

TIME SERIES ANALYSIS OF ELKHORN SLOUGH 2009-2015: PRE AND POST SILL CONSTRUCTION AT THE INLET OF PARSON'S SLOUGH

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December 16, 2015

Abstract

Wetlands provide critical ecosystem services for people such as carbon sequestration, water quality improvement, shore protection, and support of biodiversity. Elkhorn Slough is the largest salt marsh in California other than San Francisco Bay and has been drastically changed multiple times in the last 150 years. Tidal erosion became a driving force in Elkhorn Slough when a channel was cut through the sand dune for the construction of Moss Landing Harbor. In an effort to reduce the tide's speed and prevent dirt and mud from being carried out to sea, the Elkhorn Slough Tidal Wetlands Project constructed a 200 ft by 15 ft sill at the inlet of Parson's slough, which at high tide, holds a third of the total water in the Elkhorn Slough. We postulated that the zones of the Elkhorn Slough experiencing the greatest rates of bank erosion are located closer to the mouth of the slough, due to its exposure to the tide, tidal volumes of the main channel of the Elkhorn Slough have increased in each zone since Fall 2009 and since the construction of the sill at the inlet of Parson's Slough in 2011, the Parson's Slough has experienced lower erosion rates and higher deposition rate. We used GIS analyses for mudflat change, thalweg and cross sectional analyses for subtidal change, and volumetric change of the subtidal to determine how Elkhorn Slough has changed since the construction of the sill at Parson's Slough. The results support our postulates. Erosion is still occurring in Elkhorn Slough, but since the construction of the sill at Parson's Slough, the rate of erosion has decreased in most of the slough. Hotspots still occur near the mouth of the slough and in Parson's Slough. The construction of the sill in Parson's Slough has been successful at reducing rates of erosion in most parts of Elkhorn Slough.

Research Question

How have the spatial distributions and rates of tidal scour of the Elkhorn Slough intertidal zone changed over time since 2009? Which of the eight zones of the Elkhorn Slough are undergoing the greatest changes in erosion and deposition rates? How is the presence of the sill at the inlet of Parson's Slough affecting these rates?

Introduction

Wetlands provide many critical ecosystem services for people such as carbon sequestration, water quality improvement, shore protection, climate change mitigations, and ecological biodiversity (Zedler and Kercher 2005). Although wetlands are essential for quality of life, these ecosystems have commonly been degraded by anthropogenic activities. One example is the altering of wetlands for agricultural purposes (Davis and Froend 1999). California has lost more wetlands than any other state in the United States since the 1700s (Dahl 1990). Elkhorn Slough, the second largest salt marsh in California after the San Francisco Bay, is a clear example of anthropogenic impacts on wetlands within California.

Over the past 150 years, roughly half of the tidal marsh in the Elkhorn Slough, about 1,000 acres, has been decimated as a result of human interference (Watson 2011). The loss of wetlands in the slough is due to consistent flooding caused by high tidal flow and increased rates of erosion in the slough's channels as a result of this flooding. A channel was cut through the sand dune between Monterey Bay and the Elkhorn Slough for the construction of the Moss Landing Harbor in 1947, causing the channels in the slough to become deeper and wider (Marks 2011). In an effort to reduce the tide's speed and prevent dirt and mud from being carried

out to sea, the Elkhorn Slough Tidal Wetlands Project constructed a 200 ft by 15 ft sill at the inlet of Parson's slough, which at high tide, holds a third of the total water in the Elkhorn Slough (Watson 2011). The sill was completed in 2011 and was anticipated to build up the land in the marsh by trapping mud in the estuary and depositing it at plant level during high tide events. It was hoped that the marshes would become drier and healthier over time as the land in the marsh was built up to higher levels (Watson 2011).

The addition of the sill to the inlet of Parson's slough has the potential to substantially decrease high tide flow and erosion rates, positively influencing the health and longevity of the wetlands in the Elkhorn Slough. It is important, however, to monitor the effects that the sill has on its surrounding natural environment, to ensure that the expectations of benefits for the sill's presence are being met. If ignored, there is a possibility that the sill will be more harmful than beneficial for the wetland survival. For example, after the creation of the sill, a large stream of water was created, making direct contact with the bank opposite of Parson's Slough. It is possible that the impact of this stream is causing high bank erosion rates, which is one of the detrimental effects that the sill was initially built to prevent.

Since 1993, data has been collected annually to measure rates of erosion in the channels of the Elkhorn Slough. However, there is a lack of research in determining the effects of these restoration efforts on erosion rates in the Elkhorn Slough. This study will utilize time series data collected from Fall of 2009 to Fall of 2015, to analyze how the spatial distributions and rates of tidal scour of the Elkhorn Slough's intertidal and subtidal zones have changed over time. We are specifically interested in which of the eight zones of the Elkhorn Slough are undergoing the greatest changes in erosion and deposition rates, and how the addition of the sill at the inlet of Parson's Slough may be influencing these rates.

We postulated the following:

- The zones of the Elkhorn Slough experiencing the greatest rates of bank erosion are located closer to the mouth of the slough, due to its exposure to the tide
- Tidal volumes of the main channel of the Elkhorn Slough have increased in each zone since Fall 2009
- Since the construction of the sill at the inlet of Parson's Slough in 2011, the Parson's Slough has experienced lower erosion rates and higher deposition rate

The decline of wetland area has resulted in a large reduction of critical habitat for a variety of ecologically important flora and fauna. By identifying the relative rates of erosion and changes in erosion areas over time, we can determine whether or not the sill is having a positive effect on its surrounding environment, and further, assess what elements of the sill's constructional design may need to be altered for future conservation effort improvements.

Methods

Study Site

Elkhorn Slough is located along the Monterey Bay Peninsula, California and connects to the Moss Landing Harbor at its mouth and continues inland and northward for 10 kilometers (Fig. 1) (Broenkow and Breaker 2005). Since its exposure to the harbor in 1947, the slough has been subject to a myriad of disturbances including tidal flow, salinity, nutrient and pollutant exposure, and domination of mudflats (Broenkow and Breaker 2005). Current efforts to characterize hydrography of the slough to monitor erosion, monitor invasive species and pollution are part of the goals for the Elkhorn Slough Foundation and the Reserve

(Elkhornslough.org). Part of the effort to curb erosion included a sill built in Parson's slough, a small inlet branching away from the mouth of the slough as an effort to restore more "natural" tidal flow (which is otherwise unequal in its ebb and flow) and restore a wetland habitat of salt marsh instead of mudflat (Broenkow and Breaker 2005, Tidal Wetland Project).



Figure 1. Elkhorn Slough study site with polygons for zonal differentiation. Zone 1 = Foreslough, Zone 2 = Seal Bend, Zone 3 = Seal Bend to Parson's Slough, Zone 4 = Parson's Slough, Zone 5 = Midslough I, Zone 6 = Midslough II, Zone 7 = Backslough I, Zone 8 = Backslough II.

Data Collection

Multibeam sonar and LIDAR data has been collected regularly by the Seafloor Mapping Lab at CSUMB for the past two decades, and has covered the majority of the slough in the form of subtidal, intertidal and mudflat data.

For this study datasets from 2009, 2011, and 2015 (spring and fall) were used. For 2011, 50 cm DEMs have been already prepared as ArcGIS grid by the Seafloor Mapping Lab at CSUMB. All topographic data files are in NAD83 (epoch2002) from CORS P210 station and NAVD88 Geoid09 using Corpscon. The Fall 2015 dataset was collected in September 27 and 28 on the lab's *MacGinitie* vessel. Data was corrected using an Inertial Measurement Unit (IMU) to correct for pitch, roll and yaw, a 2 antennae GPS Azimuthal Measuring System for heading and aiding to record real-world location (to collect a smoothed best estimate of trajectory or SBET),

and a 468 kHz SwathPlus Interferometric Bathymetric sidescan sonar unit was used to measure wide swaths of the slough. A YSI Castaway SVP was used to collect casts to reduce refraction in measurements.

