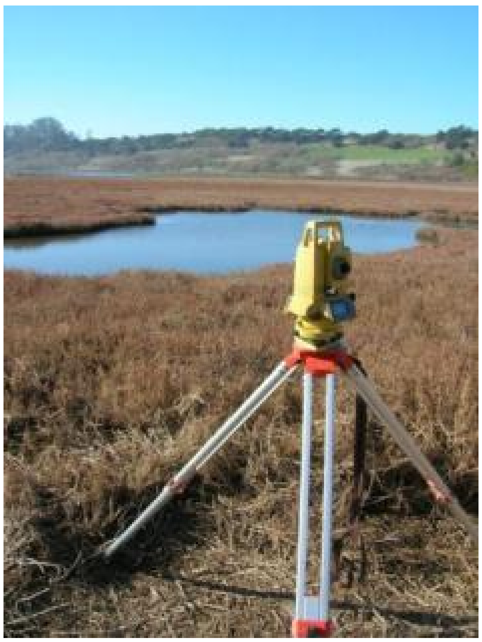

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Central Coast Watershed Studies

CCoWS

29 Years of Geomorphic Change in Elkhorn Slough, California

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Executive Summary

This study utilized high-precision surveys to estimate 29 years of elevation change on the Elkhorn Slough marsh plain. There were 3 objectives to this study: 1) characterize the spatial variation in rates of net erosion/deposition and net vertical change with respect to the benchmark, 2) compare net vertical change rates to estimates of projected rate of sea-level rise in the region, and 3) determine linkages between land cover type and rate of net vertical change. We resurveyed 11 of the 13 original cross sections using the same methodology to collect new surface elevations for comparison with the original 1980 dataset. Overall, survey points on the marsh plain averaged 0.5 cm/yr of accretion (SD = 0.4 cm/yr), but an estimated rate of overall subsidence of 0.4 cm/yr across the slough reduced vertical movement to an average of 0.1 cm/yr. When compared to a low sea level rise scenario of 0.25 cm/yr, rapid marsh deterioration will result if no management actions mitigate a rising sea. Only 26 of the 149 survey points (17%) contain vertical change rates that will outcompete a 0.25 cm/yr sea level rise scenario. Additionally, mudflat and tidal creek categories had erosion rates relative to the benchmarks of 0.7 cm/yr and 1.6 cm/yr, respectively. Respective net vertical loss becomes 1.1 cm/yr and 2.0 cm/yr, when the estimated 0.4 cm/yr background subsidence rate is considered. Further study is needed to identify and quantify individual components of benchmark movement to be able to quantify observed subsidence at each cross section, as opposed to applying a best estimate given available data.

Resource managers at Elkhorn Slough National Research Reserve have been weighing four management alternatives to reduce the rate of marsh plain loss: 1) no action, 2) a new mouth, 3) sill at the current mouth, and 4) sill at Parsons Slough to reduce tidal volume. It is recommended that resource managers focus attention to restoration alternatives that directly mitigate erosion, increase deposition, and/or mute sea level rise effects, Restoration of Parsons Slough (Alternative 4) appears to be the most cost effective way to reduce tidal volumes below the junction and mitigate erosional forces. Cross sections closer to the mouth of the Slough show some of the highest accretion rates, so a tidal sill recommended in Alternative 3 might ultimately decrease these rates by limiting tidal inundation onto the marsh plain. With the restoration of Parsons Slough, the tidal volumes will be reduced below the Parsons Slough junction that will inherently reduce tidal forces and scour, while maintaining the healthy marsh plain accretion rates closer to the mouth of the Slough. Increased biologically productive area will be a further benefit of selecting Alternative 4.

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1 Introduction

Estuaries and coastal lagoons are among the Earth's most biologically productive ecosystems. Out of all terrestrial ecosystems, wetlands provide the largest collection of ecosystem services on a per-acre basis (Costanza 1997). Yet, wetlands are among the most highly altered landscapes, with conservation lagging behind that of other terrestrial and marine systems (Kennesh 2002, Adam 2002, Van Dyke and Wasson 2005). Human modification to environmental systems during the past century has greatly accelerated salt marsh deterioration, resulting in a 50% loss of original salt marsh habitat throughout the U.S. (Kennesh 2002). Estuaries in California are among the most threatened ecosystems and contain a disproportionate number of rare, threatened, and endangered species due to anthropogenic impacts and habitat degradation (ESTWP 2007).

An exponentially increasing human population is one of the leading geomorphic agents that are drastically affecting the natural landscape (Hooke 2000). Additionally, trends suggest that by 2025 estuaries will be most significantly impacted by habitat loss and alteration associated with a rapidly increasing coastal population (Kennesh 2002). Accurate monitoring of landscape evolution is critical in this era so that sound environmental management decisions can follow.

Extensive areas of critically important salt marsh habitat at Elkhorn Slough, California (Figure 1) are converting to mudflat habitat at unprecedented rates, while tidal channels are rapidly expanding (Oliver and others 1988, ABA Consultants 1989, Lowe 1999, PWA 1992, Dean 2003, Sampey 2006, Van Dyke and Wasson 2005, PWA 2008). Resource management decisions concerning marsh conservation hinge upon an understanding of historical marsh plain elevation changes with respect to sea level.

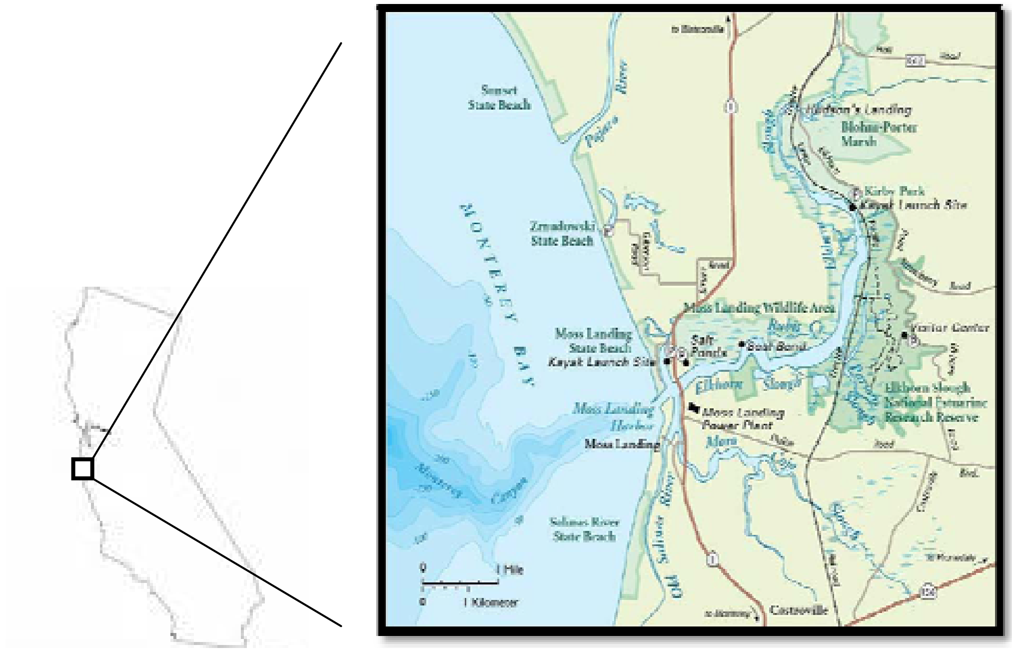


Figure 1 Study site location along the central coast of California.

Degradation of marsh plain habitat at Elkhorn Slough is largely resulting from increased tidal inundation due to the creation of a jettied harbor in 1947, which connects the mouth of the Slough to open marine conditions (Wong 1970, Phillip Williams and Associates 1992). Substantial land use changes since the mid 19th century have also affected the morphology and tidal habitats at Elkhorn Slough (Van Dyke and Wasson 2005). A railroad grade was also constructed during the 1880s and greatly influenced hydraulics, especially at the narrow gaps where broad flow once existed. Other possible factors contributing to the erosion problem include intentional and unintentional levee breaching, subsidence of marsh areas, decreases in upland sediment supply, accelerating sea-level rise, and changes to biological processes (Brennan et al. 2008, Watson 2008). Uncertainties remain regarding subsidence rates, which are critical in forecasting marsh habitat survival under increased tides, wave heights and storm surges associated with global climate change and accelerated sea-level rise (Scavia et al. 2002).

Subsidence can be defined as the sudden sinking or gradual downward settling of the Earth's surface with little or no horizontal motion. A number of natural process can lead to subsidence such as crustal motion, settling of unconsolidated sediments and peat compaction (Long et al; 2005), but subsidence can also be human induced due to groundwater extraction, which has been generally noted in the area (Galloway et al. 1999).

We use two general terms to describe subsidence at Elkhorn Slough for this project: shallow and deep subsidence. Shallow subsidence refers to any vertical change a due to compaction of sediments, decomposition of organic matter and other shallow processes. Deep subsidence refers to subsidence as a result of larger crustal motion, groundwater extraction, and tectonic activity. Shallow subsidence appears to be of greatest magnitude at Elkhorn Slough marsh plain (Van Dyke, unpublished data 2009). Deep subsidence has also been measured in the surrounding watershed (Swanson Hydrology and Geomorphology 2003) with dramatic subsidence occurring in nearby Watsonville Sloughs (Hagar and Watson 2005) and around the large Monterey Bay region after 1989 Loma Prieta earthquake (Marshall and Stein 1990).

Significant loss of wetland area has prompted efforts to restore large tracts of wetland to recover sensitive habitat and wetland function (ESTWP 2006, CALFED 2000, Steere and Schaffer 2001). The sustainability of restored tidal marsh habitat concern subsidence and landscape changes, which affect the delicate balance between relative sea-level rise and sediment deposition (Ganju et al. 2005, Orr et al. 2003). Restoration decisions need to incorporate historic marsh plain elevation changes to better prepare management alternatives.

Currently there are 4 recommended management alternatives to reduce tidal range and tidal velocity in Elkhorn Slough. These include 1) no action, 2) new ocean inlet, 3a) Highway 1 low sill, 3b) Highway 1 high sill, and 4) Parsons Slough restoration (PWA 2008). With estimated costs ranging from $0 (no action) up to $94 million (new ocean inlet), resource managers need to make sound decisions on alternatives that correspond with observed geomorphic trends and marsh plain elevation change.

Widespread coastal salt marsh at the Elkhorn Slough contains sensitive marsh plant Pickleweed (Salicornia virginica). Pickleweed generally exists within a narrow elevation zone ranging from 0.13 m to 0.42 m above mean high water (MHW) (Selisker 1985), but at Elkhorn Slough the marsh is a bit lower and the range is narrower, roughly MHW to 0.2 m above MHW. With sudden deepening Pickleweed will drown. By pinpointing the mechanism to which is largely causing the extensive marsh habitat loss, resource managers can narrow in and focus attention to certain restoration options or determine additional needs

In 1979 and 1980, a joint venture of Mid-Coast Engineers (Watsonville) and Monterey County Surveyors, Inc. (Salinas) completed property boundary surveys in preparation for land purchases. The US Fish and Wildlife Service had plans to acquire most of the private property surrounding Elkhorn Slough to create the Elkhorn Slough National Wildlife Area. This was much larger than the Elkhorn Slough National Estuarine Research Reserve that was established shortly after. An important component of these surveys, requested by the California State Lands Commission, was to determine whether portions of these parcels were below the mean high water line, presumably because submerged areas are State trust ("sovereign") lands and thus wouldn't need to be purchased. Therefore a number of elevation cross-sections were surveyed from the upland edge, across the wetlands, and to the edge of Elkhorn Slough. The 13 cross-sections on the west side of the slough that form the basis of this study were surveyed in April-May 1980 by Mid-Coast Engineers crew Lee Vaage, L. Williams and A. Cordoza; additional cross-sections on the east side were surveyed by Monterey County Surveyors.

The 1980 cross section surveys consisted of four components. First, existing survey monuments in the region (including several recently installed by the State Lands Commission) were occupied to define the horizontal and vertical control network. Then, a horizontal traverse was run between temporary benchmarks established on the slough's west bank between Hudson Landing and the Monterey Bay Salt Works. Differential levels were also run along the west bank between temporary marks set between a chiseled mark on the old Elkhorn Slough / Highway 1 Bridge (which was replaced in 1985) and Hudson Landing. Vertical control results were adjusted and consisted of 83 turning points over 8 miles. Horizontal control consisted of 48 temporary positions spread between A1 and A48. This leveling line provided elevations for installed cross section benchmark monuments plus 35 additional backsight monuments. Each monument, consisted of an approximately 2 meters long, 3/4 inch diameter galvanized iron pipe with cap marked "LS3233", was set at or near the marsh edge. Cross section points were then surveyed across the marsh with the "two-instrument radial survey" technique using a Wilde T-16 theodolite for horizontal and vertical angles and an HP 3800A EDM for distance.

This invaluable cross sectional dataset is unmatched in potential to reveal long term critical geomorphic processes, which was not the original intent of the survey. These cross sections provide the greatest potential for long term marsh plain monitoring given their spatial distribution, precision and time between surveys. California State Monterey Bay Seafloor Mapping Laboratory (SFML) has maintained an accurate monitoring of Elkhorn Slough's main channel since 2001 using high-resolution acoustic remote sensing. The marsh plain elevation dataset collected during this study will complement the work of SFML and mapping by other local research institutions to help determine larger, long term geomorphic processes occurring at Elkhorn Slough.

The current digital elevation datasets at Elkhorn Slough comprise multibeam surveys of the main channel, LiDAR flights of the region and, more recently, automated terrestrial LiDAR scanning of mudflats. Multibeam surveys are spatially limited due to vessel draft limitations, leaving the shallower tidal creeks inaccessible. LiDAR flights and terrestrial scans provide greater spatial terrestrial coverage, but do not provide a lengthy dataset to examine long term marsh plain evolution at Elkhorn Slough and not as accurate as on the ground measurements. In contrast, Lee Vaage's optical and electronic survey dataset from 1980 provides ability to capture accurate net vertical change that has occurred on the marsh plain over the last 29 years.

Sections of Elkhorn Slough's marsh plain are thought to have dropped by 10-20 cm in the past 29 years. Using GPS technology to reoccupy the 1980 survey points, Miller (2004) could not precisely quantify this change because of inaccuracies associated with comparing ellipsoid heights and orthometric heights. Currently, there is no precise model relationship between ellipsoid heights and orthometric heights due to spatial inconsistencies in the data (Meyer et al. 2007). Resurveying Lee Vaage's original 1980 cross sections using the same optical leveling techniques overcomes these inaccuracies and spatial irregularities with the geoid / ellipsoid separation.

