Coastal Wetland Loss: A Study of an Elkhorn Slough Tributary

A Capstone Project

Presented to the Faculty of Science and Environmental Policy

in the

College of Science, Media Arts, and Technology

at

California State University, Monterey Bay

in Partial Fulfillment of the Requirements for the Degree of

Bachelor of Science

By

Emiko Shironaka

29 May 2007

To the SEP Faculty,

Coastal wetland loss all over the world is becoming a matter of increasing public concern. Coastal wetlands are important because they provide protection from episodic events, habitat for rich biodiversity, research sites, places for urban and rural expansion, and tourism. California wetlands are being lost to human development. This loss decreases available habitat, effects tourism, and increases the importance of marine research to aid in the sustainable management of urban and rural communities. The focus of my study is Elkhorn Slough, one of the largest and most important remaining coastal wetlands in California.

Elkhorn Slough is a highly modified and heavily utilized marine tidal embayment surrounded by 5,000 year old salt marsh undergoing rapid environmental change due to human induced tidal scour and erosion. These environmental changes are of concern because the Slough tidal creeks have traditionally served as an important nursery ground for many fish species of commercial and recreational importance. While the widening of Elkhorn Slough's main channel due to tidal scour and erosion has been quantified in previous studies, there are not reliable data for rates of change within the tidal creeks. If these creeks are changing, i.e. getting deeper and wider and becoming more like the main channel, they will lose their value as a nursery ground for fish. Prior work obtained baseline data for some tidal creek cross-sections in the more recently opened Parsons Slough tributary of the Elkhorn Slough system. Prior studies include the Oliver et. al. 1988 study, which was the first study conducted showing the erosion of tidal scour of the slough. The Malzone 1993 study compared the Oliver et. al study to his own, which focused on the erosion of the main channel and the mouth of Parsons Slough. He quantified the rate of change by tidal scour in Parsons Slough mouth to be $3.0 \times 10^3 m^3/yr$ (Malzone 1999). The Dean 2001 work quantified tidal scour in the main channel and the mouth of Parsons Slough as well. He quantified the rate of tidal scour in Parsons Slough to be $-4.6 \times 10^4 m^3/yr$ (Dean 2003). Sampey further quantified the rate of erosion of the main channel and Parsons Slough head. He found the rate of erosion in Parsons Slough to be $1.39 x 10^6 m^3/yr$ (Sampey 2003). The purpose of my research is to measure the rates of change along Parsons Slough main tidal creek (its central channel) and compare them with those calculated for Elkhorn Slough main channel. I will test three hypotheses: the Parsons Slough tidal creek is eroding and becoming more like the Elkhorn Slough main channel environment; this tidal creek has not changed and is at equilibrium; this tidal creek is experiencing deposition and shrinking in cross-sectional area.

I used an aluminum skiff with a 5.0 horsepower motor, RV MiniMe, to reproduce a baseline erosion study from a previous 2003 study and cross-sections of the seafloor of Parsons Slough. I used a single beam depth sounder to produce cross-sectional profiles of the seafloor. I then compared my cross-sectional data to the 2003 survey. I calculated the cross-sectional area and percent change in the main channel between 2001 and 2003 and the Parsons Slough data from 2003 and my survey in 2006.

Successful restoration efforts must be continually adjusted to fit the accelerated erosion from tidal scour. A panel composed of different organizations is collaborating to create a tidal wetland plan for restoration at Elkhorn Slough. The results from this study will be used by the Elkhorn Slough National Estuarine Research Reserve (NERR) and the Tidal Wetland Management Plan to make management decisions for the Slough.

I collaborated with various people at the Elkhorn Slough Reserve. Eric Van Dyke helped provide me with georeferenced low tide images of the Reserve to use during my survey. Kerstin Wasson granted my team a permit and notified the authorities when we were on the water.

I also worked with a co-worker, Jeremiah Brantner, a Coastal and Watershed Science and Policy graduate student at the Seafloor Mapping Lab. He did the 2001 study of the Elkhorn Slough main channel. He helped me plan and execute my survey. He also taught me how to process a single beam survey, of which I had no previous knowledge. I was funded by the Center for Integrative Coastal Observation, Research, and Education (CICORE).

I have written this paper for an audience with no knowledge of the slough and some scientific background. However, I expect that this paper may also be used to make management decisions at the Elkhorn Slough Research Reserve. This capstone project is in fulfillment of the major leaning outcome number eight (MLO # 8) for scientific inquiry.

As an Earth Systems Science and Policy (ESSP) student I believe that wetland conservation is important. My survey of Parsons Slough main channel reinforced my bias that tracking the erosion of the slough is important for conservation of wetlands. I proposed that Parsons Slough was in fact eroding and at a faster rate than the main channel and could have designed my survey to yield these results. However, I took in to account my bias and designed the survey to have an equally likely probability of producing any one of my three hypotheses.

In taking on this project I had some interest in the slough. I had had some experience working for the Elkhorn Slough Foundation a previous summer. While scanning slides of Elkhorn Slough properties, I developed an appreciation for the wetland. I contacted Dr. Rikk Kvitek of the Seafloor Mapping Lab and was given the opportunity to do this project at the slough. This has been a learning experience for me.

I feel that because this survey is the first to track erosion of the tidal creeks, it is important for my survey to be repeatable. I am fortunate to have experts in the field advising me on creating and executing a successful single beam survey. It is exciting to know that future surveys will follow my same survey lines and use my results.

Sincerely,

Emiko Shironaka

Abstract

Coastal wetland loss all over the world is becoming a matter of increasing public awareness. Despite the scarcity and ecological importance of coastal wetlands along the west coast of the United States, many of the wetlands in California have already been lost. The Elkhorn Slough is one of the largest and most important remaining coastal wetlands in California, and has been designated a National Estuarine Research Reserve. The slough has five tidal embayments and tributaries which house great biological diversity. Elkhorn Slough is impacted by agriculture, fishing, tourism and other anthropogenic factors. Because of past historical events, since 1947 Elkhorn Slough experiences a daily tidal influx that continues to contribute to tidal erosion today. As the slough erodes away, the quantity of habitat decreases which in turn decreases species diversity and effects appreciation for the natural habitat. Restoration efforts continue. Past studies have quantified the widening, deepening and rate of change in the Elkhorn Slough main channel. Other studies have quantified the widening but not the deepening or rate of change of the Elkhorn Slough tributaries. This study determined whether or not the Parson Slough main channel tributary is changing as rapidly, and in the same direction, as the main channel. Knowledge of this information will help those responsible for managing the slough seek ways of controlling or mitigating tidal scour and determine whether they should also be focusing their attention on the tidal creeks.

This study asked the question: "Is Parsons Slough main channel changing at the same rate as the Elkhorn Slough main channel?". I tested three hypotheses: 1) Parsons Slough is deepening and thus has not stabilized or reached equilibrium, 2) the tidal creeks have experienced no change so they have stabilized and reached equilibrium, 3) the tidal creeks are shortening so the rate of change is decreasing. I collected and compared new bathymetry data in Parsons Slough to the results of a 2003 baseline study to quantify the rate of change. My 2006 survey ran eight cross-sections using single beam sonar and RTKGPS. I made comparisons to previous data to calculate rates of change in depth and cross-sectional area. My conclusion is that Parsons Slough is experiencing erosion from mouth to head. The mean change in average depth from 2003 to 2006 was -0.81 ± 0.39m and the mean change in average maximum depth was -1.75 ± 0.78m. The mean change in area from 2003 to 2006 was 28.8 ± 23.9m^2. The rate of change is faster in Parsons Slough than in the Elkhorn Slough main channel. The mean rate of change from 2003 to 2006 was 9.6 ± 8.0 m^2/yr with an average percent change of 10.5%/yr. Compared to the average percent change from 2001 to 2003 of the Elkhorn Slough main channel of 0.002%/yr, the Parsons Slough main channel is eroding at about 5,000 times faster at 10.5%/yr.Technical difficulties prevented us from obtaining more cross-sections for comparison. I compared six cross-sections to older data with five to twelve points for comparison in each cross-section. Future studies can continue to track the rate of change of Parsons compared to the main channel. This will help the tidal wetland managers to better manage the vital habitat that the tributaries provide.

