Chapter

A 30-Year History of the Tides and Currents in Elkhorn Slough, California

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Abstract

Elkhorn Slough was first exposed to the waters of Monterey Bay with the construction of Moss Landing Harbor in 1946. It follows a 10-km path inland from Moss Landing Harbor. Today, it is a habitat and sanctuary for a wide variety of marine mammals, fish, and seabirds. The currents, tides and physical properties of Elkhorn Slough have been observed since 1970. It is an ebb-dominated estuary due to the asymmetric rise and fall of the tides which produces ebb currents that dominate. Tidal distortion increases inland due to frictional effects and extensive mud flats and *Salicornia* marsh. Tidal distortion also produces overtides and compound tides. Tidal elevations and currents often reveal the characteristics of a standing wave system. The temperature and salinity of lower Elkhorn Slough reflect the influence of Monterey Bay waters, whereas the upper Slough is more sensitive to local processes. Maximum tidal currents in Elkhorn Slough have increased from ~75 to ~150 cm/s since 1970. This increase is primarily due to the change in tidal prism which has increased from ~2.5 to ~7.6 × 10^6 m^3 between 1956 and 2003. Finally, this increase is due to both man-made changes and continued tidal erosion.

Keywords: Elkhorn Slough, increasing tidal prism, ebb tide domination, erosion, standing wave system, man-made changes

1. Introduction

Since the late 1800s, human intervention has significantly altered the structure of Elkhorn Slough, and the circulation within it. Before 1946, Elkhorn Slough (ES) was a sluggish backwater with little influence from Monterey Bay. In 1946, the Army Corps of Engineers created Moss Landing Harbor located at the head of Monterey Submarine Canyon by cutting through the dune barrier that separated the Slough from Monterey Bay. ES is now a shallow, tidally-forced embayment that is directly coupled to Monterey Bay. Increased tidal action has led to a dramatic increase in tidal scouring, particularly in the lower part of the Slough [1]. The Slough was transformed from a fresh water, brackish environment to one that is primarily saltwater, and from an estuary that was primarily depositional to one that is now dominated by erosion. Since 1971, maximum tidal currents in the main channel at the mouth have increased from approximately 75 to 150 cm/s. The flood tide introduces relatively clear water from Monterey Bay while waters discharged during the ebb are laden with sediment eroded from the banks and bottom of the

Slough. This discharge creates a plume that extends 3 km or more offshore and is clearly visible in satellite imagery [2]. As erosion continues, the tidal prism and currents in ES increase, leading to further erosion. This behavior suggests a system with positive feedback, a situation that can become unstable.

Recent estimates of the erosional sediment losses from the Slough have ranged from 3.5×10^4 m^3/year [3] to 8×10^4 m^3/year [4]. Observations of bank erosion indicate average losses of 40 cm/year [5]. Bank erosion has widened the main channel, and the resulting increased tidal prism has led to an expanding network of tidal creeks that feed into the Slough (John Oliver, personal communication). According to Malzone and Kvitek [6], the tidal prism increased by 43% during the last decade and the surface area covered by salt water increased by 48%. Based on aerial surveys, losses to the surrounding wetlands (composed primarily of *Salicornia* marsh) have increased significantly over the past 50 years [7]. Erosion has led to an overall loss in vegetated marsh around the Slough that was most apparent during the first decade following the opening of Moss Landing Harbor.

Many environmental factors such as loss of *Salicornia* marsh, ichthyoplankton abundance, nutrient distributions, phytoplankton distributions, pesticide accumulation, and changes in biodiversity are related directly, or indirectly, to the circulation and physical properties of ES. According to Dyer [8], the physical, chemical, biological, and geological systems within a given estuary are, to a large extent, inseparable. Less is known about the physical environment of ES than perhaps some of its other defining properties. This is due in part to the spatial and temporal complexities of the circulation, and the rate at which physical changes to the system are occurring.

It is our purpose to summarize what is known about the tides, the circulation, and the physical properties of ES, based on a period of data collection that began in 1970 and continued into the early 2000s. In this regard, the manuscript is a period piece that spans a recent ~30-year period. The work contained herein is based on the work of the first author's students, M.S. theses by some of these students, and, importantly, new observations. The text covers (1) the physical setting of the Slough, (2) the tides, (3), the physical properties, and finally, (4) the conclusions. This manuscript is based primarily on information that was contained in an unpublished report by Broenkow and Breaker [9]. However, a number of significant refinements have been made to that report which are included here for the first time.

2. The setting

ES is located in central California at the eastern side of Monterey Bay mid-way between Monterey and Santa Cruz. Several tributaries (i.e., lesser sloughs) including Bennett, Moro Cojo, and Tembladero Sloughs feed directly into ES or Moss Landing Harbor. Originally, ES was somewhat removed from direct tidal flow and the Salinas River discharged directly into Monterey Bay just north of the entrance to Moss Landing Harbor (**Figure 1**). In the late 1800s, the lands surrounding ES were altered through the construction of ditches and dikes to make the low-lying marshes suitable for agriculture. Around 1900, a 150-ha area near the mouth of the Slough was diked to form evaporative salt ponds. In 1908, the mouth of the Salinas River was diverted about 7 km to the south, removing any residual tidal influence from ES. When the U.S. Army Corps of Engineers created the channel between Monterey Bay and ES in 1946, the old Salinas River channel was dredged to form what is now Moss Landing Harbor (**Figure 2**) and the Slough was opened to full tidal circulation.

ES is about 10 km long, with depths ranging from 8 m at the harbor entrance, to 0.5 m near the head of the Slough (**Figure 1**). The average depth is approximately

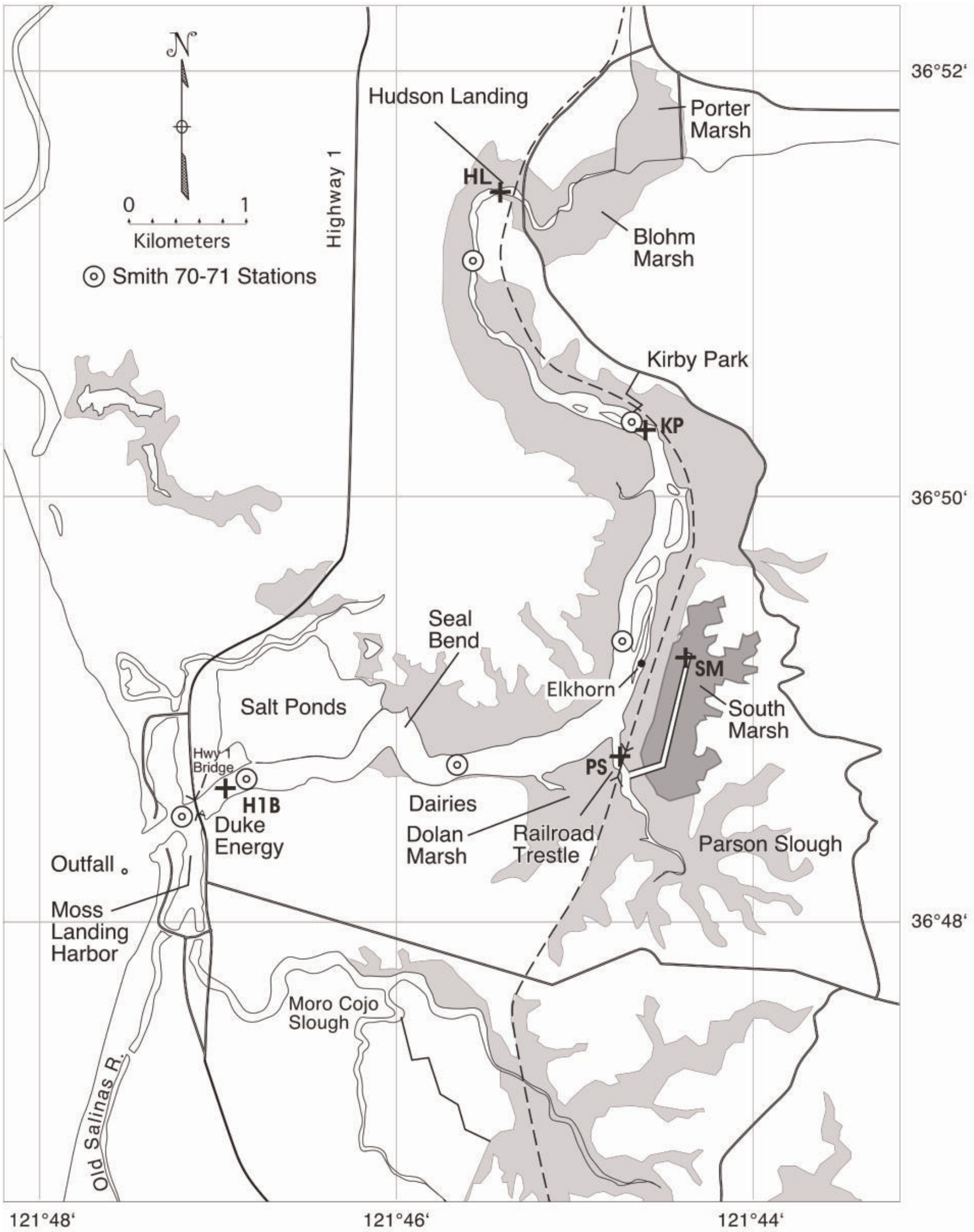


Figure 1.
Elkhorn Slough. This map was originally drawn by John Hansen from aerial photographs in 1971 and has been updated subsequently. Circles show Smith's [10] sampling stations. Crosses show tide stations.

3 m. The main channel has a width of about 200 m landward of the Highway 1 Bridge (H1B), to 90 m near the entrance of Parsons Slough. The ES drainage area is small: 585 km^3 [1], and significant fresh water enters the Slough only during winter months. The sinuous path of ES, with four major bends, has a major impact on its circulation. Because it is a complex, shallow waterway comprised of a main channel, extensive mud flats, *Salicornia* marsh, and small tidal channels, it is difficult to obtain reliable estimates of its volume, tidal prism, surface and cross-sectional areas, and bathymetry. **Figure 1** is a map of ES based on an aerial photograph taken in 1971 (Hansen, personal communication) with recent updates from 1993 aerial photographs. At low tide, the Slough consists essentially of a narrow channel whereas at high tide, waters entering the Slough inundate the surrounding mud flats, greatly increasing the surface area covered by water.

A number of prominent features in the aerial photograph of ES are shown in **Figure 3**: the lower Slough with the entrance cutting across the beach near the

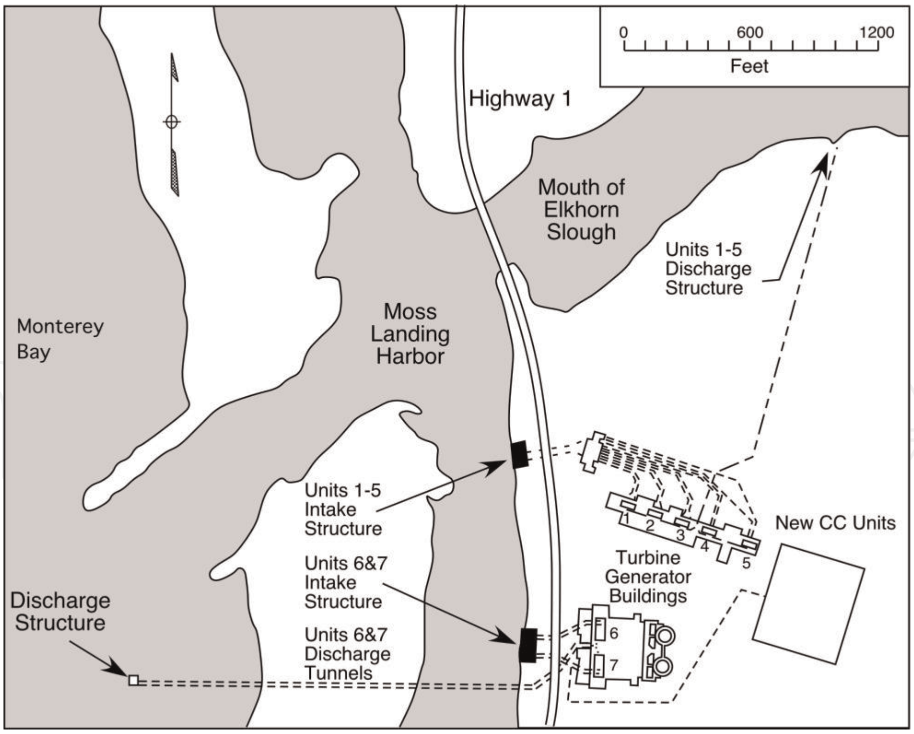


Figure 2.
Moss Landing Harbor, adapted from Duke Energy Moss Landing [10].

center; the Duke Energy Power plant with several reserve fuel storage tanks paralleling the lower slough; the now abandoned National Refractories and Minerals plant with a large tailing waste pond composed of mainly calcium carbonate precipitate, and Moss Landing Harbor with a small fishing fleet and pleasure boat moorings. The Highway 1 Bridge near the Duke power plant has been the site of a number of current meter studies. Near the main northward bend in the channel (**Figures 1** and **3**), a linear strip of land supports the Southern Pacific railroad and separates the main Slough from Parsons Slough and the South Marsh. This relatively large body of water is connected to the Slough through a 50-m wide channel under the railroad trestle. Because Parsons Slough and the South Marsh serve as one body with respect to ES, we will usually refer to them as Parsons Slough from this point on unless there is a reason to refer to them separately.

Figure 3.
A more recent aerial photograph of Elkhorn Slough taken in September 2002, looking eastward from an altitude of 1500 m (courtesy of Scott Benson).

During the past 25 years, major changes have occurred in the Slough's morphology, and these have further altered its tidal response. During the winter months when the Salinas River flows into the bay, a channel is bulldozed across the beach 7 km south of Moss Landing to prevent local flooding in the surrounding towns of Castroville and Moss Landing. The sources of freshwater entering the Slough during this period include rainfall and agricultural runoff from its small drainage basin. Moss Landing Harbor receives a continual supply of low salinity water from agricultural runoff, and before 1982, when the Monterey Regional Outfall began operation, treated sewage discharge from Castroville entered the system via Tembladero Slough south of Moss Landing Harbor. These waters now enter the south harbor at low tide through a tide gate. Recently, another tide gate limiting the flow of waters into Moro Cojo Slough has been removed, and that area is again open to tidal action. Recent changes in bottom depth at one location are readily apparent in the four profiles shown in **Figure 4**. These profiles, taken at the Highway 1 Bridge, show that bottom depth and channel width have both increased significantly since 1972.

