Philip Williams & Associates, Ltd.
Consultants in Hydrology

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

GEOMORPHIC AND HYDRODYNAMIC ANALYSIS FOR THE ESTERO de SAN ANTONIO ENHANCEMENT PLAN

Prepared for

Marin County Resource Conservation District

Prepared by

Philip B. Williams, Ph.D., P.E. President

and

C. Kelly Cuffe Hydrologist

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I. INTRODUCTION

The Marin County Resource Conservation District (MCRCD) is in the process of developing a Watershed Enhancement Plan for the 59-square mile Stemple Creek Watershed which drains into the Estero de San Antonio. The goal of the plan is to develop a practical community-based program for protecting ecologic resources while preserving viable agriculture in the watershed.

Estero de San Antonio is a coastal lagoon internationally recognized for its biologic importance. It is included within the Gulf of the Farallones National Marine Sanctuary which is an United Nations International Biosphere Reserve. The character of the Estero has been transformed by historic land use changes within the Stemple Creek watershed and continues to be affected by sedimentation and poor water quality. In addition, future adjacent land use changes and alterations in the hydrology could influence the Estero.

One of the important elements of the Enhancement Plan will be the management of the Estero itself. Its character varies greatly depending on whether the lagoon mouth is open or closed. When it is open, the Estero is tidal, has good circulation, and exhibits a typical estuarine salinity distribution. When the mouth is closed, the lagoon has poor circulation and widely varying salinities.

In order to help guide management decisions, it is important to understand the geomorphology and hydrodynamics of the lagoon, and in particular, how the opening and closing of the mouth responds to sedimentation within the Estero.

Philip Williams & Associates, Ltd. (PWA) was retained by MCRCD to address the following four main objectives:

1. Determine how the historic deposition of sediment in the Estero has affected the hydrodynamics and closure conditions of the lagoon mouth.

2. Analyze the hydrodynamics and circulation with and without the lagoon mouth closed.

3. Project how future rates of sedimentation would alter the hydrodynamics and closure conditions of the lagoon mouth if no watershed enhancement measures are undertaken.

4. Determine the feasibility of artificially opening the lagoon.

The work was carried out under two contracts: the geomorphic analysis (contract dated November 14, 1991) was funded by a grant from the California Coastal Conservancy to MCRCD;

and the hydrodynamic analysis (contract dated March 11, 1993) was funded by a grant from the Marin Community Foundation to MCRCD.

II. CONCLUSIONS AND RECOMMENDATIONS

A. CONCLUSIONS

1. Sedimentation in the Estero over the last 131 years has significantly affected the character and morphology of the lagoon, specifically:

   The potential diurnal tidal prism, the volume between mean higher high water (MHHW) and mean lower low water (MLLW), has been reduced to 7.1 million ft^3 (163 acre-ft), about 20% of the volume that existed in 1862.

   The bed of the lagoon has become shallower and is now typically about -3 ft NGVD or the level of mean lower low water (MLLW).

   Mainly because of this shallow depth, most of the lagoon does not drain below 0 ft NGVD at low tide and the effective diurnal tidal prism is only approximately 4.8 million ft^3, about 15% of the effective prism in 1862.

2. These physical changes have had a substantial impact on the hydrodynamics of the lagoon. Formerly it appears that the Estero's tidal prism was large enough to keep the lagoon fully tidal throughout the year, now the lagoon mouth has become smaller and usually closes off in the spring or summer and remains closed until the first significant flood flow of the winter. During drought periods the lagoon mouth can stay closed for more than a year.

3. Closure occurs when periods of high wave energy coincide with neap tides and low runoff. Based on monitoring in 1993, these conditions are relatively well predicted when the ratio of deep water wave power measured at the Bodega Buoy to potential tidal power exceeds about 35.

4. When the lagoon mouth closes, circulation is practically eliminated and, depending on inflow, water can back up to elevations of up to 10 ft NGVD and vary in salinity from hypersaline to nearly fresh. Anaerobic water quality conditions have also been reported when the lagoon mouth is closed.

5. With the lagoon mouth open, circulation is created directly by tidal exchange and indirectly by the density difference between the fresh water inflow and seawater.

6. If no action is taken and sediment delivery to the Estero continues at historic levels, it is anticipated that additional sedimentation would occur with further reductions in the tidal prism. Under these circumstances, the lagoon would gradually change from a seasonally

closed estuary to one that is closed most of the time. It would then be open only intermittently during and, for a short period, after significant flood flows.

7. If it is desired to completely restore the natural functioning of the lagoon by restoring the tidal prism to its historic conditions, one to two million cubic yards of sediment would have to be excavated.

8. There is some evidence based on surveys taken before and after the 1992-1993 winter floods, that natural scouring of the bed can occur, allowing some recovery of the tidal prism, provided sediment delivery to the Estero is reduced.

9. It is possible to artificially breach the lagoon mouth after it is closed. However, once inflows have declined in the spring, the entrance is likely to close again whenever strong wave action occurs during neap tides. In a typical year it is possible that several breachings would have to be made.

B. RECOMMENDATIONS

Based on this analysis, the following measures are recommended:

1. Undertake effective measures to reduce sediment delivery to the Estero. It is particularly important to reduce the delivery of coarse bedload sediments.

2. Carry out a complete bathymetric and topographic survey of the Estero.

3. Establish a monitoring program to:

    a. Continuously record water levels in the Estero to define closure and opening events.

    b. Install a stream gage on Stemple Creek to measure peak flood flows and low summer flows.

    c. Carry out periodic surveys to determine if net scour or deposition is occurring within the lagoon.