Introduction

Coastal wetlands provide protection from episodic events, habitat for rich biodiversity, marine research sites, and tourism sites and are deceasing at alarming rates (Caffrey, Silberstein et al. 2002). Episodic events occur as outcomes of catastrophic weather conditions. When hurricane Katrina hit New Orleans, the natural disaster worsened because of the loss of the wetlands that had been occurring for decades (Day et. al 1998). Oil companies had constructed pipelines through the wetlands, contributing to the problem (Day et. al 1998). The Mississippi Delta of the southern United States, the Rhone Delta of southern France and the Venice Lagoon of southern Italy are all examples of wetlands that are experiencing tidal scour due to human activity (Day et. al 1998). In each example, old river channels were cut off and a river was diked which increased the tidal prism and accelerated wetland loss (Craig et. al 1979). Estuaries make up 10 to 20% of the U.S. Pacific coastline while the Atlantic and Gulf coast's estuaries comprise 80 to 90% of the coastline (Kjerfve 1989). Despite the scarcity and ecological importance of coastal wetlands along the west coast of the US, 85% of the wetlands in California have already been lost to human development (Peters and Noss 1995). This loss decreases available habitat for birds and other inhabitants of sloughs. Wetland loss increases the importance of marine research, which evaluates the factors contributing to tidal erosion. Scientific research also helps the managers of urban and rural communities make decisions that effect wetlands, such as those in the vicinity of Elkhorn Slough. Wetland loss also affects tourism and the appreciation for the wetland because of decreasing habitat area and biodiversity (Peters and Noss 1995).

As Elkhorn Slough is one of the largest and most important remaining coastal wetlands in California, it has been designated a National Estuarine Research Reserve (NERR) (Figure 1) (Caffrey, Silberstein et al. 2002). The slough opens to Monterey Bay at Moss Landing Harbor, and extends inland about 10km to Hudson's Landing, the old port of Watsonville. The slough has five tidal embayments and tributaries. They are evaporative salt ponds, Dolan Marsh, Parsons Slough/South Marsh, North Marsh, and Bloom/Porter Marsh (Malzone and Kvitek 1994). Elkhorn Slough and surrounding salt marsh is a heavily utilized and highly modified tidal embayment. This embayment is undergoing rapid environmental change due to human induced tidal scour and erosion (Van Dyke and Wasson 2005).

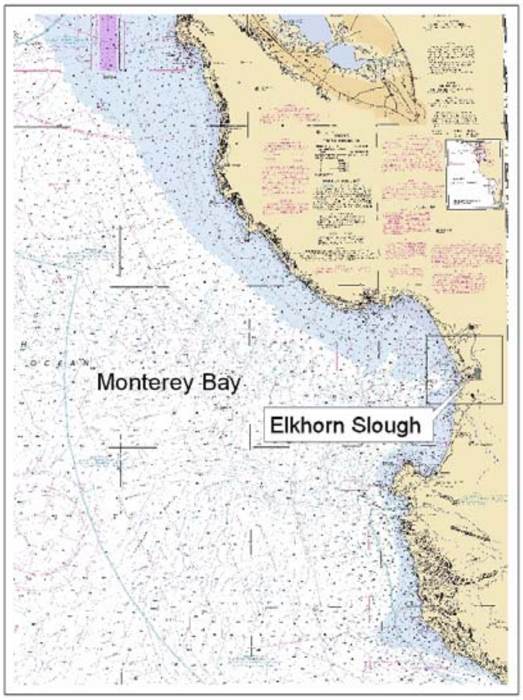

Figure 1. Monterey Bay and surrounding area showing Elkhorn Slough wetlands.

The Elkhorn Slough is a place of great biological diversity. It houses many migratory and resident bird species as well as numerous aquatic invertebrates and flora and fauna. More than 100 species of fish, 500 species of marine invertebrates and more than 265 bird species inhabit the slough. In 2000, Elkhorn Slough was named a Globally Important Bird Area by the American Bird Conservancy and a Western Hemisphere Shorebird Reserve by the Manomet Bird Observatory (Caffrey, Silberstein et al. 2002). To house the great diversity of species there is also rich and diverse habitat. The slough habitats include channels, mudflats, eelgrass beds, salt marsh, and hard substrate; the adjacent harbor, coastal dunes, and open beaches; and the grasslands, oak woodlands, chaparral, and other upland areas (Caffrey, Silberstein et al. 2002).

In addition to these diverse species and habitats, Elkhorn Slough is impacted by agriculture, fishing, tourism and other anthropogenic factors. Agricultural runoff can induce nitrification and increase algal blooms that reduce available oxygen to the water column. These impacts have decreased available habitat to the many species of Elkhorn Slough (Chapin et. al 2004). The slough and neighboring areas support farming, which includes the agricultural management of crops (Cultural Imprints pg. 144). Farmers continue to farm strawberries, artichokes, brussels spouts and other crops (Caffrey, Silberstein et al. 2002). The slough is also a nursing ground for commercially and recreationally important fish species. Many people enjoy visiting the trails or kayaking on the slough where they can observe this diversity of species. As the available habitat decreases, the biodiversity of species also decreases, and tourism is affected.

Elkhorn Slough has experienced tidal erosion since the mouth to Moss Landing Harbor was opened in 1946. The slough experiences a daily tidal influx that continues to contribute to tidal erosion today. As the slough erodes away habitat decreases which in turn decreases species diversity and affects the appreciation of natural habitat. Restoration efforts must be continually adjusted to fit the accelerated erosion from tidal scour. Elkhorn Slough has a panel composed of different organizations to create a tidal wetland plan for restoration (ESTWP 04 April 2006 Draft).

The slough has an interesting history, which has in many ways contributed to the need for restoring the slough. Elkhorn Slough has existed since the Pleistocene era and carries great historical value (Caffrey, Silberstein et. al 2002 p. 22). In 1929, the first successful planting of the Japanese pacific oyster occurred (Cultural Imprints pg. 122). Currently many fish species spawn in Elkhorn Slough. Some species include midwater schooling fish such as anchovy and herring, and bottom dwellers of sharks and rays (Malzone and Kvitek 1994). Originally the Salinas River emptied out into the ocean north of Moss Landing (Cultural Imprints p.144). At that time farmers of the area made dikes for irrigating the land. Then, in 1947, Moss Landing Harbor was dredged. This dredging allowed a direct influx of oceanic tidal surge into the mouth of Elkhorn Slough, making it a seasonal estuary. A proposed sill that was supposed to dampen the tidal surge and protect the nearby farms and wetlands, was never constructed near Highway 1. Consequently, the main channel of Elkhorn Slough became deeper and wider. The 1988 study by Oliver et. al. quantified this widening of the main channel (Malzone and Kvitek 1994). As a result of the increased tidal volume, the agricultural dikes that were put in by farmers broke down and a new area called the South Marsh opened (Figure 2). Restoration efforts and a new awareness of salt marsh habitat began in the 1980's. Also during the 1980's, an El Nino event occurred and while restoration efforts opened one tributary, now called Parsons Slough, the El Nino event opened the rest of the South Marsh area. The rest of the South Marsh area that was created is the five fingers and the surrounding tributaries which were formerly agricultural dikes (Caffrey, Silberstein et. al 2002). The rate of tidal scour was quantified by Malzone in 1993 in an effort to see if the rate was increasing or if the slough was beginning to approach equilibrium or a stable state, and more studies continued to follow. There have been dramatic modifications to the slough main channel and tributaries from tidal scour. As the slough continues to erode, it is unlikely that the system's rich biodiversity will persist in the face of such rapid habitat change and loss. Quantifying the rate of change of the slough is important for restoration efforts.