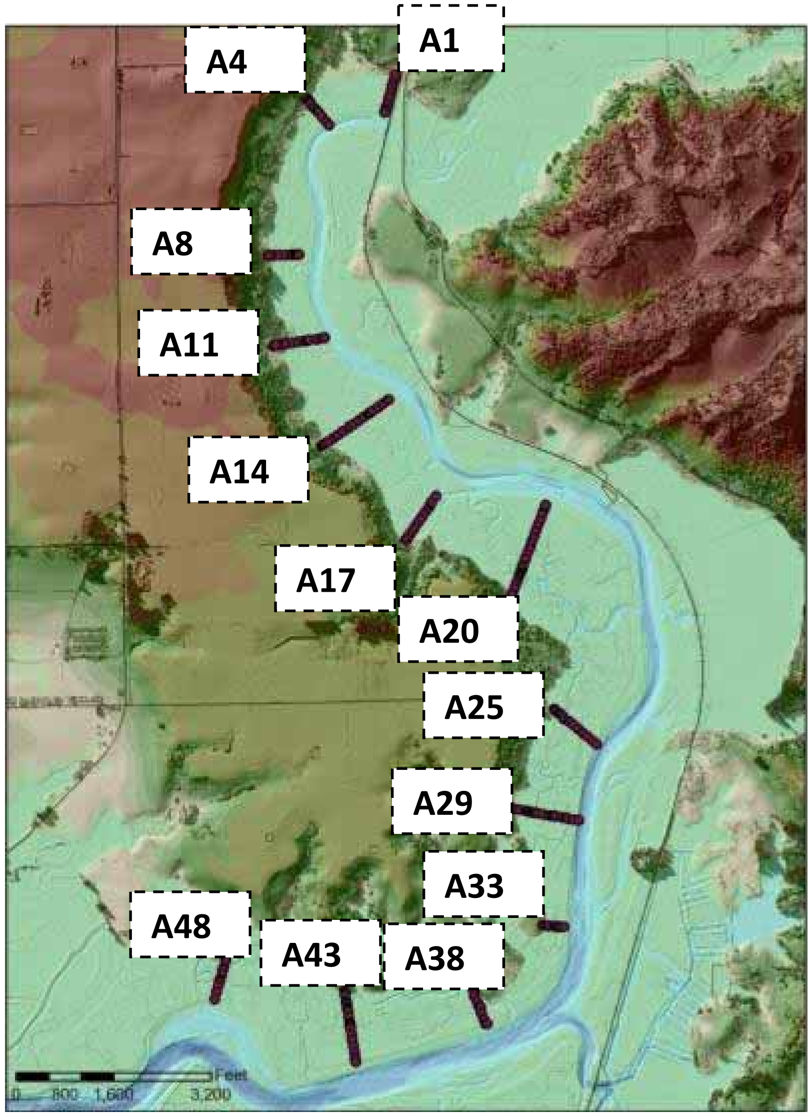


Figure 2 1980 cross section points and names plotted over 1m-resolution Digital Elevation Model (DEM) created by combining 2003 bathymetry from the Seafloor Mapping Lab and 2004 LiDAR from NOAA's Coastal Remote Sensing division, with funding from MBNMS SIMoN program. Notice spatial distribution of cross section lines and extensive marsh plain coverage.

2 Goal

The goal of this study was to reoccupy Lee Vaage's 1980 benchmarks and the original cross sections were resurveyed to assess tidal creek widening/deepening and, more importantly, marsh plain vertical change. It is understood that the tidal creeks are widening since the slough mouth opened. However, recent studies have begun to determine short term vertical movement out on the marsh. This long term vertical change dataset is a critical piece that resource managers need to understand before making restoration decisions.

The objectives of this study were to:

1) Quantify the spatial variation in rates of net erosion/deposition and net vertical change.
2) Compare measured rates of net vertical change to projected rates of sea-level rise in the region.
3) Determine linkages between land cover type and rate of vertical movement

3 Methods

In 1831, William J. Young invented the first transit instrument which was a significant improvement of engineering appliances and could be read to 3 arc minutes (Smart 1962). Today's survey grade instrumentation is digitally read to a few arc seconds. The Topcon GPT-3002W total station used in this study can reproduce angular measurements with a precision of 3 arc seconds and has a range up to 3 kilometers with the prism (TOPCON 2003). Table 1 illustrates calculated values for the expected Cartesian precision given the instrument's 3 arc seconds angular reproducibility. This electronic total station is used to precisely monitor the three-dimensional position of surveyed points using a laser pulse and, in this case, a reflective prism. Since the instrument commonly achieves sub-centimeter repeatability, data collected using this survey instrument will provide a dataset that can more accurately quantify vertical change on the marsh plain compared to Miller (2004) RTK GPS survey at Elkhorn Slough, in addition to a defensible baseline dataset for future surveys to more accurately quantify vertical change.

Distance (m)	Precision (mm)
0	0.0
10	0.1
50	0.7
100	1.5
500	7.3
1000	14.5

Table 1 Expected Cartesian precision of each foreshot at a specified distance from total station based upon angular precision of 3 arc seconds.

Original vertical angle measurements using a theodolite were recorded to a tenth of a second, which was used to calculate elevation to thousandth of a foot (0.001 ft). Since the TOPCON GPT-3002 total station used for this project reports vertical elevations to thousandths of a foot (0.001 ft), direct comparison between measurements will require examination of precision by each instrument. Table 1 shows calculated values of vertical precision as a function of prism distance for the total station.

A vertical control network was created by Lee Vaage in 1980 using a differential level loop starting from the Highway 1 Bridge at the mouth of the Slough up to the railroad crossing at Elkhorn Road (Figure 1). Using a three wire level over an 8 mile loop the elevation control error was on the order of a few hundredths of a foot, which was later factored into the station points by adjusting elevation values. These temporary turning points accurately provided elevations for the 13 cross section benchmarks, monumented by approximately 2 meter long galvanized pipe.

In November-December 2008, a Mid Coast Engineers crew under the direction of Lee Vaage re-located 10 of the 13 original cross section monuments and 11 adjacent backsight monuments. Monument recovery was performed with a Trimble 5800 RTK GPS system, beginning with five State Lands Commission benchmarks to establish the site calibration. Two original cross section monuments (A-33 and A-48) were not found and were replaced by the MidCoast Engineer crew with 1/2" diameter galvanized iron pipes with a yellow cap according to GPS coordinates. One original backsight monument (A-9) was found lying on the surface and was also reset. The monument for cross section A-11 was deeply buried under a sediment fan and willow grove; two substitute monuments [#161 and #162] were installed nearby. Visibility from A-15 to the A-16 basksight was completely obstructed by a sediment fan and willow grove, so A-15 was used as a backsight instead. Figure 3 illustrates cross section and backsight benchmarks found by the survey crew in addition to the benchmarks destroyed, missing, or not looked for.

Total station setup required a few parameters that are unique to each site and field visit: instrument height, prism height, temperature and pressure. By establishing the same cross section benchmark from 1980 and shooting to the backsight benchmark, the cross section line can be precisely located by turning a specific deflection angle and each survey point repeated. Distance and vertical angle were recorded in addition to the three-dimensional coordinates for each shot as well as any plant cover and substrate type present. Direct resurvey of the 1980 survey foreshots allows precise detection of small vertical changes.

Quality control measures were used to assess precision of collected data. Total cross section precision was an accumulation of 2 precision measurements: instrument and survey precision. Instrument precision was a function of foreshot distance and the total station's three-second angular precision. Survey precision was the vertical difference between the first and last shot of the cross section survey at the same location. Each survey started with an OPEN shot, usually at the backsight benchmark. After each cross section was completed, the CLOSING shot occurred at the OPEN location, indicating repeatability of measurements through time. Survey precision ranged from 0.0 cm to 1.1 cm, with most below 0.8 cm. Together, all of these precision values are assumed to contain the error possibilities during the survey.

Each survey shot included a new elevation value for comparison with the 1980 elevation for that point. These elevation differences were used to assess marsh plain change.

Based upon field experience from repeating cross section A1 and the stated instrument precision, an elevation difference of 2 cm is generally considered to be significantly greater than the random variations within the survey system. However, this is a conservative number and the actual observed precision is most likely better in most cases.

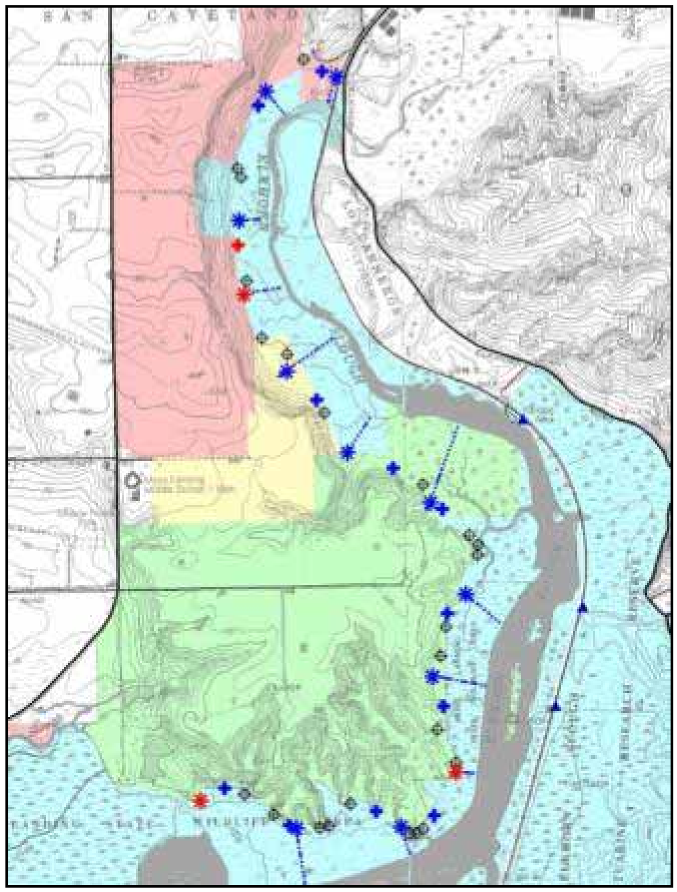


Figure 3 Cross section and backsight benchmark locations plotted over USGS topographic map with land ownership. "Asterisk" labels are cross section benchmarks and "Plus" labels correspond to backsight benchmarks. Blue points indicate benchmarks located by MidCoast Engineers, red points indicate disturbed or missing benchmarks and cross hatched points indicate benchmarks not looked for. Map courtesy of Eric Van Dyke at Elkhorn Slough National Estuarine Research Reserve.

Original 1980 survey heights were measured in a locally adjusted NGVD29 reference frame, using a benchmark loop around Elkhorn Slough and the ridge line. This is referred to as NGVD29 – CSLC, for California State Lands Commission. However, more recent and stable benchmarks are measured to a different vertical datum: NAVD88.

Elkhorn Slough NERR researchers relocated the most stable monument from the 1980 loop, a deep-rod tidal benchmark at Kirby Park. The long-term rate of subsidence at that benchmark, determined from historic (1978 and 1989 pre-Loma Prieta Earthquake) levels obtained from the National Geodetic Survey, was used to estimate its 1980 NAVD88 elevation. Using the original field notes, heights for the 1980 cross section benchmarks were then recalculated to NAVD88 relative to the Kirby Park mark. This was a major breakthrough because the current benchmark heights can be accurately surveyed to determine benchmark elevation change over the 29 year period. For the remainder of this report, elevations are given with respect to the NAVD88 datum.

Each cross section data point has four components explained in the equation below: deep subsidence, shallow subsidence, benchmark slip, and erosion/deposition. Deep subsidence is defined as the rate of elevation loss across the larger region due to tectonic strain and groundwater extraction. Shallow subsidence is a potentially greater rate of elevation loss experienced on the marsh plain and marsh plain fringe due to more localized factors such as watering/dewatering, organic decomposition, and sediment settling. These subsidence components are assumed to move the cross section foreshots and benchmark as a complete unit. Benchmark slip refers to the potential movement of the benchmark within the soil, either up or down, that is independent of the cross section. Slip can occur because a benchmark is a dense piece of metal sitting in relatively soft soil, which in some cases is frequently inundated or next to tree roots, and slips in or out of the soil. These components can be explained by Equation 1:

$$\text{Elevation} = \text{Dsub} + \text{Ssub} + \text{SLIP} + \text{SED}$$

And if Elevation = BM + Vdist, then:

$$\text{BM} + \text{Vdist} = \text{Dsub} + \text{Ssub} + \text{SLIP} + \text{SED} \quad \textbf{(Equation 1)}$$

Where; "Elevation" is the 2009 position of each foreshot, BM is the 2008 benchmark elevation, Vdist is the surveyed vertical distance to the benchmark between the benchmark and a foreshot point in the cross section, Dsub is the deep subsidence experienced at all cross sections, Ssub is the shallow subsidence experienced locally at each cross section, SLIP is the benchmark slipping independent of the cross section, and SED is the net erosion (negative) or deposition (positive) of sediment at the position of the foreshot.

Benchmark movement contains three of these components:

$$\Delta\text{BM} = \text{Dsub} + \text{Ssub} + \text{SLIP} \quad \textbf{(Equation 2)}$$

Where ΔBM is the total benchmark elevation change in 29 years, Dsub is the deep subsidence experienced at all cross sections, Ssub is the localized subsidence experienced at each cross section, and SLIP is the benchmark slipping independent of the cross section.

By correcting for these three components of benchmark movement in equation 2, we can isolate key components of each foreshot from Equation 1. By holding ΔBM to be zero, then Dsub, Ssub, and SLIP are equal to zero as well.

$$BM + Vdist = Dsub + Ssub + SLIP + SED \quad \textbf{(Equation 1)}$$

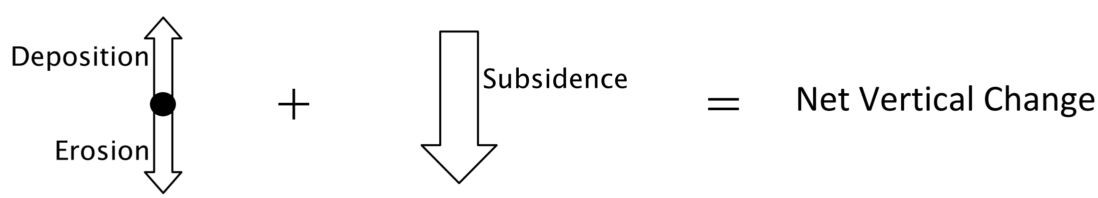
$$\Delta BM = Dsub + Ssub + SLIP \; \textbf{(Equation 2)}$$

$$BM + Vdist = \Delta BM + SED, \text{ where } \Delta BM = 0, \text{ then:}$$

$$BM + Vdist = SED \quad \textbf{(Equation 3)}$$

Since all foreshots are tied to the benchmark, holding the benchmark elevations constant over time removed any sources for elevation change observed in the foreshots other than net erosion and deposition.

Even though the top layer may be accreting sediment (SED), the entire land surface might be dropping at a faster rate (Dsub + Ssub), impeding any elevation gain due to pure deposition. Since actual subsidence observed at each cross section cannot be calculated due to the confounding "slip" component (Equation 2), a best estimate of general subsidence was applied to the net erosion/deposition rate (Equation 3) by adding in the subsidence rate. Since we know that elevation is composed of vertical movement of the top layer (erosion/deposition) along with overall landscape movement (i.e. subsidence), observed subsidence data from monitoring stations on the marsh plain and from benchmark movement around the slough were applied to our erosion/deposition dataset to gain net elevation change. These results indicate net vertical motion of the land surface.



A Continuously Operating Reference Station (CORS) was installed at ESNERR on May 25, 2005 near the headquarters. The CORS station indicates that there is regional subsidence of the uplands surrounding the Slough. The GPS has been recording accurate positions every 15 seconds over to compute a daily position and transformed to the stable North America reference frame (SNARF). Averaged data from this GPS station indicates that the uplands have been subsiding at a rate of 0.15-0.20 cm/yr for the past four years (Figure 4).