4. Ensure that the existing wave monitoring station off Bodega Bay is maintained.

5. Ensure that monitoring reports are kept in a publicly accessible location such as the Bodega Marine Laboratory Library.

6. After ten years of such monitoring evaluate whether additional management actions are worthwhile. Such actions could include a deepening of the channel to increase the tidal

prism or completely restoring the natural tidal prism by excavation of accumulated sediments.

III. NATURAL PHYSICAL CONDITIONS

Estero de San Antonio was formed over the last 10,000 years as rising sea levels after the end of the last ice age invaded the valley of Stemple Creek. This valley, like the valley of Estero Americano immediately to the north, has unusual geomorphic characteristics. Both Esteros were originally created by larger rivers than flow in them now. Travis (1952) reports that the watershed of Stemple Creek was formerly considerably larger and extended to Santa Rosa Mountain. Stemple Creek as a larger river was able to keep pace with tectonic uplift and incise a steep sinuous canyon in the coastal hills before discharging to the ocean. However, eventually more rapid tectonic uplift occurred inland and truncated the drainage (Prunuske-Chatham, 1992). Stemple Creek now has a watershed area of 59 square miles (see Figure 1), and is undersized for its valley, as can be seen on the topographic map (Figure 2).

Under the natural conditions that existed up to about 200 years ago before European settlers arrived, it is likely that watershed vegetation was largely undisturbed, and with the small sized stream flowing into the Estero, sediment delivery rates would have been low. This would explain why the process of sea level rise which appears to have averaged about 0.5 ft/century over the last 7,000 years (Atwater, 1979) has dominated over the process of sedimentation. Consequently, tidal influence extended about 4 miles inland creating a drowned river valley through the coastal hills.

Unfortunately, there is very little historic information concerning the Estero; however, it appears that in its natural state, the Estero de San Antonio would have been fully tidal year round.

It is significant that the Spanish chose to name both Estero de San Antonio and its twin to the north, Estero Americano, as *Esteros* or estuaries. Elsewhere on the California coast, the usual term used for coastal lagoons was *Laguna* or *Agua. Laguna* or "lagoon" was used to name both fully tidal and seasonally tidal systems; *aqua* or "water" was used for non-tidal lagoons. "Estero" was used for tidal channels such as the Petaluma River.

While it could be argued that the selection of the term Estero implied a fully tidal estuary, what may be more significant is that the same distinctive term was used for both Esteros. There is substantive historical evidence that Estero Americano was fully tidal in the 19th century, and allowed schooners to ship goods from the town of Valley Ford (PWA, 1986). The mouth of Estero de San Antonio is rockier than that of Estero Americano and this may have limited navigation in the same period.

The earliest definitive historic information for Estero de San Antonio is an 1862 topographic map that extends approximately 1¼ miles inland (see Figure 3). Although this map was prepared at a time when watershed characteristics would be changing due to overgrazing (Rowntree, 1973), it would appear to still be representative of the Estero's natural condition. This map shows similar open entrance channels for both Esteros with the width varying from 450 ft at high tide to 165 ft at low tide at the mouth of Estero de San Antonio.

There are several other noticeable features on the 1862 map. Immediately inside the estuary mouth there is a clear delineation of a flood tide bar of beach sands. In common with other tidal estuaries, the morphology of the area inside the mouth is influenced by the deposition of beach sands brought in on the flood tide—this area extends about 700 feet into the Estero. This portion of the Estero is still shallower than the reach further upstream, and it is interesting to note that a ford is indicated across both Estero de San Antonio and Americano at the upper end of this flood tide deposition zone in 1862.

Behind the flood tide bar, and approximately 1,000 ft further upstream, what appear to be tidal marshes are shown. Further upstream, the Estero occupies the entire width of the canyon and lines of high water and low water are shown. With the low sediment delivery from the watershed, it is possible that water depths in the lower part of the estuary could have been quite deep and similar to the 40-foot depths reported historically in the lower part of the Estero Americano (R. Gordon, 1986).

Further upstream, beyond where the Middle Road Bridge is now, the valley becomes wider. An 1857 land ownership map of the upper part of Estero Americano shows that channel to be considerably wider than now. Although not represented on the 1862 map, it is likely that Estero de San Antonio was also wider and fringed by tidal marshes further upstream.

Under natural conditions, the larger tidal prism would cause scouring of a deeper entrance channel allowing more efficient tidal drainage on the ebb tide. This would mean that the low tide elevation within the Estero would have been lower than at present and the tidal range greater.

Circulation within the Estero would have been mainly influenced by freshwater inflow. Because of its long thin configuration and large volume, circulation by tidal exchange by itself would have been fairly limited. However, even small inflows of freshwater would have induced an estuarine circulation system driven by the density differences between fresh and salt water. It is possible that under natural conditions before the watershed was degraded, summer flows would have been higher than now and sufficient to induce salinity gradients and estuarine circulation year round.

IV. HISTORIC CHANGES

Over the last 150 years, major human induced changes have occurred that greatly affect the physical functioning of the estuary. Cattle grazing, and later, arable farming in the watershed, have resulted in accelerated erosion and significant increases in sediment delivery to the Estero (SCS, 1992).