The Duke Energy of North America Power Company operates the largest power generation plant (2.5 gW) in California at Moss Landing (**Figures 2** and **3**). Before Duke Energy acquired the plant in 1998, it was operated by the Pacific Gas and Electric Company (PG&E power plant or simply PG&E). At that time, seawater coolant was pumped from the east side of Moss Landing Harbor at a maximum rate of 2.7×10^6 m^3/day, with a temperature of 7–10°C above ambient [11]. The original five power generating units (1–5) discharged coolant waters into Elkhorn Slough, while coolant waters from units 6 and 7 were discharged into the head of Monterey Submarine Canyon within 200 m of the harbor entrance. In 1998, discharges into Elkhorn Slough were eliminated. In July 2002, two new 1.1 gW gas turbine generation units became operational and their coolant waters were discharged through the offshore outfall (**Figure 2**). Until recently, the National Refractories and Minerals (NRM) operated a magnesium extraction plant, just south of the Duke Energy

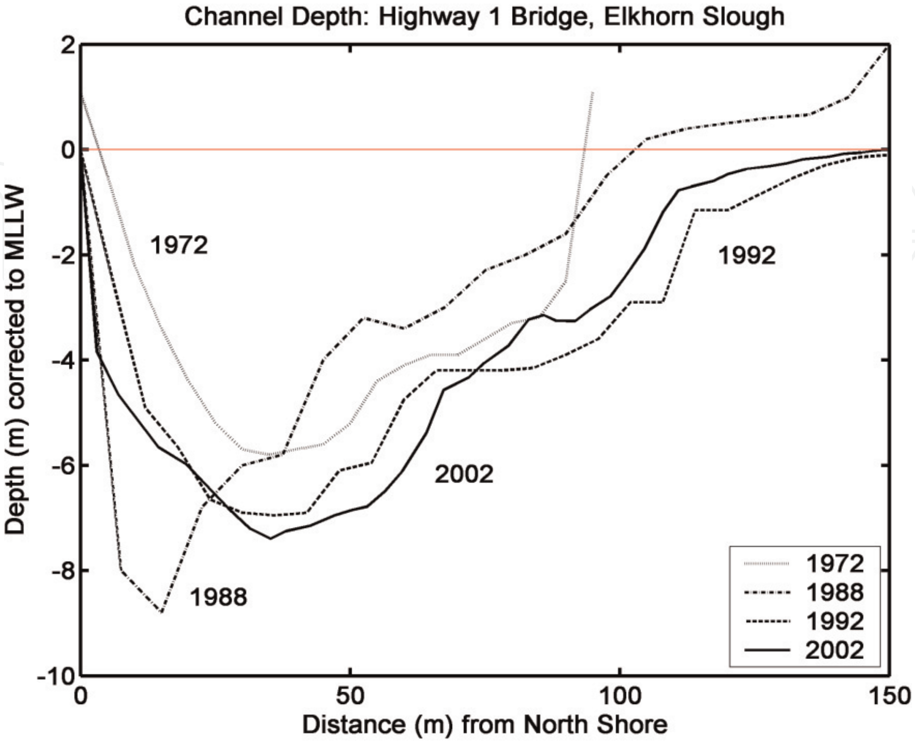


Figure 4.
Bottom profiles at Highway 1 Bridge (H1B). Depths are referenced to MLLW.

plant. The National Refractories plant ceased operation in the year 2000, but the tailing pond of $CaCO_3$ remains.

The last large-scale change to the hydrography of Elkhorn Slough was implemented by the California State Department of Fish and Game in 1983. Dairy pastures of 160 ha (1.6×10^6 m^2) were returned to tidal flooding by digging a channel across former dikes and excavating about 10% of the marsh to a depth of 2 m below MLLW. This area, called the South Marsh, is now part of the Elkhorn Slough National Estuarine Research Reserve (ESNERR). More recently, ES may have been affected by the 1989 Loma Prieta earthquake. Cracks in the surrounding marshlands have been identified that appear to be related to this event (R. Kvitek, personal communication) and there is evidence that the *Salicornia* marsh has settled (G. Greene, personal communication).

3. The tides

3.1 Introduction

The tides in ES are mixed, and thus are similar to those found elsewhere along the California coast. The form ratio for the tides in Monterey Bay is 0.96, indicating that the tides are mainly semidiurnal. A characteristic of the tides in ES is that the greatest tidal range during the tidal day corresponds to the transition *from* MHHW *to* MLLW. This is an important factor that determines in part the relative speeds of the ebb and flood currents. The mean range of the semidiurnal tide for the four principal tidal constituents ($K_1 + O_1 + M_2 + N_2$) at the Highway 1 Bridge (H1B) is about 1.2 m, with a mean diurnal range of 1.7 m. The spring range is about 2.5 m, while the neap range is about 0.9 m [12].

3.2 Tidal constituents

The observed tide is represented as a sum of harmonic constituents, each with its own amplitude and phase. The number of constituents, and their corresponding amplitudes and phases, are specific to a given location. The primary tidal constituents fall into three categories: semidiurnal, with periods of approximately half a day; diurnal, with periods of approximately a day; and long-period, with periods of two weeks, to years. The tidal analyses for Monterey Bay and ES are based on record lengths of a year or less. Consequently, it is not yet possible to resolve the longer period constituents. The M_2, K_1, O_1, S_2, P_1, and N_2 constituents (amplitudes in descending order), are the six most important constituents for Monterey Bay. In addition to these, at least 15 other constituents have been identified in tidal records collected in Monterey Bay by the National Ocean Service and recorded in the Tide Tables they have produced.

To obtain data suitable for predicting tidal height and phase, water levels in ES were measured from June 2002 to August 2003. Our 120-day records for three stations in ES were of sufficient length to separate most of the constituents listed in **Table A1**, which is included in the Appendix A, following the references. However, the tidal amplitudes obtained from these analyses were not directly comparable to those obtained earlier by the National Ocean Service from year-long observations in 1976, because the variability was distributed among slightly different constituents and because the record lengths were different. The data acquired by NOS is included in **Table A2** of the Appendix A. Our record lengths varied from 1 to 14 months (**Table A1**). Although the constituent amplitudes around the diurnal (1 cycle per day [cpd]) and semidiurnal (2 cpd) frequencies for the MB and ES stations are similar, the appearance of the higher frequency constituents between 2.8 and 3.9 cpd inside ES clearly distinguishes its tidal response from that of Monterey Bay. In addition, overtides were found with periods of 8.3, 6.2, and 4.1 h that correspond to the M_3, M_4, and M_6 constituents, respectively. The 8.3-h M_3 constituent represents one of the lunar terdiurnal components. Because its period is close to the period of the terdiurnal SO_3 compound tide (8.19 vs. 8.28 h), the SO_3 constituent could not be clearly separated from the M_3 tide.

A comparison of the tidal constituents determined from our water level measurements at six locations is shown in **Figure 5** and illustrates the differing character of the tide from MB to the head of ES: Monterey Harbor (a), representative of Monterey Bay, Moss Landing Harbor (b), the H1B (c), the entrance to Parsons Slough (d), Kirby Park (e), and Hudson's Landing (f). Log_{10} of the amplitude in mm is plotted vs. each constituent frequency in cpd. A similar constituent analysis for Monterey Bay was performed 25 years earlier by the National Ocean Service

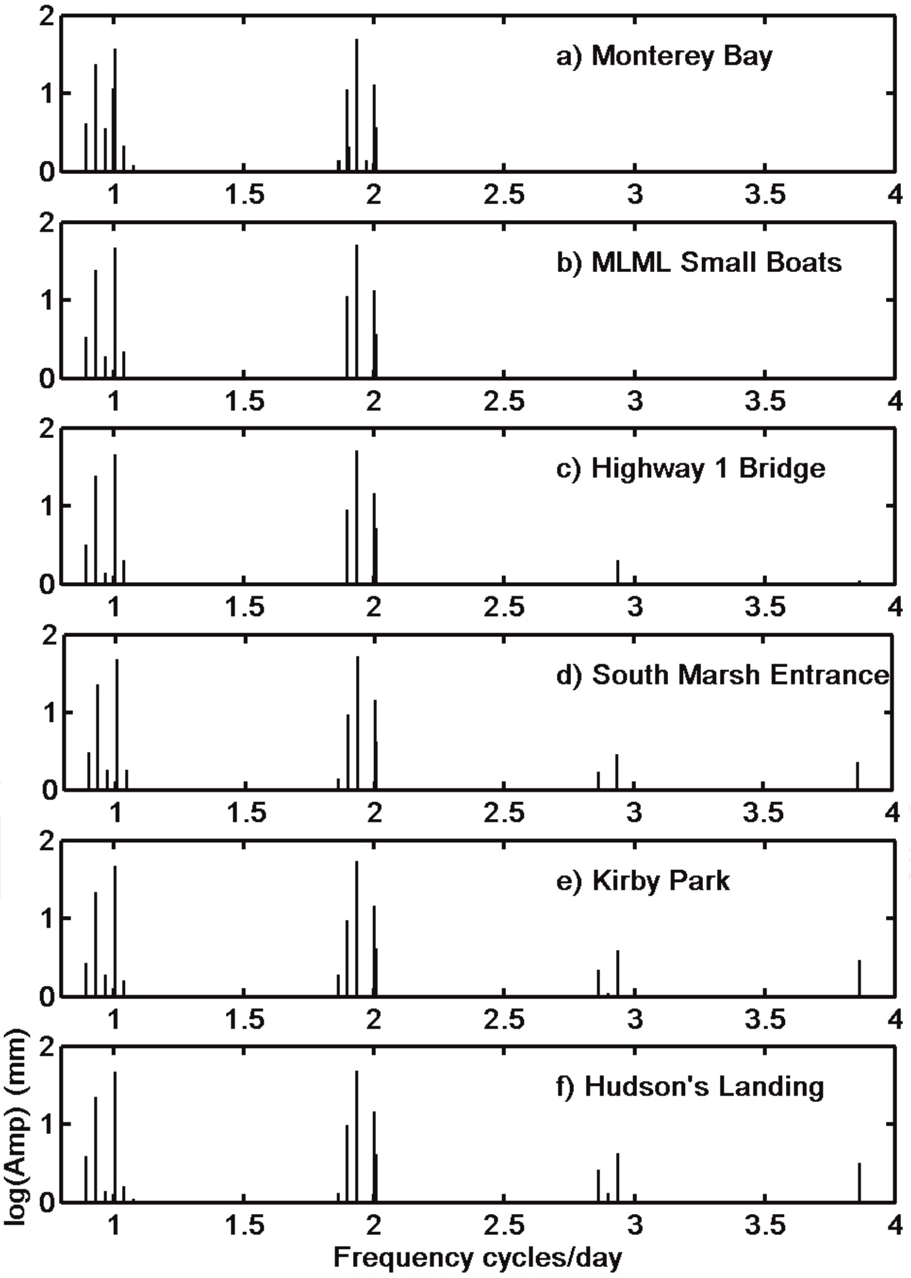


Figure 5.
*Log_{10} tidal constituent amplitude vs. frequency for five locations in Elkhorn Slough (**Figure 1**): (a) Monterey Bay (NOS, 1 year); (b) Moss Landing Harbor at MLML Small Boat Dock; (c) Lower Elkhorn Slough 200 m east of Highway 1 Bridge; (d) Railroad Trestle at the entrance to Parsons Slough; (e) Kirby Park; (f) and Hudson Landing.*

(NOS) from a 1-year record acquired in 1976 in Monterey Harbor and comparisons with our analysis are constructive.

Our least squares regression results which are summarized in **Table A1** of the Appendix A show large amplitudes for the dominant tidal constituents (M_2, K_1, O_1, S_2, P_1, and N_2) at the ES stations indicated above similar to those obtained earlier by NOS (**Table A2**). Our results in Moss Landing Harbor show insignificant values for the overtides (M_3, M_4, and M_6) and the compound tides (MK_3, $2MK_3$, MN_4, and MS_4). The amplitudes of these constituents increase significantly as we move landward, consistent with similar increases in these constituents obtained by NOS, and consistent with the increasing influence of frictional effects as the bottom depth decreases moving inland. Of particular note, we find a ~25% increase in the 2002 data compared to the 1976 data, suggesting that morphological changes in ES have modified its tidal response noticeably over a period as short as 25 years! In addition, we now include the set of tidal constituents inside the ESNERR South Marsh restoration area in **Table A1**. They demonstrate that South Marsh is not tidally choked (i.e., providing insufficient time for the unrestricted inflow and outflow of the tidal transport over a complete tidal cycle) despite being limited by the 50-m-wide, 4–6-m-deep entrance under the Southern Pacific Railroad Trestle.

Tidal phase differences in ES were estimated by Wong [13] by comparing the times of high and low water at several locations consistent with tidal propagation up the Slough. Between a point 200 m east of the H1B, and 5 km up the Slough near the Parsons Slough entrance, Wong found, on average, that high water occurred 48 min later at Parsons Slough but low water occurred only 18 min later. The large difference between the HHW and LLW phases at these two locations, emphasizes the tidal asymmetry in ES. Wong also compared these values with the NOS tide predictions from 1976 and found that the time for the tide to propagate over this portion of the Slough had increased significantly.

Based on shallow water wave theory, the expected phase speed, $c(x,t)$, for the incoming tide where tidal elevation and water depth are of the same order, is

$$c(x,t) = [\,g(h(x) + \eta(x,t))]^{1/2}, \tag{1}$$

where h is the water depth, η is the tidal elevation, and g is the acceleration of gravity. The tide propagates at 6.3 m/s for a water depth of 4 m with a free surface elevation $\eta(x,t)$ of zero. Integrating $c(x,t)$, the travel times along the Slough from the H1B to Hudson's Landing using channel depths for the diurnal mean tide (high = 1.7 m, low = 0.0 m) are 24 and 31 min. These times change to 23 and 37 min for the greatest observed tidal range (2.0 to -0.6 m).

3.3 Tidal currents

The first measurements of the tidal currents were made in 1970 by Clark [14] in the main channel on the harbor side of the Highway 1 Bridge. We note that since this record was not referenced to a standard tidal datum, the exact depth of these observations is not known but they were acquired at "mid-depth," clearly well above the bottom boundary layer. Clark made a total of five time series measurements with durations of one to two tidal days using a mechanical current meter. A 2-day sample is shown in the first (i.e., top) panel of **Figure 6**, where maximum currents of almost 40 cm/s were observed during the 0.75 m flood tide and 60 cm/s on the following 1.75 m ebb tide. Ebb domination is apparent as the flood tide lasted almost twice as long as the ebb. Clark observed that the tidal currents in ES were approximately standing wave in character because the tidal heights and currents were approximately 90° out of phase.

Wong [13] used an ENDECO 714 current meter set at a height of 1.6 m above the bottom to measure the flow near the H1B for a 2-week period in September 1986 (**Figure 6**—second panel). He found maximum speeds of 80 cm/s during the ebb tide. Because these measurements were made within the bottom boundary layer, he estimated the values to be approximately 20% lower than the corresponding free-stream velocities, assuming a logarithmic velocity distribution in the bottom boundary layer [15]. From measurements made at the H1B during a spring tide, Wong estimated speeds as high as 113 cm/s on ebb and 75 cm/s on the flood. More recent observations at the entrance to Parsons Slough (**Figure 1**) approximately 4 km from the entrance to Moss Landing Harbor indicate maximum flooding and ebbing velocities of 150 and 170 cm/s, respectively. These current speeds are significantly higher than those measured by Wong at the H1B, a result of the narrow entrance to Parsons Slough, and thus are not representative of the flows encountered in the main channel of ES. Wong found that cross-channel velocities were less than 3 cm/s at all locations, consistent with highly channelized flow. Wong's data indicated that velocities near the mouth were approximately 50% greater than Clark's measurements, apparently due to the increase in tidal prism resulting from the addition of the South Marsh to tidal flooding and to the continued effects of erosion over the 16 years between the two sets of measurements [5]. Finally, Wong [13] found that overall, over 90% of the variance in current speed in ES is caused by the tides.

We made current measurements in 1992 with an InterOcean S4 current meter suspended from the H1B, 3 m above the bottom. Again these measurements indicate increasing tidal flows at the H1B where maximum speeds on the ebb tide approaching 120 cm/s were observed (**Figure 6**—third panel). The higher-frequency ripples superimposed on the tidal current record are primarily due to seiche period oscillations in Monterey Bay [16]. Our most recent record (**Figure 6**—bottom panel) shows a 1-month sample from a 14-month time series made with an InterOcean S4 current meter located 1.1 m above the bottom (almost certainly within the bottom boundary layer) in the main channel approximately 250 m east of the H1B. Modulation of the primary diurnal and semidiurnal tidal currents by the spring and neap tides produces maximum ebb currents during the spring tide (105 cm/s) that are three times greater than the maximum ebb currents observed during the neap tide (35 cm/s). Adjusting for boundary layer attenuation, the near surface ebb and flood speeds could reach 125 and 42 cm/s, respectively.

