A bathymetric analysis of equilibrium potential within Elkhorn Slough, California

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Abstract

In the not so distant past, wetlands were a key feature along coastal California. Factors such as urban growth, land reclamation, and sea level rise due to global warming, have reduced California's coastal wetlands by an estimated 75-90%. One of these remaining wetlands is the Elkhorn Slough located approximately 100 miles south of San Francisco. The 1947 creation of Moss Landing Harbor was the most significant anthropogenic perturbation the Elkhorn Slough has experienced. The opening of the harbor altered the tidal system; from one of seasonal influence to that of daily; this change has led to substantial tidal scour.

The Elkhorn Slough National Estuarine Research Reserve (ESNERR) is currently in the process of creating a slough management plan. The intention of this plan is to assess the impact of increased tidal flow on vital slough habitats and define methods for protection of its important resources. The primary question addressed is whether or not ESNERR should engineer a costly solution to tidal scour or allow it to continue on its present course. The answer depends on how close the Elkhorn Slough is to reaching a dynamic equilibrium or stable state.

Malzone (1999) compared bathymetric data from 1988 to 1993, data comparison showed a sediment loss of $8x10^4$ m^3/yr. In 2001 Dean (2003) conducted a multibeam sonar survey of the main channel. The 2001 survey was compared to the single beam cross sections taken by Malzone in 1993. Dean showed that between 1993 and 2001 that approximately $0.45x10^6$ m^3 of sediment had eroded, an average rate of 3% of the sloughs volume per year.

The purpose of this project is to assess whether the slough is beginning to approach equilibrium by evaluating spatial and temporal change in erosion rates and the temporal changes in tidal prism. The general approach involved the creation and analysis of a time-series of high resolution digital elevation models (DEM) of the Elkhorn Slough and its surrounding watershed. Two consecutive DEMs were produced using data from the years 2001 & 2003. The two data sets were then compared to determine both the magnitude and the rate of erosion. A terrestrial LIDAR data set was also obtained and merged with a bathymetry data set to calculate the tidal prism. The results of both calculations were then compared to previous studies to determine if and where the rate of tidal scour was increasing or decreasing in the slough.

Between 2001 and 2003, the net sediment volume change was 0.47%. However, with the removal of Parson's slough mouth, from the analysis, that value changes to -1.23%. Between 2001 and 2003, 2.4×10^5 m^3 of sediment was lost, approximately 1.2×10^5 m^3/yr, 1.5 times the annual rate calculated by Malzone (1999). The most severe erosion occurred west of Parsons slough mouth with depth increasing several meters near HWY 1 bridge. Areas north of Parsons showed trends of deposition, likely resulting from bank erosion.

Introduction

Background

Wetlands are unique areas, incorporating both terrestrial and submerged habitat. These productive and complex ecosystems were historically considered useless tracks of land; productive only when drained. This view has caused the loss of many wetland areas as illustrated by California's 75-95% loss due to reclamation. (Silberstein 1989, Crampton 1993, Scharffenberger 1999). It was not until the realization that wetlands provide a host of services such as water filtration, flood control, ground water recharge and recreation (NRC 2001) that views began to change.

The Elkhorn Slough is one of California's last remaining coastal wetland areas. It is located approximately 100 miles south of San Francisco along the middle of the Monterey Bay coastline, at the head of the Monterey Bay Submarine Canyon. At 4,182± acres the combined marshes of Elkhorn and Moro Cojo Slough are the largest coastal wetland between San Francisco and Moro Bay (Scharffenberger 1999). The slough supports a vast ecosystem of unique physical niches occupied by many rare and endangered species. The slough is also an important area for approximately 250 bird species, some relying on it as an important resting area for migration (Silberstein 1989, Scharffenberger 1999, Christensen 2001).

For approximately four thousand years, the Elkhorn Slough watershed has been affected by anthropogenic factors. The Ohlone Indians managed the land, around Elkhorn Slough, by use of fire, keeping grasslands clear for hunting. In the 1700's the Spanish moved into the area setting up missions. With them came cattle which roamed free trampling native scrubs and grasses. The Spanish brought with them non-native plants and grasses which can still be found there today. The 1800's brought with them many changes to the Elkhorn Slough and surrounding area. Many farmers drained wetland areas for conversion to pasture land and agriculture. From the mid to late 1800's Hudson's landing, at the northern end of Elkhorn Slough, served as the Watsonville port. From there crops were loaded onto barges and ferried to Moss Landing to be loaded onto schooners headed for San Francisco and elsewhere. This changed in 1872 when Southern Pacific built a rail line from San Francisco along the edge of the slough. The Vierra family built the first bridge across the slough and dyked off a few hundred acres for salt evaporating ponds. Today the now abandoned salt ponds are have become the most important pelican roosting area north of Point Conception (Silberstein 1989). Large scale engineering projects, over the last century have changed the slough even more dramatically.

The various flows of water which have affected the Elkhorn Slough have undergone many changes in the last century. The Salinas River originally joined the slough near the mouth before discharging into the bay. Sometime around 1908 it is speculated that farmers dug a new Salinas River mouth approximately 6km south of the original slough mouth (Silberstein 1989, Crampton 1994). What is known is that soon after, tide gates were installed preventing freshwater from entering the slough thereby creating a tidal embayment (Silberstein 1989).

The most significant disruption to the Elkhorn Slough in recent times was the establishment of the Moss Landing Harbor in 1947. The harbor occupies the mouth of the Elkhorn Slough and supports an active fishing industry, eco-tourism, and research community. Its creation was spurred by the economic boom of the Monterey Bay fishery before, and during, World War II. During that period, the growing fishing fleet was hampered by the lack of adequate harbors. In 1946, the United States Army Corps of Engineers (USACE) began developing the Moss Landing Harbor by dredging part of the old Salinas River channel. They then broke through the sand spit barrier, which separated the slough from the Pacific Ocean. The act of breaching the sand dunes exposed the main channel to direct tidal flow and flushing (Smith 1973, Crampton 1992, PWA 1992 Malzone and Kvitek 1994, Malzone 1999). As a result, the slough has been severely affected by tidal scour, as the twice-daily tides continually scour the banks and the bottom of the slough channel. This scour results in the deepening and widening of the main channel and tidal creeks, and the loss of pickleweed habitat along the banks.

Changing Environment

Over the last 15 years, there have been several studies which have quantitatively assessed tidal scour in Elkhorn Slough. Due to the dramatic advancement in hydrographic technology, each successive study has revealed the slough and its erosional patterns at an ever increasing resolution. The first study examining tidal scour was conducted in 1988 by Oliver et al, conducted using calibrated lines laid across the slough. Six cross sections were sampled, and depth recorded at five meter increments along the cross sections. Oliver et al determined that extensive erosion had occurred since the opening of Moss Landing Harbor, resulting in a 6 meter increase in depth at the slough mouth. It was also determined that, between 1909 and 1988, there was a 250% increase in water volume.

Crampton (1993) resurveyed Oliver's original sites in 1993 and added three more cross sections. This survey was conducted through the use of a hand held GPS unit and a hand held depth meter. The GPS used at the time achieved a horizontal accuracy of 30 meters. Crampton's results estimated that 420,000m^3 of sediment had eroded resulting in a tidal prism volume of, 2.35 x10^6 m^3, an increase of 22% from Oliver et al. He also estimated that from 1946 to 1993 the average annual erosion rate for the slough was 3.4 x 10^4 m^3/yr.

Along with Crampton in 1993, Malzone and Kvitek used differential GPS (dGPS) and survey grade single beam sonar to conduct an even more detailed study. The new dGPS provided horizontal accuracy of 2m. Malzone and Kvitek conducted 67 cross sections along the main channel and 6 more across the Parson's Slough mouth. From these data Malzone (1999) calculated an erosion rate of 8.0 x 10^4 m^3/yr between 1988 and 1993.

In early 2001 Brantner surveyed the main channel from the mouth to Kirby Park.. This study gained an unprecedented level of resolution through the use of multibeam sonar and real time kinematic (RTK) GPS, a positional accuracy of 3cm horizontal was achievable. This system allowed a 100% coverage bathymetry model to be created for the surveyed area. Brantner calculated that within the surveyed area, there was a rate of loss of 4.66 x 10^6 m^3/yr of sediment between 1993 and 2001, an increase of 15% from Malzone's calculation of sediment loss.

A study by Dean (2003) in late 2001 increased the survey area to include the upper mud flats and upper slough past Kirby Park. Dean found that the erosion rate remained within an order of magnitude to the previous studies. However, the patterns of erosion had shifted, with some area becoming deposition dominant and vise versa. These results lead Dean to qualitatively divide the slough into seven sections: The Mouth, Seal bend, Seal bend to Parson's, Parson's mouth, Midslough 1, Midslough 2, Backslough 1, Backslough 2/Hudsons landing Dean found that most of the erosion occurred downstream of the mouth of Parson's Slough and interpreted this change as indication that the increasing tidal prism of Parson's Slough had become a dominant influence on tidal scour downstream.

These prior results, especially the Dean (2003) study, present a baseline for and times series of environmental change against which future measurements can be compared. The purpose of this study has been to extend this time series in an effort to assess whether or not tidal scour in the Elkhorn Slough is beginning to abate and approach equilibrium.

Management Needs

California has designated the Elkhorn Slough an ecological preserve and the National Oceanic and Atmospheric Administration has included its tidal waters as part of the Monterey Bay National Marine Sanctuary and established a National Estuarine Research Reserve (Scharffenberger 1999). Part of the reserves mission is the long term preservation of the wetland habitat, to comply with that the Elkhorn Slough National Estuarine Research Reserve (ESNERR) staff have begun to formulate a management plan to protect the long term viability of wetland habitat. The management plan includes the need to address the issue of tidal scour.

The rate and distribution of tidal scour is one of the most critical issues facing conservation efforts. Determining the rates of tidal scour gives an indication of how close the slough is to a net sediment flux of zero, resulting in equilibrium. Should the rates be decreasing the interpretation would be that the slough is getting close to equilibrium. If however the rates were increasing it would be interpreted that the slough is far from equilibrium. The determination of equilibrium within the slough is an important factor in allowing ESNERR staff to meet their goal of preserving wetland habitat. Should equilibrium be far off critical wetland habitat may be lost before equilibrium is attained. This situation would prompt the ESNERR staff to examine expensive methods for tidal scour abatement. Through the examination of a time series of bathymetric data, the equilibrium state of the slough can be determined allowing ESNERR staff to take the appropriate action.

