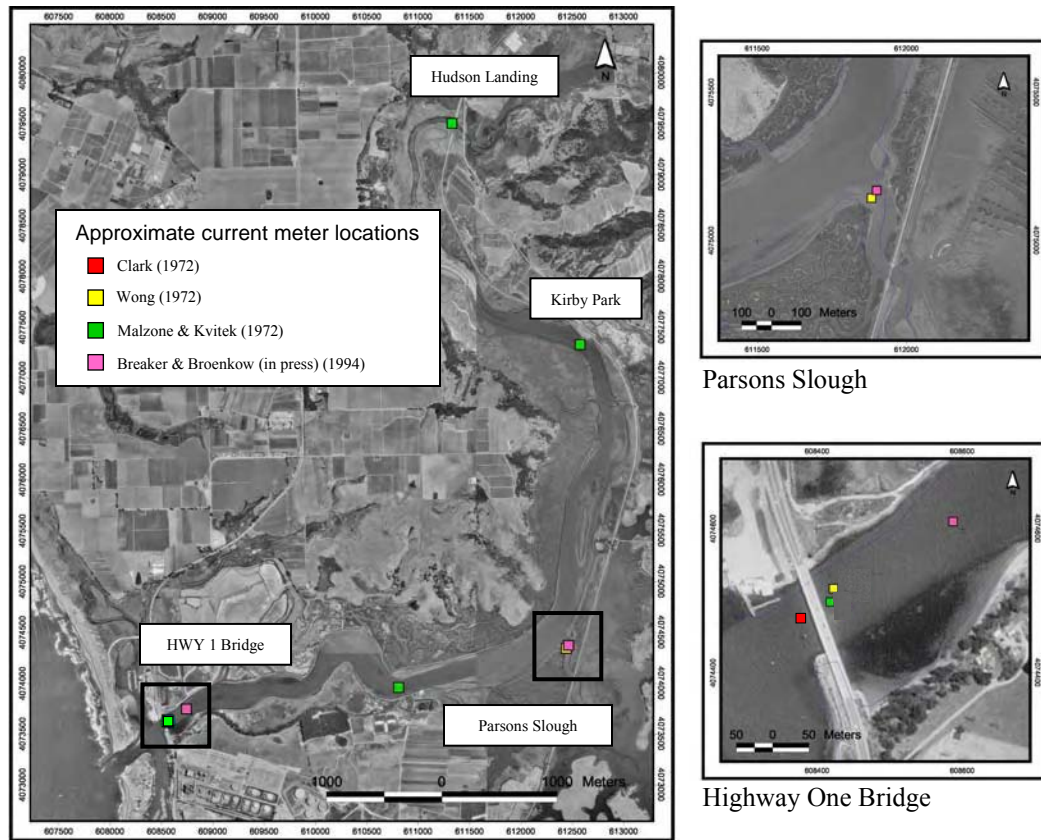


Figure 26. Approximate locations and measured current speeds collected over time in Elkhorn Slough. The locations mapped here are approximated from text descriptions or figures contained within the original literature sources.

Source	Date collected	Max flood (m/sec)	Max ebb (m/sec)
<b><u>HWY 1 Bridge</u></b>			
Clark (1972)	1970	0.48	0.61
Wong (1989)	1986	0.75	1.13
Breaker & Broenkow (1994)	1992		1.20
Malzone & Kvitek (1994)	1993	0.38	1.10
Broenkow & Breaker (in press)	2003	0.42	1.25
<b><u>Upslough</u></b>			
Malzone & Kvitek (1994) east of Seal Bend	1993		1.00
Malzone & Kvitek (1994) Kirby Park	1993		0.55
Malzone & Kvitek (1994) Hudson' Landing	1993		0.50
<b><u>Parsons Slough</u></b>			
Wong (1989)	1986	1.53	1.70
Broenkow & Breaker (in press)	2002	1.50	1.70

Table 2. Tidal current estimates in Elkhorn and Parsons Sloughs over time.

Six years later in 1992, Breaker & Broenkow (in press) duplicated Wong’s methods at the HWY 1 Bridge measuring approximately 3m above the seafloor. They recorded maximum ebb speeds of 1.20 m/sec.

In December of 1993 Malzone and Kvitek (1994) measured currents at several locations throughout the slough (Figure 26). Maximum current speeds decreased with distance upstream into the slough from 1.10 m/sec at Highway 1 Bridge, to 1.00 m/sec after Seal Bend, to 0.55 m/sec at Kirby Park, to 0.50 m/sec at Hudson’s Landing.

The most recent data available was collected by Broenkow and Breaker (in press), who positioned an Inter-Ocean S4 current meter ~ 250 m east of the HWY 1 Bridge about 1.1 meters above the channel bottom (Figure 26). From their data they observed maximum current speeds of 1.25 m/sec on the ebb tide and 0.42 m/sec on the flood tide. Maximum ebb current velocities measured at the HWY 1 Bridge since 1970 are graphed with corresponding increases in Elkhorn Slough’s tidal prism since 1956 in Figure 27. The tidal prism estimates continue to increase with time. As of the most recent estimate in 2003, the tidal prism has doubled in volume, approximately, since the first estimate in 1956.

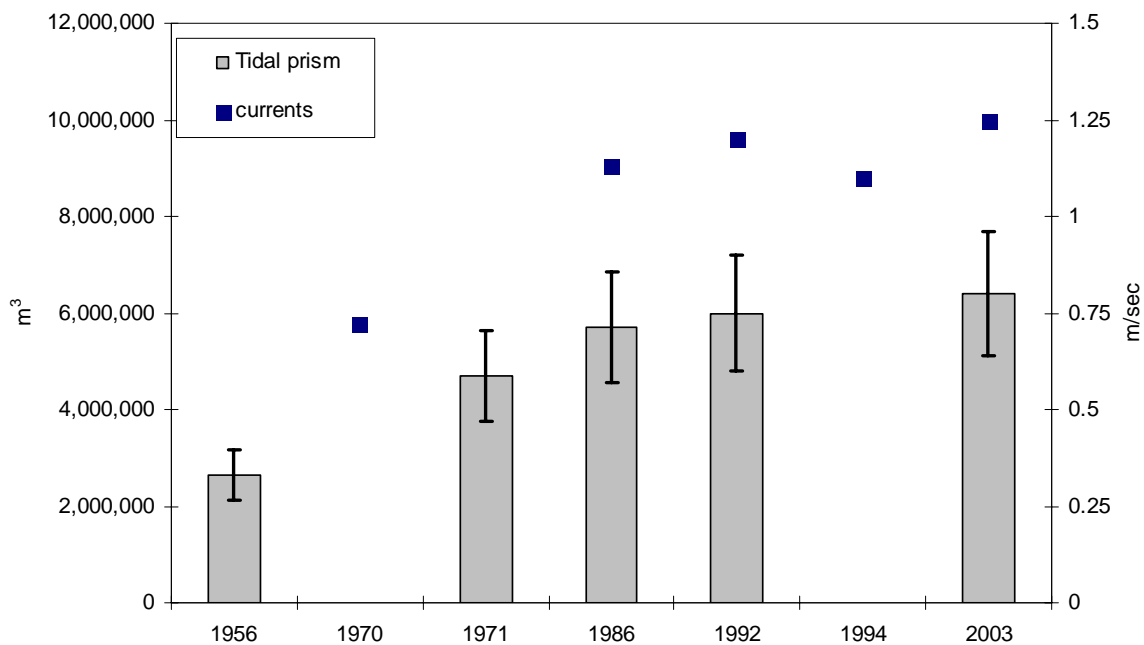


Figure 27. Comparison of increasing tidal prism (gray bars) and increasing ebb tidal currents measured at the HWY 1 Bridge (blue squares) over time in Elkhorn Slough.



## SECTION 4 - INLET STABILITY

The equilibrium-area, or channel cross-section stability analysis, concept for tidal inlets is a useful tool to help understand embayment or estuarine inlet entrance channel minimum cross-sectional areas, and their stability or instability over time. Inlet stability can be correlated to the hydraulic and sedimentation characteristics of a particular system. This section applies the inlet channel cross-section stability analysis concept to the main Elkhorn Slough entrance, and Parsons Slough entrance channel inlets. There is evidence from previous studies referred to above that currents, and tidal prism, have changed dramatically over time. Also, that entrance inlets have not remained in equilibrium with tidal prism, and continue to maintain a smaller entrance inlet area relative to the size of the embayments that they serve (i.e. Elkhorn and Parsons Slough).

Elkhorn Slough and Parsons Slough Inlets were examined to determine if the existing areas (distance between the jetties, and water depths) are in a stable condition relative to their embayment tidal prisms they serve. Hydrodynamic measurements taken over the past 30+ years at various locations at each inlet and throughout the Elkhorn Slough system were used during this stability analysis.

### History of Inlets:

The Elkhorn Slough Inlet connects the Pacific Ocean with the Elkhorn Slough embayment, which included the Parsons Slough system. The Parsons Slough Inlet serves only the Parsons Slough embayment, and connects the main channel of Elkhorn Slough with the Parsons Slough embayment. The Moss Landing Harbor Inlet serves as the closest exit to the Monterey Bay for Elkhorn Slough, the north and south harbor areas, as well as the old Salinas River mouth, and Moro Cojo Slough. Elkhorn Slough Inlet was defined to be the constriction under the Highway 1 Bridge, from 100 meters west of the bridge to approximately 200 meters east of the bridge (Figure 28). There is some debate as to the characteristic dimensions of the natural Inlet at Moss Landing; however indications are that the natural inlet was a shallow inlet approximately 100 meters wide. Figure 29 shows what the inlet at Moss Landing looked like just prior to the permanent jettied inlet that was constructed by the U.S. Army Corps of Engineers in 1947. This figure shows the indirect pathway of tidal exchange between the Monterey Bay entrance and that of the Elkhorn Slough Inlet at the Highway 1 Bridge.

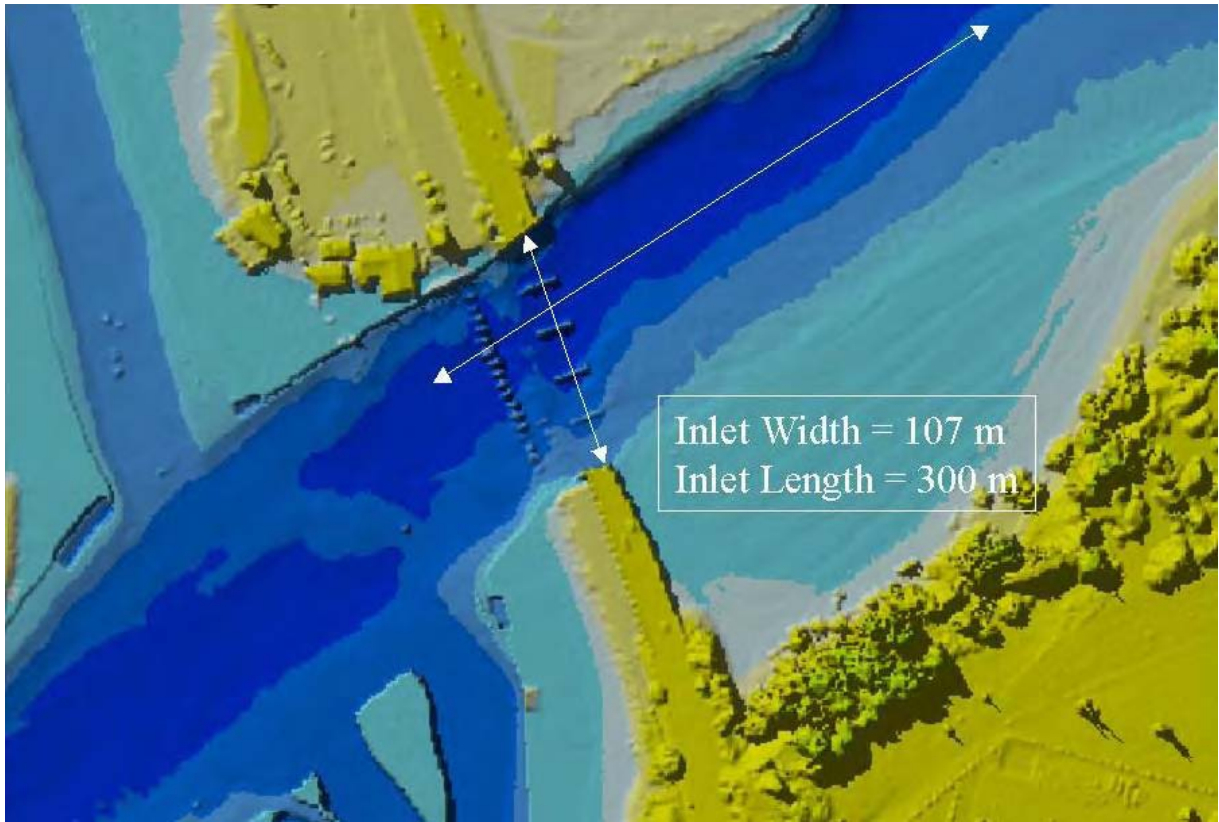


Figure 28. Dimensions of Elkhorn Slough Inlet used for inlet equilibrium stability analysis.



Figure 29. Image of Moss Landing Harbor Inlet and Elkhorn Slough Inlet prior to opening permanent inlet by the USACE in 1947 (Courtesy of ESNERR).

The inlet at Moss Landing has been shown in recent history to have migrated along the shoreline, and was located in the vicinity of today's harbor inlet. The Moss Landing Inlet was permanently fixed from migrating along the shoreline with two jetties in 1947, and has allowed year round full tidal exchange into the harbor and Elkhorn Slough system since that time (Figure 29). The Parsons Slough Inlet was modified from a constricted tidal flow inlet to free tidal flow during repair and retrofitting of the Union Pacific railway trestle. This modification included removal of many timber piles that previously inhibited free tidal flow into the embayment, and replaced them with a few concrete piles, and embankment armoring at this location in 1984 (Figure 30). Both of the above modifications to the main entrance to Elkhorn Slough and Parsons Slough inlets assisted in improving the hydraulic efficiency of tidal flow exchange for both systems. The inlets connection with larger tidal embayments became straighter, structurally stabilized, and in the case of Parsons Slough, less constricted.



Figure 30. Parsons Slough Inlet extends from under the Union Pacific Railroad trestle to main channel of Elkhorn Slough.

It is unclear whether the Elkhorn Slough Inlet was in an equilibrium state before the construction of the jettied inlet at Moss Landing, however it can be assumed that the pre-construction inlet probably varied in flow rate and cross sectional area over time. During summer months when there was little fresh water flow from the watersheds, the inlet may have been in a state of deposition and closure, and becoming shallower. Flooding conditions or high freshwater flow from the watersheds during winter months probably lead to an erosive period, with a periodic open tidal flow conditions with the Monterey Bay.

The Parsons Slough Inlet may have historically served a smaller embayment tidal prism than it does today. In order to understand how well the existing state of the inlet systems function, an inlet channel cross-section stability analysis was performed.

### Inlet Cross-Sectional Stability and Tidal Prism:

In this section, inlet area stability of the Elkhorn and Parsons Slough entrance channels will be examined to determine whether these inlet channels are in a stable equilibrium state or whether the channels will tend to scour and grow in cross-sectional area. We used the equilibrium-area concept for this inlet stability analysis. This concept has been a useful approach to understand the adjustment of an entrance channel's minimum cross-sectional area to the basic hydraulic and sedimentation characteristics of the inlet it serves. The relationship between the minimum cross-sectional flow area of an entrance channel and its tidal prism (the volume of water flowing into the embayment during the flood tidal cycle or conversely, the volume of water flowing out of the embayment during the ebb portion of the tidal cycle) was determined by O'Brien (1931, 1969) from field data of tidal inlets on the west coast of the United States. The form of this relationship defined by O'Brien is expressed in the equation:

$$A_c = C P^n \tag{1}$$

where

- $A_c$  = the minimum inlet cross-sectional area in the equilibrium condition
- $C$  = a constant
- $P$  = the tidal prism (typically during the spring tide)
- $n$  = an exponent usually slightly less than one

$C$  and  $n$  are typically determined using field data, with many of the constants found to be regionally variable (Seabergh, 1997). The above equation can be combined with a numerical hydrodynamic model to determine an equilibrium area for an inlet and evaluate if the existing inlet is in an eroding or a shoaling mode. According to Seabergh (1997) if an inlet has jetties the equation becomes:

$$A_c = 7.489 \times 10^{-5} P^{0.86} \text{ (metric units)} \tag{2}$$

In some instances wave-generated and other longshore currents along the coast can move sand into an inlet channel, reducing its cross-sectional area. Current flow in an inlet due to tides, winds, or other mechanisms will scour an inlet, increasing the cross-sectional area, if sediment deposition has reduced the channel cross section area below its equilibrium value as plotted on an Escoffier diagram (O'Brien, 1969). This concept was first developed analytically by Escoffier (1940, 1977). He developed a diagram for inlet stability analysis in which two curves are initially plotted equilibrium and inlet maximum velocity curves (Figure 31).