During December 1993, Malzone and Kvitek [6] used an S4 current meter to measure currents near the time of maximum ebb at four locations along the main channel of ES (**Figure 7**). These results show a steady decrease from slightly over 100 cm/s at the mouth, to approximately 50 cm/s at 8.5 km inland. This decrease in current speed is consistent with the reduced tidal prism landward of each measurement location. The large decrease in current speed between 2.2 km and 6.5 km is caused by the addition of waters that drain from Parsons Slough at about 3.5 km from the H1B.

Vertical current profiles in ES have been examined on several occasions. Wong [13] constructed vertical current profiles from observations acquired during May 1987 and April 1988, approximately 200 m from the H1B during peak flow on the ebb tide (**Figure 8**). He found a significant reduction in speed in the deepest 3–4 m with vertical shears as high as ∼10 cm/s/m. His data showed no well-defined core of maximum speed. He made these measurements by lowering and raising a single S4 current meter. Wong used his data to estimate a roughness length for the bottom and a thickness for the bottom boundary layer using standard boundary layer parameterizations. From a logarithmic decay law for the boundary layer, he estimated a bottom roughness length of 6.5 cm. Using this figure, he calculated a

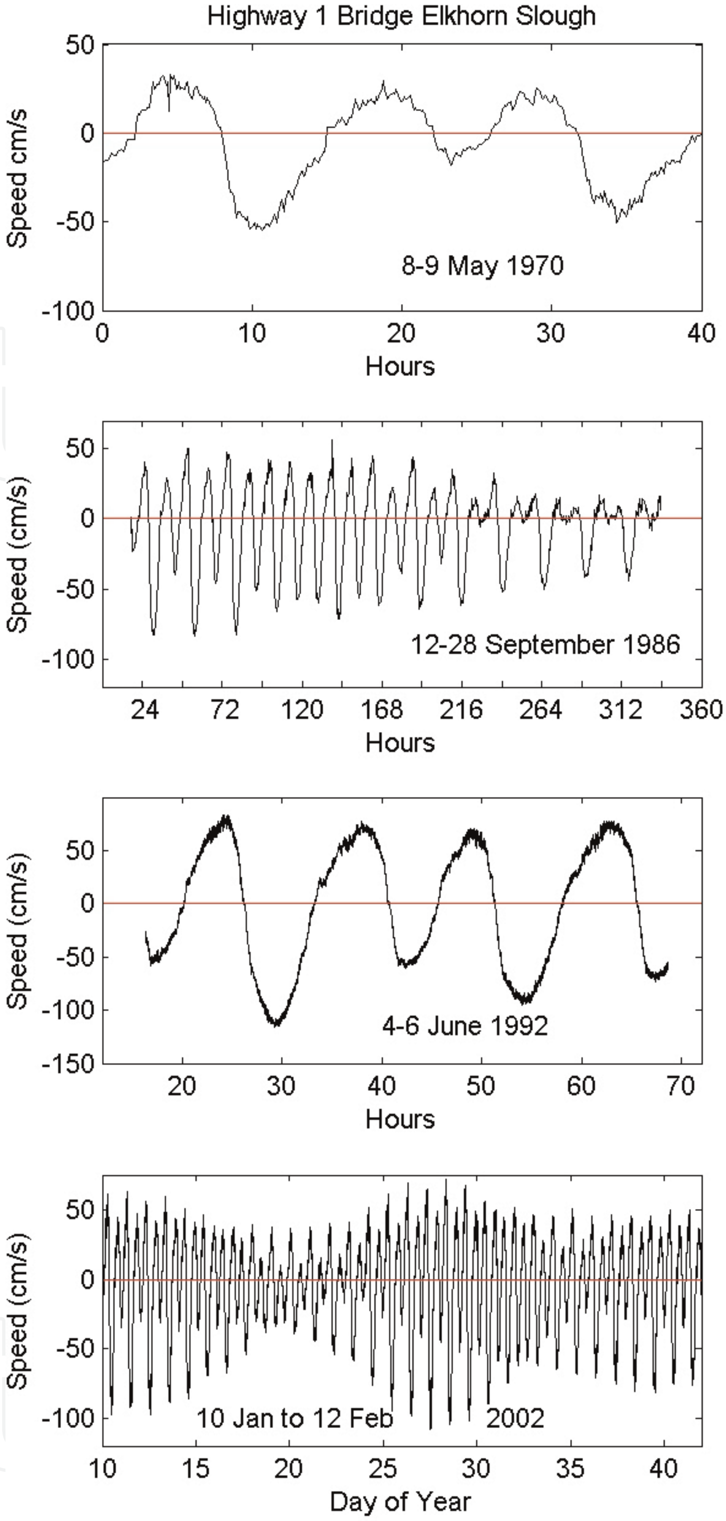


Figure 6.
Current measurements acquired in Elkhorn Slough at or near the Highway 1 Bridge (H1B). The top panel shows Clark's [14] first measurements in ES using a paper recording TSK current meter. In the second panel, Wong's [13] measurements are shown where an S4 meter suspended from the bridge was employed. In the third panel, our 1992 measurements duplicating Wong's method are shown, and finally, in the fourth or bottom panel, our S4 current measurements from January (2002) are shown using a bottom mounted current meter at 1.1 m above the bottom and 200 m east of the H1B.

friction velocity for the bottom, and used the friction velocity to estimate a thickness for the bottom boundary layer of 3.3 m, following Komar [17].

Vertical profiles constructed from current meter data collected closer to the H1B in February 1994 at different stages of the tide [4], indicate less vertical shear in the upper 5 m, but increased shear in the bottom boundary layer where the thickness of the layer itself appeared to be less than 2 m (not shown). These results taken near

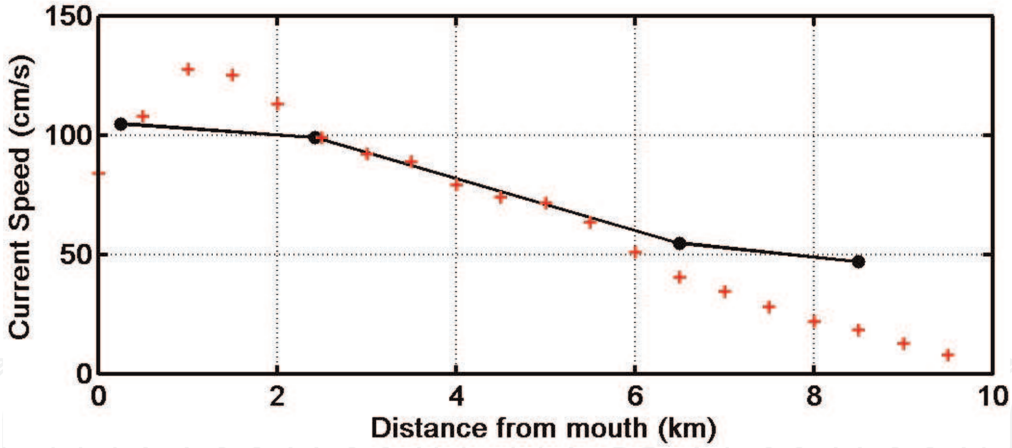


Figure 7.
The red crosses show main channel current speed measurements made near maximum ebb tide (taken from [6]). The solid black line shows results of the continuity model (redrawn from ***Figure 17****). Greatest changes are found inland of the Parsons Slough entrance.*

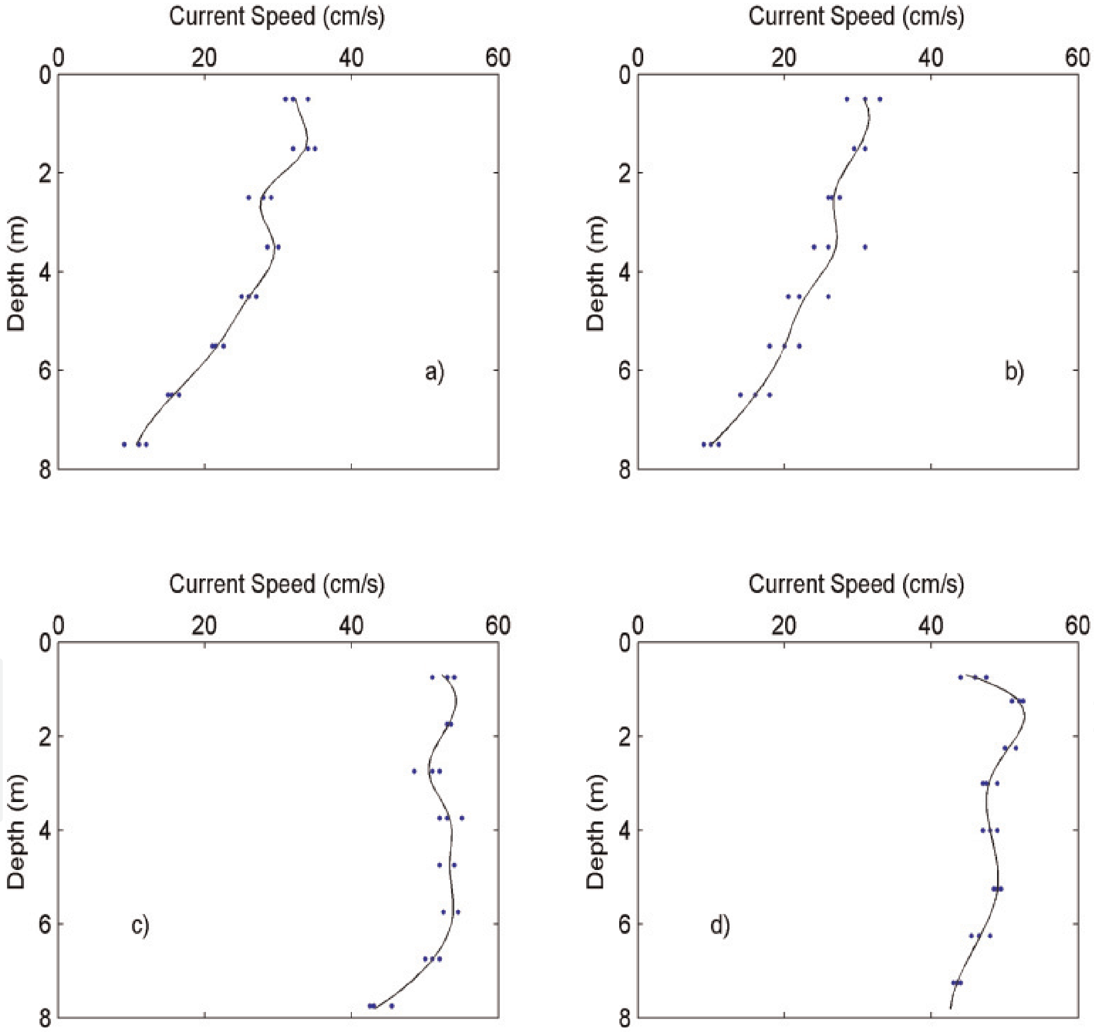


Figure 8.
Vertical current profiles in ES show deceasing current speed in the bottom boundary layer which extends up to 3 m above the bottom [13]. All times are PST + 8 h. (a) 20 May 1987, 22:30; (b) 30 May 1987, 23:00; (c) 9 April 1988, 07:30; and (d) 22 April 1988, 08:30.

the H1B where the primary channel is about 100 m wide, suggest that velocity shear near the bottom may be large enough to mix the entire water column above. Wong's and Malzone's results also demonstrate that tidal current speeds had increased during the 6-year interval between their observations.

Until 2002, no measurements of the tidal currents in and around Parsons Slough and the adjoining South Marsh had been made. This overlooked area contributes at least 30% to the tidal prism of ES, as we discuss in Section 6. As a result, ADP observations of the currents at the entrance of Parsons Slough were acquired on 20 November 2002 over a half-tidal cycle. The results are shown in **Figure 9**. We gauged the ebbing flow from the ESNERR area with nine transects made up of ten stations each spaced about 10 m apart across the 90 m wide channel. Tidal currents during the ebb cycle were acquired with speeds often in excess of 100 cm/s with a maximum speed of 112 cm/s observed during a 2-h period when the ebbing flow was most intense. Ebbing flow in this channel is deflected clockwise (looking in the direction of flow), and maximum speeds were always observed in the 5 m-deep channel close to the southern (right) bank consistent with centripetal acceleration. Horizontal shear near the south bank approached 10 cm/s/m.

Wong [13] observed a large time lag and reduced amplitude between the tide in the ES main channel and the tide in the ESNERR suggesting that the tide was restricted, indicative of tidal choking as encountered by Kjerfve and Knoppers [18] in a coastal lagoon along the U.S. East Coast. Our observations show that the principle tidal range in the ESNERR (**Table A1**) is virtually identical to that observed at the SP railroad trestle, and that HHW in the South Marsh lags that at the SP railroad trestle by only 20 min, not necessarily consistent with tidal choking. These results also indicate that relatively large volumes of water are exchanged between Parsons Slough and ES itself. Clearly, additional measurements of the tidal currents through the entrance of the Parsons Slough/South Marsh area are required to better understand this relatively new and overlooked portion of the Slough.

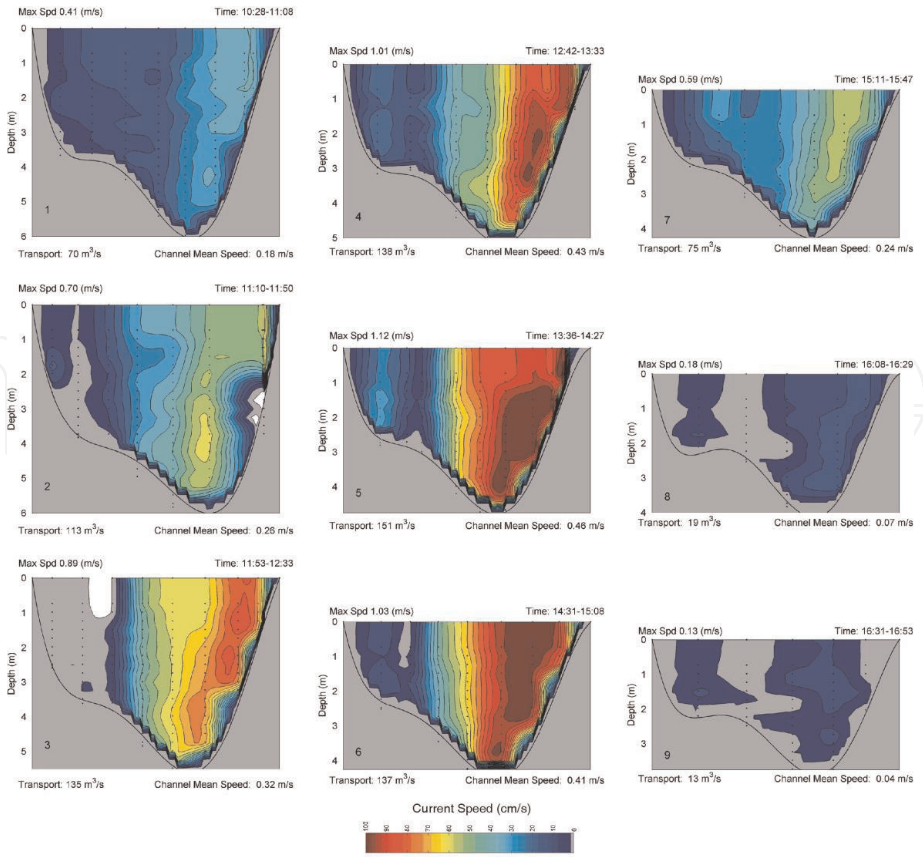


Figure 9.
ADP vertical sections of along-channel currents landward of the SP railroad trestle at the entrance to Parsons Slough. The south shore is on the right. These data were obtained through an ebb tidal cycle 20 November 2002. The integrated transport was 2.4 × 10^6 m^3.