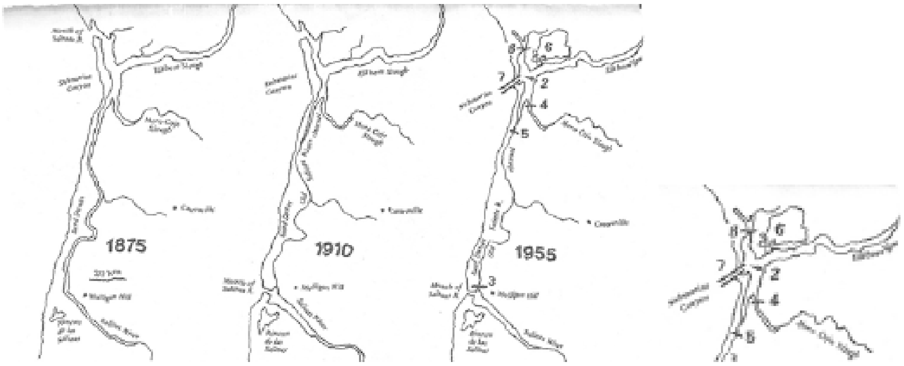

Figure 2. Principal Hydrographic changes made in the Salinas River-Mouth-Elkhorn Slough area, comparing conditions in 1875, 1910 and 1955. **1**. Hudson's Landing **2**.Moss Landing Harbor **3**.Earthen dike across old Salinas River Channel **4**.Tide Gate on Moro Cojo Slough **5**.Tide gate on old Salinas River Channel **6**.Salt ponds **7**.Jetties at Moss landing Harbor **8**.Tide Gate at Jetty Road. (Cultural Imprints p.147)

My study determined whether or not the tidal creeks are changing as rapidly and in the same direction as the main channel. Knowing this information will help those responsible for managing the slough and seeking ways of controlling or mitigating tidal scour to evaluate whether they should also be focusing their attention on the tidal creeks.

Previous studies have focused on the physical parameters of the main channel and the mouth of Parsons Slough. The first study conducted showing the erosion of tidal scour of the slough was the Oliver et. al 1988 study. The Malzone 1993 survey was the next study which measured erosion of the main channel and the mouth of Parsons Slough. Malzone quantified the rate of change by tidal scour in Parsons Slough mouth to be 3.0 x $10^3 m^3$/yr (Malzone 1999). The following study also quantified the rate of erosion of the main channel and Parsons Slough. This Dean 2001 survey quantified the rate of tidal scour in Parsons Slough to be -4.6 x $10^4 m^3$/yr (Dean 2003). A later study, the Sampey 2005 study, further quantified the rate of erosion of the main channel and the entrance of Parsons Slough. This Sampey 2005 study found the rate of erosion in Parsons Slough to be 1.39x$10^6 m^3$/yr (Sampey 2006). These previous studies are now being used by the Elkhorn Slough Wetlands Management Plan (ESTWMP Draft 3/24/06 Barb Peichel). What isn't known, however, is what is happening to the depths and cross-sectional areas of Parsons Slough. Eric VanDyke and Chris Malzone have quantified changes in the width of tidal creeks, but not depths or cross-sectional areas (Malzone 1999). I expanded on these prior works and conducted a cross-sectional area analysis of Parsons Slough main channel and compared it to previous data from Sampey in 2003 of Elkhorn Slough main channel and Parsons Slough mouth (figure 3). I was able to quantify the rate of change in Parsons Slough main channel. I used cross-sectional data from the two surveys of Elkhorn Slough main channel and Parsons Slough main channel to establish whether Parsons Slough main channel is deepening compared to the Elkhorn Slough main channel (figure 3). I tested the hypotheses:

1. The cross-sectional area of Parsons Slough main channel is deepening at a rate comparable to those found in the Elkhorn Slough main channel.

2. The cross-sectional profiles of Parsons Slough main channel have not changed and remained stable.
3. The cross-sectional area of Parsons Slough main channel is declining, and becoming less like that of the main channel.

Those responsible for managing and maintaining the environmental diversity of Elkhorn Slough are now debating what measures should be taken to preserve the rich diversity of habitats. Knowing whether tidal scour is approaching equilibrium or not will help the managers select the most appropriate course of action.

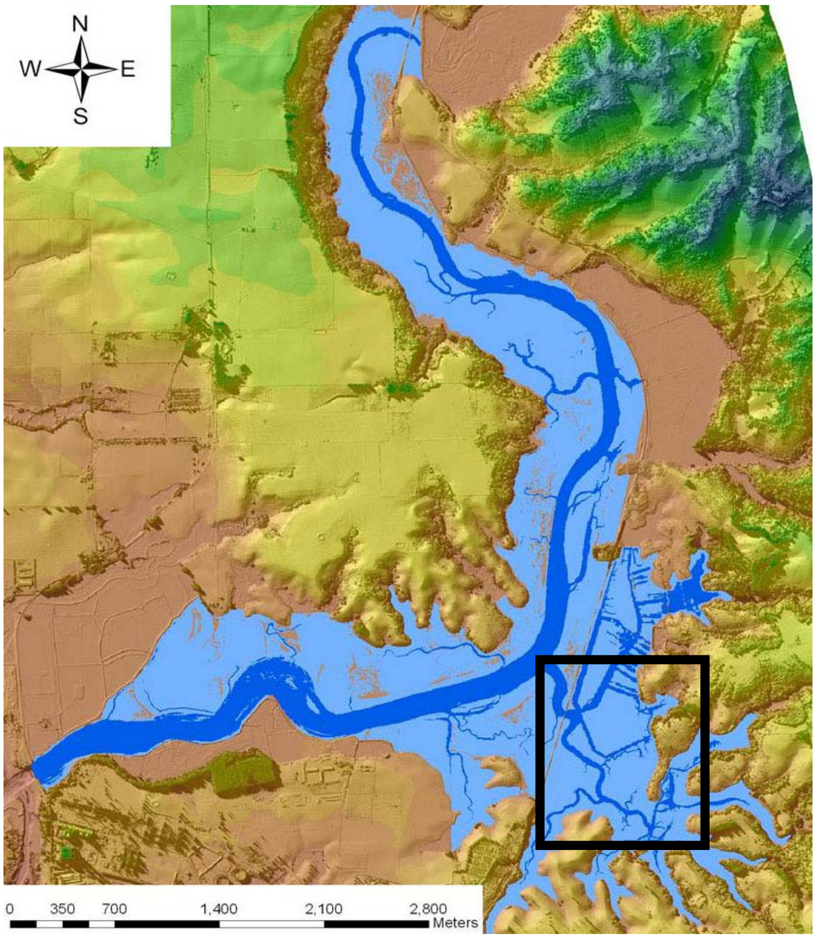

Figure 3. Area of Parsons Slough where this study was conducted.

Figure 4. The 2006 eight cross-sectional lines and survey area of Parsons Slough. These were modeled after the Sampey 2003 survey.

Methods

My general approach was to repeat and quantify the change that has occurred since the 2003 Parsons Slough bathymetric survey by Sampey (figures.3 and 4) (Sampey 2006). This tells us whether one of the Elkhorn Slough's major tributaries is widening, narrowing or reaching a state of equilibrium compared to its main channel.

Data Collection

I conducted a single beam echo sounder survey of Parsons Slough located at the South Marsh end of Elkhorn Slough (figure 3). This survey was conducted on October 31, 2006 at a +1 meter tide aboard a CSU Montery Bay aluminum skiff R/V MiniMe with a 5.0 horsepower motor. This low tide was important to ensure safe passage under the railroad bridge of Elkhorn Sloughs tributaries. The people on board this survey were myself and a graduate student, Jeremiah Brantner, who had conducted the 2001 multibeam survey of Elkhorn Slough through the Seafloor Mapping Lab at CSU Monterey Bay. As part of the Seafloor Mapping Lab, we obtained a permit from the Elkhorn Slough National Estuarine Research Reserve. We followed the Parson Slough main channel (figure 3). I also repeated the methods used by the Malzone 1993 and Sampey 2003 surveys. The 2003 data ran parallel transects. My 2006 data had a minimum of five points for comparison per cross-section to the 2003 data points. Eight of the planned cross-sectional lines were surveyed (figure 4). I created cross-section lines using Hypack software, repeating the same depth and transect lines. Navigation and positioning were achieved using a Real Time Kinematic Trimble 5800 differential global positioning system (RTK dGPS). The base station for the RTK dGPS receiver is located at the Elkhorn Slough National Estuarine Research Reserve Visitor's Center. Water depths were obtained using a 448 Interspace depth sounder. Depth soundings were recorded at 1 second intervals using Hypack software by Coastal Oceanographics, Incorporated. The RTK can produce precision accuracies of better than 2cm in the horizontal and vertical plane. The Interspace 448 depth sounder has a 9 degree transducer capable of achieving a horizontal resolution of ± 0.53m within the depth range of this study (~ 4m), and a vertical precision of 3 cm..

Data Processing

To produce a cross-sectional analysis, the raw UTM position and depth data from the 2006 survey was corrected to NAVD88 using the RTK GPS elevation data collected during the survey and a program called Corpscon that transforms ellipsoid height to geoid height (figure 5). I transferred the data to Excel and compared my cross-sectional areas with the 2003 cross-sections from that year.

