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Water levels, wetland elevations, and marsh loss

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The mission of the Elkhorn Slough Foundation and the Elkhorn Slough National Estuarine Research Reserve is conservation of estuarine ecosystems and watersheds, with particular emphasis on Elkhorn Slough, a small estuary in central California. Both organizations practice science-based management, and strongly support applied conservation research as a tool for improving coastal decision-making and management. The Elkhorn Slough Technical Report Series is a means for archiving and disseminating data sets, curricula, research findings or other information that would be useful to coastal managers, educators, and researchers, yet are unlikely to be published in the primary literature.

Introduction

The extent and density of marsh vegetation at Elkhorn Slough has been decreasing for at least seven decades (Van Dyke and Wasson 2005). Although some of this loss can be attributed to erosion along the banks of the main channel and to expanding tidal creek networks, the majority has occurred within the interior of the marshes (Figure 1). This pattern of marsh loss, resulting from longer and more frequent periods of inundation, is increasingly reported in the literature and is referred to as *ecological drowning*. Even minor alterations to the frequency and duration of tidal inundation can dramatically affect sediment deposition and erosion patterns and reduce the viability of wetland vegetation. The general cause of excessive marsh inundation is relative sea level rise due to either rising water levels or subsiding marsh elevations—or from these two processes in combination.

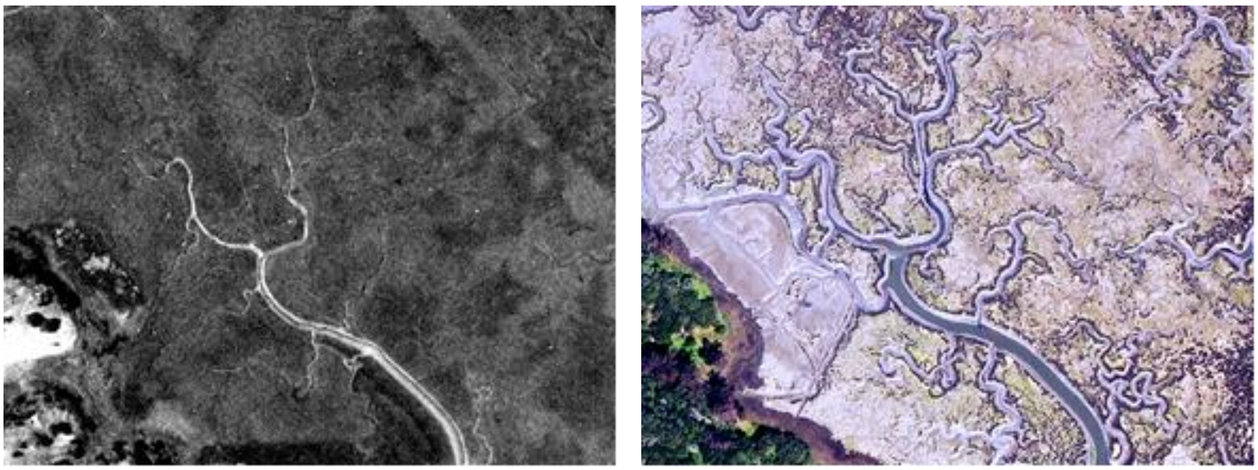

Figure 1: Marsh loss at Elkhorn Slough. Left: A tidal creek surrounded by intact salt marsh in 1931. Right: The same location in 2007. Very little marsh remains; the majority has converted to mudflat (light color).

The objectives of this report are to document water levels and wetland elevations in Elkhorn Slough's tidal wetlands and to estimate historic rates of sea level rise and marsh elevation change. Our broader goal is to increase understanding of the causes of marsh loss at Elkhorn Slough.

The key to monitoring relative sea level rise is establishing precise relationships between water levels and marsh surface elevations, measured at multiple locations and at different times. Simultaneous water level measurements will vary between even nearby locations, and both water levels and wetland elevations will vary at a single location according to various influences, some cyclic (e.g. tides, seasons) and some not (e.g. weather, seismic events).

Water levels are specified relative to tidal datums, including mean lower low water (MLLW), mean tide level (MTL), and mean higher high water (MHHW), each of which represents the average of many measurements obtained over a relatively long period. Due to the complexities of hydrodynamics and channel geometry, neither instantaneous water levels nor averaged tidal datums define a "level" surface across the system; waters will "run up" to higher levels in certain areas, and overall tidal amplitude will be greater in some areas than others. In contrast, land elevations are specified as orthometric height relative to a geodetic datum, the North American Vertical Datum of 1988 (NAVD88), which was designed to approximate a particular level surface (average sea level at a tide gauge in Quebec, Canada). As a result, for every relationship established between water levels and wetland elevation, we must specify three types of data:

- Water levels (relative to tidal datums)
- Orthometric height (relative to NAVD88 geodetic datum)
- Location, time, and date

ESNERR's efforts to monitor relative sea level rise and its impacts on coastal habitats are consistent with the emerging NOAA "Sentinel Sites" initiative. Components of ESNERR's Sentinel Site (Figure 2) include:

- A precise vertical control network (passive benchmarks and active GPS monuments)
- Accurate water level measurements (tide gauges)
- Accurate marsh elevation measurements (surface elevation tables and topographic surveys)

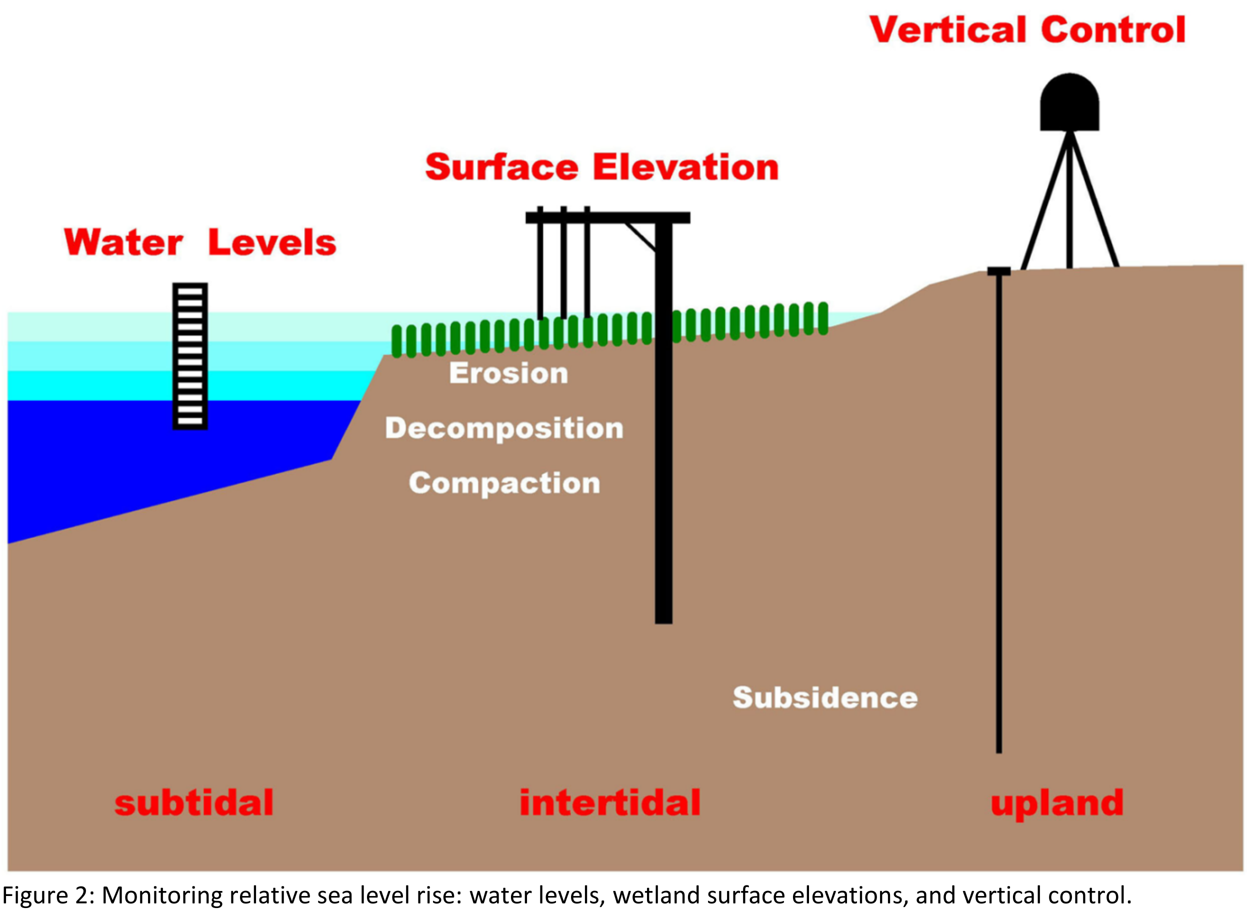

Figure 2: Monitoring relative sea level rise: water levels, wetland surface elevations, and vertical control.