Data Processing

Ground truthing data was taken at Kirby park on November 20, 2015 and December 4, 2015 to ensure accuracy of our soundings using two rapid static (20 minutes each) and one static (2 hour) recording. For the static recording, the geomarker located on the Kirby Park dock was used as a stationary point for elevation comparison over time. For the rapid static measurements, one recording was taken at the bottom of the boat launching ramp near the shoreline using a Zephyr geodetic model 1 antenna with receiver 5700. The second recording was taken towards the top of the boat launching ramp during low tide using a Zephyr geodetic model 2 antenna with receiver NetR5. The collected ground truthing data was entered into OPUS (Online Positioning User Service as part of the National Geodetic Survey website through NOAA), using the designated antenna types and heights, to determine if elevation measurements from the recording locations were consistent over time between 2009 and Fall of 2015.

Bathymetry data of Fall 2015 was imported into CARIS HIPS and SIPS 8.1 and cleaned of artifacts and incorrect data by using both swath and subset editors. Resolution was set for 1 meter. Swath editing along each track line was performed first in order to reject off-beam data, and subset editing was used as a fine editing tool to reject data of smaller artifacts across multiple track lines. Any holes in the BASE surface of cleaned data were restored by accepting back data that may fill in. Using CARIS HIPS and SIPS Export Wizard, cleaned data were exported from CARIS as ungridded high resolution XYZs in text format and imported into Fledermaus DMagic Version 7.4.1, 64bit edition. Fledermaus DMagic was used to grid and shade the XYZ data. The output SD-file was examined in Fledermaus (Version 7.4.1, 64bit edition), if all artifacts had been removed and could be re-edited back in CARIS if needed. Cell size was set to the same value as resolution in CARIS. Within Fledermaus Dmagic, an ASCII grid file was exported to be opened as a Digital Elevation Model (DEM) inside ESRI ArcMap 10.2.2.

PFMs of the intertidal laser data of 2009 and 2015 (spring and fall) were imported into Fledermaus and all erroneous points were edited manually to create cleaned high resolution (1m) XYZ data. Fledermaus DMagic was used to grid and shade the XYZ data, and an ASCII grid file was then exported to be opened as a Digital Elevation Model (DEM) inside ESRI ArcMap 10.2.2. A similar process was used for mudflat data, with the mudflat point cloud having been edited in Fledermaus for outliers, and then similarly exported using the same process to create DEMs in ArcMap.

GIS Analysis for mudflat change

Resultant DEMs of 1 meter resolution were compiled pre-sill from 2009 to post-sill construction in 2011 and 2015 Spring and Fall datasets, and were used in the raster calculator to see net positive and net negative area change between observed years before and after sill construction. This was calculated using reclassification to categorize a meter-to-pixel scale of either displacement or addition between the years surveyed. Values that landed below and above -2 and 2 meters were ignored, respectively.

Rate of change between all surveyed years was calculated to get volumetric change within the mudflat zones. To get the elapsed time between surveys, the latest date of collection was used for each raster (when the final survey was collected) as a baseline, and months between each dataset were multiplied by 12 to get a yearly rate. The slough was split into zones to focus on certain areas of erosion/deposition as a method incorporated

in Falvoro 2015 originally used in Dean 2003, although this was done manually drawing new polygons as the given zone shapefiles on the Elkhorn Slough website did not include a lot of the mudflat area, and the splitting of zones was not provided in any shapefiles, so we performed a rough estimation of their boundaries by observing where zones had been split between sections in past studies. Total volume of erosion and deposition in these sections of mudflats was calculated using the reclassify tool, and multiplying the resulting negative and positive pixel sums for each section by the absolute value of the mean for the whole section. Values found outside of -2 and 2 meter ranges were ignored.

Thalweg and Cross Section Analysis for subtidal change

Zones were previously determined in the Elkhorn Slough. Cross sections taken in each zone were used to understand changes in bathymetry of the slough (Fig 2). In order to calculate thalweg and generate a depth comparison chart, the 1 meter resolution DEMs for 2009, 2011, and 2015 were used. In ArcMap 10.2.2, the Interpolate Line Tool under the 3D Analyst extension package was utilized to create depth profiles along the thalweg for the length of the slough. Profile graphs were exported into Microsoft Excel to generate appropriate charts.

The same Interpolate Line process was used to generate three cross section model for each of the slough's eight zones from Dean (2003). Locations of cross sections within each zone were chosen by locating geographic extents that had the most complete data for all representative years. Efforts were made to place each cross section in a way that represented the start, middle, and end of each zone. When using the Interpolate Line tool, it was necessary to create a cross section with start and end points that intersected the extent of all rasters used, in order to most accurately line up data between years. Cross section graphs were populated after importing raw data from ArcMap to Microsoft Excel. Averages were assimilated into one cross section chart per zone that is representative of the overall zone.

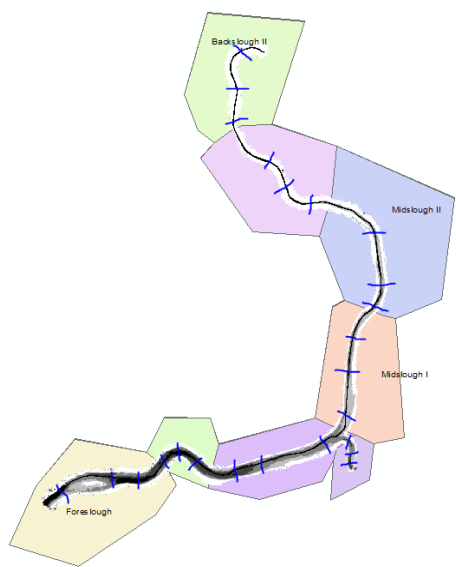


Figure 2. Locations of all Cross Sections within the Elkhorn Slough-- blue marks indicate location of a cross section. Three cross sections were placed within each zone at the deepest parts of the main channel.

Volumetric change of the subtidal zone

The Spatial Analyst Tool ‘Extract by Mask’ was used to bring 2009 and 2011 Bathymetric DEMs to the extent of the 2015 raster data. Each year was then clipped to the extent of each of the eight tidal scour zones defined by Dean (2003) in order to create a spatial subset of the rasters and compare volumetric changes by region within the slough. Resulting subset rasters were analyzed by using the classify option under Symbology properties and removing intertidal area by setting an exclusion for all data above 0 meters. Classification statistics were then used to output overall volume, depth range, and mean depth within each of the clipped layers. These estimates were used to calculate and characterize overall volumetric changes from 2009 to 2015. The difference was taken between overall volume in meters cubed between 2011 and 2009, and 2015 and 2011. These results are displayed in both overall volume difference and in percent change.

The raster for 2009 bathymetric data was found to have an unusually large amount of data missing. Using classification statistics, a rough estimate of the area of data missing was found. In order to update volumetric data in the slough for 2009 with a more accurate representation, the area of missing data was multiplied by the average depth of the slough within 2009 per zone. This was then added to calculated volume to increase accuracy to some extent. Admissions to the possible shortcomings of this method can be found in the Discussion section of this paper.

Table 1. Estimated time elapsed between surveys in order to generate yearly estimates

Survey Year	Reference Date	Elapsed time
2009	02/01	-
2011	12/01	2.833
2015 (Spring)	04/11	3.75
2015 (Fall)	09/27	0.462

To generate yearly rates of change, intertidal erosion and deposition rates, as well as subtidal volumetric data were divided by the estimated time elapsed in years (Table 1). Because surveys were taken at different times of the year, this step normalizes the data and accounts for this change (Favaloro 2015).

Results

Thalweg

The Elkhorn Slough is characterized by a gradual decrease in depth as the slough progresses from the fore slough to the back slough. Thalweg, the deepest point within the main channel, displays this. At its deepest point, the slough is just under 9.5 meters deep, and at the slough’s shallowest thalweg extends several centimeters below the banks (Figure 3). In the Foreslough and Midslough, the channel displays a deepening trend over time. From 2009 to 2015, thalweg increased by as much as two meters within these zones. Within zones 7 and 8 (Backslough), thalweg generally decreases in depth from 2009 to 2015. Within the zones upstream from Parson’s slough (5 - 8), thalweg analysis shows decreasing depth from 2009 to 2015. The thalweg at the mouth of the slough is deeper than previous years.