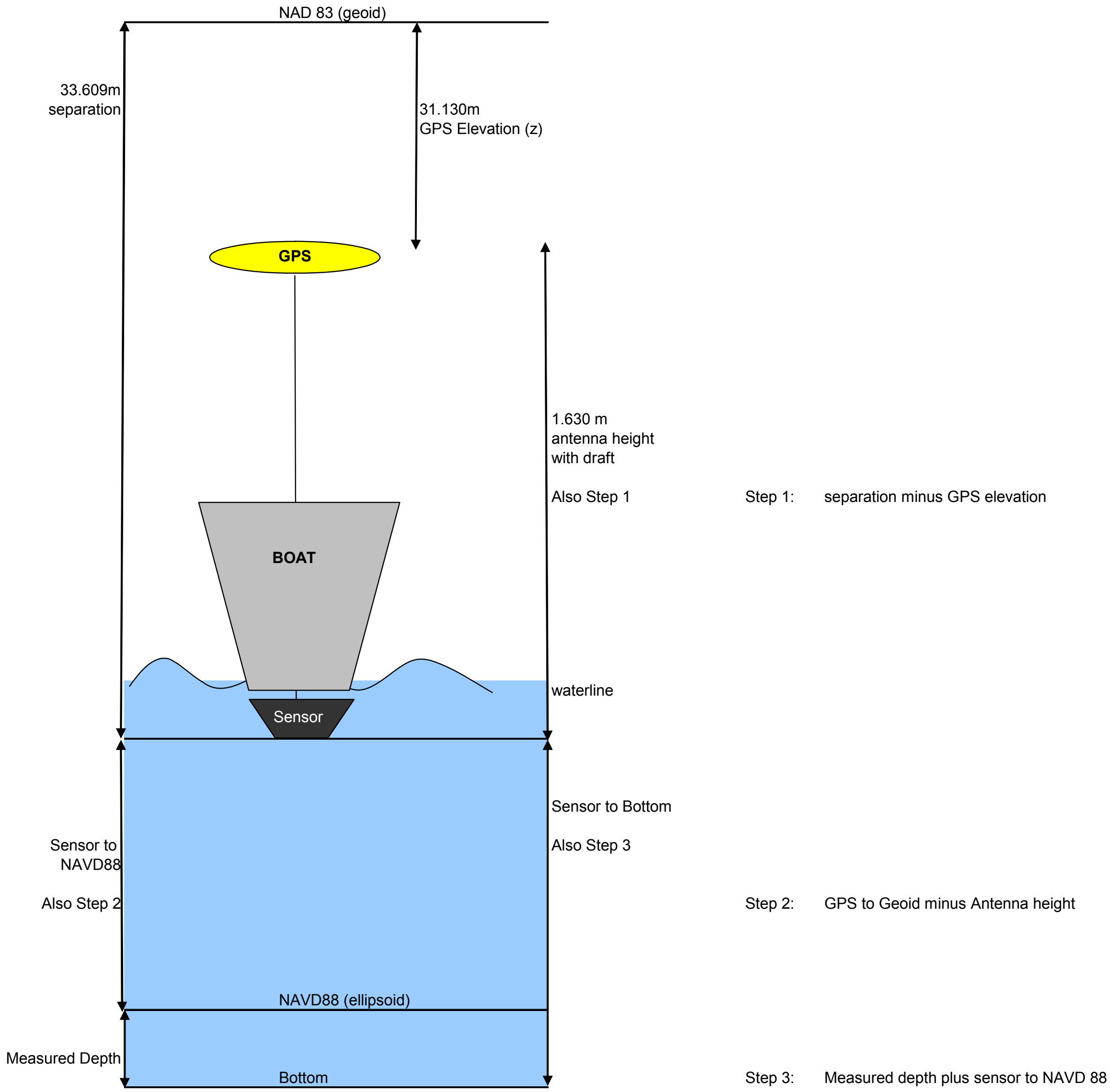

Figure 5. Diagram of Boat set-up and different datums. Solved for the depth.

Cross-sections

To determine the rates of erosion, cross-sections were produced at several locations for comparison to the 2003 study.

Excel Analysis

I used Microsoft Excel to compute the data and produce cross-sectional analyses. I exported my data from Hypack to text files that I brought into Excel. I diagrammed the set-up we used and made an excel sheet of the geoid and ellipsoid heights. I used Corpscon to get the separation between these two datums and reference the depth to NAVD88 height (figure. 5). Next, I took the UTM northings and eastings to produce profiles in Excel. I compared the 2003 and 2006 data profiles in Excel. I made a table of the 2003 and 2006 x and y distance data and subtracted the 2003 and 2006 distances. I selected comparison points in the 2003 dataset by looking for those that were within 3 meters of the 2006 x and y data points. I compared these 2003 and 2006 data points. This also helped me decide what points were within 3m of one another. To create cross-sectional graphs of the two datasets to show channel deepening or shortening, I calculated and summed the distance between points in each cross-section using simple trigonometry. I used these same distances for the 2003 and 2006 datasets and the depth values I calculated using Corpscon for 2006 and earlier corrected depth values for the 2003 dataset (figure 5). I generated cross-sections in Excel using distance on the x-axis and depth on the y-axis for the 2003 and 2006 data (Figures. 9-14).

Deleted: (Figures

In Excel, I produced cross-sectional area analyses of the different studies for comparison. I used the data from my survey and compared it to data from the 2003 survey to quantify where change occurred between 2003 and 2006(Table 2). I used these values to calculate an annual rate of cross-sectional area change for each cross-section, as well as the maximum change in depth and average change in depth (Tables 1 and 2). I borrowed the main channel data analyses from the Sampey 2005 study and performed the same calculations for rate of change. I then compared the main channel percent change to Parsons Slough percent change to see what the rate of change was for the two areas of Elkhorn Slough in comparison. I also ran a t-test of change in depth from 2003 to 2006 and distance from the main channel to find change through time.

Results

To address the question: Is Parsons Slough changing over time?", this study attempted to quantify the rate of change of the cross-sectional areas. The study produced eight cross-sections starting from the railroad bridge and moving towards Parsons Slough head (figure 4).

Equipment Problems

During our survey we encountered technical aspects that delayed obtaining all planned 68 cross-sections. On the survey, the 31st of October 2006, we collected eight cross-sectional lines worth of data. On this survey, a technical difficulty occurred with the cell phone signal. Our set-up for the survey consisted of a GPS receiver connected to a cell phone signal that used RTK and dGPS at the Elkhorn Slough visitor center (figure 6). Because the slough bottom is muddy, and the tributaries get very shallow quickly near the edges of the cross-sections, it is difficult to negotiate and run cross-sections without the equipment or skiff getting stuck. We encountered a shallow bottom and the clamps that held this equipment together fell. We quickly attempted to rescue the unit but some salt water grazed both the dGPS and the cell phone unit. We were able to save the dGPS from the saltwater, but not the cell phone unit. We had to end our survey early with only eight cross-sections of raw data. We found that in the last cross-sections (007 and 008), the system did not receive RTK corrections, and these cross-sections were omitted from the data analyses.

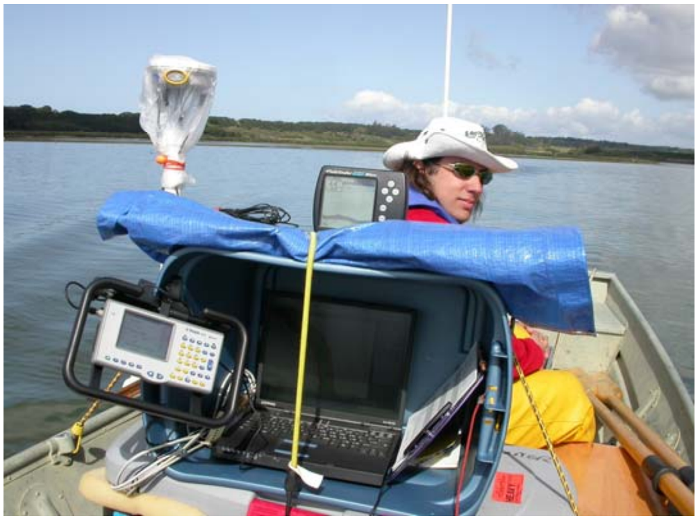

Figure 5. Single beam survey set-up including GPS receiver, ecosounder and data acquisition computer running Hypack® software.

