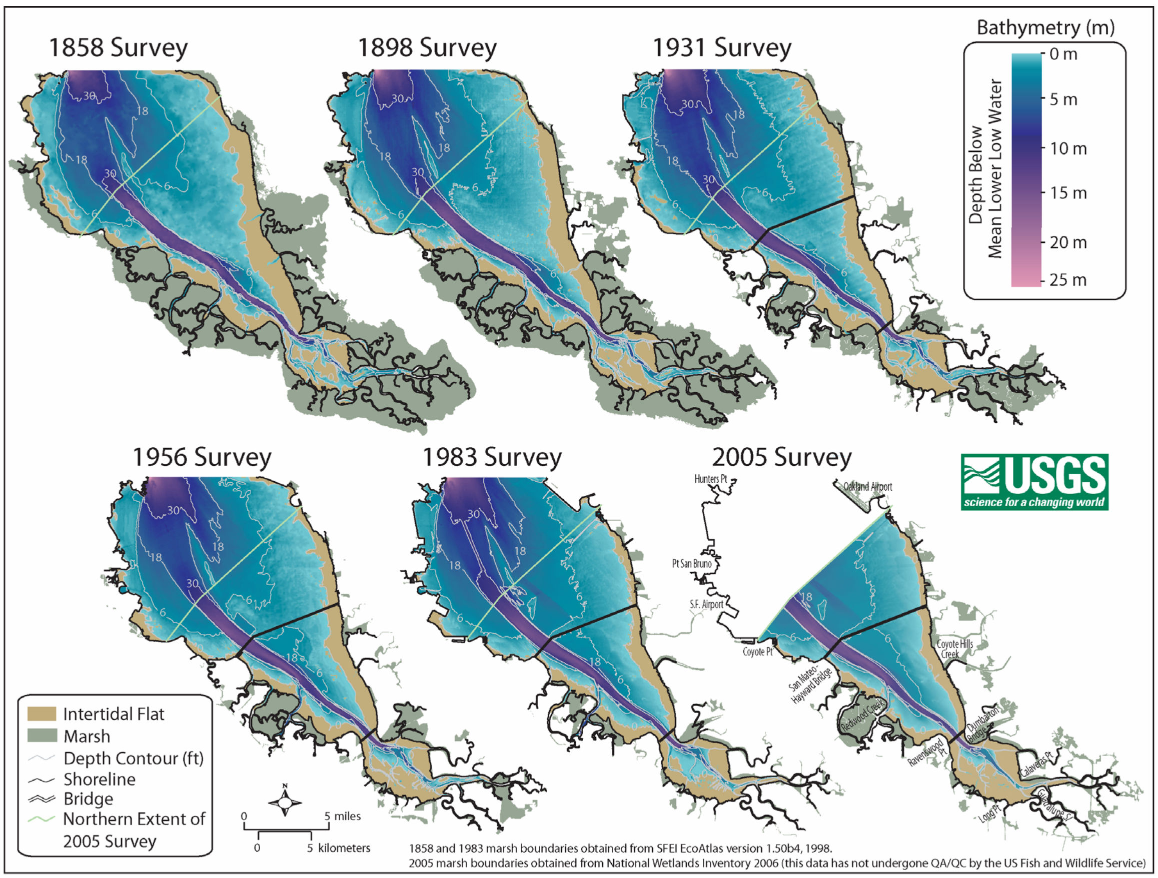
A History of Intertidal Flat Area in South San Francisco Bay, California: 1858 to 2005

By Bruce Jaffe and Amy Foxgrover



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Front Cover:

Preliminary map of intertidal flat area (region shaded brown), bathymetry, and tidal marsh in South San Francisco Bay from 1858 to 2005.

Contents

A History of Intertidal Flat Area in South San Francisco Bay, California: 1858 to 2005

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Abstract

A key question in salt pond restoration in South San Francisco Bay is whether sediment sinks created by opening ponds will result in the loss of intertidal flats. Analyses of a series of bathymetric surveys of South San Francisco Bay made from 1858 to 2005 reveal changes in intertidal flat area in both space and time that can be used to better understand the pre-restoration system. This analysis also documents baseline conditions of intertidal flats that may be altered by restoration efforts. From 1858 to 2005, intertidal flat area decreased by about 25% from 69.2 +6.4/-7.6 km^2 to 51.2 +4.8/-5.8 km^2. Intertidal flats in the north tended to decrease in area during the period of this study whereas those south of Dumbarton Bridge were either stable or increased in area. From 1983 to 2005, intertidal flats south of Dumbarton Bridge increased from 17.6 +1.7/-2.5 km^2 to 24.2 +1.0/-1.8 km^2. Intertidal flats along the east shore of the bay tended to be more erosional and decreased in area while those along the west shore of the bay did not significantly change in area. Loss of intertidal flats occurred intermittently along the eastern shore of the bay north of the Dumbarton Bridge. There was little or no loss from 1931 to 1956 and from 1983 to 2005. Predictions of future change in intertidal flat area that do not account for this spatial and temporal variability are not likely to be accurate. The causes of the spatial and temporal variability in intertidal flat area in South San Francisco Bay are not fully understood, but appear related to energy available to erode sediments, sediment redistribution from north to south in the bay, and sediment available to deposit on the flats. Improved understanding of sediment input to South San Francisco Bay, especially from Central Bay, how it is likely to change in the future, the redistribution of sediment within the bay, and ultimately its effect on intertidal flat area would aid in the management of restoration of South San Francisco Bay salt ponds.

Background and Introduction

Intertidal flats, sometimes referred to as mudflats or tidal flats, are relatively flat regions submerged at high tide and exposed at low tide. In South San Francisco Bay, intertidal flats are primarily composed of mud, especially in the far South Bay south of Dumbarton Bridge, but they can be almost entirely sand or shell material, as is the case along portions of the east shore. Intertidal flats are an important component of the South San Francisco Bay ecosystem, providing many functions including supplying a foraging habitat to hundreds of thousands of shore birds each year (Stenzel et al. 2002). A key issue in restoration of salt ponds in South San Francisco Bay is whether conversion of salt ponds to tidal wetlands will result in loss of intertidal flats. This is certainly a possibility if the balance of deposition and erosion on intertidal flats is shifted towards erosion through the creation of sediment sinks in subsided ponds opened to tidal exchange. The California Coastal Conservancy is in the process of assessing how, to what extent, and at what rate to restore salt ponds to optimize beneficial effects to the ecosystem while minimizing detrimental impacts such as loss of intertidal flats (South Bay Salt Pond Restoration Project, 2006).

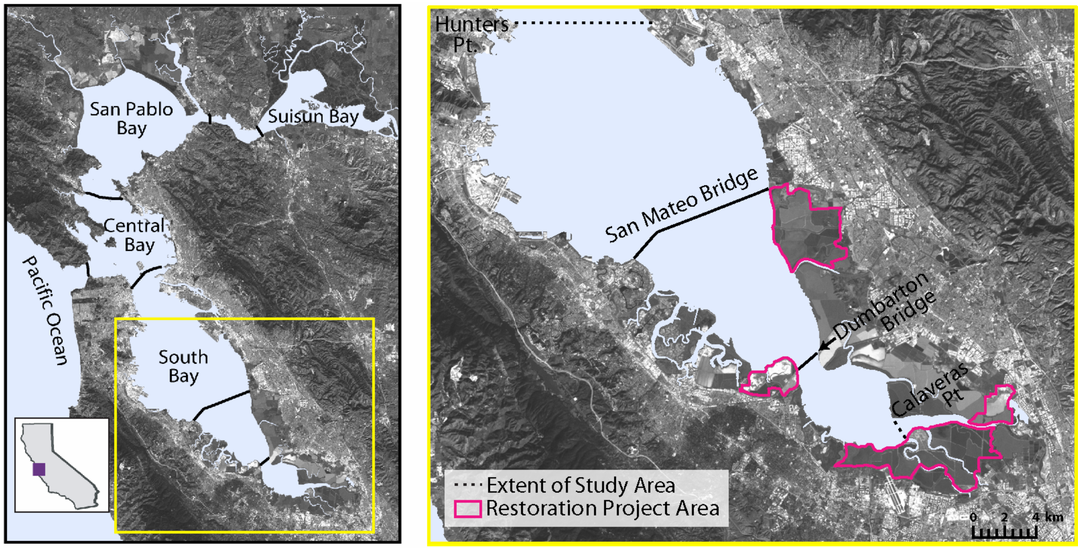

Figure 1. Location of study area showing pond complexes being considered for restoration as part of the South Bay Salt Ponds Restoration Project.

This report presents preliminary data on the history of intertidal flat area in South San Francisco Bay from 1858 to 2005. Data is presented for the region north of a line connecting Calaveras Point to Guadalupe Slough (where Coyote Creek enters the bay) to Hunter's Point (Fig. 1). The goal of this report is to document and present a preliminary analysis of the historical temporal and spatial variability of the intertidal flat area in South San Francisco Bay. These data serve as a basis for conceptual and quantitative models to predict likely responses of the intertidal flats to restoration of salt ponds in South San Francisco Bay. These data can also be used to evaluate the cause of intertidal flat change that has occurred during the last 148 years. During this time numerous factors and forcings such as wind wave erosion, tidal current redistribution of sediment, changes in sediment supply from tributaries and Central Bay, and sea level rise, altered the intertidal flat system of South San Francisco Bay. These factors and forcings will continue to alter the system as restoration proceeds.