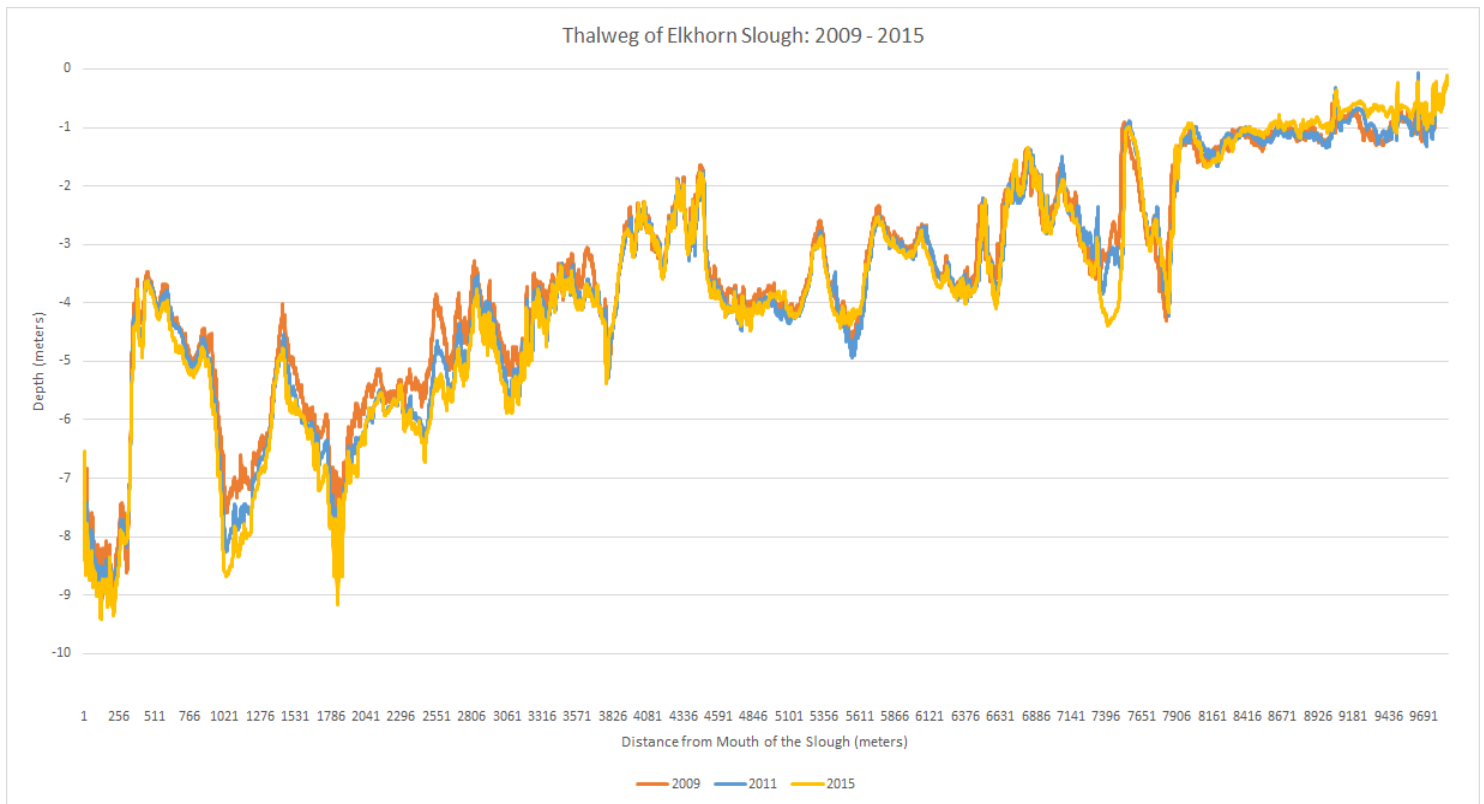


Figure 3. Elkhorn slough thalweg comparison for 2009, 2011, and 2015 depths. Depth measurements were taken at the deepest point of the main channel of the Elkhorn Slough, from the mouth (far left) to the Backslough (far right).

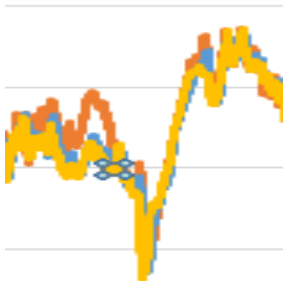
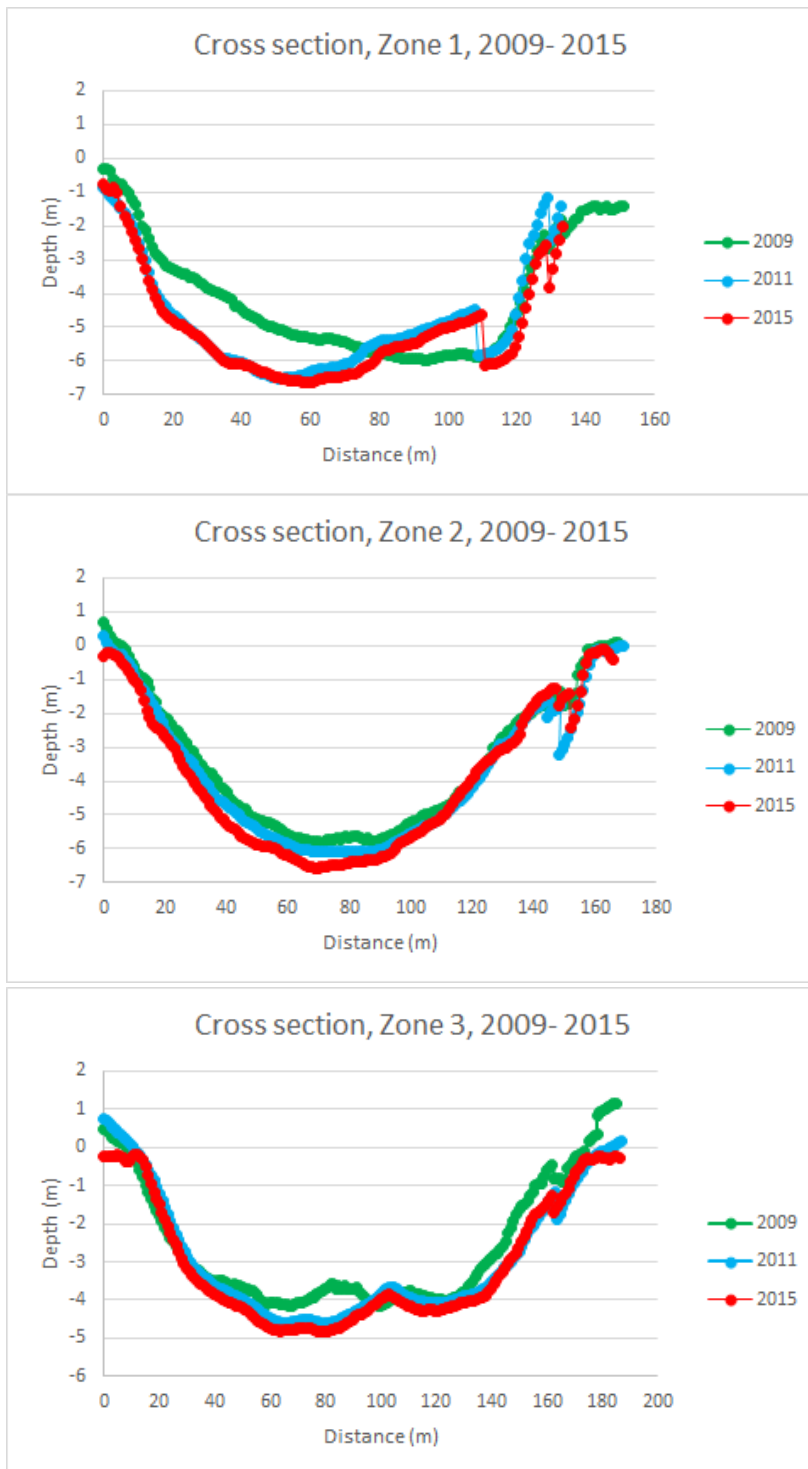


Figure 4. Thalweg at mouth to Parson's slough

Figure 4 represents the section of the Elkhorn Slough thalweg, around 3,800 meters from the mouth of the slough, which is the area of the channel where the Parson's slough lets out. There is minimal change in thalweg from 2009 to 2015 in the area of the channel where Parson's Slough opens into the main channel of Elkhorn Slough. On the other hand, the zone that received the greatest increase in thalweg in 2015 was Zone 6. Figure 3 shows a large dip in thalweg in 2015 at around 7,400 meters from the slough mouth.