The first step is to plot an inlet's maximum velocity versus the inlet's cross-sectional flow area. A single curve will represent changing inlet cross-section area conditions if tidal and other current parameters, embayment volume, and inlet plan geometry remain relatively fixed. As the inlet cross-sectional area approaches zero, velocity approaches zero because of increasing frictional forces, which are inversely proportional to channel area. If an inlet channel area increases proportionally to the embayment tidal prism, friction forces will be reduced, and inlet tidal velocities will be increased. This will only happen if tidal prism has reached a maximum, or stable point, and any inlet channel area increase will cause a decrease in velocity, as determined in the equation above. This curve can be constructed by applying the maximum velocity,  $V$ , which can be determined analytically, numerically, or by direct

measurement. The second curve that is plotted as defined by O'Brien's (1969) equations 1 or 2 above is an empirical stability criterion curve. This criterion curve shows how inlet tidal current flow will scour an area if sediment is deposited to the extent that reduction in equilibrium channel cross-sectional area occurs.

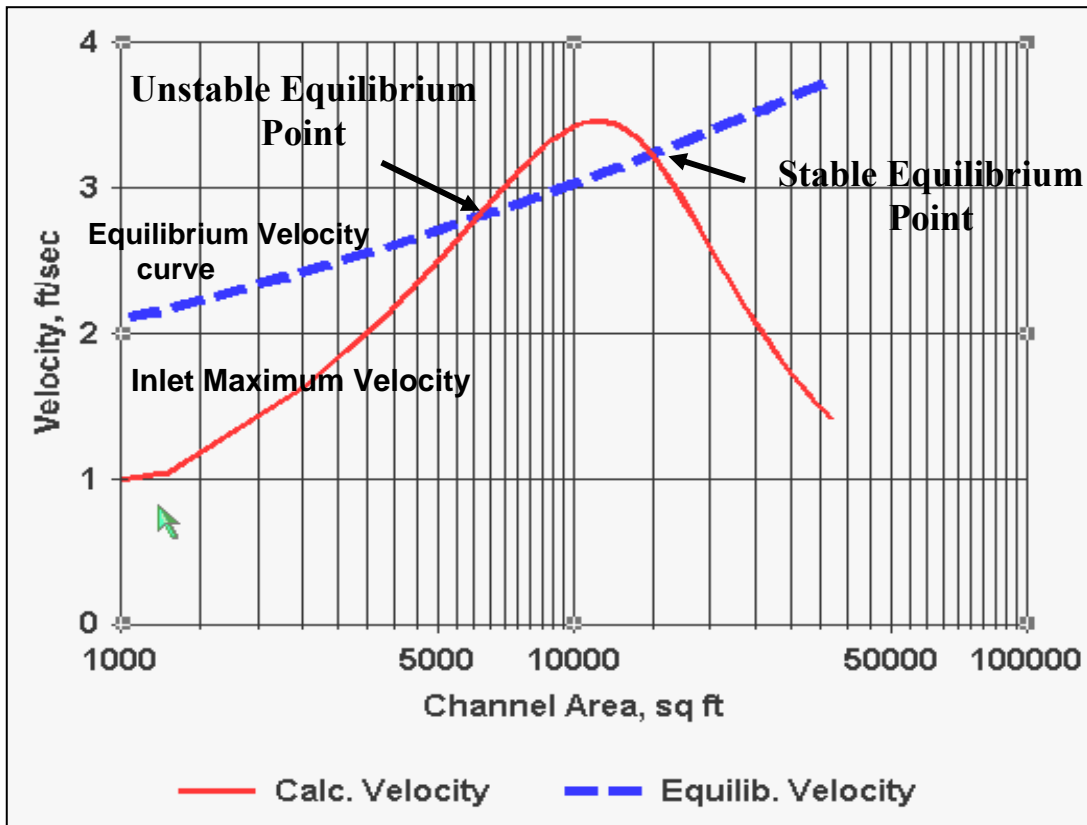


Figure 31. Example of an Escoffier Plot for Inlet Stability

The curves in Figure 31 intersect at two points, however these curves may also have only one point (a tangent), or there may be no intersection at all. According to Escoffier (1977) and O'Brien (1969), a right-side intersection of the curves, beyond the maximum current peak, is a stable inlet area point. If there is an increase in inlet area this will cause a movement along the stability curve back to its starting equilibrium point. For instance, if channel area increases (moves right on the curve from the stable equilibrium point), velocity will fall and more sediment can fill in the channel to bring it back to equilibrium (Seabergh, 1997). If the inlet area decreases through deposition beyond the equilibrium point then velocity will increase beyond equilibrium level, which will scour the inlet increasing the inlet area to the equilibrium point. If there is an intersection on the left side then the inlet is unstable, where

decreasing the area further will also result in decreased velocities, with eventual closing of the inlet. If the inlet area increases beyond this point, there is an associated increase in velocity to a maximum. At this point velocity decreases with increasing inlet area until the inlet area and velocity reach an equilibrium point. If the stability curve is tangent to the stability criterion curve then the inlet will close. O'Brien (1972) and others (Van de Kreeke, 1992) have shown that Escoffier's curve correctly approximates inlet stability. Van de Kreeke (1992) estimated that inlet stability occurs at 1.0 m/sec.

### Inlet Stability Model Analysis

This Channel Equilibrium Area (CEA) model developed by the U.S. Army Corps of Engineers Coastal Inlets Research Program (Seabergh, 1997) was used in the analysis of the stability of Elkhorn and Parsons Sloughs inlets.

The Shore Protection Manual (1984) and the Coastal Engineering Manual (2002) include a discussion of the Escoffier diagram and method used in this analysis. They characterize an inlets hydraulics by its width, depth, and length of connecting channel between ocean and bay, bay surface area, ocean tide amplitude, tidal period, and frictional characteristics (friction coefficient and entrance/exit losses) (U.S. Army Corps of Engineers, 1984, 2002). The necessary information to perform this inlet stability analysis using the CEA model includes the tidal range in the ocean, tidal period (12.42 hours in this study), the surface area of the tidal basin, the channel length, channel width, a frictional coefficient, such as Manning's n, and estimates of entrance and exit loss coefficients (Seabergh, 1997). Hydrodynamics are calculated using an analytical solution to estimate a maximum current velocity for an inlet, and the amplitude of the tide and its phase lag from the ocean high water (DiLorenzo, 1988).

Over the past 30+ years a variety of researchers have collected tidal and current data, as well as estimated tidal prism and effective surface area of Elkhorn and Parsons Sloughs. These measurements were useful in calibrating the CEA numerical model for the stability analysis. The calibration procedure involved estimation of the effective surface area of the embayment for each inlet. Since the embayments are interconnected, a trial and error procedure was performed for each site, until current measurements from the field matched the numerical model. A sensitivity analysis was also performed to ensure that both surface area and velocity used in the stability analysis were within an acceptable range of measured values. Figures 32 and 33 show tidal elevations and currents for the calibrated models of each inlet (Elkhorn and Parsons), and for each case modeled scenario (1972 through 2003 for Elkhorn Slough Inlet, and 1993 through 2003 for Parsons Slough Inlet). These time periods were based on available data from previous studies. Tables 3 and 4, and Figures 34 and 35 shows the values and representative cross sections used for model calibration. Also shown are the estimated tidal prisms that flow through the inlets during flood or ebb tides.

As noted from the tidal elevations section, the embayment tide ranges are nearly equal to the ocean tidal range, and agree with previously reported tide ranges (Broenkow and Breaker, in press). If both inlets remain open, this should indicate good flushing of the embayment systems.

Maximum velocities along Elkhorn Slough's main channel have increased over time from 0.61 to 1.25 m/s, and from 1.4 to 1.7 m/s for Parsons Slough (see previous current section above). The maximum spring tide currents presently can exceed 1.0 m/s. This current velocity value indicates the inlet cross-sectional area is not an equilibrium point for either Elkhorn or Parsons Slough inlets. This indicates that both inlet systems are in an unstable state. The validity of this will be examined by referencing the Escoffier plots for each inlet.



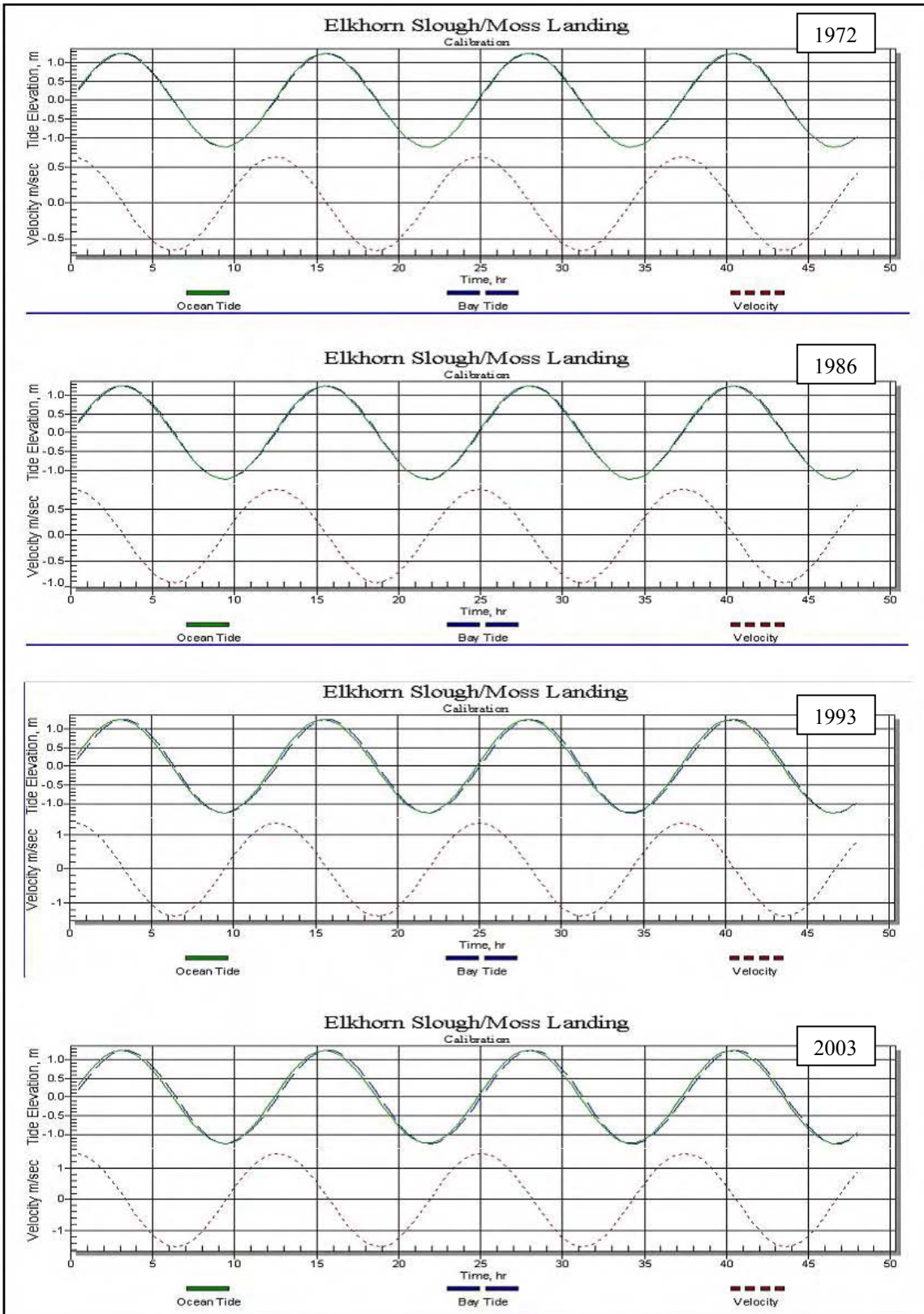


Figure 32. Calibration of Elkhorn Slough Inlet hydrodynamics – 1972-2003

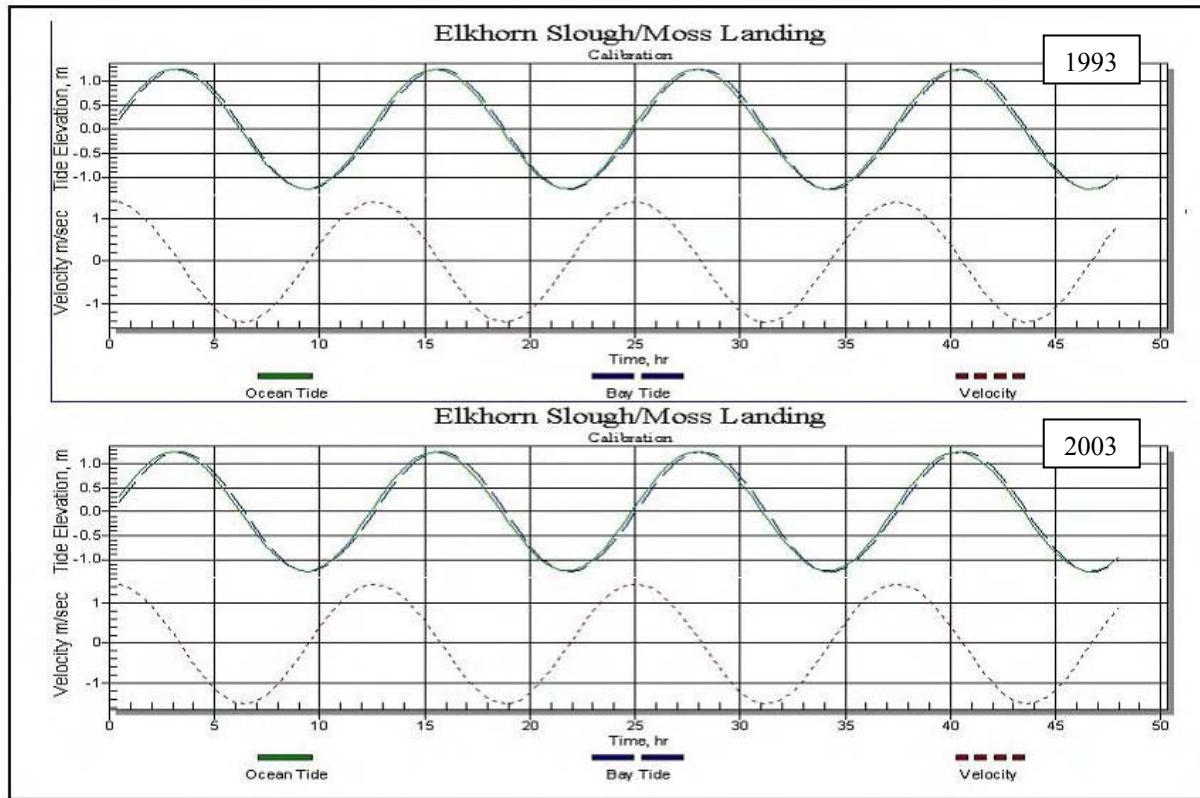
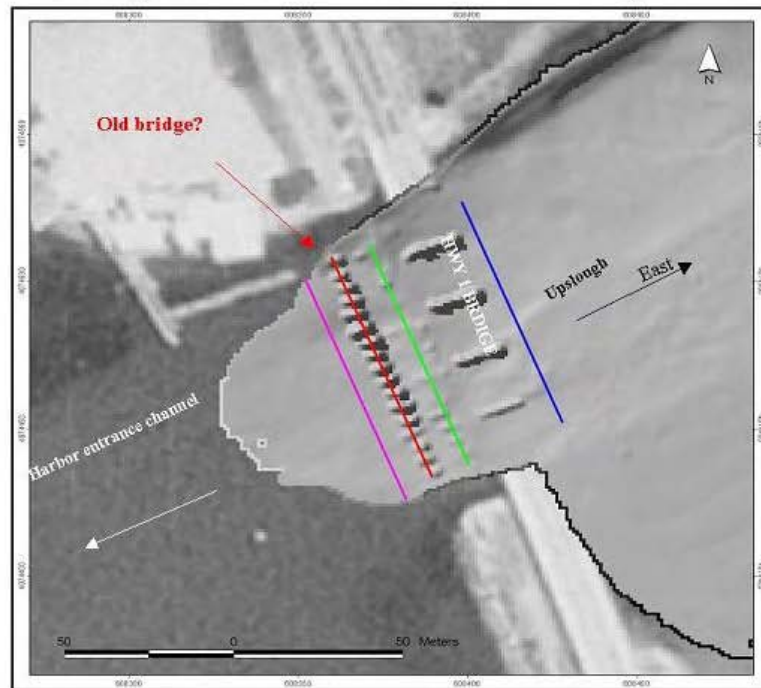