Methods

Determination of Intertidal Flat Area

Intertidal flats, as defined in this report, are the region bounded by the Mean Lower Low Water (MLLW) contour and the shoreline, which is the Mean High Water (MHW) line (Umbach, 1976). Intertidal flat area in South San Francisco Bay was determined using data from hydrographic and topographic surveys dating back to 1858. From 1858 to 1983, five surveys (1858, 1898, 1931, 1956, 1983) were conducted in South San Francisco Bay by the National Ocean Service (NOS) (formerly the U.S. Coast and Geodetic Survey, USCGS). The most recent survey of the bay was conducted in 2005 by Sea Surveyor, Inc. and relied upon tidal reduction schemes and datum conversions supplied by the National Oceanic and Atmospheric Administration's (NOAA) Center for Operational Oceanographic Products and Services (CO-OPS), (Jaffe et al., 2005). For all surveys, depth soundings were collected in the shoals at or near high water, enabling detailed mapping of the intertidal flats. Shorelines were delineated during topographic surveys that were performed in conjunction with the hydrographic surveys.

For surveys from 1858 to 1956, the MLLW contour was digitized from contours drawn by hand by NOAA (USCGS) mapmakers on the original smooth sheets (H-Sheets). For the 1983 and 2005 surveys, we digitized a MLLW contour that we drew based on sounding values. For the 1858 to 1983 surveys, shorelines were derived from NOAA (USCGS) topographic sheets (1858 and 1983 shorelines obtained from the EcoAtlas; SFEI, 1998). The 2005 shoreline was based on EcoAtlas data (SFEI, 1998) adjusted using data from May 2004 lidar survey (Foxgrover et al., 2005).

Intertidal Flat Area Uncertainty

Uncertainty in intertidal flat area derives from the use of depth soundings to determine the location of the MLLW contour and from imprecision in the location of the shoreline. By far, the largest uncertainty in intertidal flat area is in the location of the MLLW contour.

The location of the MLLW contour is affected by the accuracy of depth soundings, the interpretation of bay morphology near MLLW by the mapmaker, and the rounding scheme used for plotting soundings on H-sheets. The accuracy criteria for depth soundings varied with survey period (Schalowitz, 1964; Adams, 1942) and can be estimated at trackline crossings where two independent measures of depth are compared. Differences in sounding values at crossings result from both horizontal (positioning) and vertical (instrumental and tidal reduction) error. Criteria used by NOAA (USCGS) for acceptable trackline crossing error are summarized in Sallenger et al. (1975). The first instructions including sounding accuracy criteria were presented circa 1860 (Schalowitz, 1964) as "the allowable error at sounding-line crossings was not to be more than 3 percent of the depth, with a limiting error of five percent".

For example, if soundings were taken at a high tide of 2 m above MLLW, the 3% criteria for depth error is 0.06 m, which results in a shift of the MLLW contour approximately 35 m on the very flat slopes (<0.1 degree or 0.017%) typical near MLLW in South San Francisco Bay. The resulting difference in intertidal flat area in South San Francisco Bay would be approximately 3.5 km^2 (35 m times ~100 km of shoreline with intertidal flats) (Table 1). If soundings were taken at lower tides, the error would be less. It is also likely that accuracy has improved over time with advancements in technology (from leadline and sextant in the earlier surveys, to digital echo-sounder and Differential GPS in the last survey). Additionally, this type of error should not be biased and would tend to cancel out because a sounding is just as likely to be deeper or shallower than the true value.

It is difficult to assess the uncertainty introduced by variation in approaches to drawing the MLLW contour. Because the distance between soundings along tracklines was relatively small, from 1 m for the 2005 survey to 150 m for the 1850s survey, and the typically simple morphology in the region near MLLW, this is not a large source of uncertainty. However, a bias would be created if two mapmakers consistently located the MLLW contour 25 m landward or bayward of the other. The resulting difference in intertidal flat area in South San Francisco Bay would be approximately 2.5 km^2 (25 m times ~100 km of shoreline with intertidal flats). Inspection of the smooth sheets reveals consistency in the approach of mapmakers to drawing the MLLW contour, so bias is not of concern. The greater data density and more precise data for the 1983 and 2005 surveys constrain MLLW better than earlier surveys, further decreasing the mapmaker's interpretation as a source of uncertainty for intertidal flat area.

The rounding of sounding values will result in change in intertidal flat area by shifting the MLLW contour bayward or landward. Rounding conventions were not the same for all surveys used in this analysis (see Appendix I for notes on rounding conventions). Adams (1942) gives instructions for reporting sounding values for surveys conducted from the late 1800s to the mid 1900s as, "In order that the location of the low-water line may be more precisely delineated on the smooth sheet, the soundings in the vicinity of the line should be plotted to the nearest half-foot". With the exception of the 1850s survey (with tidal flat soundings values all shown as 0) and the 1980s and 2005 surveys with digital sounding values recorded in meters and tenths, all soundings near MLLW were plotted on smooth sheets to the nearest half foot. For the 1898, 1930s, and 1956 surveys, rounding could result in depths 0.25 feet (0.076 m) deeper or shallower than MLLW being reported as MLLW, resulting in an uncertainty in intertidal flat area.

Uncertainty in location of the shoreline also contributes to uncertainty in intertidal flat area. Morton et al. (2004) estimated an uncertainty of ~10 m or less for shoreline positions determined from USCGS and NOS topographic sheets. The USCGS standard that "no point shall be more than 2.0 mm (0.075") from it true geographic position" (Swanson, 1949) corresponds to an upper limit uncertainty of 20 m in shoreline location for the 1:10,000 scale topographic sheets that are typical for South San Francisco Bay. A 10-20 m uncertainty in location of the shoreline results in approximately 1-2 km^2 difference (10- 20 m times ~100 km of shoreline with intertidal flats) in intertidal flat area in South San Francisco Bay if the shoreline was consistently located either landward or bayward of its true position. However, comparison of the topographic sheets from different surveys reveals that hard objects (e.g.; levees) do not exhibit consistent offset in locations between sheets.

It is clear from the above that the uncertainty in intertidal flat area changed for different periods as survey techniques, standards, and sounding reporting conventions changed. Also, uncertainty is inversely related to the slope of the bay floor near MLLW. Taking all of the above into consideration, the conservative estimate of the uncertainty in intertidal flat area for South San Francisco Bay that is used in this report is based on the assumption that the MLLW contour may be either 0.076 m (1/4 foot) too deep or too shallow and results in the translation of its position landward or bayward (Table 1). The actual uncertainty is probably less because of stringent sounding-error criteria for shallow soundings (Schalowitz, 1964; Sallenger et al, 1975) and the reduction of the overall error in MLLW contour location resulting from the averaging of a large number of estimates. Uncertainty in shoreline location is considered small relative to MLLW location uncertainty and is considered to be unbiased and not contribute significantly to intertidal flat area uncertainty.

Because the slope on the bayward side of the MLLW contour tends to be steeper than the slope on the landward side, the 0.076 m depth uncertainty results in asymmetric area uncertainty with greater uncertainty landward (Fig. 2). A consequence of this is a slight tendency for overestimation of intertidal flat area for all periods.

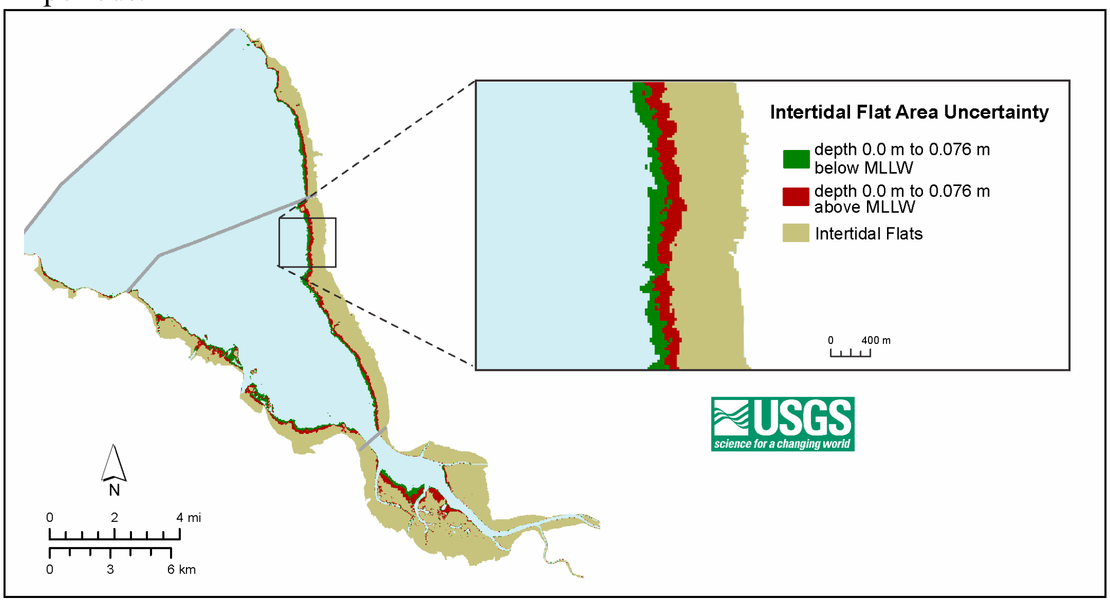

Figure 2. Uncertainty bands for intertidal flat area in 2005 using a ± 0.076 m (1/4 foot) depth uncertainty criteria. The MLLW contour is at the boundary of the green and red shaded bands. Note that the width of uncertainty bands increases as slope decreases on the landward side of the MLLW contour.