Cross Sections and Depth Profiles



Figures 4 a,b, c. Cross sections of the Foreslough (Zone 1), Seal Bend (Zone 2), and Seal Bend to Parson's Slough (Zone 3), representing depth changes in each zone for the years 2009, 2011, and 2015. Cross sections were created at the deepest part of the main channel for each zone.

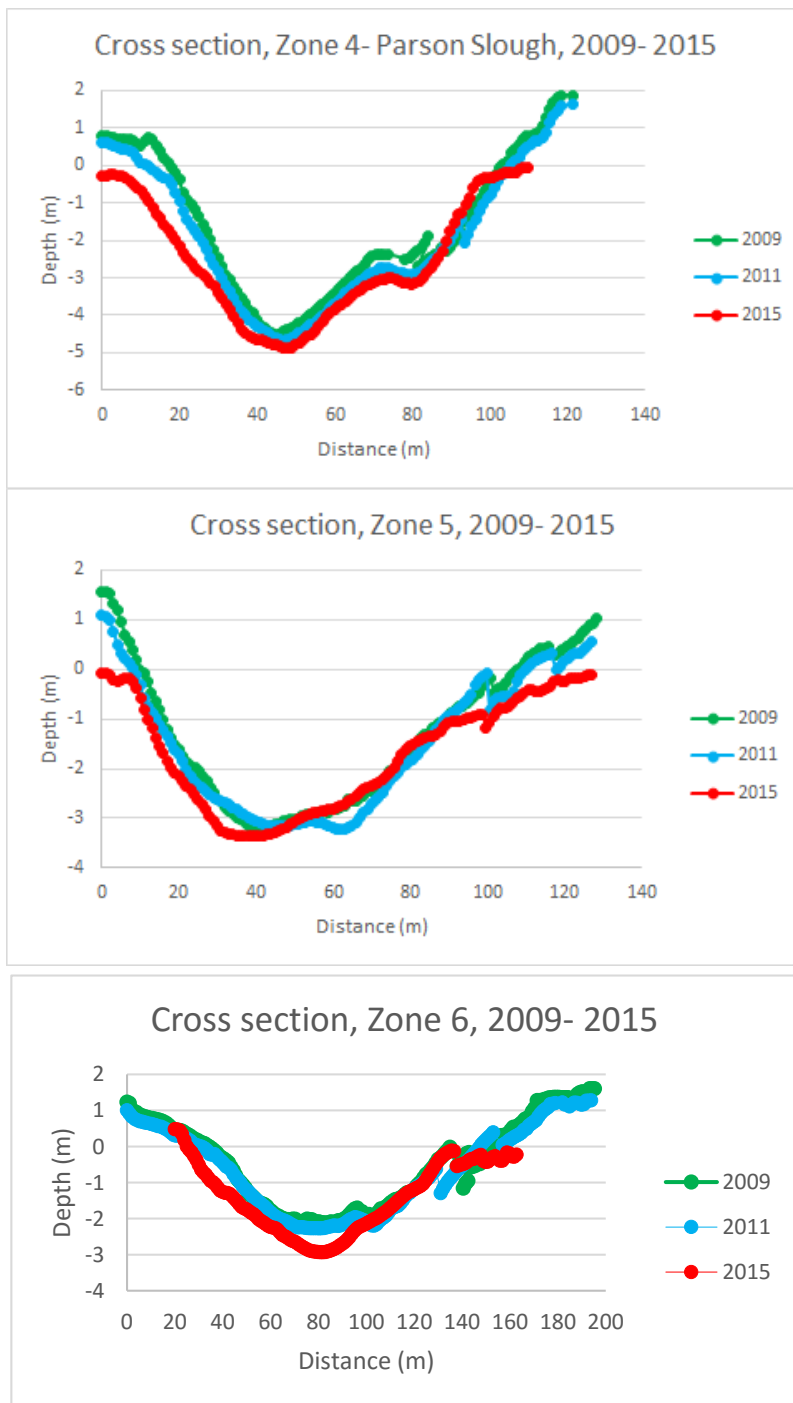


Figure 5a,b,c. Cross sections of the Parson's Slough (Zone 4), Midslough I (Zone 5), and Midslough II (Zone 6), representing depth changes in each zone for the years 2009, 2011, and 2015. Cross sections were created at the deepest part of the main channel for each zone.

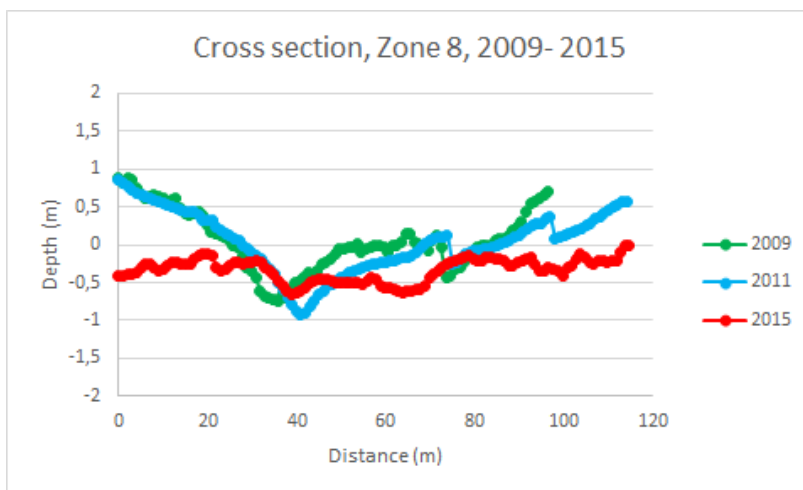
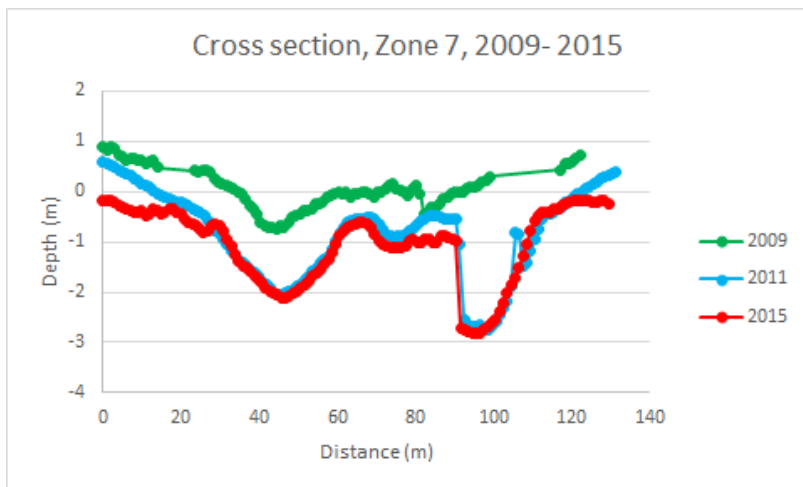


Figure 7 a, b. Cross sections of the Backslough I (Zone 7) and Backslough II (Zone 8), representing depth changes in each zone for the years 2009, 2011, and 2015. Cross sections were created at the deepest part of the main channel for each zone.

The cross sections from 2015 showed greater depths for each section of the Elkhorn Slough than 2011. The cross sections from 2011 showed greater depths than 2009 for each section. Zones 1, 2, 3, 4 and 7 showed a difference between 2009 and 2011 but little difference between 2011 and 2015 (Figs. 4 through 7). Zones 5, 6 and 8 showed higher variation from year to year. Zones 5 and 6 were deeper in 2015 than in 2009 and 2011 (Fig. 4b,c). Similar to displayed by the thalweg graph, Zone 6 experienced the greatest increase in depth than other parts of the slough. However, within Zone 5, just above the Parson's slough, the location of the thalweg shifted from 2009 to 2015, resulting in places within the channel that were shallower than previous years. Zone 8 showed decreased depth than previous years and an overall appearance of flattening and evening of terrain within the channel.

Subtidal Zone Volumetric Changes

Table 2. Changes in main channel volume for each zone in the Elkhorn Slough for 2009-2011 and 2011-2015. Positive values suggest erosion over time, while negative values suggest deposition.