Figure 33. Calibration of Parsons Slough Inlet hydrodynamics – 1993-2003

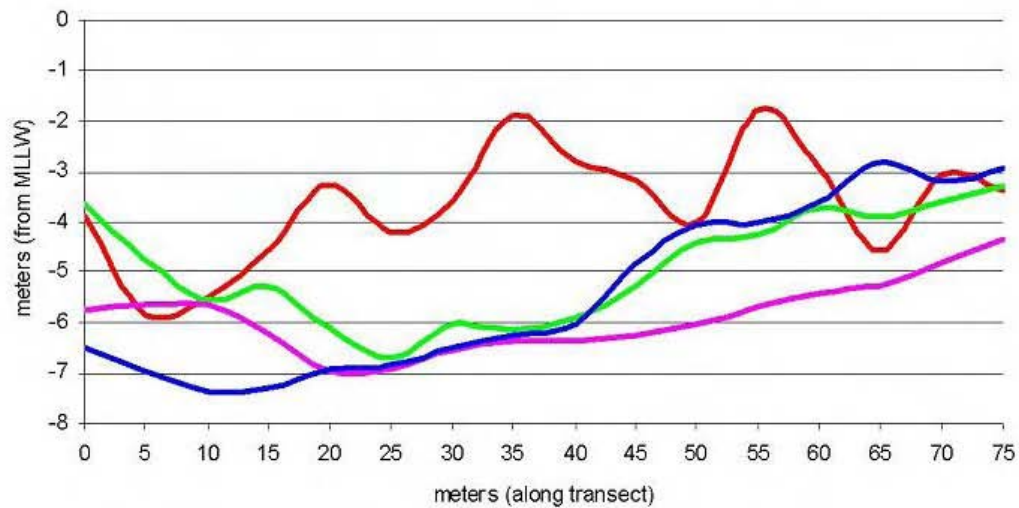
Parameters	H1B 1972	H1B 1986	H1B 1993	H1B 2003
Bay surface area ( $10^6 \text{ m}^2$ )	1.5	3.1	3.5	4.5
Hydraulic radius (m) - area/width	2.67	3.0	3.21	3.33
Channel length (m)	300	300	300	300
Channel width (m)	150	150	150	150
Calibration channel area ( $\text{m}^2$ )	400	450	450	500
Entrance loss coefficient	0.25	0.25	0.25	0.25
Exit loss coefficient	0.5	0.5	0.5	0.5
Manning's n	0.02	0.02	0.02	0.025
Calibration ocean tide range (m) - 1/2 tide range	1.25	1.25	1.25	1.25
Calibration tidal prism ( $10^6 \text{ m}^3$ )	4.25	5.7	6	6.22

## 2003 Bathymetric Cross Sections at Hwy 1 Bridge



Bathymetric cross-sections near HWY1 Bridge

- East of bridge
- Between rubble and bridge
- Rubble west of bridge
- West of rubble in harbor



East of bridge (blue) Cross Sectional Area = approx 450 m<sup>2</sup>

West of rubble in harbor (pink) cross Sectional Area = approx 455 m<sup>2</sup> (546 m<sup>2</sup> poss)

Figure 34. Representative bathymetric cross sections used in the calculation of inlet cross sectional area for the mouth of Elkhorn Slough.

Table 4. Parsons Slough Inlet Parameters and Tidal Prism				
Parameters	PS 1972	PS 1986	PS 1993	PS 2003
Bay surface area ( $10^6$ m <sup>2</sup> )			1.2	1.7
Hydraulic radius (m) - area/width			1.01	1.49
Channel length (m)			450	450
Channel width (m)			100	150
Calibration channel area (m <sup>2</sup> )			101	224
Entrance loss coefficient			0.25	0.25
Exit loss coefficient			0.5	0.5
Manning's n			0.02	0.02
Calibration ocean tide range (m) - 1/2 tide range			1.25	1.25
Calibration tidal prism ( $10^6$ m <sup>3</sup> )			1.4	1.7



Parsons Slough mouth profile

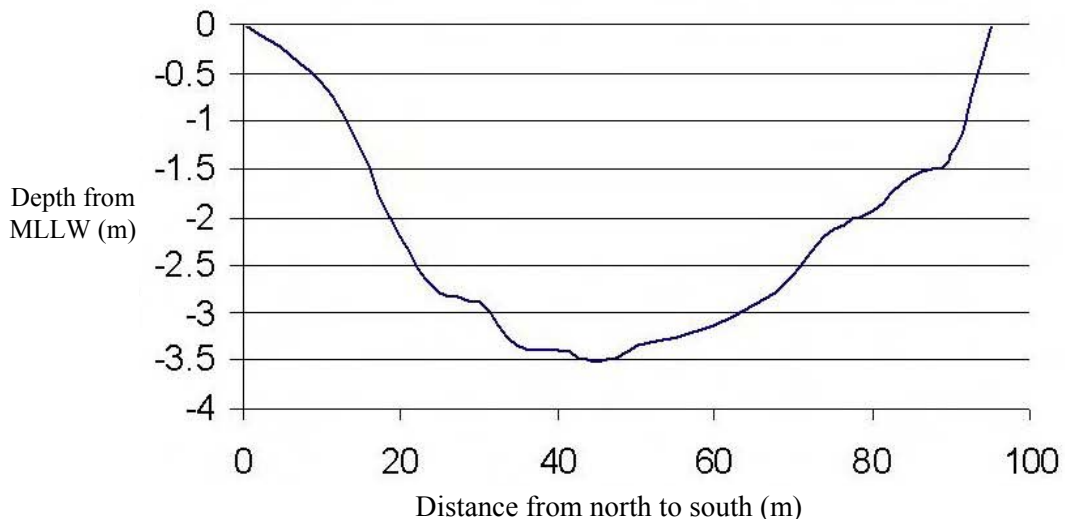


Figure 35. Representative bathymetric cross sections used in the calculation of inlet cross sectional area for the mouth of Parsons Slough.

Escoffier Plots of Inlet Stability:

The Escoffier plots for both inlets were determined based on the calibration of the hydrodynamics discussed above, and a one dimensional model for coastal inlet stability (Seabergh et al, 1997).

Figure 36 shows the stability diagram for the Elkhorn Slough Inlet which is open to the Monterey Bay. Figure 36 indicates that the inlet area has changed over time, with predicted currents in the 0.65 m/s range in 1972, and increasing with the increase in tidal surface area and tidal prism during the early 1980s to a maximum estimated velocity in the range of 1.2 m/s by 2003. The predicted tidal currents at the mouth of the Elkhorn Slough Inlet indicates an increasing trend and could potentially reach speeds in the range of 2.5 m/s. Eventually the tidal velocities would decrease to an equilibrium current velocity at just over 1 m/s, as predicted by Van de Kreeke (1992). The predicted equilibrium area point would be 700 m<sup>2</sup> if the tidal prism relationship for an unprotected inlet were applied. This would be over 1.5 times the current inlet area at the mouth of Elkhorn Slough. The complicating factor for Elkhorn Slough is that the tidal prism and effective tidal surface area has steadily grown since diked areas have been breached with full tidal flow occurring since the 1980's. The main area of the slough, as well as these formerly diked areas, show evidence of bank erosion and breaching, which will continue to increase the tidal prism surface area over time. This rate of growth in effective surface area and tidal prism through vertical and lateral erosion increased more rapidly than the inlet increase in cross sectional area, which has resulted in an increase in tidal current velocity to levels beyond equilibrium. The inlet cross sectional area for Elkhorn Slough continues to be too small to accommodate the volume of tidal water flowing through the inlet to reach an equilibrium point. This has set up a positive feedback loop as mentioned in Broenkow and Breaker (in press) where high current speeds and erosion of the slough will continue until the embayment stabilizes in surface area and tidal prism, or the mouth becomes large enough to accommodate the requirements of the sloughs surface area and tidal prism. The next section examines the state of the Parsons Slough Inlet.

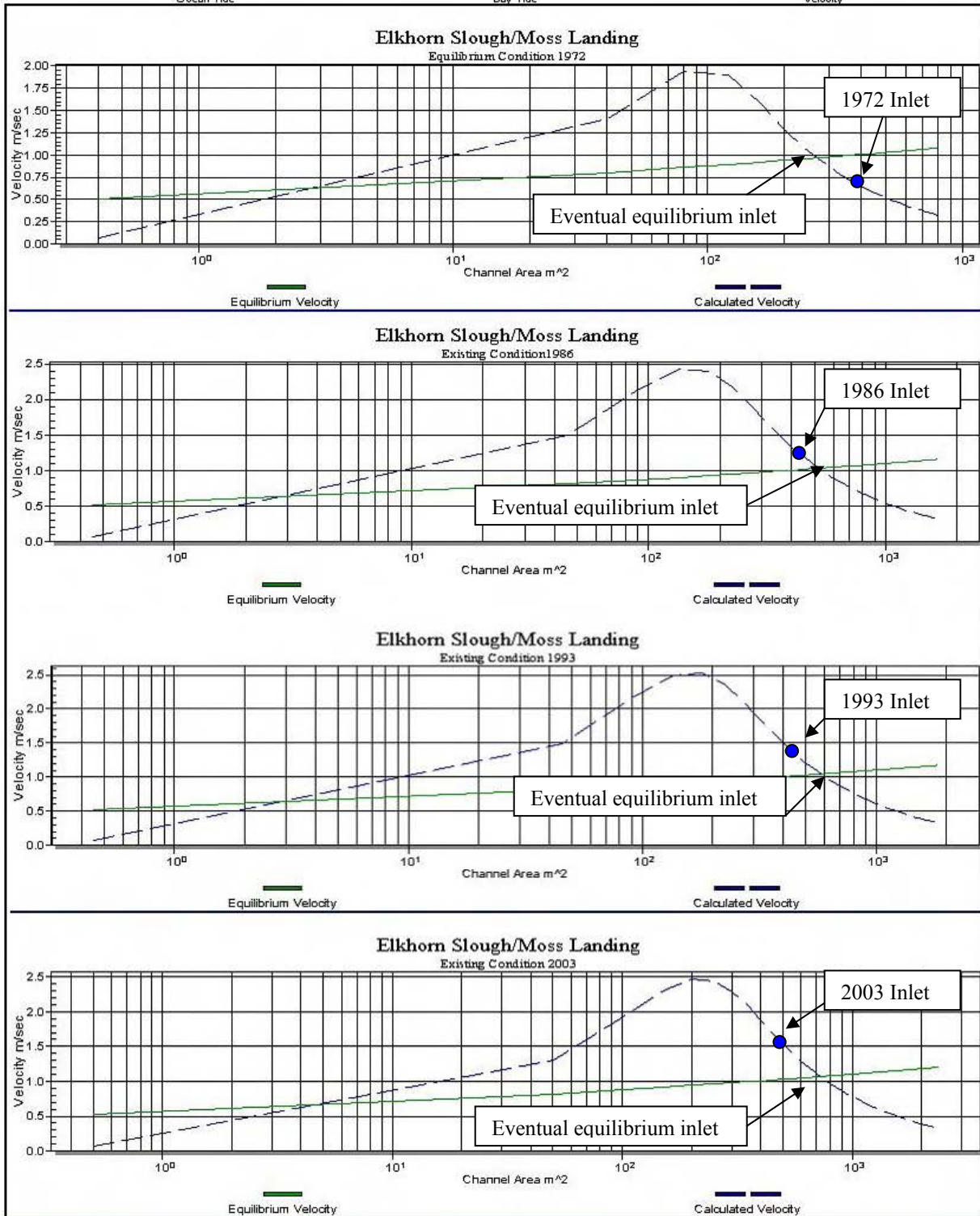


Figure 36. Escoffier plot showing Elkhorn Slough Inlet location with respect to channel area and eventual equilibrium area – 1971-2003.

Figure 37 shows the stability diagram for Parsons Slough Inlet which is open to the main channel of Elkhorn Slough. Figure 37 indicates that the inlet area has changed over time, with currents in the 1.4 m/s range in 1993 increasing to the 1.7 m/s range in 2003, coincident with an increase in effective water surface area and tidal prism during the 1990s. The currents at the mouth of Parsons Slough Inlet are expected to approach 2.0 m/s, before eventually reaching an equilibrium current state near 1.0 m/s. Estimated equilibrium area would be 300 m<sup>2</sup> if the prism relationship for an unprotected inlet were applied, which is 1.5 times the current inlet area for Parsons Slough.

The complicating factor at Parsons Slough is that the inlet area at the railroad trestle is fixed, so unless some structure limits the tidal prism and effective surface area, the currents are expected to continue to remain high. The tidal prism and surface area will continue to grow as bank erosion persists. Therefore, current speeds are expected to continue to increase.

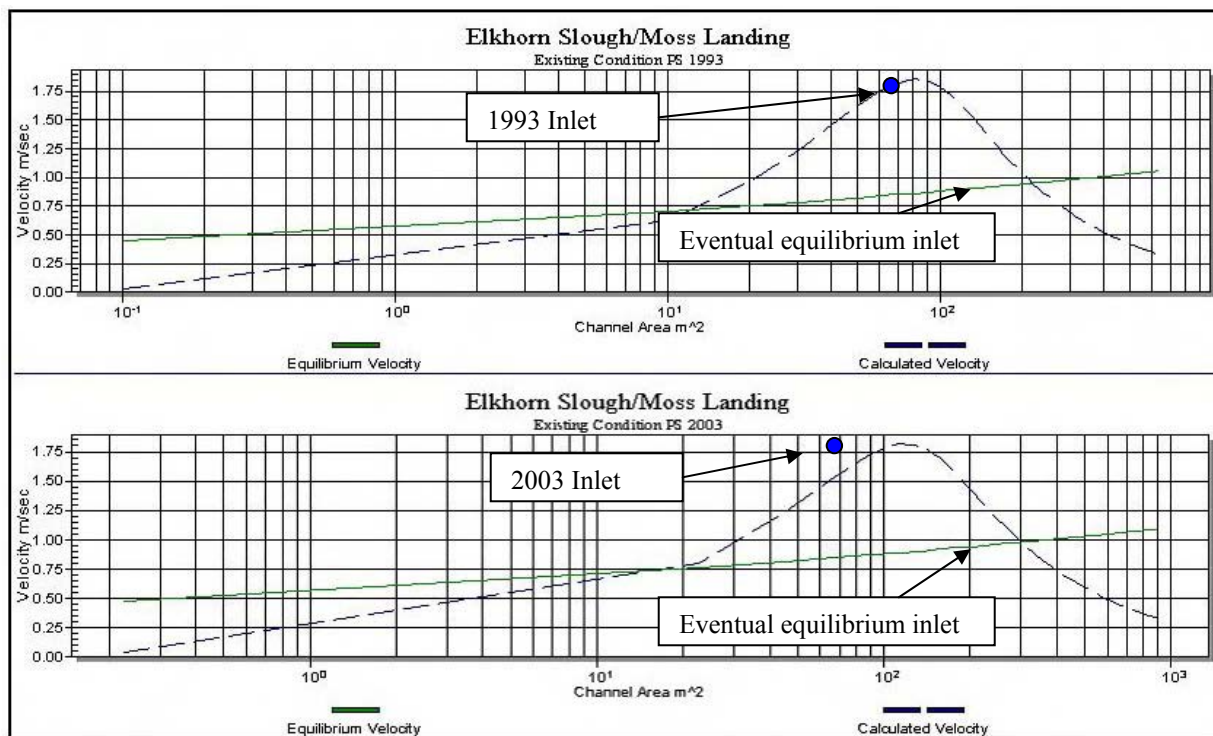


Figure 37. Escoffier plot showing Parsons Slough Inlet location with respect to channel area and eventual equilibrium area – 1993-2003.