These sediments, mainly eroded by the formation of arroyos and gullies, were conveyed downstream during large flood events. At first, the finer materials were carried through the Estero and discharged to the ocean. However, the coarser sands remained in the Estero, and have filled in the deeper parts of its channel, building up shoals in backwater areas, and depositing natural levees on the edge of the tidal marshes.

Over time, the entire Estero became shallow and the fringing shoals became larger, narrowing the channel. Eventually, the tidal marshes were smothered with sediment, converting them to floodplain meadows. Figure 2 shows the shape of the Estero today, and Figure 4 is a map showing how the Estero has narrowed between 1862 and 1989.

With increased sedimentation, the tidal prism was reduced, which in turn reduced the scouring potential of currents within the entrance channel. Consequently, the entrance channel became narrower and shallower. At some point the entrance channel became small enough to be closed off by beach sand deposited during periods of high wave energy. It is not clear when the first closure occurred, but it was possibly late in the 19th century. The first direct evidence of closure is what appears to be barren, probably hypersaline areas on adjacent marshes in the earliest aerial photos from 1942. A 1930 survey undertaken by the Coast and Geodetic Survey between June and October shows the entrance open. Ed Pozzi (1993) reports that neighbors of his walked across the bar at the mouth of the Estero in about 1910. Other anecdotal evidence (R. Gordon, 1986) indicates that Estero Americano, which had been experiencing similar changes but had a larger tidal prism, first closed in the 1930's.

Once closure occurs, the physical functioning of the Estero is transformed, with the estuary becoming a seasonal lagoon where tidal and estuarine circulation is eliminated. Once the entrance channel closes in the spring or summer, and depending on the amount of freshwater inflow, the lagoon can become hypersaline (California Fish and Game, 1977) or brackish throughout most of its length. The lagoon mouth remains closed until the first significant winter storms fill the lagoon and overtop the beach built up in the summer. Once breaching occurs, a deep channel can be scoured quickly, returning the lagoon to tidal action.

V. EXISTING CONDITIONS

A. LAGOON MORPHOLOGY

Until this study, no bathymetric survey or detailed topographic map of the Estero had been prepared since 1862. Therefore the first task in developing an understanding of the physical processes that occur in the lagoon was to characterize the morphology of the lagoon. Unfortunately, there were insufficient funds in this contract to carry out the detailed mapping that will ultimately be required for making management decisions on the Estero. Nevertheless, sufficient field survey data was collected for this study to estimate key morphometric variables.

Three field surveys were made:

1. To establish benchmarks at the mouth of the lagoon that can also be used in later surveys or monitoring work (see Appendix A).
2. To survey representative cross-sections and channel bed (thalweg) elevations together with beach profiles. This work was carried out in March 1992.
3. A second survey of channel bed elevation after the winter runoff of 1992-1993 together with additional representative cross-sections. This work was carried out in March 1993.

The surveyed cross-sections and thalweg profiles are attached in Appendix B. Figure 5 shows the 1993 channel bed profile.

An aerial photo from May 19, 1989 (enlarged to a scale of 1 inch = 200 feet) was used as a base map and together with the survey data, stage-area and stage-volume relationships were developed.

To estimate the historic changes in morphology, the area mapped in 1862 (downstream of cross-section 4 shown on Figure 2) was compared with the same area in 1993. Morphology in 1862 was developed assuming the mapped high water mark to be equivalent to about MHHW at +3 ft NGVD, and the low water mark to be at about -2 ft NGVD. (Tidal datum is shown in Appendix A.) The area directly compared in this way accounts for about 60% of the Estero's tidal prism. The change in morphology in the remaining 40% was assumed to be proportional to the changes observed in the measured area. Appendix C describes the methods used in determining the 1862 morphology.

Figure 6 shows the measured stage-area relationship for the Estero in 1993. Figure 7 compares the measured stage-volume relationship for 1993 with the estimated value for 1862.

The morphometric analysis shows that significant sedimentation and loss of tidal prism has occurred since 1862. Table 1 summarizes the change in tidal prism. It can be seen that the total loss of potential diurnal tidal prism has been about 1 million cubic yards, averaging about 5 acre-ft/yr. The potential tidal prism is now only about 20% of its original volume.

The massive sedimentation that has occurred during historic time is confirmed by soil corings. Figure 8 shows a surveyed cross-section with three corings made close to the mouth in what was identified as tidal marsh, in 1862. The historic marshplain was found at an elevation of about 2.5 ft NGVD overlain with 2 to 3 feet of sediment. Allowing for some compaction (perhaps about half a foot) due to the overburden, the marshplain surface would have been between MHW and MHHW—a typical elevation for a tidal marsh in a fully tidal system. (Harvey, *et. al.*, 1990)

Other corings made further inland show up to 7 ft of coarser riverine sediment overlying marsh or mudflats (see Appendix D).

Because of hazardous conditions at the entrance, we were not able to obtain direct measurements of the inlet channel geometry. However, channel width can be obtained from aerial photos and prior hydrographic surveys, and channel depth can be estimated from empirical relationships of tidal prism with inlet channel area (Jarrett, 1976) using a width-to-depth ratio of 12 observed at Bolinas Lagoon (Johnson, 1973a).

The entrance channel cross-sectional area, A, below mean sea level (NGVD) is given by

$$A = 1.91 \text{ x } 10^{-6} \boldsymbol{P}^{1.1}$$

where, $\boldsymbol{P}$, is the potential diurnal tidal prism. Table 2 summarizes how estimated channel dimensions have changed over time.