Comparisons

In postprocessing, we found that the cross-sectional areas between each survey showed more erosion near the mouth and head and less erosion near the middle of the tributaries (Table 1). Table 1 shows the changes in average depth and maximum depth and Table 2 shows average change in area per cross-section from 2003 to 2006.

Table 1. 2003 to 2006 Changes in average depth and maximum depth for each cross-section.

Cross-section	AVG Δ Depth (m)	MAX ∆ Depth (m)
RRBridge	-1.00	-2.10
002-0858	-0.41	-1.06
003-0903	-0.62	-1.27
004-0908	-0.39	-0.90
005-0914	-1.35	-2.84
006-0917	-1.08	-2.32
Mean ± sd	**-0.81 ± 0.39**	**-1.75 ± 0.78**

Average Depth changes

Cross-section 005 experienced the largest average change in depth at 1.35 ± 0.39m. Cross-section 005 experienced erosion except for the right side near the bank (figure 13). This could be for two reasons. Because we collected our data with the Interspace 448 depth sounder, we could produce accuracies in the vertical plane of ± 0.03m. However, the 2003 survey collected data with a Hummingbird depth sounder, which produces accuracies in the vertical plane of ± 0.30m. If the 2006 value falls within that vertical accuracy level of ± 0.30m, the appearance of deposition may be due to the vertical resolution. The second reason could be due to geomorphology. As you approach the bank side, the depth becomes shallow fast. Therefore, if the two data points were within 3m of one another in the horizontal plane, the values could be represented as shallow from being closer to the bank edge. Cross-section 004 experienced the least amount of erosion at 0.39 ± 0.39m. The cross-sectional profile of cross-section 004 shows erosion for all the 2006 data points compared to the 2003 data points (figure 12).Because the standard deviation is the same as the average depth value, this cross-section could be experiencing no change from 2003 to 2006. The average of all the cross-sectional average depths was 0.81 ± 0.39m. All average changes in depth experienced erosion (Table 1).

Deleted: of ±

Maximum Depth changes

The cross-section 005 shows the largest maximum change in depth at 2.84 ± 0.78m of erosion (Table 1 and figure 13). The smallest change in maximum depth was from cross-section 004 with 0.90± 0.78m of erosion (Table 1 and figure 12). The average of maximum change in depth for all the cross-sections was 1.75 ± 0.78m of erosion (Table 1). The depth changes show more erosion near the mouth and head and less towards the middle. However, cross-sections 005 and 006 show right bank side deposition (figures 13 and 14). This apparent deposition may be from the second reason I stated above for both cross-sections. The cross section data points are 1.58m apart for cross-section 005 and 1.52m apart for cross-section 006 in the horizontal plane and therefore, show deposition instead of erosion. Therefore, it is more accurate to say that there is more erosion near the mouth and it is unknown if the erosion decreases and then increases again near the head or if the erosion increases from mouth to head. Maximum change in depth has the same trend as average change in depth.

Area changes

The largest change in total cross-sectional area was cross-section RR Bridge with 73.4 ± 23.9m^2 of erosion (Table 2 and figure 9). The smallest change in cross-sectional area was cross-section 002 at 10.4 ± 23.9m^2 of erosion (Table 2 and figure 10). All cross-sections have experienced erosion since 2003.The average of the entire cross-sectional changes in area was 28.8 ± 23.9m^2 of erosion (Table 2). This shows no clear trend of change in area. Looking at percent change per year, there was the least amount of change at cross-section 002 with 5.5%/yr (Table 2 and figure 10). Cross-section 005 showed the most change with 16.6% per year (Table 2 and figure 13). The average percent change was 10.5% per year (Table 2). For percent change, the head changed more than the mouth. All the cross-sections experienced erosion from 2003 to 2006 in change in area (Table 2).

Table 2. Parsons Slough main channel area changes, rate of change and percent change for years 2003 to 2006 of each cross-section.

Cross Section	x-section area 2003 (m^2)	x-section area area 2006 (m^2)	∆ Area (m^2)	Rate Δ/x-section (m^2/yr)	% change/yr
RRBridge	302.7± 2.7	376.1 ± 0.3	73.4	24.5	8.1%
002-0858	62.5 ± 0.8	72.9 ± 0.1	10.4	3.5	5.5%
003-0903	61.1± 1.7	80.0 ± 0.2	18.9	6.3	10.3%
004-0908	57.3 ± 1.0	67.8 ± 0.1	10.5	3.5	6.1%
005-0914	73.6 ± 0.6	110.3 ± 0.1	36.6	12.2	16.6%
006-0917	47.0 ± 0.6	70.2 ± 0.1	23.2	7.7	16.4%
Mean ± sd			**28.8 ± 23.9**	**9.6 ± 8.0**	**10.5%**

Rate of Change

To address the question, "Is Parsons Slough main channel changing over time?", I quantified the rate of change of the cross-sectional areas by dividing the 2003 to 2006 difference in area by the 3 years elapsed time between the studies (Table 2). These values were also reported as percent change in cross-sectional area (Table 2).The largest rate of change in terms of total area lost was cross-section RRbridge with 24.5 ± 8.0m^2/yr, where as the cross-sections with the highest percent annual change were cross-sections 005 with 16.6% change/yr and 006 with 16.4% change/yr. The survey shows that the erosion rate in terms of percent is greatest near the head of Parsons Slough, but in terms of total area lost erosion is greatest near the mouth.

2003 Study

Compared to the Elkhorn Slough main channel, the average percent change/yr for Parsons Slough was 10.5%/yr in 2006 (Table 2). The average percent change of the Elkhorn Slough main channel was 0.002%/yr (Table 3). Because the Elkhorn Slough main channel is experiencing erosion at a slower rate than Parsons Slough erosion rate, and has a smaller % change/yr, neither Parsons Slough nor the main channel show evidence of reaching a state of equilibrium. However, Parsons Slough is eroding about 5,000 times faster, and is therefore experiencing a larger erosion rate of 9.6 ± 8.0 m^2/yr due to the daily tidal influx and narrow nature of the channel.

Table 3 Elkhorn Slough main channel area changes, rate of change and percent change for years 2001 to 2003 of each slough zone, from Sampey 2005 Elkhorn Slough main channel study.

Slough zone	Area (m2)	Δ Area (m2)	Rate Δ/x-section (m2/yr)	% change/yr
Foreslough (FS)	131583.0	-11.20	-5.6	-0.004%
Seal bend (SB)	89361.0	24.21	12.1	0.014%
Seal bend to Parson's (SB_P)	144811.0	-19.73	-9.9	-0.007%
Midslough1 (MS1)	122441.0	-16.30	-8.2	-0.007%
Midslough2 (MS2)	71989.0	-2.28	-1.1	-0.002%
Backslough1 (BS1)	8328.0	2.75	1.4	0.017%
Backslough2 (BS2)	22448.0	2.89	1.4	0.006%
Mean ± sd			**-1.4 ± 7.5**	**0.002%**

T-test

A t-test of the changes in cross-sectional depths showed a confidence interval of the means of -0.42 < -0.81 < 1.20 (Table 4). With an alpha level of 0.05 and a t-statistic of 2.447, the null hypothesis that the difference between 2003 and 2006 were zero was rejected. Therefore, the depths from 2003 to 2006 are not reaching an equilibrium state. A regression of changes in depth and distance from the main channel showed an r-squared value of 0.16, where closer to 1 shows a strong correlation (Figure 7). Omitting the RR bridge since it was a higher value due to the large volume of water entering under the small area under the railroad bridge, gave us a r-square of 0.58 (Figure 8). This value increased showing a correlation of distance and changes in depth. Erosion increased in depth from 2003 to 2006 from mouth to head.