Figure 10 shows a time series obtained from an S4 current meter deployed close to the location where the ADP measurements were acquired and during the same period. Vigorous tidal flows are observed that approach 100 cm/s during the ebb tide and values that approach 60 cm/s during the flood. Higher frequency oscillations superimposed on the tidal records are due to the natural seiche oscillations of Monterey Bay [16].

All of the current measurements made in Elkhorn Slough until 2003 were acquired at a single location in the cross-slough direction, usually in the main channel. Hence, cross-channel shear had not been measured, although its importance in making volume transport calculations was well recognized. Without some knowledge of cross-channel current variability, it is impossible to obtain even crude estimates of the water volume exchange between the Slough and the Bay over a complete tidal day.

To address this shortcoming and, at the same time, obtain a more reliable estimate of the tidal prism, we made a series of acoustic Doppler profiler (ADP) measurements (Pinkel [19]) at 10 locations across the channel, 250 m east of the H1B on 2 January 2003 (**Figures 1** and **11**). We held a small boat stationary using a mooring line stretched across the 190-m-wide channel of the Slough. The data were binned in 0.25 m increments and averaged for two minutes to reduce Doppler noise to less than 1 cm/s. The lack of vessel motion ensured that high quality data were acquired. We completed six cross-channel profiles during a 6.9-h flood tidal cycle with a tidal range of −0.43 to 1.19 m referenced to MLLW.

At the beginning of the flood cycle, the typically 10–20 cm/s flow was centered over the northern (right) and southern (left) channels (**Figure 11**). As the flow increased, core speeds of 50 cm/s were observed near the mid-channel shoal. At maximum flood, the ∼60 cm/s core remained near the center of the channel, and not in the 4.5 m deep channel located near the north bank. As the flow subsided, the current core moved toward the southern channel. The vertical sections in **Figure 11** show a core maximum

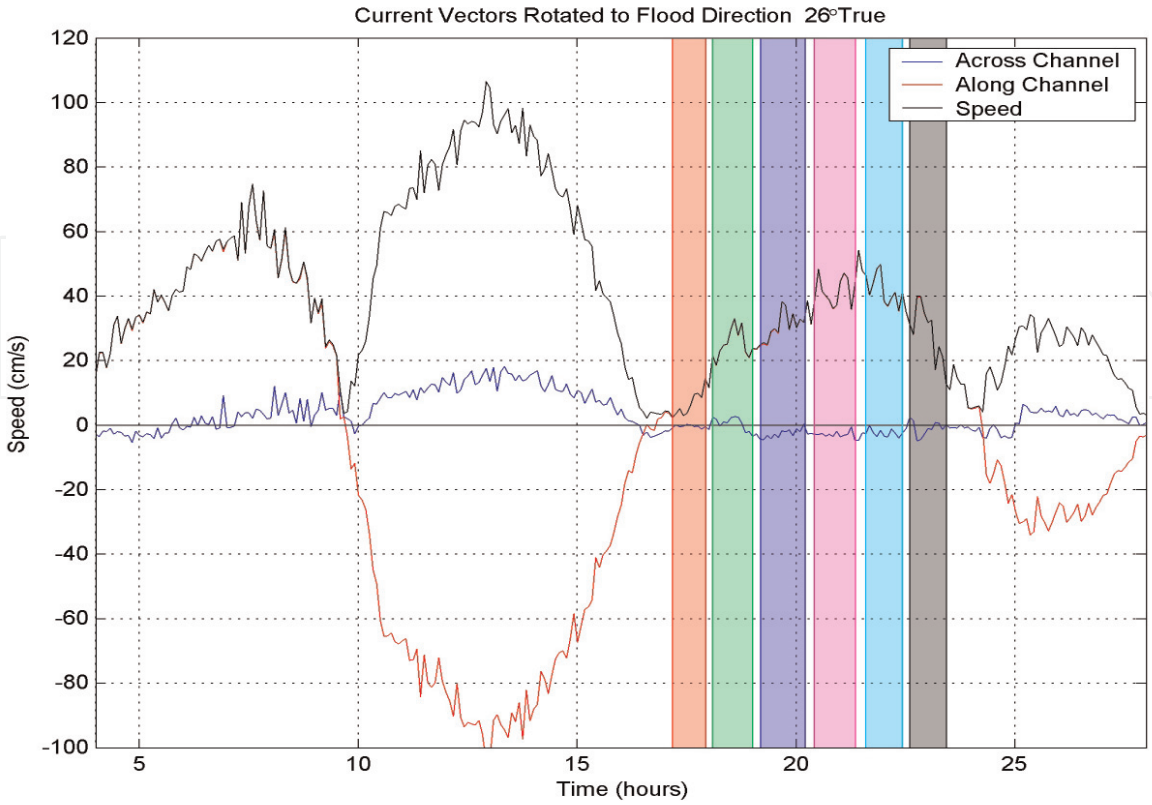


Figure 10.
S4 Current meter time series acquired on 2 January 2003 during the ADP cross sections shown in ***Figure 9****. Shown are the along-channel and cross-channel velocities as well as the total speeds. Note the large variability caused by seiche motions in Monterey Bay. The shaded bars show the periods of the six ADP cross sections.*

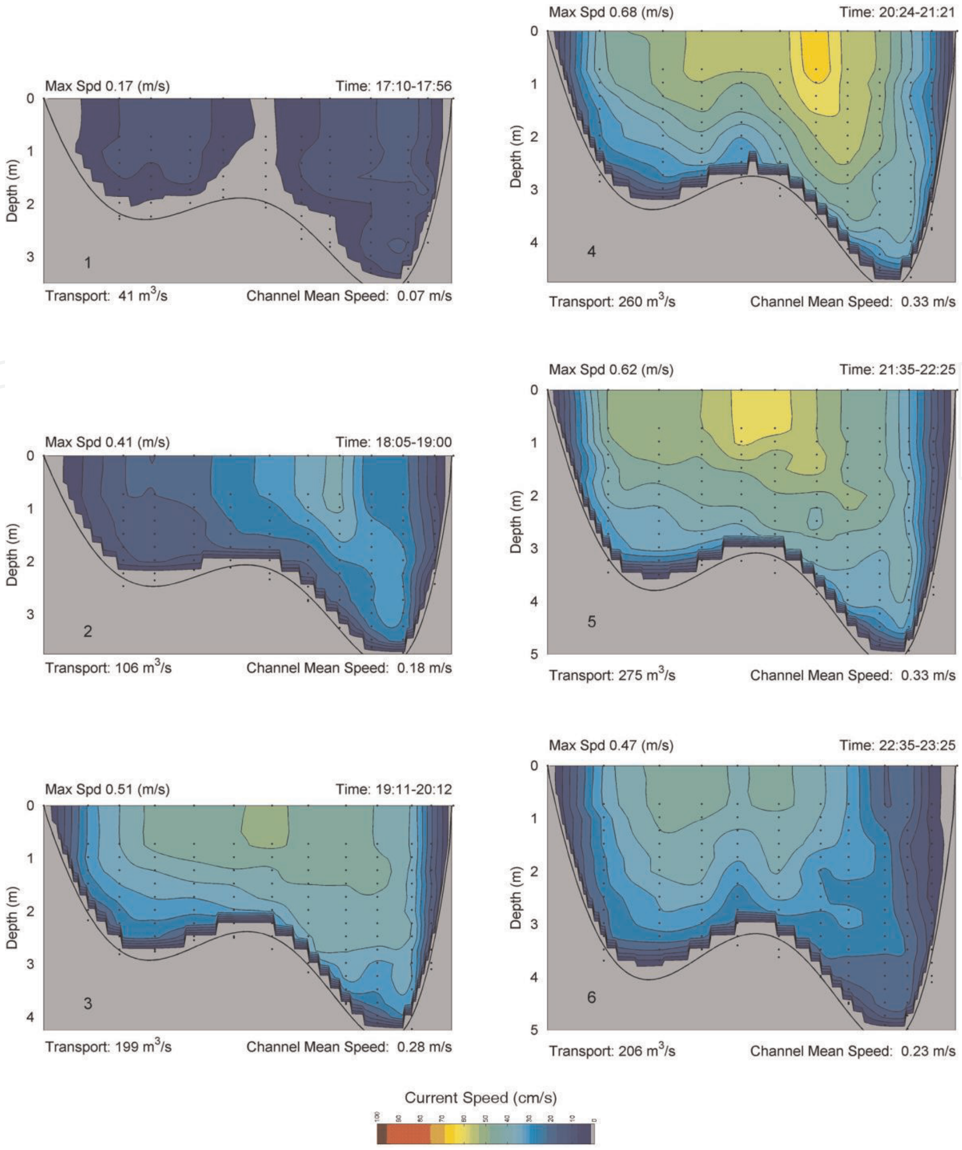


Figure 11.
ADP vertical sections of along-channel currents 250 m east of H1B show vertical and horizontal shear. The north shore is on the right. These data were obtained through a flood tide cycle on 2 January 2003. The integrated transport was $4.9 \times 10^6\ m^3$.

with near surface speeds of 62 cm/s about midway through the tidal cycle. Greatest horizontal shear occurs between the core and the north shore (right side of **Figure 11**) but does not exceed 2 cm/s/m. Flow at all depths was in the flooding direction. Because of the time required to acquire the data, these profiles were, of course, not synoptic.

4. Estimating the tidal prism

In this section, we address the tidal prism, a crucial factor that essentially determines the tidal currents. The tidal prism is the volume of water exchanged between a bay and its parent body of water over a tidal cycle. Also, the current regime of an estuary is strongly influenced by three factors: morphology, river flow, and tidal forcing. The ratio of river flow to tidal volume characterizes the physical transport of water and other materials through the system. Hence, one of the most important problems is to evaluate the total tidal transport through the Slough.

From the conservation of volume, the average current speed is directly related to the tidal prism and inversely related to the cross-sectional area. This may be expressed as

$$u_{max} = 4/3(rc/2)(A/S)(H/T), \tag{2}$$

giving the mid-channel maximum tidal current, u_{max}, in an enclosed basin [20]. A is the surface area of the basin inland from the main tidal channel, S is the cross-sectional area through which the current flows, H is the half-tidal range, and T is the half-tidal period. The factor 4/3 represents horizontal shear: the mid-channel current is about 1/3 greater than the cross-sectional mean current, and $rc/2$ relates the mean velocity for the half-tidal period to the maximum half-tidal velocity. Finally, the tidal prism corresponds to the volume AH.

Where the tides are mainly mixed diurnal and semidiurnal, the tidal prism is often taken to represent that volume of water associated with the change in elevation between MHHW and MLLW, but other tidal transitions could be used. To the extent that other sources and sinks of salt and fresh water contribute to the total volume of water in ES, the tidal prism will depart from the total water flux that is exchanged over a tidal cycle. The tidal prism can be estimated in several ways: by metering water fluxes through a vertical section on successive ebb and flood tides, by mapping sea level in the embayment at various tide levels, or by measuring the surface area and thickness of the discharge plume at an appropriate stage of the tide. The tidal prism for ES has been estimated using the first two methods with varying degrees of success, and the differences obtained from these methods provide at least one measure of the uncertainty in estimating this quantity.

During a 1956 survey of tidal inlets on the Pacific coast, Johnson [21] reported a tidal prism of 2.65×10^6 m^3 for ES, but the details of its estimation were not given. Smith [10] constructed a cross-sectional model for ES from which he estimated the tidal prism and the volume of slough waters at different tidal stages. He divided the Slough into three provinces: main channel, mud flats, and marsh. An idealized cross-section for ES, based on this classification scheme, identifies these provinces (**Figure 12**). He observed a predicted tide height of 0.88 m at the mud flat level and 1.45 m at the *Salicornia* marsh level. These heights are referenced to the tidal datum: 0.0 m at MLLW. Using Hansen's map (the basis for **Figure 1**), which was based on aerial photographs, he estimated the areas for each of these surfaces. The volumes obtained using this approach (i.e., the first method above) were then compared with volume transport estimates obtained using the second method, based on Clark's current meter measurements at the H1B. By adjusting the elevations of the mud flats and marsh, Smith showed reasonable agreement between the two methods. Smith's estimate of the tidal prism for HHW to LLW was 4.7×10^6 m^3. Smith used his results to estimate that the tidal prism extended 4.8 km into the Slough, assuming insignificant mixing between the ambient slough water and new

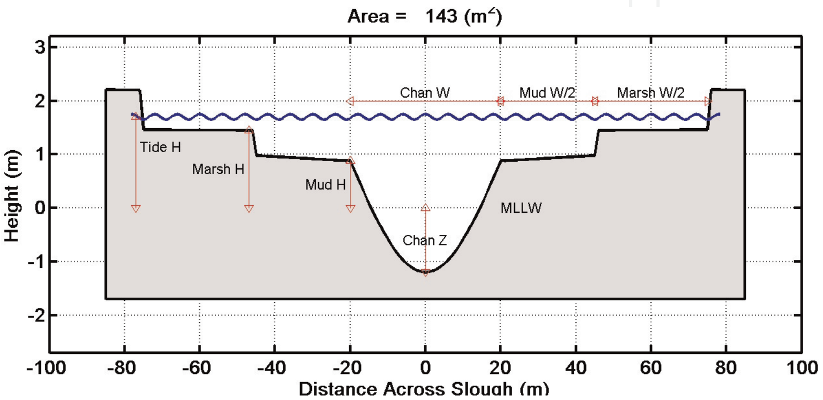


Figure 12.
Idealized cross section of ES. Mean sea level occurs near the edge of the mud flats, and the Salicornia *marsh is about 1.45 m above MLLW. Adapted from Smith [10]. Labeled quantities are used in Smith's volume continuity model of the currents.*

tidal volumes. Of historical note, a foam line produced by waters discharged from the PG&E power plant was often observed 4–5 km inland. Because coolant waters are now discharged directly into Monterey Bay, this foam line is no longer present. Continuing, in 1992, we applied Smith's model to a new aerial photograph that included the ESNERR South Marsh reclamation area, a province of the Slough that did not exist in 1974. The tidal prism from this work was estimated to be 6.2×10^6 m^3 (**Figure 13**).

Clark [14] used observations of u_{max} at the H1B and H/T to form a regression relationship whose intercept provides an estimate of the non-tidal flow, and whose slope provides a measure of A/S, the ratio of the flooded surface area to the cross-sectional area (**Figure 14**). This regression can also be used to estimate maximum tidal flows. Using comparisons of data from different periods, we can illustrate changes in the tidal flow and thus changes in the tidal prism. Using this approach, Wong found an intercept of about 10 cm/s indicating a net non-tidal flow directed out of the Slough. Because the values were relatively small, however, its significance is uncertain. Several factors most likely accounted for the net seaward flow according to Wong, including recent rainfall, agricultural runoff, and the discharge of cooling water into the lower slough from the PG&E power plant which operated the Slough outfall at that time.

U_{max} vs. H/T has been plotted for measurements that were acquired between 1971 and 1992 (**Figure 14**). The increase in regression slopes, based on a linear least squares fit to the data, indicates that maximum currents and thus the tidal prism (by an increase in the surface area, A) have increased by nearly a factor of two since 1971. At least two factors have contributed to increased tidal fluxes. The first was the restoration of formerly diked pasture which led to tidal flooding (**Table 1**). This sudden increase in surface area clearly contributed to Wong's [13] observed increase in tidal currents. However, erosion continues to enlarge the Slough at rates which have been documented on several occasions, e.g., [3–5], and this process continues to enhance the tidal flow, unabated.

