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Twenty-Nine Years of Geomorphic Change at Elkhorn Slough, California

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TWENTY-NINE YEARS OF GEOMORPHIC CHANGE AT ELKHORN SLOUGH, CALIFORNIA

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DEDICATION

This work is dedicated to all of my friends, family and thesis committee for their continued support throughout this entire process.

ABSTRACT

Twenty-Nine Years of Geomorphic Change at Elkhorn Slough,
California
by
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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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We are also grateful for Mr. Lee Vaage and his MidCoast Engineers survey team (Miles Wadsworth, John Puffer) for their significant contribution and ability to reoccupy the original 1980 survey. This project was also greatly enhanced by Elkhorn Slough researcher Eric Van Dyke, who provided significant contributions to this project. The report was improved by Dr. Fred Watson's editorial comments. This thesis report was, in part, a technical report to Elkhorn Slough National Estuarine Research Reserve with funding from David and Lucile Packard Foundation.

1. WETLAND POLICY AT ELKHORN SLOUGH

Estuaries and coastal lagoons are among the most biologically productive ecosystems and provide the largest collection of ecosystem services on a per-acre basis (Costanza 1997). Wetlands are home to numerous terrestrial and aquatic organisms, many of which provide substantial commercial and recreational value. Despite their economic and ecological value, wetlands are still among the most highly manipulated landscapes with their 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).

An exponentially increasing human population is one of the leading geomorphic agents that are drastically affecting the natural landscape (Hooke 2000). People want to live and work near the coast, but population pressure limits acceptable building sites (Silberstein and Campbell 1989). Coastal marsh has been drained for agriculture and/or filled for development since the late 1800s with initiation of the Swamp Lands Act. 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).

Wetlands and estuaries provide significant economic value and important functions within coastal ecosystems. Located at the margin between freshwater and open ocean, wetlands provide numerous benefits such as pollution attenuation, storm flow control, flood mitigation, critical aquatic and wildlife habitat, and recreation, just to name a few. These are the larger factors that ultimately spark human desire to rehabilitate and restore degraded landscapes.

Estuaries comprise a range of valuable habitats that are mostly differentiated upon degree of wetness and salinity. “Salt marsh” is defined as a transitional intertidal environment between the upland and salty/brackish water. The salt marsh is home to halophytic vegetation which can survive in the saline conditions and provide habitat for a wide variety of wildlife species. These critical habitat areas combine to provide a rich ecosystem essential for birds, marine invertebrates and fishes. Additionally, properly functioning coastal wetlands minimize shoreline erosion and filter pollutants.

One of the most critical problems facing many coastal wetlands is a high rate of relative sea-level rise due to a combination of eustatic sea-level rise and local subsidence (Pont et al. 2002, Watson 2008). Wetland loss is primarily reflected by shoreline recession due to erosion and drowning (Phillips 1986). Wetland survival hinges upon a delicate balance between overall slope of the land, rates of sea-level rise and marsh plain surface accretion. Therefore geomorphological and ecological processes are both critical inputs to tidal wetland management and restoration strategies (Fagherazzi 2004).

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 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).

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). Had the Moss Landing Harbor not been constructed, Elkhorn Slough would have eventually filled in with sediment and slowly evolve into a dry alluvial valley, in approximately 3,000 years, similar to the Salinas Valley (Schwartz et al. 1989).

Governments around the world have imposed tougher regulations to protect existing wetlands. Many restoration efforts are taking place to mitigate or restore degraded and damaged wetland habitat. In the Florida Everglades, the largest effort in United States history is underway to restore the natural flow of water that has been diverted by canals, spillways, and human manipulation. Over the last 150 years, approximately 90% of the tidal marshes that fringed San Francisco Bay have been destroyed as a result of progressive diking and filling for agricultural, salt pond, and commercial development. Within the last three decades, however, large efforts have been made to restore degraded areas into functioning wetland ecosystems.

Federal involvement in wetlands was first initiated in 1849 with the Swamp Lands Act, which was "to aid the state of Louisiana in constructing necessary levees and drains to reclaim the swamp and overflowed land therein." Later in 1950, this act was extended to 12 other states including California. This Act lead the charge to destruct sensitive and ecologically valuable wetland habitat in the United States. Although our school of thought has relatively changed since then, levee systems and dikes are still apparent today and effecting tidal distribution. Areas that were once drained have rapidly subsided due to compaction and dewatering of the soils. This has lead to widespread marsh plain degradation, which has become a large portion of tidal wetland management and restoration.

Wetland loss was not an issue to society until the 1970's when the public became concerned for their surrounding environments, which lead the Federal Government into the "Environmental Decade." Amendments to the Federal Water Pollution Control Act (became known as Clean Water Act) in 1972 and 1977 ultimately led to Section 404, which prohibits discharge of dredged or fill material into the waters of the United States, unless authorized by obtaining a site specific Section 404 permit through the Army Corps of Engineers (Weems and Canter 1995, Kelly 2001). After a series of court cases that expanded U.S. Army Corps of Engineers jurisdiction from "navigable waterways" to include adjacent wetlands, President Carter issued an Executive Order (11990) that made all federal agencies consider wetlands protection in their actions. The decade of 1970 made significant changes in environmental policy to minimize destruction, loss, and degradation of wetlands.

Environmental policy continued in the 1980s with the 1985 "Swamp buster" provision to the Food Security Act, which declared that anyone converting wetlands to agriculture would be denied agricultural loans, payments and benefits. Agriculture was a major cause of wetland loss prior to 1980, where the Clean Water Act Section 404 and the swamp buster provision helped alleviate this cause. However, the focus of environmental policy caused a shift from agriculture to suburban development as the major cause of wetland loss.

In conjunction with Clean Water Act Section 404, a wetland delineation manual was created by the U.S. Army Corps of Engineers to assist regulatory agencies define the wetland for permitting. Initially created by multiple agencies in 1987, it was unified 2 years later by the U.S.

Army Corps of Engineers for consistency. Even though the manual was significant revised to produce a second version, these changes have been removed and 1987 manual is still used today.

In 1986, President George W. Bush, Senior promised to achieve "no net loss of wetlands" after an outcry from wetlands conservation organization Ducks Unlimited (Searchinger 1992). This ultimately led to the North American Wetlands Conservation Act, signed in December of 1989, which provides funding to buy and protect wetlands throughout continental North America. Controversy existed with this Act because it was estimated that 75% of wetlands in the United States were located on private property (National Research Council 2001).

Implementation of mitigation programs from the No Net Loss policy has, ironically, resulted in the continued loss of natural wetlands on the premise that restored or created wetlands will replace the functions and values lost by destruction of natural wetlands because restored or created wetlands are very different from natural wetlands (Whigham 1999). This mitigation program is often criticized because of its focus on quantity and not quality; by not focusing on restoring the ecological processes associated with healthy wetlands but rather building areas of “wet” lands (i.e. golf course water hazards).

In light of effective and ineffective environmental policy aimed to protect our nation’s wetlands, significant efforts are now being implemented to restore healthy functioning ecosystems through collaborative resource management actions. Whigham (1999) concluded that the “failings of current wetland protection and mitigation policies are also due, in part, to the lack of ecologically sound wetland assessment methods for guiding decision making processes.” The Tidal Wetland Project (TWP) at Elkhorn Slough, California was created in 2004 to assemble key resource partners to improve the decision making process. TWP is a large collaborative stakeholder group comprised of over 100 coastal resource managers, scientific experts, regulatory and jurisdictional agencies, conservation organizations and public stakeholders to collectively determine conservation and restoration strategies at Elkhorn Slough.

The implementation of restoration projects requires a thorough understanding of not only the permitting and regulation process, but technical and political feasibility, funding needs, stakeholder interests and research gaps (ESTWP 2007). Restoration strategies are being evaluated using an ecosystem-based management approach. This thesis aims to fit into the ecosystem-based management by providing Elkhorn Slough with critically important long term geomorphic evaluation to not only complement the high resolution remote sensing mapping efforts to date, but to fill in the research gap on long term marsh plain elevation change.

2. 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.

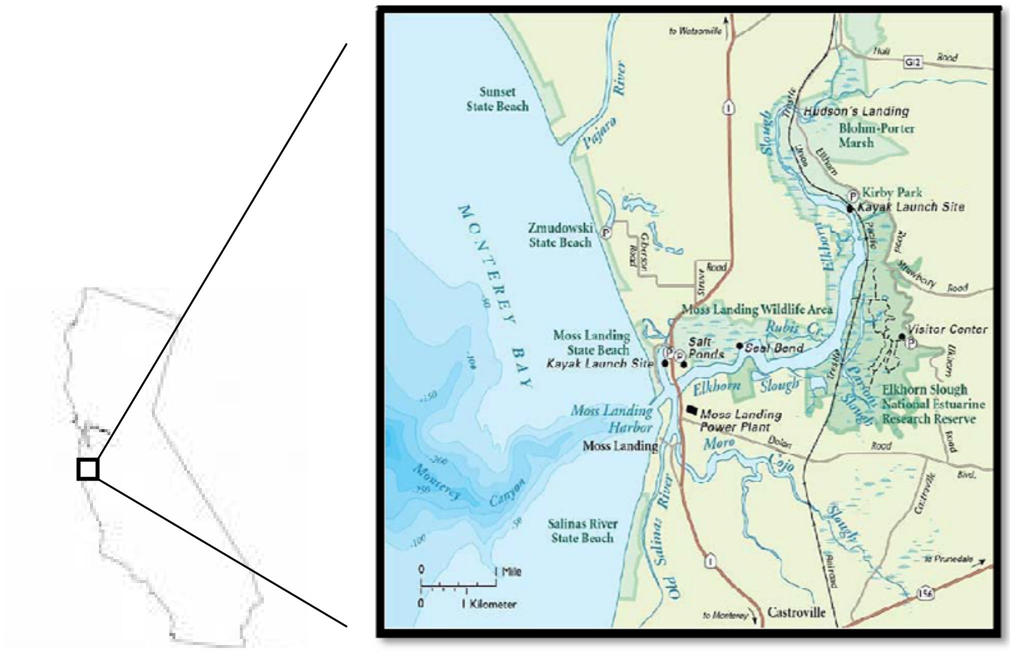


Figure 1 Study site location along the central coast of California.

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.

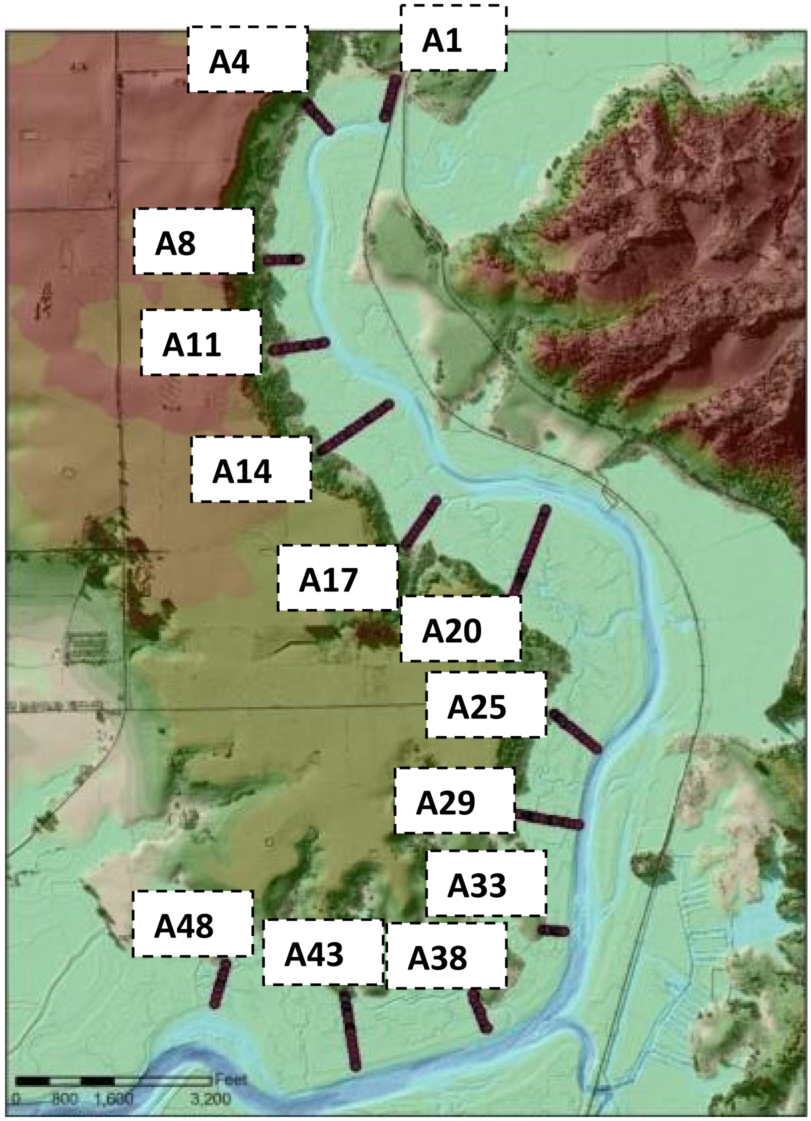


Figure 2 1980 cross section points and names plotted over 1m-resolution Digital Elevation Model (DEM) created by combining 2003 bathymetry from the Seafloor Mapping Lab and 2004 LiDAR from NOAA's Coastal Remote Sensing division, with funding from MBNMS SIMoN program. Notice spatial distribution of cross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

3. GOALS AND OBJECTIVES

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

4. 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.