Critical areas affected by tidal scour have been identified as a result of the mapping efforts of SFML. This project had three goals: creating a bathymetric model of the slough environment, accomplished by the use of multibeam sonar, single beam sonar and terrestrial LIDAR, quantifying rates and spatial distribution of erosion and deposition accomplished via GIS analysis, and calculating the tidal prism of the slough in GIS for comparison to previous estimates. To determine the equilibrium state of the Elkhorn Slough six hypotheses were tested between the 2001 and 2003 data sets.

H_o: Between 2001 and 2003, no sediment change occurred and tidal prism remained the same as previous estimates therefore equilibrium has been obtained.
H_1: Between 2001 and 2003, erosion rate has slowed bringing the slough closer to equilibrium.
H_2: Between 2001 and 2003, erosion rate has increased bringing the slough further from equilibrium.
H_3: Between 2001 and 2003 spatial pattern of erosion changed
H_4: Between 2001 and 2003 spatial pattern of erosion did not change.
H_5: Between 2001 and 2003 tidal prism of Elkhorn Slough changed.

Results are to be given to ESNERR and the Monterey Bay National Marine Sanctuary Integrated Monitoring Network (SIMoN) for use in policies affecting the Elkhorn Slough and associated watershed.

Methods

General Approach

The assessment of equilibrium within Elkhorn Slough first required a set of high resolution digital elevation models (DEM) to be created. Data from which the DEMs were created was collected by several collaborating institutions and state-of-the-art technologies: The Seafloor Mapping Lab at California State University Monterey Bay (SFML) collected bathymetric data with both multibeam and single beam sonar systems, the National Oceanic and Atmospheric Administration's (NOAA) Coastal Remote Sensing division partnered with the Monterey Bay National Marine Sanctuary (MBNMS), conducted over-flights of the slough with aircraft-based terrestrial LIDAR (Light Detection And Ranging) system. The RTK GPS tide data was collected during the 2003 multibeam survey, the LIDAR flight, and the single beam survey. These data sets were mosaicked to produce a high resolution (1m) DEM of the Elkhorn Slough. The complete DEM was used to calculate the tidal prism, in 2003, using the volume calculator in ESRI Spatial Analyst. The calculated tidal prism was then compared to previous estimates to determine if change had occurred. The two bathymetric DEMs from 2001 and 2003 were used for determination of the rate and spatial distribution of tidal scour by performing a raster subtraction in Arcview. Unlike Dean (2003) this analysis allowed for a much higher resolution of spatial distribution and magnitude of tidal scour to be attained. It should be noted that the 2001 survey used predicted tides at the HWY 1 bridge while the 2003 survey used RTK tide. This resulted is an increasing yet unknown degradation in accuracy, of sediment change determination, from the mouth of the slough to Hudson's Landing. Due to resolution limitations from compounded error of all instruments used during the surveys and tide artifacts in the 2001 data only erosion and deposition that occurred outside ±20cm was used. This provided the best possible determination of the magnitude and spatial distribution of tidal scour within the Elkhorn Slough.

To determine the validity of the zones created by Dean (2003) an Analysis of Variance (ANOVA) test was used. The ANOVA provided a way to test the mean change in depth for the zones, and from that to make a quantitative assessment of the zones established by Dean (2003)

Data collection

This study was conducted through the use of two multibeam bathymetry data sets. Set one was collected July 7th, October 15th and 17th, and November 17th, 2001. Set two was collected March 19-20, March 31, September 29-30 and October 1, 2003.

For the collection of the 2001 and 2003 data sets the California State University Seafloor Mapping Lab (SFML) utilized the R/V MacGinitie, a custom built Sea Ark, "Little Giant", with a length of 27' (8.2m) and a draft of approximately 16" (~40cm). Bathymetric data was collected using a RESON 8101 (240 kHz) Multibeam sonar unit and Triton Imaging Inc. Isis data acquisition software.

Navigation was provided by the use of Coastal Oceanographics HYPACK navigation software. A Trimble 5700 Global Positioning system (GPS) receiver capable of RTK corrections was used for primary navigation and *in situ* tide height data collection. Tidal height and positional accuracy of the vessel was obtained via the RTK base station signal broadcast from the nearby Elkhorn Slough visitor center. A GPS Azimuth Measurement Subsystem (GAMS) was used to track vessel heading. Tracking of the vessels four axis of movement, Pitch, Yaw, Roll and Heave, was achieved by using a Position and Orientation System for Marine Vessels (POS/MV) in conjunction with an Internal Motion Unit (IMU). To adjust the bathymetry measurements for changes in speed of sound, we collected data with a sound velocity profiler (SV+) from Applied Micosystems LTD.

Data Processing

Upon the completion of the surveys, the raw data was exported, in a XTF format and imported into CARIS HIPS. HIPS software combines the motion and navigation data into a "readable" format for post processing (HDCS) Tide data collected during the survey was utilized by applying a smoothing algorithm to the collected points resulting in a tide model to apply to the soundings. Sound velocity data was also applied to the sounding data to correct for refraction, which may have occurred due to density changes in the water column.

Once the data was converted and all corrections applied automatic filters were run, to remove obvious low quality data. Data was then manually edited (Swath and Subset editor) to further clean out erroneous data.

Once this process was completed, I then exported the data as XYZ positions (easting, northing and depth) as a text file, at 1m resolution using the Universal Transverse Mercator (UTM) coordinate system Zone 10 north. All depth values were referenced to the North American Vertical Datum 1988 (NAVD88).

Images and XYZ grids were generated based on the resulting depth data.

GIS Analysis

GIS Analysis was completed using ESRI Arcview 9.x software. A simple raster subtraction was used to determine the amount of erosion that had taken place between surveys. To obtain the erosion between 2001 and 2003, I subtracted, in Arcview, the 2003 bathymetry DEM from the 2001 bathymetry DEM. These calculations resulted in a new raster data set, which indicated erosion as negative values and deposition as positive values. Values returned from the raster subtraction which were inside ±20cm were disregarded due to data collection system vertical resolution limitations and 2001 data tide artifacts. These data were color coded, reds\greens showing areas of erosion, blues\purples showing deposition. The cut/fill function in 3D Analyst, which calculates the required amount sediment removal or addition needed to make one surface match the other, allowed for a highly accurate eroded sediment volume to be obtained.

The tidal volume of the slough was determined through the merging of the multibeam, single beam, and LIDAR data sets creating a continuous DEM of tidally affected areas of the slough. This merged data set was analyzed using the Arcview volume utility function in Spatial Analyst which calculates the volume from the DEM surface to a user defined plane. To constrain the volume calculations to the areas affected by tides an analysis mask, determined by aerial photography at high tide, was used. The sub tidal volume was calculated by defining a plane at 0 and having Arcview calculate the below plain volume. The MHW volume was based on a 1.58m plane. This value was acquired from the MHW values used by Noble tec Tide and Currents prediction software for the Elkhorn Slough HWY 1 bridge. The value was checked against *in situ* tide measurements, taken with a Trimble 5700, equipped with RTK corrections during the 2003 multibeam survey. By subtracting the MHW volume from the subtidal volume resulted in the estimation of the Elkhorn Slough tidal prism.

Statistical Analysis

In order to assess the validity of the eight sections determined by Dean(2003) through qualitative observations, an Analysis of variance (ANOVA) was used. Due to the large amount of data created by using 1m DEM's it was not practical to use the entirety of the data. Instead results were obtained by using cross section locations established by Malzone and Kvitek (1994). Depth data at these locations were extracted from the 2001 and 2003 data. These depths were subtracted and the mean change in depth was recorded for each cross section. Each cross section was given a number 1-7 corresponding to the zone the cross section was in. Parson's Slough was left out of the analysis due to the large deposition occurring there likely not due to natural processes. These data were input into the statistical package Systat 10 where an ANOVA was preformed to detect differences in the zones and a post hoc Tukey test was run to determine within which zones the differences occurred. For the ANOVA two hypothesis were tested: 1) The mean depth change was the same of all zones. 2) There was a difference in the mean depth change within the zones. Hypothesis were rejected or accepted based on an alpha level of 0.05.