Deleted: of -

Table 4. independent samples t-test of Parsons Slough main channel cross-sections 2003 to 2006

95% Confidence Interval	plus	mean	minus	$t_{(\alpha/2)}$*sd/sqrt(n)	$t_{0.05(2),6}$
$t_{(\alpha/2)}$*sd/sqrt(n) ± μ	-0.42	-0.81	1.20	0.39	2.447
Above t statistic (2.447)?	no	no	no	α = 0.05	

Ho: s1-s2=0 Ha: s1-s2≠0

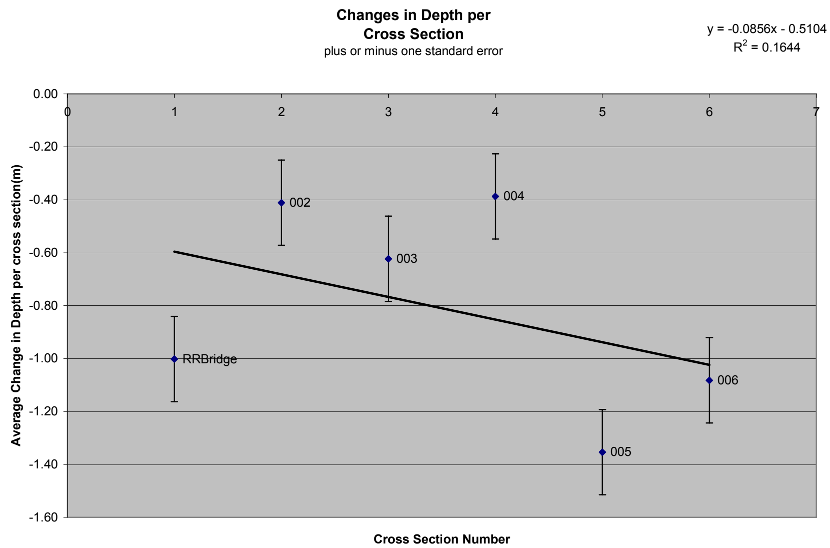

Figure 7. Regression of changes in depth and distance from the Elkhorn Slough main channel. The black bars indicated plus or minus one standard error.

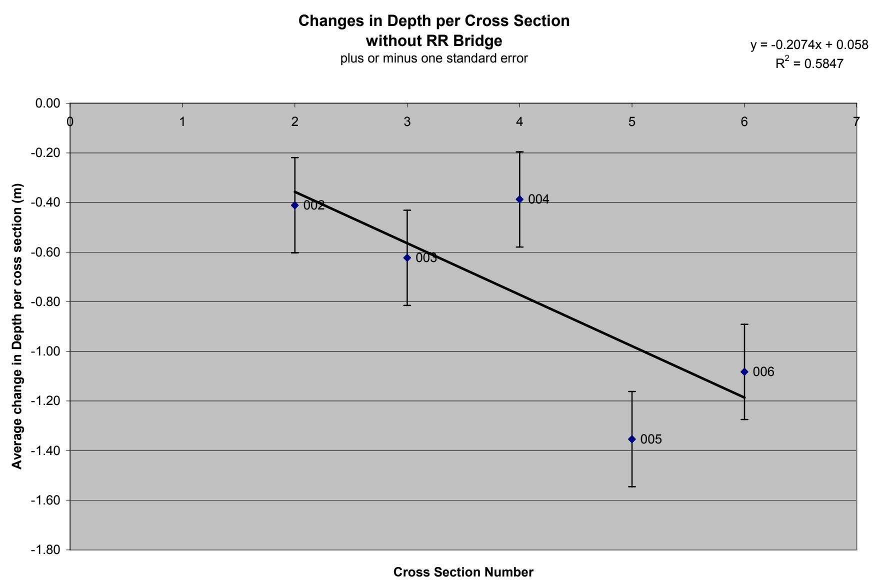

Figure 8. Regression of changes in depth and distance from the Elkhorn Slough main channel without the RRBridge cross-section. The black bars indicated plus or minus one standard error.

Deleted: section.The

Cross-section Comparisons

The cross-sections must be analyzed for comparison. I only chose data points from the 2006 and 2003 datasets for comparison with points that were within three meters of one another in the x and y directions. The RR Bridge cross-section had nine data points from the 2006 and 2003 data sets that were within three meters of one another in the x and y direction (figure. 9). The cross-section 002-0858 had twelve points for comparison (figure. 10). The cross-section 003-0903 had the least amount with five points for comparison (figure.11). The cross-section 004-0908 had six points for comparison (figure. 12). The cross-section 005-0914 had twelve points for comparison (figure. 13). Cross-section 006-0917 had ten points for comparison (figure. 14). Because the 2003 survey ran lines up and down the tributaries and did some cross-sections and my 2006 survey only ran cross-sections, based on these transects, I matched the closest points to the old survey. I ended up with five to twelve points for comparison for my cross-sections, a very low number. Because cross-sections are now established from my survey, there is the capacity for better comparisons for the future.

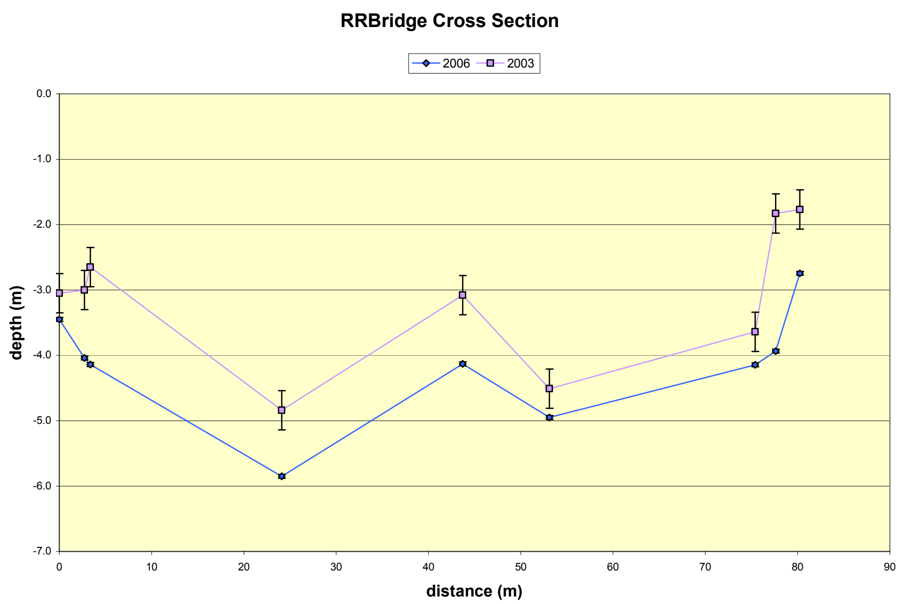

Figure 9. Railroad Bridge cross-section. X-axis displays distance from the first comparable data point to the last. The y-axis shows the depth measurements for the 2003 and 2006 datasets. The error bars depict the precision of the Hummingbird sonar system used by Sampey in 2003 [0.3m] and the Interspace 448 used in this 2006 study [0.03m].

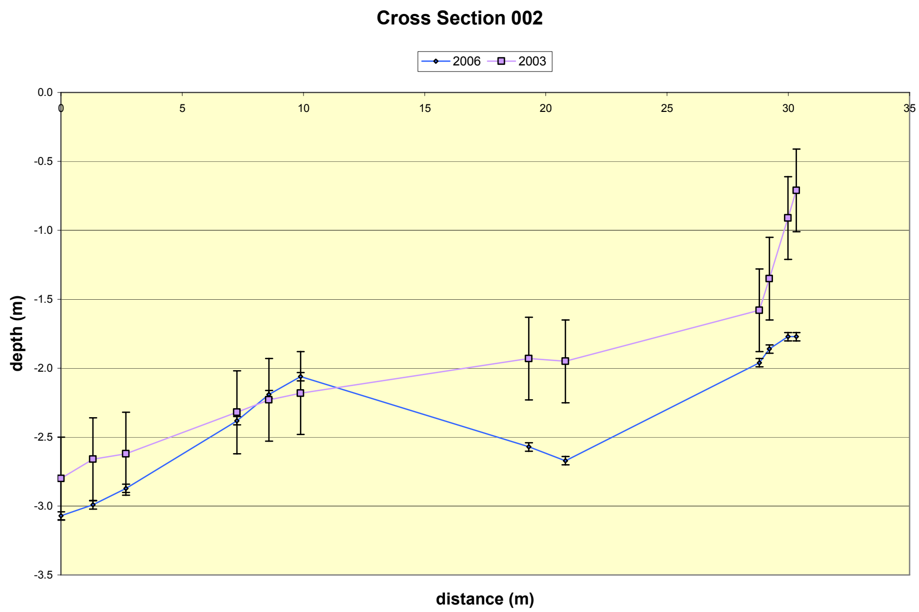

Figure 10. Second cross-section. X-axis displays distance from the first comparable data point to the last. The y-axis shows the depth measurements for the 2003 and 2006 datasets. The error bars depict the precision of the Hummingbird sonar system used by Sampey in 2003 [0.3m] and the Interspace 448 used in this 2006 study [0.03m].