Vertical Control Network

Water levels are determined by averaging measurements made directly from a tide gauge. Surprisingly, no such direct method exists for measuring orthometric heights. In the past, precise differential leveling was the preferred method for transferring absolute water levels from a tide gauge to relative heights along a network of permanent benchmarks. Completing these long-distance leveling runs was labor intensive and expensive—imagine today's cost for running precise levels between Quebec and Elkhorn Slough! For this reason, the network of benchmarks that bisects Elkhorn Slough had not been updated since shortly before the 1989 Loma Prieta Earthquake (and likely never will again). As published datasheets for benchmarks in the Elkhorn area warn: "The height was derived from older observations constrained to new heights in a crustal motion area. The height is approximate in relation to other heights in its vicinity" and "Repeat measurements at this control monument indicate possible vertical movement."

In 2007-2008, a partnership between NOAA's National Geodetic Survey (NGS), NOAA's Center for Operational Oceanographic Products and Services (CO-OPS), and slough research staff completed 12 km of precise levels between Dolan Road to the south and Hudson Landing to the north. Through this effort, height differences between existing benchmarks were determined, and several new benchmarks were installed and added to the network. But because there was no source for absolute elevation control anywhere near the survey area, this new level line provided only relative heights, showing how much adjacent benchmarks were higher or lower than one another but not whether the elevation of entire network had changed during the two decades since 1989.

To establish absolute elevations at Elkhorn Slough benchmarks, an additional eight km of precise levels were run to the north of Elkhorn Slough in January 2011 under the leadership of licensed surveyor Kathy Pugh. The target of this second survey was a deep-rod benchmark in the Pajaro Valley that was chosen for several reasons: it is the nearest stable monument beyond Elkhorn Slough (16 m deep in upland soil), it was included in an extensive, post-earthquake network of precise levels (Marshall et al. 1991), and it was included in a recent, region wide GPS height modernization project (California Spatial Reference Center 2009). Therefore its current absolute elevation is well established.

The complete Elkhorn Slough vertical control network consists of 28 existing or newly installed passive benchmarks, a continuously operating GPS station (CORS), four water level monitoring stations (two in the main channel and two in major tidal creeks), and eight paired surface elevation table monuments with associated feldspar marker horizons—all connected through 20 km of precise, double-run differential levels (Figure 3). Updated benchmark elevations are documented in Appendix 2.

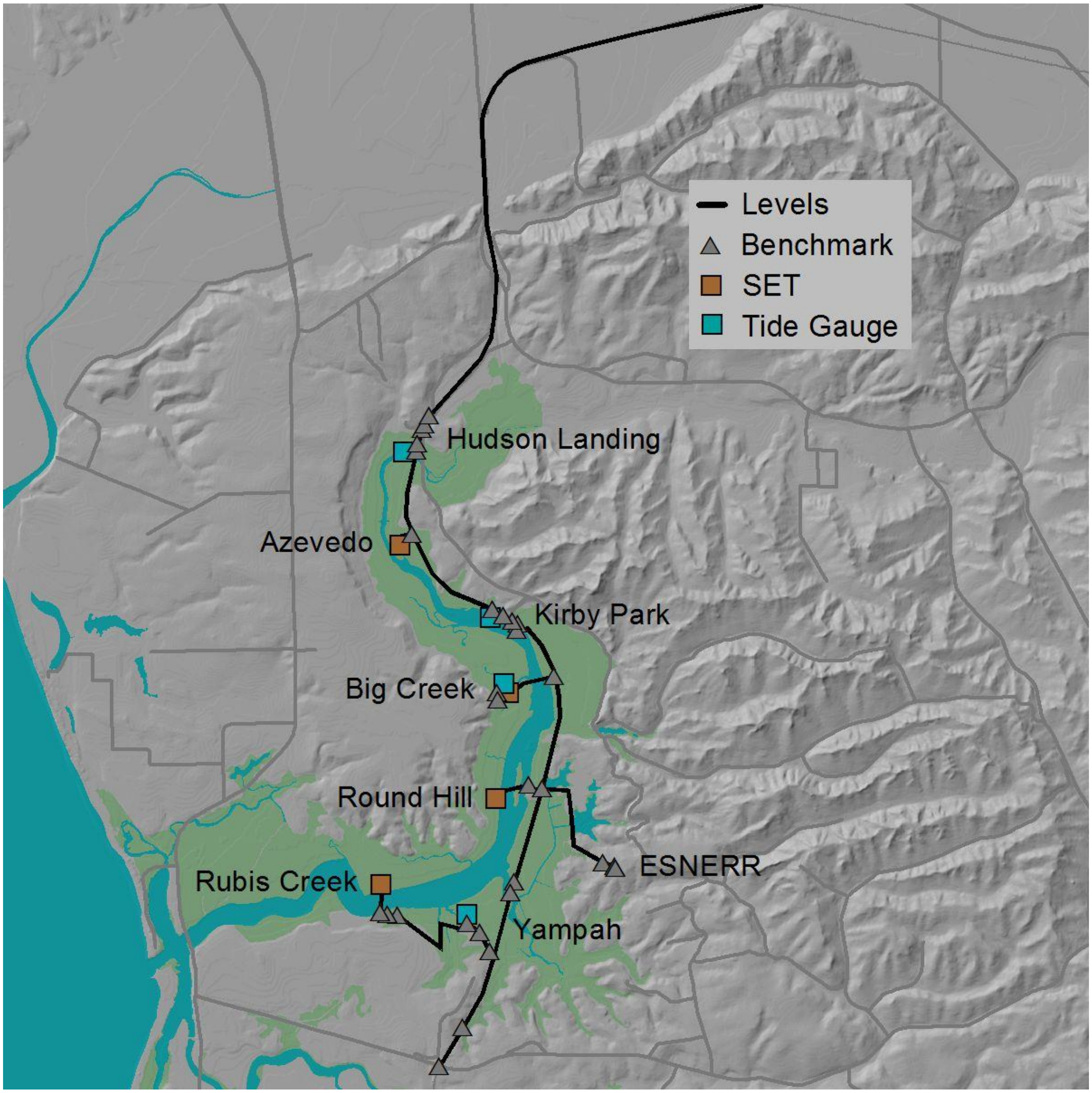

Figure 3: Elkhorn Slough vertical control network.

Water Levels

Through a cooperative agreement with NOAA's Center for Operational Oceanographic Products and Services, we measured water levels at Elkhorn Slough in 2007-2009. Tide gauges were installed at four locations: two in the main channel and two within the slough's deepest tidal creek systems. This data, in conjunction with concurrent data from NOAA's long-term station at Monterey, allowed us to calculate updated tidal datums and analyze tidal constituents and characteristics. Archived water level data, analyses, and tidal predictions for the four new Elkhorn Slough stations (9413631, 9413643, 9413651, and 9413663) are available online at http://tidesandcurrents.noaa.gov/. Updated NAVD88 datum values are documented in Appendix 1.

Between 1976 and 1978, California's Marine Boundary Program measured and analyzed water levels at six stations throughout Elkhorn Slough (National Ocean Service 1982), including two that we reoccupied in 2007-2009. Comparison of these older 1977 tidal datums (updated to the 1983-2001 tidal epoch) with our new 2008 datums shows that MHW has risen by 1.79 mm/yr at mid-slough (Kirby Park), a value that is consistent with regional and global sea level trends. This number should be treated with some caution, though, since the annual rate of sea level rise is highly variable. Even after 34 years of continuous measurement, NOAA reports a 95% confidence interval of +/- 1.35 mm/yr for the long-term station at Monterey!

Apart from ongoing sea level rise, Elkhorn Slough's tidal characteristics (type, phase lag, mean range, tidal datums) have changed only minimally after more than three decades (Figure 4). The most noticeable change is that tidal amplitude increase ("ramp up") has reversed between the mid and upper slough (Kirby Park to Hudson Landing). This trend is significant because tidal amplitude likely increased after construction of the artificial mouth at Moss Landing, a change that may have contributed to rapid marsh loss in the upper slough. Equally important, from the perspective of marsh loss, is the significantly higher water levels recorded at tidal creek locations (Yampah Marsh and Big Creek) compared with those in the main channel. No tidal creek sites were monitored in 1976-1978.