### Historical Note and Summary of Inlet Stability:

Important in the examination of inlet cross-sectional area stability are changes that occur in embayment size. Man-made changes can affect inlet stability. The inlet stability discussed here is in reference to the size, or cross-sectional area of the channel that would be expected to occur for given inlet conditions. These conditions include surface area of the embayment, channel length, and bottom roughness of the channel. Most likely the embayment size served



by the Elkhorn Slough Inlet was increased by construction of the Moss Landing Harbor permanent entrance in the mid 1940s. Inlet widths at Elkhorn Slough Inlet historically were noted to be as wide as 100 m and very shallow before harbor construction. Inlet area (and thus width) is proportional to the embayment area drained by the inlet. With the addition of a permanent Parsons Slough Inlet that is open to full tidal flow, there is a larger embayment surface area serving Elkhorn Slough Inlet than there was following the construction of the Moss Landing Harbor Inlet in 1947. Therefore a larger equilibrium cross-section inlet area is required to accommodate this larger volume of water flowing through the inlet each day, and thus more depth for the given width between the inlets is expected to occur to achieve the necessary equilibrium cross-sectional area.

The Moss Landing Harbor Inlet was stabilized with jetties that are approximately 191 meters apart (Figure 38). The spacing of the Elkhorn Slough Inlet at the Highway 1 Bridge is 107 meters and relatively narrow for the embayment it serves. Elkhorn Slough had a tidal prism in 2003 of approximately  $6.2 * 10^6 \text{ m}^3$ , with an effective surface area of  $4.5 * 10^6 \text{ m}^2$  (Figure 39). This increase in tidal prism and surface area since the opening of the Moss Landing Inlet, and opening of previously diked areas has resulted in currents for Elkhorn and Parsons Inlets to increase over time, with high currents funneling through the entrance channels.

Negative impacts of this type of narrow inlet include increased scour of channels and bank areas, with resultant loss of existing habitat if currents continue to accelerate as expected. Previous maximum currents were probably near equilibrium and on the order of 1 m/s at Elkhorn Slough Inlet before the addition of the Parsons Slough prism and surface area in the 1980s. Based on the analysis the maximum currents are predicted to reach as high as 2.4 meters per second. The higher currents result in a deeper and wider channel depth, with more forcing of the sediments to an ebb scour seaward of the inlet entrance. Observations since the mid 1980s indicate a scouring effect seaward of the Elkhorn Slough inlet as observed by Oliver (personal communication).

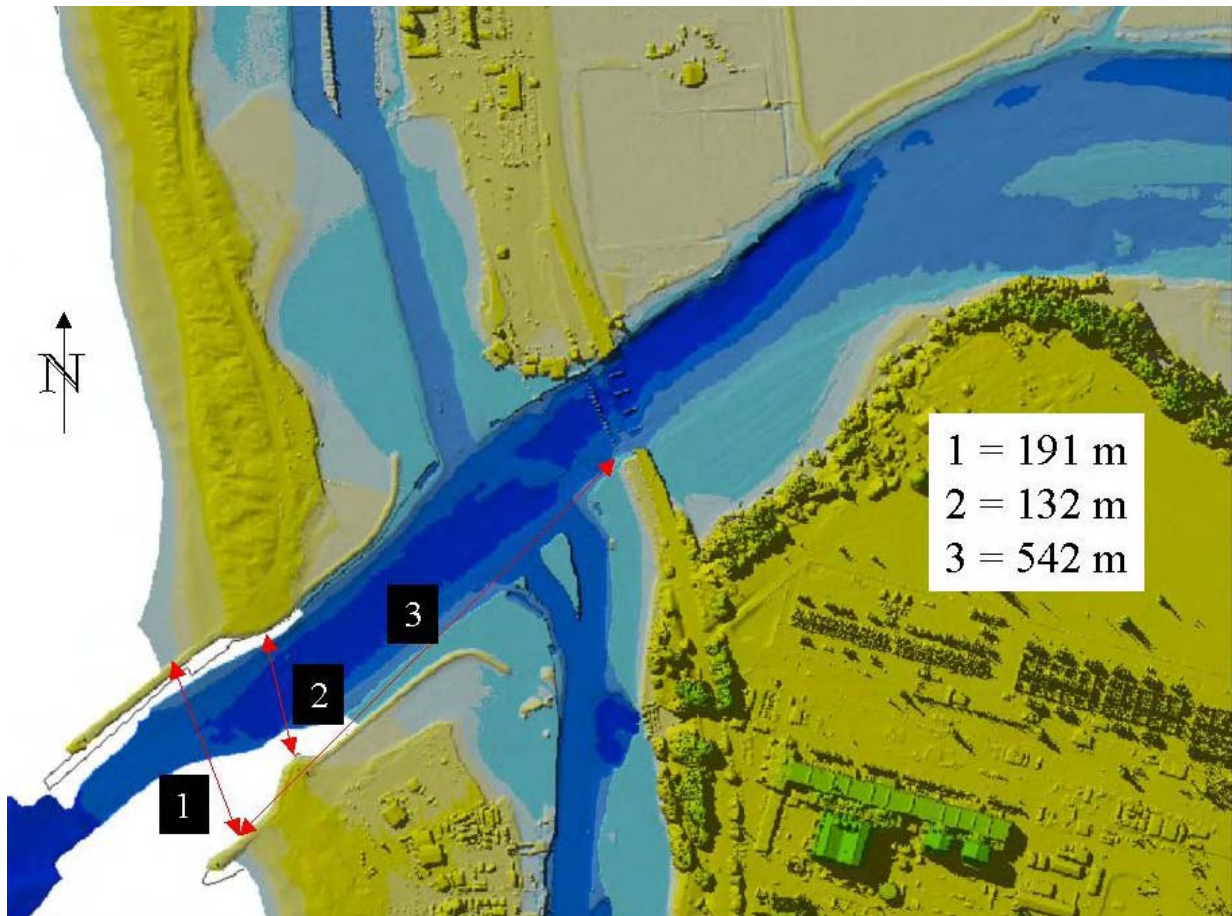
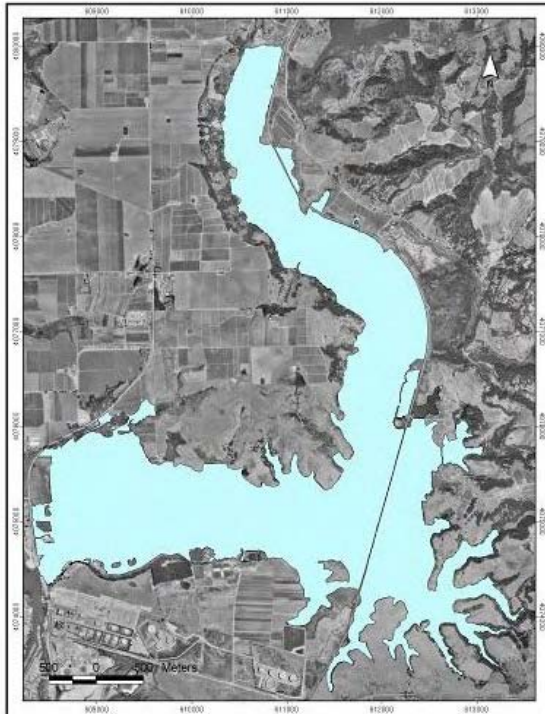
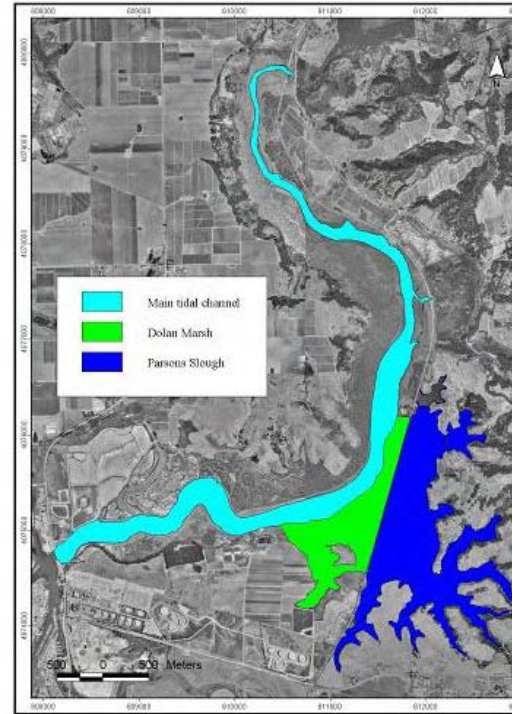


Figure 38. Dimensions of permanent Moss Landing Inlet entrance channel.



1. Modified wetlands area from ESNERR GIS (from HWY 1 Bridge, not including North Marsh or Bloom/Porter Marsh)



2. Main tidal channel (outline of CSUMB multibeam data, Dolan Marsh, and Parsons Slough (both modified from ESNERR 2000))

Map	Area (sq m)
Elkhorn Slough System (2003)	4,500,000
Main tidal channel (2003)	1,611,773
Parsons Slough (2000)	1,700,000
Dolan Marsh (2000)	780,379

Figure 39. Shows (1) potential surface area of the Elkhorn Slough system, (2) Parsons Slough, Dolan Marsh, and Elkhorn Slough tidal channel surface areas and the estimates of surface area for each in meters squared.

The Parsons Slough Inlet in its pre-1984 state had limited the tidal exchange. As a result, lower current flows were observed in Elkhorn Slough. Parsons Slough was opened to full tidal flow during management efforts to increase water circulation in the Parsons Slough area. It was made even more hydraulically efficient after the repair of the Union Pacific railroad trestle. This has resulted in higher current flows through the inlet since that time because of the large

volume of tidal water exchange to inlet area ratio. The inlet spacing varies between 50 and 160 m. It is a relatively shallow inlet, and has shown to have high current velocities on both the flood and ebb stages of the tide. The inlet is not approaching equilibrium because its depths range from 2.5 to 5.7 m, which is less than the Elkhorn Slough Inlet. The Elkhorn Slough Inlet has depths to 10 m under the Highway 1 Bridge. The tidal prism of Parsons Slough Inlet was recently calculated to be  $1.7 * 10^6 \text{ m}^3$ , which is just about one third that of the Elkhorn Slough tidal prism (Figure 39).

#### Cautionary Note

Many multi-inlet tidal systems respond over time in a manner where one inlet becomes more hydraulically efficient than the other inlet. This would result in one inlet scouring more rapidly than the other, potentially adding tidal prism and effective surface area to the entire system, as is the case with Parson and Elkhorn Slough. If the embayment is segmented enough that the embayment serving one inlet is not significantly affected by the other inlet, this may not occur. Careful observation of the inlet channels must be maintained to see if this could occur for the Elkhorn-Parsons Slough system. The entrance channels at both inlets should be surveyed annually for the next few years, if possible, in order to determine the long-term evolution of the inlet system.

## SECTION 5 – CONCLUSIONS

Increase in tidal prism, tidal surface area, and tidal currents following the completion of the Moss Landing Harbor in 1947 has caused severe erosion in the majority of Elkhorn Slough. Furthermore, the exposure of Parsons Slough in 1984 and other previously diked areas to tidal flow have caused an increase in the tidal prism. This causes more water to enter and leave the system in the same amount of time. What was once a low-energy depositional estuary has become a high-energy erosional tidal embayment. Severe erosion along curves and constrictions of the tidal channel have scoured the tidal channel clean of unconsolidated sediment. Consolidated clay beds (deposited in times of lower-energy) have been differentially eroded, leaving them exposed on the present tidal channel floor and banks.

Numerous textbook examples of deep tidal scour and undercut channel banks were identified along an erosional gradient that extends up the entire Slough. The geology of Elkhorn Slough cannot support the present tidal current regime without further erosion taking place. A past tidal channel clay layer (identified as the most resistant strata to tidal erosion) in proximity to the HWY 1 Bridge has already been entirely eroded through. Furthermore, a regional geological assessment suggests that there are no erosion-resistant bedrock formations within the Slough vicinity that will prevent additional erosion if reached. Further erosion is expected to continue in areas that have already been severely scoured and increased erosion is expected in the soft, unconsolidated clay deposits near Hudsons Landing. As more and more sediment is removed from the system (vertically from the tidal channel and laterally from mud banks and tidal creeks) the tidal prism and the tidal surface area will increase. This has the potential to cause a corresponding increase in tidal currents, establishing a positive feedback loop as mentioned in Broenkow and Breaker (in press).

In February of 2006, SEI collected four sediment cores from two locations within Elkhorn Slough and analyzed them using Sedflume (see Appendix A). Sediment critical shear strengths, sizes and bulk densities, with depth, were measured. The sediment sizes and bulk densities augmented an already extensive dataset of sediment cores collected in Elkhorn Slough since 1983. Using Sedflume, the critical shear strengths of the sediments, as depth increases, were measured. The critical flow velocities required to mobilize sediments were roughly approximated from the Sedflume data, providing a spatial description of sediment strength in Elkhorn Slough. A more detailed analysis is required, however, before an accurate assessment of the spatial variability in sediment shear strength can be estimated.

The inlet stability analysis indicates that the inlets to both the Elkhorn and Parsons Sloughs are unstable. The inlet openings are smaller than that required by the model for the system to be at an equilibrium point. The inlet stability trends, based on repeated bathymetric surveys, and tidal prism estimates, are that the embayments will continue to grow in extent and depth more rapidly than the inlet areas will expand. The currents velocities are therefore predicted to continue to rise, with inlet instability at both locations for the foreseeable future. It is expected that the current velocities will continue to exceed the critical bed velocity necessary to mobilize and erode sediments, as indicated by the Sedflume analysis (Appendix A). As sediment continues to erode and tidal prisms and surface areas increase in size, the tidal current velocities will increase due to the fixed-width constrictions of the inlets. If no preventative

action takes place, the system will continue to be erosive until both inlets are in equilibrium with a stable tidal prism and surface area of each slough. The geological composition and inlet analysis assessment strongly encourages the need for additional engineering to reduce the flow of water in and out of the slough as a means for ameliorating the erosive nature of the present slough system.

## SECTION 6 –RECOMMENDATIONS

Potential repairs and improvements to the Elkhorn and Parsons Slough Inlets should include plans to stabilize existing habitats, methods to protect or prevent further erosion from occurring, and engineering solutions to reduce the tidal prism and effective surface area of Elkhorn and Parsons Sloughs. Controlling the tidal prism and surface area should reduce tidal currents, and bring the Slough system into a state of inlet equilibrium without the potential damaging effects of long term erosion that a “No action alternative” would likely result in.

Some specific recommendations for future action are as follows:

1. Continued development of the Elkhorn Slough Tidal Wetland Plan’s conceptual model of the key physical processes causing tidal erosion for the Elkhorn Slough system.
2. Estimate the future loss of sedimentary habitats from different parts the slough using the most realistic erosion rates for each area.
3. Develop preliminary engineering designs to control local erosion, such as near Kirby Park, and in the Elkhorn system as a whole.
4. Evaluate the ecological impacts of implementing these designs in contrast to a “No Action Alternative”.
5. Implement the most effective and ecologically sound erosion control strategies to protect local areas such as Kirby Park.
6. Implement experimental phases of reduction in tidal currents by muting flows into Bennett Slough, Old Salinas River Channel, and Parsons Slough.
7. Closely monitor the geomorphology, water currents, and ecology of the inlets at Parsons Slough and the HWY 1 Bridge.
8. Collect additional sediment samples at important sedimentary features which appear in the multibeam and sub-bottom imagery and in places where data is scarce, such as between the harbor jetties, the possible sand ridge just east of the HWY 1 Bridge, the potential debris pile at the end of the Parsons Slough channel, the depositional area west from Kirby Park, and from the unconsolidated clay remaining in the upper slough.
9. Evaluate the impacts of continued tidal erosion on the stability of the harbor mouth and jetty system.
10. Collect sediment cores from several locations in the slough to estimate the spatial variability in sediment composition, erosion rates and shear strength.
11. Model future changes in tidal currents at the HWY 1 Bridge with and without engineering solutions to reduce tidal erosion throughout the slough.

The long-term solutions to address the problem would therefore involve a combination of: (1) implementation of tidal prism and effective surface area reduction; (2) placement of sediment into areas scoured for habitat restoration efforts; and (3) erosion control measures along banks and levees that are experiencing severe erosion.