The effect of choosing higher or lower values for depth uncertainty on total South San Francisco Bay intertidal flat area for 2005 is shown in Figure 3. Choosing a less conservative depth uncertainty value of 0.038 m (1/8 foot) decreases intertidal flat area uncertainty by 45% from the 0.076 m (1/4 foot) depth uncertainty adopted for this report. Choosing an extremely conservative depth uncertainty value of 0.15 m (1/2 foot) increases intertidal flat area uncertainty by about 95% for the 2005 survey.

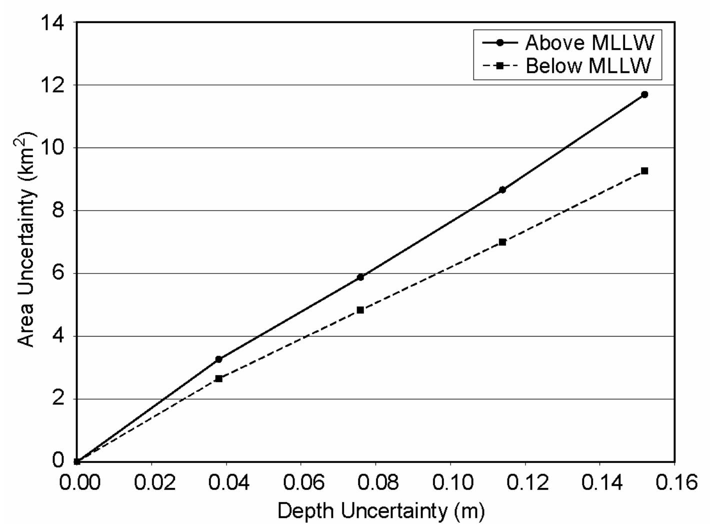

Figure 3. Variation in intertidal flat area uncertainty for South San Francisco Bay for 2005 as a function of depth uncertainty.

Calculation of Intertidal Flat Area Uncertainty

To calculate the uncertainty in intertidal flat area arising from depth uncertainty it was necessary to construct a series of bathymetric models of South San Francisco Bay because uncertainty depends on slope. Each model of the bay floor is based on thousands to millions of individual depth soundings and depth contours. The generation of accurate bathymetric models is a time intensive process involving a number of steps (Foxgrover et al., 2004) because the model must honor the data and have realistic morphology in area not supported by data. For earlier surveys (pre 1930s), no digital data existed and the soundings were manually digitized from Mylar copies of the original NOS H-sheets. Soundings from more recent surveys were obtained in digital format. Depth contours were either traced from H-sheets or added based upon sounding values. The digitized soundings and shorelines were entered into a GIS and georeferenced to a common horizontal datum. An ArcInfo surface modeling module (TopoGrid) was used to generate 50 m resolution bathymetric grids for the NOS (USCGS) surveys (Foxgrover et al. 2004) and a 25 m resolution grid for the 2005 survey.

The bathymetric model for the intertidal flat in 1858 is a special case. Prior to 1860 it was common practice to display zeros for all soundings above the MLLW plane of reference, without regard to the actual elevations (Schalowitz, 1964). This is a result of plotting practices at that time and does not accurately reflect the slope of the intertidal flats. To create a more realistic slope in the intertidal, we artificially generated contours to mimic the slopes documented in the 1890s surveys in which soundings above MLLW were retained. Contours were placed at approximately ½ and ¼ of the distance between the shoreline and MLLW (Appendix I). These contours were assigned values of 25% and 50%, respectively; of Mean Tide Level (MTL) as estimated from surrounding tide stations.

To augment the bathymetric models, marsh extent was also documented. For all periods except 2005, the marsh extent was derived from topographic sheets (1850s and 1980s marsh extent from SFEI EcoAtlas, 1998). The 2005 marsh extent was acquired from the National Wetlands Inventory and based upon aerial imagery (this data has not yet undergone QA/QC from the U.S. Fish and Wildlife Service).

Estimate of Average Intertidal Flat Width

To estimate a metric for change in intertidal flat width over time, we calculated an average intertidal flat width by dividing intertidal flat area by an estimate of shoreline length. This is only a rough metric because the length of shoreline varies with complexity, scale of the map, and distance between digitized points (it is fractal) and this length changes over time. For this report, we used a straight-line approximation for sections of shorelines with similar orientations, which resulted in segments ranging from several kilometers to 5-10 km long. We also calculated a width uncertainty by dividing the area uncertainty by the estimate of shoreline length. Where this value was less than 0.1 km, we report a value of 0.1 km.

Results

The history of intertidal flat area, bathymetry, and tidal marsh for the South San Francisco Bay is shown in Figure 4. The pattern of intertidal flat area change is complex in detail, although inspection of Figure 4 reveals general trends and coherent patterns such as loss over time, similar behavior for large sections of flats, differences between the northern and southern flats, and differences between flats along the eastern and western shores of the bay.

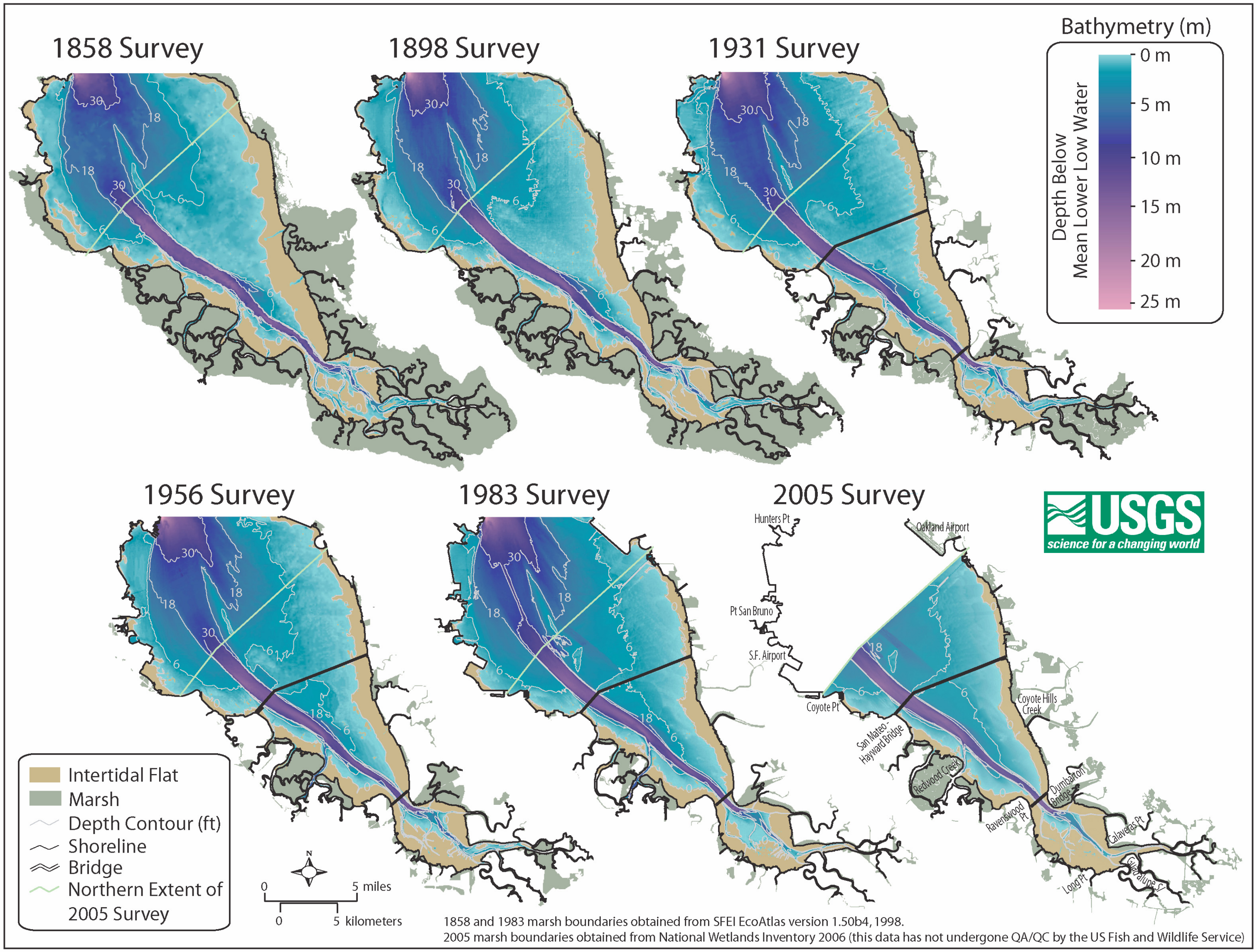

Figure 4. Preliminary maps of intertidal flat area (region shaded brown), bathymetry, and tidal marsh in South San Francisco Bay from 1858 to 2005.