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

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

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.

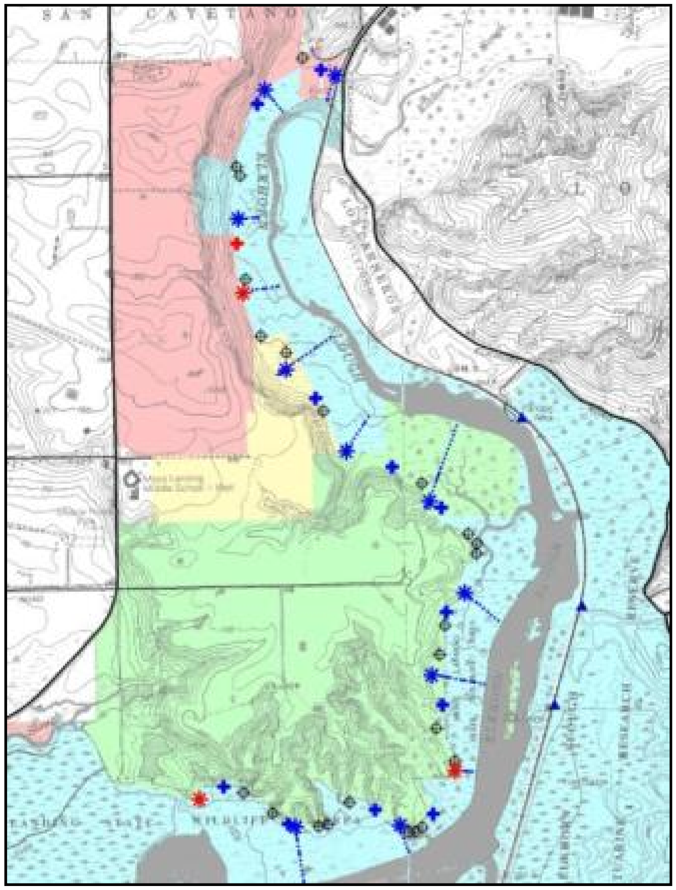


Figure 3 Cross section and backsight benchmark locations plotted over USGS topographic map with land ownership. "Asterisk" labels are cross section benchmarks and "Plus" labels correspond to backsight benchmarks. Blue points indicate benchmarks located by MidCoast Engineers, red points indicate disturbed 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.

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.

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:

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

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.

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.

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

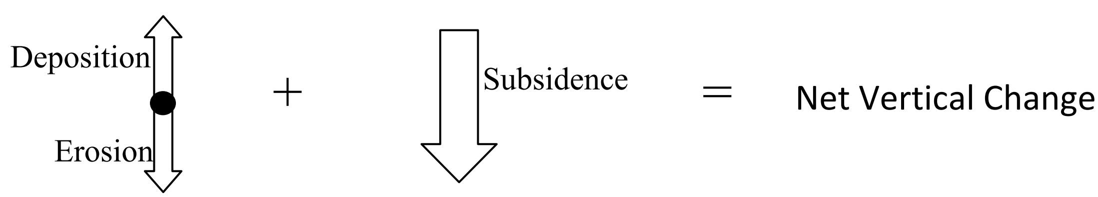
$$\Delta\text{BM} = \text{Dsub} + \text{Ssub} + \text{SLIP} \ \textbf{(Equation 2)}$$

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

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

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).

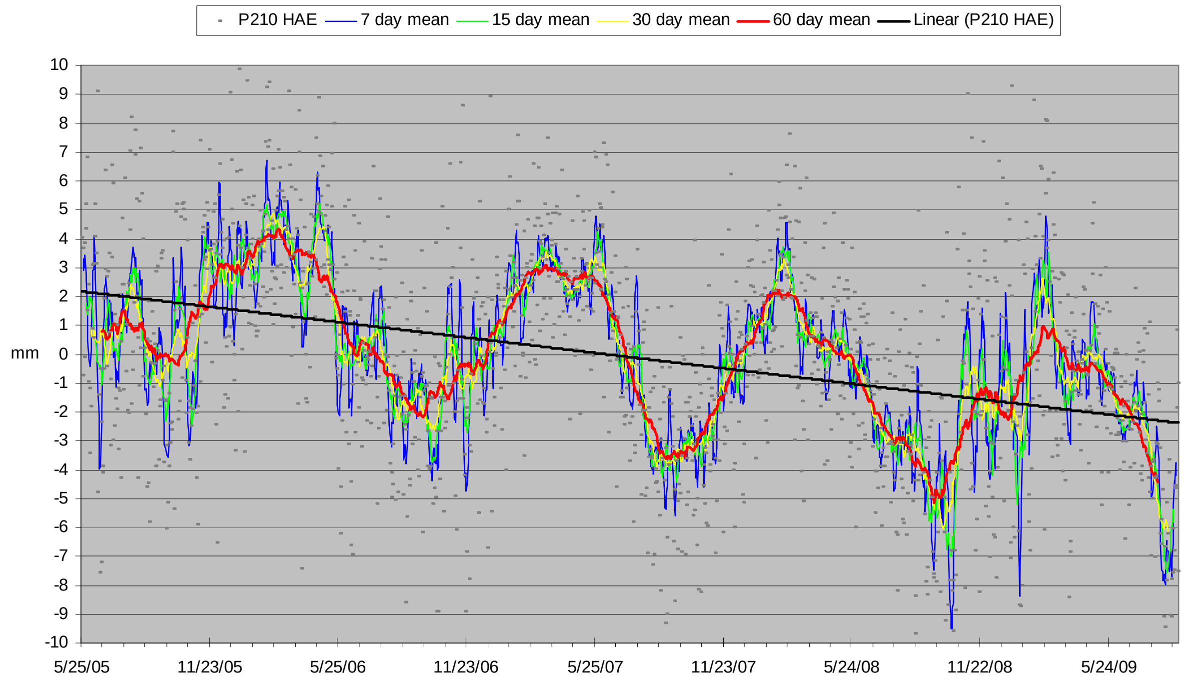


Figure 4 Averaged daily positions at Elkhorn Slough CORS since May 25, 2005. Average rate of 0.10 cm/yr was determined over the past four years.

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.

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:

> <u>Objective 1:</u> 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.

> <u>Objective 2:</u> 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.

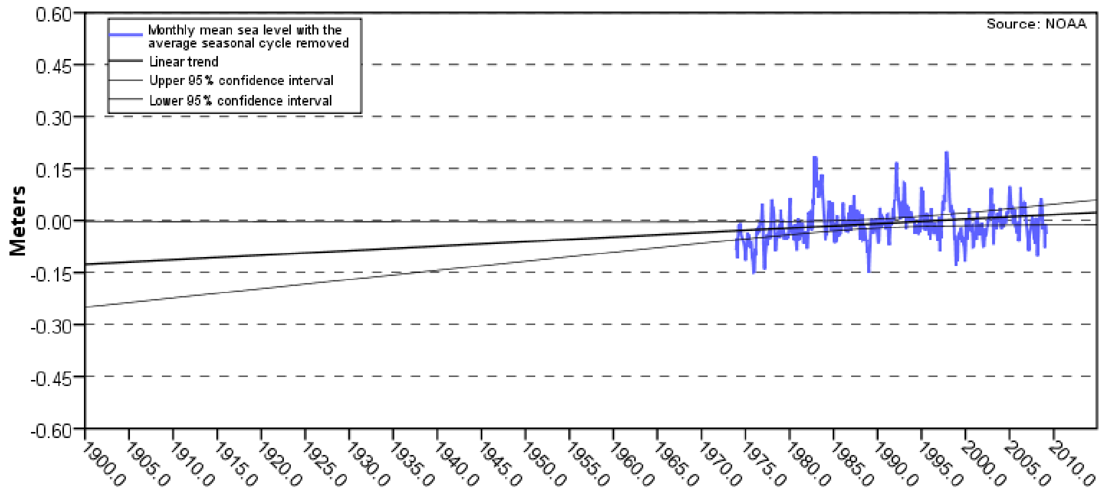


Figure 5 Mean sea level trend for Monterey, CA. Blue line is the monthly mean sea level with the average seasonal cycle removed. Solid black line is the linear trend of 0.134 cm/yr. Thinner solid lines represents the upper and lower 95% confidence intervals of +/- 0.135 cm/yr.

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.

5. 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.

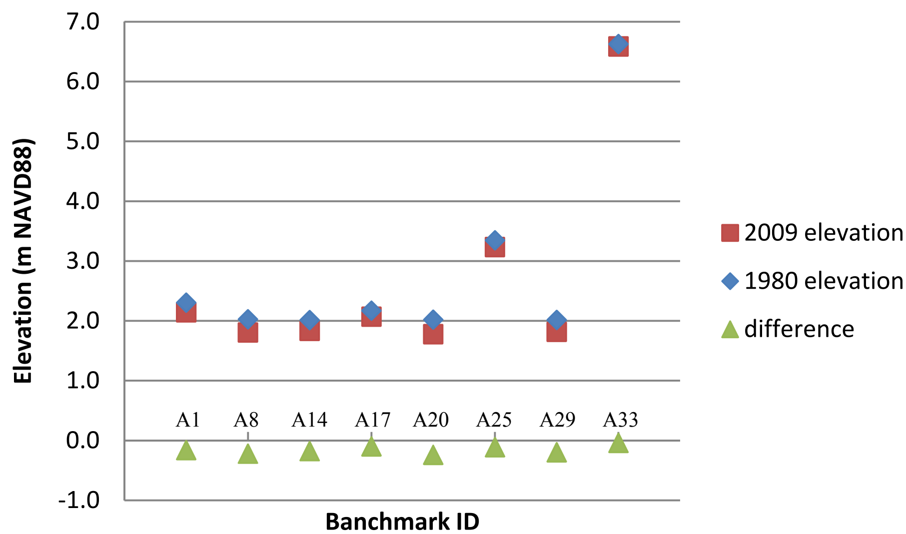


Figure 6. Absolute elevations of surveyed benchmarks compared to adjusted and converted 1980 elevations. Average benchmark elevation difference is -17.4 cm.

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.

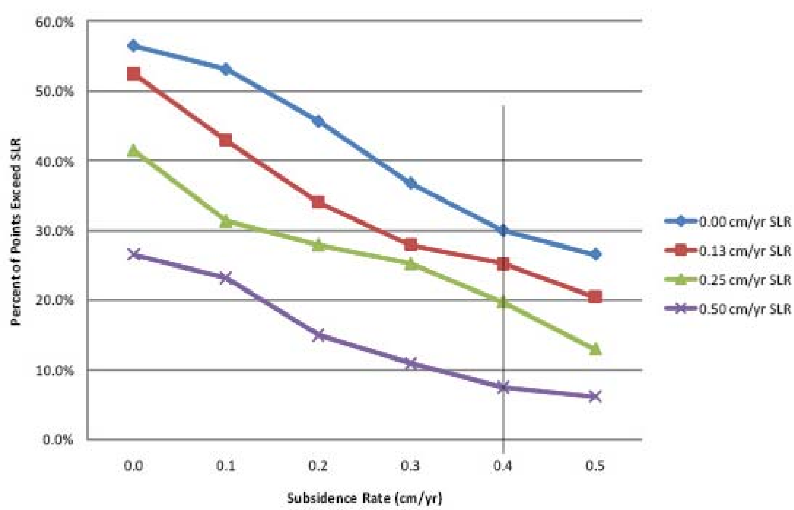


Figure 7 Sensitivity analysis using variable rates of sea level rise and subsidence on marsh plain inundation.

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.