RESULTS

Tidal prism

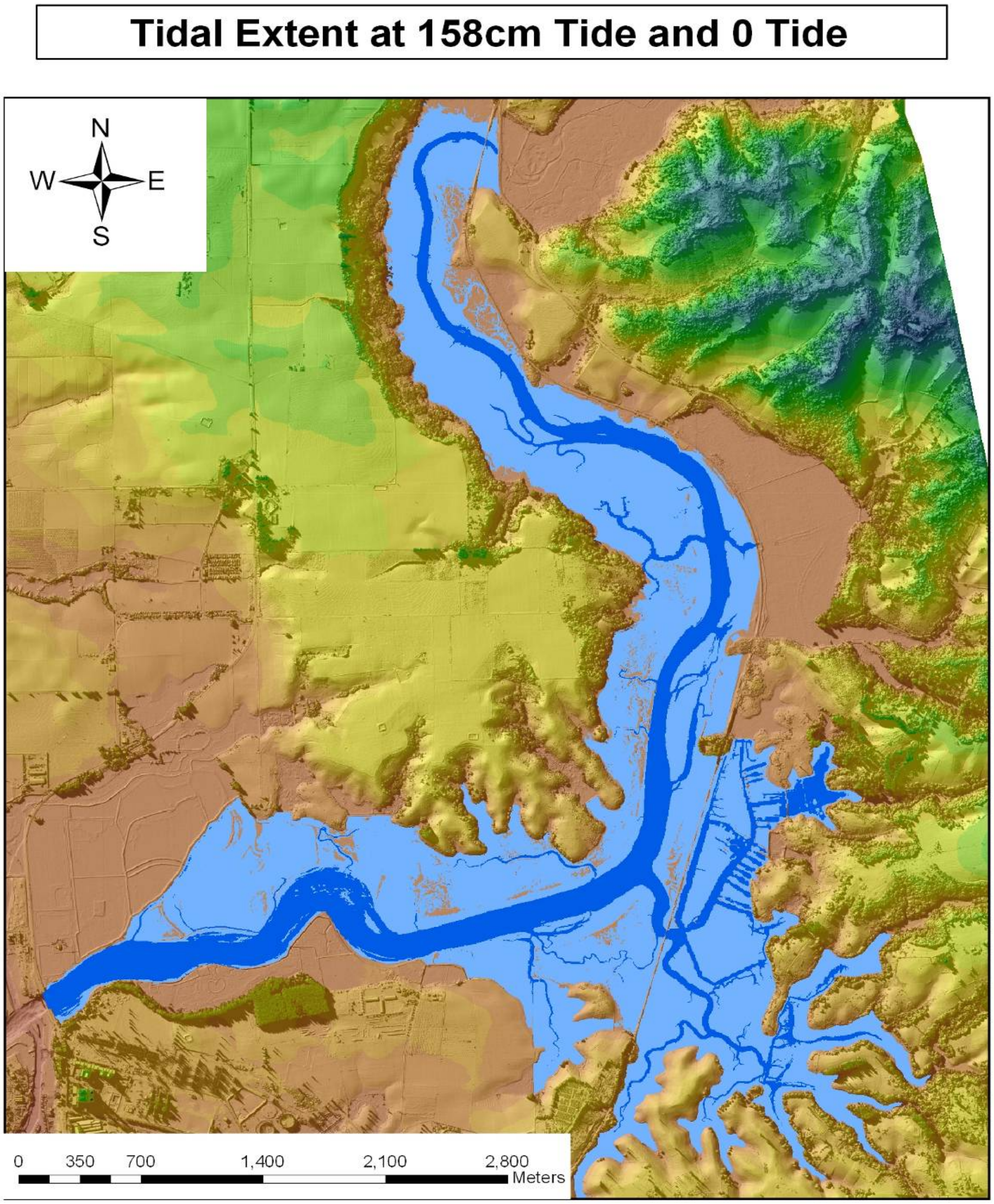

Figure 1 High water extent at 1.5.m tide shown in light blue. Subtidal extent shown in dark blue.

Malzone (1999) calculated tidal prism to be 5.53 x 10^6 m^3. Tidal prism calculated from 2003 survey data was 6.22 x 10^6 m^3 ± 1.00 x 10^6. This represents a 12.71% increase in tidal prism. Of the total tidal prism calculated, Parsons Slough accounted for 30% of the tidal prism with a volume of 1.39 x 10^6 m^3. The percentage of the tidal prism accounted for by Parsons is comparable with previous estimates (Dean 2003)

ANOVA of Dean Slough Zones 2001-2003

Ho: $\mu_1=\mu_2=\mu_3=\mu_4=\mu_5=\mu_6=\mu_7$
Ha: $\mu_1\neq\mu_2\neq\mu_3\neq\mu_4\neq\mu_5\neq\mu_6\neq\mu_7$

Source	Sum-of-Squares	df	Mean-Square	F-ratio	P
LOCATION	1.272	6	0.212	4.33	0.002
Error	1.714	35	0.049		

An ANOVA comparison of the slough zones (figure 2) showed a statistically significant difference (p= 0.002). With my alpha level set to 0.05 the null hypothesis was rejected. A post hoc Tukey test indicated that the differences were between Sea Bend and Midslough 1 (p=0.005) and between Midslough 1 and Backslough 1 (p=0.006). While Dean's divisions do not hold up quantitatively and there are no clearly defined new zones, other than the entire slough. I have continued with the analysis using Dean's zones to both facilitate multi-year comparisons and enabled others who have adopted Dean's zones to continue to use them in their research.

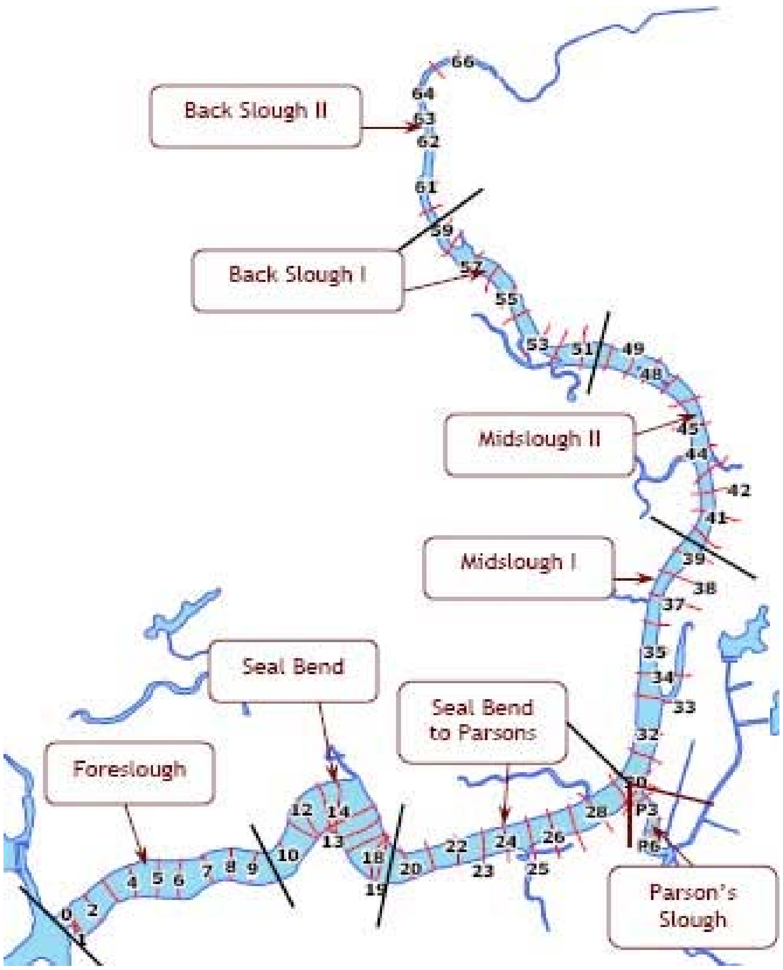

Figure 2 showing Dean zones and Malzone cross sections. Image credit Dean 2003

Thalwag changes 2001-2005

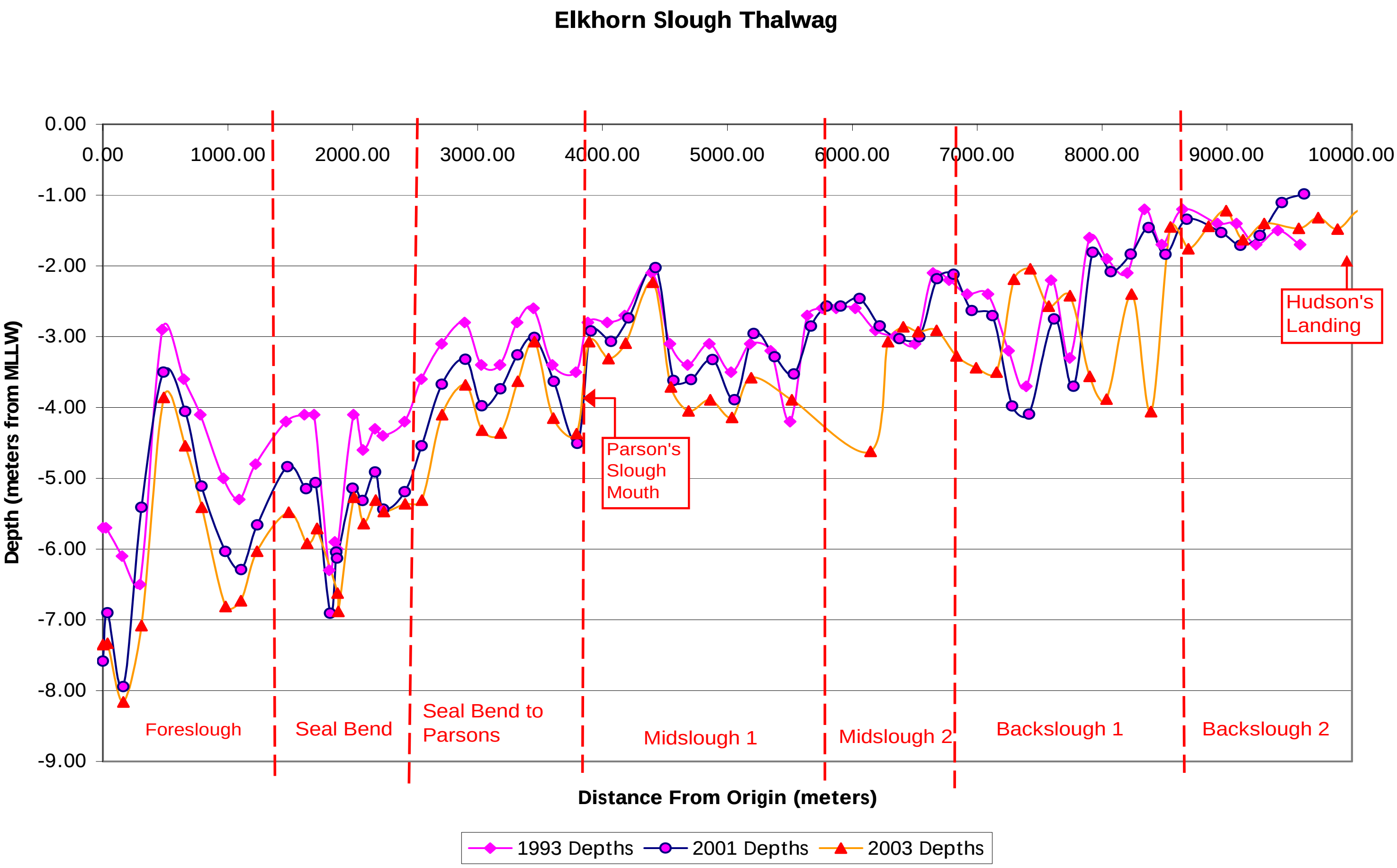

Figure 3 Change in thalwag 1993 to 2003

It can be seen from figure 2 that the thalwag continues to deepen along the length of the man channel. From 2001 to 2003 the majority of the slough showed deepening, however backslough 2 indicated and area of sediment deposition. All areas west of Parson's Slough, toward the mouth, show a significant deepening trend within the main channel. Notice the drastic deepening in Midslough 2 caused by the lengthening of a deep hole along the axis of the main channel (Figure 3).

Change from 2001 to 2003

The overall trend visible from the raster subtractions and cross section analysis between 2001 and 2003 is a deepening of the main channel and a shoaling of the mudflats e.g. at Highway One bridge, below (Figure 3).