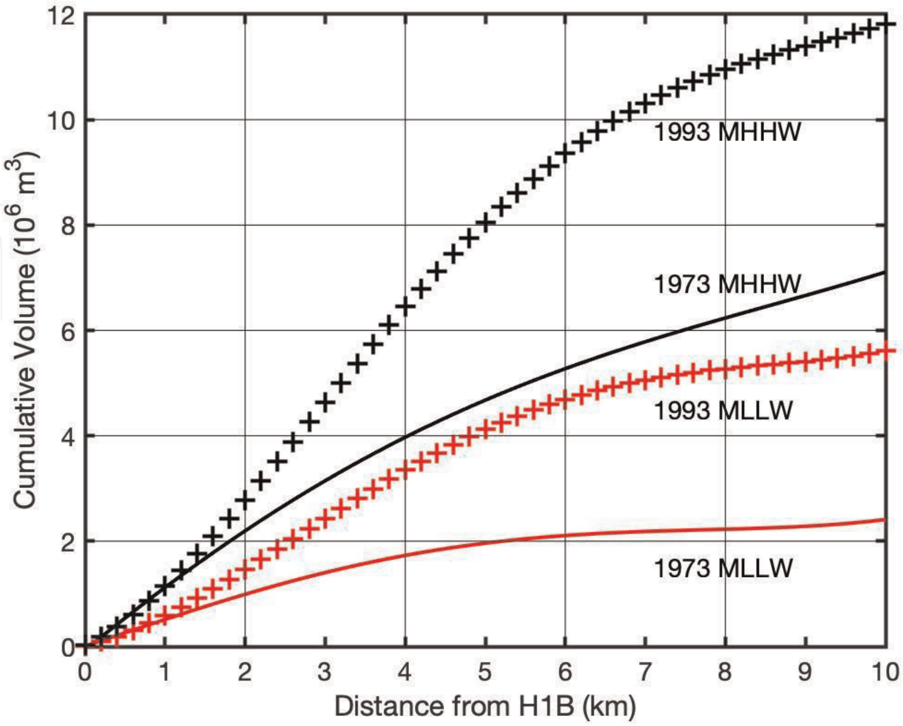


Figure 13.
Cumulative volume of water in ES at MLLW and MHHW from Smith [10] and as re-evaluated in 1993 from more recent aerial photographs. The volume between MLLW and MHHW is defined as the tidal prism, and estimated to be 4.7 × 10^6 m^3 in 1973 and 6.2 × 10^6 m^3 in 1993.

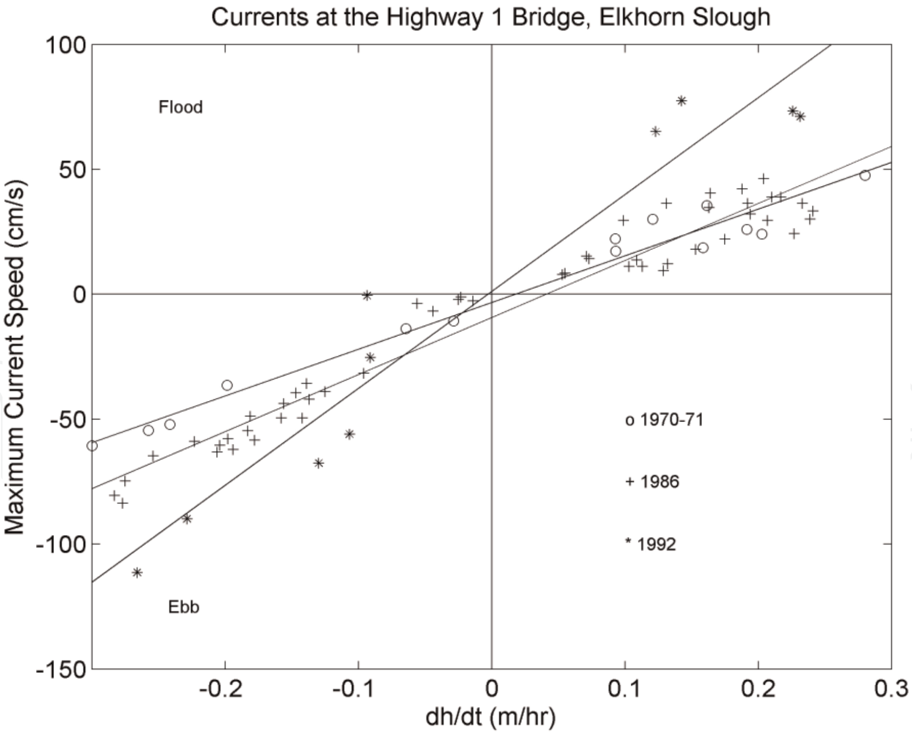


Figure 14.
Summary of current meter observations at the H1B. Y-axis values give smoothed along channel maximum speeds during a single half-tidal cycle. X-axis values are the ratios of the predicted or observed tidal range and half-tidal period (Eq. (2)). The symbols "o" represent Clark's [14] observations, "+" represent Wong's [13] measurements, and "" represent our 1992 data. The least squares regression lines show a systematic increase in time which reflects the increase in tidal prism.*

Location	**Date**	**Surface area**		**Tidal volume**	
		km^2	**%**	**1×10 m^3**	**%**
Parsons Slough and South Marsh	1984	1.8	20	1600	30
North Marsh	1985	0.6	7	53	1
Dolan Marsh	1986	0.3	3	130	2
Salt Ponds	1984–88	0.6	7	510	9
Bloom/Porter Marsh	1989	1	11	22	1

Table 1.
Recent additions to the Elkhorn Slough system that contribute to tidal volume increase and salt water incursion [6].

Our newer estimates of the tidal prism and total volume of water in ES also indicate major increases. The tidal prism from these more recent estimates is approximately 6.2×10^6 m^3 (**Figure 13**), a 32% increase in approximately 20 years. Interpreting recent changes to the water budget in ES is further complicated by the 1989 Loma Prieta earthquake which may have caused subsidence in the upper Slough. In addition to the restoration area discussed earlier, other additions have been made to ES which have increased its volume since the mid-1980s. Man-made alterations to the Slough and the approximate increases in surface area and volume caused by these changes are listed in **Table 1** [6]. The Parsons Slough area (**Figure 1**) is the major contributor to these increases. Also, the bottom depth at the entrance channel to Parsons Slough has increased from about 3 m in 1993 [6] to almost 5 m in August 2002 based on recent measurements.

In addition to water volume, current measurements in ES have been used to estimate several related parameters of interest including non-tidal contributions to the circulation, and the geometry of the Slough. Using Eq. (2), Clark estimated the ratio *A*/*S* for Elkhorn Slough. Then, using measurements of the cross-sectional area at the Highway 1 Bridge (**Figure 4**), he estimated the effective surface area of the Slough to be 1.5 and 1.1 × 10^6 m^2 at high and low tides, respectively. Using a similar approach, Wong [13] obtained estimates of the effective surface area, which were almost twice those obtained by Clark. According to Wong, the increase in surface area was caused primarily by restoration of Parsons Slough, and this lead to accelerated erosion through increased tidal action.

Wong also calculated the tidal volume using the product of the tidal height and the effective surface area. He compared his volume estimates with previous values from Smith [10] who estimated the volume as the product of water height and the areas that covered the channel, the mud flats, and the marsh. Wong found that the mean tidal prism had increased from slightly over 4 × 10^6 to almost 7 × 10^6 m^3, and that the total water volume at high tide had increased from approximately 9 × 10^6 to 10 × 10^6 m^3. Although the uncertainty associated with these estimates is high, they show a trend toward higher values which we believe is significant. Wong found that the mean diurnal tide flushes roughly 75% of the total volume of water from the Slough. Based on these results and the assumption that the remaining waters in the Slough do not mix with the incoming waters from Monterey Bay, he estimated that the tidal prism would extend almost 5 km inland from the mouth, only slightly larger than the value of 4.8 km obtained by Smith [10].

5. Physical properties and processes

5.1 Distribution of physical properties

Three distinct water types result from the physical processes in ES [10, 22]. The primary water type consists of offshore waters which enter the Slough with the flood tide and is characterized by cool temperatures ranging from 9 to 16°C, and salinities that range from slightly over 33 to almost 34 parts per thousand (ppt). The second water type consists of relatively fresh water mainly derived from agricultural runoff from the Old Salinas River channel through South Moss Landing Harbor. Because this water is of low salinity (<10 ppt), it is less dense than the waters from Monterey Bay and forms a thin surface layer. According to Smith [10], this water did not usually extend its influence beyond the South Harbor basin because pumping by the PG&E power plant was sufficient to maintain a net flow of offshore water into the harbor. As the pumping rates at the power plant have increased, the influence of fresh water entering the Slough from the South Harbor has correspondingly been reduced.

The third water type is formed in the upper Slough. During summer, this water is of higher salinity due to excess evaporation, and during winter, it is usually of lower salinity due to precipitation and runoff. Because this water type is formed in the upper Slough (5–10 km from the mouth), it may lie beyond the inland reach of the tidal prism and was found to have longer residence times than lower slough waters. Although the characteristics of this water type were well-documented from data collected in the 1970s, the properties and extent of this water type may have changed due to the increased tidal prism. For example, the reach of the tidal prism may extend further up the Slough today than it did 30 years ago. Because the volumes of water associated with the second and third water types are small in comparison to the offshore waters, their influence is primarily restricted to where they enter the Slough (South Moss Landing Harbor), or are formed (in the upper Slough). From measurements made over 25-h periods at the H1B and in the upper

Slough during 1971 and 1975, variations in temperature and salinity were highly correlated with tidal forcing at periods of 12 and 24 h [10, 22]. The ratio of the 12 and 24-h salinity amplitudes were similar to the corresponding tidal height amplitudes. The amplitudes for temperature and dissolved oxygen, however, showed a higher correlation at 24 h than at 12 h, suggesting that diurnal variations in heating/cooling and biological photosynthesis/respiration contributed significantly to these variations. In the lower slough (0 to ~5 km from the mouth), the influence of offshore waters decreased the effect of diurnal heating. As indicated earlier, tidal forcing causes the waters of ES to be well-mixed particularly along the main channel. Vertical profiles of temperature and salinity show little vertical stratification, except during periods of heavy rainfall in the winter [10].

The physical properties of ES vary on a seasonal basis. Seasonal changes in temperature and salinity in the upper slough are due to local influences, whereas seasonal changes in the lower Slough primarily reflect changes that occur in Monterey Bay. In **Figure 15**, temperature (upper panel) and salinity (lower panel) as a function of time and distance from the mouth are shown for the period July 1974 to May 1976. All sampling was done at high tide to remove the large tidal influences. The upper Slough is warmer than the lower Slough during the summer, and temperatures of 22°C have been observed. During winter, temperatures are cooler or about the same as offshore waters. In the upper Slough, temperatures during the winter as low as 12°C have been observed. A 14-month temperature time series (not shown) demonstrates that during the summer spring tide, pulses of relatively warm (>18°C) upper slough waters reach the lower Slough, and during winter, pulses of cool (<12°C) upper slough waters reach the lower Slough. ES, because of its direct connection to the bay, is also affected by El Nino conditions, and higher temperatures (~2 to 4°C) may be observed during these episodes.

In the upper Slough, salinity (**Figure 15**, lower panel) is affected by precipitation, runoff, and evaporation. During late winter, when precipitation is greatest, salinities as low as 17 ppt have been observed. During late summer, when evaporation is maximum, salinities in the upper slough have reached 37 ppt. Thus, the characteristics of the Slough can vary from typically estuarine during periods of heavy precipitation in the winter, to an evaporative basin during the summer. We note that due to the occurrence of recent dry years along the central California coast, characterizing ES as typically estuarine during the winter may be less appropriate than characterizing the upper Slough as an evaporative basin during the summer.

Finally, Smith [10] concluded that the area above the tidal prism, i.e., the upper Slough, was essentially isolated from offshore influence in the lower Slough, and tended to develop a separate physical identity. Although increased tidal action might reduce the contrast between upper and lower slough water masses, recent work on phytoplankton community structure in ES shows that these waters have retained their separate identities (N. Welschmeyer, personal communication).

5.2 Diffusion and mixing

The tides contribute to horizontal as well as vertical mixing in ES. The effects of horizontal mixing can be quantified by estimating the coefficient of eddy diffusivity, K_X. The magnitude of the along-channel diffusivity has been variously estimated using both physical and chemical parameters. When salinity is used to estimate K_X, both fresh water discharge and evaporative fluxes will affect estimates of K_X, if they are significant. Smith [10] estimated eddy diffusivities for ES using salinity data acquired during June and October of 1971, periods with no precipitation. Smith used the one-dimensional advection-diffusion equation balancing the seaward eddy diffusive salt flux with the landward advective salt flux to produce

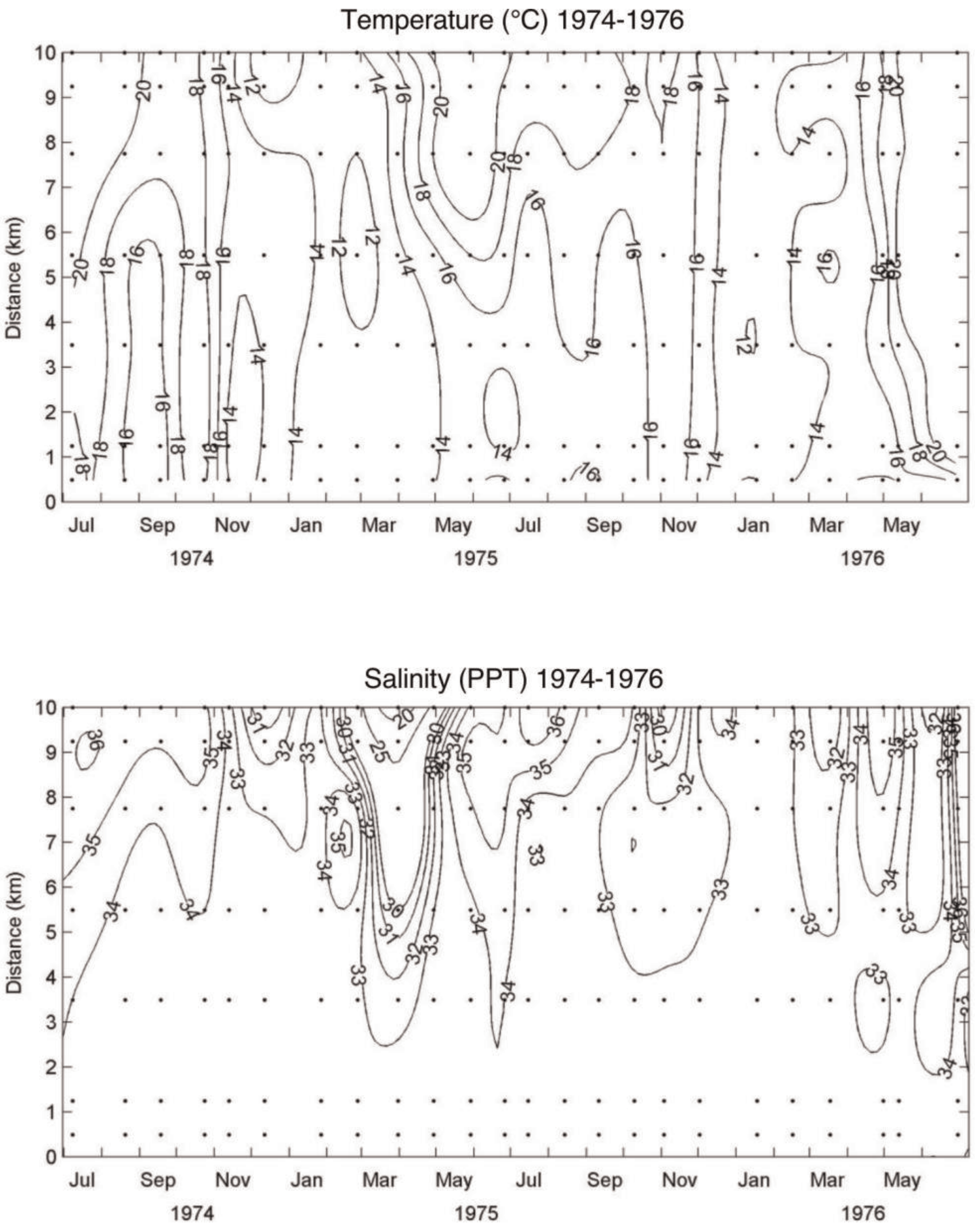


Figure 15.
Seasonal variation in temperature (upper panel) and salinity (lower panel) in ES between 1974 and 1976 (redrawn from Broenkow [22]).