Change in Intertidal Flat Area for the Portion of South San Francisco Bay Surveyed from 1858 to 2005

This section presents data for the portion of South San Francisco Bay surveyed six times from 1858 to 2005, which is defined by the region north of a line connecting Calaveras Point to Guadalupe Slough (where Coyote Creek enters South San Francisco Bay) to the northern extent of the 2005 bathymetric survey (Fig. 4). Intertidal flat area decreased by about 25% from 1858 to 2005 from 69.2 +6.4/ -7.6 km^2 to 51.2 +4.8/-5.8 km^2 (Table 2, Figure 5). Between the last two surveys, from 1983 to 2005, intertidal flat area could have been constant when considering the uncertainty bounds used in this report (46.4 +5.7/-6.0 km^2 in 1983; 51.2 +4.8/-5.8 km^2 in 2005). Another complexity in behavior of the system is that the rate of intertidal flat loss appears to be fairly constant from 1858 to 1956, and then increased from 1956 to 1983. This increased rate of loss occurred during a period of erosion and removal of sediment from the subtidal of South San Francisco Bay for use in bay fill and cement production (Foxgrover et al., 2004). The relative stability in intertidal flat area from 1983 to 2005 was accompanied by deposition in the main channel and shallow subtidal regions.

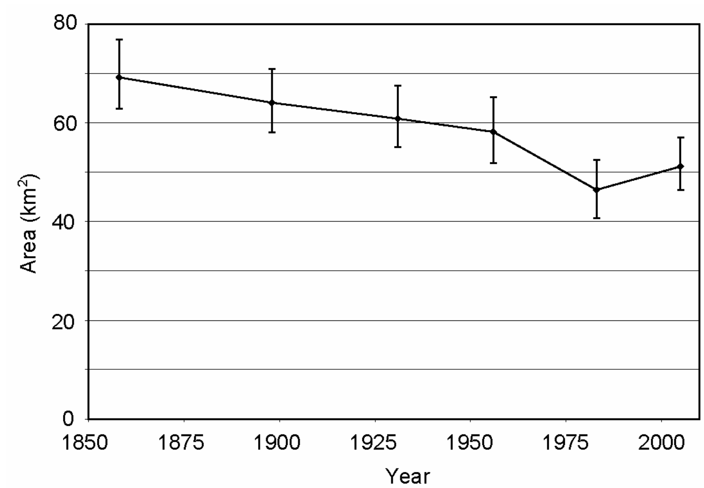

Figure 5. Intertidal flat area in South San Francisco Bay south of the 2005 survey northern boundary from 1858 to 2005. Error bars indicate change in area resulting in ± 0.076 m (1/4 foot) depth uncertainty about MLLW.

The vast majority of intertidal flat area change was the result of erosion or accretion at the bayward edge (MLLW). Reclamation and conversion of mudflats to marsh south of San Francisco and Oakland airports resulted in approximately 8 km^2 of intertidal flat loss from 1858 to 1983 (Fig. 6). Erosion of the shoreline during the same time period created approximately 7 km^2 of new intertidal flats, which nearly offsets the loss from reclamation and marsh formation. Of the 18 km^2 of loss, only about 1 km^2 (6%) was from change near the shoreline.

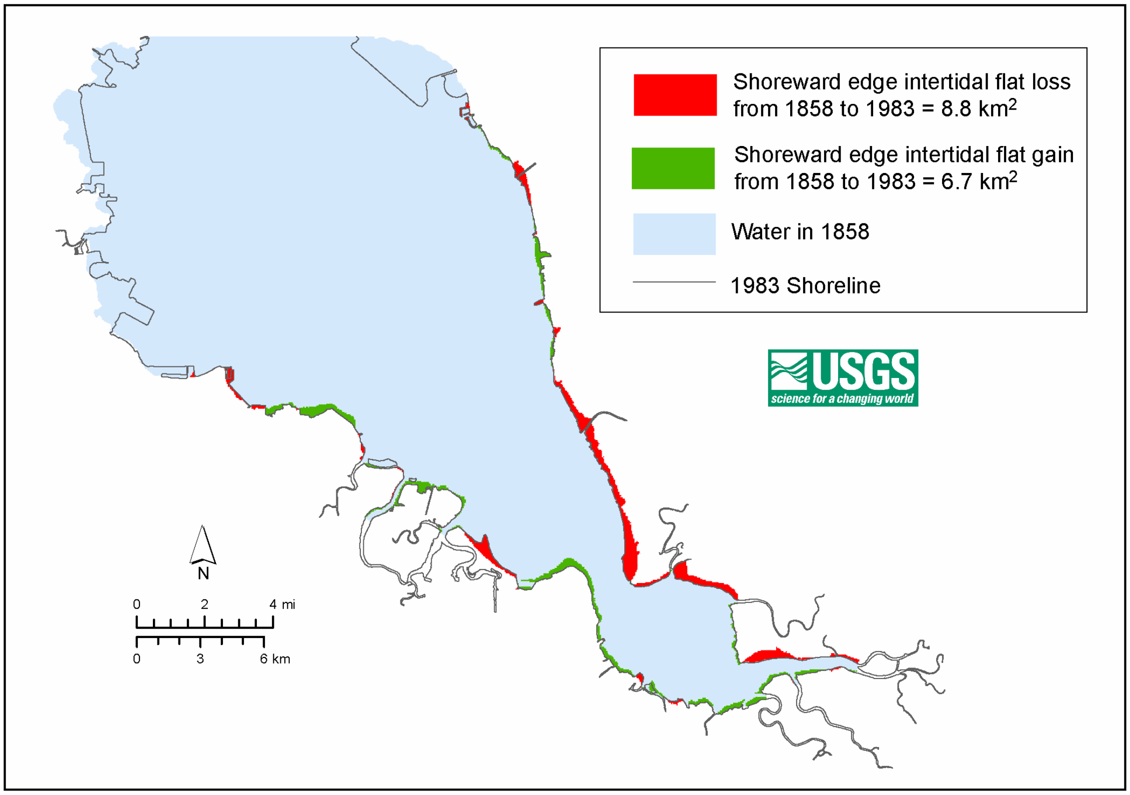

Figure 6. Intertidal flat change at the shoreward edge from 1858 to 1983. Areas shaded red were intertidal flat in 1858 lost to reclamation and marsh formation by 1983. Areas in green were land in 1858 that became intertidal flats.

Erosion of intertidal flats, shown by a landward shift in the MLLW in Figure 7, occurred between every survey in some portions of the bay (e.g.; the west shore, north of Dumbarton Bridge). In contrast, erosion of intertidal flats occurred intermittently along the eastern shore of the bay north of the Dumbarton Bridge. There, the 1983 and 2005 MLLW contours coincide, but are landward of the 1931 and 1956 MLLW contours, which also coincide indicating erosion from 1956 to 1983, but no significant erosion from 1931 to 1956 or from 1983 to 2005.

Regional Changes in Intertidal Flat Area

To further examine the spatial and temporal variability of intertidal flat change, the study area was divided into eight regions (Fig. 8). Change in intertidal flat area was variable (Table 3, Fig. 9), although coherent patterns of change emerge when examining north-south trends (Table 4, Fig. 10) and east-west trends (Table 5, Fig. 11).

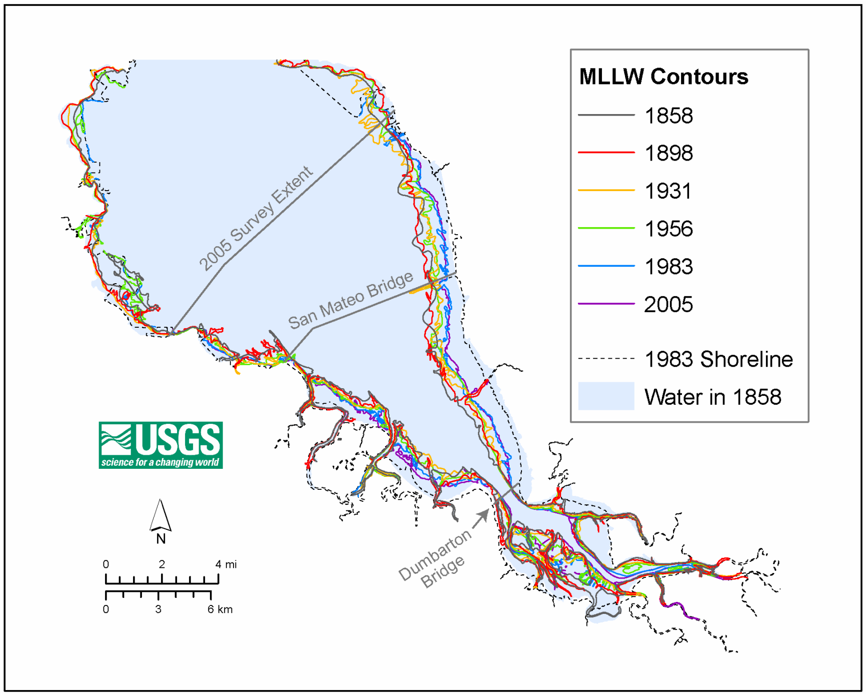

Figure 7. Bayward boundary of intertidal flats (MLLW contour) for South San Francisco Bay for surveys conducted from 1858 to 2005. The extent of water in 1853 and the 1983 shoreline are shown for reference.