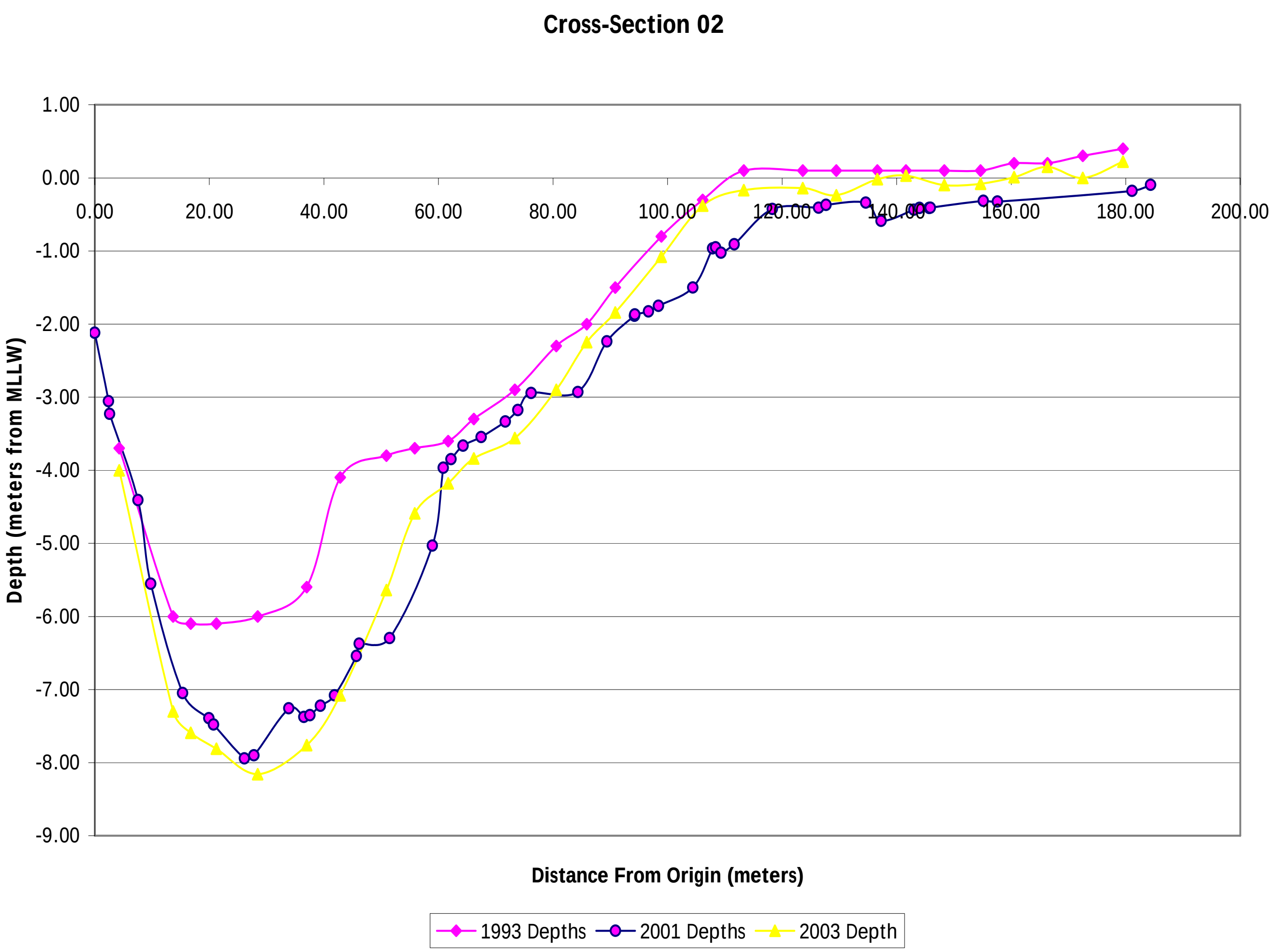

Figure 42: Cross section 2 near the mouth of Elkhorn Slough showing the deepening of the channel and shoaling of the mudflats.

The net change within the main channel of the Elkhorn Slough is -1.23% suggesting an erosion dominated system. However, when the cross section analysis from Parsons Slough is included in the average, the net system change is a positive 0.47%.

Sediment lost

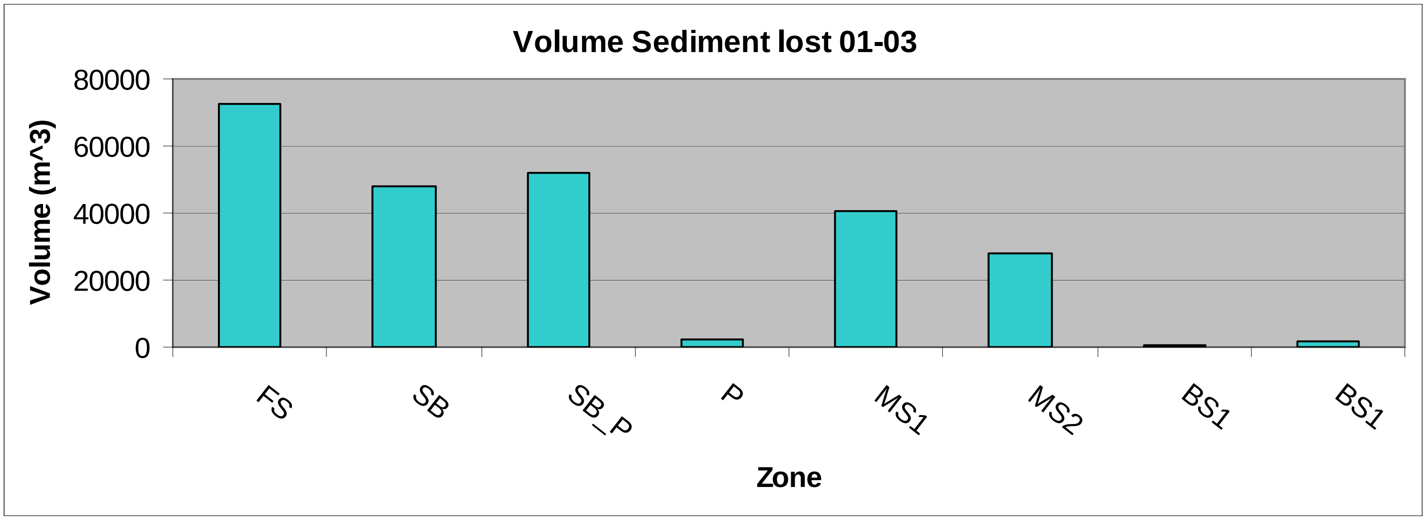

Figure 5: Volume of sediment eroded for each slough zone from 2001-2003

Table 1: Slough zones Sediment lost and percent of total.

Zone	Volume (m^3)	Area (m^2)	%total Volume
Foreslough (FS)	72301.38	131583.00	29.42%
Seal bend (SB)	47733.78	89361.00	19.42%
Seal bend to Parson's (SB_P)	52100.88	144811.00	21.20%
Parsons (P)	2497.81	7423.00	1.02%
Midslough1 (MS1)	40687.28	122441.00	16.56%
Midslough2 (MS2)	28164.71	71989.00	11.46%
Backslough1 (BS1)	664.65	8328.00	0.27%
BS1 (BS2)	1586.77	22448.00	0.65%
Total	**245737.26**	**598384.00**	

Figure 4 and Table 1 show the volume and percentage of sediment loss between 2001 and 2003 and the percentage that each zone is accounted for in the total. 70% of the total sediment volume lost lies west of Parsons Slough mouth this corresponds with pattern observed by Dean (2003) between 1993-2001.

Zones in depth

The following section will examine each Slough section in detail. Each detailed analysis will begin with an aerial photograph taken in 2003 overlaid with the spatial distribution of erosion/deposition along with the corresponding magnitude. The following results were calculated via raster subtraction in ArcView.

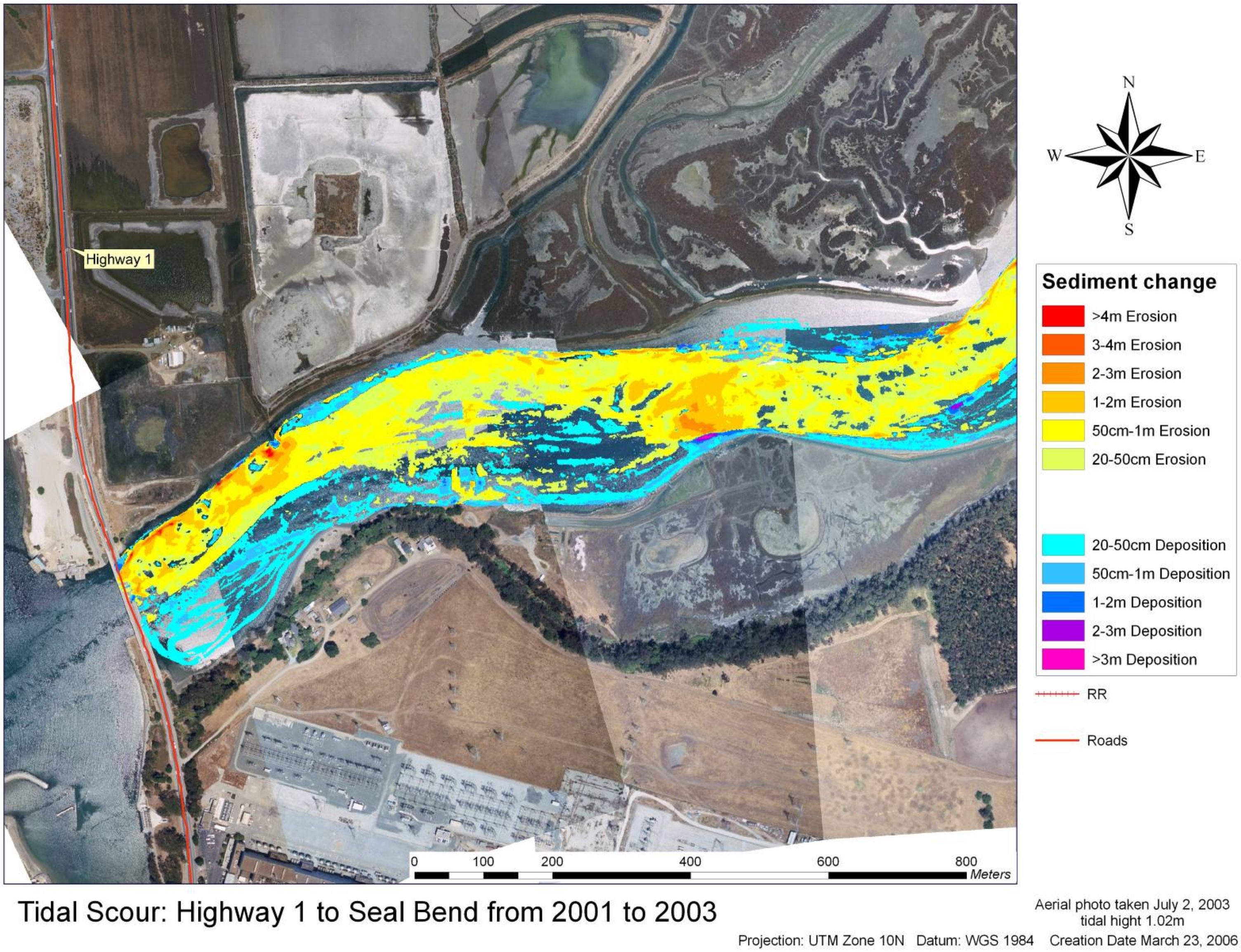

Figure 6: Magnitude of erosion in the Foreslough zone. Note the large amount of erosion in the northern bank approximately 150m from the Hwy 1 bridge (left side of the image)