B. HYDROLOGY

Average precipitation in the 59-square mile watershed of Estero de San Antonio is approximately 30 inches and is highly seasonal with 90% occurring in the period November to April.

Unfortunately there is no measured stream flow data for Stemple Creek. A recording gage at the Highway 1 Bridge was installed by the Santa Rosa Wastewater Study but this location is influenced by lagoon stages and due to malfunctions did not provide reliable data in the study period. (M. Commins, 1992))

Based on regional flood frequency analysis, 10-year and 100-year flood peaks at Highway 1 would be of the order of 5,800 and 7,500 cfs, respectively, which are sufficient to transport large volumes of bed load into the Estero (Waananen and Crippen, 1977).

Seasonal flows into the Estero have been roughly estimated using a regression model developed by the Santa Rosa Wastewater Study (Dearth, *et. al*. 1988). This model estimates Stemple Creek average monthly flows based on correlation of gaged streamflow measurements and precipitation records from the nearby Salmon Creek Watershed. Appendix E tabulates this computed streamflow data for the historical periods of 1959-1981, and 1989-1993. Figure 9 shows the average monthly hydrograph. It can be seen that in an average year, predicted inflows decline to below about 2 cfs by June and do not substantially increase until at least November. Monthly flows of about generally 100-150 cfs occur during the winter and spring months of November through March.

C. LAGOON HYDRODYNAMICS

The Estero currently functions as a seasonal lagoon in which the typical mode of behavior is as follows: In the winter and early spring the lagoon is fully tidal. Varying amounts of freshwater inflow creates a salinity gradient and estuarine circulation system within the lagoon. Except for a few days during flood peaks, water levels in the Estero are determined by mainly tidal influence. By the summer, the lagoon mouth has closed, estuarine and tidal circulation has ceased, and water levels in the lagoon are dictated by the balance of freshwater inflow, seepage through the beach and evaporation. Eventually, with the advent of winter storms, water levels in the lagoon rise until they overtop the barrier beach, and scour out a new tidal channel, hence restoring tidal circulation.

There had been no water level measurements taken in the Estero prior to this study. A continuous water level monitoring was conducted during the period between January 26 and June 24, 1993 at the Franklin School Road Bridge about 1½ miles above the mouth. Unfortunately, the water level recorder malfunctioned between January 26 and March 9. Nevertheless the monitoring period included a period of fully tidal conditions, the period of closure, and subsequent ponded water level conditions. Figure 10a and b show the monitoring data during lagoon closure event. Appendix F shows the complete monitoring record together with tides adjusted for the mouth of Tomales Bay, and local precipitation.

In the fully tidal period (until about April 1st) it can be seen that the water level fluctuations closely follow the tide in Bodega Bay. The higher high tides in the Estero are sometimes slightly higher than Bodega Bay tides. This could be caused by wave set up in the entrance channel or by streamflow. The lower high tides in the Estero are somewhat lower than Bodega Bay tides—this indicates the constricting effect of the entrance channel that limits inflow until the tide is high enough (at about +2 NGVD). It can also be seen that at low tide the Estero does not drain below about 0 ft NGVD at the Franklin School Bridge.

As part of this study a tidal hydrodynamic model was set up to simulate tidal flows into the Estero calibrated with simultaneous synoptic tide measurements taken at the Franklin School Road Bridge and the Middle Road Bridge, and with visual readings on tide staffs installed at the mouth. Appendix F shows these measurements. Tidal amplitudes and lags are shown in Table 3.

In calibrating this model, which is described in Appendix G, it became evident that the tidal hydrodynamics of the lagoon are strongly dependent on the entrance channel geometry. Moreover, in other small tidal estuaries we have measured significant variations in inlet channel cross-sectional area between the ebb and flood of a single tidal cycle and between spring and neap tides (Goodwin and Williams, 1991). This variation creates considerable uncertainty in a key variable and limits the usefulness of tidal hydrodynamic model predictions for the Estero.

Based on the Franklin School Road Bridge monitoring record it can be seen that the actual tidal prism is about 67% of the potential tidal prism and that the diurnal tidal circulation (actual diurnal tidal prism divided by lagoon volume) is about 60%. Because of the long thin configuration of the Estero, the tidal excursion—the distance up the Estero whose volume is replaced on a tidal cycle—is about 6000 ft out of the total length of 20,000 ft. This means that the water in the upstream 14,000 ft would tend to move back and forth within the Estero on a diurnal tidal cycle. However, whenever there is significant freshwater inflow an estuarine circulation system would develop that would exchange water in the upper part of the Estero with the lower part (Figure 11). Density driven currents can occur one to two orders of magnitude greater than the freshwater inflow rate (McDowell, 1977). If this were true for Estero de San Antonio, inflows of the order of 1 cfs to 10 cfs could be sufficient to exchange the water volume of the Estero within a few days when the entrance channel is open.

Once the entrance closes, the mixing within the Estero is probably dominated by wind driven currents. The water level varies but typically declines over the summer in response to seepage and evaporation until late fall as inflow rates drop to a fraction of a cfs. We have estimated seepage rates of the order of about 0.5 cfs for a similar barrier beach at Big Lagoon in Marin County. Monitoring of the water level at Estero de San Antonio in 1993 indicates a decline of about 0.4 ft in May and June. This indicates that in a dry year once the lagoon mouth closes, water levels can decline about 2 ft by the end of September due to evaporation, reducing the volume by about 40%. If average salinity in the lagoon were close to that of seawater at the time of closure, this reduction in volume is sufficient to cause hypersaline conditions.