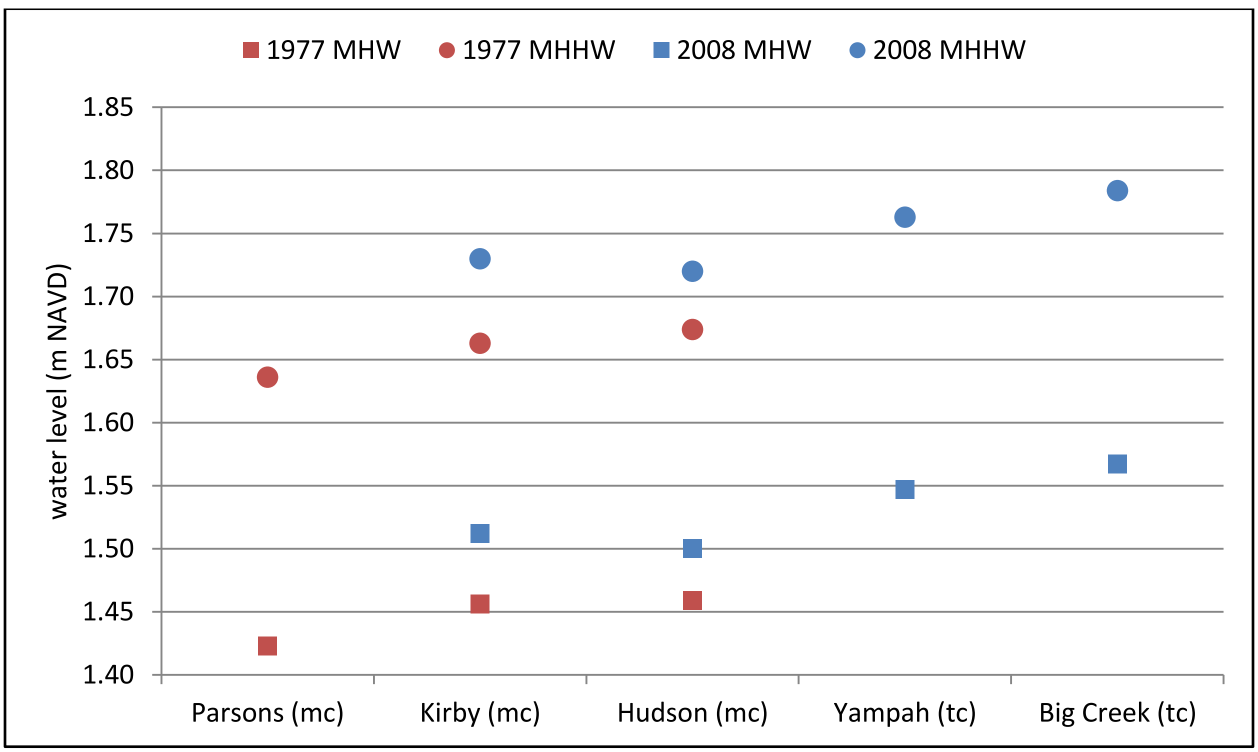

Figure 4: Comparison of MHW and MHHW tidal datums between 1976-1978 and 2007-2009 (mc = main channel; tc = tidal creek).

Subsidence

The relative sea level rise equation includes a number of factors that can reinforce the effects of rising water levels, including root decomposition, sediment compaction, groundwater withdrawal, and tectonic activity. Because decomposition and compaction generally occur near the marsh surface, we characterize them as *shallow subsidence*. In contrast, we characterize the lowering of surface elevation due to groundwater withdrawal or tectonic activity as *deep subsidence*.

To develop an estimated rate of regional deep subsidence at Elkhorn Slough, we obtained field data from historic leveling projects from the National Geodetic Survey. Precise leveling runs were completed in 1972 (Gilroy to Santa Cruz via Watsonville), 1978 (Santa Cruz to Monterey via Watsonville), and 1989 (Gilroy to Monterey via Watsonville). Benchmarks in the region are a mix of disks attached to surface features and metal rods driven twenty meters or more into the earth. Because a benchmark follows ground movement beneath its lowest point, these uniform subsidence rates suggest that gradual elevation loss is occurring relatively deep in the earth throughout the region. Comparison of measured benchmark elevations between surveys reveals a remarkably consistent elevation loss of about 2 mm/yr across the Pajaro Valley through Elkhorn Slough and as much as 4 mm/yr across the Salinas Valley (Figure 5). An obvious exception is where the level line crosses bedrock at the GraniteRock quarry near Aromas; here the deep subsidence rate approaches zero. The only other exceptions are benchmarks at wetland sites—particularly at Parsons Slough and Tembladero Slough (the Parsons benchmark, with a deep subsidence rate approaching 7 mm/yr, is a steel rod driven more than 21 m deep).

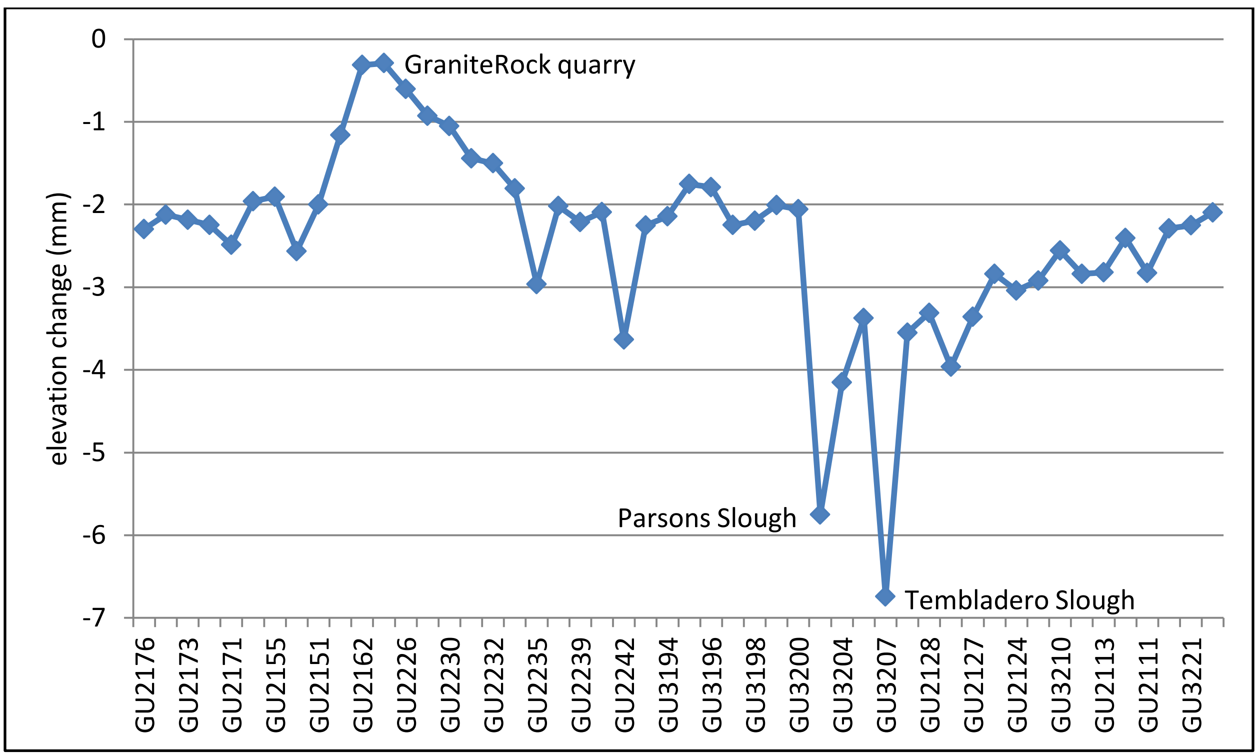

Figure 5: Benchmark elevation differences, 1972-1989. Regional subsidence averaged 2-4 mm/yr, with lower rates on bedrock and increased rates at Parsons Slough and other wetlands (left: southern Santa Clara Valley; middle: Elkhorn Slough; right: Monterey).

Between 1989 and 1990, benchmark elevations dropped abruptly as a result of the Loma Prieta Earthquake. Elevation loss correlated with distance from the quake's epicenter, even on bedrock. At Elkhorn Slough, elevation loss ranged from 43 mm at Hudson Landing down to 7 mm at Hummingbird Island (Figure 6).