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

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%

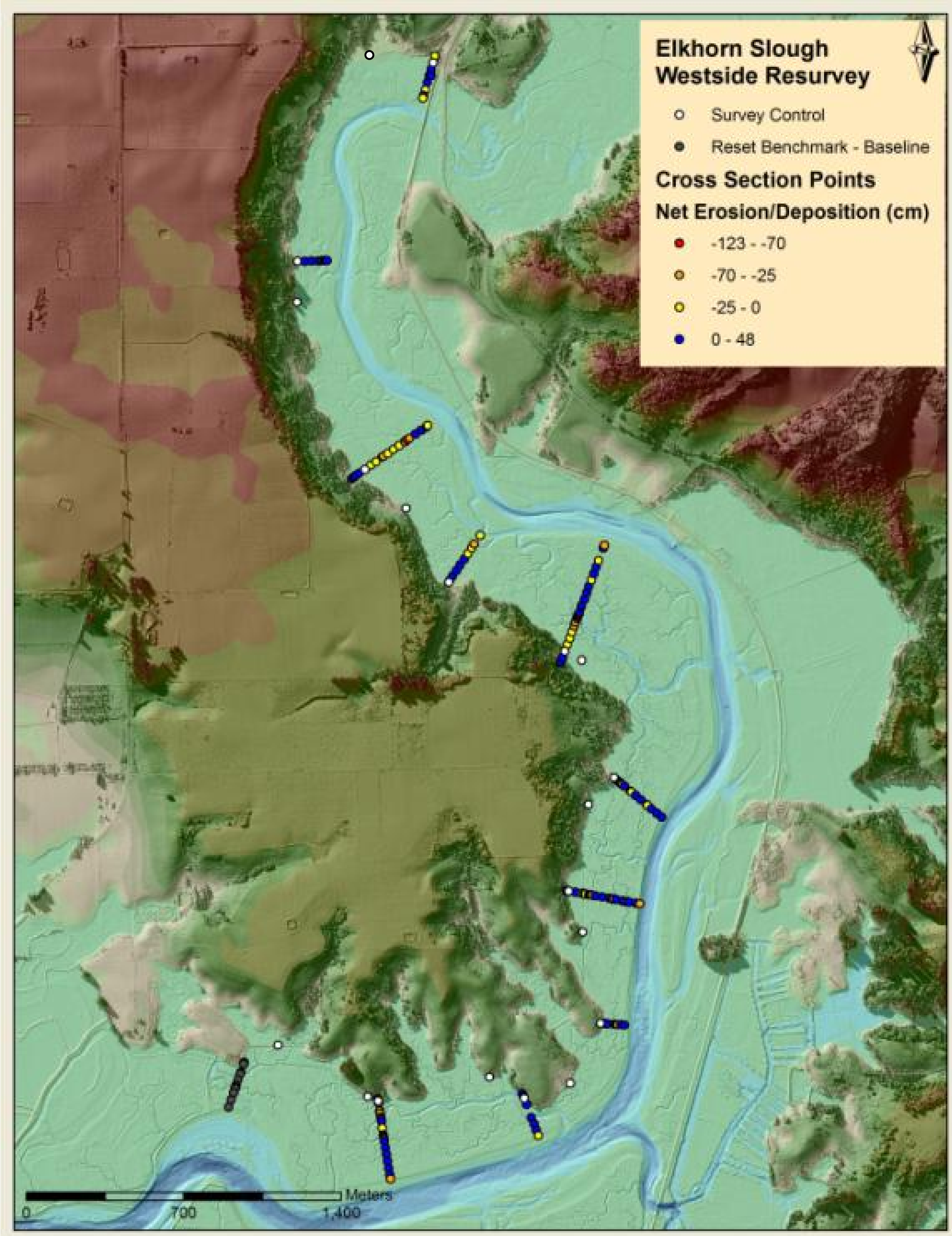


Figure 8 2009 cross section points plotted on 1m-resolution Digital Elevation Model (DEM) illustrating positive (+) and negative (-) net vertical change. Grayed out points indicate a cross section not comparable with 1980 due to a reset benchmark.

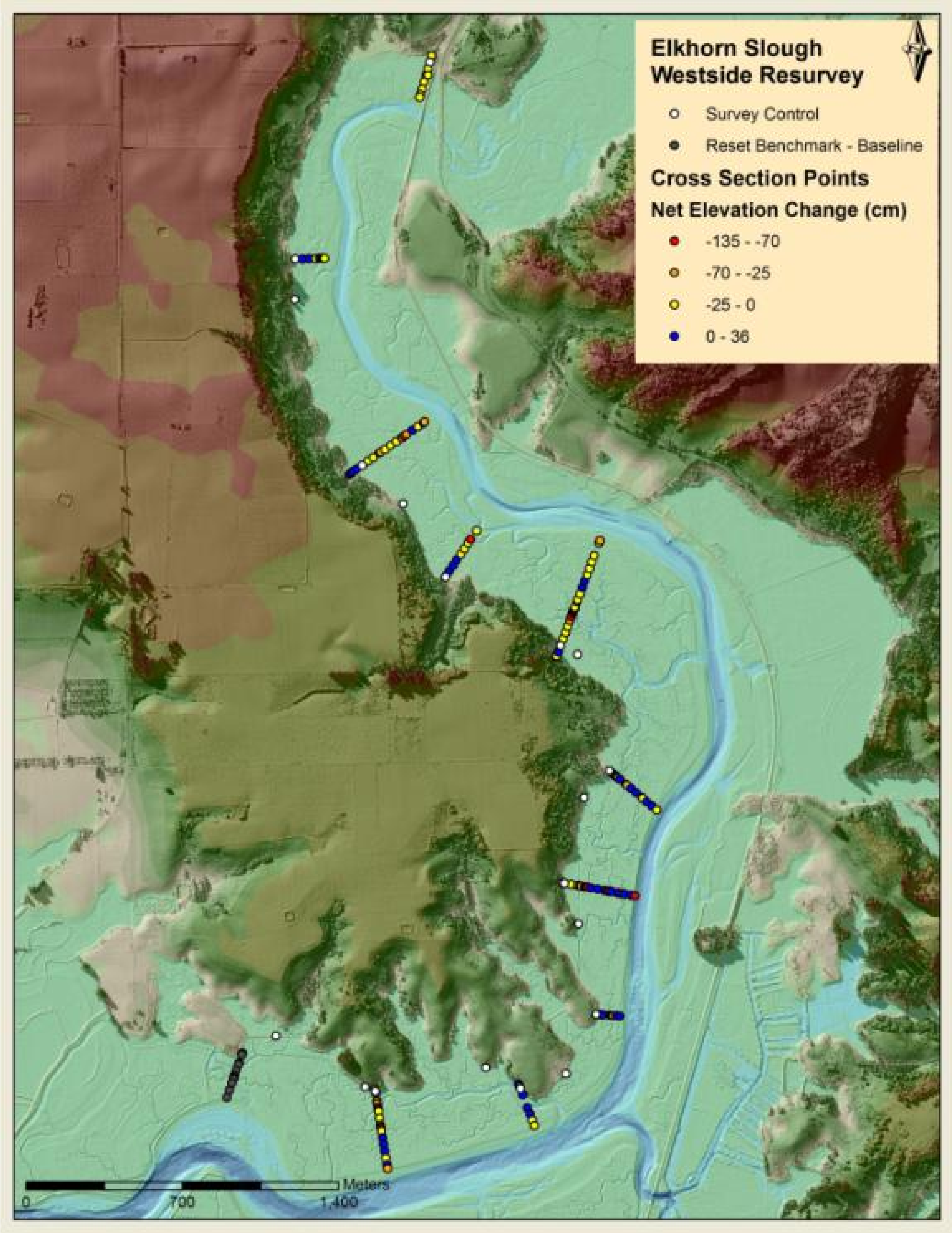


Figure 9 2009 cross section points plotted on 1m-resolution Digital Elevation Model (DEM) illustrating positive (+) and negative (-) net vertical change. Grayed out points indicate a cross section not comparable with 1980 due to a reset benchmark.

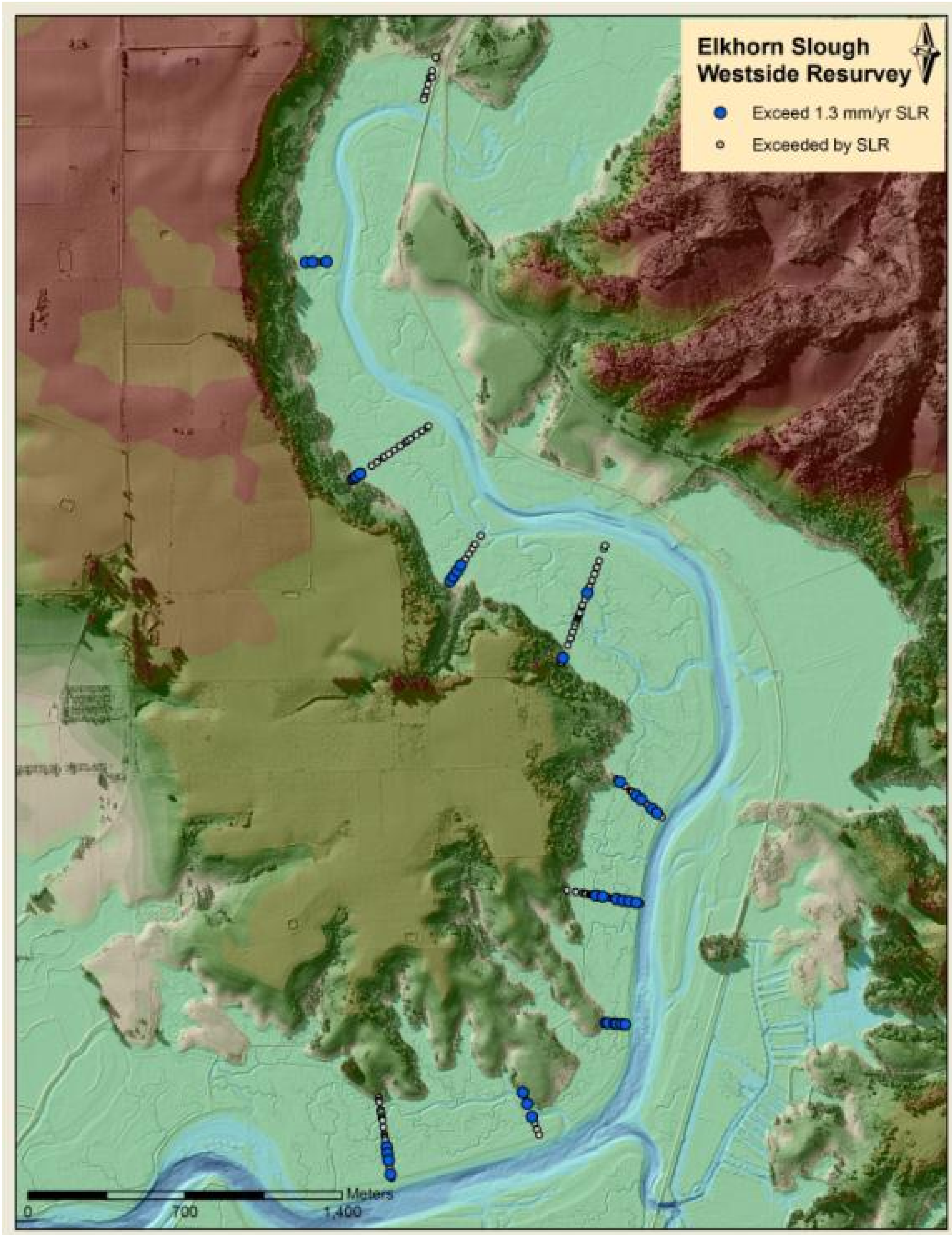


Figure 10 2009 cross section points plotted on 1m-resolution Digital Elevation Model (DEM) that have net vertical change rates that either exceed or not exceed the 0.13 cm/yr sea level rise scenario. Only 25% of surveyed points exceed 0.13 cm/yr.

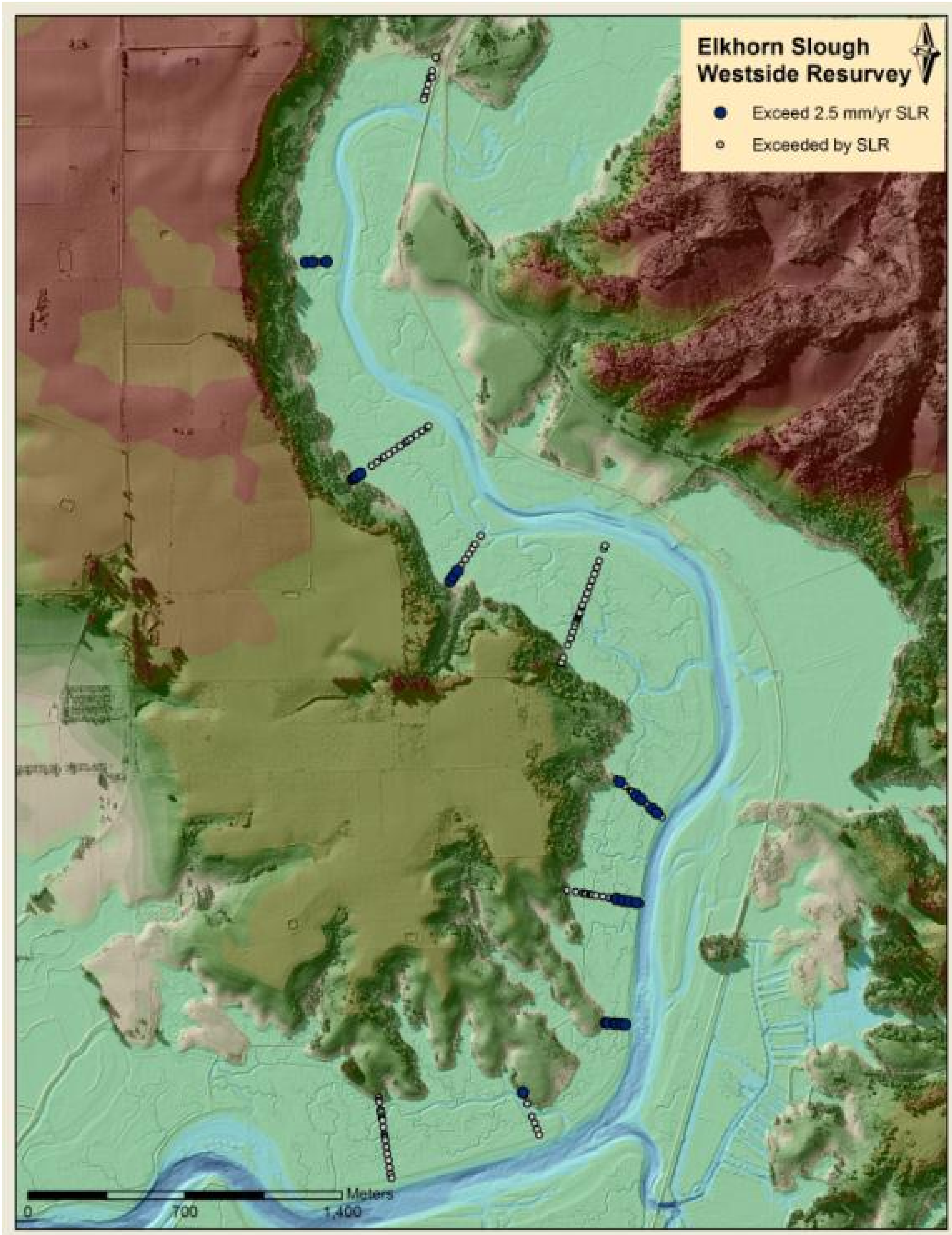


Figure 11 2009 cross section points plotted on 1m-resolution Digital Elevation Model (DEM) that have net vertical change rates that either exceed or not exceed the 0.25 cm/yr sea level rise scenario. Only 17% of surveyed points exceed 0.25 cm/yr.