the local time rate of change in salinity. He calculated the non-tidal landward velocity from observed evaporation rates from a nearby reservoir. From his results, the mean diffusivities for the summer can represented by a second-order polynomial as

$$\ln\left(K_X \times 10^{-3}\right) = 0.095 - 1.65X + 9.00X^2, \tag{3}$$

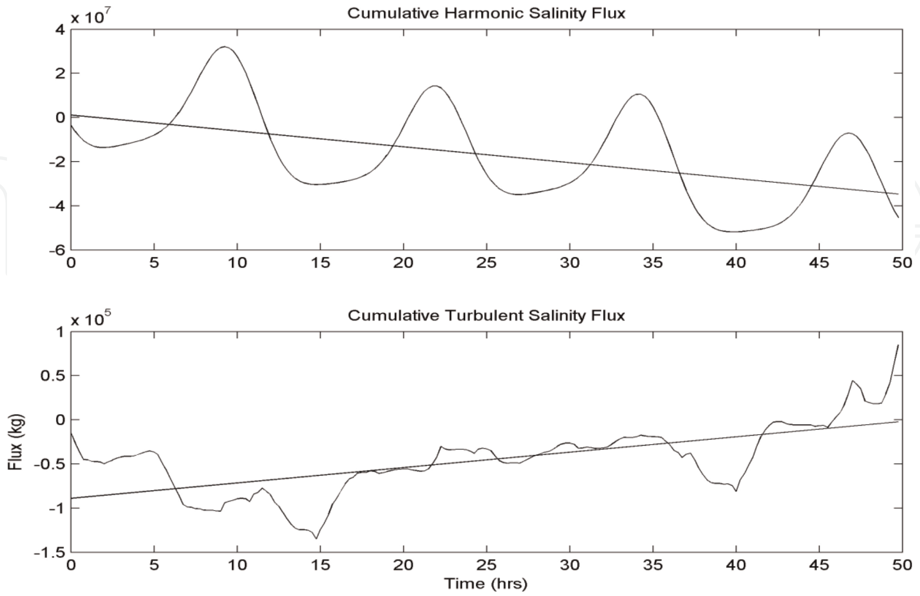
where K_X is the eddy diffusivity (m^2/s) and X is distance from the mouth (km). Smith's table correctly sets the eddy diffusivity at 1 km from the mouth as infinite which is the case when lower slough waters exit the Slough and do not return. Monthly mean K_X values, obtained over the length of the Slough, decreased by almost two orders of magnitude from the lower Slough ($\sim 500 \times 10^3$ cm^2/s) to the head of the Slough ($\sim 6 \times 10^3$ cm^2/s). These values from Smith are also in good agreement with similar estimates of K_X obtained in other well-mixed estuaries [23]. The relatively high values of eddy diffusivity in the lower Slough demonstrate the importance of the tides as the dominant forcing mechanism. Because similar results were obtained in successive months, Smith concluded that a balance between evaporation and tidal diffusion provided a satisfactory explanation for the increase in salinity that was observed.

Reilly [24] calculated Reynolds fluxes to estimate eddy diffusivity in the lower Slough. In September 1975, he measured currents and salinity in the main channel at two depths, 1 m above the bottom and 1 m below the surface, based on a 50-hour time series acquired 3 km inland from the H1B. Reilly decomposed observations of salinity and the along-channel component of velocity into mean, periodic, and turbulent components, following Hansen [25]. He then obtained estimates of the salt transport by taking the product of the various components of salinity and velocity, with the cross-sectional area of the channel at the location where the measurements were acquired. Cumulative fluxes of salinity for the periodic (i.e., tidal) and fluctuating (i.e., turbulent) components are shown in **Figure 16**.

The periodic Reynolds fluxes (upper panel) promote a seaward salt flux, whereas the turbulent Reynolds fluxes (lower panel) promote a landward flux. We note that Reilly's estimates of eddy diffusivity compare favorably with those obtained by Smith. However, because Smith's analysis was based on an integral taken over the summer season, his method is to be preferred.

5.3 Residence time

The flushing or residence time of slough waters is of considerable importance regarding the fate of pollutants and other dissolved materials. As indicated earlier, most of the water that leaves the Slough on the outgoing tide does not re-enter on the incoming tide. Thus, the residence time for waters in the lower Slough is short, on the order of a tidal cycle or a few cycles at most. However, the degree to which waters from the upper slough mix with waters from the lower slough is not


Cumulative Harmonic Salinity Flux

Cumulative Turbulent Salinity Flux

Figure 16.
Cumulative salinity fluxes in ES from Reilly's Reynolds flux calculations are shown [24]. Observations were made over a 50-hour period that were acquired near the "Dairies". Upper panel shows the harmonic salt flux U_pS_pA*, where* U_p *and* S_p *amplitudes are computed from harmonic analysis of the* M_2 *and* K_1 *tidal periods. Lower panel shows turbulent salt flux* $U'S'A$*, where* U' *and* S' *are turbulent residuals following harmonic analysis. The trend lines indicate a seaward tidal flux and a landward turbulent flux. Note the different scales used to represent the fluxes.*

well-established and is almost certainly seasonally dependent. During summer, the waters in the upper Slough become somewhat isolated from the waters in the lower Slough. In winter, during periods of precipitation, inflows from connecting tributaries and runoff enter the Slough and circulate into the lower Slough where they become part of the tidal prism. Smith [10] estimated that this sequence of events probably took upwards of a month in 1970, following a period of major precipitation. He also used his previously-derived eddy diffusivities (Section 5) to obtain estimates of residence times of about 30 days in the upper Slough during summer.

Because the tidal prism has increased since Smith's work, residence times in the upper slough are likely to have decreased. Near-surface temperature measurements taken across the channel between Parsons Slough and Kirby Park in July 2002 indicate that in areas outside the main channel, temperatures are slightly higher along the banks. This suggests that circulation in wider portions of the Slough may be weaker than flow along the main channel.

6. Discussion

6.1 Tidal asymmetry

The fact that higher high water always precedes lower low water in Elkhorn Slough is one reason that ebb current speeds exceed flood current speeds. The advance of the flood tide and the retreat of the ebb tide are retarded by frictional effects. The mud flats and *Salicornia* marsh areas are large compared to the channel area and they contribute to these frictional effects and thus to the retardation. The retardation, however, is apparently greater on the incoming tide than it is on the outgoing tide and we will say more about this in what follows. According to Wong [13], this retardation contributes to the tidal asymmetry where the duration of the ebb tide is reduced relative to that of the flood tide.

Because the asymmetry between flood and ebb currents is cumulative, the effect on tidal height becomes more pronounced towards the head of the Slough. Distortion of the incoming tidal wave also occurs as a result of the frictional effects associated with the bottom and lateral boundaries and is compounded by the effects of decreasing bottom depth, narrowness of the entrance, and decrease in channel cross section toward the head of the Slough. This distortion produces a number of new shallow water tidal constituents including overtides and compound tides. Overtides arise as the incoming tidal wave runs into shallow water where the trough is retarded more than the crest due to bottom friction and thus the wave loses its simple harmonic form [26]. These frictional effects lead to the production of compound tides which also occur in ES. The existence of overtides and compound tides is clearly evident from the tidal records at Kirby Park, approximately 7 km from the harbor entrance. Finally, because tidal heights and currents have often been found to be roughly 90° out of phase, the tides in ES may approximate a standing wave system.

6.2 Generation of overtides and compound tides

Observations presented in Section 3 revealed the presence of higher frequency tidal constituents in ES. Because of tidal transformations, the tidal regime in ES differs from that of Monterey Bay. Tidal periods of 8.4, 8.3, 8.2, 6.2, and 4.1 h were found that correspond to the $2MK_3$, M_3, MK_3, M_4, and M_6 tidal constituents, respectively. The 8.3-h M_3 lunar terdiurnal tide is not classified as a shallow water constituent [26] and may originate outside the Slough. The 6.2-h M_4 and the 4.1-h

M_6 constituents are overtides that represent the first harmonic of the primary M_2 tide, and the sixth-diurnal tides, respectively. The $2MK_3$ (8.4 h) and the MK_3 (8.2 h) constituents, or terdiurnal components, are compound tides that correspond to the sums ($MK_3 = M_2 + K_1$), or differences ($2MK_3 = 2M_2 - K_1$) of the primary M_2 and K_1 constituents. We find the amplitudes of these constituents to increase monotonically with distance inland. However, the amplitudes of the primary constituents do not decrease significantly with distance up the Slough. M2 increases by 40 mm and K1 is nearly constant. That the M2 amplitude inside ESNERR is only slightly smaller than at the entrance to Parsons Slough clearly suggests that the return flow during ebb at this location is not at the present time choked or partially choked [18].

According to Wong [13] and Clark [14], the time of maximum ebb flow occurred slightly later than or midway through the ebb tide, while the time of maximum flood tide occurs slightly later than midway through the flood tide, towards the time of high water. They attributed this delay during the flood tide to the volume of water that must be transported across the tidal flats which may also contribute to the observed overtides in ES [30]. We have examined this process using a month-long current record from January 2002 (**Figure 6**, bottom panel). From a cross-correlation analysis between the mean corrected pressure (i.e., tidal elevation) and the along-channel current speed, we found that the maximum lag was 3.24 h, which is very close to quadrature for the dominant M_2 tide (12.42 h). Harmonic analysis of these data showed that the phase angle between the dominant semidiurnal and diurnal harmonic constituents for tidal elevation and current speed (M_2 and K_1) were 84° and 88°, respectively, consistent with Clark and Wong's standing wave description of the tidal regime in ES.

Considerable research has been conducted on tidal transformations in well-mixed estuaries, primarily along the U.S. East Coast [27–30]. In many respects, their results should be generally applicable to any well-mixed estuary. However, there is one important difference between the tides along the East Coast and West Coast of the U.S. Along the East Coast, they are semidiurnal, whereas along the West Coast, they are mixed, mainly semidiurnal, and the greatest tidal range occurs from higher high water to lower low water. This characteristic produces initial conditions for tides entering shallow embayments along the West Coast that clearly favor ebb domination prior to any tidal transformation. Once the tide has entered the estuary, shallow water effects produce overtides and compound tides which experience down-channel evolution in amplitude and remain phase-locked to the parent tides throughout the estuary [29]. According to Parker [31], the increase in amplitude of the overtides and compound tides with distance up the Slough occurs at the expense of the fundamental constituents to which they are harmonically related through the nonlinear transfer of momentum and energy. However, we note that our results are not necessarily consistent with Parker's explanation since we found that although the amplitudes of the overtides and compound tides did increase with distance inland, the amplitudes of the primary constituents did not decrease significantly over the same distance.

According to Boon and Byrne [32], distortion of the incoming tide leads to temporal asymmetries in the rise and fall of the surface tide. These, in turn, result in temporal and amplitude asymmetries in the velocity field. Further, these asymmetries cause estuaries to be either flood- or ebb-dominant. According to Friedrichs and Aubrey [30], non-linear tidal distortion has two principal causes, frictional interaction between the tide and the channel bottom which leads to shorter flood tides, and intertidal storage which causes the ebb tides to be shorter. Based on the work of Friedrichs and Aubrey, intertidal storage due to the presence of the extensive *Salicornia* marsh and mud flats in ES may be a principal factor that contributes to the dominance of the ebb tide in ES.

Basic mathematics can be used to illustrate how certain estuarine tidal transformations arise. First, we show one simple approach that illustrates how both overtides and compound tides can be generated. We assume that shallow-water effects are proportional to the square (or higher power) of tidal sea level, following Pugh [33]. Take two primary constituents such as M_2 and K_1, whose frequencies are ω_2 and ω_1, form their sum, and square the result,

$$\begin{aligned}[\eta_{M2}\cos 2\omega_2 t + \eta_{K1}\cos 2\omega_1 t]^2 = 1/2\left(\eta_{M2}{}^2 + \eta_{K1}{}^2\right) + 1/2\left(\eta_{M2}{}^2\right)\cos 4\omega_2 t \\ + 1/2\left(\eta_{K1}{}^2\right)\cos 4\omega_1 t + \eta_{M2}\eta_{K1}\cos 2(\omega_1 + \omega_2)t \\ + \eta_{M2}\eta_{K1}\cos 2(\omega_1 - \omega_2)t, \end{aligned} \tag{4}$$

where η is the free surface elevation, t is time, $\omega = 2\pi/T$, and T is the constituent period. This expansion contains additional harmonics with frequencies $4\omega_2$ and $4\omega_1$ which represent the overtides.

The last two terms contain the sum and difference frequencies for ω_2 and ω_1 which represent the compound tides. Also, the first term contains the sum, $1/2(\eta_{M2}{}^2 + \eta_{K1}{}^2)$, which corresponds to an increase in mean sea level. Observations in many estuaries have shown an increase in mean sea level for the incoming tide as the head of the estuary is approached [33]. Closer at hand, the NOS tide survey in 1976 [12] shows that mean sea level may increase by as much as 30 mm (0.1 ft) between the H1B and Hudson's Landing.

To illustrate an alternate approach for the generation of overtides, we employ the one-dimensional equations of motion and continuity to illustrate how the relevant hydrodynamics apply to tidal transformations. For the along-channel ("x") momentum equation, we have the following,

$$\frac{\partial u}{\partial t} + u\frac{\partial u}{\partial x} = -g\frac{\partial \eta}{\partial x} \tag{5}$$

where x, t, η, and g are distance along the x-axis, time, surface elevation, and the acceleration of gravity, respectively, and u is the along-channel current velocity. The governing equation for continuity which employs the same variables with the addition of H, the bottom depth, can be expressed as,

$$(H + \eta)\ \frac{\partial u}{\partial x} + u\frac{\partial \eta}{\partial x} = -\partial\eta/\partial t. \tag{6}$$

This equation has been modified slightly to take into account the geometry that we often apply to estuaries where the rates of mass transport into and out of a vertical column are equated [34]. These two simultaneous nonlinear differential equations can be solved, as shown in Officer [34], to obtain a solution for $\eta(x,t)$, of the following form,

$$\eta(x,t) = \eta_o\ \cos(kx + \omega t) - \left(3gk\eta_o{}^2\omega/4c^3\right)\ \mathrm{x}\ \sin\{2(kx + \omega t)\} \tag{7}$$

where only terms of order $\eta_o{}^2$ or lower have been retained. η_o is the tidal amplitude at an arbitrary point of origin for x and t, and k is the wave number, $2\pi/L$, where L is the shallow water wavelength, g is the acceleration of gravity, and $c = gH$, the shallow water wave velocity. The second term in (7) captures the essence of overtide generation where $\eta(x,t)$ is seen to be directly proportional to x, the distance in the up-estuary direction. As x increases, H generally decreases which also contributes to increasing amplitude as the tidal wave propagates inland. The increase in $\eta(x,t)$ clearly reflects the increasing distortion experienced by the incoming tidal wave as it propagates in the up-slough direction. Finally, our tidal observations presented in **Table A1** show a monotonic increase in the M_4 and M_6 overtides and in the MK_3, $2MK_3$, and SO_3 compound tides between the H1B and the head of ES.