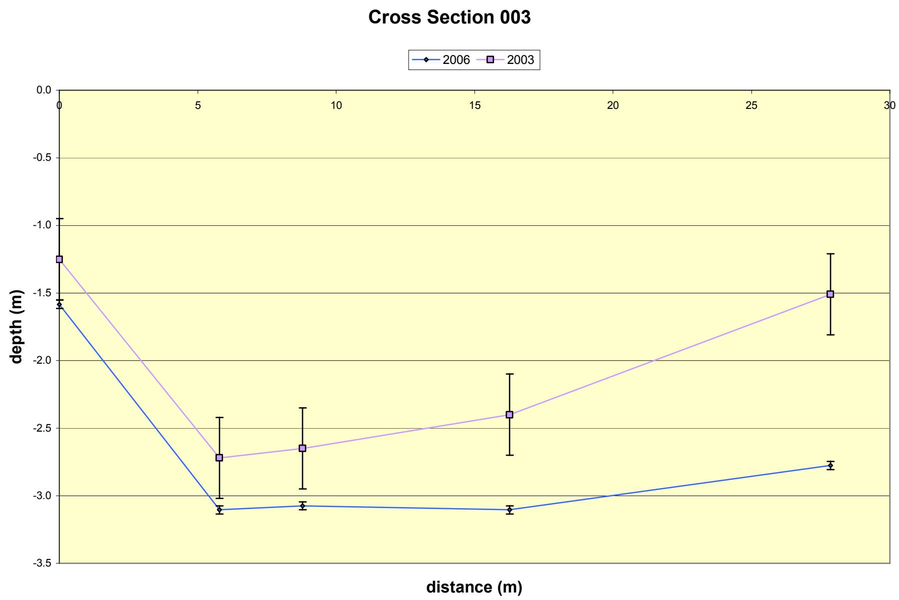

Figure 11. Third cross-section. X-axis displays distance from the first comparable data point to the last. The y-axis shows the depth measurements for the 2003 and 2006 datasets. The error bars depict the precision of the Hummingbird sonar system used by Sampey in 2003 [0.3m] and the Interspace 448 used in this 2006 study [0.03m].

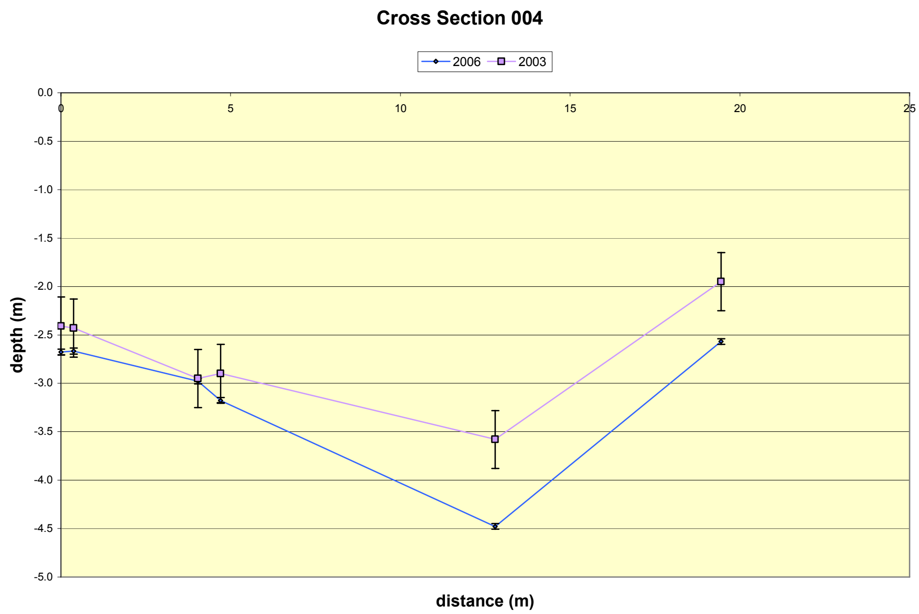

Figure12. Fourth cross-section. X-axis displays distance from the first comparable data point to the last. The y-axis shows the depth measurements for the 2003 and 2006 datasets. The error bars depict the precision of the Hummingbird sonar system used by Sampey in 2003 [0.3m] and the Interspace 448 used in this 2006 study [0.03m].

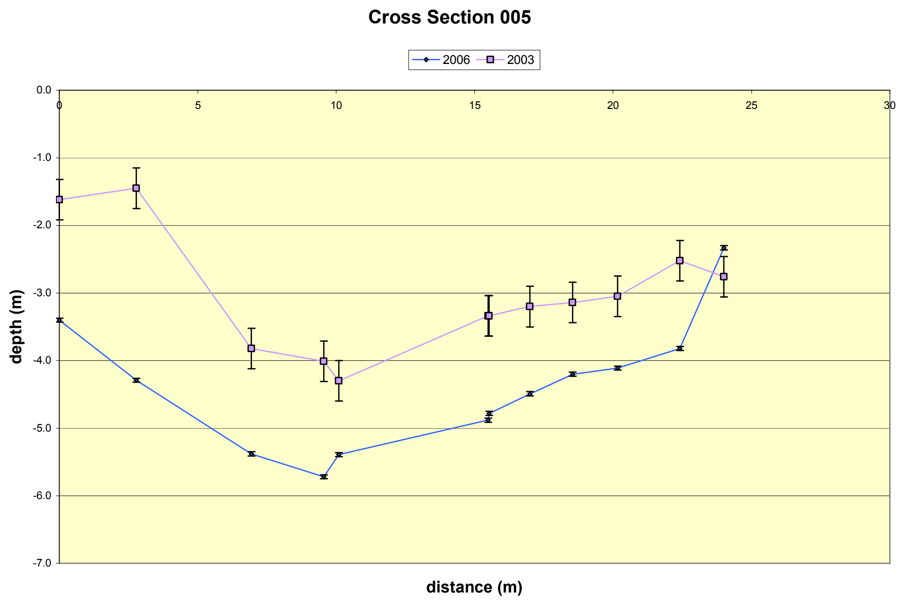

Figure 13. Fifth cross-section. X-axis displays distance from the first comparable data point to the last. The y-axis shows the depth measurements for the 2003 and 2006 datasets. The error bars depict the precision of the Hummingbird sonar system used by Sampey in 2003 [0.3m] and the Interspace 448 used in this 2006 study [0.03m].

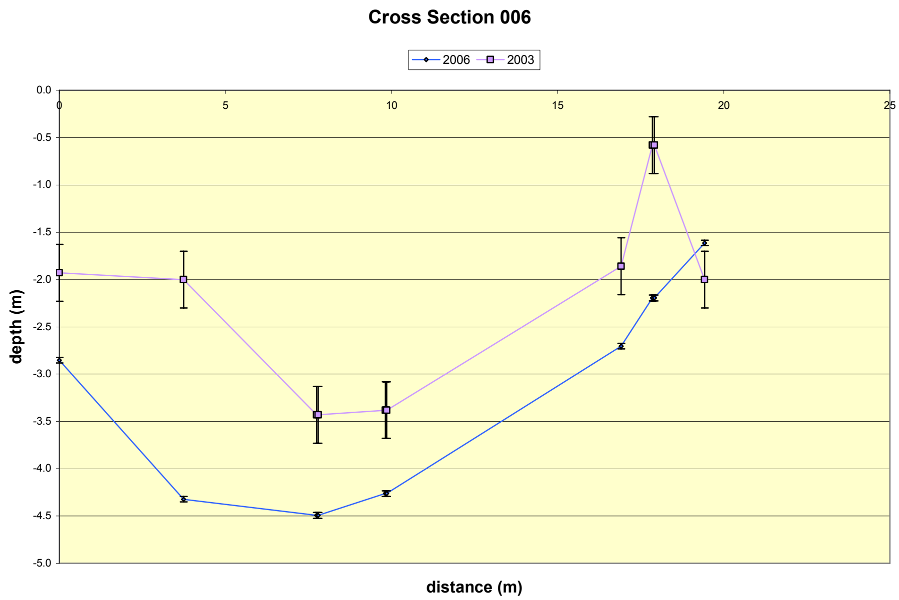

Figure 14. Sixth cross-section. X-axis displays distance from the first comparable data point to the last. The y-axis shows the depth measurements for the 2003 and 2006 datasets. The error bars depict the precision of the Hummingbird sonar system used by Sampey in 2003 [0.3m] and the Interspace 448 used in this 2006 study [0.03m].