Table 2: change in cross section area of Foreslough 2001-2003

cross section		Foreslough CSA change	% change
	0	14.81	3.51%
	1	8.29	1.97%
	2	33.30	6.30%
	3	0.40	0.09%
	4	-63.99	-13.97%
	5	35.53	6.55%
	6	52.98	9.71%
	7	-102.20	-18.66%
	8	-5.44	-0.94%
	9	-85.66	-17.13%
mean		**-11.20**	**-2.26%**
Std Dev		**51.11**	**9.90%**

The Foreslough is composed of the area between the Highway one bridge and Seal Bend (Figure 6). This zone accounts for 29.42% of the total sediment volume eroded (Table 1). Depths in the Foreslough exceeded 10m making this the deepest part of the slough. The north side of the channel is almost vertical in some places while the south side of the channel shallows to a broad mudflat. While this area did contain the majority of the sediment lost, the mean cross section area only increased by 2.26%. The thalwag in this area deepened by 1-2m however the areas along the banks shoaled by up to 1m. The largest change in depth for the entire slough was within this zone. A small area on the north bank approximately 200m from the Hwy 1 bridge experienced between 4-5m of erosion. Evidence suggests that this area of erosion was not the result of channel erosion, but failure of an old dyke hidden below MLLW

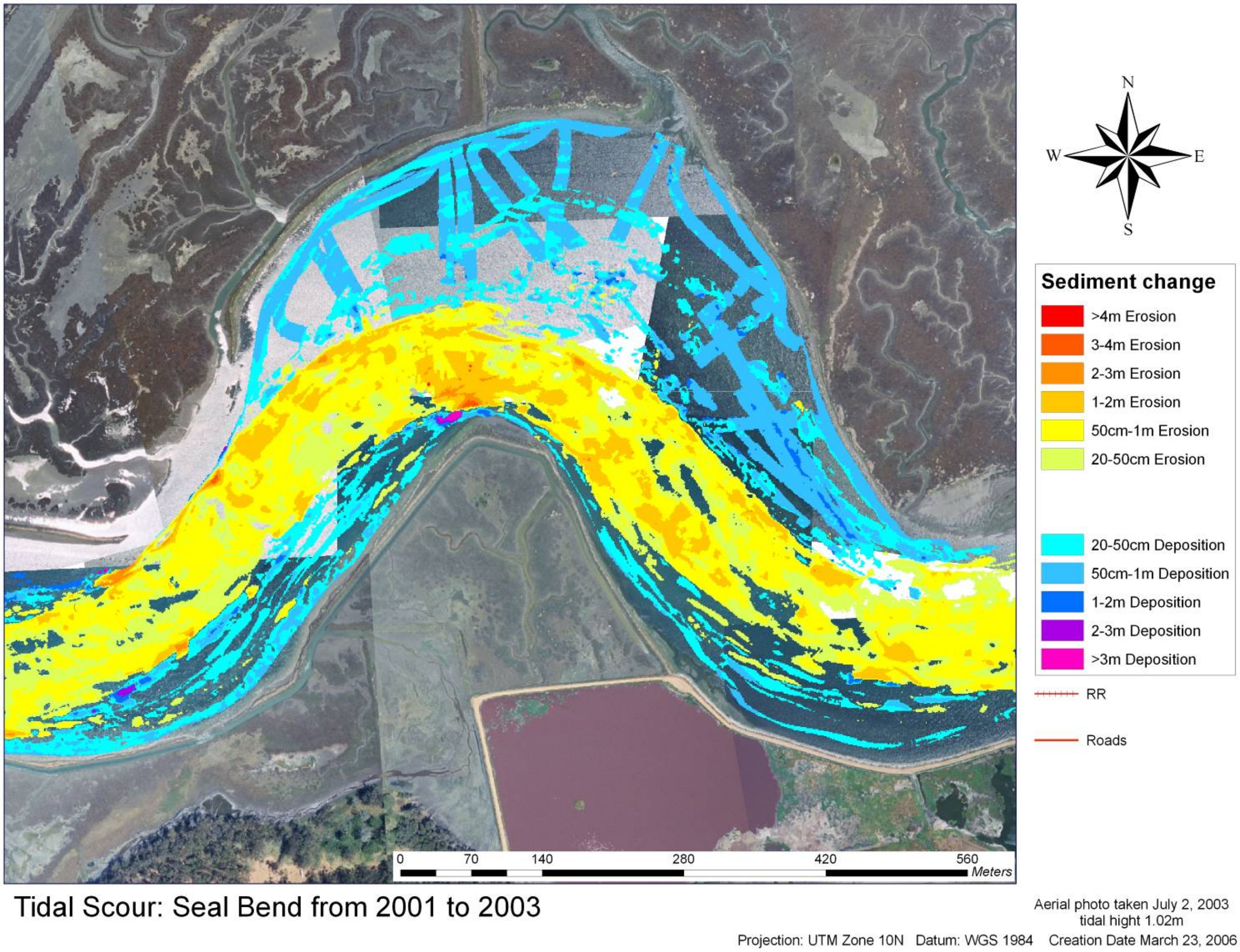

Figure 7: Seal Bend magnitude of erosion. Shoaling occurring on the north side of the bend.

Table 3: change in cross section area of Seal Bend 2001-2003

cross section	Sealbend CSA change	% change
10	-65.05	-15.90%
11	42.88	7.78%
12	55.91	10.09%
13	120.08	24.66%
14	56.81	8.96%
15	-39.80	-5.94%
16	34.54	6.04%
17	0.75	0.13%
18	22.43	4.26%
19	13.58	2.56%
mean	**24.21**	**4.26%**
Std Dev	**52.12**	**10.64%**

Seal Bend accounts for the third largest percentage of sediment lost in the slough with 19.42% (Table 1). The majority of sediment loss occurred along the thalwag where depth increased up to a meter. Due to favorable tides, the 2003 survey was able to extend coverage in the north end of Seal Bend. Results show that the area has shoaled up by up to 1m. Results from the cross section analysis show that this area is experiencing net deposition which is accounted for by the shoaling occurring along the banks. Net deposition in this area may be an indication that little sediment is flushing out the mouth and instead is only shifting around within the zone.

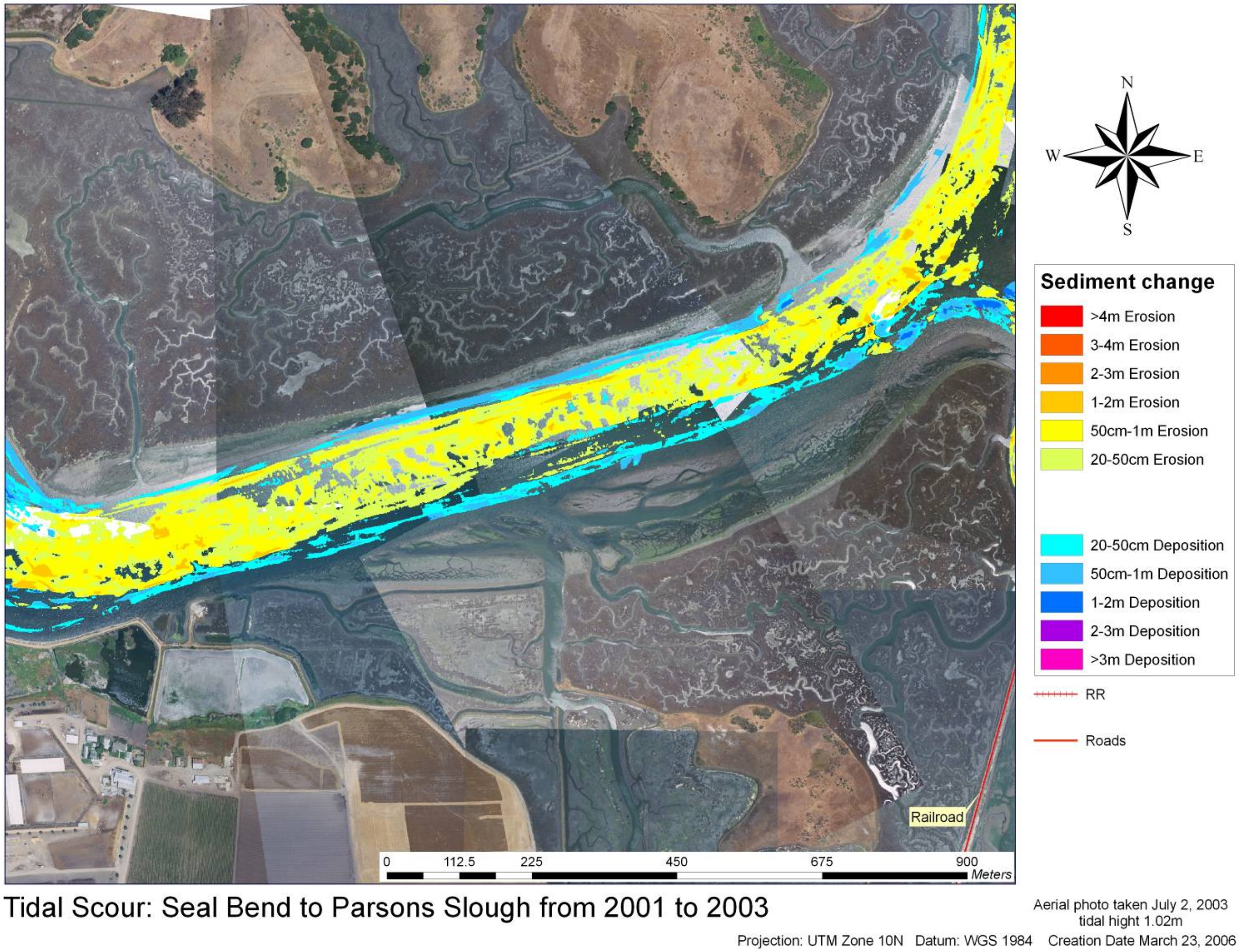

Figure 8: Note the consistent erosion taking place along this zone.