Salinity stratification may also occur in Estero de San Antonio once the entrance channel has closed (Figure 12). This has been observed in other closed California coastal lagoons where stratification creates high temperatures and anoxic conditions within most of the water column. (PWA, 1990)

With the first winter runoff, the lagoon fills until the barrier beach overtops. Based on observations by Ed Pozzi of the maximum lagoon water levels reached, it appears that breaching occurs at a maximum elevation of about +10 ft NGVD. Assuming an initial low water level in October of about +2 ft, an inflow of about 35 million cubic ft would be required to fill the lagoon to +10 ft NGVD (see Figure 7). Comparison with typical monthly inflows (Figure 9) indicates that in an average year filling and breaching would occur by mid-December.

D. COASTAL PROCESSES

The entrance to Estero de San Antonio is located within Bodega Bay but exposed to waves from the WNW to the SSW. In general, two types of waves affect the beach at the mouth of the Estero.

Waves known as "seas," generated by local winds, are steep (low wave height to wave length ratio) have short periods, and tend to erode the beach, flattening its profile. As seas tend to be more intense during the winter it is the effect of these types of waves that creates what is sometimes called the "winter" beach. In the summer long period swells dominate which are generated by storms thousands of miles away across the Pacific. These waves tend to build up the beach and steepen its profile creating the "summer" beach.

As waves move from deep water to shallow water they change character and lose energy due to refraction and diffraction. Of most interest to this study is the power of waves breaking on the beach that will suspend beach sands that can then be deposited in the entrance channel. It was not within the scope of this study to carry out an analysis of the translation of waves in Bodega Bay. However, deep-water wave power can be used as a good index of shallow water wave power.

Deep-water wave power is defined as:

$$\phi_w = \frac{\gamma H_s^2 L}{16 T_w} = \frac{\gamma g H_s^2 T_w}{32\pi} \ \mathit{ftlb/ft/sec}$$

where

H_s = significant wave height in feet
L = wave length in ft
T_w = wave period in seconds
γ = unit weight of sea water = 64 lb/ft^3

Fortunately, a continuous wave recorder is maintained off Bodega Bay (see Figure 13). From data collected by the Bodega wave buoy, we can analyze the significant wave heights, steepness, energy, and wave power while the lagoon was tidal and during closure events. Appendix H shows plots of these parameters for 1992- 93. Figure 13 shows the running 6-hour average wave power during the period of closure in March and April 1993. It can be seen that this included a period of extreme wave conditions on March 24 with 19-ft swells occurring.

A beach profile was surveyed in June 1993 after the mouth had closed but while the beach was still building (see Appendix B). Extrapolation of the berm crest profile indicates an elevation at about +11 ft at the inlet, consistent with observations that the lagoon opens when the elevation reaches about +10 ft NGVD.

E. LAGOON CLOSURE

The process of closure of a coastal lagoon is complex and imperfectly described. O'Brien (1971), and Johnson (1973b) conceptually described the mechanics of closure as when the littoral transport of beach sand into the entrance channel by wave action was greater than the ability of the tidal current to scour the channel. O'Brien proposed an empirical closure relationship for Pacific Coast Lagoons as a ratio *C,* between wave power, which drives the littoral transport; and tidal power, which determines the scouring of the channel, to define when lagoon mouths are fully tidal and when they are closed.

$$C = \frac{\phi_w}{\phi'_T}$$

O'Brien defined tidal power as ϕ'_T :

$$\phi'_T = \frac{\gamma P h_r}{T_t b} \ \mathit{ftlb/ft/sec}$$

where

P = tidal prism in ft^3
h_r = tidal range in ft
T_t = tidal period in seconds
b = width of entrance channel in ft

For this analysis we have further defined these terms as

P = potential tidal prism
h_r = potential tidal range offshore
T_t = ebb tide period = 6.25 hours

Goodwin (PWA, 1993b) has refined the definition of the closure criteria to take into account the additional role of stream flow in scouring on the ebb tide. The stream power is added to give the total tidal power ϕ'_T :

$$\phi_T = \frac{\gamma h_r}{b}\left(\frac{P}{T_t} + Q\right)$$

where

Q = river flow in ft3/sec

for this analysis we have defined *C* $\frac{\phi_w}{\phi_T}$ as averaged over a 6-hour period.

For small lagoons, such as Estero de San Antonio, the closure mechanism can be complicated. It appears that closure may be more influenced by the onshore movement of beach sands during intrinsic high-energy wave conditions than longshore littoral transport. At this stage it is not clear whether there is any difference between the effects of swells or seas in mobilizing the movement of sand into the entrance channel. The magnitude of the effective tidal prism—the volume of water actually flooding and ebbing through the entrance channel—dictates the effectiveness of scouring by ebb tide flows removing sand deposited in the channel during the flood.

In addition, it is clear that the spring-neap variation in tidal amplitude has a significant role in closure. During the neap tides ebb tide scouring is weakest and it is more likely that any sand mobilized by wave action during the flood tide will settle out and remain in the entrance channel. Monitoring of the Estero during the spring of 1993 (Figure 10) shows two closure events, one initiated on April 1, and the other which permanently closed the entrance on April 16. Both of these occurred during neap tides. A period of extreme wave energy occurred on March 23 during a spring tide and higher runoff and failed to close the Estuary.