With respect to the tides in estuaries, the magnitude and phase of each constituent reflect the hydrodynamic processes that are important. For estuaries where the M_2 tide is dominant, its first harmonic, the M_4 tide, is usually the dominant overtide, as in ES. The phase relationship between the M_2 and M_4 components determines the direction and magnitude of the tidal asymmetry [29]. Ebb-dominance is further enhanced by inefficient water exchange around high water in estuaries with relatively deep channels and extensive intertidal water storage. Low water velocities in intertidal marshes and mud flats cause the high tide to propagate slower than the low tide [30]. At low tide, the marshes and flats are empty while the channels serve to accelerate the flow in the down-channel direction. The extensive mud flats and marshes in ES contribute to weak or sluggish water exchange around the time of high tide, as indicated by the results of Wong [13].

To expand on this topic slightly, we refer back to the idealized cross-section for ES (**Figure 12**). One aspect of this model cross-section is that the mud flats slope downward toward the main channel. We expect these slopes to retard rising water levels on the incoming tide, and accelerate flow back into the main channel on the return tide. This mechanism should contribute to the asymmetry of the tides in ES depending on the magnitude of the slopes and their extent, and, most importantly, helps to explain why the incoming tide experiences greater retardation than the outgoing tide. Thus, intertidal water storage due to sloping muds flats may also be a significant factor that contributes to ebb-dominance in ES.

6.3 Industrial effects

The original PG&E power plant at Moss Landing began operations in 1952 [1]. Intake cooling for seven generators was supplied by water from Moss Landing Harbor (**Figure 2**). Of the original generators two discharged their 40% effluent through a pipe into Monterey Bay just south of the harbor entrance about 200 m offshore. Five of the original generators discharged about 60% of the heated effluent approximately 0.5 km inland from the H1B; however, this was stopped in 1995 when these units were retired. In 1998, Duke Energy assumed operation of the power plant and has upgraded two of the original units and has added two new turbine generators. The mean temperature of the effluent is approximately 11°C higher than the intake temperature. Intake rates increased from the original design rate of 1.4×10^3 m^3/min, to almost 3.0×10^3 m^3/min circa 1980 [11]. Presently, the average and maximum expected intake flow rates for the original units are approximately 1.8 and 2.3×10^3 m^3/min. The two new generators add almost 1.0×10^3 m^3/min to the flow. The effluent is discharged directly at the head of Monterey Submarine Canyon through the existing underground piping.

The power plant intake provides a continuous landward flow independent of the tide. It has no effect on the exchange of waters in ES itself unlike the previous situation through the now abandoned slough outfall. However, it is still interesting to compare the power plant coolant water flow with the tidal prism of ES. For an intake rate of 3.0×10^3 m^3/min, the total volume over a half tidal day (12.4 h) is 2.2×10^6 m^3. If we use our estimate of the tidal prism of 6.2×10^6 m^3 (1993), then the coolant water flow represents 35% of the ES tidal prism. Although the plant intake and discharge has no effect on the Slough, it dominates the water budget of

Moss Landing Harbor. The present intake rate through the harbor entrance with a cross-sectional area of 300 m^2, decreases the ebb current speed by roughly 15 cm/s or about 10% of the observed maximum ebb current speeds under the H1B.

6.4 Tidal prism revisited

To put the various tidal transport results in perspective and because of the continuing physical changes in the channel, mud flats and marsh, including the addition of the restoration area, we have updated Smith's model based on more recent data acquired during 2002 and 2003. ADP current measurements were also acquired as part of this data collection effort. We have used the following approach to obtain updated estimates of the tidal prism for Parsons Slough, for the location near the H1B, and finally, for the entire Slough. Additional details concerning the methods and results can be found in Broenkow and Breaker [9].

Smith's parameterized cross-section model was employed together with a recent bathymetric map from Malzone [4] in conjunction with the volume continuity equation given earlier (Eq. (2)) to estimate the mid-channel tidal currents and the tidal prism. Using the model with a U-shaped channel, sloping mud flats, and level *Salicornia* marsh, we first calculated the updated cross-sectional area. By integrating the cross-sectional area along the length of the Slough, we then obtained a new water volume. Finally, by integrating the channel, mud flat and marsh widths, we obtained updated surface areas. These values were then used in Eq. (2) to estimate the volume transports during a half tidal cycle through the seaward-most sections of Elkhorn Slough and Parsons Slough. The values entering the model were subsequently adjusted within reasonable limits given the uncertainties involved to produce volume transports that were generally consistent with the recently-acquired ADP current measurements.

The computed mid-channel current speeds are shown in **Figure 17a** and indicate values consistently in excess of 150 cm/s over the first 2 km from the entrance of ES. The tidal prism for Parsons Slough was estimated to be 2.4×10^6 m^3 and that for the H1B to be 4.9×10^6 m^3. The results for the entire Slough produce a somewhat larger tidal prism than those predicted by the earlier results (**Figure 17b**). The maximum tidal prism, i.e., the difference between the cumulative high and low tidal volumes, is approximately 7.6×10^6 m^3 and can be inferred directly from **Figure 17b**. The contribution to the cumulative volume from Parsons Slough corresponds to the step increase observed in **Figure 17b** between 2 and 4 km from the entrance to ES. The model estimate for Parsons Slough itself represents over 30% of the tidal prism for the entire Slough.

6.5 Classification

It is difficult to compare ES with some of the more well-known estuaries along the West Coast, such as Puget Sound, the Columbia River, and San Francisco Bay, because its characteristics differ significantly, particularly its spatial scales and recent evolutionary development. One estuary that is similar in some respects, however, is Morro Bay, located approximately 150 km south of ES just north of Pt. Conception. Morro Bay is a bar-built estuary or barrier-lagoon [35]. Like ES, it has a well-defined entrance channel that feeds into the bay itself with a bay interior that is essentially marine-dominated. In summer, salinities increase by several parts per thousand (ppt) inside the bay due to excess evaporation. Although the tidal prism for ES and Morro Bay are similar, the surface area of Morro Bay is almost twice that of ES [21]. Perhaps the largest difference between these estuaries is that while ES is growing rapidly, Morro Bay appears to be filling gradually [36].

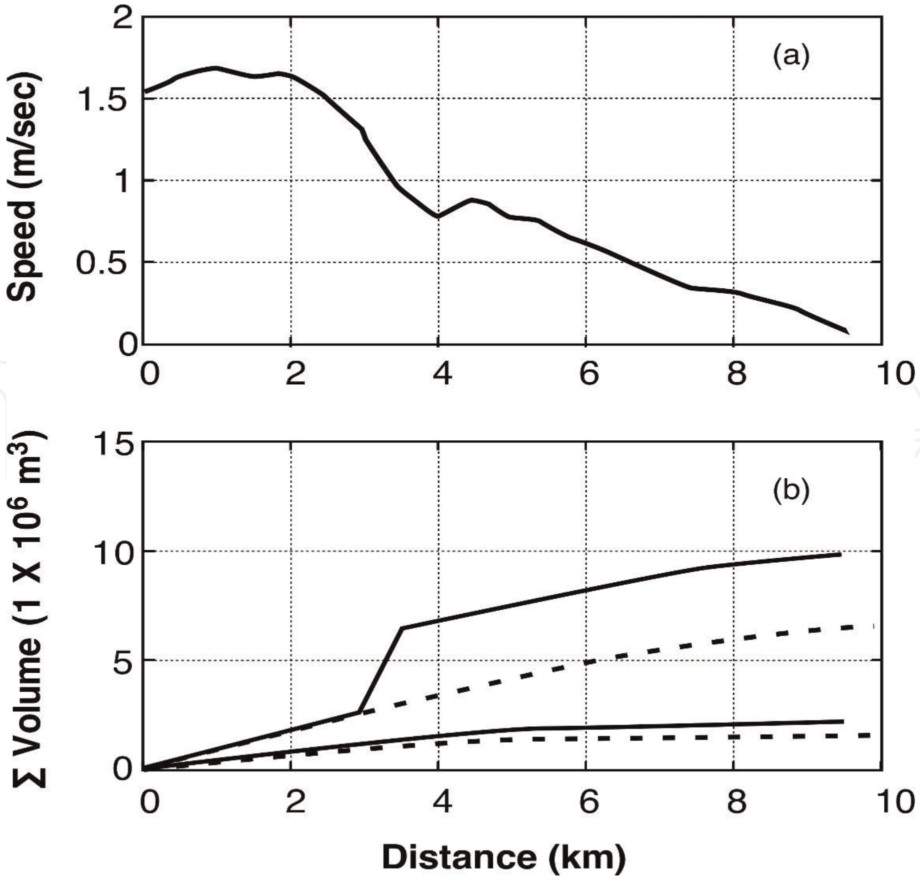


Figure 17.
The upper panel (a) shows the computed mid-channel current speed using the continuity model. The lower panel (b) shows the cumulative tidal volume at given stages of the tide. The tidal prism is the difference between the high and low tide cumulative volumes. The dotted line represents the results from Smith's [10] model.

Formally, a slough is a swamp-like region, inlet, or backwater. According to most accounts, e.g., [1], ES certainly qualified for the name prior to 1946 before the entrance to Moss Landing Harbor was created. However, now the name is inappropriate since its character has changed dramatically through direct tidal exchange between ES and Monterey Bay. However, some of the tributaries that feed into ES are still sloughs in the formal sense. ES appears to be unique in this region because it continues to expand, whereas many other inlets/estuaries appear to be filling in over time. Various terms have been used to describe Elkhorn Slough such as a "seasonal estuary" or as a "tidal embayment." Both terms are appropriate. Because of vigorous tidal forcing, and because density stratification from fresh water discharge occurs only in winter, vertical mixing is intense especially at constrictions such as the H1B and the Parsons Slough railroad trestle. ES is nearly vertically homogeneous in the main channels where most observations have been made. Although ES is vertically well-mixed, it is not necessarily laterally homogeneous. Although the data are few, the observations of temperature and salinity in the Slough, particularly in the wider portions, indicate cross-slough gradients that are consistent with increased warming and higher salinities in these shallower regions. During the summer, ES is a negative estuary because excess evaporation produces higher salinities in the upper slough leading to decreasing salinities toward the mouth. Values greater than 37 ppt have been observed leading to what some authors call "hypersaline" conditions where salinities in this case were higher than salinities in offshore waters. During winter when increased precipitation often occurs, fresh water fluxes increase with additional input from the adjoining sloughs, causing ES to resemble a true estuary with salinities increasing toward the Bay.

7. Conclusions

Elkhorn Slough is unique: unlike estuaries which have evolved over hundreds or thousands of years, this estuary was transformed from a sluggish backwater in 1946 when Moss Landing Harbor was formed, to a vigorous, rapidly growing estuary that has become a habitat for many fish, marine, mammals and sea birds. This transformation has taken place in less than 50 years and continues today.

ES is an ebb-dominated embayment which produces asymmetric tides. The ebb tidal currents are stronger than the flood currents and the duration of the transition from high to low tides is shorter than the reverse. The presence of extensive mudflats and *Salicornia* marsh distorts the incoming tide through water storage on the mudflats and through increased friction. Thus, the mud flats slope downward may be an important factor in contributing to the tidal asymmetry in ES. The distortion experienced by the incoming tidal wave produces a number of shallow water constituents including the M_3, M_4, and M_6 overtides, and the $2MK_3$ and MK_3 compound tides. The degree to which ebb domination is due to the form of the incoming tide, i.e., mixed, mainly semidiurnal, or to the overtides and compound tides that are generated is an open question. Tidal currents are maximum along the main channel and their vertical structure indicates that slough waters are well mixed between the bottom boundary layer and the surface. Tidal currents near the H1B at maximum ebb have increased from approximately 75 to 150 cm/s over the past 30 years. This increase in current speed can be attributed primarily to the increase in tidal prism which has increased from approximately 2.5 to 7.6×10^6 m^3 between 1956 and 2003. The increase in tidal prism is the result of both man-made changes to the Slough, and the continuing process of tidal erosion. We note that these changes are not independent as far as the circulation of ES is concerned. When the man-made effects of increasing the surface area of the Slough occurred in 1983, the corresponding increase in the tidal prism required that the tidal currents increase in accordance with the tidal prism. Thus, that the mud flats slope downward may be an important factor in contributing to the tidal asymmetry in ES.

As in most estuaries, the tidal response in ES shows both standing and progressive wave character. Since the incoming tide is subject to frictional dissipation as it progresses up the Slough, the combined response of both waves consists of a mixture of a standing wave (without amplification) and a progressive wave. From harmonic analysis of the currents in the lower slough, we find that currents lag tidal elevation by 84° and 88° for the M_2 and K_1 constituents, respectively. Thus standing wave behavior appears to dominate, in agreement with Dyer [8] who indicates that most estuaries display characteristics that are consistent with standing wave behavior.

The physical properties of ES vary seasonally and with location. Temperature and salinity in the lower slough reflect primarily the influence of Monterey Bay waters, whereas the temperature and salinity of the waters in the upper slough ($>\sim5$ km from the mouth) tend to reflect the influence of heating and precipitation (or their converses) from the atmosphere. During the summer, both temperature and salinity are higher in the upper slough due to local heating and excess evaporation, respectively. During the winter, salinities can reach values of less than 20 ppt during periods of heavy precipitation.

Our knowledge of the circulation and distribution of physical properties in ES are, to a large extent, based on data collected during the 1970s and 1980s. However, the results presented here show that the Slough is changing rapidly. In the past, waters in upper ES were distinct from lower ES with the high tide interface located near the entrance to the Parsons Slough and South Marsh additions. As the tidal prism increases, this boundary between upper ES and Monterey Bay waters will move inland, and waters in the lower slough will be more ocean-like. With future observations, we will be able to confirm or reject these ideas.

Few measurements have been made in Parsons Slough and the adjoining South Marsh. This overlooked area contributes over 30% to the tidal prism for ES. From recent observations, we have observed vigorous tidal flows entering (∼60 cm/s) and leaving (>100 cm/s) Parsons Slough through its entrance located under the narrow railroad trestle (**Figures 9** and **10**). Recent current measurements near the entrance indicate that relatively large volumes of water are exchanged between Parsons Slough and ES itself. It is recommended that new observations of water elevation, temperature, and salinity in the South Marsh/Parsons Slough area, and current measurements through the entrance to Parsons Slough be acquired to better understand this relatively new portion of ES and its contribution to the overall water budget of the Slough per se.

The volume of water taken in by the Duke Energy Power Plant on a daily basis is relatively large compared to the tidal prism of ES. For an intake rate of 2.0×10^3 m^3/min, the total volume of water taken in by the power plant is almost 50% of the tidal prism over a tidal day. However, the intake has essentially no effect on the Slough itself, but profoundly affects the circulation of Moss Landing Harbor and increases the current speeds for the incoming tide through the harbor entrance by up to 10 cm/s.

Residence time for waters in the lower slough is relatively short, on the order of a tidal cycle or perhaps several cycles at most. Summertime diffusive residence times for the upper Slough based on data collected in 1973–1974 were of the order of 30 days. Because of the increase in tidal prism in ES since that time, residence times in the upper Slough have almost certainly decreased. New observations in the upper Slough will be required to address this important question.