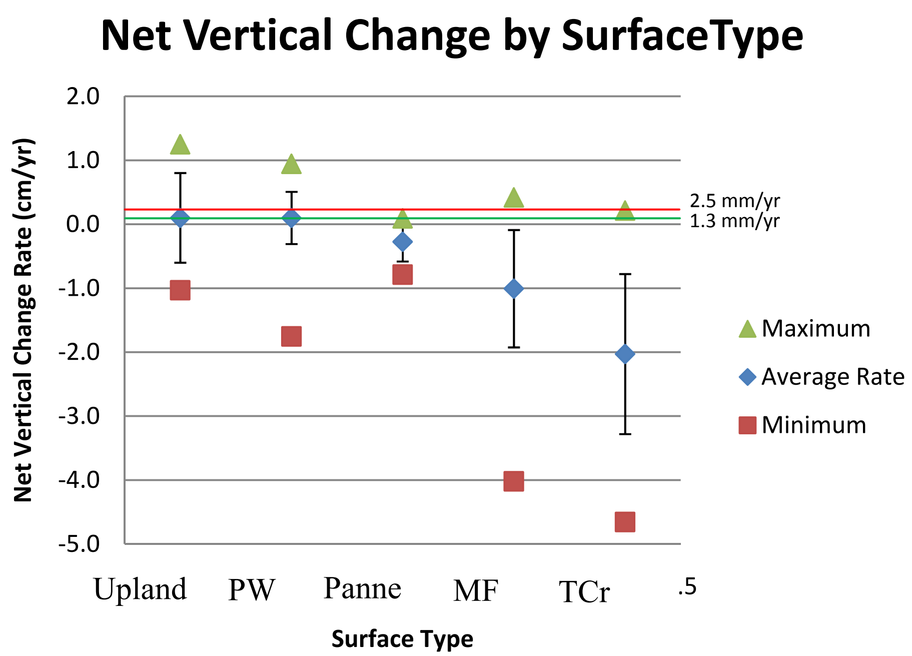


Figure 12 Average rates of net vertical change per 2009 surface type category. Blue diamonds represent the mean rate and the upper/lower limits are plus/minus the standard deviation. Maximum and minimum values plotted in green triangles and red squares, respectively. Surface type categories become less 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.

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

	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 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.

		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

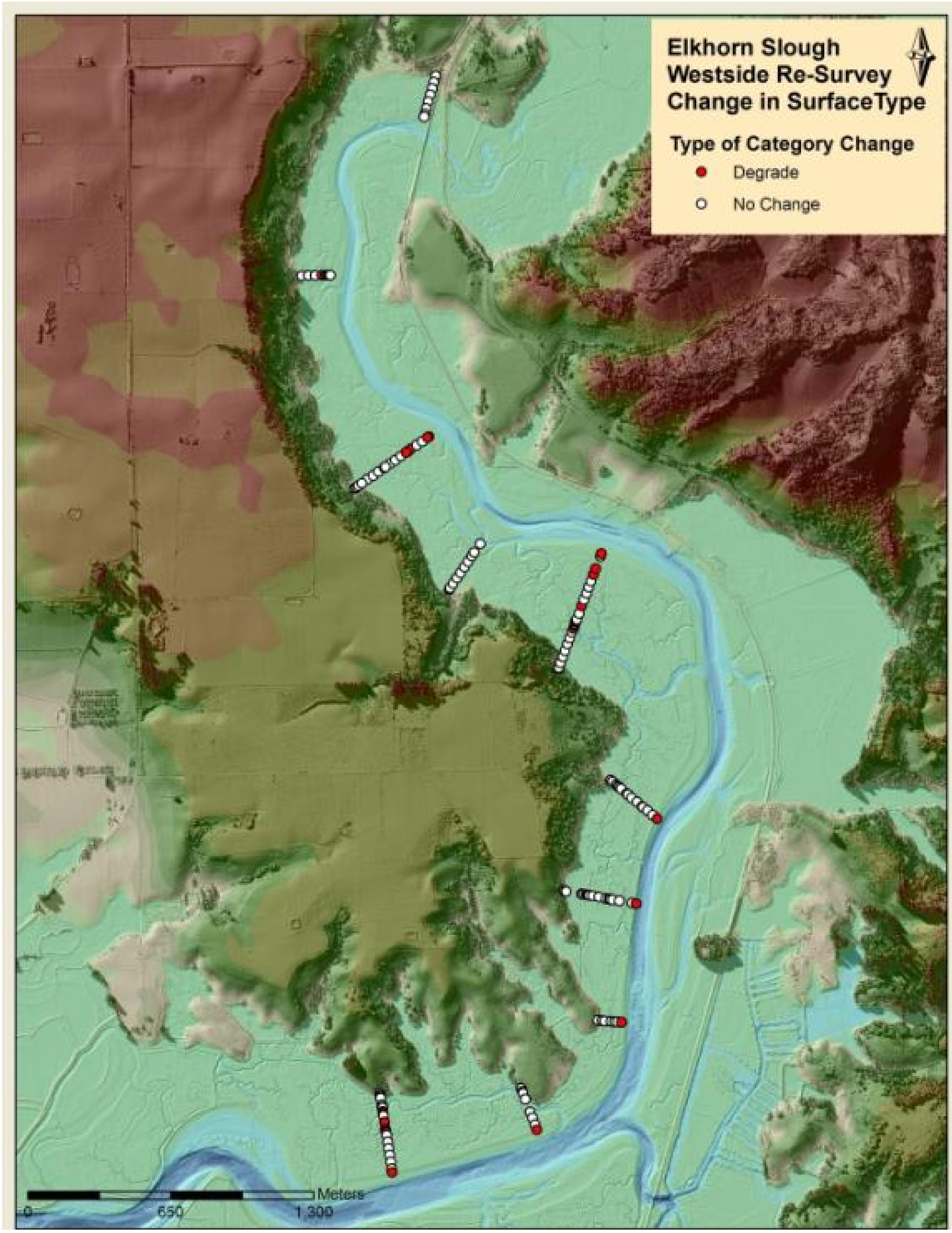


Figure 13 Distribution of "degradational" changes in surface type between surveys. "Degradational" changes would be surface types that shift from left to right in Figure 12.

6. 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.

7. 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.

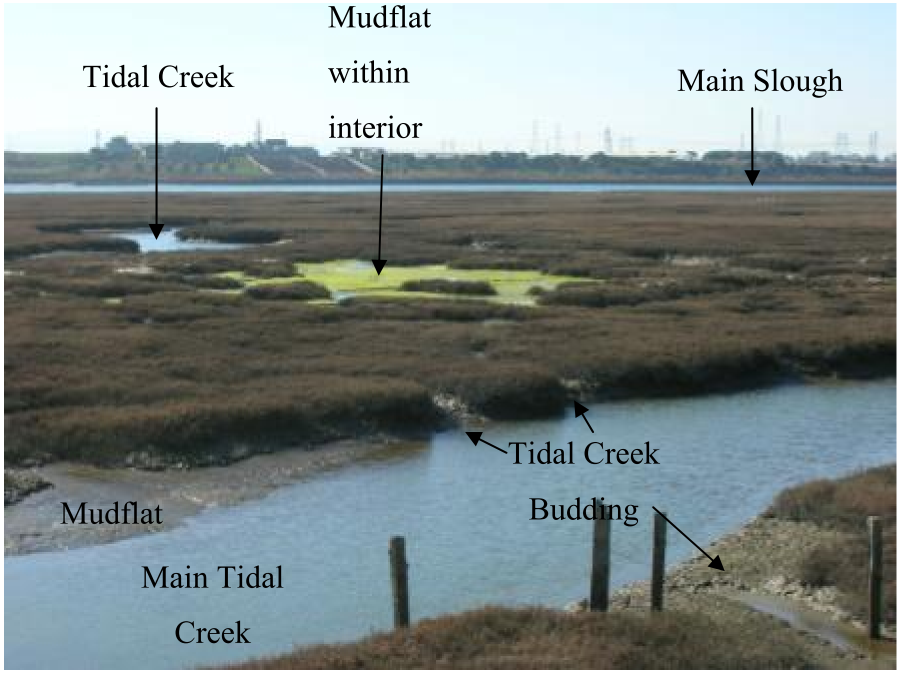


Figure 15 Cross section A43 looking south from the upland.