Table 4: change in cross section area of Seal Bend to Parson's 2001-2003

cross section	Sealbend to Parsons CSA change	% change
20	-48.53	-10.40%
21	-49.89	-11.40%
22	-13.02	-3.10%
23	-31.76	-8.51%
24	-26.94	-7.26%
25	-27.36	-8.80%
26	-26.89	-9.34%
27	-4.07	-1.35%
28	1.40	0.39%
29	29.76	6.51%
Mean	**-19.73**	**-5.33%**
Std Dev	**24.11**	**5.76%**

The Seal Bend to Parsons Slough (Figure 8) accounted for 21.2% of the total sediment lost within the slough (Table 1). The erosion taking place in this area is more evenly distributed as confirmed by the comparatively small standard deviation in the cross section analysis (Table 4). Changes in depth were also even along the length of the zone, a trend shown in the 1993 to 2001 data.

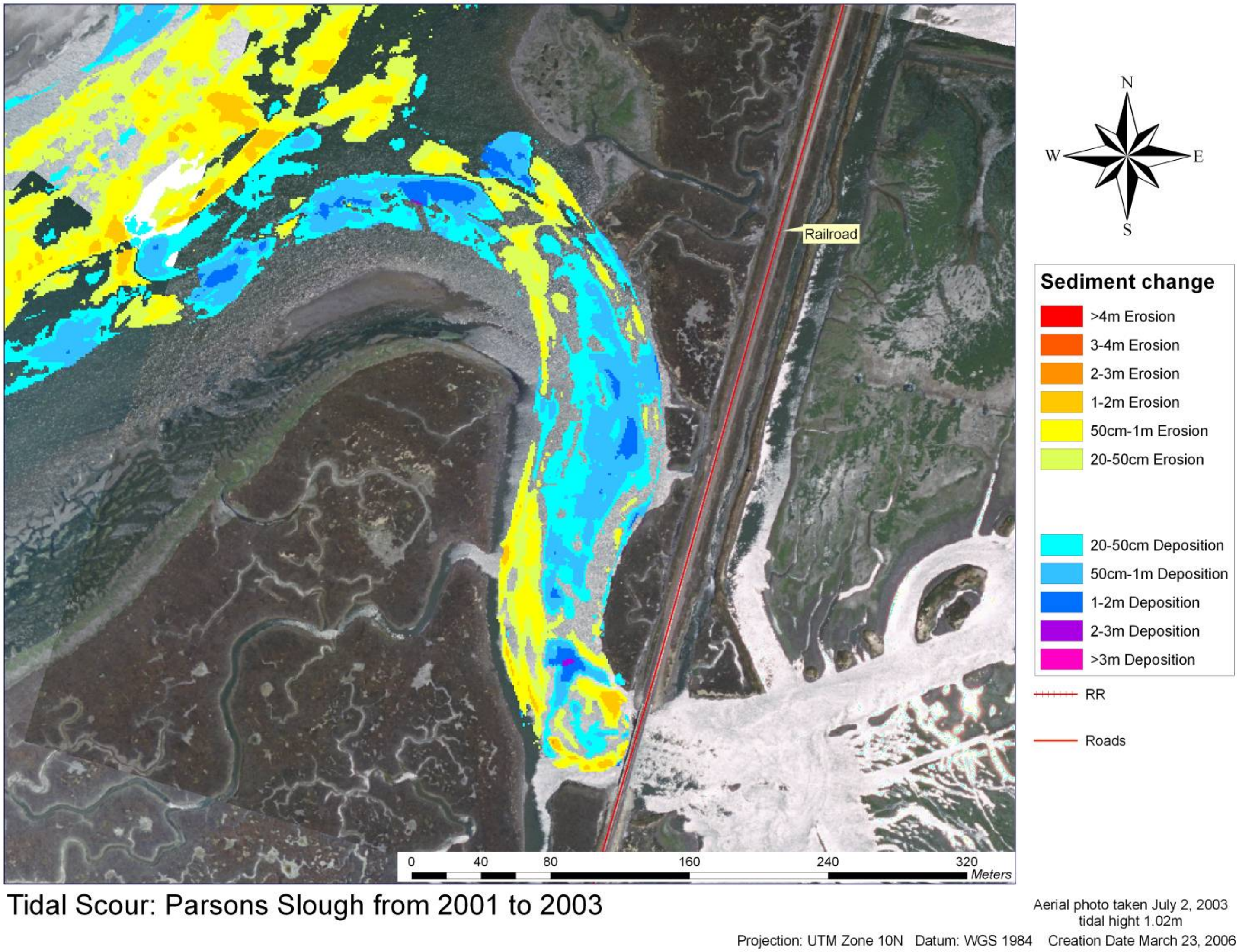

Figure 9: Parsons Slough Mouth. From 2001 to 2003 a large amount of deposition had occurred.

Table 5: change in cross section area of Parson's 2001-2003

Cross section	**Parsons CSA change**	**% change**
67	73.85	22.11%
68	87.23	35.19%
69	33.44	22.14%
70	31.84	15.19%
71	8.83	4.74%
72	34.01	15.56%
mean	**44.87**	**19.16%**
Std Dev	**29.50**	**10.11%**

The mouth of Parsons Slough experienced the highest percentage of deposition. Erosion accounted for only 1.02% of the total eroded sediment volume. All cross sections and raster subtractions at Parson's indicate a positive change from 2001 to 2003 (Table 5) Dean's findings from 1993-2001 (Figure 9). However, roughly 2 months before the 2003 survey, the railroad bridge that crosses Parson's Slough mouth was replaced. The replacement of the bridge is a likely cause of the discrepancy.

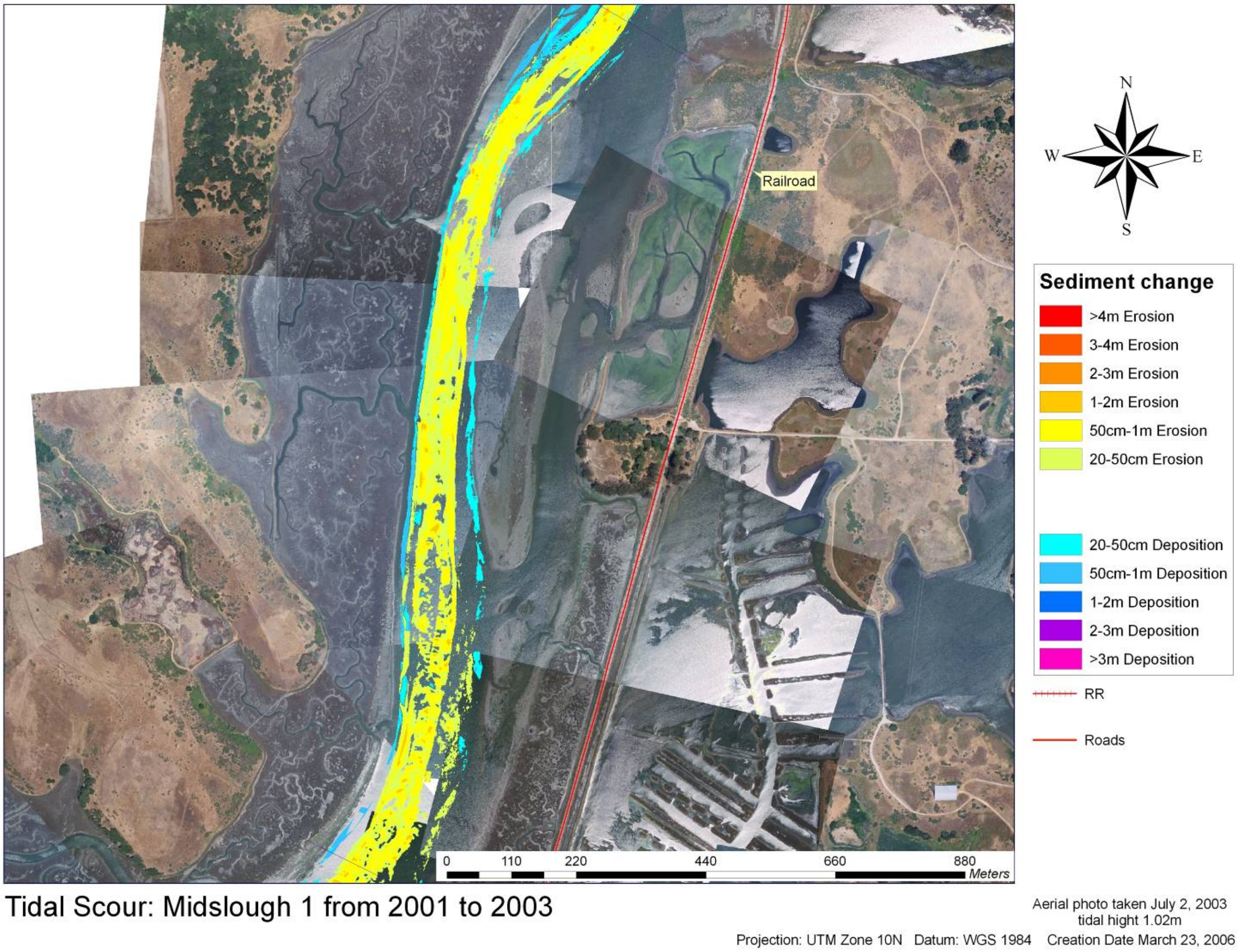

Figure 10: Magnitude of erosion at Midslough 1. Narrow lines of deposition along the banks and erosion in the channel is the defining pattern along the upper slough.