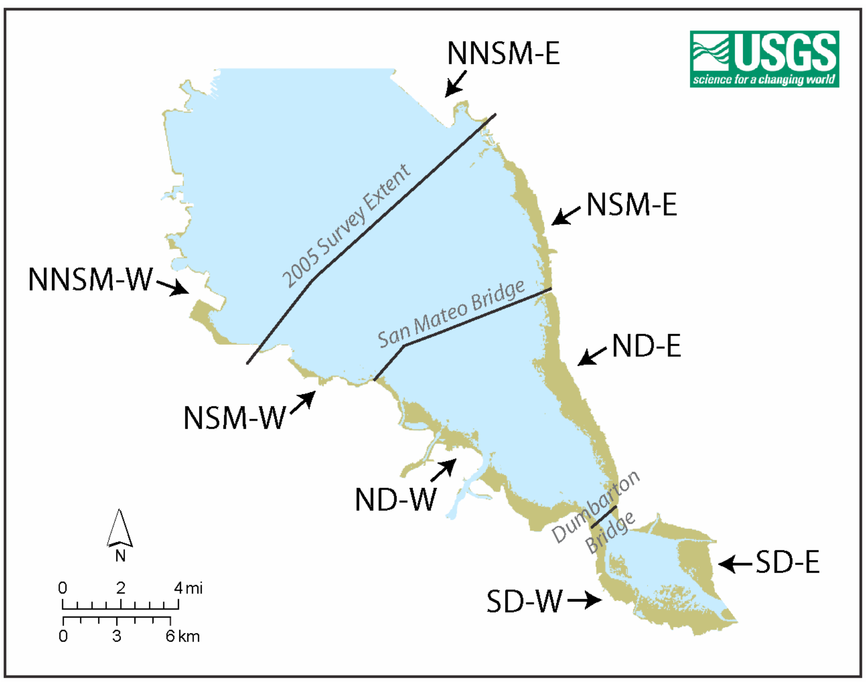

Figure 8. Regions in South San Francisco Bay used in the analysis of spatial and temporal variability of intertidal flat area.

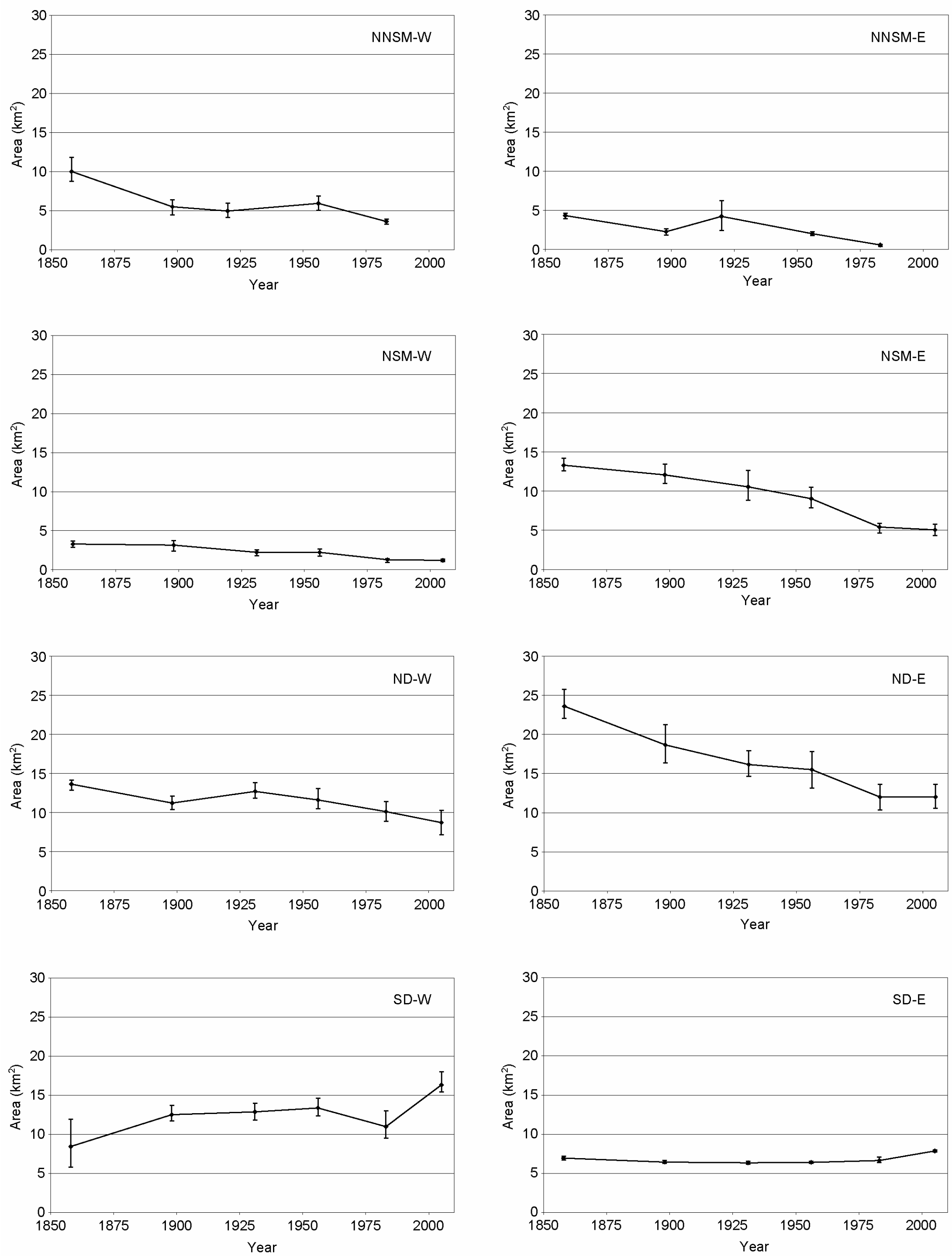

Figure 9. Change in intertidal flat area from 1858 to 2005 for regions shown in Figure 8. Error bars indicate change in area resulting from ± 0.076 m (1/4 foot) depth uncertainty about MLLW.

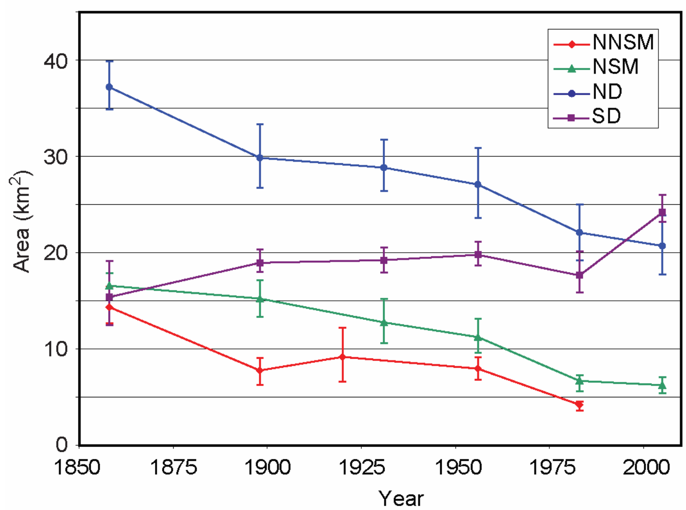

Figure 10. North-south variation in intertidal flat area in South San Francisco Bay south of the 2005 survey northern boundary from 1858 to 2005. Intertidal flats in the north tended to decrease in area whereas ones south of Dumbarton Bridge were either stable or increased. From 1983 to 2005, intertidal flat area south of Dumbarton Bridge increased from 17.6 +1.7/-2.5 km^2 to 24.2 +1.0/-1.8 km^2. Error bars indicate change in area resulting from ± 0.076 m (1/4 foot) depth uncertainty about MLLW.

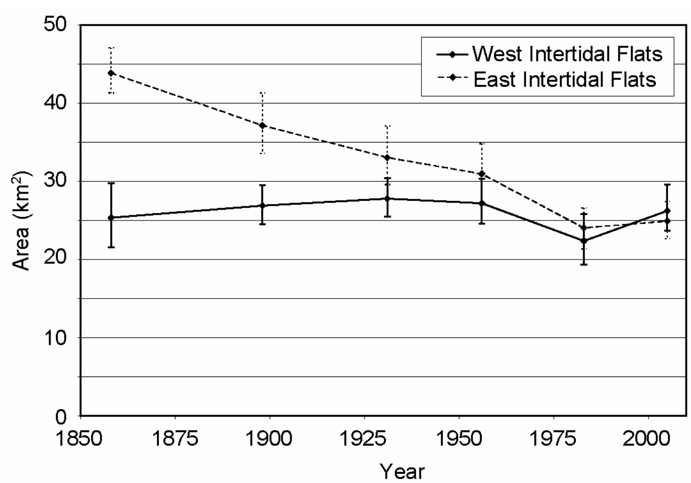

Figure 11. East-west variation in change in intertidal flat area in South San Francisco Bay south of the 2005 survey northern boundary from 1858 to 2005. From 1858 to 1983, intertidal flats along the east shore of the bay decreased in area. From 1983 to 2005, area was constant within the uncertainty of the analysis. Intertidal flats along the west shore of the bay did not significantly increase or decrease in area. Error bars indicate change in area resulting in ± 0.076 m (1/4 foot) depth uncertainty about MLLW.

The combined north-south and east-west trends are presented in Figure 12. In brief, the east shore of the bay had abundant intertidal flats in 1858 that eroded in the subsequent 148 years. The area south of Dumbarton, especially along the west shore, gained intertidal flat area through the filling of subtidal channels and gained or lost area though the contraction or expansion of a subtidal basin in its northern section (Fig. 4). From 1983 to 2005, intertidal flat area south of Dumbarton Bridge increased by about 35% from 17.6 +1.7/-2.5 km^2 to 24.2 +1.0/-1.8 km^2 (Table 4). In 2005, intertidal flats were the major component of the bay south of Dumbarton Bridge, accounting for about 70% of the total area.