	2009 - 2011		2011 - 2015	
	Change (meters)	Change (%)	Change (meters)	Change (%)
Zone 1	189,272.82	25%	110562.405	12%
Zone 2	38,535.62	9%	24290.375	5%
Zone 3	-51,693.57	-6%	50706.218	6%
Zone 4 (Parson's)	14,144.41	19%	12690.185	14%
Zone 5	25,268.71	8%	16571.7355	5%
Zone 6	19,291.43	8%	13934.101	5%
Zone 7	16,016.06	18%	-1870.549	-2%
Zone 8	1,551.63	5%	-6805.91	-21%

Table 3. Total changes in main channel volume of the Elkhorn Slough and Parson's Slough between 2009-2011 and between 2011-2015. Positive values suggest erosion over time.

	2009 - 2011		2011 - 2015	
	Change (meters)	Change (%)	Change (meters)	Change (%)
Total Elkhorn Slough	252,387.11	9%	220078.5605	7%
Parson's Slough	14,144.41	19%	12690.185	14%
Upstream of Parson's	62,127.84	9%	21829.3775	3%
Downstream of Parson's	176,114.87	9%	185558.998	8%

Table 4. Average annual changes in main channel volume for each zone of the Elkhorn Slough within time periods of 2009-2011 and 2011-2015. Positive values suggest erosion over time, while negative values suggest deposition.

	2009 - 2011		2011 - 2015	
	Average Annual Change	Average Annual % Change	Average Annual Change	Average Annual % Change
Zone 1	66810.03	8.7%	29483.31	3.1%
Zone 2	13602.41	3.3%	6477.43	1.4%
Zone 3	-18246.94	-2.1%	13521.66	1.6%
Zone 4 (Parson's)	4992.73	6.7%	3384.05	3.8%
Zone 5	8919.42	2.8%	4419.13	1.3%
Zone 6	6809.54	2.7%	3715.76	1.4%
Zone 7	5653.39	6.4%	-498.81	-0.5%
Zone 8	547.7	1.8%	-1814.91	-5.6%

Table 5. Average annual changes in total main channel volume of the Elkhorn Slough and Parson's Slough between 2009-2011 and between 2011-2015. Positive values suggest erosion over time.

	2009 - 2011		2011 - 2015	
	Average Annual Change	Average Annual % Change	Average Annual Change	Average Annual % Change
Total Elkhorn Slough	89088.29	3.2%	58687.62	1.9%
Parson's Slough	4992.73	6.7%	3384.05	3.8%
Upstream of Parson's	21930.05	3.2%	5821.17	0.8%
Downstream of Parson's	62165.5	3.0%	49482.4	2.2%

Between 2009 and 2011, the zones that experienced the greatest total volumetric changes were zones 1, 4, and 7. Between 2011 and 2015, zones 1, 4, and 8 experienced the greatest changes in volume. In the 2009-2011 time period, the only zone that experience deposition (versus erosion) was zone 3, while from 2011-2015, zones 7 and 8 both experienced deposition (Table 2). These findings were identical to the average annual volumetric change results per zone of the Elkhorn Slough (Table 4).

The Parson's Slough had a lower overall change in volume after the addition of the sill (2011-2015), compared to the period before the sill was put into place at the inlet of Parson's Slough (2009-2011) (Table 2). Average annual changes in main channel volume in the Parson's Slough between 2011 and 2015 were also lower, compared to the average annual changes between 2009 and 2011 (Table 4).

Overall, the Elkhorn Slough, Parson's Slough, and areas upstream and downstream of the Parson's Slough all experienced less total erosion and volumetric change of the main channel between 2011 and 2015 compared to the 2009-2011 time period (Table 3). The average annual volumetric changes in total main channel volume of these regions also suggested a decrease in erosion activity between 2011 and 2015 compared to 2009-2011 (Table 5).

Table 6. Net Positive and Net Negative Change in slough. Raster subtractions yielded sums of pixels that included a net negative change and net positive change between years.

Years Examined	Net Negative Area difference	Net Positive Area addition
2011-2015	-50559	401414
2009-2011	-241620	218347
2015f-2015s	-8091	582605

Mudflat changes

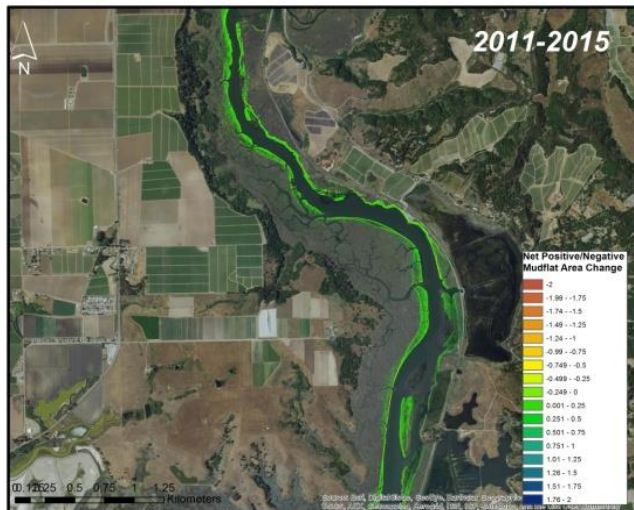
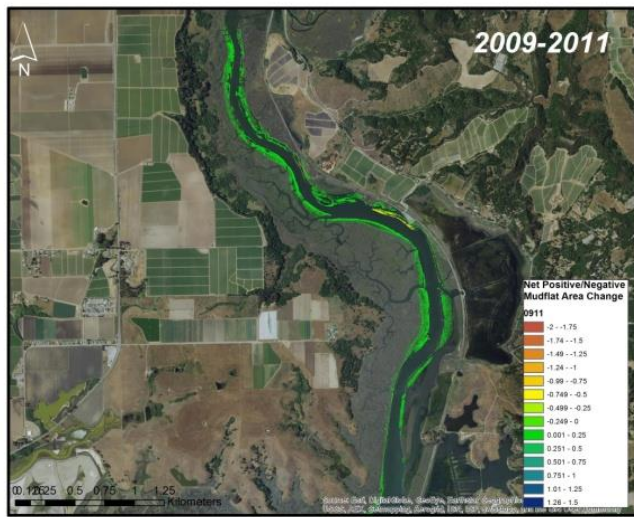
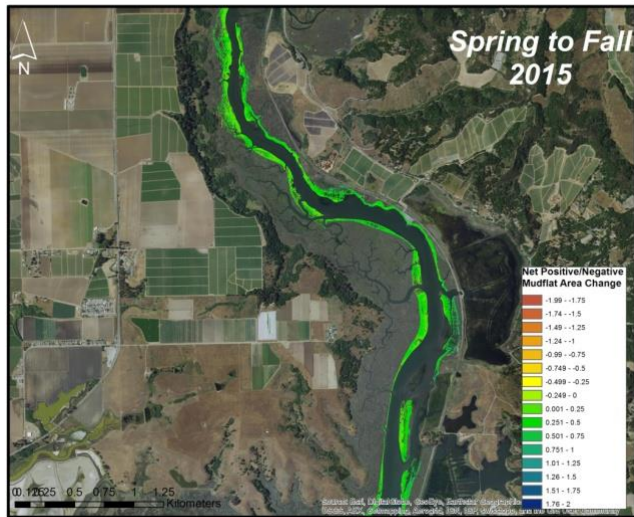


Figure 6abc. Net Positive and Negative change for Upper Slough region. Values represent elevation differences between survey dates yielded from raster subtractions. Units are in meters.