Deep subsidence has also been measured by comparing precise levels between 1978 and 2007 at benchmarks along the railroad through Elkhorn. These are fairly consistent at 0.34 cm/yr, which includes the 1989 Loma Prieta earthquake (Van Dyke, unpublished data 2009). These are mostly deep-rod benchmarks at non-wetland sites within 20 m of the slough wetlands. However, 3 of these deep rod monuments lie next to the railroad embankment crossing in Parsons Slough's wetlands and have subsided at a higher rate of 0.47 cm/yr.

Shallow subsidence has been measured by ESNERR staff on the marsh plain, away from the margins. This marsh plain subsidence is measured at 8 surface elevation tables during the past three years. Results indicate an average rate of 0.53 cm/yr for marsh plain subsidence (Van Dyke, unpublished data 2009). This estimate does not incorporate sporadic sudden elevation loss such as occurred in the 1989 Loma Prieta earthquake. Average subsidence rates in these areas would be larger over the study period of 29 years due to rapid subsidence in 1989.

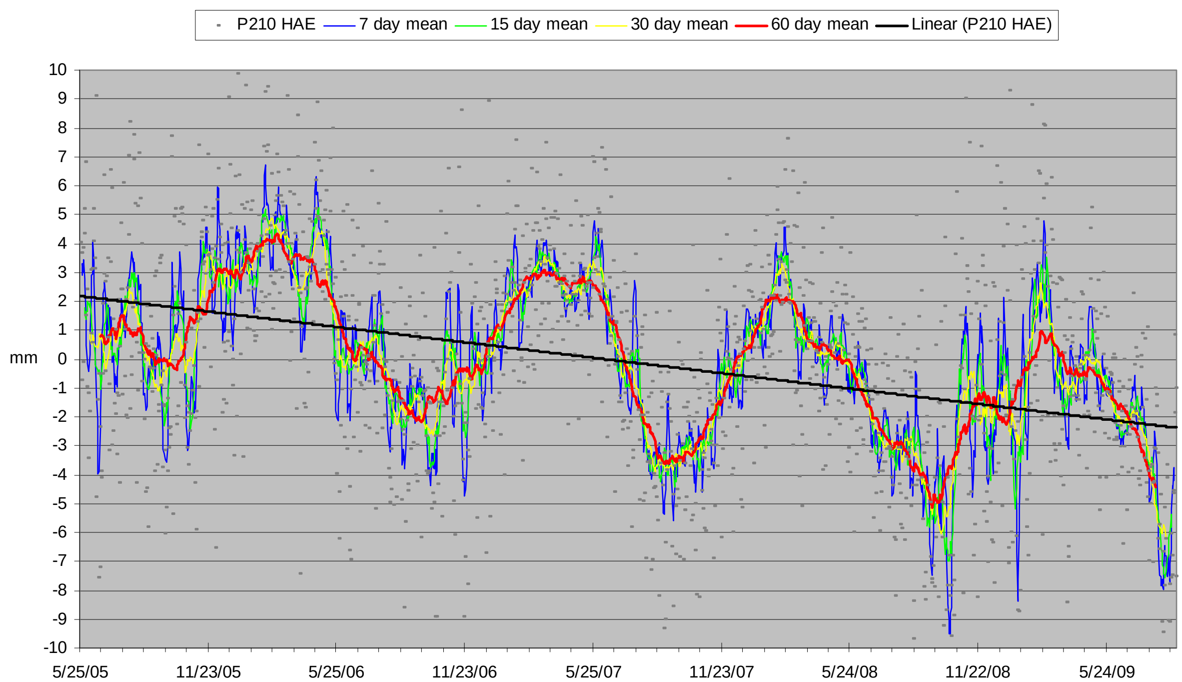


Figure 4 Averaged daily positions at Elkhorn Slough CORS since May 25, 2005. Average rate of 0.10 cm/yr was determined over the past four years.

Parson's Slough deep rod monument data was determined to be our best proxy for estimating subsidence observed on the cross sections. For analysis to determine net vertical change in this study, we used 0.4 cm/yr as our assumed subsidence rate. This is a critical point because the results are targeting small changes in elevation, so any large sources of error could potentially alter the final outcomes. However, this is the best available data at this time and assumed to be a conservative estimate, so actual subsidence could be larger in certain areas.

Meeting the project objectives stated in the Goals section requires a common approach using Geographic Information Software (GIS), but each requires a separate, more specific methodology:

> Objective 1: Quantify the spatial variation in rates of net erosion/deposition and net vertical change.

Analysis of spatial variation can be achieved by plotting vertical change in each point using ArcGIS 9.2 to see if spatial trends emerge. Interpretation focused on trends within each cross section as well as comparison between each cross section. Rates were determined by dividing the total observed change by the time span of 29 years.

> Objective 2: Compare measured rates of net vertical change to projected rates of sea-level rise in the region.

Comparison between the published rates of projected sea-level rise and measured rates of marsh elevation differences highlighted areas more vulnerable to sea-level rise impacts. Using ArcGIS 9.2 to spatially compare net vertical change rates determined if the marsh plain elevation is keeping up with sea-level rise. The Tidal Wetland project uses sea-level rise scenarios of 0.2-0.3 cm/yr for low estimates and 0.7 cm/yr for high estimates. This study queried the data based on a low estimate of 0.25 cm/yr. In addition to projected rates (regionally), the National Oceanographic and Atmospheric Administration (NOAA) provided a mean sea level trend for Monterey, CA, which gives a local sea level trend (Figure 5). This study compared observed rates of elevation change with the projected sea-level rise rates of 0.13 and 0.25 cm/yr using ArcGIS to select observed rates that exceed these scenarios.

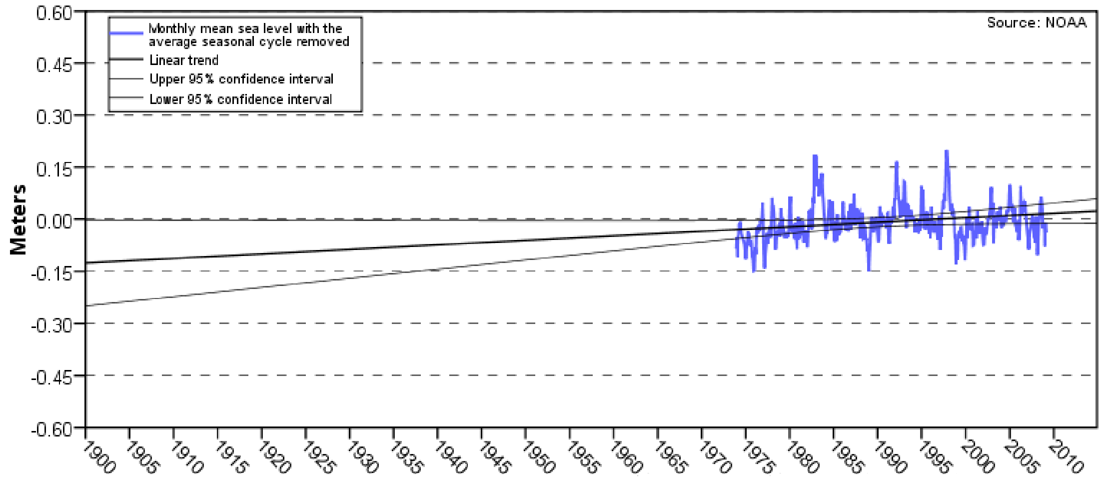


Figure 5 Mean sea level trend for Monterey, CA. Blue line is the monthly mean sea level with the average seasonal cycle removed. Solid black line is the linear trend of 0.134 cm/yr. Thinner solid lines represents the upper and lower 95% confidence intervals of +/- 0.135 cm/yr.

Objective 3: Determine linkages between land cover type and rate of vertical movement.

Spatial comparison between plant cover over 29 year period illustrated changes in plant community structure. Of critical importance was to identify and assess areas that are converting from marsh to mudflat and more stable areas that are unchanged. In addition, categorizations of surface type (Upland, Pickleweed, Panne, Tidal Creek and Mudflat) were used to analyze differences in vertical change rates.

Initial field data were tabulated in Microsoft Excel for further processing. Two types of field methods were employed during this study. Earlier cross sections used the backsight benchmarks to establish the original horizontal reference framework from 1980. This provided coordinates already georeferenced in the NAD 27 CA State Plane IV system (also known as FIPS 0404). All remaining cross sections used the backsight benchmark to "0-set" the total station and turn the specified deflection angle to reoccupy the 1980 cross section line. The subsequent dataset required trigonometry calculations to produce Northing, Easting and Elevation (NEZ) coordinates based on the benchmarks NEZ coordinates. Tabulated data were then plotted in ArcGIS 9.2 for spatial analysis.

4 Results

With the 2009 benchmark heights corrected to 1980 elevations, elevation differences between 1980 and 2009 were quantified as net erosion/deposition. An adjustment of 0.4 cm/yr subsidence was applied to net erosion/deposition rates, which was assumed to correct for vertical movement experienced by the entire cross section, which resulted in net vertical change. This is the arithmetic sum of the net erosion/deposition rate for each point and estimated rate of subsidence. Benchmark heights in 1980 and 2009 are plotted in Figure 6. Maximum elevation change occurred at cross section A-20 and A-8 with a net loss of 24.2 cm and 22.2 cm, respectively. There were no elevation gains for any of the surveyed benchmarks. Average elevation change between 1980 and 2009 was 17.4 cm downward.

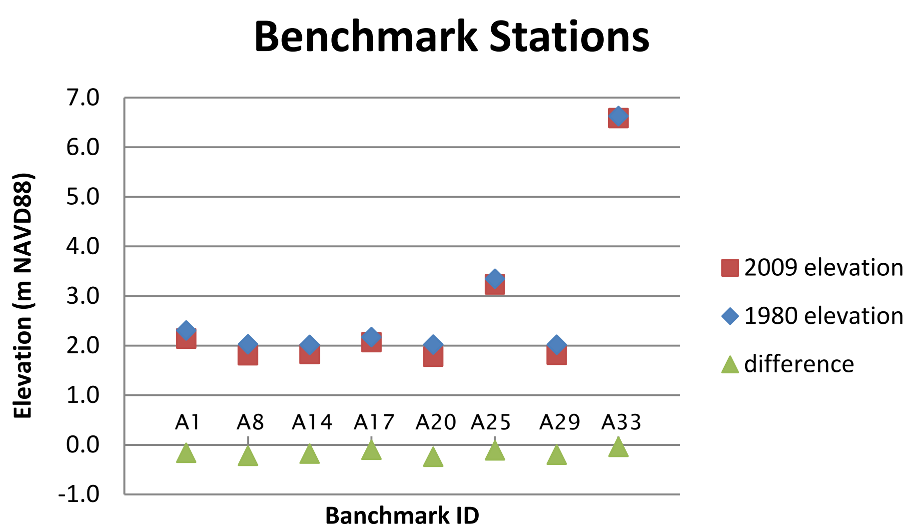


Figure 6 Absolute elevations of surveyed benchmarks compared to adjusted and converted 1980 elevations. Average benchmark elevation difference is -17.4 cm.

Tabulated and processed cross section data were plotted in GIS for spatial analysis. The resulting measurements are net erosion/deposition. Since all foreshots are tied to the benchmark, holding the benchmark elevations constant over time removed any sources for elevation change observed in the foreshots other than net erosion and deposition (Equation 3). Net erosion and deposition between 2009 and 1980 were divided into 4 natural breaks in the data and illustrated in Figure 8. Spatial trends emerge when assessing areas of extensive erosion and areas that are accreting over time. Individual cross sectional plots of distance versus elevation from 1980 and 2009 surveys can be seen in Appendix A.

Adjusting the net erosion/deposition rate using an estimated 0.4 cm/yr subsidence scenario provided net elevation change rates of the past 29 years, including the 1989 Loma Prieta earthquake. By shifting the 2009 framework down by 11.9 cm (0.4 cm/yr over 29 years), only subsidence and net erosion/deposition were factored into the results. Figure 9 illustrates these results, which were divided into 4 natural breaks in the data.

Rates of both future sea level change and regional subsidence are not well known and may vary beyond the values used in this report. A sensitivity analysis illustrates how a wide range of those two variables interact to provide differing degrees of marsh plain inundation. A subsidence rate ranging from 0.0 to 0.5 cm/yr was applied to the net erosion/deposition data (yielding net vertical change) and compared to sea level rise estimates of 0.0, 0.13, 0.25, and 0.50 cm/yr. These results predicted how many of the survey points have a net vertical change rate that exceeds sea level rise estimates for each applied subsidence rate and sea level rise estimate scenario. The sensitivity analysis results are presented in Figure 7.

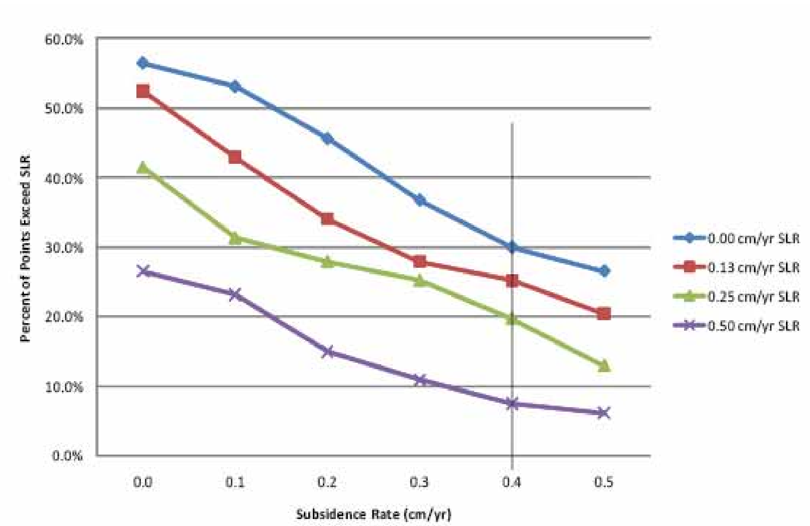


Figure 7 Sensitivity analysis using variable rates of sea level rise and subsidence on marsh plain inundation.

Sea-level rise scenarios were compared to the observed change rates of net vertical change and plotted in Figures 10 and 11. Figure 10 uses the observed rate of 0.13 cm/yr, as provided by NOAA mean sea level trends. Figure 11 uses the low estimate of 0.25 cm/yr, as implemented by the Tidal Wetland Project. Table 2 summarizes these results and compares to no change in sea level.

The observed rates of net erosion/deposition and net elevation change were categorized based on 2009 surface type categories: upland, Pickleweed (PW), panne, mudflats (MF), and tidal creeks (TCr). Averaged rates by surface type categories are presented in Figure 12. The supporting data from this graph is tabulated in table 4. A matrix style table was created to illustrate surface type changes between surveys and is presented in table 5 and mapped spatially in Figure 13.

Sea Level Rise Rate	Exceed SLR Rate	Exceeded by SLR Rate
0 cm/yr	28%	72%
0.13 cm/yr	25%	75%
0.25 cm/yr	17%	83%

Table 2: Percent of total survey points with net vertical change rates in comparison to sea level rise scenarios (total 149 points).