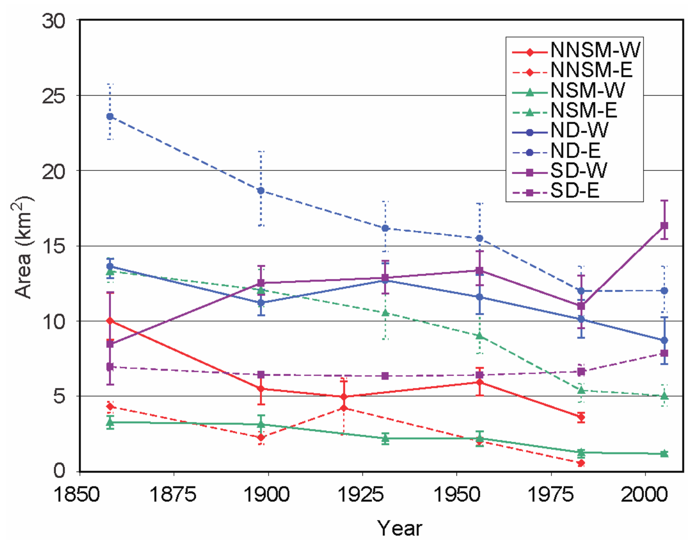

Figure 12. Spatial and temporal variation in intertidal flat area in South San Francisco Bay south of the northern boundary of the 2005 survey from 1858 to 2005. Error bars indicate change in area resulting in ± 0.076 m (1/4 foot) depth uncertainty about MLLW. Dashed lines are regions along the east shore; solid lines are regions along the west shore.

Regional Changes in Intertidal Flat Width

Average intertidal flat width, a rough metric to quantify flats, generally decreased throughout the study period for all portions of the bay except south of Dumbarton Bridge (Table 6, Figs. 4, 7). In 1858, the widest intertidal flats, 1.8 +0.1 -0.2 km on average, were on the east shore of the bay between the present locations of the Dumbarton and San Mateo Bridges. In 2005, intertidal flats were widest on the western shore south of Dumbarton Bridge, 1.4 +0.1 -0.1 km on average, and extended more than 2 km into the bay in places (Fig. 4).

Discussion

Caveats on Intertidal Flat Area

Although we have attempted to quantify intertidal flat uncertainty for each survey we have not addressed issues of comparing areas between surveys. Hydrographic surveys customarily are conducted over the span of a few years and at different times of year. Seasonal or longer variations in intertidal flat area caused by cycles in sediment input, wave height, winds, tidal currents or other factors confounds the detection of long-term trends. Thomson-Becker and Luoma (1985) found that grain size on intertidal flats along the west shore South San Francisco Bay near Palo Alto coarsened during seasons with greater tidal velocities and wind speeds and fined during periods when precipitation was high (increased runoff delivering sediment to the bay). Because the grain size changes with erosion and deposition, intertidal flat area may have changed with grain size. Anecdotal evidence of rapid accretion on the order of 5 to 10 cm on the flats of South San Francisco Bay supports such seasonal changes (pers. comms. Janet Thompson and Fred Nichols). The magnitude of seasonal or interannual variation in intertidal flat area in South San Francisco Bay is not know and is potentially an important knowledge gap in understanding the natural intertidal flat system and the effects of salt pond restoration on intertidal flat area.

Another factor that would bias the comparison of surveys is the change in the method for determining the MLLW sounding datum. For the surveys after 1898, the MLLW datum was calculated using the method of simultaneous comparisons (Dedrick, 1983). It is possible that the 1898 survey also used simultaneous comparison to determine the MLLW datum. Simultaneous comparisons allows a short time series of local water levels to be used, in conjunction with a long time series from a primary station, to calculate tidal metrics for the standard 19-year tidal epoch (Swanson, 1974). A MLLW datum based on a tidal epoch averages out short-term fluctuations (e.g. effects of the phase of the moon or seasonal steric effects). Because the 1858, and possibly the 1898, surveys used a short time series of water levels from local tide stations to calculate the MLLW datum, short-term fluctuations in MLLW is reflected in the datum. Because of the differences in MLLW datum determination, additional caution should be used when drawing conclusions based on comparisons of intertidal flat areas from the earlier surveys with ones from the 20th century.

Trends

The spatial and temporal trends in intertidal flat area are consistent, in general, with our knowledge of the hydrodynamics and the sediment dynamics of South San Francisco Bay, but also require new conceptual models to be fully explained. A greater rate of loss of intertidal flats along the eastern shore than the western shore (Tables 3, 5; Figs. 9, 11, 12) is consistent with wave-induced erosion from the higher wave energy there caused by the predominate westerly and northwesterly winds (Hayes, 1984). Another contributing factor could be that the sediments, which are sandier and contain oyster shells, are more erodable along the bay's eastern shore than in regions where the bay floor is compacted mud. It should be noted that there is also a significant loss of intertidal flats along portions of the west shore that occur in the "lower" wave energy regime (Table 3; Figs. 4, 7, 9, 12).

The stability of the intertidal flats south of Dumbarton Bridge is consistent with low wave energy caused by the short fetches in this region and constriction near Dumbarton Bridge restricting propagation of waves from the north into the far south bay. Stability and growth of intertidal flats south of Dumbarton Bridge is also consistent with a reduced tidal prism from loss of tidal marshes, which could decrease tidal velocities, leading to filling of subtidal channels. However, filling of subtidal channels in this region from 1858 to 1898 predated the largest loss of tidal marshes, which occurred from 1898 to 1931. A possible explanation for the filling of subtidal channels from 1858 to 1898 is an increased sediment supply to the far south bay, either associated with the vast quantities of debris from hydraulic gold mining that entered the San Francisco Estuary (Jaffe et al, 1998; Jaffe et al., accepted) or with increased load from local tributaries, causing a disequilibrium between hydrodynamics and subtidal channel size.

The stability of intertidal flats south of Dumbarton Bridge from 1931 to 1983 (Tables 3, 4; Figs. 9, 10), which includes the period with subsidence induced by groundwater withdrawal in San Jose from the 1930s to 1960s (Poland and Ireland, 1982), is evidence of an abundance of sediment supply to this region. There was sufficient sediment to maintain the intertidal flats even though there was about 1 m of subsidence in some portions of this region (Poland and Ireland, 1982; Foxgrover et al., 2004). A conceptual model for the long-term sediment transport pattern of South San Francisco Bay is that sediment redistributes from north to south where it is available for deposition in the shallows to maintain or grow intertidal flats south of Dumbarton Bridge. This conceptual model is supported by the history of intertidal flat area and of net volume change in bay sediments; the region south of Dumbarton Bridge is the only one with net deposition for all time periods since 1858 (Foxgrover et al., 2004). A key unknown in predicting the effects of restoration on intertidal flats (and other components of the bay and marsh geomorphic system) is the supply of sediment from Central San Francisco Bay. If there is net sediment inflow, then the likelihood for successful restoration is increased and impacts related to a paucity of sediment, such as loss of intertidal flats, would be minimized. Research to improve understanding of sediment exchange between South and Central San Francisco Bays would aid in the management of restoration of South San Francisco Bay salt ponds.

The trend of decreased intertidal flat area over time north of Dumbarton Bridge is consistent with the conceptual model of waves eroding the flat's bayward edge and shore-protection measures preventing erosion of the shore, which would otherwise compensate for loss bayward. Loss is also occurring where the shoreline is prograding (e.g.; north of San Mateo Bridge along the east shore), which indicates a shift in intertidal flat morphology, possibly resulting from sediment supply constraints or change in the erodibility of sediments.

Another cause of intertidal flat loss is sea level rise, which creates sediment demand to maintain flats. For each centimeter of sea level rise, about 1 million cubic meters of sediment (0.01 m times 100 km^2) is required to raise the intertidal flat system, which includes a subtidal portion that acts to dissipate wave energy, to keep up with sea level. From 1855 to 1999, the trend in mean sea level rise at San

Francisco was 0.145 cm/yr (Flick et al., 2003). This corresponds to about 0.15 million cubic meters of sediment each year to maintain intertidal flats, which is a small number in a sediment budget for South San Francisco Bay. An analysis of data from 1870 to 2004 from a global network of tide gauges showed sea level rise has been accelerating (Church and White, 2006). If this acceleration continues at the same rate, sea level in 2100 would be 31 ± 3 cm higher than in 1990, which corresponds to a sediment demand of about 31 ± 3 million cubic meters (0.3 million cubic meters per year).

Cayan et al. (submitted) provide a range of future sea level rise estimates for California from a set of climate simulations governed by lower, middle-upper, and higher green house gas emission scenarios. Projecting sea level rise from the ocean warming in global climate models, observational evidence of sea level rise, and separate calculations using a simple climate model yields a range of potential sea level increases, from 11 cm to 72 cm for California, by the 2070-2099 period (Climate Action Team, 2006; Cayen et al., submitted). The projected 0.1 to about 1.0 cm/yr average sea level rise for the next hundred years corresponds to an average of 0.1 to 1.0 million cubic meters of sediment each year to maintain the intertidal flats of South San Francisco Bay. Sediment required to maintain the intertidal flats of South San Francisco Bay to keep up with an accelerated sea level rise is a large term in a sediment budget. If the sea level rise is in the higher part of the range of estimates, the increased sediment demand for the entire bay system could severely impact restoration, especially north of Dumbarton Bridge.