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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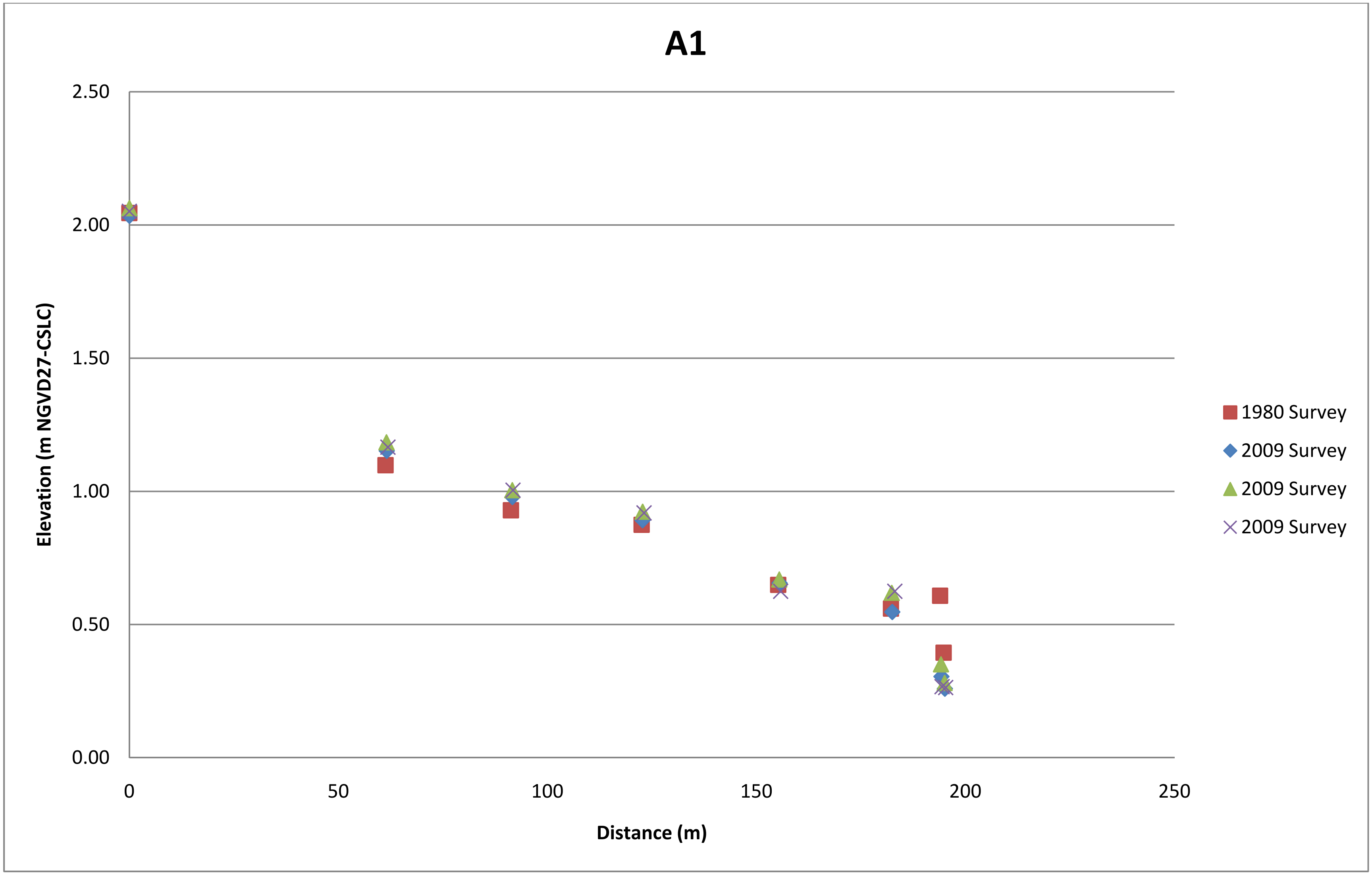
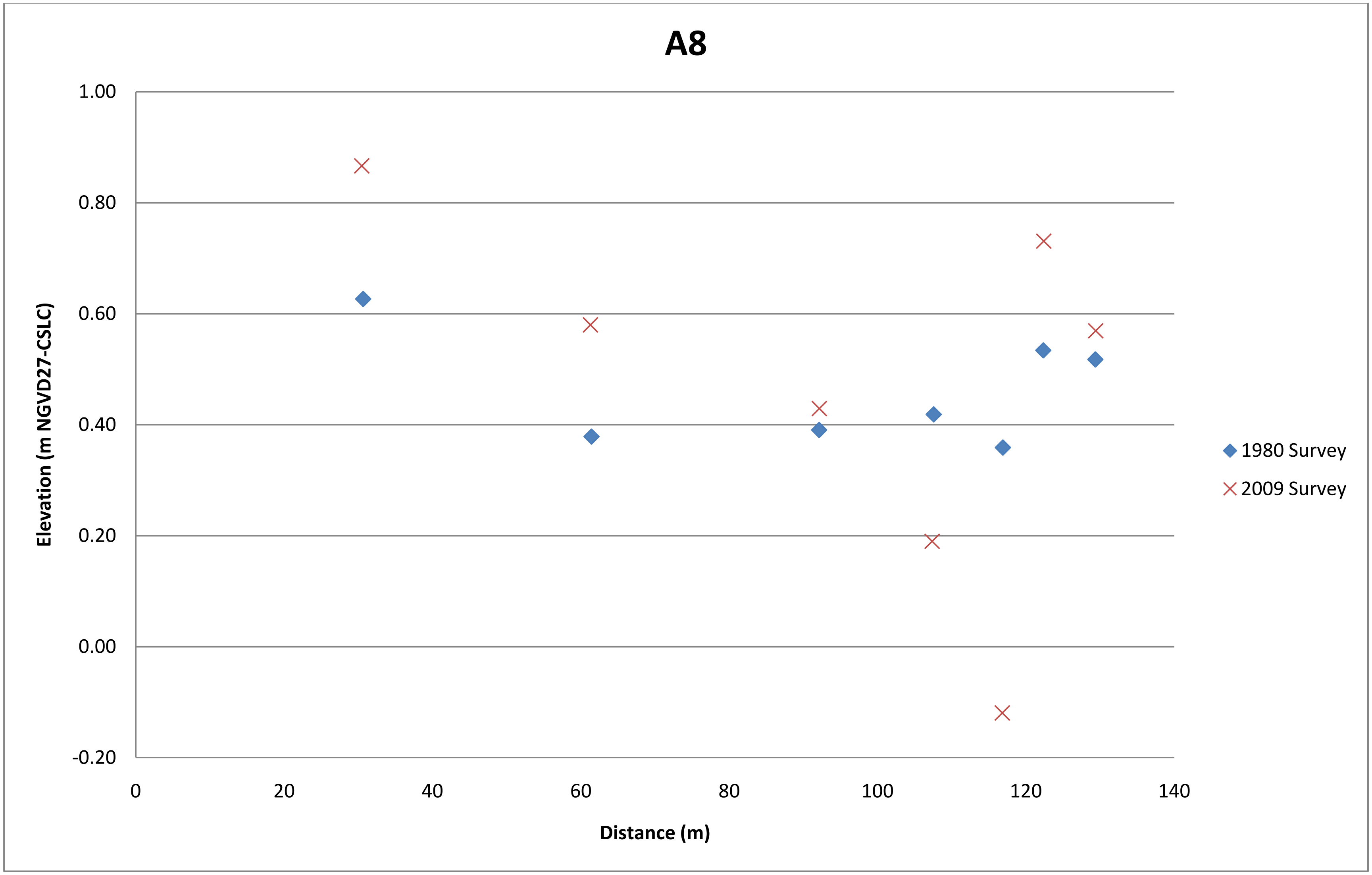
APPENDIX A

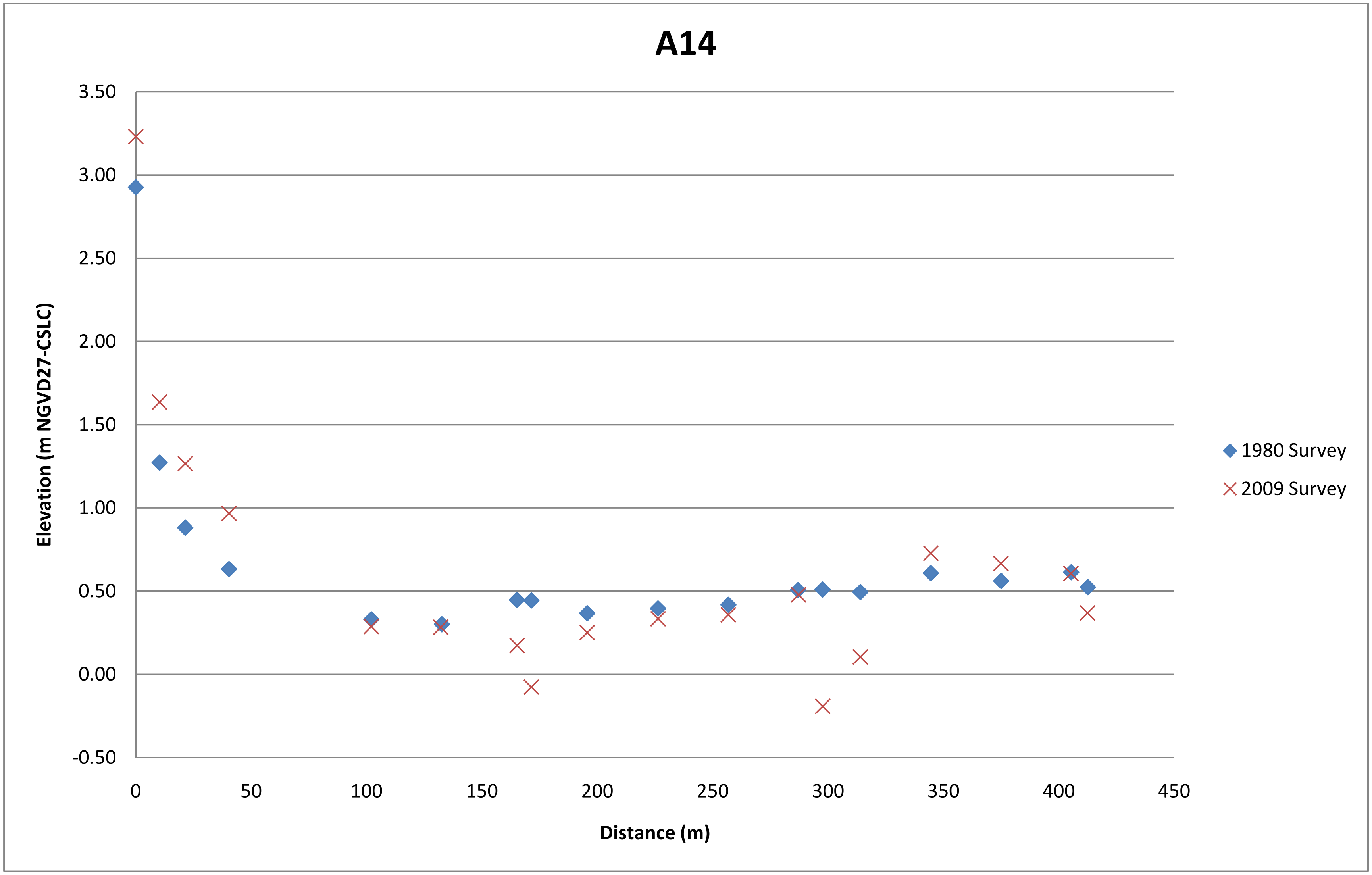
CROSS SECTIONAL PLOTS ILLUSTRATING 1980 AND 2009 ELEVATIONS



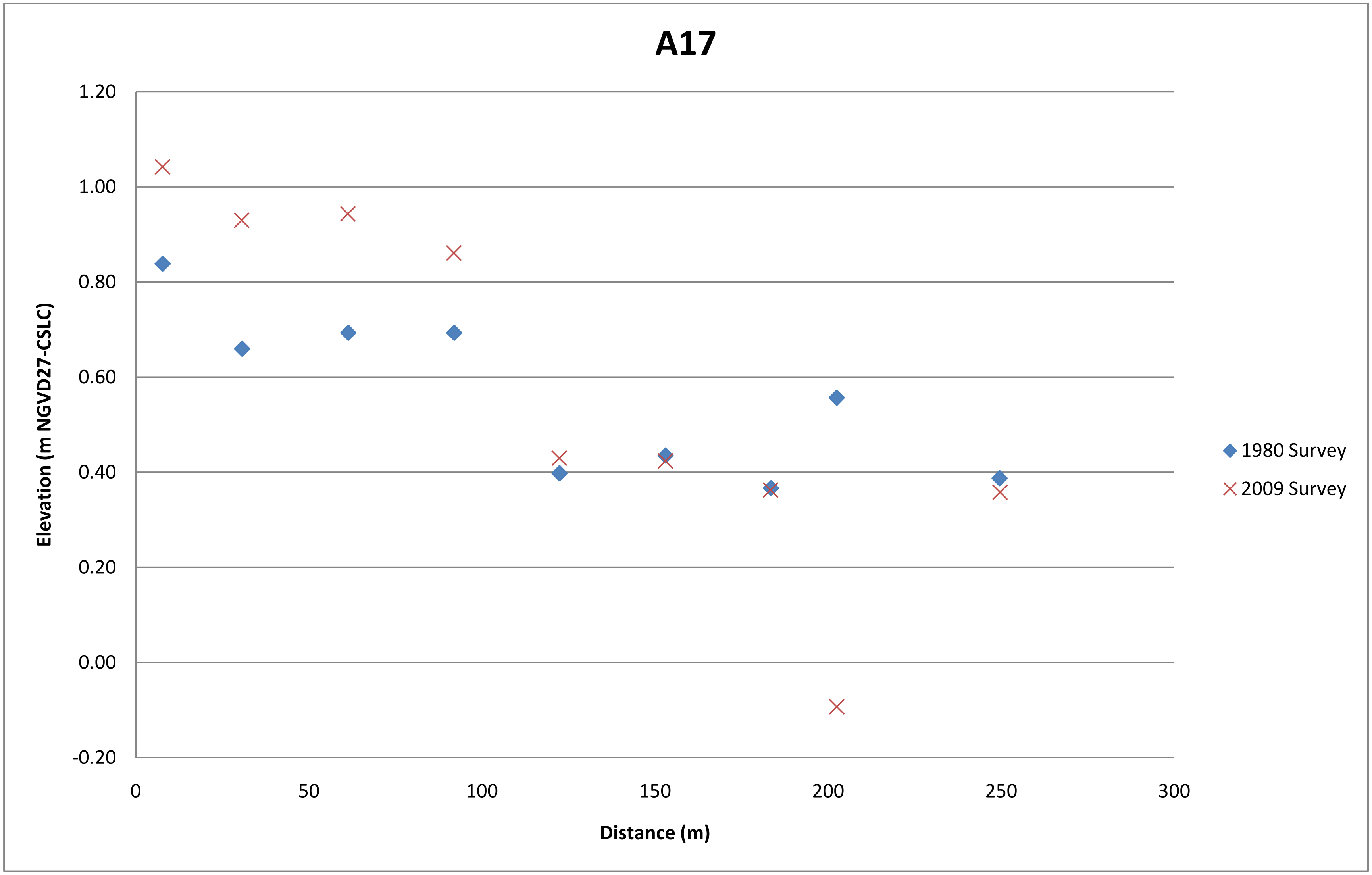
Appendix A – Cross Section Plots illustrating 1980 and 2009 elevations