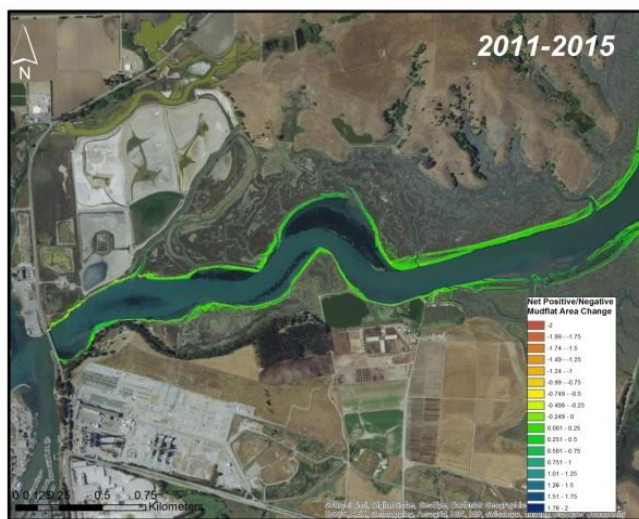
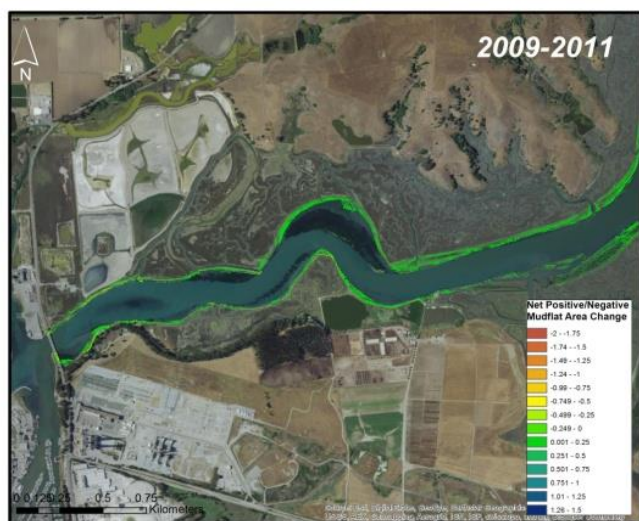
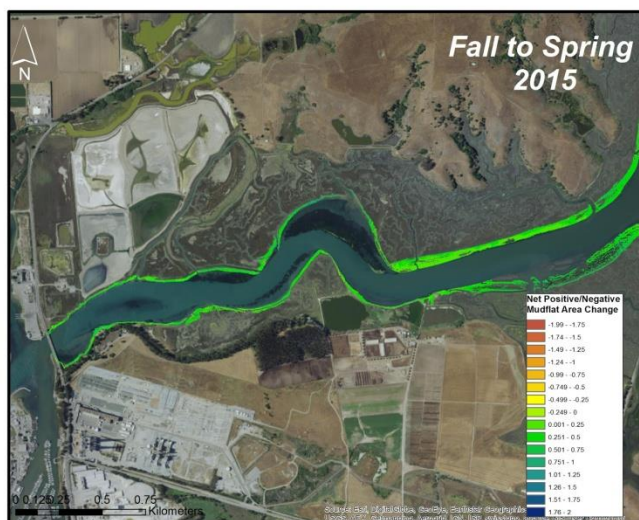


Figure 7abc. Net Positive and Negative change for Lower Slough region. Values represent elevation differences between survey dates yielded from raster subtractions. Units are in meters.

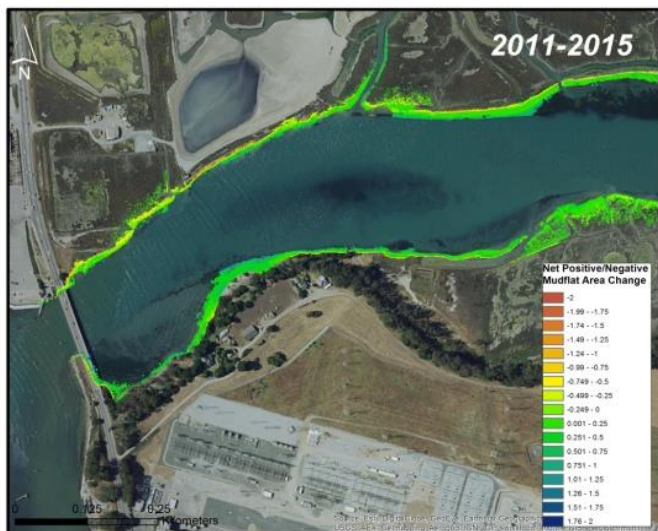
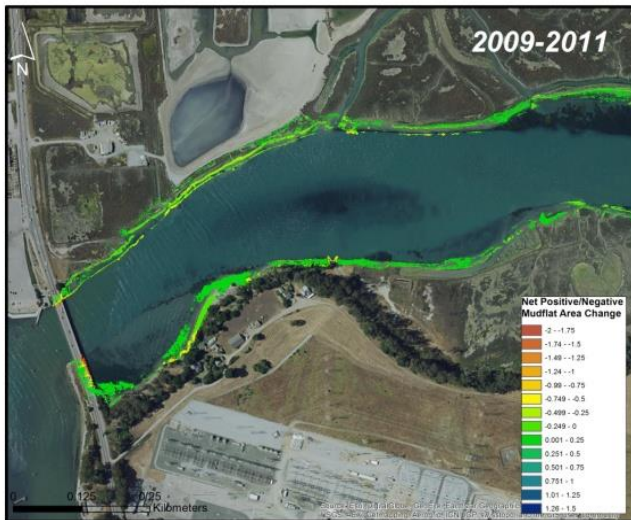
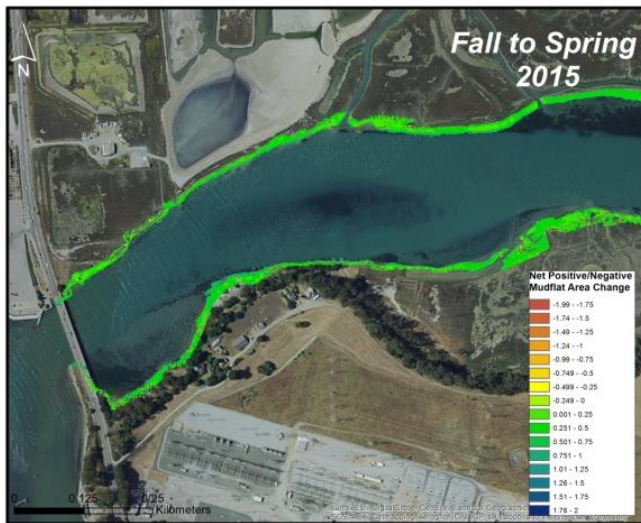


Figure 8abc. Net Positive and Negative change for mouth of slough leading into Moss Landing Harbor. Values represent elevation differences yielded from raster subtractions. Units are in meters.

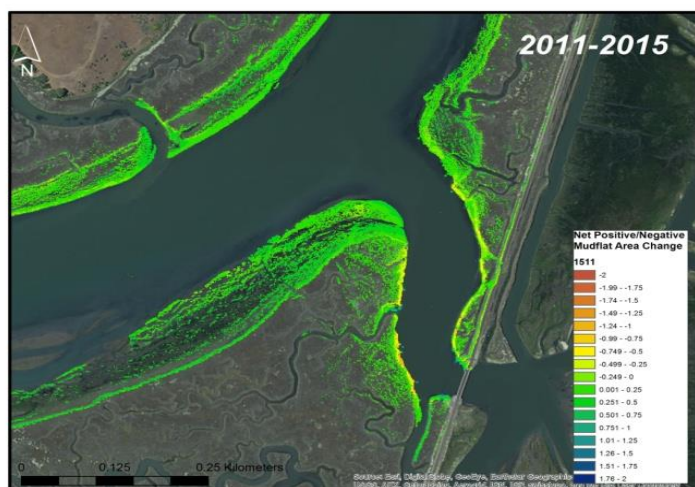
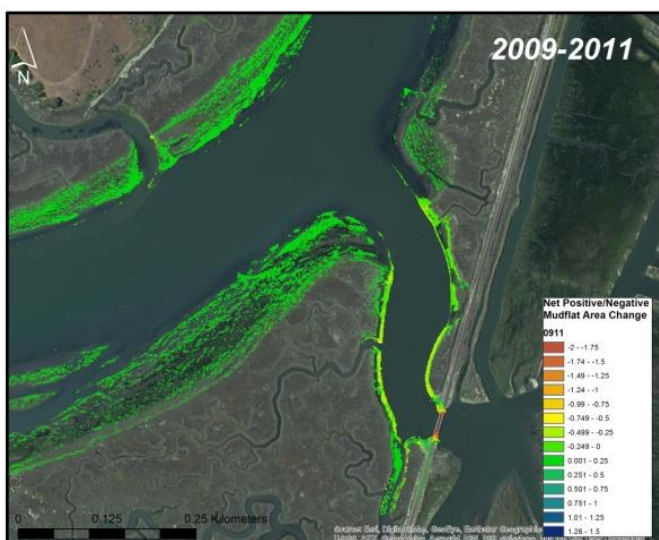
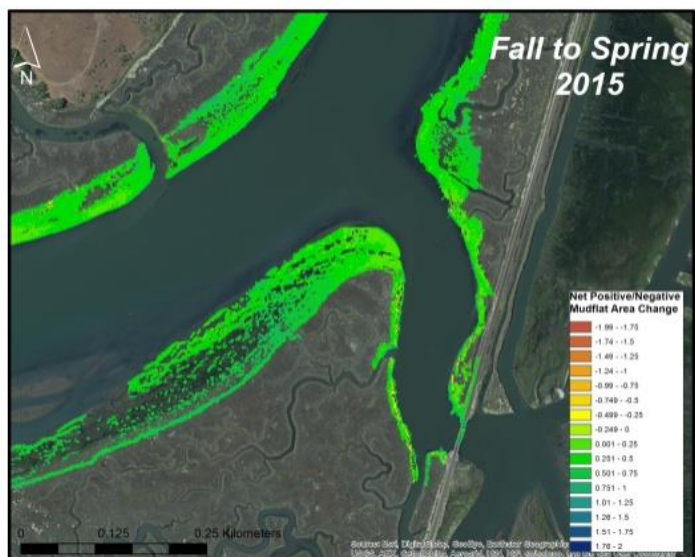