Additional research to improve understanding of the causes of historic intertidal flat loss and the likely effects of accelerated sea level rise would aid in the management of restoration of South San Francisco Bay salt ponds.

Deviations from Trends

There are significant deviations from the spatial and temporal trends of intertidal flat loss in South San Francisco Bay. Consideration of spatial variation in wind, wave, and tidal energy; sediment characteristics; human activities, and other factors affecting the sediment dynamics redistributing sediment in South San Francisco Bay are likely to provide significant insights into the cause of the variations.

Deviations from the general trend of loss of intertidal flat area over time are of the utmost importance for understanding causes for intertidal flat change and have significant implications for management of restoration of the salt ponds. Pulses of sediment to South San Francisco Bay are evident in the intermittent change in the MLLW (Fig. 7) and intertidal flat area (Tables 3, 4; Figs. 9, 12). When a sediment pulse enters, the MLLW contour maintains its position, as is the case for the periods from 1931 to 1956 and from 1983 to 2005 (Fig. 7). Intertidal flat loss is either slowed or reversed during these periods of large sediment input (Fig. 9). The sediment pulse periods correspond with deposition or decreased erosion in the subtidal (Foxgrover et al., 2004). To increase the certainty of predictions for the effects of salt pond restoration on intertidal flats and other components of the bay and marsh system, we need to improve the understanding of the cause and likelihood of continued sediment pulse events in the future.

Summary

A preliminary analysis of bathymetric surveys to document the history of intertidal flat area in South San Francisco Bay from 1858 to 2005 revealed changes in both space and time. Major changes included:

- Intertidal flat area in South San Francisco Bay decreased by about 25% from 69.2 +6.4/-7.6 km^2 in 1858 to 51.2 +4.8/ -5.8 km^2 in 2005.
- Intertidal flats in the north tended to decrease in area whereas those south of Dumbarton Bridge were either stable or increased in area. From 1983 to 2005, intertidal flat area south of Dumbarton Bridge increased from 17.6 +1.7/-2.5 km^2 to 24.2 +1.0/-1.8 km^2.
- Intertidal flats along the east shore of the bay decreased in area while those along the west shore of the bay did not significantly change in area.
- Loss of intertidal flat area occurred stepwise along the eastern shore of the bay north of the Dumbarton Bridge. There was little or no loss from 1931 to 1956 and from 1983 to 2005. Other time periods had significant loss of intertidal flats.
- The causes for the spatial and temporal changes in intertidal flat area in South San Francisco Bay are not fully understood. A key knowledge gap is the sediment input to the system. Improved understanding of sediment input, especially from Central Bay, how it is likely to change in the future, and it redistribution and effect on intertidal flat area would aid in the management of restoration of South San Francisco Bay salt ponds.

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Tables

Table 1. Terms contributing to intertidal flat area uncertainty for South San Francisco Bay. A slope of 0.1 degrees (0.017%) and 100 km of shoreline with intertidal flats were used to convert depth uncertainty to area uncertainty.

	Estimate of Uncertainty			
	Depth Near MLLW (m)	**MLLW Contour Position (m)**	**Intertidal Flat Area (km^2)**	**Notes**
Soundings near MLLW	< 0.06	< 35	< 3.5	Not biased, tend to cancel out
Drawing MLLW Contour	-	< 25	< 2.5	Not biased, tend to cancel out
Shoreline Location	-	10-20	< 1-2	Not biased, tend to cancel out
Sounding Rounding	< 0.076	< 45	< 4.5	Could be biased, varies with survey, < for 1983, 2005 surveys
Used in this Report	0.076	varies	< 7.6	Depends on survey, calculated from actual slopes near MLLW

Table 2. History of intertidal flat area in South San Francisco Bay south of the northern boundary of the 2005 survey. Entries for uncertainly above or below MLLW is the change in intertidal flat area caused by the landward (above MLLW) or bayward (below MLLW) shift in the MLLW contour resulting from a ± 0.076 m (1/4 foot) change in depth.

Year	Intertidal Flat Area (km^2)	Uncertainty Above MLLW (km^2)	Uncertainty Below MLLW (km^2)
1858	69.2	7.6	6.4
1898	64.1	6.8	6.0
1931	60.8	6.7	5.8
1956	58.1	7.1	6.3
1983	46.4	6.0	5.7
2005	51.2	5.8	4.8

Table 3. History of variation in intertidal flat area in South San Francisco Bay in regions defined in Figure 8. Entries for uncertainly above or below MLLW is the change in intertidal flat area caused by the landward (above MLLW) or bayward (below MLLW) shift in the MLLW contour resulting from a ± 0.076 m (1/4 foot) change in depth.

	Intertidal Flat Area (km^2)					
	1858	**1898**	**1920**	**1956**	**1983**	**2005**
NNSM-W	10.0	5.5	5.0	5.9	3.6	not surveyed
uncertainty above MLLW	1.8	0.9	1.0	0.9	0.3	not surveyed
uncertainty below MLLW	1.3	1.0	0.8	0.9	0.4	not surveyed
NNSM-E	4.3	2.3	4.2	2.0	0.6	not surveyed
uncertainty above MLLW	0.3	0.4	2.0	0.2	0.1	not surveyed
uncertainty below MLLW	0.4	0.4	1.8	0.3	0.2	not surveyed

	1858	**1898**	**1931**	**1956**	**1983**	**2005**
NSM-W	3.3	3.2	2.2	2.2	1.3	1.2
uncertainty above MLLW	0.4	0.6	0.4	0.4	0.2	0.1
uncertainty below MLLW	0.4	0.8	0.4	0.5	0.3	0.1
NSM-E	13.3	12.1	10.5	9.0	5.4	5.1
uncertainty above MLLW	0.9	1.4	2.1	1.5	0.4	0.7
uncertainty below MLLW	0.7	1.1	1.7	1.2	0.8	0.7
ND-W	13.6	11.2	12.7	11.6	10.1	8.7
uncertainty above MLLW	0.5	0.9	1.1	1.5	1.3	1.5
uncertainty below MLLW	0.8	0.8	0.9	1.1	1.2	1.5
ND-E	23.6	18.7	16.2	15.5	12.0	12.0
uncertainty above MLLW	2.1	2.6	1.8	2.3	1.6	1.6
uncertainty below MLLW	1.5	2.3	1.5	2.4	1.6	1.4
SD-W	8.5	12.5	12.9	13.4	11.0	16.3
uncertainty above MLLW	3.5	1.2	1.1	1.3	2.0	1.7
uncertainty below MLLW	2.7	0.8	1.1	1.0	1.5	0.9
SD-E	7.0	6.4	6.4	6.4	6.7	7.9
uncertainty above MLLW	0.2	0.2	0.2	0.1	0.5	0.2
uncertainty below MLLW	0.3	0.2	0.2	0.1	0.3	0.1

Table 4. History of north-south variation in intertidal flat area in South San Francisco Bay in regions defined in Figure 8. Entries for uncertainly above or below MLLW is the change in intertidal flat area caused by the landward (above MLLW) or bayward (below MLLW) shift in the MLLW contour resulting from a ± 0.076 m (1/4 foot) change in depth.

	Intertidal Flat Area (km²)					
	1858	**1898**	**1920**	**1956**	**1983**	**2005**
NNSM	14.4	7.8	9.2	8.0	4.2	not surveyed
uncertainty above MLLW	2.1	1.3	3.0	1.2	0.3	not surveyed
uncertainty below MLLW	1.7	1.5	2.6	1.1	0.6	not surveyed
	1858	**1898**	**1931**	**1956**	**1983**	**2005**
NSM	16.6	15.2	12.8	11.3	6.7	6.3
uncertainty above MLLW	1.3	2.0	2.4	1.9	0.6	0.8
uncertainty below MLLW	1.2	1.9	2.1	1.7	1.1	0.8
ND	37.2	29.9	28.9	27.1	22.1	20.7
uncertainty above MLLW	2.7	3.5	2.9	3.8	2.9	3.2
uncertainty below MLLW	2.3	3.1	2.4	3.5	2.9	2.9
SD	15.4	19.0	19.2	19.8	17.6	24.2
uncertainty above MLLW	3.7	1.4	1.3	1.4	2.5	1.8
uncertainty below MLLW	2.9	0.9	1.3	1.1	1.7	1.0

Table 5. History of east-west variation in intertidal flat area in South San Francisco Bay in regions defined in Figure 8. Entries for uncertainly above or below MLLW is the change in intertidal flat area caused by the landward (above MLLW) or bayward (below MLLW) shift in the MLLW contour resulting from a ± 0.076 m (1/4 foot) change in depth.

	Intertidal Flat Area (km²)					
	1858	**1898**	**1931**	**1956**	**1983**	**2005**
West Intertidal Flats	25.4	26.9	27.8	27.2	22.4	26.2
uncertainty above MLLW	4.4	2.6	2.6	3.2	3.5	3.3
uncertainty below MLLW	3.8	2.4	2.3	2.6	3.0	2.6
East Intertidal Flats	43.9	37.2	33.1	30.9	24.1	24.9
uncertainty above MLLW	3.3	4.2	4.1	3.9	2.5	2.5
uncertainty below MLLW	2.5	3.6	3.5	3.6	2.7	2.2

Table 6. History of variation in average intertidal flat width in South San Francisco Bay in regions defined in Figure 8. This metric is calculated by dividing intertidal flat area by an estimate of shoreline length. Shoreline lengths are straight-line approximations for sections of shorelines with similar orientations, which resulted in segments ranging from several kilometers to 5-10 km long. Shoreline lengths used were NNSM-W 23 km, NNSM-E 8 km, NSM-W 8 km, NSM-E 10 km, ND-W 17 km, ND-E 13 km, SD-W 12 km, SD-E 9 km. Width uncertainty was calculated by dividing the area uncertainty (Table 2) by the estimate of shoreline length. Where this value was less than 0.1 km, we report a value of 0.1 km.