The closure conditions can also be greatly affected by streamflow. For Estero de San Antonio the actual mean tidal prism is 2.7 million ft^3 which means the average outflow over a 6.25 hour ebb tide is approximately 120 cfs. The minimum recorded neap tide fluctuation recorded at Franklin School Bridge is about 1.4 ft (between 2.2 and 0.8 ft NGVD on March 18, see Figure 10) which would account for an actual tidal prism of about 2.1 million ft^3 or an outflow of about 90 cfs. It can therefore be seen that streamflows of the order of 90 cfs would prevent flood tide currents during the neap period, significantly reducing deposition in the entrance channel. As can be seen from Figure 9 in an average year, the period December through February would typically have flows higher than 90 cfs.

The most critical conditions for closure occur in the spring when periods of high wave energy coincide with neap tides and low runoff. This is best shown by measurements taken during the study period 1992 to 1993. In January, 1992 the mouth was closed but had reopened by March. Water level readings taken by Ed Pozzi until June indicate the lagoon as tidal during this period, however he reports the mouth closed by July 4th. In January 1993 the lagoon was tidal. In the period until June it is noticeable that the summer was unusually calm (see Appendix H). Figure 10 shows that in 1993 the first closure event occurred during the neap tide period of April 1 when there was intense wave action (Figure 13). Estero Americano also closed permanently on April 1, 1993 (see Table 4). However it appears that there was still sufficient runoff at Estero de San Antonio to start eroding a channel through the beach when wave energy dropped on about April 7. Subsequently another period of high wave energy coincided with a neap tide on April 16 closing the entrance channel for the rest of the season. Average predicted flows had dropped from about 50 cfs on April 1 to about 11 cfs on April 16.

Table 5 shows wave and tidal characteristics for the extreme wave condition on March 24th and two closure events in April, and computes the closure criterion of wave power to tidal power. It can be seen that closure occurred when this ratio was greater than about 35. This ratio is useful for evaluating the impact of long-term changes in the Estero. For example it can be seen that even under the most extreme wave conditions occurring at neap tide, the 1862 tidal prism would have been large enough for the closure criterion to be well below 35 even with no inflow, indicating that the Estero mouth was always open under natural conditions.

It is useful to compare the closure conditions of Estero de San Antonio with other California Coastal lagoons. Figure 14 is a plot of average annual wave power against potential diurnal tidal prism which shows closure conditions for lagoons listed in Table 6. Although there is a considerable uncertainty in this plot, it is interesting to note that in 1862 Estero de San Antonio's tidal prism was large enough to place it very close to the "always open" line whereas, now with its reduced tidal prism, it falls well within the seasonally closed category.

VI. FUTURE CONDITIONS

Over the next 50 years two physical processes will continue to have a major affect on the Estero.

Sea level is projected to rise, which by itself will increase the tidal prism of the lagoon. There is an international scientific consensus that global warming will cause an accelerated rise in sea level even if drastic actions are taken to reduce greenhouse gases (NRC, 1987) There is considerable disagreement on the magnitude—or more precisely the timing of a given change. Predictions range from 1.5 ft to 5 ft over the next century with about 0.5 to 2 ft occurring in the next 50 years. Without the greenhouse effect sea level is projected to rise about 0.5 ft in the next century.

A 0.5 ft rise would increase the potential diurnal tidal prism by about 1.1 million ft^3 (to 8.2 X $10^6 ft^3$) an increase of 4%.

If there were no changes in watershed management practices within the Stemple Creek watershed, such an increase in tidal prism would be more than counterbalanced by the effect of sedimentation in the Estero. Historic sedimentation has reduced the potential diurnal tidal prism at an average rate of 200,000 ft^3 per year over the last 131 years. This is about ten times the rate of increase in tidal prism due to historic sea level rise. Although most of the sedimentation would have occurred in the late 19th century it is likely that sediment delivery to the Estero continues to be considerably higher than natural conditions, resulting in net filling of the Estero.

The most significant affect of future sedimentation would be the deposition of sands within the channel gradually raising the bed. This might cause only a small reduction in potential tidal prism, but because it would reduce the hydraulic effectiveness of the channel it could cause a significant reduction in the actual tidal prism—particularly during the neap tides—thereby increasing the frequency of closure. It is conceivable that the reduction in tidal prism would allow sufficient shoaling at the entrance channel to practically eliminate tidal effects during neap tides.

With these conditions, higher streamflow would be required to keep the Estero tidal. For example, if a closure criterion value of 35 defines the critical conditions for closure of the lagoon, it means that a further 20% reduction in tidal prism would require an increase in streamflow of about 50 cfs to maintain the same tidal power. A closure event like that which occurred on April 1, 1993, would therefore require about 100 cfs instead of 50 cfs to keep the entrance channel open. Under these circumstances it can be seen (Appendix E) that the period of opening would diminish to typically the January-February period when there is high enough streamflow, and that the number and frequency of years when there would be no tidal action throughout the year would increase.

VII. ALTERNATIVE MANAGEMENT APPROACHES

A. WATERSHED MANAGEMENT

It is probable that extremely large floods will continue to deliver pulses of sediment to the Estero. However if sediment delivery from the smaller floods—the 2- to 10-year events, can be significantly reduced it is possible that scouring of the bed would take place. This would increase the hydraulic efficiency of the channel and allow some recovery of the effective tidal prism.

An indication that such scouring can take place was found somewhat fortuitously by measurements of the bed profile before and after the 1992-1993 winter floods. It appears that flood flows in 1993 were of the order of the 2- to 5-year event and occurred after 6 years of drought As can be seen in Figure 15, up to 5 ft of erosion occurred in areas of the lower estuary, due to these increase flows.