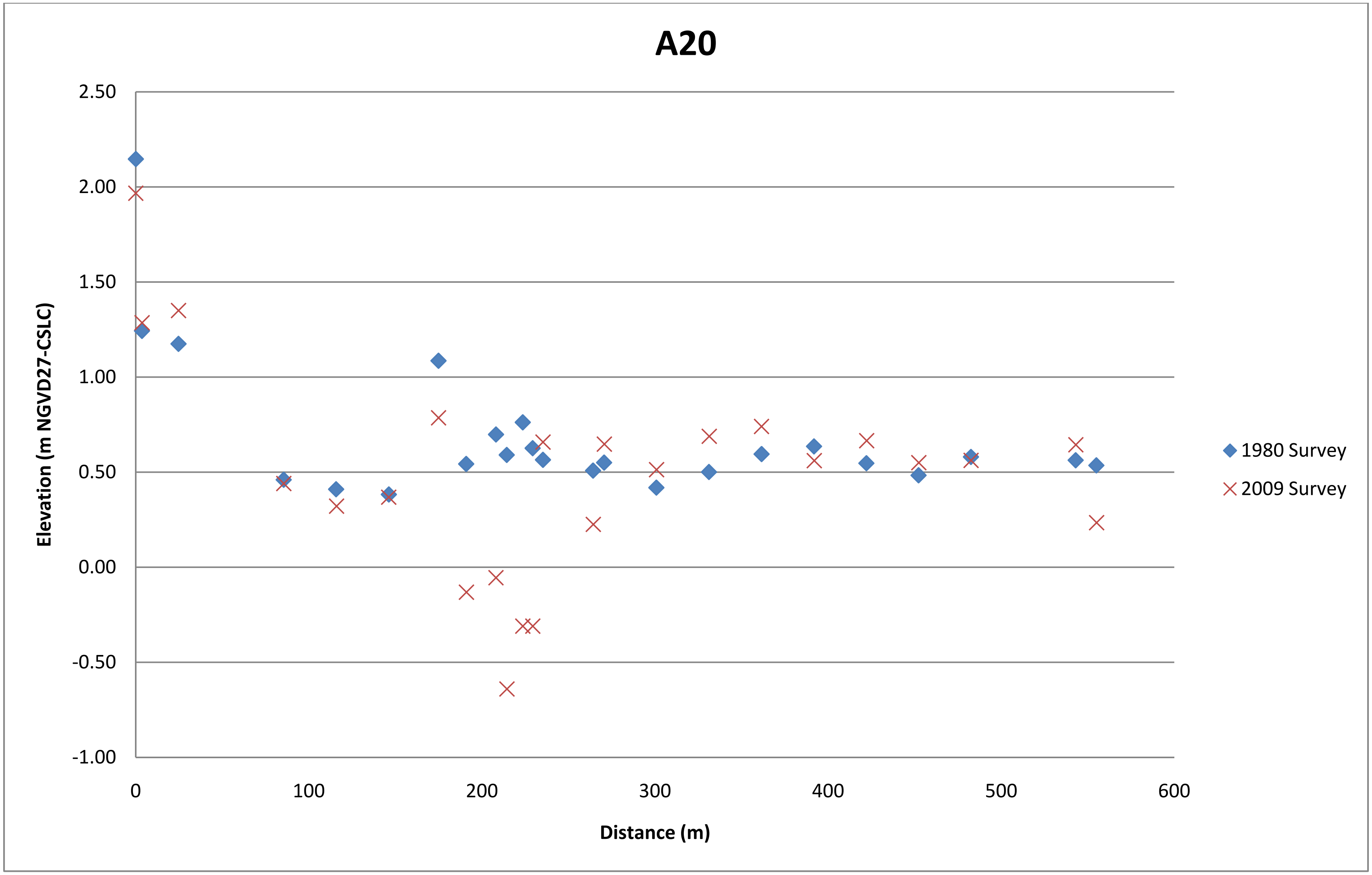
Appendix A – Cross Section Plots illustrating 1980 and 2009 elevations



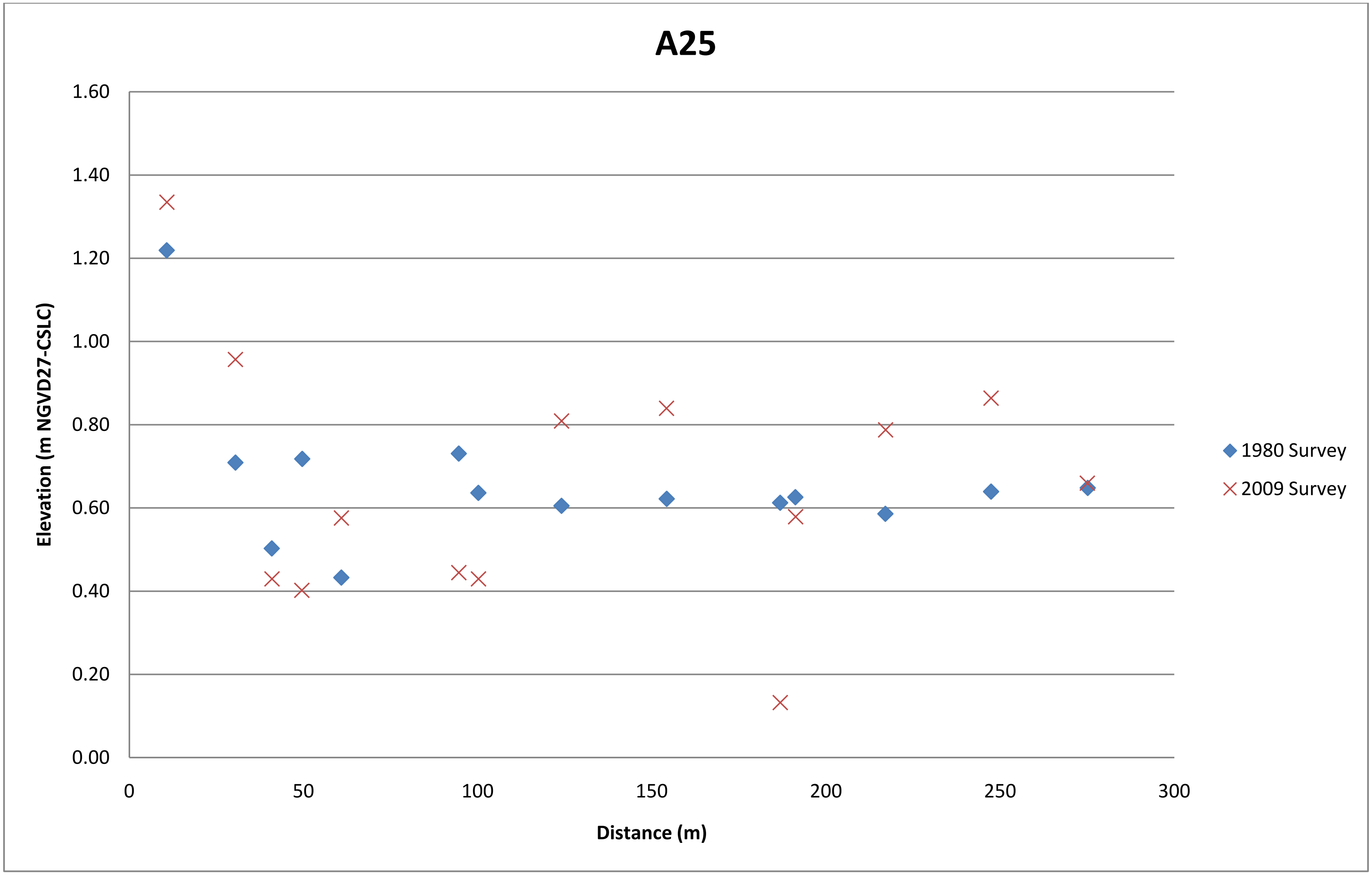
Appendix A – Cross Section Plots illustrating 1980 and 2009 elevations



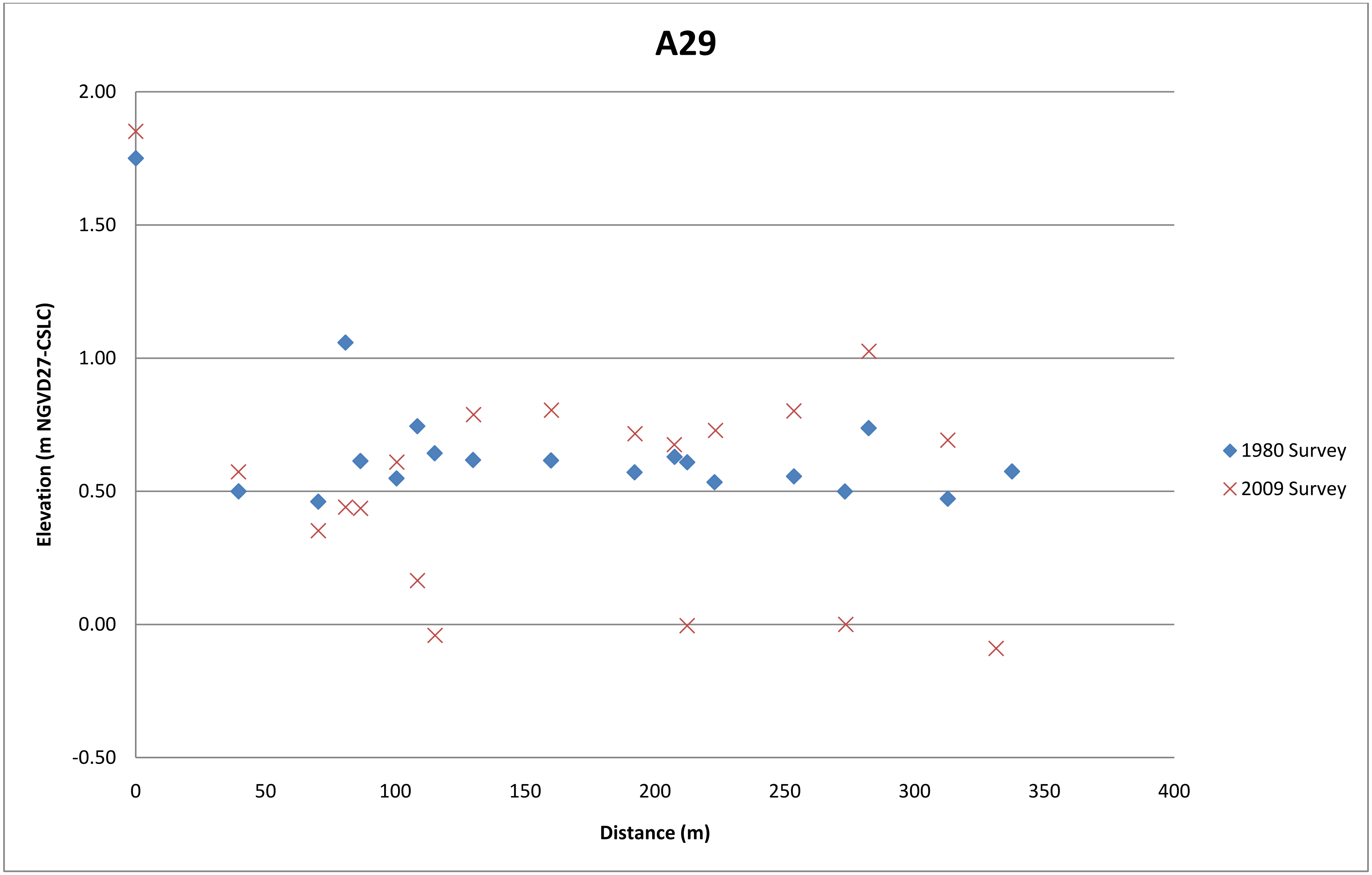
Appendix A – Cross Section Plots illustrating 1980 and 2009 elevations



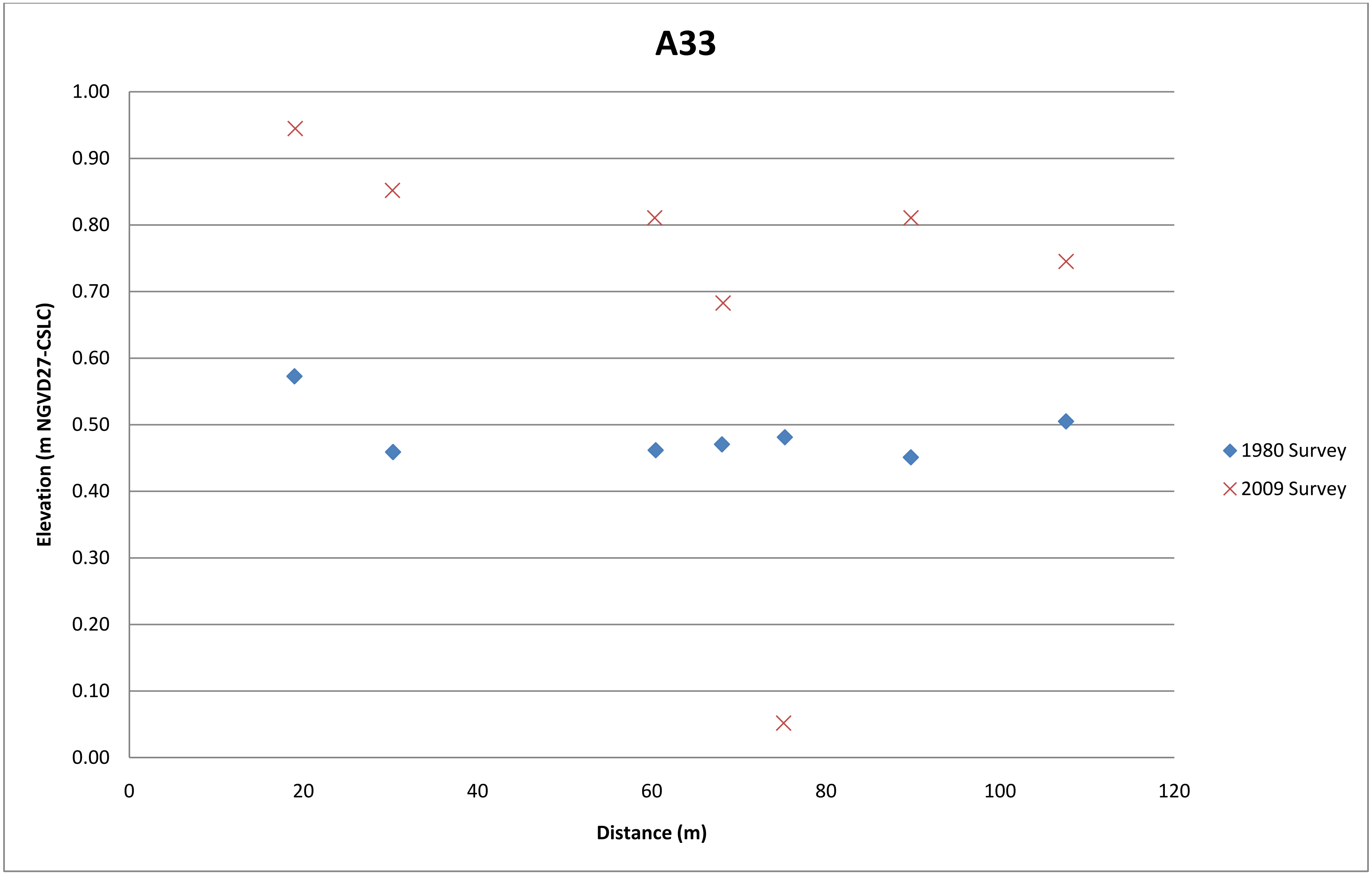
Appendix A – Cross Section Plots illustrating 1980 and 2009 elevations