## SECTION 7 – REFERENCES AND INFORMATION CONSIDERED

- Bates, L.B. and Jackson, J.A., 1984, Dictionary of Geologic Terms, 3<sup>rd</sup> Edition. Anchors Books, Bantam Doubleday Publishing Group, Inc. 1540 Broadway, New York, New York 10036.
- Best, T. and Griggs, G.B., 1991. A sediment budget for the Santa Cruz littoral cell, California. Shoreline to Abyss S.E.P.M. Special Publication No. 46.
- Brantner J.E., 2001. Rates of erosion and habitat loss in Elkhorn Slough. Seaside, CA: California State University, Monterey Bay. 24 p.
- Broenkow and Breaker (in review) A 30-year history of tide and current measurements in Elkhorn Slough, California. Submitted to Estuarine, Coastal and Shelf Science.
- Byrne, R. J., Gammisch, R. A., and Thomas, G. R. 1980. "Tidal Prism-Inlet Area Relations for Small Tidal Inlets," Proceedings of the Seventeenth Coastal Engineering Conference, American Society of Civil Engineers, Sydney, Australia, Vol III, Ch 151, pp 23-28.
- Caffrey, J.M., and Broenkow, W.W., 2002. Chapter 4 Hydrology, IN: Changes in a California Estuary: an Ecosystem Profile of Elkhorn Slough. Elkhorn Slough Foundation, Moss Landing, CA.
- Chapman, S., 1923. "A Note on the Fluctuation of Water Level in a Tidal Power Reservoir," Phil. Mag. and Jour. of Science, XLVI, 101-108.
- Church, J. C., and E. B. Thornton, 1993. "Effects of breaking wave induced turbulence within a longshore current model", Coastal Engineering, vol. 20: 1-28.
- Clark, L.R., 1972. Long period wave characteristics in Moss Landing Harbor and Elkhorn Slough. M.A. Thesis, Moss Landing Marine Laboratories and Department of Natural Sciences, San Jose State University.
- Crampton TA., 1994. Long term effects of Moss Landing Harbor on the wetlands of Elkhorn Slough. SantaCruz, CA: University of California, Santa Cruz. 81 p.
- 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.
- Dean, E. W., 2003. Tidal scour in Elkhorn Slough, California: A bathymetric analysis. California State University, Monterey Bay. 128 p.
- DiLorenzo, J.L., 1988. "The Overtide and Filtering Response of Small Inlet-Bay Systems," Hydrodynamics and Sediment Dynamics of Tidal Inlets", ed. D.G. Aubrey and L. Weishar, 24-53, Springer-Verlag Publishing, New York, N.Y.
- Escoffier, F. F., 1940. "The Stability of Tidal Inlets," Shore and Beach, Vol 8, No. 4, pp 114-115.
- Escoffier, F.F., 1977. Hydraulics and stability of tidal inlets, GITI Report 13, U.S. Army Engineer Waterways Experiment Station, Vicksburg, MS.
- Escoffier, F.F. and Walton, T.L. Jr., 1979. "Inlet Stability Solutions for Tributary Inflow," Jour. Waterways and Harbors Division, WW4, 105, ASCE, 341-355.
- Greene, H.G., 1977. Geology of the Monterey Bay region. US Geological Survey Open-File Report OF 77-718, 347 pp.



- Greene, H.G., Gardner-Taggart, J., Ledbetter, M.T., Barminski, R., Chase, T.E., Hicks, K.R., Baxter, C., 1991. Offshore liquefaction and onshore liquefaction at Moss Landing spit, central California-Result of the October 17, 1989, Loma Prieta earthquake, *Geology*, v 19, 9, pp. 945-949.
- Hakanson, L. and M. Jansson, 2002. *Principles of Lake Sedimentology*. Blackburn Press, Caldwell, New Jersey, USA.
- Haltiner, J.P. and D. Thor, 1991. Sedimentation processes in Morro Bay CA. Proceedings of the Coastal Sediments '91 Conference, Seattle, Washington, June 25-27. Sponsored by the ASCE Waterway, Port Coastal and Ocean Division.
- Hornberger MI, 1991. Paleoenvironment of Elkhorn Slough and Surrounding Wetland Habitats: A Geological Study Using an Ecological Approach: Master's Thesis, Moss Landing Marine Laboratories, San Jose State University.
- Huertos, M.L., and Shennan, C., 2002. Chapter 5 Soils, IN: Changes in a California Estuary: an Ecosystem Profile of Elkhorn Slough. Elkhorn Slough Foundation, Moss Landing, CA.
- Keulegan, G.H., 1967. Tidal Flow in Entrances: Water Level Fluctuations of Basins in Communication with the Seas, Committee on Tidal Hydraulics Technical Bulletin No.14, U.S. Army Engineers Waterways Experiment Station, Vicksburg, MS.
- LeConte, L. J., 1905. "Discussion of "Notes on the improvement of river and harbor outlets in the United States," Paper No. 1009 by D. A. Watts, *Transactions, American Society of Civil Engineers* LV, December, p. 306-308.
- Oliver, J.S., King, J.A., Hornberger, M. Schwartz, D.L. (no date), Extensive salt marsh erosion caused by human activities in Elkhorn Slough, CA, 26 p.
- Oliver JS, King J, Hornberger M, Schwartz D, 1988 Erosion of Wetland Habitats by Increasing Tidal Currents from Harbor Construction and Breaching Dikes in Elkhorn Slough, California.
- Onishi, Y., Graber, H., and Trent, D.S., 1993, Preliminary modeling of wave-enhanced sediment and contaminant transport in New Bedford harbor, in A.J. Mehta, ed., *Nearshore and Estuarine Cohesive Sediment Dynamics*, Coastal and Estuarine Studies, American Geophysical Union, Washington, 541-557.
- McNeil, J., C. Taylor, and W. Lick, 1996, Measurements of erosion of undisturbed bottom sediments with depth, *J. Hydr. Engr.*, 122(6):316-324.
- Malzone CM. 1999. Tidal scour and its relation to erosion and sediment transport in Elkhorn Slough [thesis]. San Jose, CA: San Jose State University. 73 p.
- Malzone C, Kvitek R. 1994. Tidal scour, erosion, and habitat loss in Elkhorn Slough, California. Moss Landing, CA: Elkhorn Slough Foundation. 24 p.
- Mehta, A. J., 1986. "Estuarine Cohesive Sediment Dynamics", Springer Verlag, Lecture Notes on Coastal and Estuarine Studies, Vol 14, ISBN 3-540-96296-4.
- Mimura, N., 1993, Rates of erosion and deposition of cohesive sediment under wave action, in A.J. Mehta, ed., *Nearshore and Estuarine Cohesive Sediment Dynamics*, Coastal and Estuarine Studies, American Geophysical Union, Washington, 247-264.
- Mitts, P., 2003. Deposition and provenance of modern coarse sediment in Monterey Submarine Canyon. Unpublished Masters Thesis, San Jose State University *through* Moss Landing Marine Laboratories.

- O'Brien, M.P., 1931. "Estuary Tidal Prisms Related to Entrance Areas," *Civil Engineering*, 738-739.
- O'Brien, M. P., 1969. "Equilibrium flow areas of inlets on sandy coasts," *Journal of Waterways and Harbors Division* 95(WW1), ASCE, February, p 43-52.
- O'Brien, M.P. and Dean, R.G., 1972. "Hydraulics and Sedimentary Stability of Coastal Inlets", Proceedings of the 13th Coastal Engineering Conference, ASCE, 761-780.
- Ozsoy, E., 1978. "notes published in Stability of Tidal Inlets by P. Bruun", Elsevier Science Publishing, New York, N.Y.
- Philip Williams & Associates, Ltd. (PWA 1992), 1992. Elkhorn Slough tidal hydraulics erosion study. Prepared for: U.S. Army Corps of Engineers, San Francisco district.
- Roberts, J., R. Jepsen, D. Gotthard, and W. Lick, 1998, Effects of particle size and bulk density on erosion of quartz particles, *J. Hydr. Engrg.*, 124(12):1261-1267.
- Schwartz, D., 2002 Chapter 2 Geology, IN: Changes in a California Estuary: an Ecosystem Profile of Elkhorn Slough. Elkhorn Slough Foundation, Moss Landing, CA.
- Schwartz, D.L., 1983. Geological history of Elkhorn Slough, Monterey County, California. M.S. Thesis, San Jose State University, San Jose, CA.
- Schwartz, D.L. Mullins, H.T., Belknap, D.F., 1986. Holocene Geologic History of a Transform Margin estuary: Elkhorn Slough, Central California. *Estuarine, Coastal, and Shelf Science* 22:285-302.
- Seabergh, W.C. and Kraus, N.C., 1997. PC program for coastal inlet stability analysis using Escoffier method, Coastal and Hydraulics Engineering Technical Note ERDC/CHL CHETN IV-11, U.S. Army Engineer Research and Development Center, Vicksburg, MS.
- Seelig, W.N., Harris, D.L., and Herchenroder, B.E., 1977. "A Spatially Integrated Numerical Model of Inlet Hydraulics," GITI Report No. 14, U.S. Army Coastal Engineering Research Center, Fort Belvoir, VA.
- Smith RE., 1974. The hydrography of Elkhorn Slough, a shallow California coastal embayment. Moss Landing Marine Laboratories Technical Publication 73-2. Moss Landing, CA: Moss Landing Marine Laboratories. 88 p.
- Starke, G.W., and Howard, A.D., 1968, Polygenetic origin of Monterey Submarine Canyon. *Geological Society of America Bulletin*, 79, pp 813-826.
- U.S. Army Corps of Engineers, 1984. Shore Protection Manual, Coastal Engineering Research Center, Ft. Belvoir, VA.
- U.S. Army Corps of Engineers, 2002. Coastal Engineering Manual, Engineering Research and Development Center, Coastal and Hydraulics Laboratory, Vicksburg, MS.
- Van de Kreeke, J., 1967. "Water Level Fluctuations and Flow in Tidal Inlets," *Jour. Waterways Harbors Division*, WW4, ASCE, 97-106.
- Van de Kreeke, J., 1992. "Stability of Tidal Inlets; Escoffier's Analysis," *Shore and Beach*, Vol.60, No.1, 9-12.
- Verbeek, H., Kuijper, C., Cornelisse, J.C., and Winterwerp, J., 1993, Deposition of graded natural muds in the Netherlands, in A.J. Mehta, ed., *Nearshore and Estuarine Cohesive Sediment Dynamics*, Coastal and Estuarine Studies, American Geophysical Union, Washington, 185-204.

- Wagner, D.L., Greene, H.G., Saucedo, G.J., Pridmore, C.L., 2002, Geologic Map of the Monterey Bay 30' x 60' Quadrangle and adjacent areas, California. California Department of Conservation, California Geological Survey. [http://www.mbnmssimon.org/sections/geology/maps\\_graphs.php?sec=g](http://www.mbnmssimon.org/sections/geology/maps_graphs.php?sec=g)
- Walton, T.L. Jr. and Escoffier, F.F., 1981. "Linearized Solution to the Inlet Equation with Inertia," Jour. Waterways and Harbors Division, WW3, ASCE, 191-195. BR>
- Wasson K, Van Dyke E, Kvitek R, Brantner J, Bane S., 2002. "Tidal Erosion at Elkhorn Slough". In: Carless J editor. Ecosystem observations for the Monterey Bay National Marine Sanctuary, 2001. Monterey, CA: Monterey Bay National Marine Sanctuary. p 13-14.
- Wentworth, C.R., 1922. A scale of grade and class terms for clastic sediments. Jour. Geology, 30:377-392.
- Wong, C.S., 1989. Observations of tides and tidal currents in Elkhorn Slough, California. M.S. Thesis, Moss Landing Marine Laboratories, San Jose State University.
- Xu, J.P., 1999. Local wave climate and long-term bed shear stress characteristics in Monterey Bay, CA. Mar. Geol. vol. 159, pp. 341-343.

## **APPENDIX A – Sedflume Analysis**

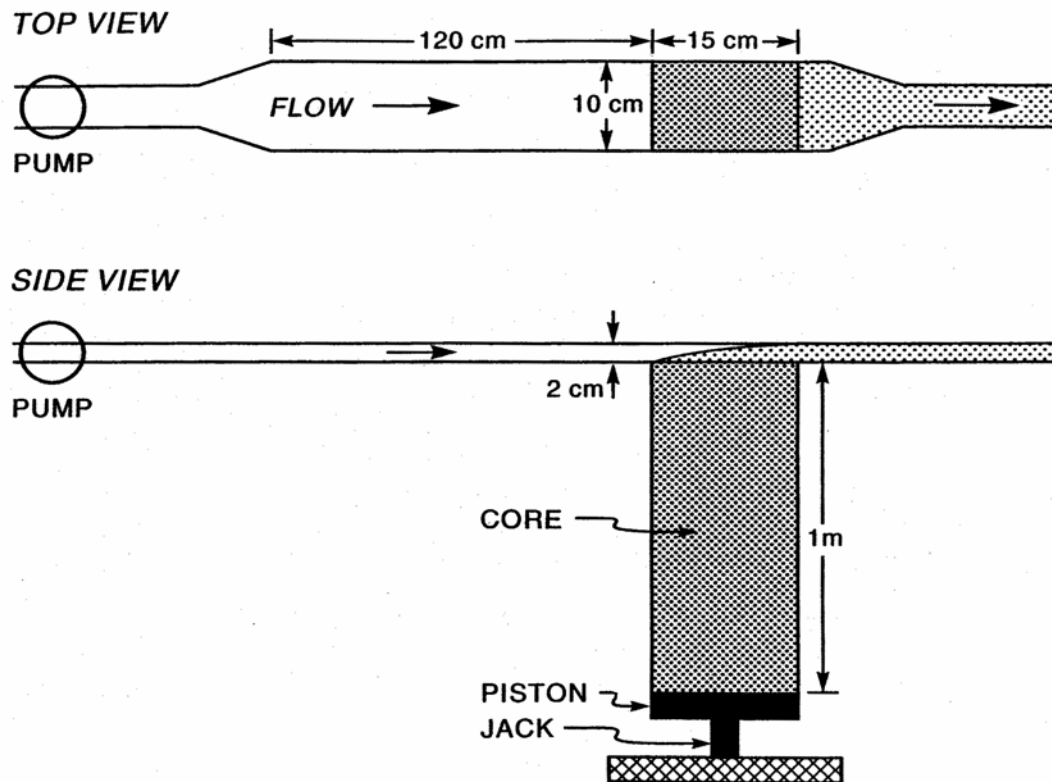
Sea Engineering, Inc. (SEI) conducted a Sedflume analysis on four sediment cores obtained at Elkhorn Slough, near Moss Landing Harbor, California. These cores were collected offshore in areas from 1-3 m in water depth. The primary goal of this work was to characterize the stability of the sediments in several locations of the tidal prism. The cores were eroded using Sedflume to determine erosion rates as a function of shear stress and depth. Critical shear stresses were also determined for each vertical interval sampled. In addition, each core was sub-sampled at vertical intervals to determine sediment bulk density and particle size distribution. The following sections describe the procedures used in the Sedflume analysis, present the Sedflume data, and provide a description of the results.

### **Experimental Procedures**

A detailed description of Sedflume and its application are given in McNeil et al (1996) and Roberts et al (1998). The following section provides a general description of the Sedflume analysis conducted for this study.

#### ***Description of Sedflume***

Sedflume is shown in Figure A.1 and is essentially a straight flume that has a test section with an open bottom through which a rectangular cross-section core containing sediment can be inserted. The main components of the flume are the core; the test section; an inlet section for uniform, fully-developed, turbulent flow; a flow exit section; a water storage tank; and a pump to force water through the system. The coring tube, test section, inlet section, and exit section are made of clear acrylic so that the sediment-water interactions can be observed. The coring barrel has a rectangular cross-section, 10 cm by 15 cm, and can be up to 1 m in length.



**Figure A.1. Sedflume Diagram**

Water is pumped through the system from a 500 gallon storage tank, through a 5 cm diameter pipe, and then through a flow converter into the rectangular duct shown. This duct is 2 cm in height, 10 cm in width, and 120 cm in length; it connects to the test section, which has the same cross-sectional area and is 15 cm long. The flow converter changes the shape of the cross-section from circular to the rectangular duct shape while maintaining a constant cross-sectional area. A ball valve regulates the flow so that the flow into the duct can be carefully controlled. Also, there is a small valve in the duct immediately downstream from the test section that is opened at higher flow rates to keep the pressure in the duct and over the test section at atmospheric conditions.

At the start of each test, a core containing sediments collected from the site is prepared. The core and the sediment it contains are then inserted into the bottom of the test section. An operator moves the sediment upward using a piston that is inside the core and is connected to a hydraulic jack with a 1 m drive stroke. The jack is driven by the release of pressure that is regulated with a switch and valve system. By this means, the sediments can be raised and made level with the bottom of the test section. The speed of the hydraulic jack movement can be controlled at a variable rate in measurable increments as small as 0.5 mm.

Water is forced through the duct and the test section over the surface of the sediments. The shear produced by this flow causes the sediments to erode. As the sediments in the core erode,

they are continually moved upward by the operator so that the sediment-water interface remains level with the bottom of the test and inlet sections. The erosion rate is recorded as the upward movement of the sediments in the coring tube over time.