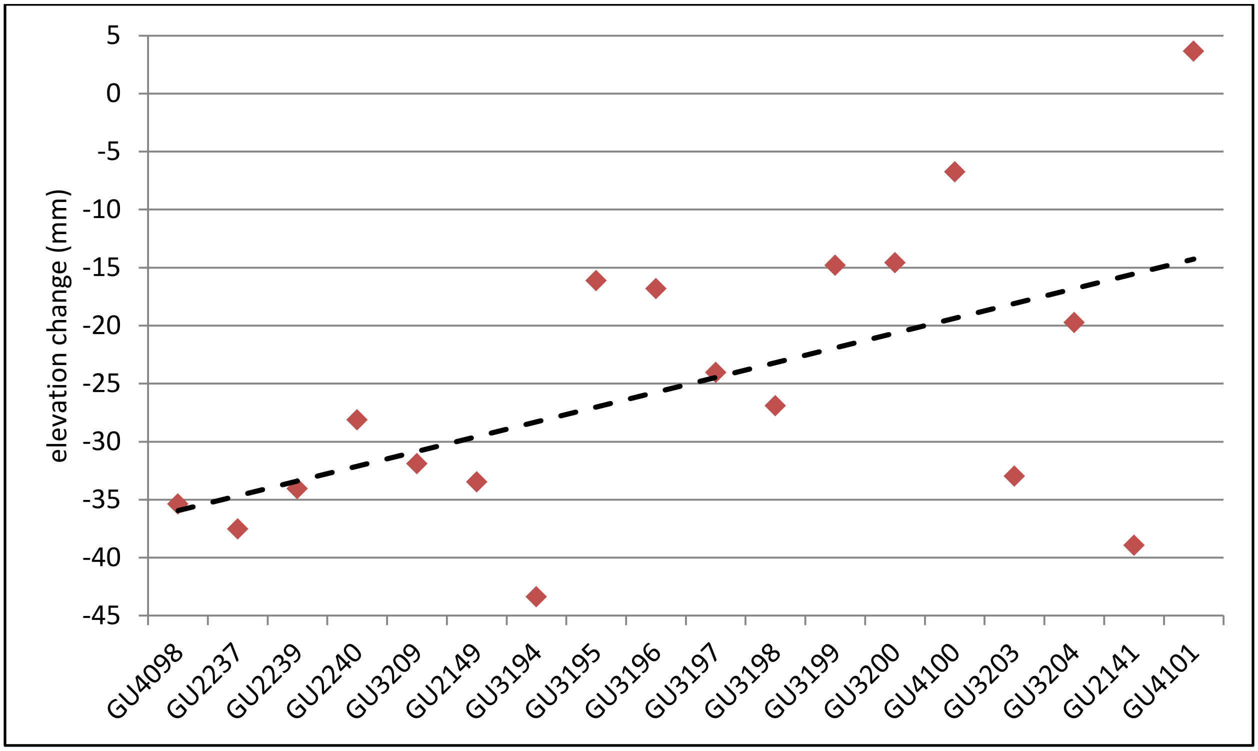

Figure 6: Benchmark elevation differences resulting from the1989 Loma Prieta Earthquake (left: Pajaro Valley; middle: Elkhorn Slough; right: Dolan Road). Dashed line is the north/south decreasing trend.

Because no leveling survey was completed at Elkhorn Slough after the 1989 earthquake, it has not been possible to estimate post-quake subsidence using benchmarks. We use an alternative approach, estimating recent regional subsidence by monitoring ellipsoid height changes at ESNERR's continuously operating GPS station (CORS P210). Position data collected by the GPS receiver since its installation in 2005 reveals not only rapid horizontal motion (more than 30 mm/yr north and east), but also a dramatic annual "up and down" cycle bounding an overall subsidence trend of 0.37 mm/yr (Figure 7). A CORS station, like a deep-rod benchmark, records vertical movement that occurs relatively deep in the earth, beneath the base of its drilled mounting. The two methods may not be exactly compatible—benchmark levels are relative to the NAVD88 datum, while the GPS data is relative to the Stable North America Reference Frame (SNARF)—but should be close. Station information for Elkhorn CORS P210, including near real-time data, is available online at http://www.ngs.noaa.gov/CORS. Information on SNARF is at http://www.unavco.org/community_science/workinggroups_projects/snarf/snarf.html.

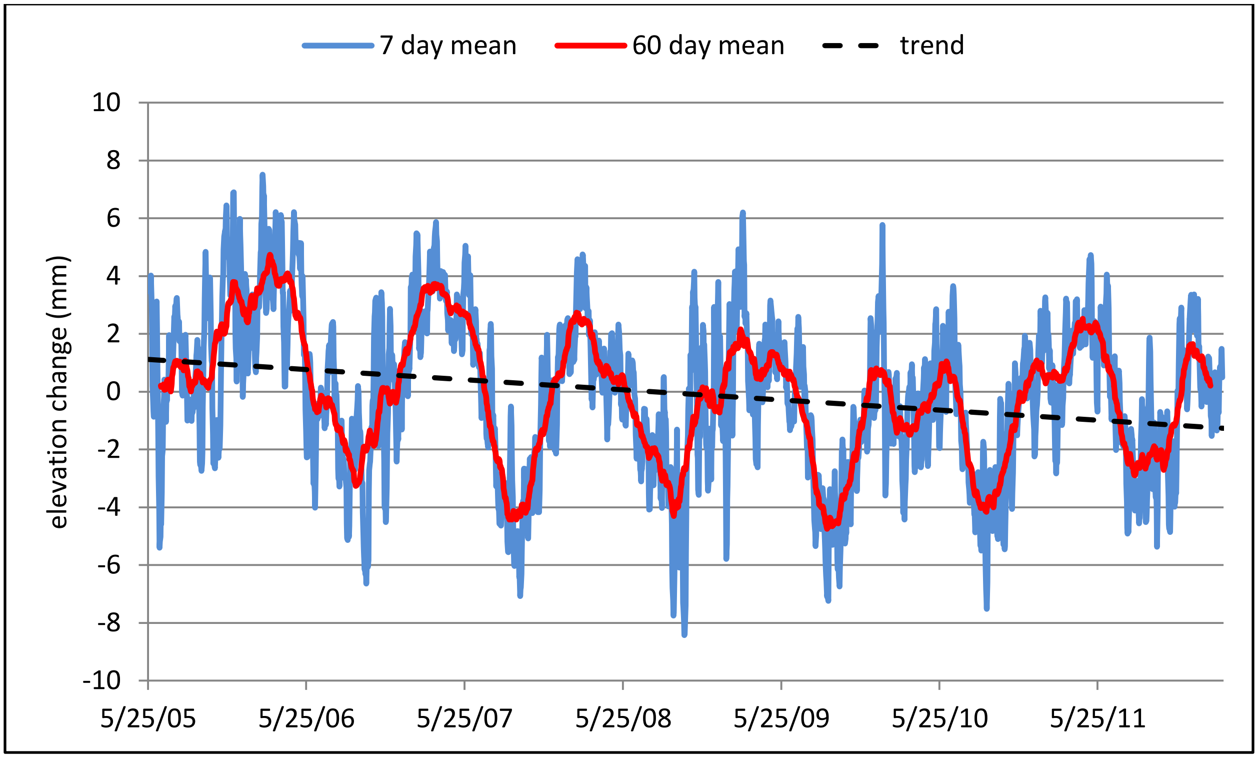

Figure 7: Elevations at Elkhorn CORS P210 since May 2005. Colored lines are running averages; the black dashed line shows the downward trend of -0.37 mm/yr.

In 2008, the Central Coast Height Modernization Project completed GPS surveys across a broad network of benchmarks, including several in the Elkhorn Slough area. This project provides additional confirmation of regional deep subsidence. Previously published elevations that were in agreement with the new surveys served as the basis for calculating new elevations for those benchmarks that fit poorly. Many Monterey Bay area elevations that were rejected were substantially lower than their older published elevations; none were higher (Figure 8). The project report (California Spatial Reference Center 2009) suggests several possible reasons for these lower elevations: "In general, such trends may be examined in the light of a localized geoidal modeling deficiency, geotectonic processes (vertical crustal motion), geomorphological processes (benchmark instability), or the existence of a severe systematic error in the geodetic leveling associated with the published elevations."