Table 6: change in cross section area of Midslough 1 2001-2003

	Midslough 1	
cross section	**CSA change**	**% change**
30	-14.25	-5.42%
31	-25.37	-9.83%
32	-8.93	-3.86%
33	-13.32	-8.67%
34	-20.06	-11.35%
35	-25.15	-14.03%
36	-31.95	-19.75%
37	-14.74	-9.39%
38	-28.85	-18.24%
39	19.66	9.89%
mean	**-16.30**	**-9.07%**
Std Dev	**14.68**	**8.36%**

Midslough 1begines north of the sharp northward turn in the slough (Figure 10). From 1993 to 2001 this section accounted for only 4% of the total eroded sediment. This percentage has increased by 4 times and now accounts for 16.56% of the total. The slim line of deposition and the lack of mud banks along the main channel suggest that the deposition seen is the result of marsh clasping into the channel.

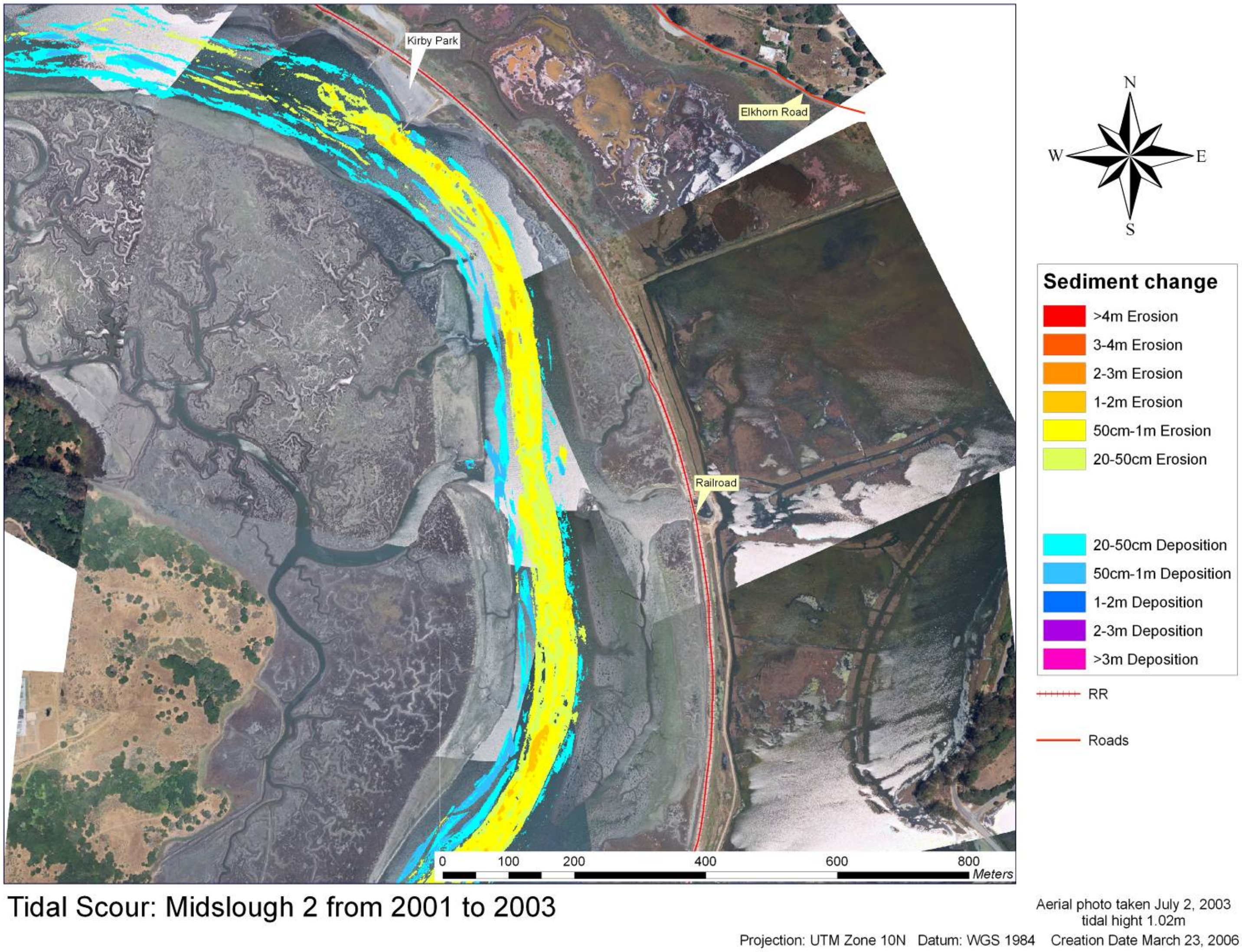

Figure 11: Midslough 2 is the last area where large areas of change have occurred along the channel

Table 7: change in cross section area of Midslough 2 2001-2003

	Midslough 2	
cross section	**CSA change**	**% change**
40	-5.23	-3.09%
41	27.61	18.31%
42	-19.26	-13.00%
43	-15.86	-8.86%
44	17.89	13.50%
45	-20.77	-16.90%
46	-16.97	-12.88%
47	-11.97	-7.95%
48	0.06	0.04%
49	8.96	7.69%
50	10.51	8.08%
mean	**-2.28**	**-1.37%**
Std Dev	**16.52**	**11.80%**

Midslough 2 occupies the gentle curve to the west that the slough takes near Kirby Park. Results for this zone show mild erosion, averaging from 0.5-1.5m with relatively small changes in cross section area (Table 7).

Deposition in this zone is a much more dominant factor. The upper part of the zone is almost entirely depositional (Figure 11) and from here on out the channel becomes spotted with areas of deposition and erosion.

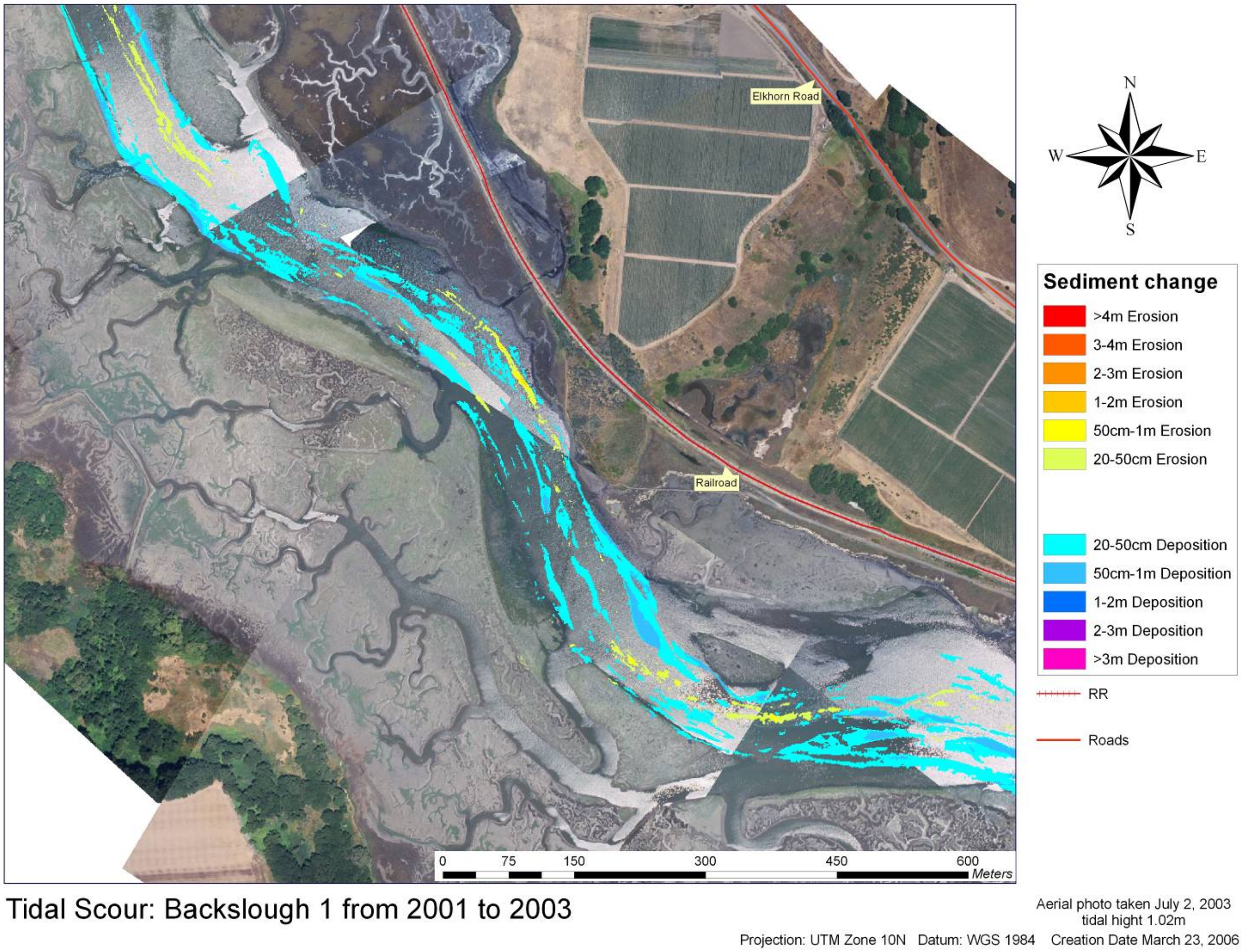

Figure 12: Magnitude of erosion at Backslough 2

Table 8: change in cross section area of Backslough 1 2001-2003

	Backslough 1	
cross section	**CSA change**	**% change**
51	10.51	8.08%
52	10.04	8.75%
53	-2.59	-2.44%
54	13.07	13.55%
55	-16.62	-24.47%
56	-0.68	-1.28%
57	-16.62	-24.47%
58	17.40	26.72%
59	10.24	19.52%
mean	**2.75**	**2.66%**
Std Dev	**12.65**	**17.90%**

Between 2001 and 2003, Backslough 1 shifted from erosion dominated area to one of deposition. Deposition in this zone averaged between .5 and 1m. The thalwag in this area has shifted since 2001, leading to the high standard deviation in CSA in between these data sets.