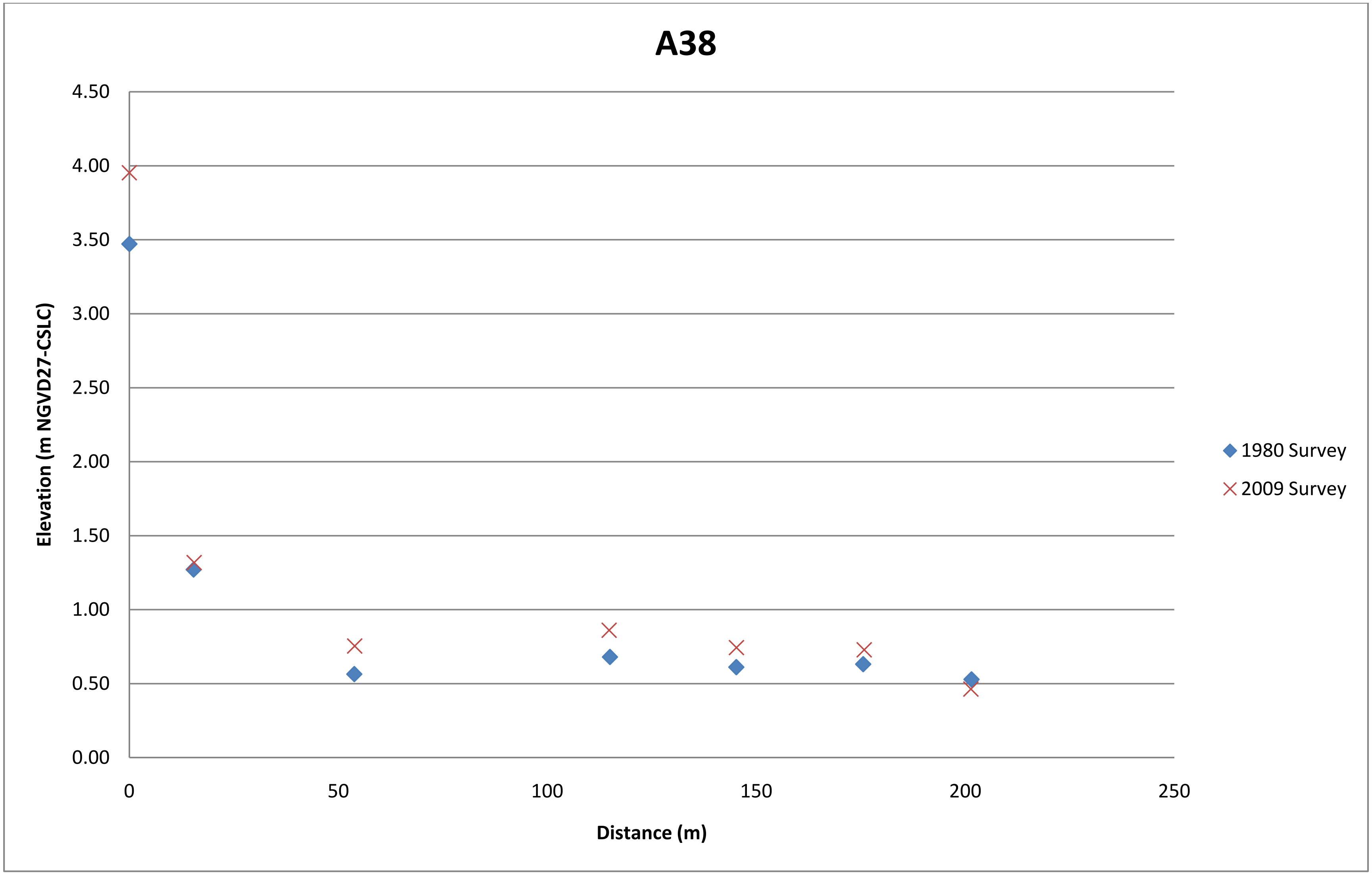
Appendix A – Cross Section Plots illustrating 1980 and 2009 elevations



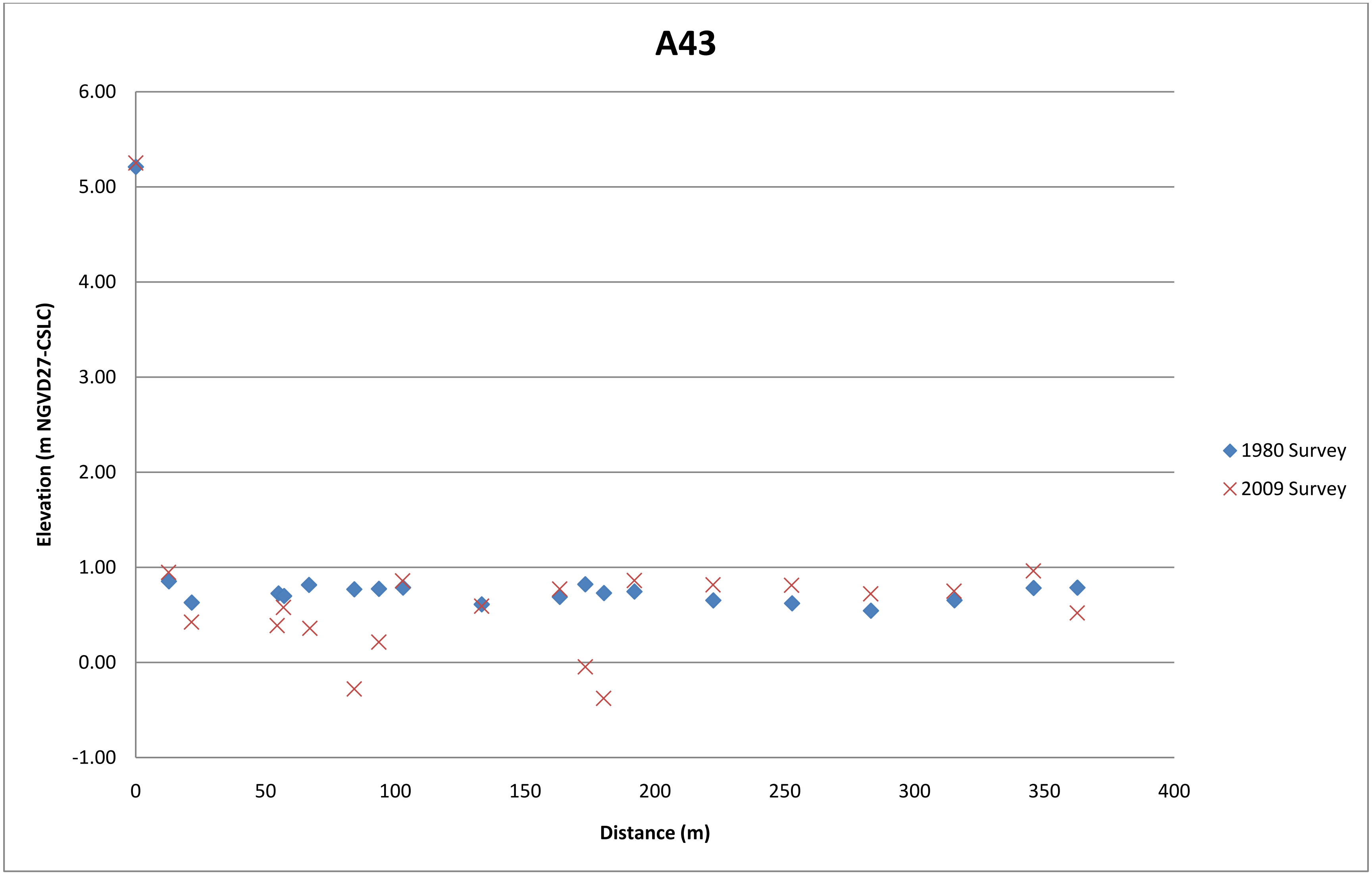
Appendix A – Cross Section Plots illustrating 1980 and 2009 elevations



Appendix A – Cross Section Plots illustrating 1980 and 2009 elevations



Appendix A – Cross Section Plots illustrating 1980 and 2009 elevations



Appendix A – Cross Section Plots illustrating 1980 and 2009 elevations

APPENDIX B

1980 AND 2009 SURVEY DATA

DEFINITIONS:

Sdist – Slope Distance

Hdist – Horizontal Distance

Vangle – Vertical Angle

Dec Deg – Vertical Angle in Decimal Degrees

Vdist – Vertical Distance relative to benchmark height

Z – Elevation based upon benchmark elevation and vertical distance (for table as shown: NAVD88)

Zdiff – elevation difference between 1980 and 2009

Graph Dist – distance used to plot data points using the most upland shot as 0, rather than positive or negative distance from the benchmark

12/12/2008 Topcon GPT-3002W

Brian Spear, Douglas Smith, Eric Van Dyke

1980 Survey				2009 Survey					RESULTS		
Sdist (ft)	Vdist (ft)	Z (ft)	Description	Sdist (ft)	Hdist (m)	Z (ft)	Vdist (ft)	Description	Z Diff (ft)	Z Diff (cm)	Graph dist (m)
-101.24	2.10	9.66	Upland	-102.190	-31.135	9.624	2.065	Upland	-0.035	2.3	0.000
A1		7.559	A1 Station	0.000	0.000	7.559	0.000	A1 Station			31.135
99.80	-1.01	6.55	PW	99.785	30.417	6.729	-0.830	PW	0.177	8.8	61.552
198.19	-1.56	6.00	PW	198.410	60.480	6.159	-1.400	PW	0.162	8.3	91.614
300.78	-1.74	5.82	PW	300.565	91.606	5.874	-1.685	PW	0.056	5.1	122.741
408.01	-2.48	5.08	PW	408.110	124.389	5.099	-2.460	EOPW	0.021	4.0	155.524
496.47	-2.77	4.79	PW	496.550	151.349	4.744	-2.815	PW	-0.042	2.1	182.484
535.05	-2.62	4.94	EOPW	535.100	163.090	3.949	-3.610	MF	-0.995	-26.9	194.224
537.80	-3.32	4.24	EOW	537.840	163.924	3.799	-3.760	MF	-0.444	-10.1	195.059
A2								0set			
					OPEN	4.890					
					CLOSE	4.915					

12/20/2008 Topcon GPT-3002W

Brian Spear and Laura Albrecht

1980 Survey				2009 Survey					RESULTS		
Sdist (ft)	Vdist (ft)	Z (ft)	Description	Sdist (ft)	Hdist (m)	Z (ft)	Vdist (ft)	Description	Z Diff (ft)	Z Diff (cm)	Graph dist (m)
-101.24	2.10	9.66	Upland	-102.145	-31.118	9.719	2.160	Upland	0.060	1.8	0.000
A1	0.00	7.559	A1 Station	0.000	0.000	7.559	0.000	A1 Station			31.118
99.80	-1.01	6.55	PW	99.650	30.385	6.834	-0.725	PW	0.282	8.6	61.503
198.19	-1.56	6.00	PW	198.380	60.462	6.244	-1.315	PW	0.247	7.5	91.581
300.78	-1.74	5.82	PW	300.695	91.649	5.979	-1.580	PW	0.161	4.9	122.768
408.01	-2.48	5.08	PW	407.955	124.347	5.144	-2.415	EOPW	0.066	2.0	155.465
496.47	-2.77	4.79	PW	496.210	151.245	4.979	-2.580	PW	0.193	5.9	182.363
535.05	-2.62	4.94	EOPW	534.885	163.033	4.099	-3.460	MF	-0.845	-25.8	194.152
537.80	-3.32	4.24	EOW	537.740	163.900	3.869	-3.690	MF	-0.374	-11.4	195.018
A2								0set			
					OPEN	4.920					
					CLOSE	4.930					