Discussion

The cross-section analyses I produced relate directly to my research question, "Is Parsons Slough changing over time?". I tested three hypotheses: Parsons Slough is deepening so it has not stabilized or reached equilibrium, Parsons Slough has experienced no change so it has stabilized and reached equilibrium, and Parsons Slough is shoaling or narrowing and thus experiencing deposition rather than erosion. I found that the Parsons Slough main channel has an average rate of change in area of $9.6 \pm 8.0m^2/yr$ and an average percent change of 10.5%/yr of erosion. Sampey (2006) reported that the Elkhorn Slough main channel in 2003 had an average rate of change in area of $-1.4 \pm 7.5m^2/yr$ but an average percent change/yr of 0.002% of erosion along its entire length. Indeed, the rates of erosion along all the cross-sections measured in Parsons Slough from 2003 to 2006 (Table 2) were much higher than the percent changes reported by Sampey (2006) for the Elkhorn Slough main channel between 2001 and 2003 (Table 3). On average, Parsons Slough is experiencing more erosion than the Elkhorn Slough main channel. The rates of erosion in terms of absolute area are higher at the mouth, but in terms of percent increase in cross-sectional area are higher toward the head. Cross-sections 005 had 1.58m and 006 had 1.52m of right bank side values that were within 3m in the horizontal direction. These horizontal values could have been shallower because the bank gets shallow faster near the bank side. Also, there is a trend of more change in maximum depth near Parsons Slough head than the mouth. This indicates that Parsons Slough is deepening more towards the head than the mouth. I calculated the RR bridge cross-section nearer the Elkhorn Slough main channel to be deepening by 2.10 ± 0.78m. I calculated the 006 cross-section towards Parsons Slough head to be deepening by 2.32 ± 0.78m. There was more erosion near the mouth at the RR Bridge cross-section and less towards Parsons Slough head at the 006 cross-section for change in average depth. The average area change was more towards the head but less in the middle. The RR Bridge had an average area change of 73.4 ± 23.9m^2 of erosion and the 006 cross-section experienced 23.2 ± 23.9m^2 of erosion. This indicates that Parsons Slough is eroding more near the head than in the middle, still supporting the hypothesis that Parsons Slough is eroding. Compared to the Elkhorn Slough main channel Parsons Slough main channel is eroding, and at a much faster rate of 10.5%/yr compared to the main channel of 0.002%/yr of erosion.

Because I was only able to complete eight cross-sections, my data is not as strong as if I had been able to complete all 68 planned cross-sectional lines. Also, because we received no RTK data from the last two cross-sections, we had to omit cross-section 007 and 008. More data collection could show changes within the tributaries. For example, there could be more erosion in the middle and less at the end of Parsons Slough, a place that we were unable to survey. A second weakness is in the comparisons. Because the 2003 survey ran lines up and down the tributaries with some cross-sections, it was difficult to plan the 2006 survey and compare the data points. We planned cross-sections that seemed nearest the 2003 cross-sections. In postprocessing however, it was difficult to find data that were close to one another. I chose data points that were within 3m of one another for comparison. My eight cross-sections had five to twelve data points for comparison. Had the cross-sections in 2003 been exactly on top of my 2006 data points I could have had many more data points to compare, making a more accurate comparison.

Strengths of my survey include the way in which we surveyed. Because we collected so many data points (one every 1 second) I was able to find enough points to compare to the old 2003 data. I was also able to produce cross-sections to compare my data to the old data. I was able to quantify the rate of change using these analyses of Parsons Slough and compare that to the rate of change of the main channel. This showed that there was significantly less change in the Elkhorn Slough main channel than Parsons and that within Parsons there was erosion from mouth to head in terms of percent change.

The multibeam survey done by Sampey in 2005, showed there to be 44.9 ± 21.8m^2 of average change in area near Parsons. Malzone showed that Parsons accounted for 30% of the volume of sediment of the slough. I was able to show that Parsons rate of change is faster than the main channel at an average percent change of 10.5%/yr and that erosion increases from mouth to head.

The Elkhorn Slough Tidal Wetland Management team can now use this data to help preserve the vital habitat of leopard sharks, which spawn in the tributaries, and other animals (Carlisle et. al 2005). Knowing where the tributaries are deepening and infilling will help TWMP managers make important decisions for the fate of tributary species, such as the leopard shark.

New questions that could be asked include determining the effect that deepening and widening have on the different species that reside in the tributaries compared to the main channel. This habitat degradation could affect the species that are specific to the tributaries because of the narrow and deep nature of the tributaries compared to the wide and shallow nature of the main channel. Tracking the rate of change of not just Parsons Slough but also its tributaries compared to the main channel over time is important for management of the slough. Adding more cross sections to the data analysis increases the certainty of what the trends of the slough are. Now that I have established a repeatable baseline survey, future surveys can be done to track the rate of change of Parsons Slough compared to the Elkhorn Slough main channel. Future surveys should also add more cross sections in the tributaries for comparison. This is important for management and protection of the great biodiversity of the tributaries within Elkhorn Slough.

Literature Cited

Caffrey J., Silberstein M. et. al.2002.*Changes in a California Estuary: A profile of Elkhorn Slough*. Elkhorn Slough Foundation, Moss Landing, CA. (p.1-10,129)

Carlilie A., Starr RM., Cailliet GM. 2005. Movements and Habitat use of Female Leopard Sharks in Elkhorn Slough, California. [MS Thesis]: Moss Landing, California. Moss Landing Marine Laboratories.

Chapin TP et. al.2004.Nitrate *Sources and Sinks in Elkhorn Slough, California: Results from Long-term Continuous in situ Nitrate Analyzers*: Estuaries, v.27 (5), p.882-894

Craig N. J. , Turner R. E. and Day J. W. Jr. *Land loss in coastal Louisiana (U.S.A.)*. Center for Wetland Resources, Louisiana State University, 70803 Baton Rouge, Louisiana, USA. Environmental Management**.** Springer New York ISSN: 0364-152X (Paper). V. 3(2). March 1979. P. 133 - 144

Day J.W. Jr.; Scarton F.; Rismondo A., and Are D..1998. *Rapid Deterioration of a Salt Marsh in Venice Lagoon, Italy*. Journal of Coastal Research, 14(2), 583-590. Royal Palm Beach (Florida), ISSN 0749-0208.

Dean EW.2003.*Tidal Scour in Elkhorn Slough, California: A Bathymetric Analysis*. Seaside, CA: California State University, Monterey Bay. (?)p.

Gordon BL.1977.*Monterey Bay Area: Natural History and Cultural Imprints*. The Boxwood Press, Pacific Grove, CA.321.p

Kjerfve B. 1989 *Estuarine geomorphology and physical oceanography*. In J. W. Day Jr. C.A. S. Hall, W.M. Kemp, and A. Yanez-Arancibia, eds. Estuarine Ecology.p.47-78 New York: John Wiley

MacGinite GE.1935.*Ecological aspects of a California marine estuary: American Midland Naturalist*.v.16, p.629-765.

Malzone CM.1999.*Tidal Scour and its Relation to Erosion and Sediment Transport in Elkhorn Slough* [MS Thesis]: San Jose, California. San Jose State University.

Malzone CM et Kvitek R. 1994. *Tidal Scour, Erosion, and Habitat Loss in Elkhorn Slough, California*. A Report of the Elkhorn Slough Foundation pursuant to National Oceanic and Atmospheric Administration Award # NA37OM0523. Moss Landing Marine Laboratories, Moss Landing, California.

RL Peters et. RF Noss. *America's Endangered Ecosystems*. Defenders of Wildlife. Fall 1995. available via the internet: http://www.defenders.org/amee03.html

Oliver JS. King JA. Hornberger M. Schwartz DL. *Extensive Salt marsh erosion caused by human activities in Elkhorn Slough, California*.

Peichel B. *Elkhorn Slough Tidal Wetland Plan* Meeting Notes 04 April 2006

Sampey J. *2006. A bathymetric analysis of equilibrium potential within Elkhorn Slough, California.* Seaside, CA: California State University, Monterey Bay.

Van Dyke E. and Wasson K.2005. *Historical Ecology of a Califonia Estuary: 150 Years of Habitat Change*: Estuaries.v.28 (2).173-189p.