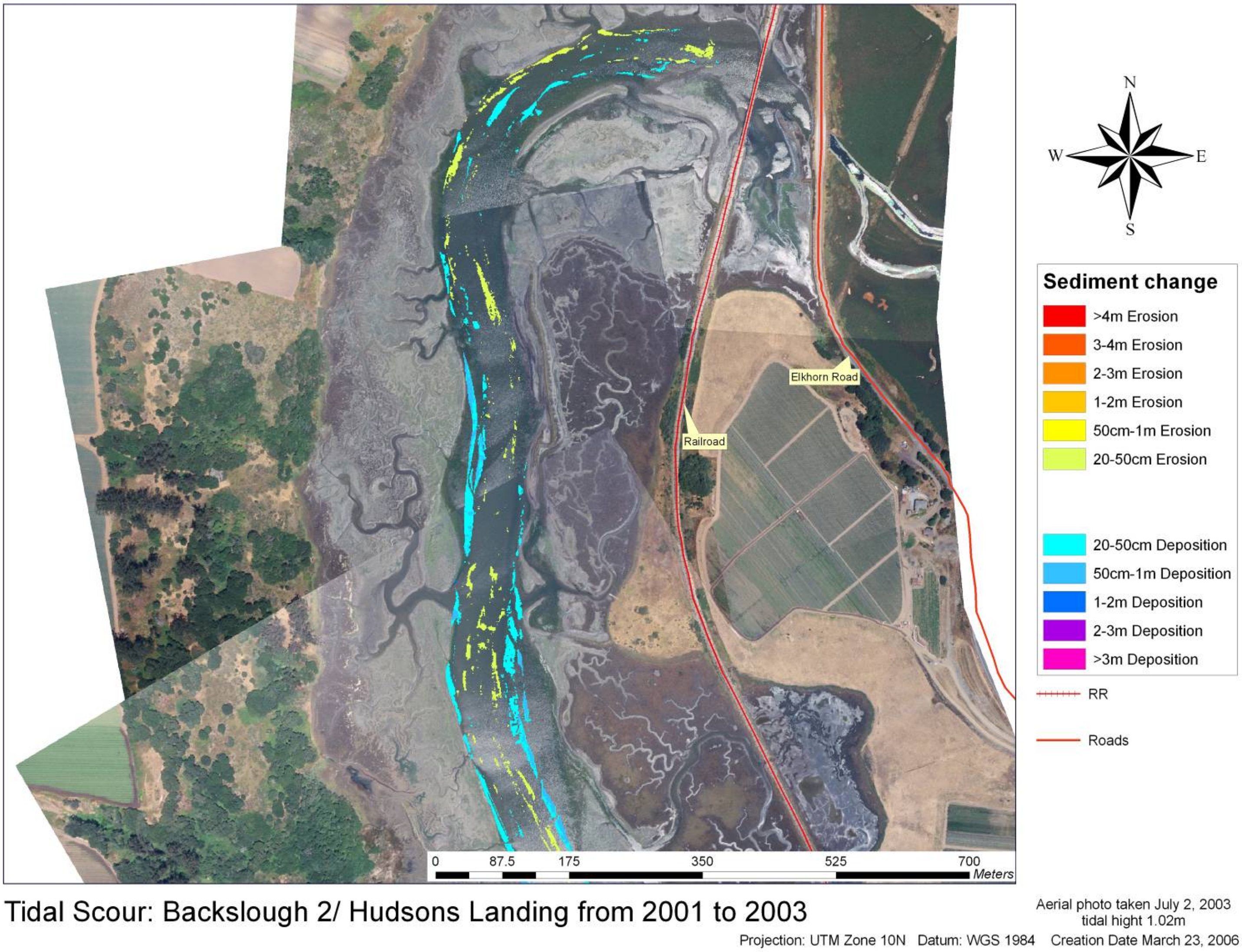

Figure 13: Magnitude of change in Backslough 2

Table 9: change in cross section area of Backslough 2 2001-2003

	Backslough 2	
cross section	**CSA change**	**% change**
60	13.48	26.38%
61	-0.45	-0.98%
62	2.67	6.22%
63	3.76	9.24%
64	-1.34	-4.43%
65	-0.77	-2.88%
means	**2.89**	**5.59%**
Std Dev	**5.57**	**11.50%**

Backslough 2 experienced very little overall change; the change that did occur was an even mix of erosion and deposition. Other than Parsons Slough, the Backslough 2 area had the highest positive CSA change. However the deposition may be misleading. In the northern part of the zone there is deposition along the channel and erosion along the banks. This points to bank failure and slippage (Figure 13). As the banks fail the sediment through tidal flow moves to the center of the channel giving the effect of a more purely depositional area

Precision

During the two surveys RTK corrections were calculated from base stations set up at the ESNERR visitor center. The locations of the base stations at ESNERR did change between the two surveys. During the 2001 survey the base station was located at the overlook. For the 2003 survey a permanent base station was set up at the visitor center. During both surveys RTK corrections were lost due to cell phone signal "holes", during these events dGPS was used for corrections. This resulted in a loss of accuracy, from centimeter with RTK to meter with dGPS. The areas where reception of the RTK signal was lost, and dGPS was used, the location of some soundings could be off by up to several meters. This potentially has a dramatic affect on the results of the raster subtractions. Unfortunately the locations where RTK signal was lost were not recorded during the surveys, this leave no way of identifying these areas in the grids.

During the 2001 survey RTK tide data was not collected. For this data set predicted tides were used based on the HWY 1 bridge. Due to the sinuosity of the slough, predicted tides become less accurate as one works their way up the slough towards Hudson's Landing. As a result tide artifacts become more prevalent along the slough axis. Dean (2003) found no effective way to counter this issue and tide artifacts remain. The analysis between 2001 and 2003 accounted for these artifacts by excluding areas where change was ±20cm. In doing this much of the change due to tide artifacts have been substantially reduced. To reduce these problems in future studies all surveys conducted after 2003 should collect real-time tide data to assure the most accurate results.

Discussion

The continual flow of the tides over the last half century has resulted in constant erosion of the Elkhorn Slough. Based on the results of my analyses, there is no evidence to suggest that the Elkhorn Slough is near equilibrium.

The volume of sediment loss in between 2001 and 2003 surveys was 2.4×10^5 m^3. Approximately (1.2×10^5 m^3/yr) 1.5 times the annual rate calculated by Malzone (1999). Based on this evidence, there is reason to believe that the erosion rate is increasing.

Much of the patterns discussed by Dean (2003) are consistent with the measured values of the 2001-2003 study. As in Dean's analysis the Foreslough still accounts for the most volume of sediment lost. However in this area, much of the sediment was lost from the channel while the mudflats experienced deposition. Also, the area from Seal Bend to Parsons experienced the least amount of variability in cross section, indicating that this area of the slough is the most consistent in erosion and deposition patterns. The Backslough remains a depositional dominated region as was seen between 1993 and 2001. The deposition pattern in this region, especially in the upper reaches of the back slough, is consistent with bank failure. These patterns suggest that the marsh habitat is at great risk of eroding into the main channel.

A major inconsistency seen between Dean (2003) and this study was the change in Parsons Slough between from 2001 to 2003. Parson's Slough mouth experienced high deposition, likely caused by the replacement of the railroad bridge crossing over it.

Conclusion

The goal of this project is to assess the equilibrium potential of the Elkhorn Slough. Given the evidence from this series of data, equilibrium may not be reached anytime in the near future.

The comparison of the data sets revealed that the slough is constantly changing. With every surge of the tides, sediment is shifted. With the daily tidal currents, many cubic meters of sediment are lost per year. With every cubic meter of sediment lost, the marsh habitat further degrades. The 2001 and 2003 surveys have a greatly improved data resolution this has allowed for a more complete understanding of tidal scour. These data sets have shown that the Elkhorn Slough may be worse off than anyone had previously thought. The erosion in some areas of the slough is phenomenal, and the volume of sediment lost per year is far greater than any previous estimate. Through sea level rise and human influence, the Elkhorn Slough is threatening to disappear altogether, transforming from the wonderful marshland seen today to a shallow lagoon with no hint of its former glory.

This presents a tremendous challenge to resource managers who are tasked to preserve the vital habitat the Elkhorn Slough provides. The information provided by this study will be going directly into the strategic planning currently occurring at the slough. This study has provided resource managers with the spatial and temporal distribution of tidal scour. This information will allow resource managers to better plan locations to concentrate on and the time scale that it must be done. These two surveys were the first to use multibeam sonar generating a 100% coverage DEM which allowed for unprecedented understanding of tidal scour. The complete picture formed by the use of this new technology greatly enhances the strategic planning currently occurring at the slough. For long term monitoring regular survey must be completed in order to monitor the success of management efforts.

Bibliography

Crampton TA. 1994. *Long term effects of Moss Landing Harbor on the wetlands of Elkhorn Slough.* Santa Cruz, CA: University of Santa Cruz.

Christensen B. 2001. California Resources Agency Coastal Impact Assistance Program Project Proposal Form, Sacramento, CA: California Coastal Commission.

Dean EW. 2003. *Tidal scour in Elkhorn Slough California: A bathymetric analysis*. Seaside, CA: California State University Monterey Bay.

Malzone CM, 1999. *Tidal scour and its relation to erosion and sediment transport in Elkhorn Slough* [thesis]. San Jose, CA: San Jose State University.

Malzone C, Kvitek R. 1994. *Tidal scour, erosion and habitat loss in Elkhorn Slough, California.* Moss Landing, CA: Elkhorn Slough Foundation

Malzone C, Kvitek R. 1994. *Tidal scour, erosion and habitat loss in Elkhorn Slough, California: executive summary.* Moss Landing, CA: Elkhorn Slough Foundation

Oliver JS, King JA, Hornberger M Schwartz DL. 1998. *Extensive salt marsh erosion caused by human activities in Elkhorn Slough, California.*

Philip Williams & Associates, Ltd. (PWA 1992). 1992 *Elkhorn Slough tidal hydraulics erosion study.* Prepared for: U.S. Army Corps of Engineers, San Francisco district.

Scharffenberger T. 1999. *Elkhorn Slough watershed conservation plan*. Moss Landing, CA: Elkhorn Slough Foundation. Moss Landing, CA: Moss Landing Marine Laboratories.

Silberstein M, Campbell E. 1989. *Elkhorn Slough.* Monterey CA: Monterey Bay Aquarium.

Smith RE. 1973. *The hydrography of Elkhorn Slough a shallow California costal embayment.* Moss Landing Marine Laboratories, Moss Landing, CA: Moss Landing Marine Laboratories.