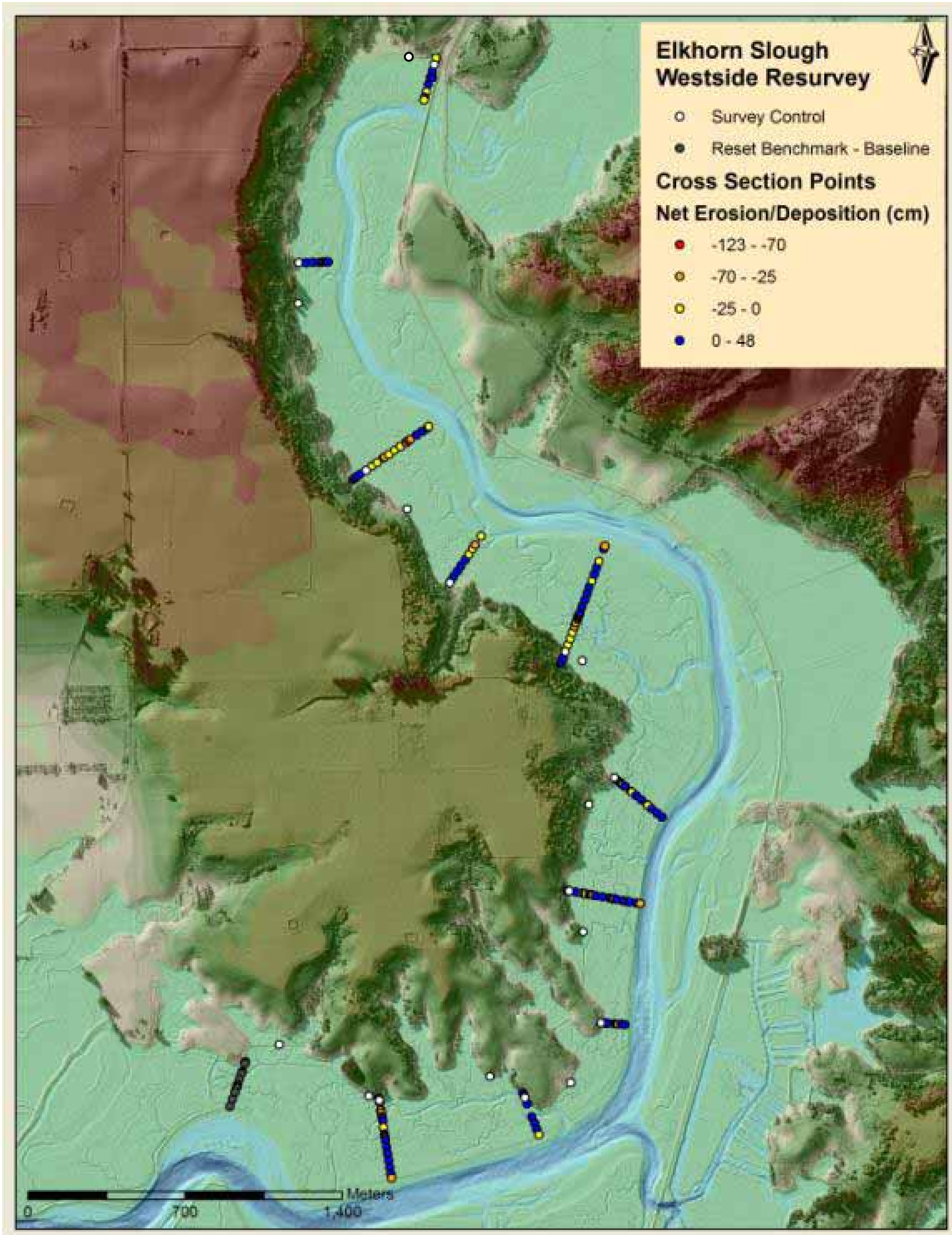


Figure 8 2009 cross section points plotted on 1m-resolution Digital Elevation Model (DEM) illustrating positive (+) and negative (-) net vertical change. Grayed out points indicate a cross section not comparable with 1980 due to a reset benchmark.

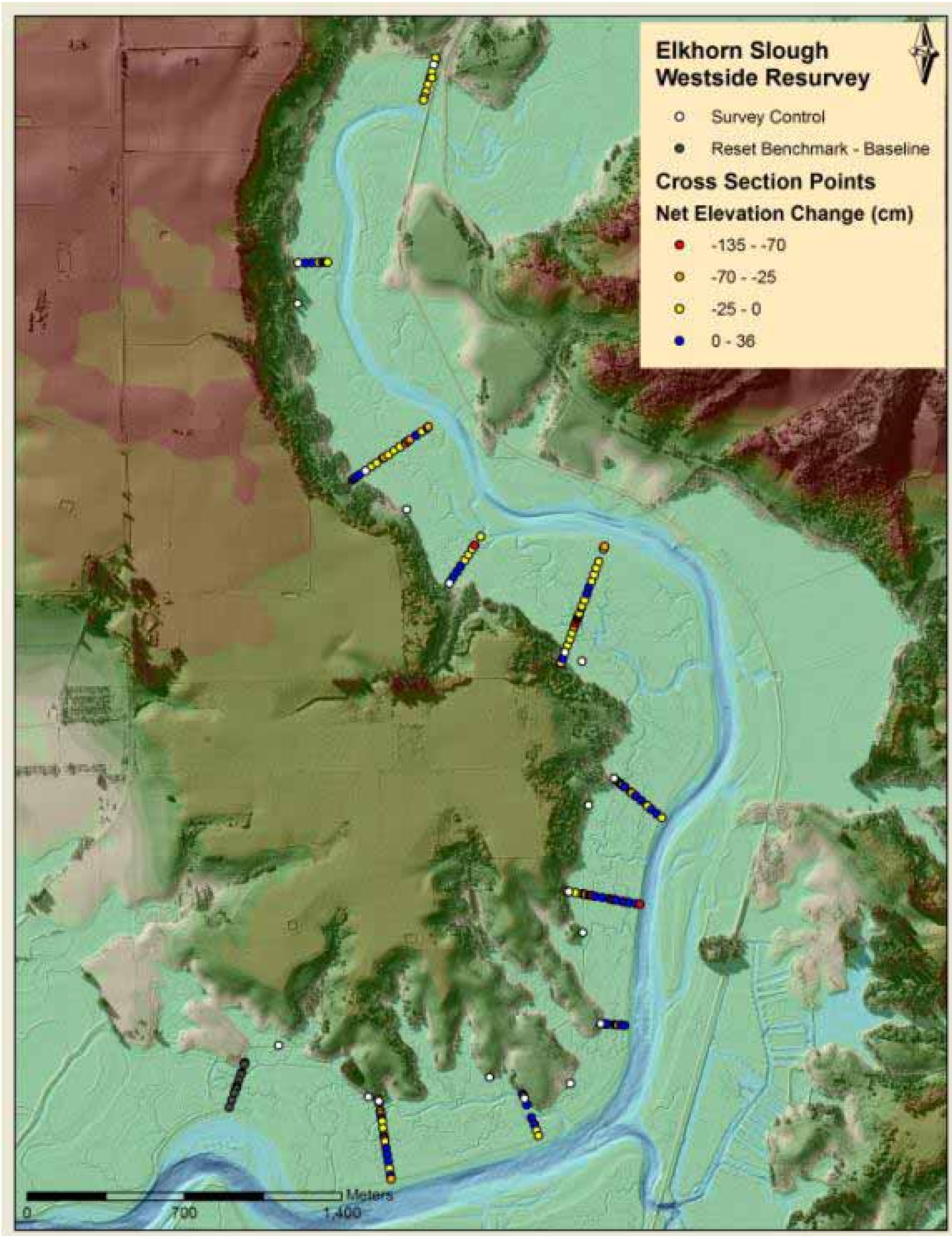


Figure 9 2009 cross section points plotted on 1m-resolution Digital Elevation Model (DEM) illustrating positive (+) and negative (-) net vertical change. Grayed out points indicate a cross section not comparable with 1980 due to a reset benchmark.

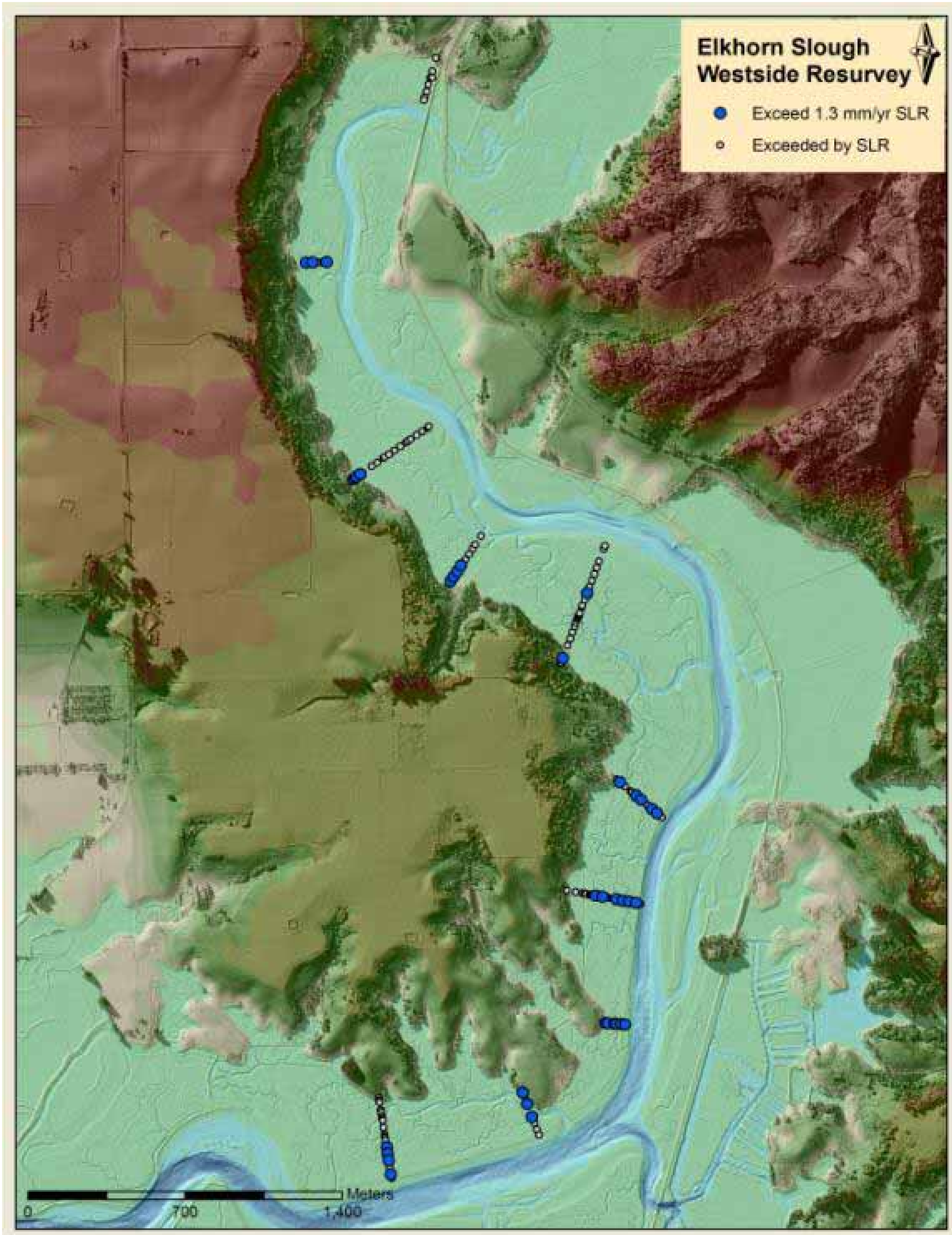


Figure 10 2009 cross section points plotted on 1m-resolution Digital Elevation Model (DEM) that have net vertical change rates that either exceed or not exceed the 0.13 cm/yr sea level rise scenario. Only 25% of surveyed points exceed 0.13 cm/yr.

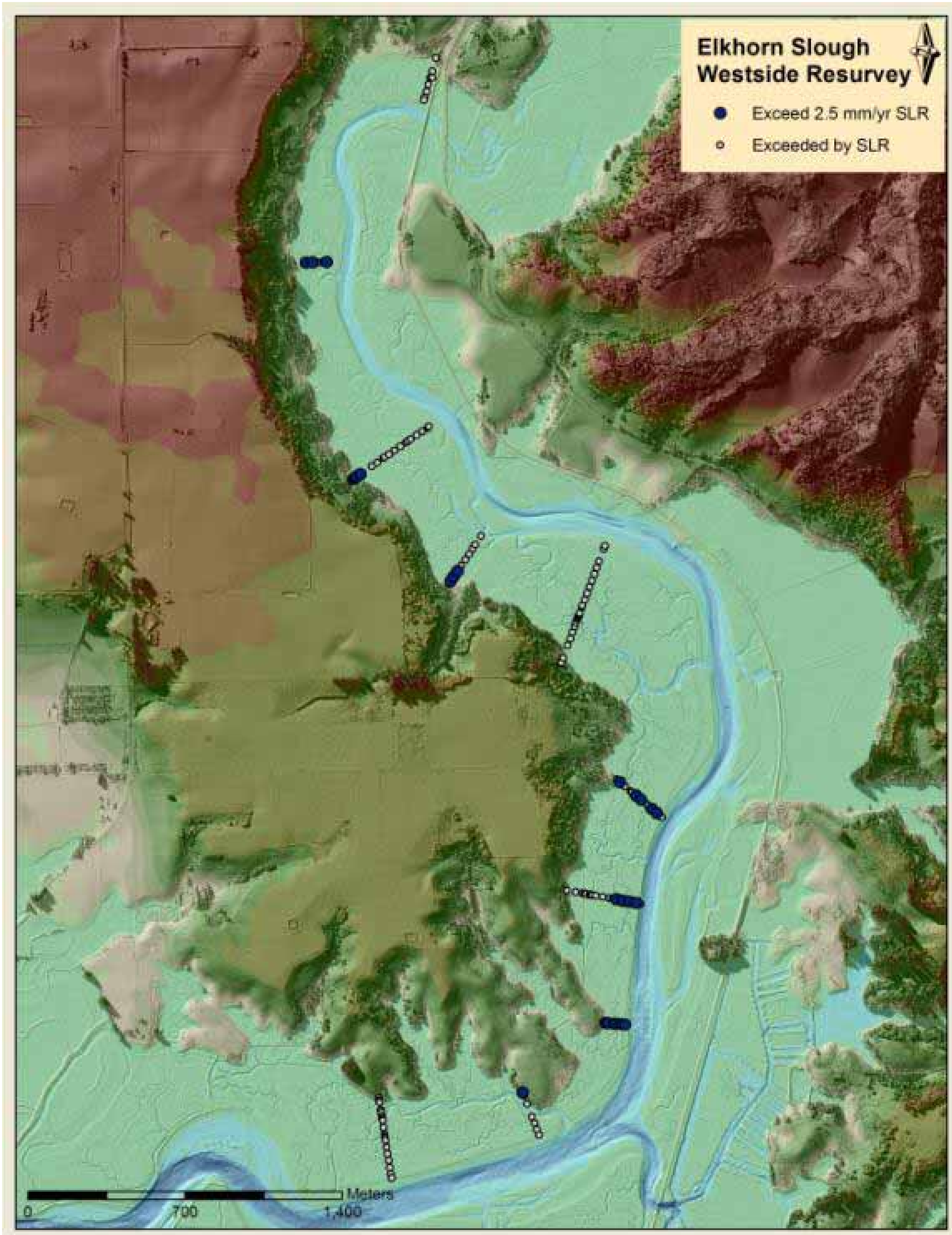


Figure 11 2009 cross section points plotted on 1m-resolution Digital Elevation Model (DEM) that have net vertical change rates that either exceed or not exceed the 0.25 cm/yr sea level rise scenario. Only 17% of surveyed points exceed 0.25 cm/yr.