### ***Sedflume Core Collection***

Four sediment cores were collected from the Elkhorn Slough by SEI personnel on February 13, 2006. At each coring location, a GPS system was used to position the vessel at a fixed sampling station. A pole was attached with clamps to the 10 cm by 15 cm rectangular core. A valve was temporarily affixed to the top of the core tube to provide suction when the core was pulled out of the sediment bed. The core was then lowered into the water and positioned perpendicular to the sediment bed. Pressure was applied by hand until at least 20 cm, and no more than 100 cm, of the core penetrated into the sediment bed.

Upon penetration of the core barrel into the sediment bed, the valve opened upward and allowed the sediment to enter the core tube and water to exit without disturbing the sediment surface or deeper strata. When the barrel was lifted from the sediment bed, the valve closed and retained the sediment inside the core tube. During the sampling effort, the core was immediately inspected visually for length and quality ensuring that undisturbed surficial sediments were present in the core. The cores were capped and transported at ambient temperature to the SEI Sedflume Laboratory in Santa Cruz, California. All cores arrived intact with sediment structure and surface preserved.

### ***Measurements of Sediment Erosion Rates***

The procedure for measuring the erosion rates of the sediments as a function of shear stress and depth were as follows. The sediment core was inserted into the Sedflume test section using the hydraulic jack until the sediment surface was even with the bottom of the Sedflume channel. A measurement was made of the core length. The flume was then run at a specific flow rate corresponding to a particular shear stress (McNeil et al., 1996). Erosion rates were obtained by measuring the core length at different time intervals, taking the difference between each successive measurement, and dividing by the time interval as shown in Equation 1:

$$E = \frac{\Delta z}{T} \quad (1)$$

E = Erosion rate

$\Delta z$  = Amount of sediment eroded

T = Time

In order to measure erosion rates at several different shear stresses using only one core, the following procedure was used. Starting at a low shear stress, the flume was run sequentially at higher shear stresses with each succeeding shear stress being twice the previous one. Generally about four shear stresses were run sequentially. Each shear stress was run until at least 1 to 2 mm but no more than 2 cm were eroded for that shear stress. The time interval was recorded for each run with a stopwatch. The flow was then increased to the next shear stress, and so on until the highest shear stress was run. This cycle was repeated until all of the

sediment had eroded from the core. If after three cycles a particular shear stress showed a rate of erosion less than  $10^{-4}$  cm/s, it was dropped from the cycle; if the erosion rates decreased significantly after many cycles, a higher shear stress was implemented in the cycle.

### ***Determination of Critical Shear Stress***

The critical shear stress of a sediment bed,  $\tau_{cr}$ , is defined quantitatively as the shear stress at which a very small, but accurately measurable, rate of erosion occurs. For Sedflume studies, this rate of erosion has been practically defined as  $10^{-4}$  cm/s. This represents 1 mm of erosion in approximately 15 minutes. Since it is difficult to measure  $\tau_{cr}$  exactly at  $10^{-4}$  cm/s, erosion rates were determined above and below  $10^{-4}$  cm/s. The  $\tau_{cr}$  was then determined by linear interpolation. The technique gives the  $\tau_{cr}$  with at least 20% accuracy (McNeil et al. 1996; Roberts et al., 1998).

### ***Measurement of Sediment Bulk Properties***

In addition to erosion rate measurements, samples were collected from each core to determine the water content, bulk density, and particle size of the sediments. Samples were collected from the surface of the Sedflume cores at the end of each erosion cycle. This allowed up to 5 samples to be collected approximately every 5 cm for analysis (depending upon core sample depth).

Bulk density was determined in the SEI Sedflume laboratory by water content analysis using methods outlined in Hakanson and Jansson (2002). This consisted of determining the wet and dry weight of the collected sample to determine the water content,  $W$ , from Equation 2.

$$W = \frac{M_w - M_d}{M_w} \quad (2)$$

$W$  = water content

$M_w$  = wet weight of sample

$M_d$  = dry weight of sample

Once the water content was calculated, the bulk density,  $\rho_b$ , was determined from Equation 3.

$$\rho_b = \frac{\rho_w \rho_s}{\rho_w + (\rho_s - \rho_w)W} \quad (3)$$

$\rho_w$  = density of water (1 g/cm<sup>3</sup>)

$\rho_s$  = density of sediment particle (2.65 g/cm<sup>3</sup>)

Particle size distributions were determined using laser diffraction analysis. Samples collected from the Sedflume core were prepared and inserted into a Beckman Coulter LS 13 320. Each sample was analyzed in three 1-minute intervals and the results of the three analyses were averaged. This method is valid for particle sizes between 0.04 and 2000  $\mu\text{m}$ . Any fraction over 2000  $\mu\text{m}$  was weighed and compared to total sample weight to determine the weight percentage greater than 2000  $\mu\text{m}$ . During the analysis no significant fraction over 2000  $\mu\text{m}$  was sampled.

Table A.1 summarizes all measurements conducted during the Sedflume analysis.

**Table A.1. Parameters measured and computed for the Elkhorn Slough coring sites.**

Measurement	Definition	Units	Detection Limit
Bulk Density, $\rho_b$ (wet/dry weight)	$\rho_b = \frac{\rho_w \rho_s}{\rho_w + (\rho_s - \rho_w)W}$	g/cm <sup>3</sup>	Same as water content
Water Content	$W = \frac{M_w - M_d}{M_w}$	unit less	0.1g in sample weight ranging from 10 to 50 g
Particle Size Distribution	Distribution of particle sizes by volume percentage using laser diffraction	μm	0.04 μm – 2000 μm
Erosion Rate	$E = \Delta z/T$	cm/s	$\Delta z > 0.5\text{mm}$ $T > 15\text{s}$
Critical Shear Stress $\tau_{cr}$	Shear stress when erosion rate equals $10^{-4}$ cm/s	N/m <sup>2</sup>	0 to 11.0 N/m <sup>2</sup> This value is interpolated as described in the text.

W = water content

$M_w$  = wet weight of sample

$M_d$  = dry weight of sample

$\Delta z$  = amount of sediment eroded

T = time

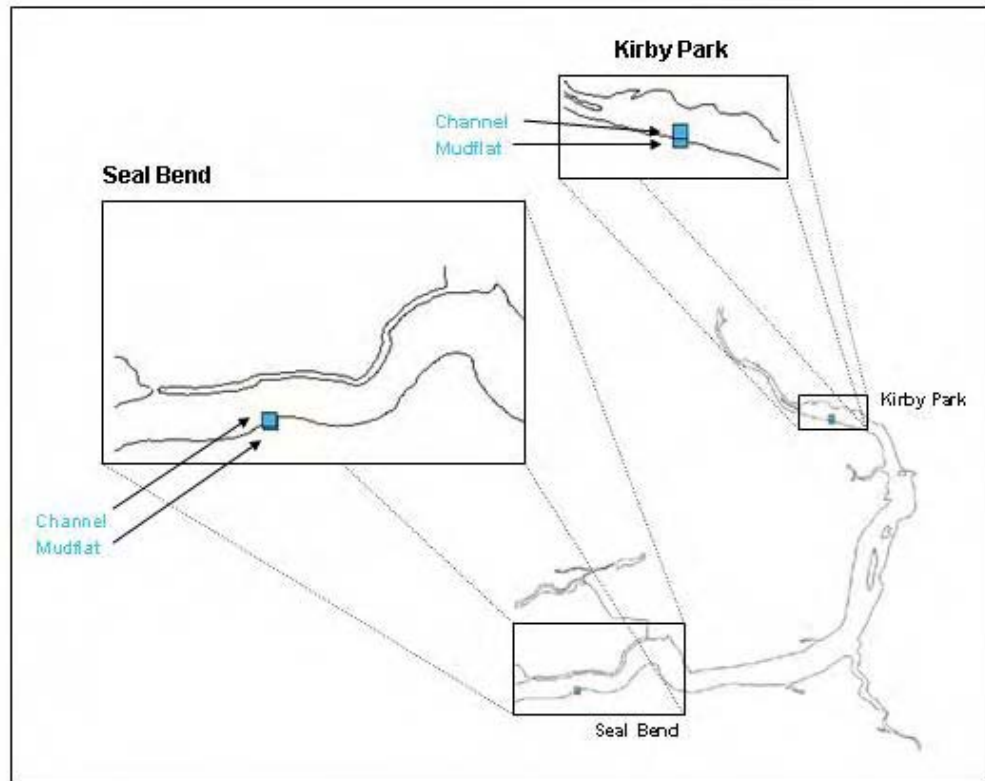
$\rho_w$  = density of water (1 g/cm<sup>3</sup>)

$\rho_s$  = density of sediment (2.65 g/cm<sup>3</sup>)



## Sedflume Core Analysis

SEI collected 4 sediment cores in February, 2006 from two locations within the Elkhorn Slough tidal prism. The first two samples were taken from an area just west of Seal Bend (Figure A.2), one in the channel, and one in the mudflat. The other two were taken upstream near Kirby Park, in the channel and mudflat. Relevant information about location and depth of each core is presented in Table A.2. A general Sedflume analysis and description follows.



**Figure A.2. Elkhorn Slough (bottom right) with enlargements of Seal Bend and Kirby Park Sedflume core locations. The enlargements denote the channel and mudflat sampling locations.**

**Table A.2. SEI core locations and descriptions.**

<b>Core</b>	<b>Date</b>	<b>Time</b>	<b>Description</b>	<b>Longitude</b>	<b>Latitude</b>
<b>SFKP01</b>	2/13/2006	9:50	Kirby Park mudflat	-121.74802	36.84026
<b>SFKP02</b>	2/13/2006	10:27	Kirby Park channel	-121.74802	36.84061
<b>SFSB01</b>	2/13/2006	12:00	Seal Bend mudflat	-121.77478	36.81184
<b>SFSB02</b>	2/13/2006	12:20	Seal Bend channel	-121.77483	36.81199

***Core - SFSB01***

Core SFSB01 was collected at an elevation above MLLW from the mudflat just west of Seal Bend. The core consisted of dark gray, bioturbated clay with visual worm tubes. As seen in the image in Figure A.3, the clay transitions from a lighter gray color to a darker gray color as depth increases. The lighter color likely indicates oxidized surface sediments.

Figure A.3 shows the results of the Sedflume erosion analysis of core SFSB01. The erosion rate plot shows the down-core erosion rate profile from each shear stress cycle that was run on the core. The range of shear stresses was  $0.1 \text{ N/m}^2$  -  $6.4 \text{ N/m}^2$ . Shear stresses where erosion rates were zero are plotted as  $1 \times 10^{-5} \text{ cm/s}$  on the graph for simplicity. The sediment surface (depth =0) is plotted at the top of the graph with down-core depth increasing down the Y-axis. Variations in erosion rate are shown for each shear stress run on the core. Figure A.4 shows the bulk density and  $D_{50}$  (median particle size) as a function of depth. Table A.2 summarizes the bulk density,  $D_{50}$ , and calculated  $\tau_{cr}$  for the core.

In general, the erosion rate data reflects a typical increase of consolidation (i.e. lower erosion rates) with depth. Sediments erode relatively easy at the surface and with more difficulty with increasing depth. At certain elevations (e.g. shear stress of  $0.8 \text{ N/m}^2$  at a depth of 10.5 cm), stiffer sediment layers were encountered, which are reflected by slower erosion rates even at larger shear stresses. Also, at certain elevations in the core, sediments that erode easier were encountered (e.g. shear stress of  $0.8 \text{ N/m}^2$  at a depth of 15 cm). Bulk density increased with depth from  $1.30 \text{ g/cm}^3$  to  $1.45 \text{ g/cm}^3$ , approximately. The bulk density profile is evidence of increased sediment consolidation with depth as well. Median sediment sizes at intervals in the core were relatively depth-uniform, varying between 10 and 20  $\mu\text{m}$ , approximately. Sediments within this range are considered very fine silts. The mean value of bulk density in the core was  $1.40 \text{ g/cm}^3$ . The mean value of sediment size in the core was 17.2  $\mu\text{m}$ .

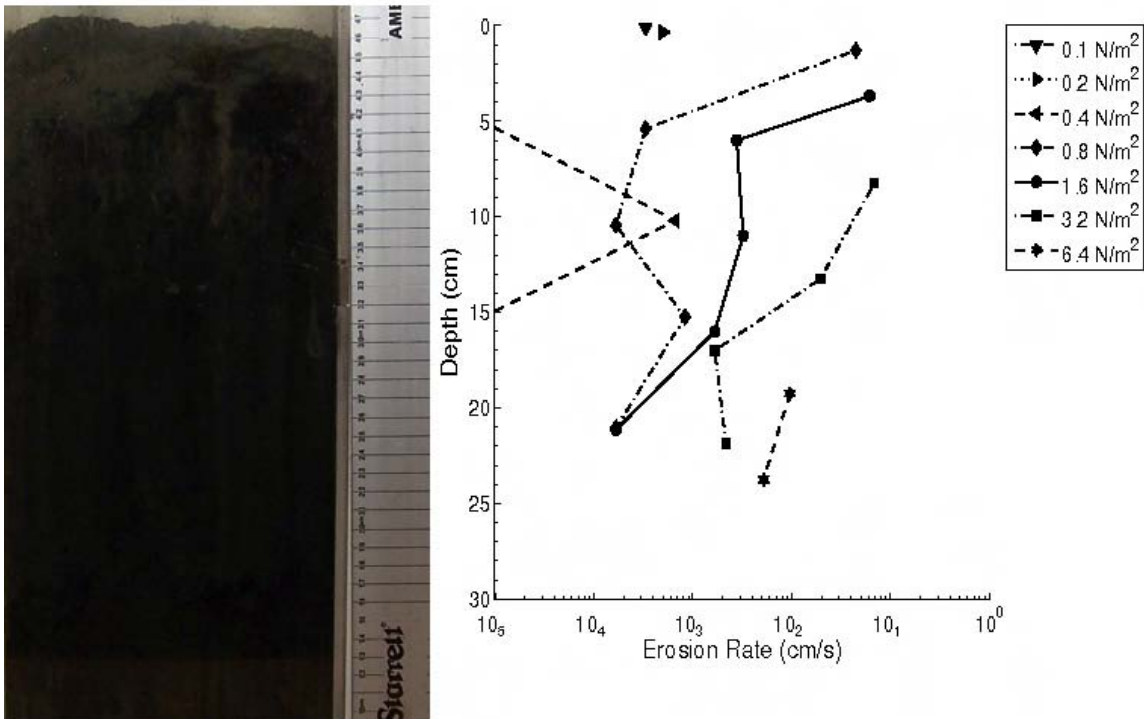


Figure A.3. Sedflume core image (core SFSB01) and corresponding erosion rates vs. depth of core for several shear stresses.

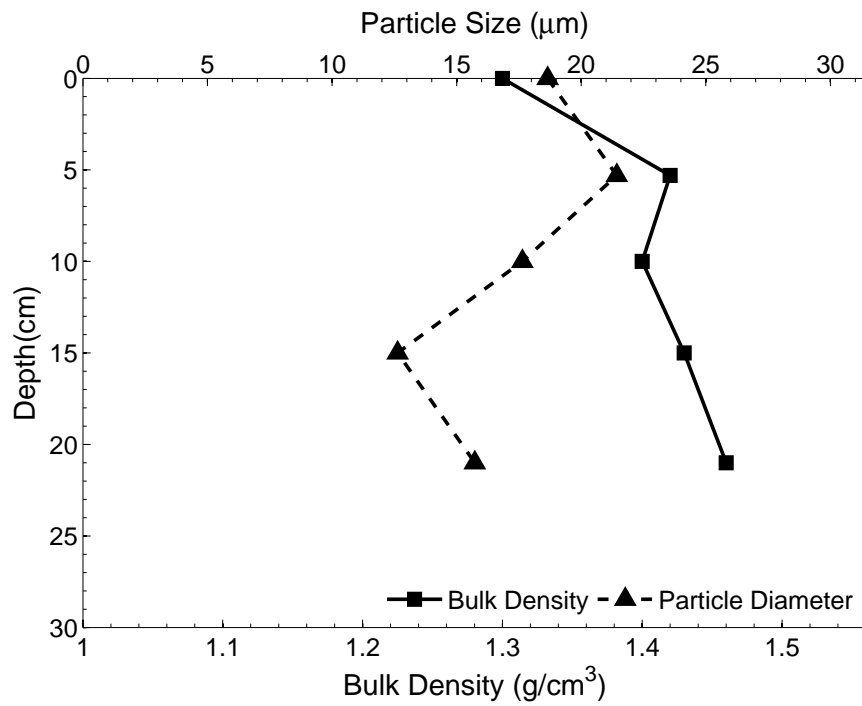


Figure A.4. Bulk densities and median particle sizes vs. core depth for core SFSB01.