	Average Intertidal Flat Width (km)					
	1858	**1898**	**1920**	**1956**	**1983**	**2005**
NNSM-W	0.4	0.2	0.2	0.3	0.2	not surveyed
uncertainty above MLLW	0.1	0.1	0.1	0.1	0.1	not surveyed
uncertainty below MLLW	0.1	0.1	0.1	0.1	0.1	not surveyed
NNSM-E	0.5	0.3	0.5	0.3	0.1	not surveyed
uncertainty above MLLW	0.1	0.1	0.2	0.1	0.1	not surveyed
uncertainty below MLLW	0.1	0.1	0.2	0.1	0.1	not surveyed

	1858	**1898**	**1931**	**1956**	**1983**	**2005**
NSM-W	0.4	0.4	0.3	0.3	0.2	0.2
uncertainty above MLLW	0.1	0.1	0.1	0.1	0.1	0.1
uncertainty below MLLW	0.1	0.1	0.1	0.1	0.1	0.1
NSM-E	1.3	1.2	1.1	0.9	0.5	0.5
uncertainty above MLLW	0.1	0.1	0.2	0.1	0.1	0.1
uncertainty below MLLW	0.1	0.1	0.2	0.1	0.1	0.1
ND-W	0.8	0.7	0.7	0.7	0.6	0.5
uncertainty above MLLW	0.1	0.1	0.1	0.1	0.1	0.1
uncertainty below MLLW	0.1	0.1	0.1	0.1	0.1	0.1
ND-E	1.8	1.4	1.2	1.2	0.9	0.9
uncertainty above MLLW	0.2	0.2	0.1	0.2	0.1	0.1
uncertainty below MLLW	0.1	0.2	0.1	0.2	0.1	0.1
SD-W	0.7	1.0	1.1	1.1	0.9	1.4
uncertainty above MLLW	0.3	0.1	0.1	0.1	0.2	0.1
uncertainty below MLLW	0.2	0.1	0.1	0.1	0.1	0.1
SD-E	0.8	0.7	0.7	0.7	0.7	0.9
uncertainty above MLLW	0.1	0.1	0.1	0.1	0.1	0.1
uncertainty below MLLW	0.1	0.1	0.1	0.1	0.1	0.1

Appendix I- South San Francisco Bay Intertidal Flat Notes

Data Source and Sounding Precision and Rounding

1850s

- Soundings plotted in integral feet in shallows (or ¼ fathom in main channel).
- Soundings above MLLW all replaced with zeros.
- Original sounding books record depth to tenths of feet. Maps obtained from the State Lands Commission (the work of Kent Dedrick) have the zero soundings above MLLW substituted with actual values in feet and tenths, as recorded in the sounding books. These maps cover the majority of South Bay on the eastern shore and south of the Dumbarton Bridge and will be incorporated into this work in the future.
- MLLW contour digitized from H-sheets.

1890s

- About half of the H-sheets (H2304, H2315, H2412) show soundings plotted in ¼ foot increments.
- H2411, H2413, H2414 and H2415 are plotted ½ foot increments.
- MLLW contour digitized from H-sheets.

1930s

- Northernmost H-sheet (H4137) soundings are in integral feet, for all other sheets shallow soundings are plottted in ½ foot increments, and soundings in the main channel in integral feet.
- H4137 was digitized by us, for the 6 other sheets soundings were downloaded off of GEODAS.
- GEODAS header states that smooth sheets were "digitized for NOS under Ashville Contract, lead line assumed, non-acoustic depth measurement (in feet)". Soundings in GEODAS are in meters and tenths, but otherwise are identical to values on H-sheets.
- Depth contours are hard to distinguish on scanned H-sheets (especially in the shallows), therefore some of the contours are based upon sounding values.
- MLLW contour digitized from H-sheets and soundings.

1950s

- Select intertidal soundings (+/- 0.7 feet MLLW) plotted in ½ foot increments while other soundings plotted in integral feet. Limited number of 3.5 and 6.5 ft soundings displayed (presumably for more accurate placement of contour lines), all other soundings plotted in integral feet.
- Soundings downloaded from GEODAS. GEODAS headers state that "smooth sheets were digitized for NOS under Ashville Contract. Digital echo sounder

with graphical record assumed, units in feet." Soundings in GEODAS are in meters and tenths, but otherwise are identical to values on H-sheets.

- MLLW contour digitized from H-sheets and soundings.

1980s

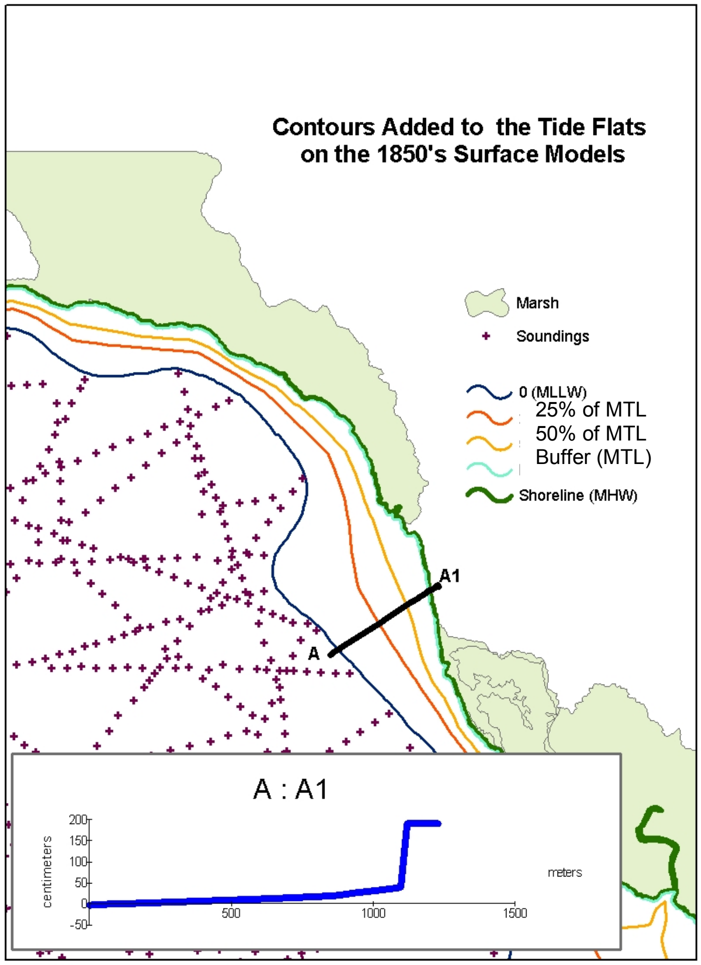
- Soundings downloaded from GEODAS. Digital soundings from GEODAS are the reduced soundings in meters and tenths.
- GEODAS headers state that all sheets were originally recorded in feet and tenths except H10132 which claims meters and tenths (not likely) and H10102, H10158, and H9927 just say feet (not tenths). Headers also state that digital echo sounder with graphical record assumed.
- On H-sheets select shallow soundings (+/- 0.7 ft MLLW) plotted in ½ foot increments. All other soundings plotted in integral feet with a shoal based rounding scheme applied. Therefore soundings downloaded from GEODAS do not identically match the H-sheets.
- Contours digitized based upon sounding values, not H-sheets.
- Because of rounding, placement of the MLLW contour is different when compared to H-sheets.
- Descriptive report states that values for H09984 and H10070 do not have appropriate tide corrector values. It is unknown whether or not the soundings in GEODAS have been corrected.

<u>Estimating 1850s Intertidal Flat Slope Where Only 0 Sounding Values Exist</u>

A new coverage was created to which contours were added based on our estimate of intertidal flat slope. The first contour was drawn at ½ the distance between MHW and MLLW paralleling the shoreline. The second contour was drawn at ½ the distance between the first contour and MHW.

The first contour (1/2 the distance between MHW and MLLW) was assigned an elevation of: MTL / 4. The second contour (1/2 the distance between MHW and MLLW), was assigned an elevation of: MTL / 2. These contours, when combined with the shoreline (MHW) and shoreline buffer (see section 9), produce a tidal flat profile that compares to the slope observed from more recent surveys (see figure below).

We also added supplementary soundings (values estimated from surrounding soundings) to the narrow channels crossing the tidal flats at steam outlets to prevent discontinuity of channels as a result of sparse soundings.



Profile of modified 1858 tidal flat.

Descriptive Report Notes

1850s

- H628 – the reducers for H-sheets 421, 628, 629, & 636 appear to be referred to the plane of MLLW within the allowable error of 0.5ft.
- H637 has some pts within 0.5ft error, some may be in error up to a foot due to limited tide data.

1890s

- H2304 – a number of shell banks were found which do not show on the old chart. The shoreline seems to be growing out into the bay
- H2315 – some changes in mud flats and shell banks found where not previously shown on chart.
- H2411, H2412, H2413, H2414, and H2415 have no notes in the Descriptive Reports.

1930s

- H4137 refers to using simultaneous comparison for reducing soundings.