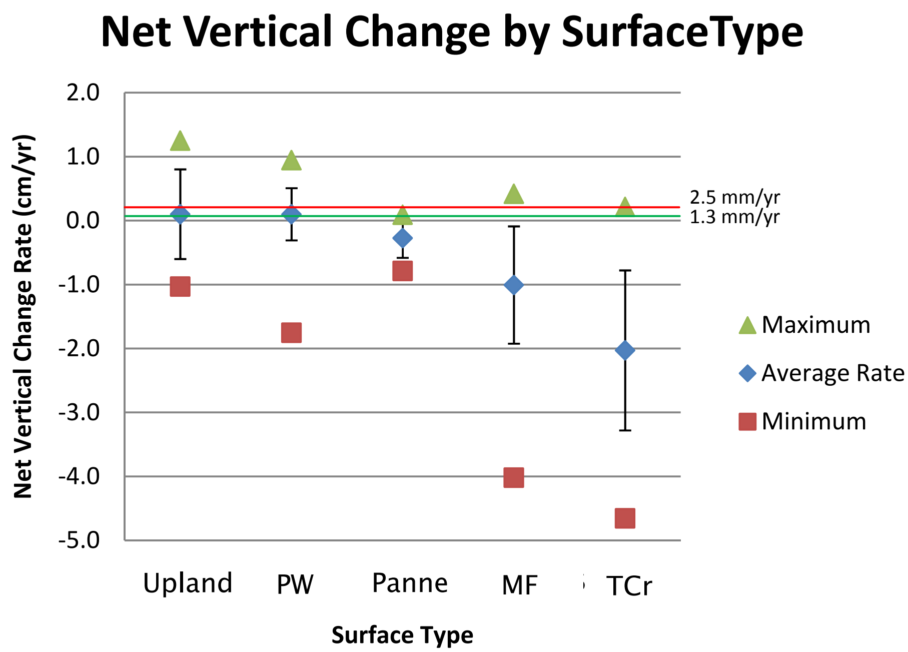


Figure 12 Average rates of net vertical change per 2009 surface type category. Blue diamonds represent the mean rate and the upper/lower limits are plus/minus the standard deviation. Maximum and minimum values plotted in green triangles and red squares, respectively. Surface type categories become less stable and more dynamic from left to right. Sea level rates used in the analysis are plotted in horizontal lines with corresponding rates displayed to the right side of the plot.

	Upland	PW	Panne	MF	TCr
Average	1	1	-3	-10	-20
Max	13	9	1	4	2
Min	-10	-18	-8	-40	-47
St Dev	7	4	3	9	13

Table 3 Vertical change rates by categorized 2009 surface type. Units are in mm/yr. PW: Pickleweed, MF: Mudflat, TCr: Tidal Creek.

		2009 Surface Type			
		PW	PANNE	TCr	MF
1980 Surface Type	PW	41	4	4	8
	PANNE	0	3	0	0
	TCr	4	1	25	6
	MF	0	2	0	16

Table 4 Surface type changes between 1980 and 2009 survey points (149 total points). Grey cells represent no change, orange cells represent "degrading" changes and green cells indicate "stabilizing" changes. The green cells are more likely to be associated with categorizing errors and not actual realized changes because it seems unlikely that a tidal creek in this environment would fill in to create Pickleweed marsh.

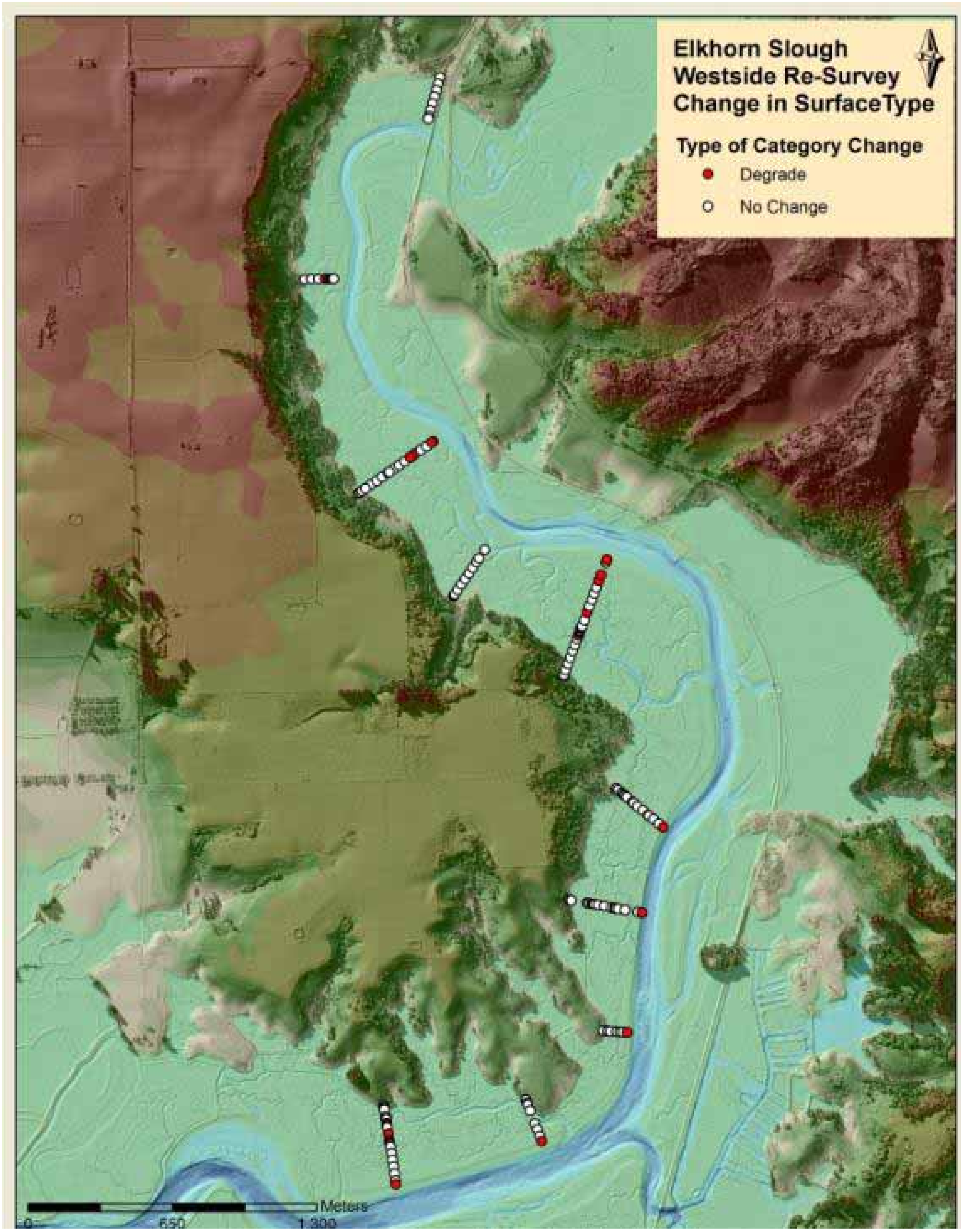


Figure 13 Distribution of “degradational” changes in surface type between surveys. “Degradational” changes would be surface types that shift from left to right in Figure 12.

5 Discussion

Before this study began, the marsh plain at Elkhorn Slough was assumed to have dropped by 10-20 cm, based on results from Miller (2004). There was a general understanding that the marsh surface was subsiding, possibly due to the Loma Prieta earthquake or excessive groundwater extraction in nearby aquifers to name a few. Results from this study indicate that a variety of geomorphic processes are simultaneously adding to cumulative change in the marsh plain elevation. The marsh plain has marginally accreted in excess of shallow subsidence on average since 1980, while the tidal creeks and mudflats have dropped elevation due to erosion, which is consistent with the findings of Watson 2008. Each of the land surface types are generally changing elevation in the direction that they are expected to (Pickleweed accreting, tidal creeks eroding, etc). For example, tidal creeks are expected to be more dynamic due to greater tidal forces and the results reflect this assumption (Figure 12).

Sensitivity analysis results (Figure 7) indicate the balance between erosion/deposition and subsidence for overall vertical movement of the marsh plain. Figure 8 illustrates the influence of net erosion/deposition; with no applied subsidence or sea level rise only 43.5% are losing elevation (erosion).

Marsh plain survival hinges upon positive net surface elevation change that keeps pace with sea level rise. This vertical accretion requires trapping sediment delivered by diurnal high tides. Accretion is clearly illustrated in 8. However, subtracting the 0.4 cm/yr surface subsidence rate yielded much lower "net" elevation change presenting a dire scenario (Figure 9). Figures 10 and 11 provide context to these vertical changes by comparing to modest sea level rise rates. The general conclusion is that even though areas are accreting over time, the background surface subsidence rate is great enough to keep the marsh plain from matching sea level rise.

The spatial variation in net erosion/deposition, illustrated in Figure 10, highlighted certain areas that are receiving more erosion than others. This figure also highlights areas that are more stable. The results from this line of analysis will assist resource managers prioritize and decide what restoration options to implement and where to focus restoration effort.

Sea level scenarios were selected from NOAA data for Monterey Bay, CA. This study quantifies both net erosion/deposition and vertical change and we cannot quantify the acceleration or deceleration of those rates. Therefore, an assumption is made for the sea level comparison that the rates are constant over time and independent of sea level rise. Figures 10-11 show areas of the slough that will not keep a pace with the various sea-level rise projections, assuming that the net elevation change rates do not increase with accelerated sea level rise. This analysis was provided as a conceptual predictive tool to illustrate what will happen if no management actions are sought and accretion rates go unchanged in the face of 2 modest sea level rise scenarios.

The third objective indicated which surface types are more dynamic. Figure 12 and table 3 rank each 2009 surface type based on net vertical change rates. More dynamic surface types should be the focus of management actions taken at Elkhorn Slough to alleviate further marsh plain degradation. Table 2 contains a frequency table displaying surface type changes between surveys. Figure 13 further illustrates areas of degradation between surveys. Particular attention should be given to the ends of the cross sections located closest to the main Slough channel, where consistent degradation has occurred for each cross section. This is indicative of the main channel widening and eroding back the marsh plain along its banks via lateral erosion.

A critical point to be made regarding the dataset from this study is that the ground elevations in each cross section were measured with respect to the benchmark for that cross section. In 1980, the cross section benchmarks were accurately leveled to local vertical control points and adjusted to a localized NGVD29 vertical framework, referred to as NGVD29-CSLC. Horizontal coordinates were collected in NAD27 CA State Plane IV coordinate system. There was some “leaning” documented for a few benchmark stakes, however the results did not indicate a radical vertical shift in any of the benchmarks. The 2008/2009 survey reoccupied the same location on the Earth (within reasonable precision) as in 1980 and remeasured elevations with respect to the benchmark. Since there are no major active faults running between the benchmarks and subsequent foreshots, we can assume that any elevation change is with respect to the benchmark.

Any actual change in the benchmarks with respect to the cross section (i.e. pipe slip) will affect the overall results. We know through our survey work that benchmarks have moved since 1980 on average 17.4 cm of downward movement, but we were unable to quantify the amount of that change is attributed to pipe slip independent of the cross section and actual subsidence of the entire cross section. Determining amount of pipe slip will provide a correction factor that can be subtracted out from the observed benchmark elevation changes to yield actual subsidence for each cross section. Instead of using our best estimate of subsidence given available data, actual subsidence at the cross section level can be quantified and applied to the net vertical change results. Additional work is needed to pinpoint the components of benchmark movement, direction and magnitude that will further advance this study.

It should be noted that it would be inefficient to resurvey all cross sections again in a few years. High precision remote sensing equipment has the capability to survey the entire slough in a matter of day, whereas this project took months of strenuous and cumbersome field work. If interest continues to repeat the survey, then it is recommended to select key cross section points to be monitored on an annual or semiannual basis. Marking the cross section point with flagging and GPS will assist in easily reoccupying selected points.

6 Conclusions

> Objective 1: Quantify the spatial variation in rates of net erosion/deposition and net vertical change.

It appears that the marsh plain is functioning by collecting and trapping sediment to accrete, however the subsidence applied in this analysis impedes vertical growth of marsh plain to an average rate of 0.1 cm/yr and tidal creeks are offsetting any vertical progress as well by severely eroding within the marsh plain. Cross sections indicate net deposition in the marsh plain interior where Pickleweed dominates. Negative vertical differences (indicating erosion and/or subsidence) occur in areas where tidal creeks and tidal waters are flowing into the marsh plain margin. There is evidence of tidal creek widening and extension, but the most harmful extensions are aimed towards the marsh plain interior. Cross sections 14, 17 and 20 appear to be experiencing the greatest impacts due to inland tidal creek extension. More water is able to access the marsh plain interior, resulting in accretion on the Pickleweed, but also resulting in extensive erosion within the channel and where the marsh plain evolves into to mudflats. Cross sections generally indicate that surface elevations have dropped near tidal creeks and mudflats near the marsh plain toe, where the upland meets the Pickleweed. The main channel is also widening, as indicated by consistent elevation loss at survey points near the main channel of the Slough (e.g. Appendix A; Figures 8 and 9).

> Objective 2: Compare measured rates of net vertical change to projected rates of sea-level rise in the region.

Sea-level rise scenarios appear to play a significant role in the future of Elkhorn Slough, largely because of subsidence, if no management actions are taken to mitigate these impacts. The low scenario used by the Tidal Wetland Project of 0.25 cm/yr outpaces most of the slough given the quantified net vertical change rates, resulting in a vast degradation of the marsh plain if the vertical change rates do not increase to compete with sea level rise. Even sea level trends from NOAA buoy observations in Monterey Bay provide a grim picture of the wetland environments, with just a 0.13 cm/yr estimate. Attention should be focused on cross sections 14, 17 and 20, which are being eroded from within the marsh plain interior due to tidal creek extension and budding into the middle of the marsh plain.

> Objective 3: Determine linkages between land cover type and rate of vertical movement.

Five surface types have been categorized and ranked based on stability in Figure 12. It is clear that the Pickleweed, which is synonymous with the salt marsh portion of the marsh plain, is the most vertically stable and is accreting at variable rates. Some of these rates are enough to outpace sea-level rise, others are not. Figure 12 and table 4 also document the process by which the healthy marsh plain surface erodes into a tidal creek. Pannes can be the beginning stages of tidal creek formation, by focusing water in these areas because of a slight drop in elevation. As the panne elevation drops further and spreads over time, it becomes more of a mudflat. The nearest source of tidal flows will begin down cutting these areas because of increased stress from drop in elevation compared to the surrounding area. Once the water has found its path during the panne formation process, it continues to remove sediment as it becomes a mudflat and then into a tidal creek. For surface types to convert into a tidal creek would be because a nearby tidal creek has budded or headcut into that surface.