**Table A.2. Bulk density,  $D_{50}$ , critical shear stress with depth for SFSB01.**

<b>Depth (cm)</b>	<b><math>D_{50}</math> (<math>\mu\text{m}</math>)</b>	<b><math>\rho_b</math> (<math>\text{g}/\text{cm}^3</math>)</b>	<b><math>\tau_{cr}</math> (<math>\text{N}/\text{m}^2</math>)</b>
0.0	18.7	1.30	0.03
5.3	21.4	1.42	0.52
10.0	17.6	1.40	0.23
15.0	12.6	1.43	0.45
21.0	15.7	1.46	0.64
<b>Mean</b>	17.2	1.40	0.37

### ***Core - SFSB02***

Core SFSB02 was collected from the channel west of Seal Bend, in approximately 3 m (10 ft) of water. The core consisted of light brown and gray clay, with some soft flocculated sediments on the surface. It was difficult to obtain a core sample of the substrate in this location. Therefore, a shorter (in depth) core was obtained. As seen in the image in Figure A.5, the clay transitions from a light brown color to a gray color throughout the core.

Figure A.5 shows the results of the Sedflume erosion analysis of core SFSB02. The erosion rate plot shows the down-core erosion rate profile from each shear stress cycle that was run on the core. Figure A.6 shows the bulk density and  $D_{50}$  (median particle size) as a function of depth. Table A.3 summarizes the bulk density,  $D_{50}$ , and calculated  $\tau_{cr}$  for the core.

In general, the erosion rate data reflects easy-to-erode sediments near the surface, a stiffer layer of sediments below the surficial sediments (~5 cm depth), and another easy-to-erode section of sediments beneath that (~10 cm depth). Bulk density increases with depth from  $1.40 \text{ g}/\text{cm}^3$  to  $1.50 \text{ g}/\text{cm}^3$ , approximately. The bulk density profile is consistent with sediment consolidation as depth increases. Sediment sizes increased slightly with depth. However, the sediment sizes were still classified as very fine silts (10-15  $\mu\text{m}$ ). The mean value of bulk density in the core was  $1.47 \text{ g}/\text{cm}^3$ . The mean value of sediment size in the core was 11.2  $\mu\text{m}$ .

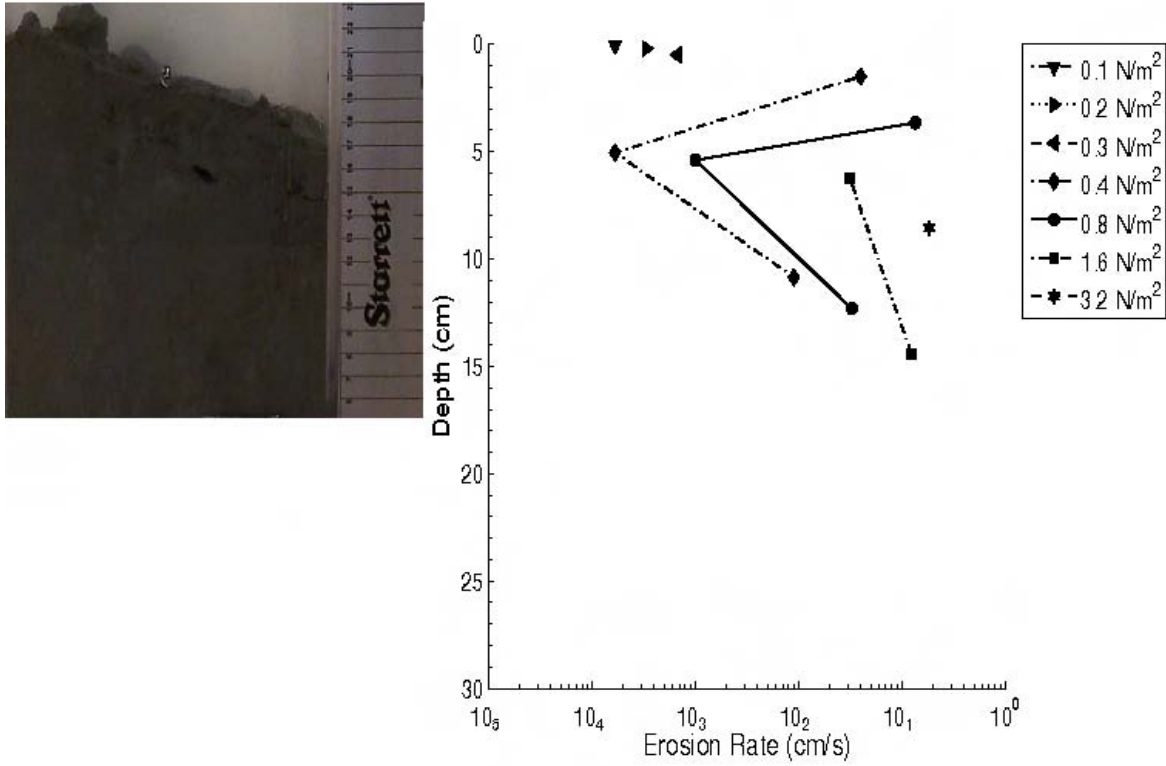


Figure A.5. Sedflume core image (core SFSB02) and corresponding erosion rates vs. depth of core for several shear stresses.

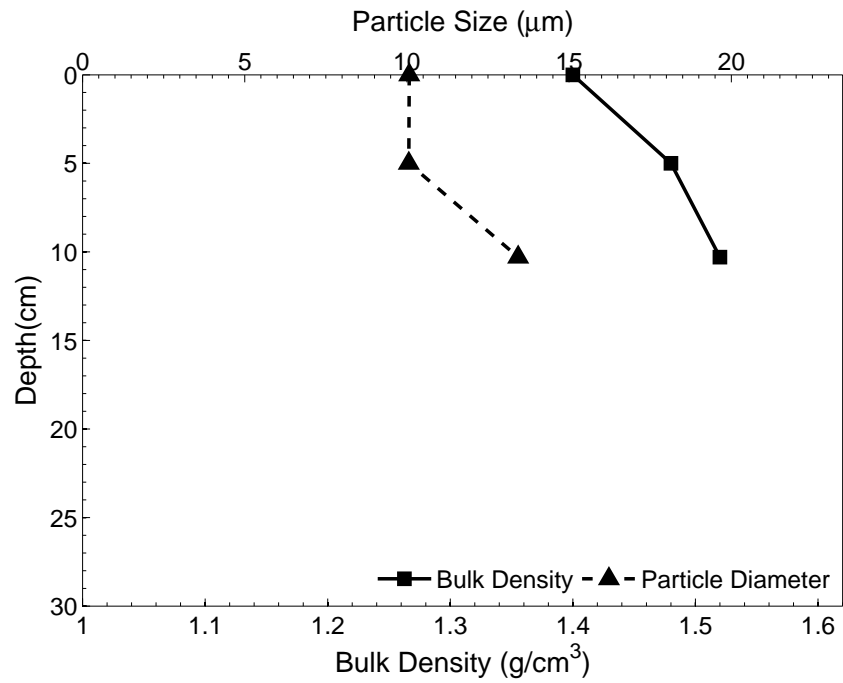


Figure A.6. Bulk densities and median particle sizes vs. core depth for core SFSB02.

**Table A.3. Bulk density,  $D_{50}$ , critical shear stress with depth for SFSB02.**

Depth (cm)	$D_{50}$ ( $\mu\text{m}$ )	$\rho_b$ ( $\text{g}/\text{cm}^3$ )	$\tau_{cr}$ ( $\text{N}/\text{m}^2$ )
0.0	10.1	1.40	0.06
5.0	10.1	1.48	0.32
10.3	13.4	1.52	0.20
<b>Mean</b>	11.2	1.47	0.19

**Core - SFKP01**

Core SFKP01 was collected upstream from Seal Bend, at the Kirby Park mudflat, in approximately 1 m (3.2 ft) of water. The core consisted of dark colored clay with some small shells near the surface. There was no layer of flocculated sediments at the surface. Further down in depth, worm tubes were visible, which eroded to reveal a stiffer layer of clay. The remainder of the core comprised of dark gray clay with some shell fragments near the bottom of the core.

Figure A.7 shows the results of the Sedflume erosion analysis of core SFKP01. The erosion rate plot shows the down-core erosion rate profile from each shear stress cycle that was run on the core. Figure A.8 shows the bulk density and  $D_{50}$  (median particle size) as a function of depth. Table A.4 summarizes the bulk density,  $D_{50}$ , and calculated  $\tau_{cr}$  for the core.

In general, the erosion rate data reflects easy to erode sediments near the surface and stiffer layers of sediment below, which result in lower erosion rates. Some exceptions exist, for instance, at depths of approximately 10 cm (under a shear stress of  $3.2 \text{ N}/\text{m}^2$ ) and 15 cm (under a shear stress of  $1.6 \text{ N}/\text{m}^2$ ). The sediments become easier to erode at these depths. A stiff layer of sediment was encountered at a depth of approximately 16 cm under a shear stress of  $6.4 \text{ N}/\text{m}^2$ . A relatively easy to erode layer of sediment was observed at depths greater than that.

Bulk density increased with depth in this core from  $1.20 \text{ g}/\text{cm}^3$  to  $1.40 \text{ g}/\text{cm}^3$ , approximately. The one exception was the lower bulk density of sediments encountered at a depth of 20 cm, at which the bulk density decreased from the previous value. The decrease in bulk density is in accordance with a sharp increase in sediment size at the same depth. Sediment sizes remained relatively small ( $<20 \mu\text{m}$ ) until a depth of approximately 20 cm. Then, the sediment layer changes from a fine silty layer to a fine sandy layer. The mean value of bulk density in the core was  $1.32 \text{ g}/\text{cm}^3$ . The mean value of sediment size in the core was  $34.3 \mu\text{m}$ .

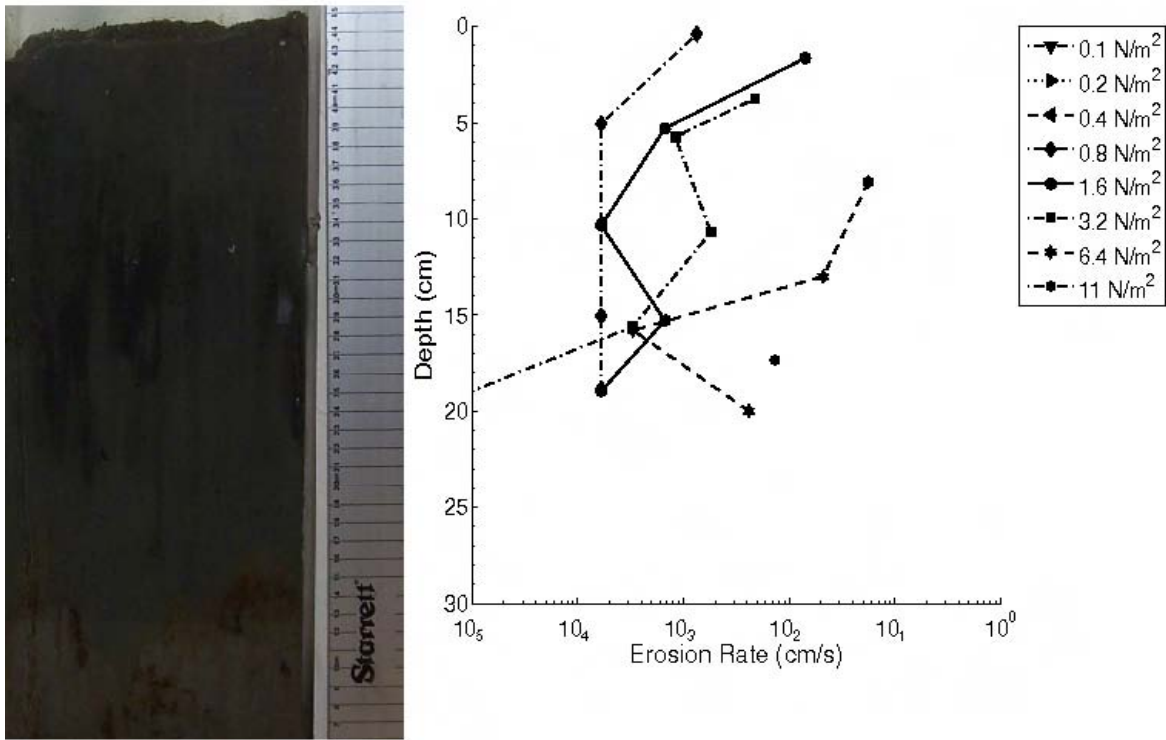


Figure A.7. Sedflume core image (core SFKP01) and corresponding erosion rates vs. depth of core for several shear stresses.

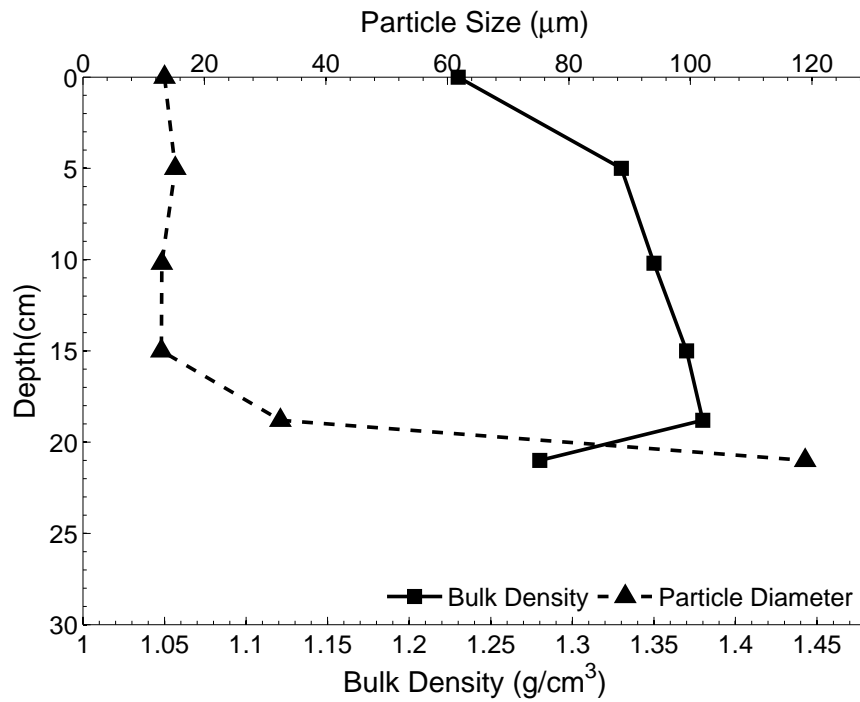


Figure A.8. Bulk densities and median particle sizes vs. core depth for core SFKP01.

**Table A.4. Bulk density,  $D_{50}$ , critical shear stress with depth for SFKP01.**

Depth (cm)	$D_{50}$ ( $\mu\text{m}$ )	$\rho_b$ ( $\text{g}/\text{cm}^3$ )	$\tau_{cr}$ ( $\text{N}/\text{m}^2$ )
0.0	13.4	1.23	0.43
5.0	15.2	1.33	0.64
10.2	13.0	1.35	0.64
15.0	12.9	1.37	0.64
18.8	32.5	1.38	0.64
21.0	118.9	1.28	n/a
<b>Mean</b>	<b>34.3</b>	<b>1.32</b>	<b>0.60</b>

***Core - SFKP02***

Core SFKP02 was collected in proximity to SFKP01, in the channel near Kirby Park, in approximately 2 m (7 ft) of water. The core consisted of gray colored clay with some flocculated sediments near the surface. Beneath the surficial sediments, there was a bioturbated layer with visible worm tubes.

Figure A.9 shows the results of the Sedflume erosion analysis of core SFKP02. The erosion rate plot shows the down-core erosion rate profile from each shear stress cycle that was run on the core. Figure A.10 shows the bulk density and  $D_{50}$  (median particle size) as a function of depth. Table A.5 summarizes the bulk density,  $D_{50}$ , and calculated  $\tau_{cr}$  for the core.

In general, the erosion rate data reflects sediments that become easier to erode as depth increases. This is counterintuitive because the bulk density increased and the sediment diameters decreased with increasing depth. An increase in bulk density typically signifies a thicker sediment consistency and a lower erosion rate.