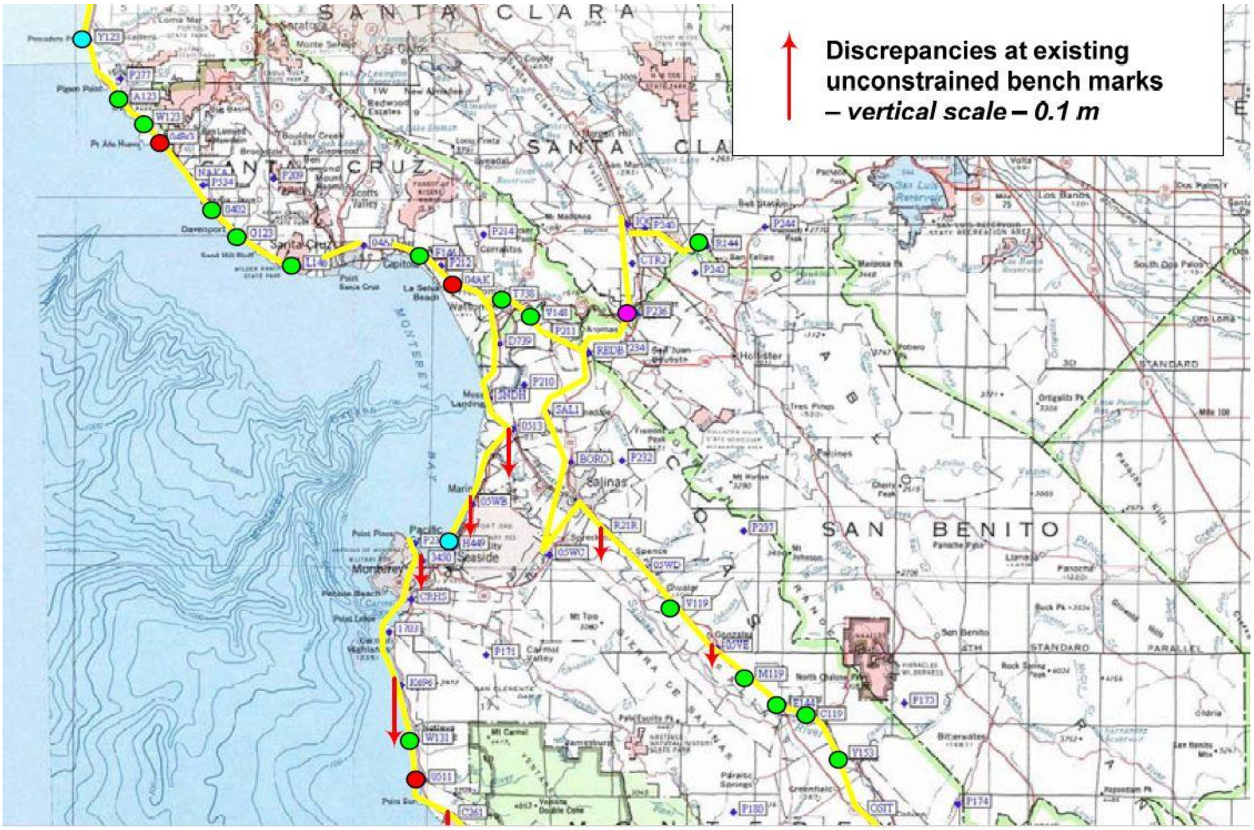

Figure 8: 2008 Central Coast Height Modernization surveys. Published benchmark elevations (colored circles) were used to establish new benchmark elevations (arrows). In the Monterey Bay area, the new elevations were uniformly lower than previously published, indicating subsidence.

Marsh Elevations

We performed topographic surveys to determine the elevation of the marsh at each of our monitoring sites. We surveyed between 75 and 100 random points at each site, transferring absolute elevations from the vertical control network. Frequency distributions and sorted elevation profiles demonstrate that Elkhorn Slough's marshes are low in the tidal frame—slightly above MHW—and occupy a remarkably narrow range—less than 40 cm overall, including vegetated portions of tidal channels at lower elevations and channel banks at higher elevations (Figures 9, 10). The marsh plain itself occupies a range of about 12 cm. Lower slough marshes are 2-3 cm lower in absolute elevation than marshes in the upper slough.

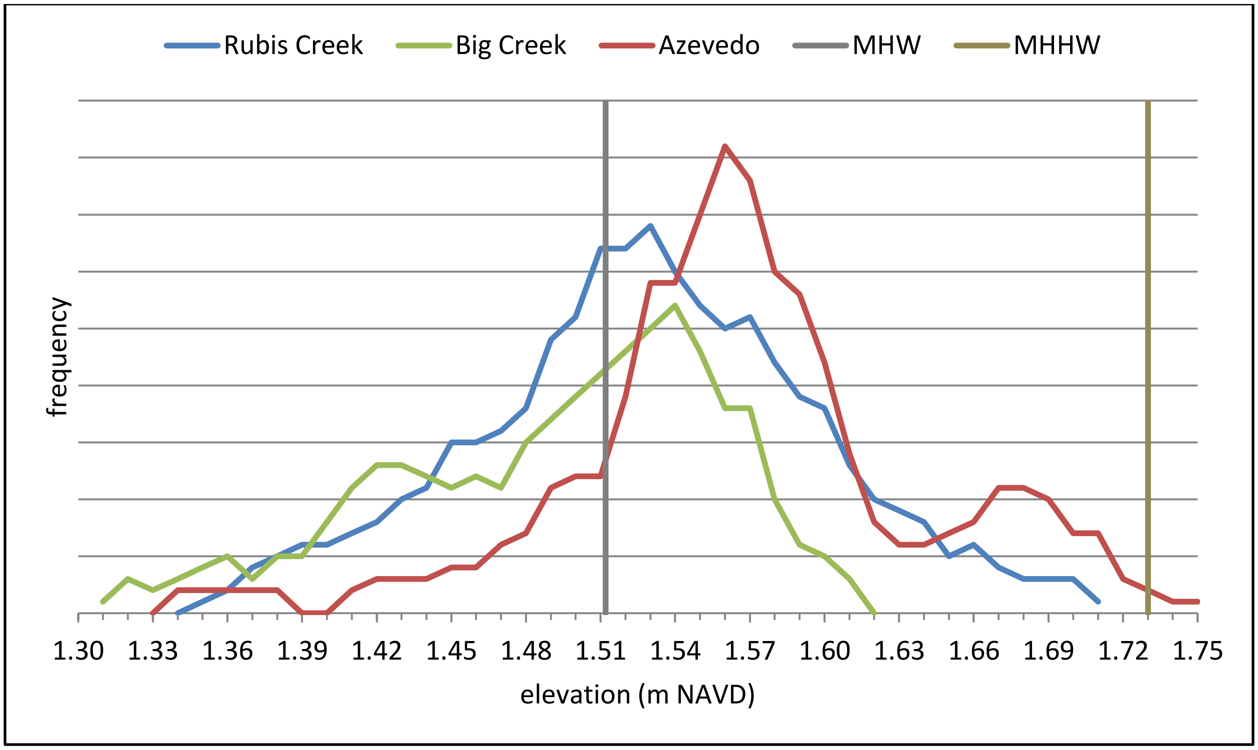

Figure 9: Frequency distribution of salt marsh elevations. Elkhorn Slough's marshes are low in the tidal frame (1.53 m at Rubis Creek, 1.54 m at Big Creek, 1.56 m at Azevedo Marsh).

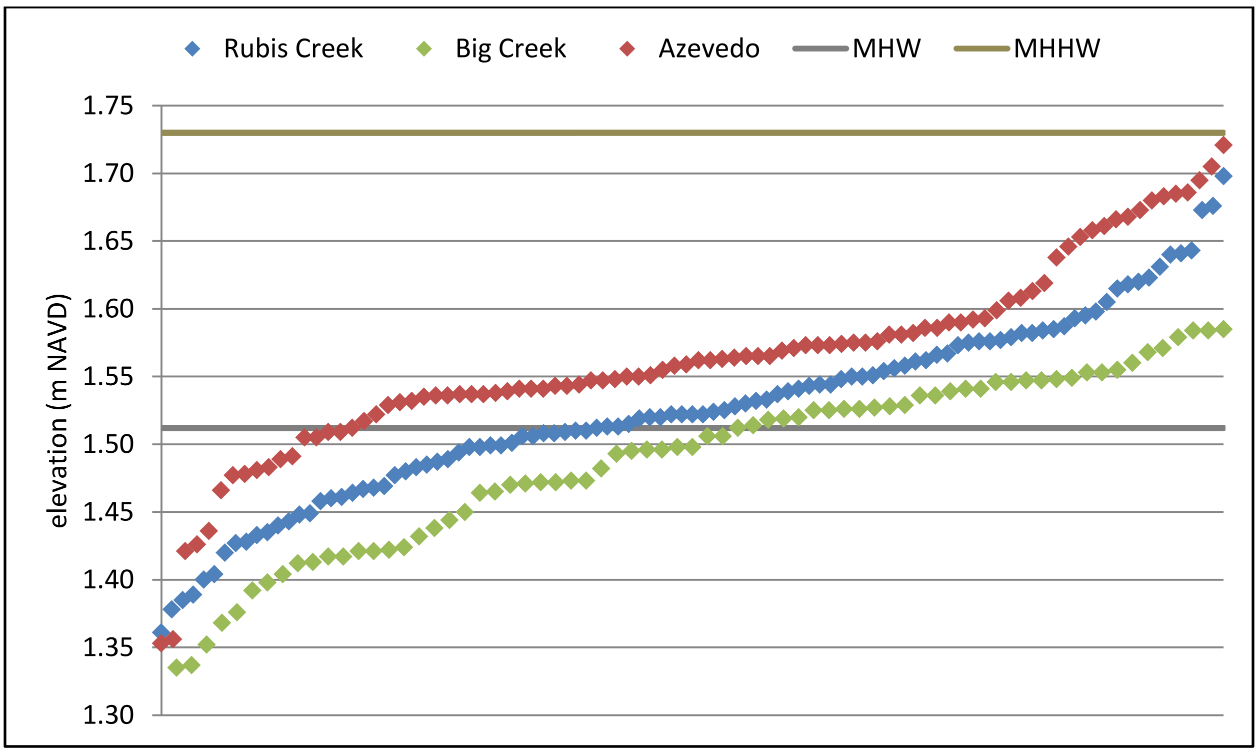

Figure 10: Sorted salt marsh elevations. Profiles reveal the elevation range at each site.