Tidal creeks extend headward into the Pickleweed-dominated salt marsh and bud onto the marsh plain. If a low spot gets created a panne will form. Over time this panne will erode further into mudflats and then eventually into a tidal creek. Meanwhile the tidal creek continues to extend, widen and deepen as it connects the main channel with the marsh plain interior. Figures 14 and 15 illustrate this process. The main slough provides water to the tidal creek, which is extending and budding into the marsh plain interior. These tidal creeks frequently flood their banks at higher tides, which has resulted in mudflats if sufficient deposition has not occurred on the Pickleweed.

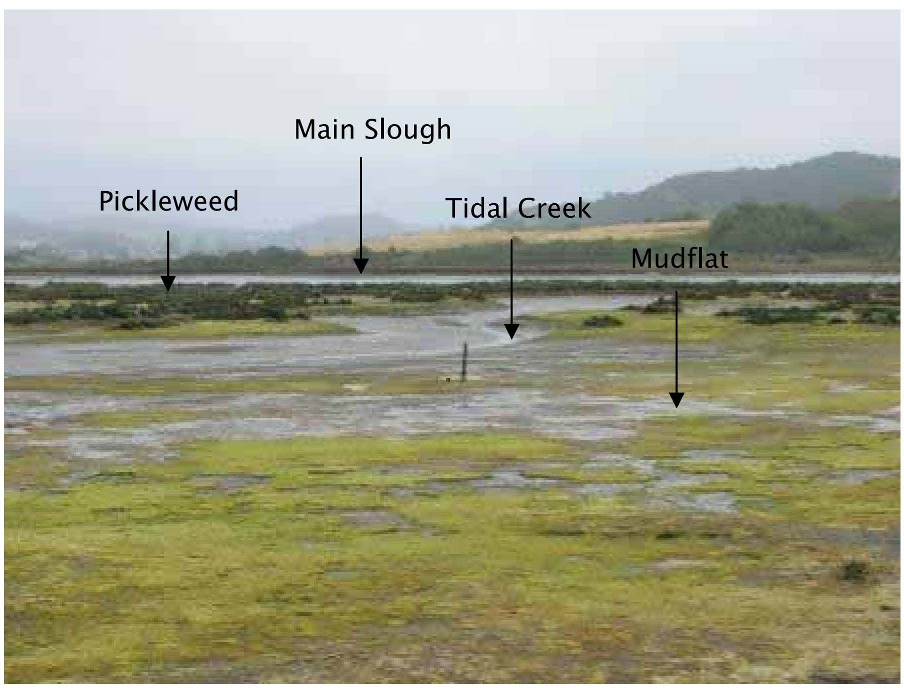


Figure 14 Cross section A8 looking NE from the interior.

Figure 8 shows areas that are eroding, particularly in areas around cross sections A14, A17 and A20. These eroding areas tend to occur near tidal creeks and mudflats.

Figure 12 ranks the surface type category by net vertical change rate and illustrates which categories are more dynamic. There appears to be a correlation between erosive areas with categories shows that tidal creek extension and widening is a major cause of marsh plain loss. Not only do tidal creeks cause more erosion, they assist in the conversion of marsh plain into mudflats through frequent flooding and scouring, which will then eventually form a channel and become into tidal creeks.

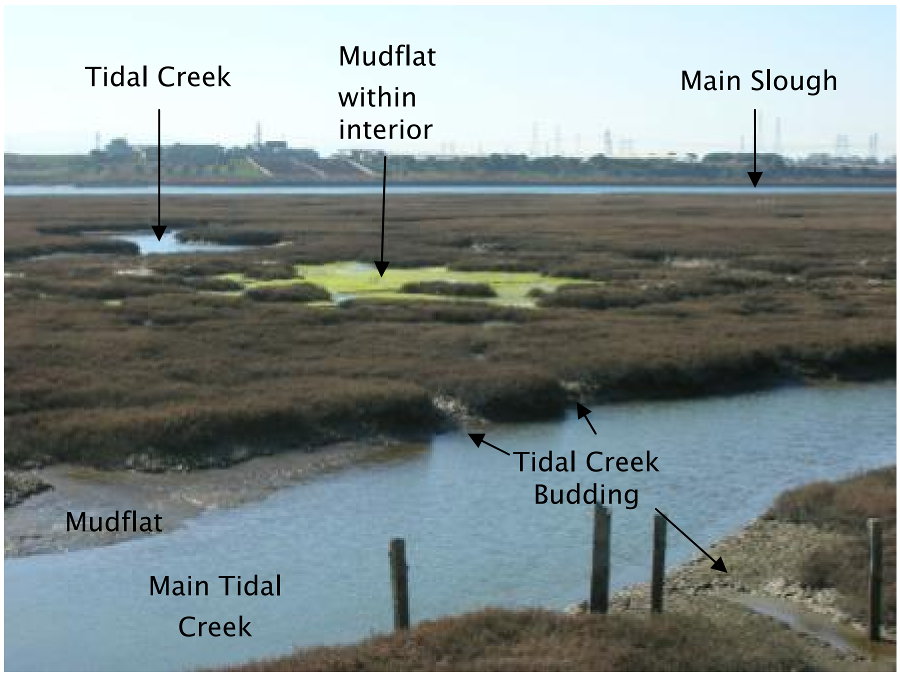


Figure 15 Cross section A43 looking south from the upland.

Phillip Williams and Associates provided Elkhorn Slough National Estuarine Research Reserve with 4 restoration alternatives to limit degradation of the marsh plain and the habitats it provides. In short, those alternatives consisted of 1) no action, 2) a new ocean inlet, 3) a low or high sill under Highway 1, and 4) Parsons Slough restoration. Given that the tidal creeks are a geomorphic driver of marsh plain deterioration, tidal influences need to be muted to reduce tidal volumes and sheer stress exerted on the tidal creek banks and mudflats.

Out of the 4 restoration alternatives suggested by Phillip Williams and Associates, Alternative 1, “no action”, should not be considered because Figures 10 and 11 illustrate the extent of the slough that will be outpaced by sea-level rise. A combination of a rising sea and subsiding lands appears to be detrimental for Elkhorn Slough marsh plain habitat. Alternative 2, “new ocean inlet”, should not be considered because the constructed barrier will completely block tidal exchange between Elkhorn Slough and Moss Landing, possibly resulting in inhibited marsh accretion rates and thus net vertical gain due to the subsidence experienced in the area. Even though marsh plain erosion would disappear due to blocked tidal forces, the marsh plain would still need to accrete to maintain proper elevation amidst compaction and settling of the land surface. Alternative 3, “tidal barrier at Highway 1”, is a possible effective alternative to mute, but not eliminate tides, allowing for marsh plain accretion, while limiting tidal creek extension and widening. Alternative 4, “restoration of Parsons Slough”, is also an effective alternative that will decrease tidal scour and tidal creek extension below the Parsons Slough junction.

It is recommended that resource managers focus attention on restoration alternatives that directly mitigate erosion, increase deposition, and/or mute sea level rise effects, Restoration of Parsons Slough (Alternative 4) appears to be the most cost effective way to reduce tidal volumes below the junction and mitigate the erosional forces that are causing such widespread erosion. Cross sections closer to the mouth of the Slough show some of the highest accretion rates, so a tidal sill recommended in Alternative 3 might ultimately decrease these rates by limiting tidal inundation onto the marsh plain. With the restoration of Parsons Slough, the tidal volumes will be reduced below the Parsons Slough junction that will inherently reduce tidal forces and scour, while maintaining the healthy marsh plain.

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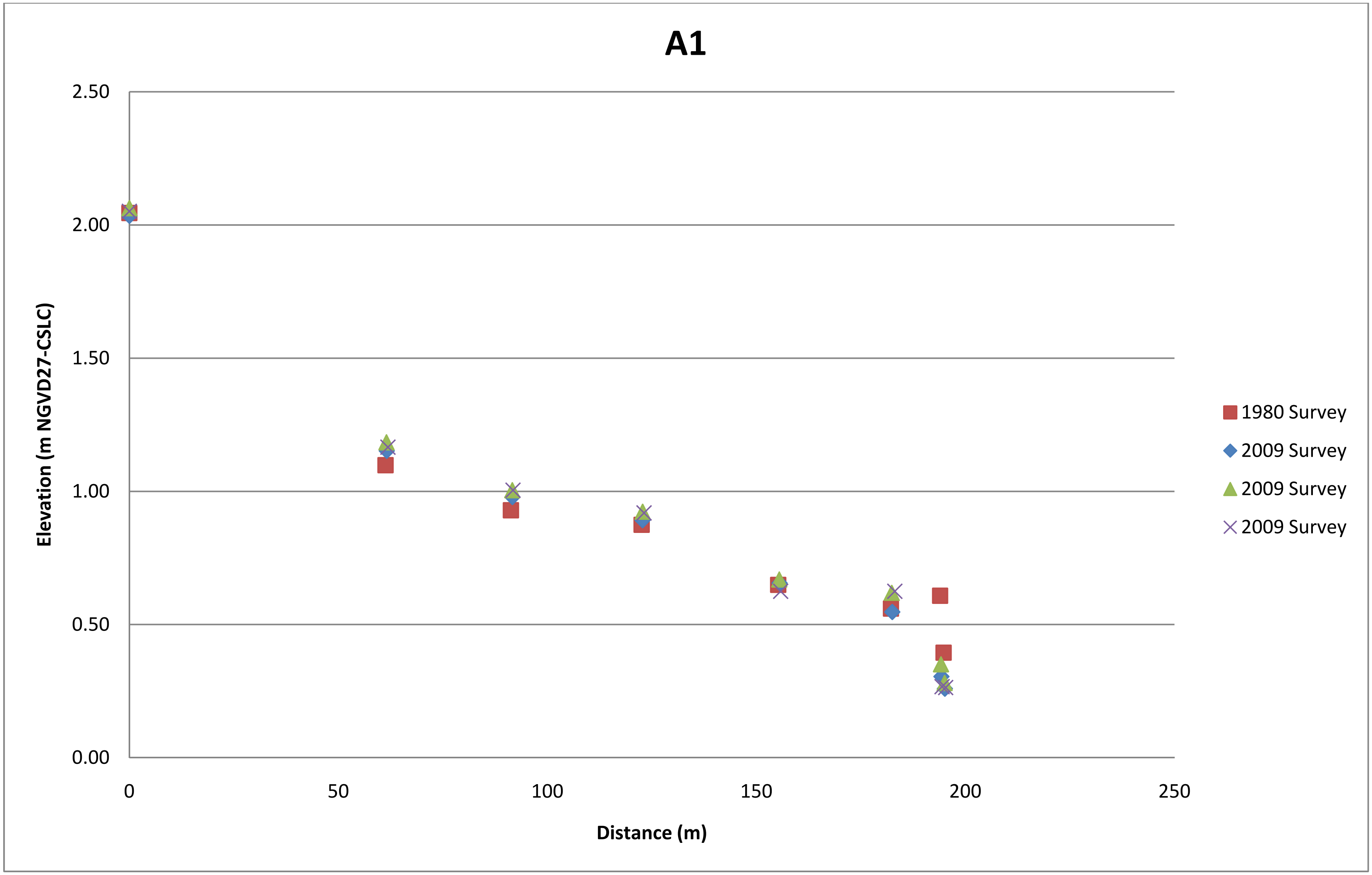
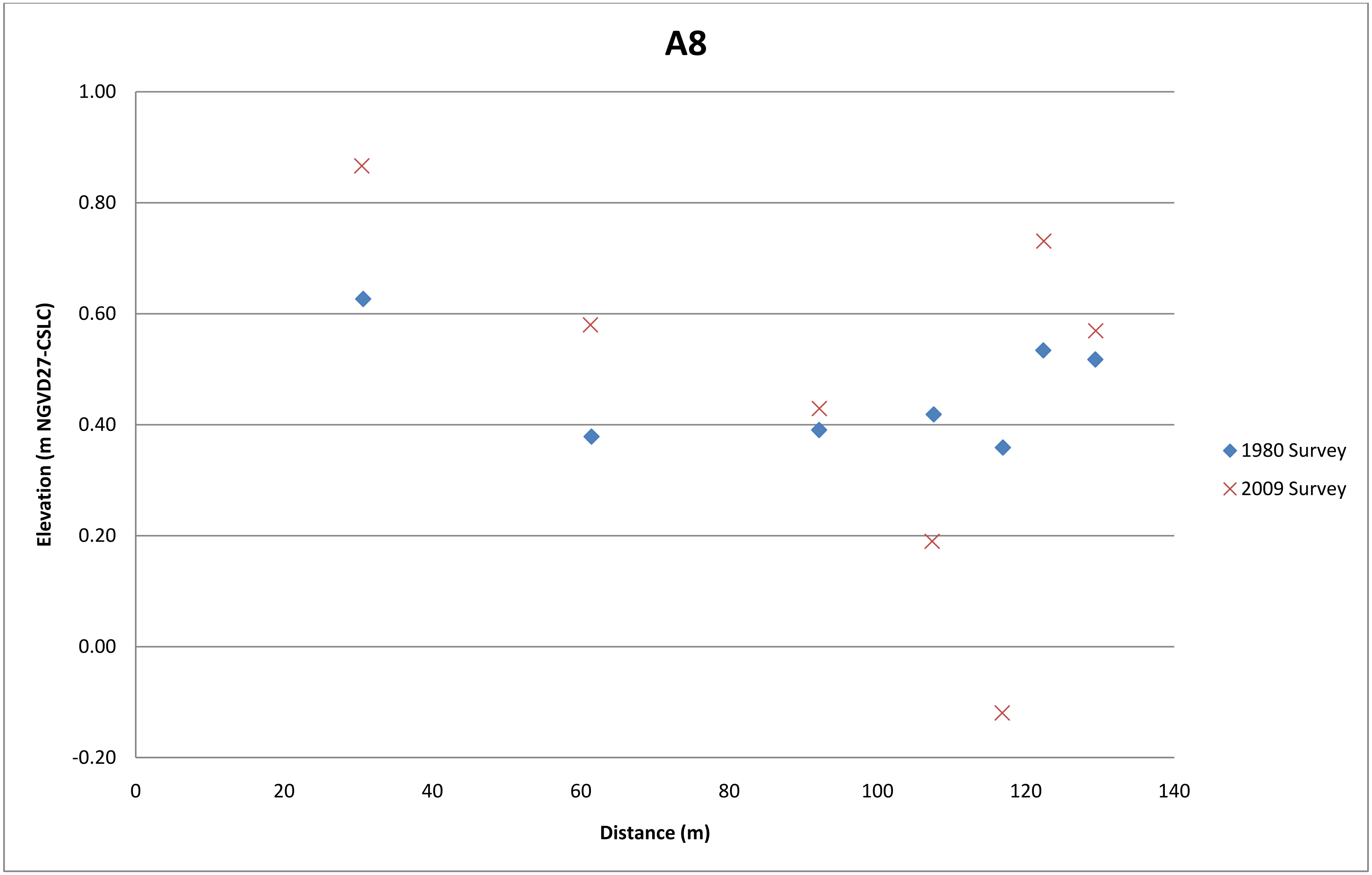
8 Appendix A

Cross Sectional Plots of comparable cross sections illustrating 1980 and 2009 elevations.