Figure 9abc. Net Positive and Negative change for Parson's Slough. Values represent elevation differences yielded from raster subtractions. Units are in meters.

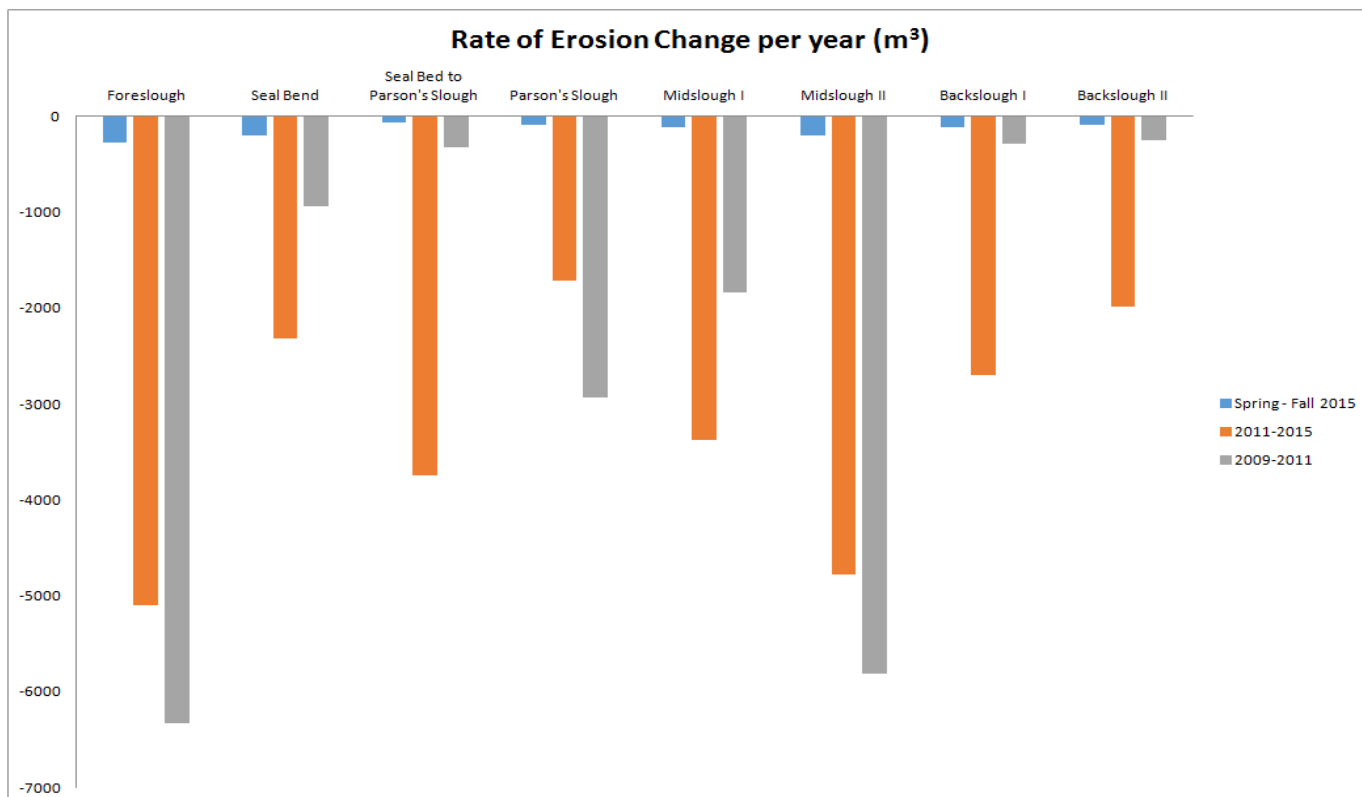


Figure 10. Rate of Erosion Change per year. Results in this figure are summarized from Table X. The rate represents the total volume displaced between survey dates examined in GIS.

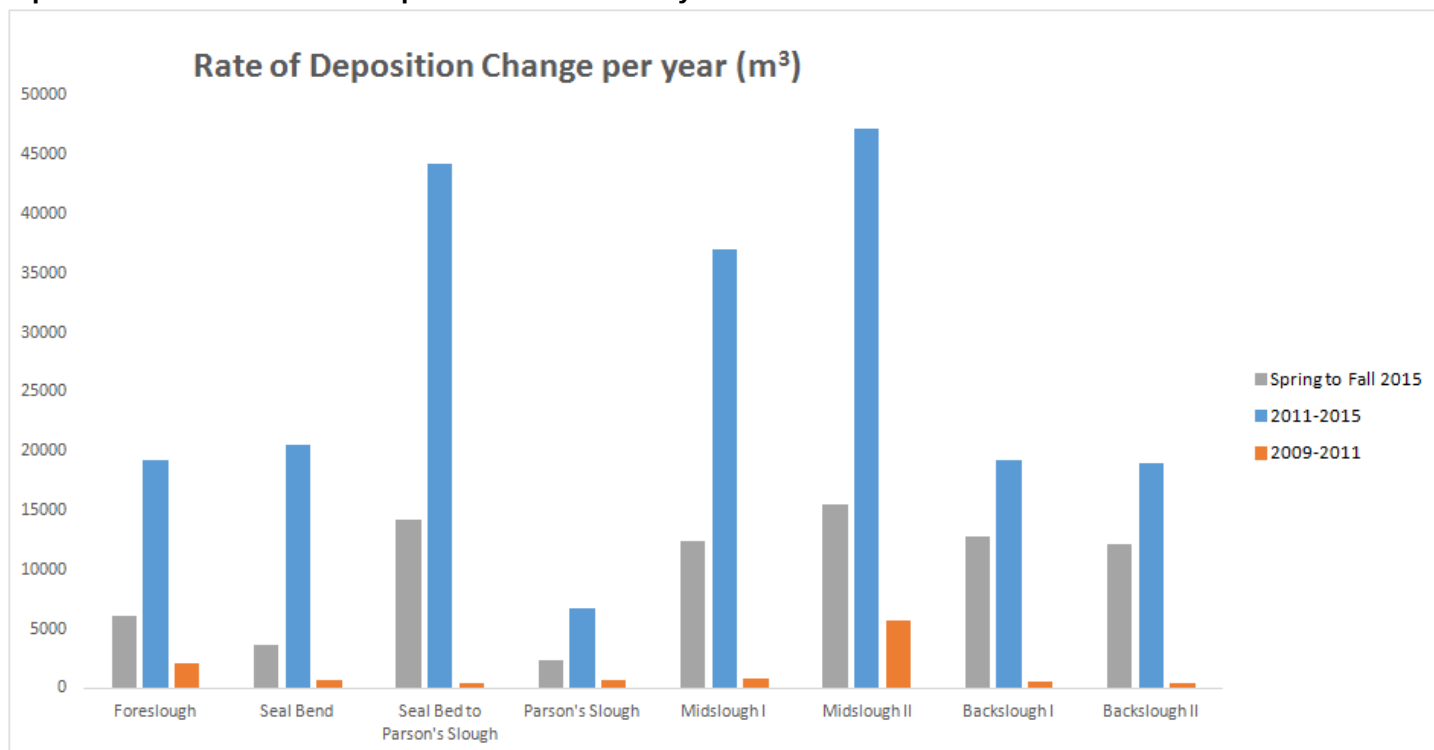


Figure 11. Rate of Deposition Change per year. Results in this figure are summarized from Table X. The rate represents the total volume displaced between survey dates examined in GIS.