Down core, a stiffer sediment layer was encountered at a depth of approximately 5 cm. Bulk density increased with depth in this core from  $1.20 \text{ g}/\text{cm}^3$  to  $1.40 \text{ g}/\text{cm}^3$ , approximately. The mean value of bulk density in the core was  $1.37 \text{ g}/\text{cm}^3$ . The mean value of sediment size in the core was  $10.2 \mu\text{m}$ .



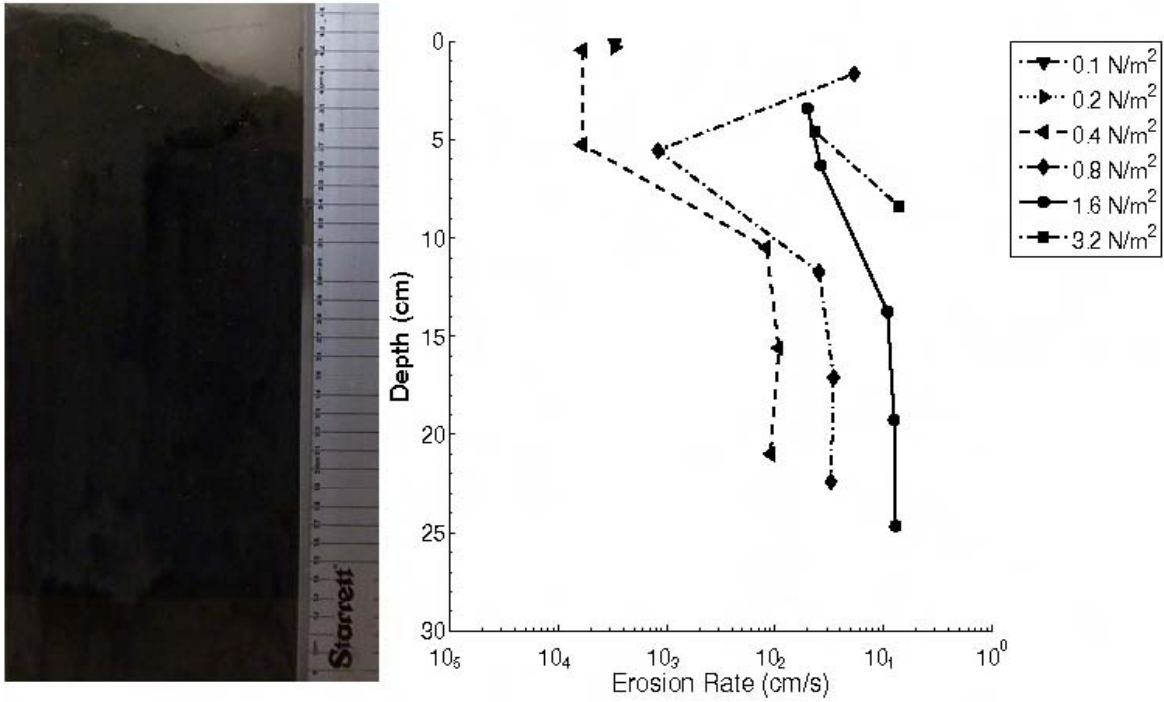


Figure A.9. Sedflume core image (core SFKP02) and corresponding erosion rates vs. depth of core for several shear stresses.

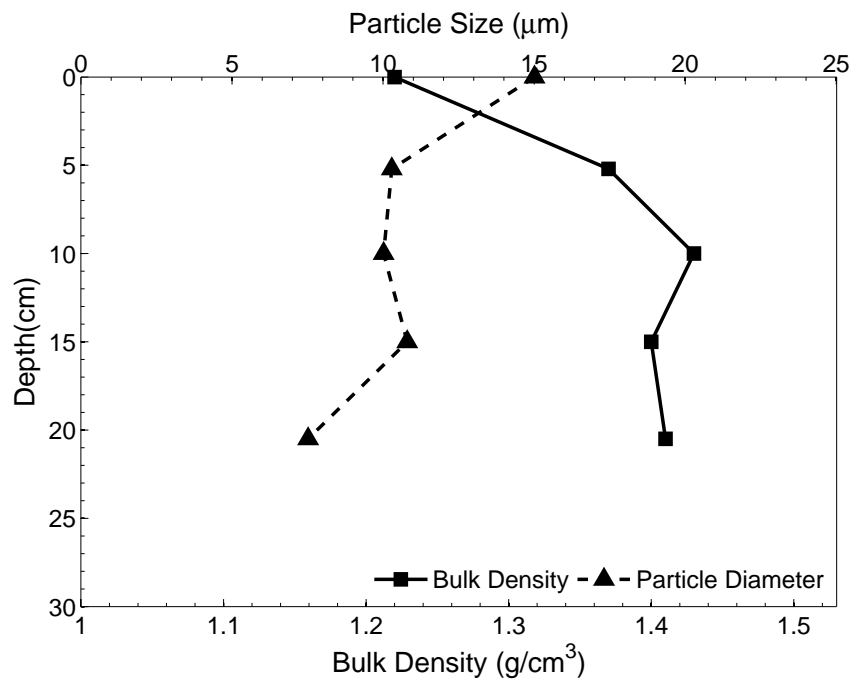


Figure A.10. Bulk densities and median particle sizes vs. core depth for core SFKP02.

**Table A.5. Bulk density,  $D_{50}$ , critical shear stress with depth for SFKP02.**

Depth (cm)	$D_{50}$ ( $\mu\text{m}$ )	$\rho_b$ ( $\text{g}/\text{cm}^3$ )	$\tau_{cr}$ ( $\text{N}/\text{m}^2$ )
0.0	15.0	1.22	0.03
5.2	10.3	1.37	0.32
10.0	10.0	1.43	0.20
15.0	10.8	1.40	0.20
20.5	7.5	1.41	0.20
<b>Mean</b>	10.7	1.37	0.19

## Elkhorn Slough Core Analysis

### *Site Comparisons*

Comparisons were made between the SEI sampled Elkhorn Slough sediment cores to obtain a better understanding of the spatial variability in core structure and characteristics. A plot of the critical shear stress profile for each core is shown in Figure A.11. Critical shear stress is defined as the force required to mobilize sediment, defined in this report at an erosion rate of  $10^{-4}$  cm/s (McNeil et al., 1996; Roberts et al., 1998; Jones and Lick, 2001).

The variability between the mudflat and the channel samples was analyzed at each location, Seal Bend (SB) and Kirby Park (KP). There was no obvious trend in down-core sediment size or bulk density between the mudflat and channel locations. The median sediment sizes were between 7  $\mu\text{m}$  and 20  $\mu\text{m}$  (fine silts) for all locations (except for one instance of larger sediment observed in core SFKP01 at a depth of 20 cm.). The bulk density ranges for all locations varied between unconsolidated surface sediments to consolidated sediments with increasing depth (1.2  $\text{g}/\text{cm}^3$  and 1.45  $\text{g}/\text{cm}^3$ , approximately).

The down-core critical shear stress profiles between the mudflat and channel locations were variable, however. In general, the cores sampled in the mudflats had higher critical shear stresses (by a factor of 2 to 3) than those sampled in the deeper channels. The cores sampled in the mudflats contained critical shear stresses in the range of 0.03  $\text{N}/\text{m}^2$  – 0.64  $\text{N}/\text{m}^2$ . The cores sampled in the deeper channels had sediments with critical shear stresses in the range of 0.03  $\text{N}/\text{m}^2$  – 0.32  $\text{N}/\text{m}^2$ , approximately. The depth-averaged critical shear stress for locations SFSB01 and SFKP01 (mudflats) are 0.37  $\text{N}/\text{m}^2$  and 0.60  $\text{N}/\text{m}^2$ , respectively. The depth-averaged critical shear stresses for the channel locations SFSB02 and SFKP02 are approximately 0.19  $\text{N}/\text{m}^2$  each.

The critical shear stresses measured from the mudflat cores show greater down-core variability than those measured from the channel cores. Core SFKP01 has a relatively larger critical shear stress near the surface (0.4  $\text{N}/\text{m}^2$ ), which approaches and remains at 0.64  $\text{N}/\text{m}^2$  as depth increases. Core SFSB01 has a relatively low critical shear stress at the surface (0.06  $\text{N}/\text{m}^2$ ), increases to a relatively larger value at a depth of 5 cm, decreases to a value similar to the samples from the channel (0.20  $\text{N}/\text{m}^2$ ) and increases with increasing depth, approaching a relatively larger critical stress of 0.64  $\text{N}/\text{m}^2$ .

The cores sampled from the channels, however, show relatively little down-core variation. Cores SFKP02 and SFSB02 follow similar critical shear stress magnitude trends at the same depths within the cores. An increase in critical shear stress is observed at a depth of 5 cm, but then remains relatively constant with increasing depths. None of the cores sampled had a critical shear stress larger than  $0.64 \text{ N/m}^2$  within the top 20 cm of the core.

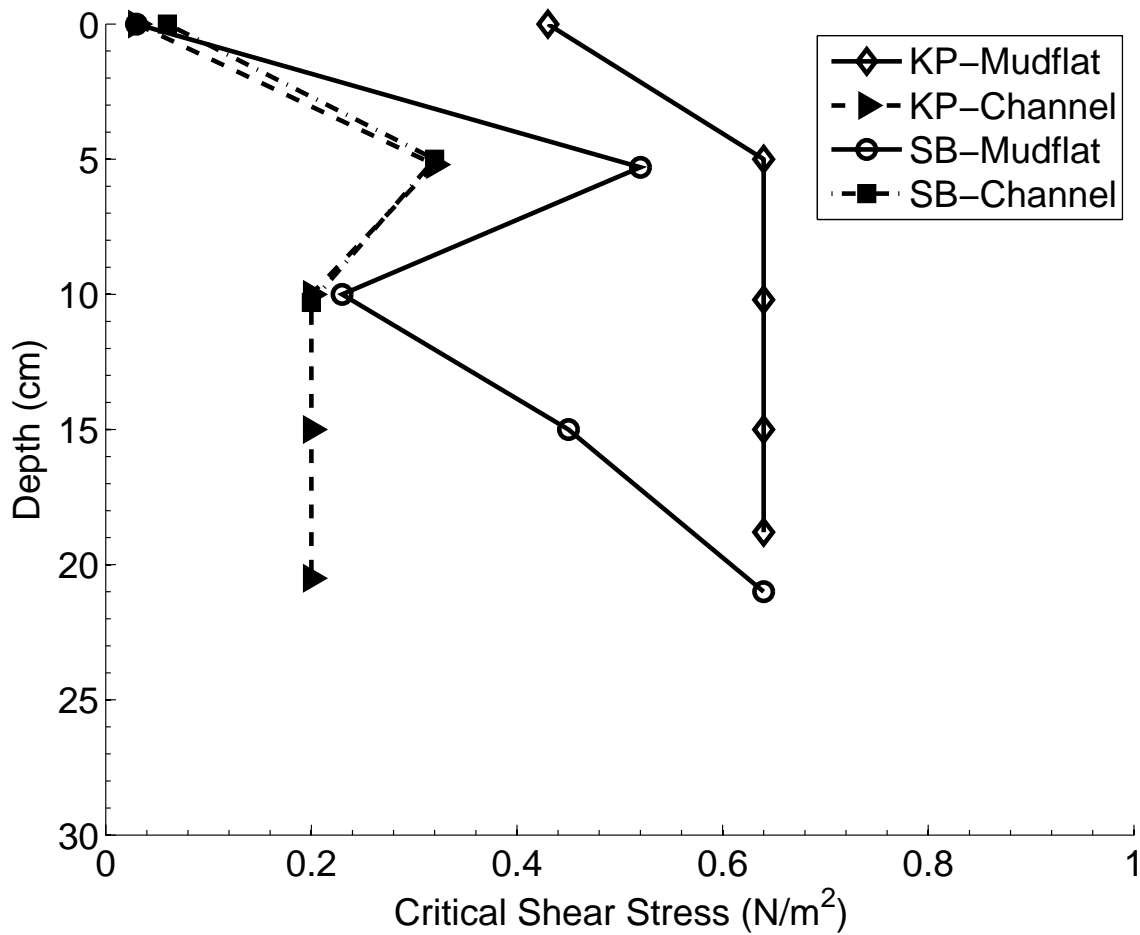


Figure A.11. Critical shear stress values vs. depth (as computed by a Sedflume analysis) for the four SEI cores sampled from Elkhorn Slough. KP – Kirby Park; SB – Seal Bend.

**Bottom Shear Stress and Velocity**

In an effort to approximate the potential mobility of the Elkhorn Slough sediments in the sampled areas, estimates of the mean fluid velocities from measured bottom shear stresses were computed. With spatially limited data about the sediment shear strength available (from the Sedflume analysis), it was possible to quantify a situation of idealized flow in Elkhorn Slough. *It should be noted, however, that a detailed hydrodynamic analysis is required to*

accurately describe the hydrodynamics and potential for sediment mobility in the Elkhorn Slough and Parson's Slough tidal prisms.

The bottom *shear stress* is the force exerted by the fluid flow on the sediment bed that causes sediment to erode. The *critical shear stress* is the shear stress at which a measurable quantity of sediment begins to mobilize. The shear stress can be expressed as a function of mean fluid velocity in the water column. The shear stress exerted by turbulent open channel flow is typically calculated from:

$$\tau = \rho C_f u^2 \quad [1]$$

where  $\tau$  is the shear stress acting on the sediment (dynes/cm<sup>2</sup>),  $C_f$  is a friction coefficient that depends on many factors (including sediment size, water velocity and water depth),  $\rho$  is the water density (1.0 g/cm<sup>3</sup>), and  $u$  is the mean fluid velocity (cm/s) in the water column .

If the near-bottom shear stress is known, the mean fluid velocity can be calculated by estimating the friction coefficient. In the same manner, if the critical shear stress is known, the critical fluid velocity can be estimated. Predicting velocity from shear stress is difficult, however, because the bed friction,  $C_f$ , is dependent upon many different variables that vary both temporally and spatially in any real region of fluid flow. It is not an easy-to-measure quantity. In common open channel flows, the coefficient of friction has been found to vary typically between 0.001 and 0.006, with a value of 0.003 commonly used (Church and Thornton, 1993). Friction coefficients have been found to vary by an order of magnitude depending on the environment. A  $C_f$  of 0.003 will be used for preliminary fluid velocity estimates in this report.

Table A.6 exhibits the estimated critical mean fluid velocities for the Seal Bend and Kirby Park Sedflume cores. These values estimate the velocity at which sediment potentially is mobilized. As computed, the velocities required to initiate sediment mobilization are between 25 and 45 cm/s. Larger critical velocities are required to mobilize sediment in the mudflats, where the shear stresses required to transport the sediment were larger.

**Table A.6. Increased friction coefficient and corresponding shear velocity.**

Core	Location	$C_f$	$\tau_c$ (dynes/cm <sup>2</sup> )	$U_c$ (cm/s)
SFSB01	Mudflat	0.003	3.7	35.1
SFSB02	Channel	0.003	1.9	25.2
SFKP01	Mudflat	0.003	6.0	44.7
SFKP02	Channel	0.003	1.9	25.2

An experiment was conducted by Stanford University in which current velocities were measured at several locations within Elkhorn Slough. Preliminary estimates of current speeds from the analysis imply that on ebbing tides, the mean depth averaged currents at Seal Bend exceed 40-60 cm/s approximately 15% of the time (personal communication with Nick Nidzieko); potentially exceeding the critical velocities required to mobilize sediment.

Caution should be used while interpreting this data, however, as this does not attempt to explain the slough system dynamics under all conditions. For one, the net tidal transport in the system is often more important than the potential for erosion. Secondly, it is possible for occasional erosion to be observed in a net-depositional system. The measured mean currents described above do show the potential for sediment mobility, but do not reflect the net transport of sediments through each region. To make an accurate assessment of the rate of slough-erosion, a thorough hydrodynamic and sediment flux study is required. These studies are currently underway by Stanford University personnel.

### ***Conclusions***

Sea Engineering, Inc. sampled 4 sediment box cores within Elkhorn Slough, near Moss Landing Harbor, CA. The objective was to ascertain the characteristics of the underlying sediments in the regions of study. The cores were subjected to a Sedflume analysis, from which erosion rates at different core elevations were obtained. Additionally, sediment sizes and bulk densities were computed at specific elevations within each core.

Critical shear stresses were computed from the Sedflume analysis. These values were used to roughly approximate the velocities that are required to initiate sediment motion at the four coring sites. This is a study that made some simple assumptions about site characteristics. The mean fluid velocity was computed from the measured critical shear stresses in the cores and a simple approximation of the bottom friction was made.

With these considerations in mind, a rough approximation of the shear velocities required to initiate sediment motion was computed and can be compared to observed flows in Elkhorn Slough.