At each monitoring site we have installed a pair of surface elevation table (SET) monuments with associated feldspar horizons to mark the original marsh surface. We return to each monument at 9-12 month intervals with the SET, a specialized leveling instrument, and measure the average distance between the marsh surface and the base of the monument, approximately 5.5 m below the instrument plate (Figure 11, left). This measurement includes processes occurring at the surface (e.g. deposition of new sediment or surface erosion) as well as process that occur at somewhat deeper levels (e.g. decomposition of organic material in the root zone and compaction of marsh sediments). At the same time, we measure the thickness of accumulated sediment above the feldspar horizon (Figure 11, right). This measurement allows us to separate elevation gain or loss due to sediment deposition or erosion from subsurface processes.

Figure 11: Surface elevation table and feldspar marker horizon. Left: SET measurements at Round Hill monitoring site. Right: Marsh plug showing feldspar horizon beneath newly deposited sediment.

We have been taking SET measurements from each of the eight monuments for more than five years (Figure 12). Despite substantial variability between periods and sites, the overall rate of marsh surface elevation gain has averaged about 1.0 mm/yr; this rate decreases from lower to upper slough (1.5 mm/yr in the lower slough, 0.9 mm/yr in the mid slough, and 0.2 mm/yr in the upper slough).

Sediment accumulation above the feldspar layer is relatively consistent between periods but varies between sites. Accretion averaged about 4.5 mm/yr in the lower slough, between 3.6 and 4.3 mm/yr in the mid slough, and 3.4 mm/yr in the upper slough.

By subtracting sediment thickness from surface elevation, we can quantify elevation change below the height of the original marsh surface, independent of accretion. Again, variability has been large between periods, but the overall trend has been downward, with the average rate of shallow subsidence ranging from 2.1 to 3.4 mm/yr.

The rate of relative sea level rise—the combination of rising water level plus shallow subsidence—has been increasing even faster than the relatively high accretion rates. This trend, if it continues, will inevitably lead to drowning and further marsh loss.

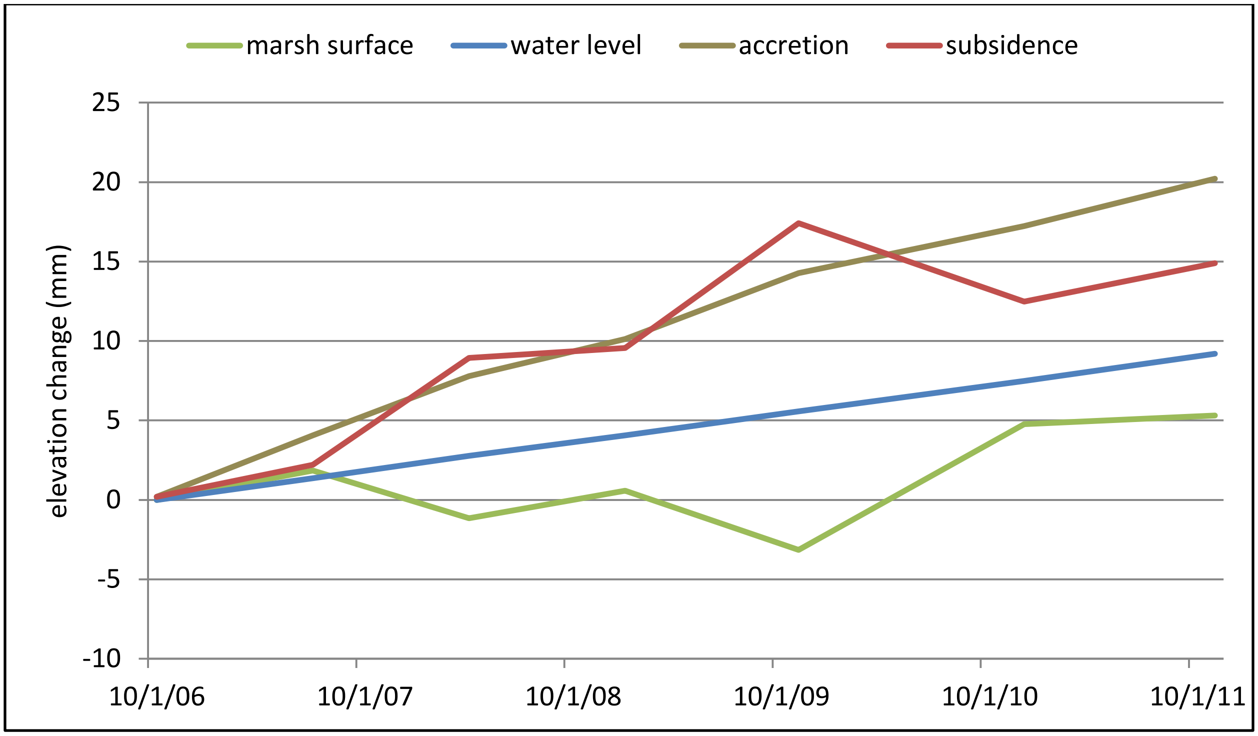

Figure 12: Mean rates of marsh surface elevation gain, rising water level, sediment accretion, and shallow subsidence measured at 8 SET stations. Relative sea level rise (water level plus subsidence) is outpacing sediment accretion.

An ideal method for studying long-term elevation change in Elkhorn Slough's marshes would be to travel back in time. We essentially have this ability in the form of 13 historic marsh elevation transects that were surveyed in 1980. This unique dataset is the product of a US Fish and Wildlife Service / California State Lands Commission collaboration to determine whether the slough's tidal wetlands were above or below the mean high water line; that is, privately owned or in the public trust.

In 2009, California State University Monterey Bay graduate student Brian Spear completed Masters research in partnership with ESNERR, resurveying as many of these transects as possible using traditional optical survey equipment and methods (Figure 13). Traditional methods were chosen because a CSUMB team's earlier survey of the 1980 transects using topographic GPS, and our survey using carefully processed airborne LiDAR data, both proved promising but suffered from inadequate vertical control. Prerequisite to Brian's project was recovery of the set of control monuments (galvanized pipes) that had been installed in 1980. We were fortunate that Lee Vaage, the professional surveyor who had led the field team three decades earlier, was willing to lead this recovery effort. Ultimately, 21 of the original pipes were found.

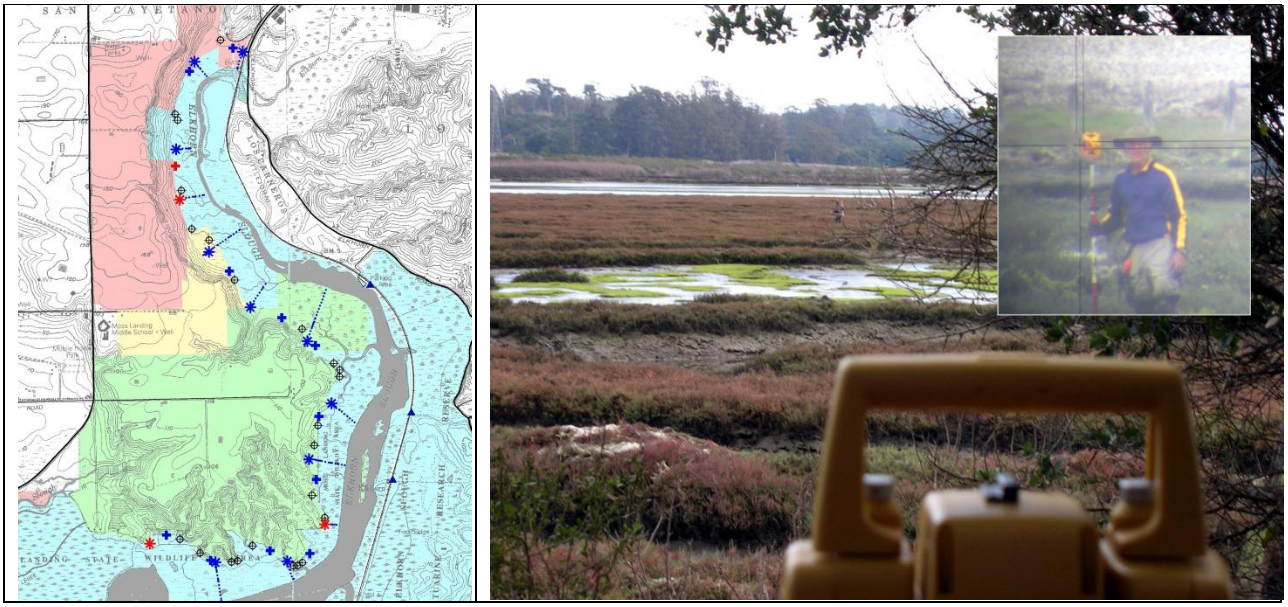

Figure 13: Repeat survey of marsh elevation transects. Left: 1980 transect and monument locations (blue = relocated in 2009, red = not relocated). Right: Surveying marsh elevations with traditional optical methods.