Appendix A – Cross Section Plots illustrating 1980 and 2009 elevations



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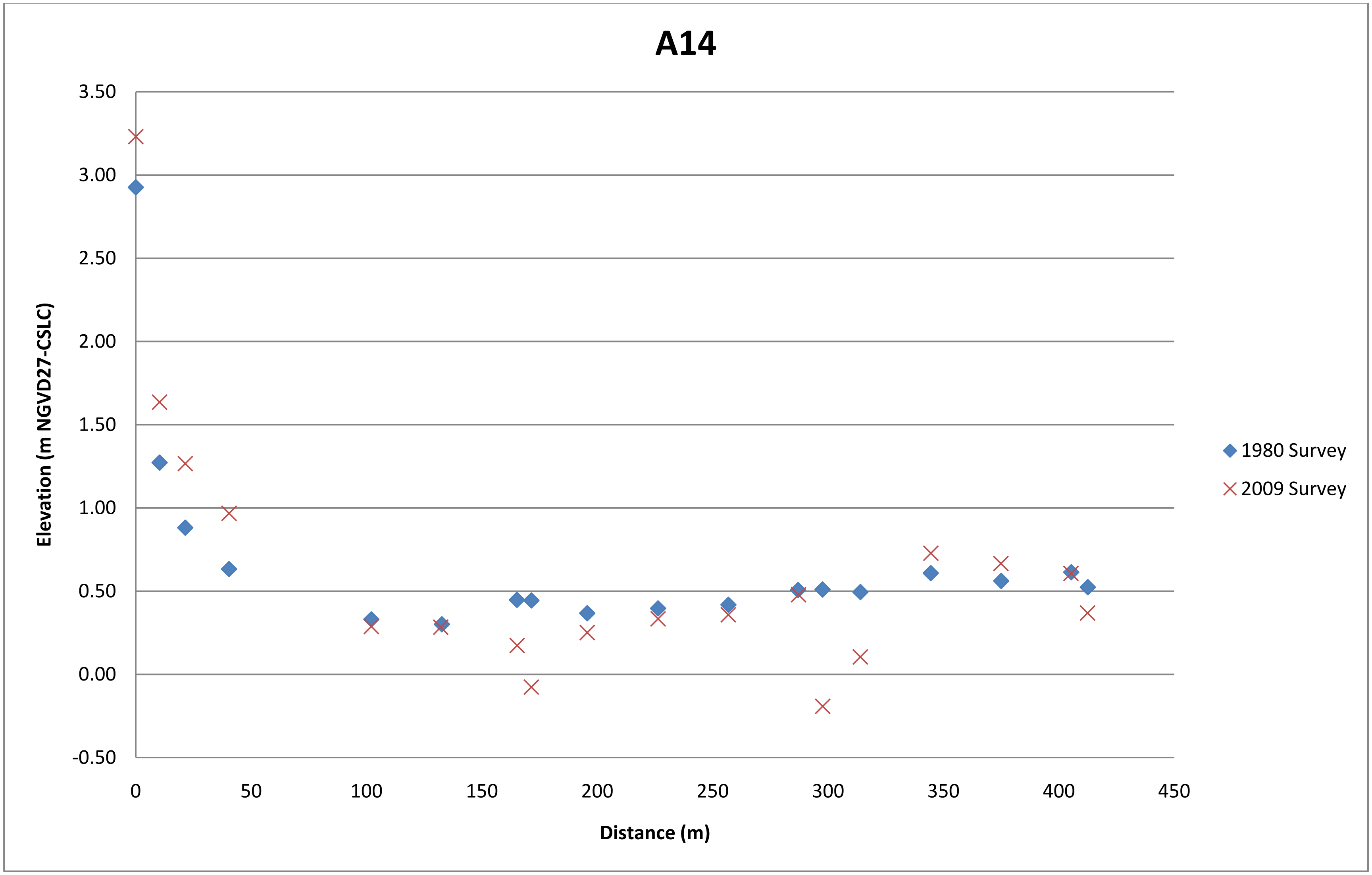

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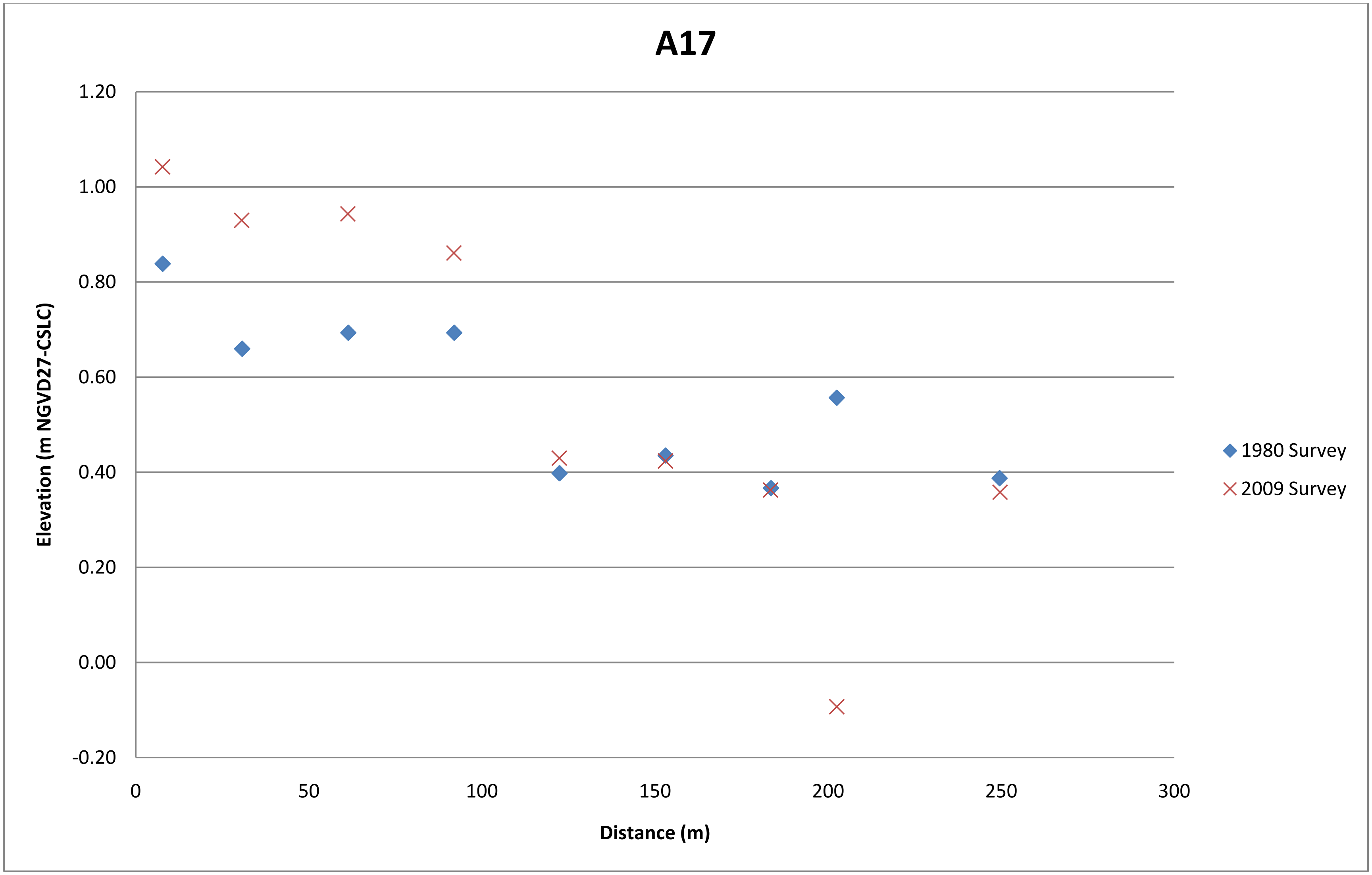

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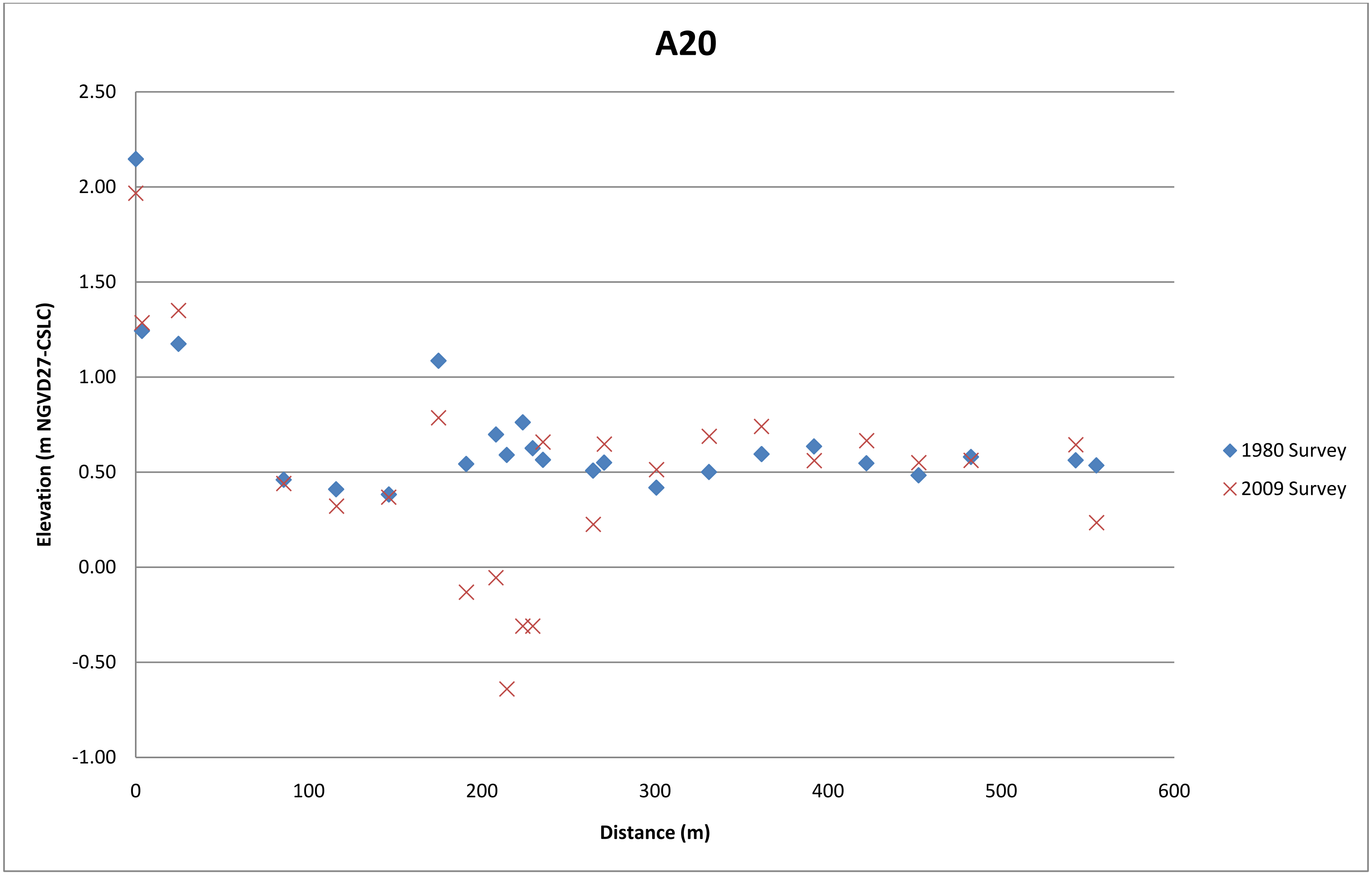
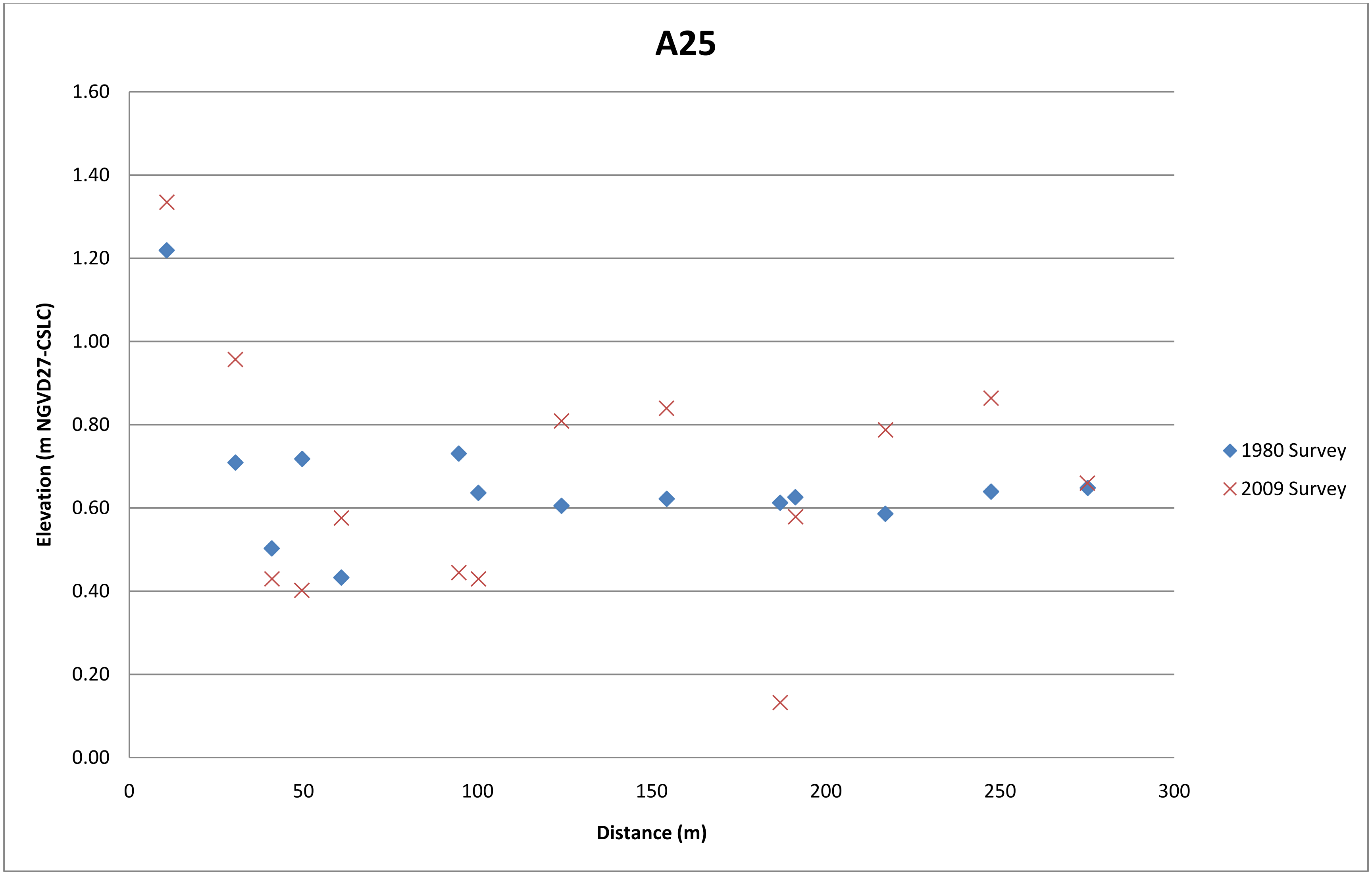