Measures can be undertaken to significantly reduce the delivery of sediments and particularly coarse sediment to the Estero. For example, gully control measures, riparian and flood plain restoration, rehabilitation of rangeland, and exclusion of livestock from stream banks would all cumulatively tend to reduce sediment delivery during flood events.

B. RESTORATION OF NATURAL TIDAL PRISM

The natural functioning of the Estero could be restored by recreating the tidal prism that existed in 1862. This would require the excavation of between 1 to 2 million cubic yards (cy) of sediment. Most of this material would be removed from floodplain meadows or wetlands that have filled the Estero over the last 130 years.

It is also possible to implement incremental increases in the tidal prism. Probably the most cost effective measure would be to deepen the Estero channel by removing about 2 feet of accumulated sediment. Assuming excavation of about 5,000 ft of channel 30 ft wide would require removal of about 10,000 cy. This would allow more effective tidal drainage, increasing the effective tidal prism. If this allowed the Estero to drain one foot lower at low tide, the effective tidal prism could be increased roughly 20%.

C. ARTIFICIAL BREACHING

The biologic assessment for the enhancement plan has recommended maintaining tidal action in the Estero if at all possible to improve fish habitat (Maron, 1992). It is feasible to extend the period of tidal action within the lagoon by artificially excavating an entrance channel across the beach after a closure event. During the period 1982 through 1991, the mouth of Estero Americano was maintained open in this fashion using a bulldozer equipped with low ground pressure tracks. It typically required up to 10 days of grading to create a new channel and final breaching was done at low tide (Peter Hain, November 22, 1993). The period for which data is available, 1985 to 1991, shows that usually the lagoon stays tidal once the mouth is breached (Table 4). However this appears to have been an unusually calm period and probably under-represents the frequency of closure at Estero Americano.

It is expected that Estero de San Antonio would behave similarly to Estero Americano but would be more likely to have repeated closures because of its smaller tidal prism. Assuming a closure criterion value of approximately 35 it can be determined that with virtually no inflow in the summer, the tidal prism will be insufficient to keep the entrance channel open whenever the deep-water wave power exceeds about 20,000 ftlb/ft/sec during neap tides. Inspection of the wave data (Appendix H) shows that during the summer and fall of 1992 wave power was less than this value and it is likely that had the entrance channel been excavated it would have stayed open. In 1993, however, it can be seen that had the entrance channel been excavated after closure on April 16 it almost certainly would have closed again at the beginning of June when a period of high wave power coincided again with the neap tide. Based on winter storm precipitation data, 1993 appears to be a more normal year than the calm period of 1992. It therefore appears that artificial breaching would be required several times in a typical year, most likely in the spring and fall.

The cost of each breaching would be similar to the cost of breaching Estero Americano and of the order of $10,000 including equipment rental (P. Hain, 1993).

D. MONITORING

A better definition of cost effective management measures could be obtained by analyzing some simple, monitoring data collected over the next 10 years. These should be carried out in coordination with ecologic and water quality studies in order to specifically define management goals for the Estero. The following information would enable us to better define the closure conditions and the physical evolution of the lagoon should it be considered desirable to reduce the frequency and period of closure:

1. Continuous water level recordings of the lagoon to identify opening and closure events as well as tidal fluctuations and summer water balance parameters. Preferably this would be a station close to the mouth, however for ease of access, the Franklin School Road Bridge site is satisfactory.

2. Establish a recording stream gage on Stemple Creek to determine flood peaks and summer inflow. This gage would have to be located where flood stages are not influenced by maximum level of the lagoon.

3. Carry out a detailed topographic and bathymetric survey at a scale of 1 inch = 50 ft with 1 ft contours for areas below about +15 ft NGVD to accurately determine the morphometric characteristics of the Estero. This survey should then be repeated after 10 years to analyze morphologic changes and net deposition. The mapping could also be used to provide input data for modeling tidal hydrodynamics and salinity distributions.

4. Carry out bed profile and cross-section transect surveys once a year to evaluate the impact of each winters flood flows.

5. Ensure that the Bodega wave station continues in operation over the next ten years.

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TABLES

TABLE 1

HISTORICAL CHANGE IN TIDAL PRISM AT ESTERO DE SAN ANTONIO

Date	1862 Tidal Prism (x 10^6 ft^3)	1993 Tidal Prism (x 10^6 ft^3)
Potential Mean Tidal Prism MHW — MLW	24	4.6
Potential Diurnal Tidal Prism MHHW — MLLW	33	7.1
Actual Mean Tidal Prism	24*	2.7**
Actual Diurnal Tidal Prism	32†	4.8‡

NOTES:

* Assumes tidal range is +2 to -2 ft NGVD

** Assumes tidal range is +2 to 0 NGVD

† Assumes tidal range is +3 to -2 NGVD

‡ Assumes tidal range is +3 to 0 NGVD

TABLE 2

HISTORIC CHANGES IN INLET CHANNEL DIMENSIONS

Year	**Observed Channel Width (ft)**		**Calculated Channel Dimensions** [†]			**Potential Diurnal Tidal Prism (ft^3)**
	MHW	**MLLW**	**Area below MSL (ft)**[‡]	**Depth Below MSL (ft)**[‡]	**Width MSL (ft)**[‡]	
1862	450	165	506	7	85	33
1930	337	84	—	—	—	—
1993	—	—	120	3.2	38	7.1