Comparing Brian's 2009 resurvey with the original 1980 data (adjusted to today's NAVD88 vertical datum) yields 5 mm/yr average sediment accretion, a rate that could easily outpace current sea level rise (and a rate that's greater than we measure at our SET stations). Unfortunately, careful inspection of the results suggests that this apparent accretion rate is exaggerated—the 2009 elevations, when sorted, "step" upward between transects, indicating that at least some of the transect monuments have actually "slipped" downward into the mud (Figure 14). It's likely no coincidence that those transects with monuments set low on unconsolidated marsh show the greatest apparent accretion rate, while those with monuments set higher upslope in solid ground show lower rates. With this additional confounding factor, it's impossible to separate the contributions of accretion, shallow subsidence, and simple monument slip. Nevertheless, comparison of 1980 profiles and tidal datums alongside the corresponding 2009 profiles and tidal datums demonstrates that marsh elevations were already low in the tidal frame 29 years ago—as they are today—and confirms that substantial bank erosion and deepening and widening of tidal creek networks has occurred since 1980 (Figure 15).

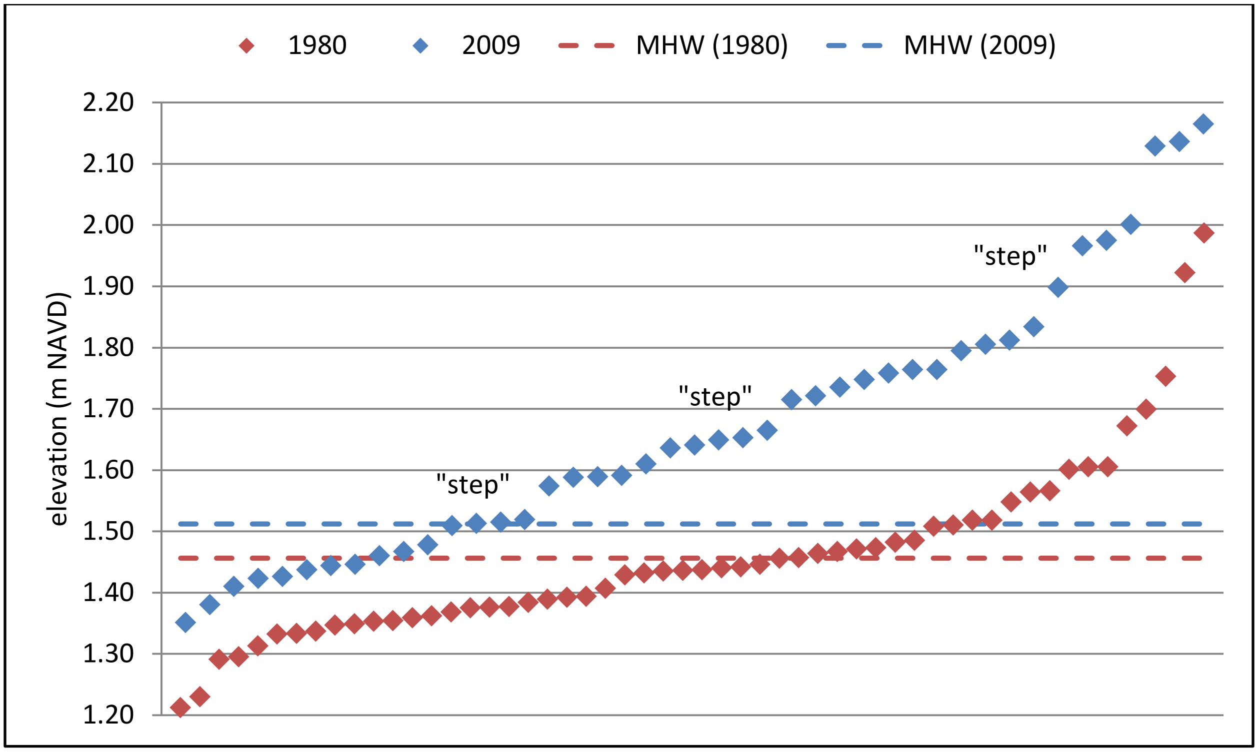

Figure 14: Repeat survey of 1980 marsh transects. Sorted 2009 elevations increase faster than sea level rise and “step” upward between transects, suggesting downward slippage of the transect monuments.

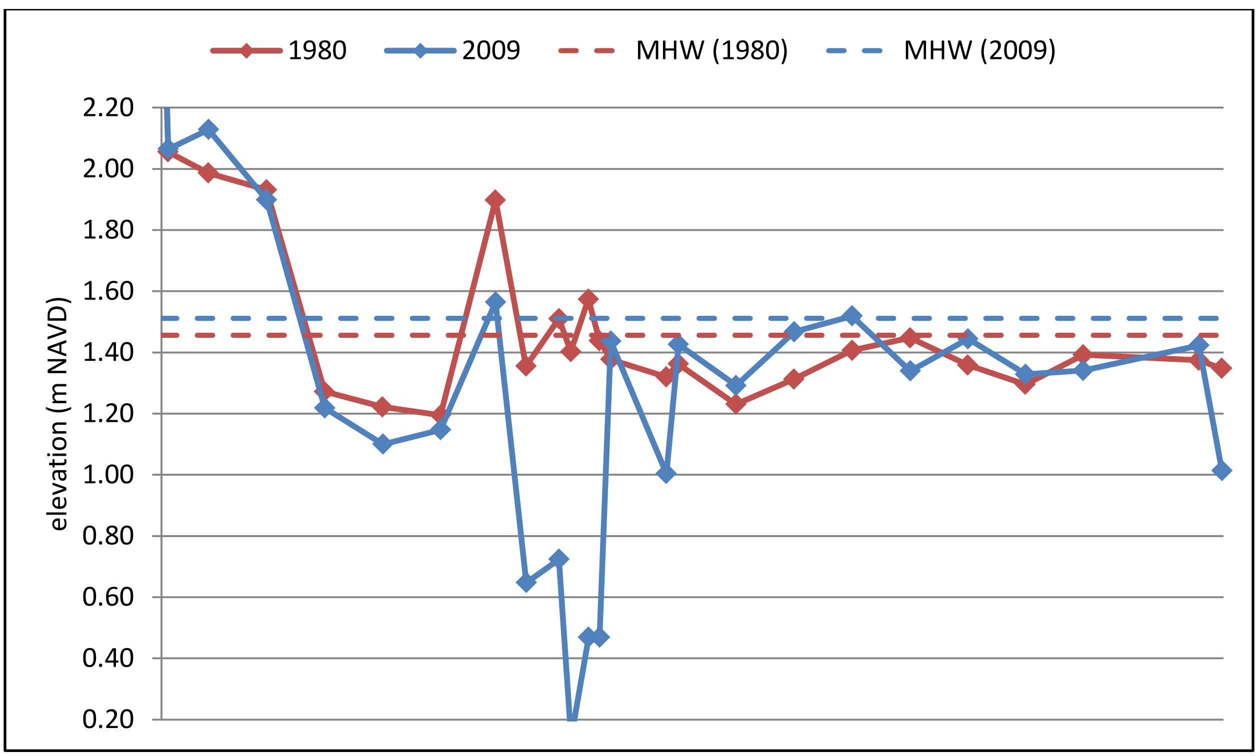

Figure 15: Repeat survey of 1980 marsh transects. Profiles for transect A14 (left: upland; right: main channel). Note tidal creek expansion (left of center) and bank erosion (far right).

Summary: Rates of Change

Table 1 summarizes the calculated or estimated rates of change described in this document.