Appendix A – Cross Section Plots illustrating 1980 and 2009 elevations



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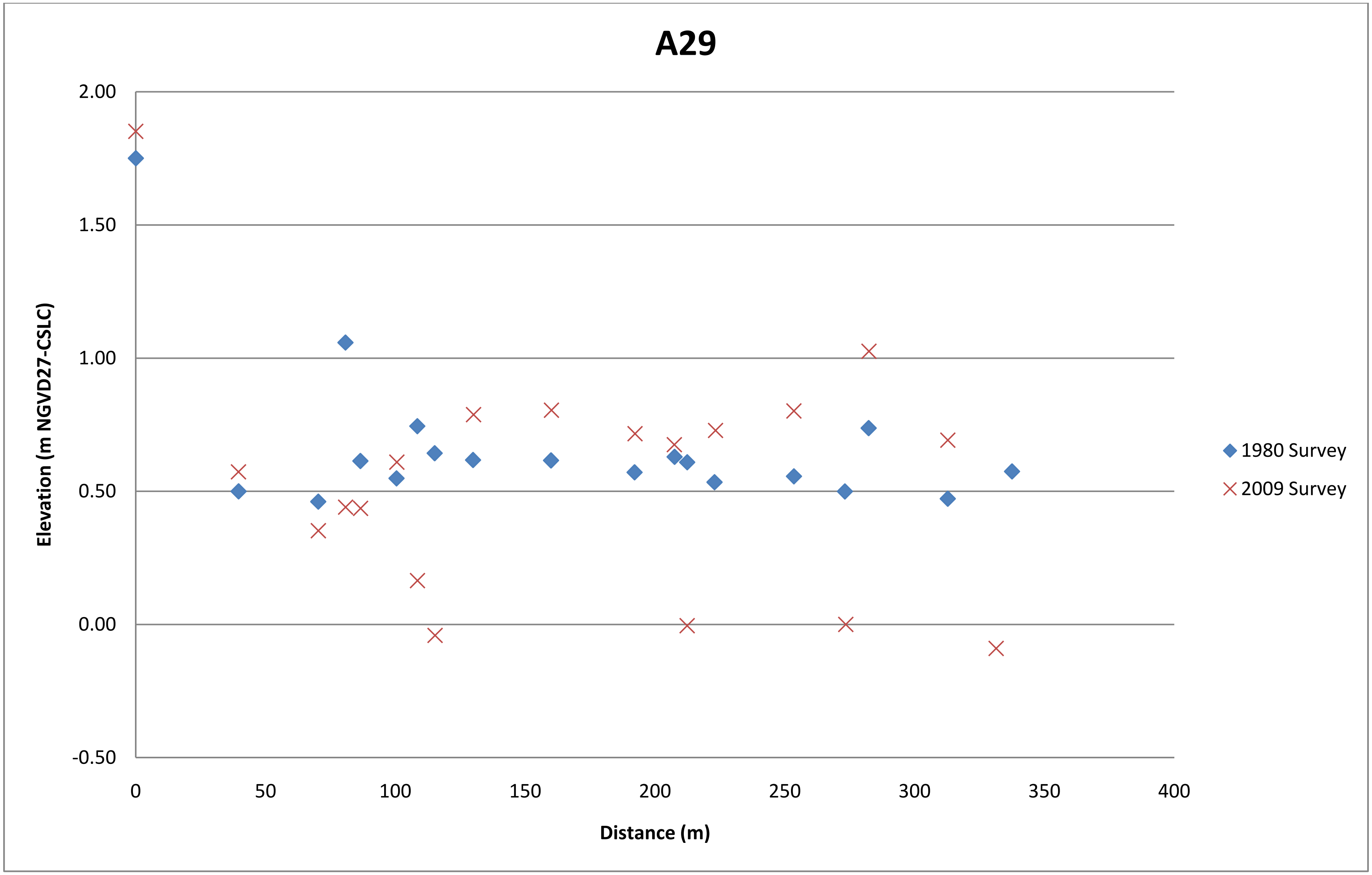

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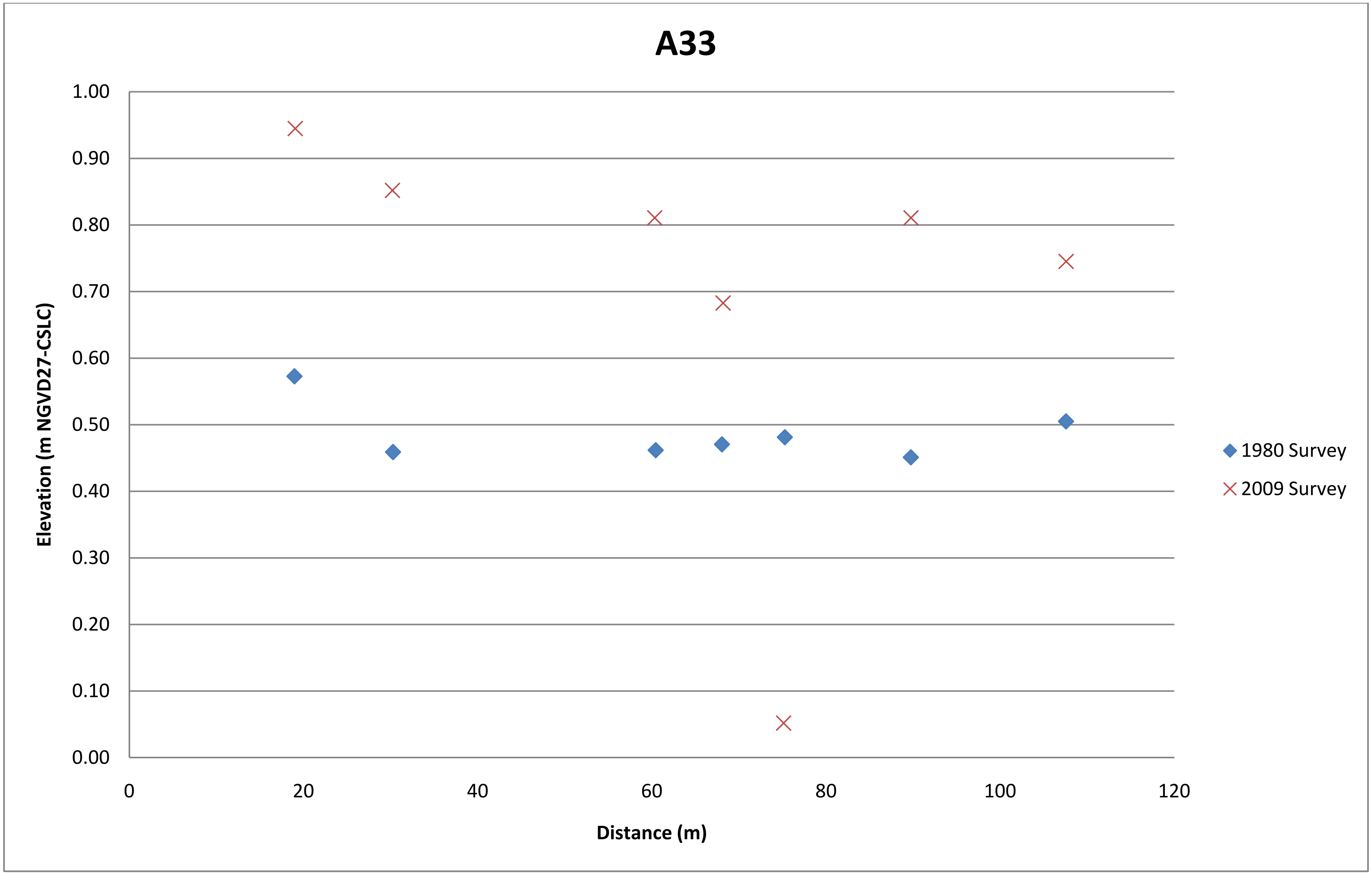

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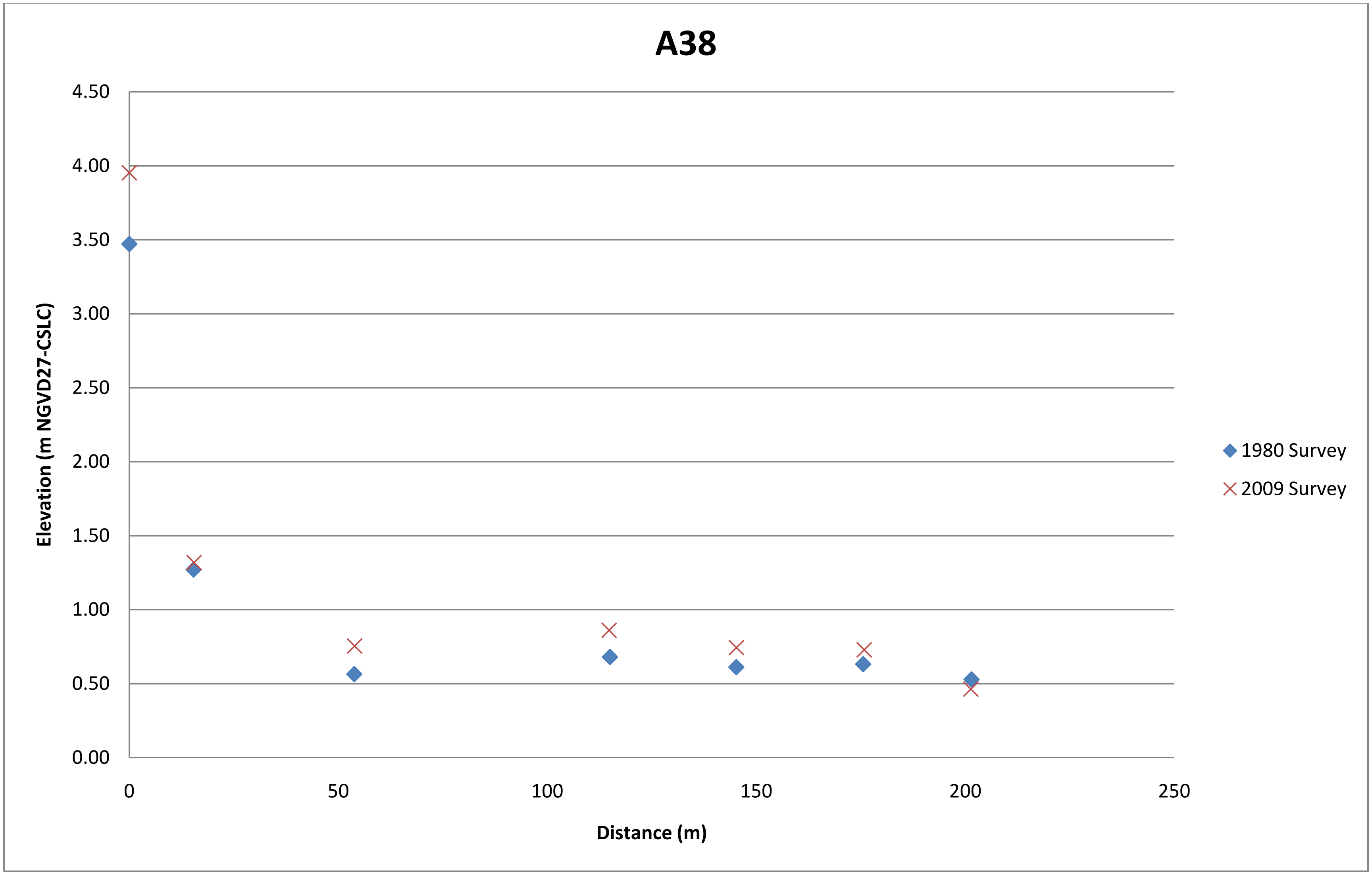

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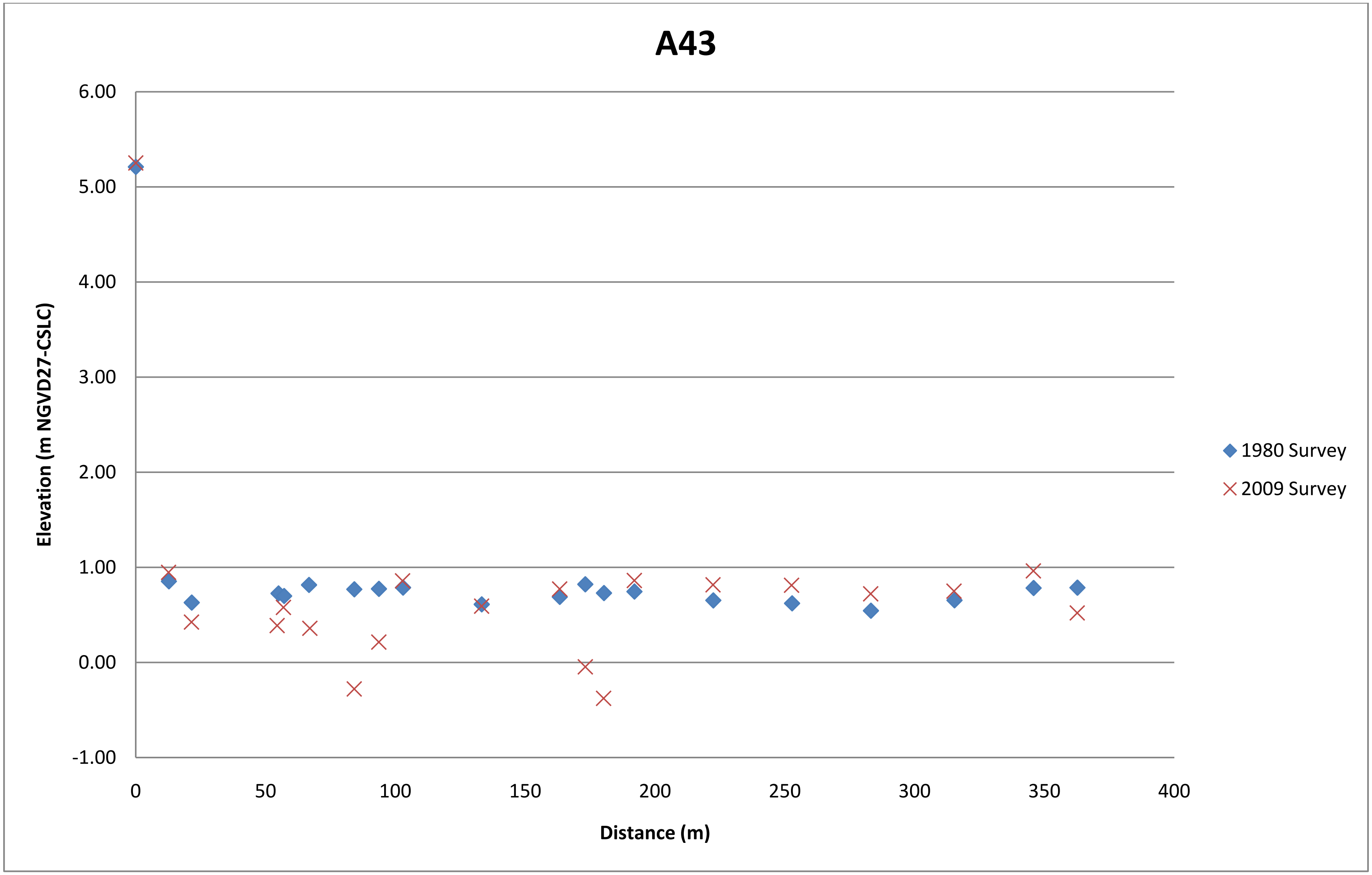

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