Spring-Fall 2015 (y=5/12)	Sum of Net Negative Pixels	Sum of Net Positive Pixels	Mean of Subtraction Raster (zonal)	Actual Rate Erosion	Actual Rate Deposition
Foreslough	-1888	42256	0.347034	-273	6110.107
Seal Bend	-1205	21787	0.400688	-201.179	3637.416
Seal Bed to Parson's Slough	-490	99726	0.343521	-70.1355	14274.15
Parson's Slough	-687	17688	0.322898	-92.4297	2379.762
Midslough I	-788	83220	0.359828	-118.143	12477.03
Midslough II	-1363	106867	0.347906	-197.582	15491.55
Backslough I	-938	106064	0.288534	-112.769	12751.28
Backslough II	-726	105208	0.278733	-84.3166	12218.71
2011-2015 (y=3.75)					
Foreslough	-9674	36405	0.140643	-5102.18	19200.43
Seal Bend	-2759	24421	0.223728	-2314.74	20488.72
Seal Bed to Parson's Slough	-5623	66433	0.177454	-3741.83	44207.91
Parson's Slough	-4059	16080	0.112454	-1711.69	6780.994
Midslough I	-5604	61464	0.16061	-3375.21	37018.93
Midslough II	-7482	73920	0.170302	-4778.26	47207.81
Backslough I	-8713	61853	0.082748	-2703.68	19193.25
Backslough II	-6382	61014	0.083076	-1988.21	19007.97
2009-2011 (y=2.833)					
Foreslough	-36641	12227	-0.06094	-6327.04	2111.316
Seal Bend	-43172	31680	-0.00766	-936.727	687.3788
Seal Bed to Parson's Slough	-12279	18785	-0.00939	-326.617	499.6742
Parson's Slough	-13163	2966	-0.07873	-2936.11	661.5891
Midslough I	-39266	17630	-0.01648	-1833.77	823.3403
Midslough II	-55287	54634	-0.03712	-5814.21	5745.537
Backslough I	-30287	58495	0.003405	-292.17	564.2848
Backslough II	-11755	21925	0.007643	-254.558	474.7924

Table 7. represents methodology and results for erosion and deposition rates of each zone in the Elkhorn Slough. Means were calculated for each zone using masks as displayed in Figure 1. No values between -2 and 2 meters were excluded.

There was a large observed net negative change immediately before and after sill construction in the slough, although a net positive change was largest for the years proceeding sill construction (Table 7). We noticed an anomaly in the data where between fall and spring of 2015, there was a large net positive gain in area of the slough compared to other year-spans (Table 7). Hotspots for change were found inland within Parson's Slough, as well as near the mouth of the slough entering into Moss Landing Harbor (Figs 6-9abc). Rate of erosion was highest in the Foreslough and Midslough II sections for most year spans except for Spring to Fall 2015, where the rate of erosion was similar to Seal Bend (Figure 10, Table 7). The rate of deposition was highest for the Seal Bend to Parson's slough and Midslough II sections, and remained highest in all years without exceptions (Fig 11, Table 7). Parson's slough maintained a low rate of erosion and deposition relative

to other sites due to its size, however, deposition rate was higher after sill construction for both 2011-2015 and 2015 spring and fall changes (Table 7).

Discussion

The results of this study support our postulates. The zones of the Elkhorn Slough experiencing the greatest rates of bank erosion are located closer to the mouth of the slough, due to its exposure to the tide. The results of the results of the volumetric analyses of the subtidal zone confirm that the mouth of the slough experienced the greatest rates of erosion. The postulate that tidal volumes of the main channel of the Elkhorn Slough have increased in each zone since Fall 2009 was supported by the results of volumetric analyses, thalweg analyses and cross sectional analyses. However, the rates of erosion have decreased since the installation of the sill at Parson's Slough. We postulated that since the construction of the sill at the inlet of Parson's Slough in 2011, the Parson's Slough has experienced lower erosion rates and higher deposition rate. This postulate was supported by all of the analyses we conducted. The annual average percent of change at Parson's Slough decreased from 6.7 percent change to 3.8 percent change.

This study demonstrates that there has been less erosion in Elkhorn Slough between the 2011-2015 datasets than between 2009-2011 datasets. Cross sectional data showed more differences occurred between the 2009 dataset and the 2011 dataset than between 2011 and 2015. Thalweg data showed that most of the depth changes occurred near the mouth of the slough and slowed in the back of the slough. Volumetric data showed that percent change in Elkhorn Slough main channel has decreased between 2009-2011 datasets and 2011-2015 datasets. One exception is the large erosion rates at the deepest points within zone 6, an area that otherwise had only small increases in overall erosion. Changes in mudflat data showed hotspots for change were found inland within Parson's Slough, as well as near the mouth of the slough entering into Moss Landing Harbor.

We expected to see more erosion than deposition overall and while there was erosion in some locations, the data suggested that there was a large net positive gain between fall and spring of 2015. We observed less erosion at Parson's Slough from 2011 to 2015, suggesting that the sill was successful at reducing rate of erosion.

The results from the mudflat changes show areas of deposition. The back slough is characterized by higher rates of deposition than the mid and foreslough within the subtidal channel. The hotspots of change that we observed correspond with previous studies (Favaloro 2015). As observed in previous years, there were hotspots for erosion in the foreslough and in Parson's Slough. Favaloro (2015) observed a trend in Parson's Slough that shifted from erosion to deposition. The results from our analyses support this trend with more deposition in Parson's Slough. The sediment that eroded from the banks could have deposited on the mudflats, making it seem as if deposition occurred but it was not deposition in the traditional sense where sediment was moved from outer streams toward the main channel.

There were multiple sources of error with the analyses which could have led to less accurate results. Using polygons created for the CSUMB Seafloor Mapping Lab which were synonymous with previous studies may yield rates closer to those of before because creating new polygons from looking at previously created posters may have created some disconnect between previous studies and this one.

There could have been errors made while cleaning the data in Fledermaus. Artifacts could have been kept instead of rejected because they appeared to be parts of the intertidal or they were higher elevations than mudflats realistically sit in the slough. Data that could have suggested more erosion may have been rejected in

an effort to make the data cleaner. Important features of the intertidal may have been rejected. These errors could yield different results in terms of rate of change and where erosion and deposition were seen. On the other side of this kind of data cleaning, values that could have been artifacts versus actual data may not have been rejected, leading to our conclusion that there was more deposition than there actually was. Comparing the pointmap created in Fledermaus to an aerial image can prevent this mistake in the future.

When generating cross sections and thalweg using the interpolate line tool, constraints with the tool made it necessary to draw over each cross section individually for 2009, 2011, and 2015. This method creates room for error as hand-drawing estimated lines on top of each other is not a precise and reliable way to capture the exact same locations. Lines are estimated to be within ± 1 meter range of each other on the water's surface.

2009 Bathymetric data had missing data for an area of approximately 300,000 square meters within the entirety of the slough. This large section of missing data made it impossible to accurately characterize subtidal volume changes in the slough. To rectify this error, volumetric data for 2009 was calculated using average depth per zone values for all missing data. While this brings volumetric data closer to accurate values, this method is rough and does not account for many possible variations. Thus comparisons to subtidal volumetric changes are more appropriate and reliable from a time scale between 2011 and 2015.

Another source of error was that the pixels from the DEMs did not overlap perfectly because someone skipped a step when they were converting the files for use in GIS. The raster subtractions were not as accurate as they could have been. This could have led to variation in the hotspots that we observed. There were multiple sources of error that could have been remedied with more careful eyes, better management of time and potentially asking for help when we weren't certain of an analytical method.

Conclusion

Erosion is still occurring in Elkhorn Slough, but since the construction of the sill at Parson's Slough, the rate of erosion has decreased in most of the slough. Hotspots still occur near the mouth of the slough and in Parson's Slough. The construction of the sill in Parson's Slough has been successful at reducing rates of erosion in most parts of Elkhorn Slough.

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