MHW sea level rise, 1976-2009 (from tide gauges)	1.79 mm/yr
Marsh surface elevation gain, 2006-2011 (from SETs/feldspar horizons)	1.0 mm/yr
Marsh sediment accretion, 2006-2011 (from SETs/feldspar horizons)	3.9 mm/yr
Marsh shallow subsidence, 2006-2011 (from SETs/feldspar horizons)	2.9 mm/yr
Deep subsidence, 1978-1989 (from benchmarks)	1.8-5.8 mm/yr
Deep subsidence, 1989 Loma Prieta Earthquake (from benchmarks)	7.0-33.0 mm/yr
Deep subsidence, 2005-2011 (from CORS P210)	0.37 mm/yr

Table 1: Rates of water level and wetland elevation change at Elkhorn Slough.

Next Steps

As with any ecological monitoring, understanding relative sea level rise at Elkhorn Slough is an effort that will never be "finished"—especially with mounting climate change.

The single most important ongoing task will be to continue measuring sediment accretion and marsh surface elevation at the SET stations. It is only with time that the trends behind these highly variable processes will become clear.

The greatest remaining research needs are to quantify the magnitude of marsh subsidence, and to identify the underlying mechanisms. A feasible strategy for monitoring subsidence is repeated long term (hours to days) static GPS observations from monuments driven into the marsh. This approach has been described in detail by the National Geodetic Survey (Geoghegan et al. 2009). Monuments should be located near the existing SET stations, and can be driven to various depths to help distinguish potential causes. A suitable GPS receiver and antenna are already available at ESNERR (they are property of the CSUMB Seafloor Mapping Lab., with whom the project could be a partnership).

Acknowledgments

This work could not have proceeded without partnerships with NOAA's National Geodetic Survey (special thanks to Steve Breidenbach, Marti Ikehara, and Galen Scott), with NOAA's Center for Operational Oceanographic Products and Services (special thanks to Allison Allen and Steve Hudziak), and with the CSUMB Seafloor Mapping Lab. (Rikk Kvitek and Doug Smith). Thanks to licensed surveyors Lee Vaage and Kathy Pugh, to geodesist Mike Potterfield, and to marsh ecologist Jill Rooth. Special thanks to honorary-member-of-the-research-team Ron Eby. And thanks to so many others too numerous name.

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Appendix 1: Tidal Datums

Table 2 documents current tidal datums calculated from water level data collected at four Elkhorn Slough locations in 2007-2009. Two of the tide gauges were in the Slough's main channel; two were in major tidal creeks (see Figure 3 for locations). Datum values are NAVD88 meters for the current tidal epoch (1983-2001). These values are relative to the updated tidal benchmark elevations listed in Appendix 2; therefore they supersede the NAVD88 values listed on the NOAA CO-OPS website (http://tidesandcurrents.noaa.gov/).

	Kirby (mc) 9413651	**Hudson (mc) 9413663**	**Yampah (tc) 9413631**	**Big Creek (tc) 9413643**
MHHW	1.730	1.720	1.763	1.784
MHW	1.512	1.500	1.547	1.567
MTL	0.946	0.931	0.994	1.011
MLW	0.380	0.363	0.440	0.454
MLLW	0.050	0.040	0.127	0.122

Table 2: Updated Elkhorn Slough Tidal Datums (mc = main channel; tc = tidal creek).

Appendix 2: Benchmark Elevations

Table 3 documents current elevations for new and existing benchmarks in the Elkhorn Slough area. Heights were determined by geodetic leveling in 2007 and 2011 and held to the published elevation for benchmark GU4098. Values are NAVD88 meters. These values supersede the older readjusted NAVD88 elevations listed on NGS published datasheets (available at: http://www.ngs.noaa.gov/cgibin/datasheet.prl). Discrepancies between these updated elevations and published elevations are shown in Figure 16.

PID	**Designator**	**Location**	**NAVD88**
GU4098	V 1448	Pajaro Valley (deep rod)	14.856
GU2237	S 1236	Pajaro Valley (disk)	12.679
GU2239	T 1236	Pajaro Valley (disk)	11.138
GU2240	U 1236	Pajaro Valley (disk)	9.427
GU3209	J 1320	Warner Lake (disk)	7.297
GU2149	37	Hudson Landing Road (pipe)	6.404
GU3194	3663 E	Hudson Landing tidal (deep rod)	7.563
GU3195	3663 D	Hudson Landing tidal (deep rod)	4.757
GU3196	3663 C	Hudson Landing tidal (deep rod)	4.132
GU3197	3663 B	Hudson Landing tidal (deep rod)	3.109
GU3198	3663 A	Hudson Landing tidal (deep rod)	2.477
	ELKS1	N. Azevedo (disk)	2.571
GU3199	3651 B	Kirby Park tidal (deep rod)	2.112
GU3200	3651 C	Kirby Park tidal (deep rod)	2.190
	3651 E	Kirby Park tidal (disk)	3.498
	3651 J	Kirby Park tidal (deep rod)	2.383
	3651 H	Kirby Park tidal (disk)	2.056
	ELKS2	N. Marsh (disk)	1.973
GU4100	X 1448	Hummingbird Island (deep rod)	2.977
	ELKS3	Hummingbird Island (disk)	2.495
GU3203	3631 B	Parsons Slough tidal (deep rod)	1.847
GU3204	3631 A	Parsons Slough tidal (deep rod)	1.817
	3631 H	Yampah Marsh tidal (deep rod)	1.473
	3631 J	Yampah Marsh tidal (deep rod)	2.305
	3631 K	Yampah Marsh tidal (deep rod)	1.364
GU2141	U 20 reset	Wrecking Yard (disk)	8.577
GU4101	Y1448	Dolan Road (disk)	10.478
GU4102	A1449	Moro Cojo (deep rod)	0.502
GU4104	B1449	Highway 156 (disk)	6.974

Table 3: Updated Elkhorn Slough benchmark elevations.

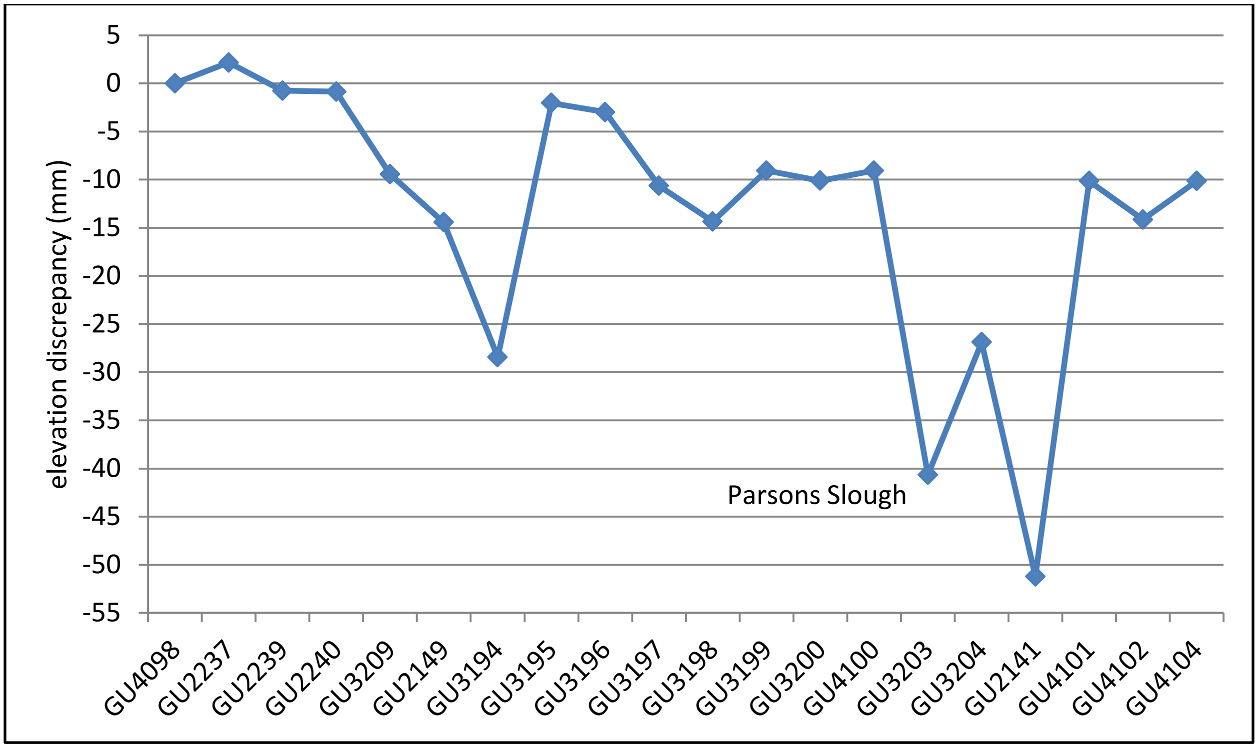

Figure 16: Discrepancies between updated and published benchmark elevations (left: Pajaro Valley; middle: Elkhorn Slough; right: Dolan Road).