As of the early 2000s, few if any observations have been made of the ES discharge plume in Monterey Bay. Cursory observations show that the plume is discharged to the southwest and becomes entrained in the circulation of Monterey Bay. At its maximum extent, the plume may extend as far as 3 km offshore. These sediment laden plumes provide further evidence of the erosional processes at work inside the Slough. On daily time scales, the plume provides a clear indication of the sediment erosion that takes place within the Slough. On longer time scales, this erosion eventually contributes to sediment transport through Monterey Submarine Canyon. For sediment, nutrient and water budgets, we must know more about the fate of the plume as it becomes entrained in Monterey Bay waters, and learn more about the pathway taken by waters which enter the Slough and Harbor on the incoming tide.

It is interesting to note that the four estimates of the tidal prism for ES that have been made over the past 47 years show a somewhat linear increase over time (**Figure 18**). However, changes in the tidal prism have often occurred rather abruptly due to human intervention, such as the restoration of Parsons Slough and South Marsh in 1983; as a result, the slope of the trend in **Figure 18** is not constant, as might otherwise be inferred. We believe the accuracy of the tidal prism estimates is about ± 20%, although more conservative estimates have been reported for other estuaries, e.g., O'Brien, ±15% [37]. In lieu of a better predictor, the slope of the linear trend in **Figure 18** is approximately 0.1×10^6 m^3/year over the 47 years between 1956 and 2003. We also note that although the uncertainty of the individual estimates of the tidal prism may be relatively large, the uncertainty of the slope

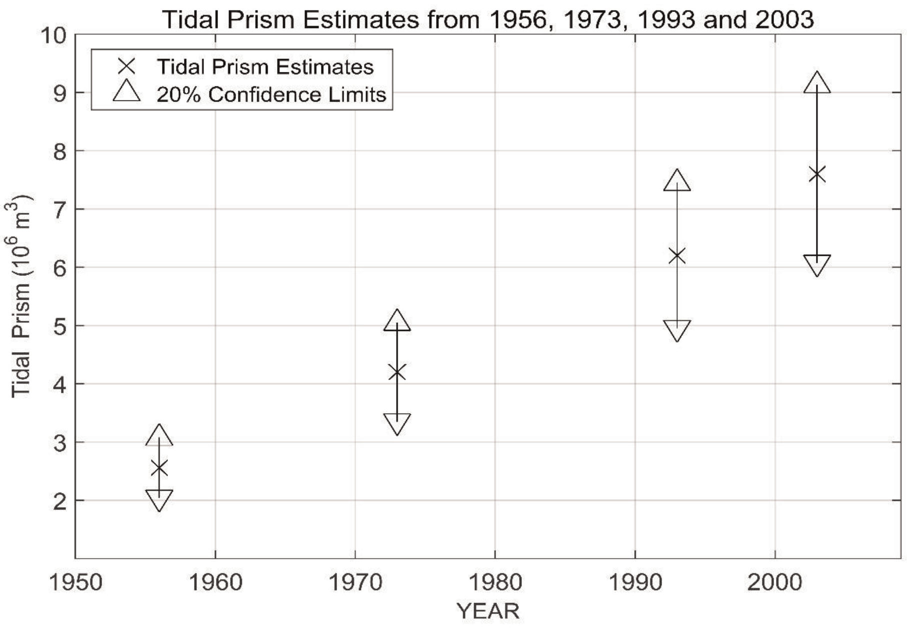


Figure 18.
Elkhorn Slough tidal prism estimates including the estimated uncertainties.

itself should be less uncertain because it is based on four independent estimates. To the extent that the continuing process of tidal erosion is an important mechanism for increasing the tidal prism in ES (vs. abrupt man-made changes), this predictor may be useful.

Acknowledgements

The work described here has been conducted over many years by the students at Moss Landing Marine Laboratories, and most of this has resulted in theses prepared for M.S. degrees directed by the first author. These students have contributed their own insights into the mechanisms working in Elkhorn Slough and Moss Landing Harbor. This chapter is dedicated to Lee Clark, Richard Smith, Paul Reilly, and Cary Wong whose original contributions form the basis for this document. They were assisted by many student colleagues in their field work, some of which was done as projects in classes taught at Moss Landing Marine Laboratories. Michael McMahan provided critical assistance during the January 2003 field work. We express our appreciation to past students, and more recently to Bill Watson and Alex Kanalakis, who have assisted us in data collection in Elkhorn Slough. Yong Sung Kim, and Ed Armstrong have assisted us in recompiling and recalculating some of the early results. Assistance during the preparation of this manuscript was also provided by the following individuals: Scott Benson, Kevin Contreras, John Oliver, and Jian Zheng Our work on Elkhorn Slough has been funded under a number of grants from the U.S. Department of Commerce, Office of Sea Grant, the Pacific Gas and Electric Company, the National Oceanic and Atmospheric Administration and the Elkhorn Slough Foundation.

A. Appendix

See **Tables A1** and **A2**.

Name	**N**	**Tidal constituents 2002-2003**						
	°/h	**Amplitudes (mm)**						
		MB	**SB**	**H1B**	**PS**	**KP**	**HL**	**SM**
J1	15.5854	22	18	18	16	16	14	
K1	15.0411	366	359	361	360	361	343	457
K2	30.0821	37	37	40	37	37	37	
L2	29.5285	7	8	6	16	21	28	
M1	14.4967	12	11	12	12	13	12	
M2	28.9841	493	507	484	516	527	531	512
M3	43.4762		3	5	8	10	11	15
M4	57.9682		5	7	23	30	32	23
M6	86.9523		1	2	9	12	14	15
N2	28.4397	112	111	108	111	114	114	
2N2	27.8954	13	15	15	14	13	15	
O1	13.9430	230	232	233	223	222	219	206
OO1	16.1391	11	11	14	15	16	14	
P1	14.9589	114	107	108	116	115	110	
Q1	13.3987	41	38	40	40	39	40	
2Q1	12.8543	5	3	3	3	4	3	
S1	15.0000	10	16	10	19	16	37	
S2	30.0000	130	141	138	147	149	147	111
T2	29.9589	7	7	5	11	11	13	
lmbda2	29.4556	3	4	4	7	8	13	
mu2	27.9682	12	11	10	5	6	9	
nu2	28.5126	22	19	22	21	22	21	
rho1	13.4715	8	5	9	9	10	10	
MK3	44.0252		2	10	21	26	33	36
2MK3	42.9271		3	6	15	20	24	19
MN4	57.4238		2	3	10	12	13	18
MS4	58.9841		1	3	14	17	18	13

Name	**N**	**Tidal constituents 2002–2003**						
	°/h	**Phase (h)**						
		MB	**SB**	**H1B**	**PS**	**KP**	**HL**	**SM**
J1	15.5854	15.0	6.7	7.2	8.0	8.5	9.0	
K1	15.0411	14.6	6.8	6.5	7.3	7.4	7.6	6.6
K2	30.0821	5.7	9.6	9.5	9.8	9.8	9.8	
L2	29.5285	7.5	9.2	9.7	9.2	9.3	9.3	
M1	14.4967	15.6	8.3	9.0	9.0	9.3	9.6	
M2	28.9841	6.2	10.3	10.3	10.7	10.8	10.9	10.9
M3	43.4762		0.5	0.6	1.7	1.9	2.4	2.0
M4	57.9682		5.2	6.0	0.2	0.2	0.5	0.9

Name	**N**	**Tidal constituents 2002–2003**						
	°/h	**Phase (h)**						
		MB	**SB**	**H1B**	**PS**	**KP**	**HL**	**SM**
M6	86.9523		2.0	2.2	1.7	1.7	1.7	1.9
N2	28.4397	5.4	9.6	9.6	10.1	10.2	10.4	
2N2	27.8954	4.4	8.9	8.9	9.1	9.2	9.4	
O1	13.9430	14.6	6.0	6.0	6.5	6.7	6.9	6.5
OO1	16.1391	15.5	7.8	8.2	8.4	8.4	7.7	
P1	14.9589	14.4	6.7	6.4	7.1	7.3	8.0	
Q1	13.3987	14.6	5.7	5.7	6.5	6.8	7.0	
2Q1	12.8543	15.5	11.7	4.5	13.1	15.0	17.7	
S1	15.0000	21.3	1.0	18.4	22.2	22.6	2.8	
S2	30.0000	6.0	10.0	10.0	10.4	10.6	10.6	10.0
T2	29.9589	5.6	9.5	9.3	9.5	9.5	9.5	
lmbda2	29.4556	6.1	9.5	9.5	8.6	8.6	8.5	
mu2	27.9682	4.1	8.7	8.0	11.5	12.1	12.5	
nu2	28.5126	5.7	9.7	9.8	10.2	10.1	10.5	
rho1	13.4715	14.6	4.6	5.5	6.3	6.0	6.3	
MK3	44.0252		5.2	4.3	4.6	4.6	4.9	4.2
2MK3	42.9271		3.8	4.3	4.6	4.8	5.1	5.8
MN4	57.4238		5.1	5.8	6.3	0.1	0.4	0.5
MS4	58.9841		5.5	0.0	0.6	0.6	1.0	1.7

Locations and duration of tide height observations			
MH	9413450 Monterey Harbor 12 months	36.36.3′ N	121. 53.3′ W
SB	MLML small boat dock Moss Landing Harbor 3 months	36°48.247′ N	121°47.166′ W
H1B	250 m east of Highway 1 Bridge 14 months	36°48.667′ N	121°46.997′ W
PS	Near SP Trestle Parson Slough entrance 4 months	36°48.951′ N	121°44.704′ W
KP	Kirby Park 4 months	36°50.951′ N	121°44.817′ W
HL	Hudson's Landing head of Elkhorn Slough 3 months	36°51.453′ N	121°45.434′ W
SM	South Marsh landward of SP trestle 1 month	36°49.209′ N	121°44.259′ W

Table A1.
Tidal height amplitude in Moss Landing Harbor and Elkhorn Slough determined from 1-month to 14-month observations, beginning in June 2002. N is the constituent speed number in degrees per hour (°/h). The record lengths are: H1B 14-months; SB, PS, KP, HL 3-months; SM 1-month.

Name	**N**	**NOS historical tidal constituents 1976**					
	°/h	**Amplitudes (mm)**					
		OP	**GF**	**PM**	**ELK**	**KP**	**RR**
J1	15.5854	16	18	17	17	16	21
K1	15.0411	356	366	361	356	366	348
K2	30.0821	39	35	34	38	35	37
L2	29.5285	6	14	14	9	15	12

Name	**N**	**NOS historical tidal constituents 1976**					
	°/h	**Amplitudes (mm)**					
		OP	**GF**	**PM**	**ELK**	**KP**	**RR**
M1	14.4967	6	16	16	15	15	19
M2	28.9841	484	502	508	495	523	522
M3	43.4762	2			9		11
M4	57.9682	3	2	6	15	20	25
M6	86.9523	1	1	1	2	2	4
M8	115.9364	1	1	0	2	2	3
N2	28.4397	105	120	121	109	124	116
2N2	27.8954	14	16	16	15	16	14
O1	13.9430	228	223	218	221	211	217
OO1	16.1391	12	9	9	9	9	17
P1	14.9589	113	121	120	113	121	110
Q1	13.3987	43	43	42	38	41	38
2Q1	12.8543	10	6	6	5	5	4
R2	30.0411	1	1	1	2	1	5
S1	15.0000	5			4		13
S2	30.0000	130	128	126	132	127	134
S4	60.0000	3	2	0	1	2	2
S6	90.0000	1	1	1	1	0	1
T2	29.9589	10	8	7	7	8	10
lmbda2	29.4556	1	3	4	4	4	8
mu2	27.9682	16	12	12	5	12	5
nu2	28.5126	19	23	23	19	24	19
rho1	13.4715	10	9	8	7	8	5
MK3	44.0252	1			18		26
2MK3	42.9271	2			14		25
MN4	57.4238	2			7		12
MS4	58.9841	1			10		16
2SM2	31.0159	4			3		4
Mf	1.0980	25			12		12
MSf	1.0159	10			9		13
Mm	0.5444	3			7		13
Sa	0.0411	96			109		166
Ssa	0.0821	38			43		50
Name	**N**	**NOS historical tidal constituents 1976**					
	°/h	**Phase(h)**					
		OP	**GF**	**PM**	**ELK**	**KP**	**RR**
J1	15.5854	15.3	14.8	14.8	16.1	15.0	16.8
K1	15.0411	14.7	14.9	14.9	15.0	15.1	15.3

Name	**N**	**NOS historical tidal constituents 1976**					
	°/h	**Phase(h)**					
		OP	**GF**	**PM**	**ELK**	**KP**	**RR**
K2	30.0821	5.4	6.1	6.1	5.6	6.4	5.9
L2	29.5285	6.6	7.2	7.2	5.6	7.3	5.9
M1	14.4967	16.1	14.9	14.9	17.1	15.1	18.3
M2	28.9841	6.2	6.3	6.4	6.5	6.5	6.6
M3	43.4762	8.2			0.8		0.8
M4	57.9682	5.3	6.1	1.8	2.1	1.9	2.2
M6	86.9523	3.9	1.3	1.5	1.5	0.8	1.4
M8	115.9364	1.1	2.1	2.9	0.4	0.2	0.5
N2	28.4397	5.4	5.5	5.5	5.8	5.7	6.0
2N2	27.8954	4.0	4.6	4.7	5.1	4.9	5.7
O1	13.9430	14.5	14.9	14.9	15.0	15.2	15.4
OO1	16.1391	14.0	14.8	14.8	16.2	14.9	17.1
P1	14.9589	14.6	14.9	14.9	14.6	15.1	15.2
Q1	13.3987	13.8	14.9	15.0	15.3	15.3	15.9
2Q1	12.8543	10.9	15.0	15.0	16.5	15.3	16.1
R2	30.0411	7.2	6.1	6.2	7.1	6.4	8.2
S1	15.0000	22.5			1.0		17.6
S2	30.0000	6.0	6.1	6.2	6.3	6.4	6.6
S4	60.0000	5.6	5.2	4.6	2.0	2.1	3.1
S6	90.0000	0.9	3.5	3.6	1.4	0.5	1.5
T2	29.9589	5.0	6.1	6.2	5.4	6.4	5.3
lmbda2	29.4556	11.0	6.2	6.3	5.0	6.5	4.6
mu2	27.9682	4.5	5.9	5.9	5.4	5.9	7.9
nu2	28.5126	5.4	5.6	5.7	5.9	5.9	6.1
rho1	13.4715	17.9	14.9	15.0	14.9	15.3	16.8
MK3	44.0252	6.8			4.3		4.6
2MK3	42.9271	3.3			4.8		4.9
MN4	57.4238	5.7			1.9		2.0
MS4	58.9841	2.6			2.2		2.3
2SM2	31.0159	10.4			9.9		10.1
Mf	1.0980	116.9			155.9		228.3
MSf	1.0159	173.5			343.4		34.1
Mm	0.5444	59.9			420.1		122.7
Sa	0.0411	5196.2			5033.0		5303.3
Ssa	0.0821	2778.3			2695.5		1883.4
NOS station number and location www.co-ops.nos.noaa.gov							
OP	9413616 Ocean Pier, Moss Landing				36.48.1′ N	121.47.4′ W	
GF	9413617 General Fish Co. Pier ML Harbor				36.48.1′ N	121.47.2′ W	

	NOS station number and location www.co-ops.nos.noaa.gov		
PM	9413624 Pacific Mariculture Dock ES	36.48.8′ N	121.45.5′ W
ELK	9413631 Elkhorn Slough at Elkhorn	36.49.1′ N	121.44.8′ W
KP	9413651 Kirby Park, Elkhorn Slough	36.50.5′ N	121.44.8′ W
RR	9413663 Elkhorn Slough Railroad Bridge	36.51.4′ N	121.45.3′ W

Table A2.
Tidal height amplitude in Moss Landing Harbor and Elkhorn Slough determined from 12-month observations in 1976 by the National Ocean Survey.

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