[†] Calculated based on Jarret's Equation (1976)

[‡] Assuming width to depth ratio of 12:1

TABLE 3

TIDAL CHARACTERISTICS AT ESTERO de SAN ANTONIO MEASURED MARCH 19th - llth, 1993

Tide	Tomales Bay[†] Entrance (ft NGVD)	Franklin School Bridge (FSB) (ft NGVD)	Middle Road Bridge (MRB) (ft NGVD)
Higher High Water	3.50	3.36	3.42
High Water	2.30	2.01	2.19
Low Water	-1.56	0.12	0.46
Lower Low Water	-2.40	0.08	0.46

[†] Adjusted from observed tides at Presidio Gage; corrections for Tomales Bay Entrance are as follows:

	High Tide	**Low Tide**
Tomales Bay Entrance	x 0.87 ft -12 min	x 0.91 ft +20 min

TABLE 4

CLOSURE EVENTS AT ESTERO de SAN ANTONIO AND AMERICANO 1984-1993

Year	Estero Americano[1]	Estero de San Antonio
1984	4/9	?
1985	?	?
1986	3/22	?
1986	4/18	?
1987	2/7	?
1988	none	?
1989	none	?
1990	none	?
1991	4/7	?
1992	none	between 6/9 and 7/4[‡]
1993	4/1	partial 4/1
1993	—	4/16

[†] Data provided by P. Hain, California Fish Growers

[‡] Reported by Ed Pozzi, Rancher

TABLE 5

CLOSURE CONDITIONS AT ESTERO de SAN ANTONIO

Date of Closure Event	H_s Signif. Wave Height (ft)	L Wave Length (ft)	T_w Wave Period (sec)	h_r Potential Tidal Range (ft)	P Potential Tidal Prism (ft^3)	Q Est. Stream Flow‡ (ft3/sec)	Est.* MSL Inlet Width (ft)	Φ_W Deep Water Wave Power† (ftlb/ft/sec)	Φ_T Potential Tidal Power (ftlb/ft/sec)	$\frac{\Phi_W}{\Phi_T}$
3/24/93	11	752	12	4.4 (-1.4 to 3)	$6.2X10^6$	75	38	3,373,716	99,216	34
4/1/93	17	576	11	4.3 (-1.9 to 2.4)	$5.3X10^6$	51	38	2,478,398	79,278	31
4/16/93	16	600	11	3.9 (-1.8 to 2.1)	$4.6X10^6$	11	38	2,034,330	54,104	38

Notes

* Cross-section area = 120 ft^2 below MSL and w/d ratio = 12:1 (from Bolinas Lagoon inlet cross-sectional plots)

† Averaged over 6 hours

‡ Estimate based on ratio of Redwood Creek (Marin County) daily flows to monthly average flows

TABLE 6.

TIDAL INLET CHARACTERISTICS FOR SOME CALIFORNIA COASTAL LAGOONS

Site Location		Potential Tidal Prism ($10^6 ft^3$)		Annual Deep-Water Wave Power (10^{11} ft-lb$_F$/ft/yr)	Closure Conditions
		Diurnal	Mean		
1	Smith River Estuary	35	24	303	(Infrequent)
2	Lake Earl	430	320	329	Frequent
3	Freshwater Lagoon	35	25	348	Always
4	Stone Lagoon	86	64	348	(Frequent)
5	Big Lagoon	240	180	348	(Frequent)
6	Eel River Delta	200	140	371	(Infrequent)
7	Russian River Estuary	76.2	56.6	(300)[a]	Frequent
9a	Estero de San Antonio, 1862	33	24	(200)	(Never)
9b	Estero de San Antonio, 1993	7.1	4.6	(200)	Frequent
10	Tomales Bay	1580	1070	209	Never
11	Abbotts Lagoon	17	11	307	Frequent
12	Drakes Estero	490	340	26	Never
13	Bolinas Lagoon, 1968	71.6	—	117	Never
14	Pescadero	6.8[b]	4.6[b]	(200)	(Frequent)
15a	Mugu, 1857	170	120	(100)	(Never)
15b	Mugu, 1976	27	19	(100)	Frequent
16	Carpinteria	4.8[b]	1.5[b]	(50)	Infrequent
17	Agua Hedionda, 1976	80	55[b]	28	Never
18	Batiquitos, 1976	0.33	0.23	(30)	Always
19a	San Dieguito, 1889	37	24	(30)	Never
19b	San Dieguito, 1976	0.2	0.14	(30)	Frequent
21	Los Penasquitos, 1976	2	0.75	(30)	Frequent
22a	Tijuana, 1852	67.5	47.9	(100)	Never
22b	Tijuana, 1928	34.4	20.0	(100)	Never
22c	Tijuana, 1977	14.8	8.3	(100)	Infrequent
22d	Tijuana, 1986	12.6[b]	4.8[b]	(100)	Infrequent
23	Bolsas Bay, 1874	—	38	(30)	Never
25a	San Lorenzo River, est. 1853	N/A	17.4	(200)	—
25b	San Lorenzo River, c. 1980's	N/A	3.69	(200)	Frequent

Sources: Johnson 1973, Williams 1984, Coats 1986, Williams & Swanson 1987, Goodwin & Lin 1992, Goodwin & Cuffe 1993, Rowntree 1973

[a] Parenthesis indicate an estimate of deep-water wave power.

[b] Indicates that tidal prism data based on a large-scale topographic map.