1/18/2009 Topcon GPT-3002W

Brian Spear and Jonathan Frame

1980 Survey				2009 Survey					RESULTS		
Sdist (ft)	Vdist (ft)	Z (ft)	Description	Sdist (ft)	Hdist (m)	Z (ft)	Vdist (ft)	Description	Z Diff (ft)	Z Diff (cm)	Graph dist (m)
-101.24	2.10	9.66	Upland	-102.895	-31.348	9.865	2.306	Upland	0.000	0.0	0.000
A1	0.00	7.559	A1 Station	0.000	0.000	7.559	0.000	A1 Station			31.348
99.80	-1.01	6.55	PW	100.070	30.466	6.774	-0.785	PW	-7.337	-223.6	61.814
198.19	-1.56	6.00	PW	198.195	58.199	6.244	-1.315	PW	-7.312	-222.9	89.547
300.78	-1.74	5.82	PW	301.030	91.758	5.964	-1.595	PW	-7.413	-225.9	123.106
408.01	-2.48	5.08	PW	408.275	124.442	4.999	-2.560	MF	-7.638	-232.8	155.790
496.47	-2.77	4.79	PW	497.860	151.739	4.999	-2.560	MF/PW	-7.346	-223.9	183.087
535.05	-2.62	4.94	EOPW	534.945	163.050	3.824	-3.735	MF	-8.679	-264.5	194.398
537.80	-3.32	4.24	EOW	537.800	163.916	3.814	-3.745	MF	-7.988	-243.5	195.264
A2								0set			
					OPEN	4.905					
					CLOSE	4.915					

Benchmark Elevations

1980	7.559	ft NAVD88
2009	7.028	ft NAVD88

4/22/2009 ~ TOPCON GTS-211D

Brian Spear, Ron Eby

1980 Survey							2009 Survey									RESULTS		
Sdist (ft)	Hdist (ft)	Hdist (m)	Vdist (ft)	Z (ft)	Z (m)	Description	Sdist (ft)	Hdist (ft)	Hdist (m)	Vangle	Dec Deg	Vdist (ft)	Z (ft)	Z (m)	Description	Z Diff (ft)	Z Diff (cm)	Graph Dist (m)
-84.19	-84.009	-25.606	5.516	11.986	3.653	Upland				Too Overgrown					Upland			
A8				6.470	1.972	Toe							6.470	1.972	A8 BM			
100.59	100.577	30.656	-1.642	4.828	1.472	PW	99.950	99.946	30.464	3.770	90.490	-0.855	5.615	1.711	PW	0.787	24.0	30.5
201.57	201.555	61.434	-2.456	4.014	1.223	MF	201.085	201.077	61.288	3.771	90.511	-1.795	4.675	1.425	MF/panne	0.661	20.1	61.3
302.23	302.220	92.117	-2.417	4.053	1.235	TCr	302.345	302.336	92.152	3.768	90.434	-2.290	4.180	1.274	MF/panne	0.127	3.9	92.2
352.92	352.912	107.568	-2.325	4.145	1.263	EOTCr	352.210	352.197	107.350	3.771	90.501	-3.075	3.395	1.035	MF/panne	-0.750	-22.9	107.3
383.51	383.502	116.891	-2.521	3.949	1.204	EOTCr	383.210	383.188	116.796	3.775	90.612	-4.090	2.380	0.725	TCr	-1.569	-47.8	116.8
401.39	401.385	122.342	-1.946	4.524	1.379	PW	401.600	401.598	122.407	3.758	90.186	-1.300	5.170	1.576	PW	0.646	19.7	122.4
424.41	424.405	129.359	-2.000	4.470	1.362	EOPW	424.545	424.541	129.400	3.760	90.248	-1.830	4.640	1.414	PW	0.170	5.2	129.4
A9															0set			

Benchmark Elevations

1980	6.470	ft NAVD88
2009	5.920	ft NAVD88

OPEN	99.950	90:29:25	90.490	-0.855
CLOSE	99.890	90:28:12	90.470	-0.820
				0.035 ft

*** BS reset by MidCoast Engineers in Winter 2008

4/23/2009 ~ TOPCON GTS-211D

Brian Spear, Ron Eby

1980 Survey					2009 Survey								RESULTS		
Hdist (ft)	Vdist (ft)	Z (ft)	Z (m)	Description	Hdist (ft)	Hdist (m)	Vangle	Dec Deg	Vdist (ft)	Z(ft)	Z (m)	Description	Z Diff (ft)	Z Diff (cm)	Graph Dist (m)
-233.32	5.950	12.367	3.770	Upland	-233.305	-71.111	88:17:40	88.294	6.950	13.367	4.074	Upland	1.000	30.5	0.000
-199.53	0.524	6.941	2.116	upland	-199.525	-60.815	89:30:31	89.509	1.715	8.132	2.479	thule grass mat	1.191	36.3	10.296
-163.06	-0.759	5.658	1.725	Toe	-162.865	-49.641	89:49:20	89.822	0.505	6.922	2.110	thule grass mat	1.264	38.5	21.470
-100.84	-1.574	4.843	1.476	PW	-100.655	-30.680	98:16:17	98.271	-0.475	5.942	1.811	PW	1.099	33.5	40.432
A14		6.417	1.956	Levee						6.417	1.956	A14 BM			
101.51	-2.565	3.852	1.174		101.600	30.968	268:28:27	268.474	-2.705	3.712	1.132	MF	-0.140	-4.3	102.079
201.78	-2.663	3.754	1.144		200.215	61.026	269:13:19	269.222	-2.720	3.697	1.127	MF	-0.057	-1.7	132.137
308.47	-2.181	4.236	1.291	EOTCr	308.885	94.148	269:25:41	269.428	-3.080	3.337	1.017	TCr eob	-0.899	-27.4	165.260
329.06	-2.192	4.225	1.288	EOTCr	328.915	100.253	269:19:13	269.320	-3.900	2.517	0.767	TCr	-1.708	-52.1	171.365
408.38	-2.445	3.972	1.211		408.535	124.521	269:36:12	269.603	-2.825	3.592	1.095	MF	-0.380	-11.6	195.633
509.10	-2.350	4.067	1.240		509.170	155.195	269:42:43	269.712	-2.555	3.862	1.177	MF	-0.205	-6.2	226.306
609.11	-2.278	4.139	1.262		609.025	185.631	269:45:59	269.766	-2.475	3.942	1.202	MF	-0.197	-6.0	256.742
708.17	-1.988	4.429	1.350	EOTCr	708.830	216.051	269:49:51	269.831	-2.080	4.337	1.322	MF	-0.092	-2.8	287.163
743.00	-1.977	4.440	1.353	EOTCr	743.145	226.511	269:40:10	269.669	-4.280	2.137	0.651	TCr	-2.303	-70.2	297.622
796.84	-2.027	4.390	1.338		796.660	242.822	269:45:42	269.762	-3.305	3.112	0.949	PW	-1.278	-39.0	313.933
896.86	-1.654	4.763	1.452		896.965	273.395	269:55:07	269.919	-1.260	5.157	1.572	PW	0.394	12.0	344.506
996.93	-1.808	4.609	1.405		996.480	303.727	269:54:53	269.915	-1.465	4.952	1.509	PW	0.343	10.5	374.838
1096.56	-1.637	4.780	1.457		1096.025	334.068	269:54:43	269.912	-1.660	4.757	1.450	MF	-0.023	-0.7	405.180
1120.17	-1.932	4.485	1.367	EOPW	1119.735	341.295	269:52:26	269.874	-2.440	3.977	1.212	MF	-0.508	-15.5	412.407
A15												0 SET			

Benchmark Elevations							
			OPEN	827.340	269:59:49	269.997	0.230
1980	6.417	ft NAVD88	CLOSE	827.345	270:00:55	270.015	0.235
2009	6.014	ft NAVD88					0.005

4/23/2009 ~ TOPCON GTS-211D

Brian Spear, Ron Eby

1980 Survey					2009 Survey								RESULTS		
Hdist (ft)	Vdist (ft)	Z (ft)	Z (m)	Description	Hdist (ft)	Hdist (m)	Vangle	Dec Deg	Vdist (ft)	Z(ft)	Z (m)	Description	Z Diff (ft)	Z Diff (cm)	Graph Dist (m)
48.909	3.159	10.134	3.089	Upland			Too Overgrown					Upland			
A17		6.975	2.126	A17						6.975	2.126	A17 BM			
25.40	-1.419	5.556	1.693	Toe	25.315	7.716	268:17:56	268.299	-0.750	6.225	1.897	PW	0.669	20.4	7.7
100.78	-2.005	4.970	1.515	PW	100.345	30.585	269:21:37	269.360	-1.120	5.855	1.785	PW	0.885	27.0	30.6
201.40	-1.895	5.080	1.548	PW	201.020	61.271	269:41:37	269.694	-1.075	5.900	1.798	PW	0.820	25.0	61.3
301.75	-1.895	5.080	1.548	PW	301.525	91.905	269:44:37	269.744	-1.345	5.630	1.716	PW	0.550	16.8	91.9
401.54	-2.864	4.111	1.253	MF	401.345	122.330	269:36:20	269.606	-2.760	4.215	1.285	MF	0.104	3.2	122.3
502.11	-2.742	4.233	1.290	MF	501.995	153.008	269:40:57	269.683	-2.780	4.195	1.279	MF	-0.038	-1.2	153.0
602.01	-2.967	4.008	1.222	MF	601.580	183.362	269:42:57	269.716	-2.980	3.995	1.218	MF	-0.013	-0.4	183.4
664.31	-2.343	4.632	1.412	EOTCr	664.315	202.483	269:36:48	269.613	-4.475	2.500	0.762	TCr Bank	-2.132	-65.0	202.5
703.29	-1.650	5.325	1.623	EOTCr			Too Deep				0.000	TCr Th			
818.64	-2.898	4.077	1.243	EOPW	819.060	249.649	269:47:24	269.790	-2.995	3.980	1.213	MF	-0.097	-3.0	249.6
A15												0set			

Benchmark Elevations

1980	6.975	ft NAVD88
2009	6.789	ft NAVD88

OPEN NA

CLOSE NA

4/3/2009 Topcon GPT-3002W

Brian Spear, Randy Hollowell, Ron Eby

1980 Survey					2009 Survey								RESULTS		
Hdist (ft)	Vdist (ft)	Z (ft)	Z (m)	Description	Hdist (ft)	Hdist (m)	Vangle	Dec Deg	Vdist (ft)	Z(ft)	Z (m)	Description	Z Diff (ft)	Z Diff (cm)	Graph Dist (m)
-180.479	3.371	9.805	2.988	Upland	-180.755	-55.094124	89:07:08	89.119	2.780	9.214	2.808	Upland	-0.591	-18.0	0.000
-168.87	0.406	6.840	2.085	Toe	-168.87	-51.470052	89:48:57	89.816	0.545	6.979	2.127	Fringe	0.139	4.2	3.624
-99.63	0.181	6.615	2.016	PW	-99.78	-30.41142	89:34:02	89.567	0.755	7.189	2.191	PW	0.574	17.5	24.683
A20		6.434	1.961	A20						6.434	1.961	A20 BM			
99.77	-2.164	4.270	1.301	MF	99.75	30.4033428	268:42:59	268.716	-2.230	4.204	1.281	MF	-0.066	-2.0	85.497
199.16	-2.328	4.106	1.251	MF	199.81	60.900564	269:14:57	269.249	-2.620	3.814	1.162	MF	-0.292	-8.9	115.995
299.10	-2.418	4.016	1.224	MF	298.65	91.026996	269:31:39	269.528	-2.465	3.969	1.210	MF	-0.047	-1.4	146.121
393.25	-0.110	6.324	1.927	EOTCr	393.17	119.836692	269:50:25	269.840	-1.095	5.339	1.627	TOBank	-0.985	-30.0	174.931
445.78	-1.891	4.543	1.385	PANNE	445.92	135.914892	269:28:21	269.473	-4.105	2.329	0.710	MidBank	-2.214	-67.5	191.009
502.24	-1.382	5.052	1.540	EOTCr	501.95	152.99436	269:33:35	269.560	-3.855	2.579	0.786	MidBank	-2.473	-75.4	208.088
522.64	-1.736	4.698	1.432	EOTCr	522.71	159.322008	269:22:00	269.367	-5.775	0.659	0.201	TCr Th	-4.039	-123.1	214.416
553.00	-1.173	5.261	1.603	EOTCr	552.86	168.511728	269:30:48	269.513	-4.690	1.744	0.531	TCr	-3.517	-107.2	223.606
571.74	-1.619	4.815	1.468	EOTCr	571.80	174.28464	269:31:48	269.530	-4.690	1.744	0.531	TCr	-3.071	-93.6	229.379
591.27	-1.820	4.614	1.406	PW	591.18	180.19014	269:51:07	269.852	-1.515	4.919	1.499	PW (nr Panne)	0.305	9.3	235.284
686.30	-2.006	4.428	1.350	EOTCr	686.39	209.211672	269:45:15	269.754	-2.935	3.499	1.066	EOTCr	-0.929	-28.3	264.306
707.18	-1.868	4.566	1.392	EOTCr	707.41	215.618568	269:52:27	269.874	-1.550	4.884	1.489	PW/EOPanne	0.318	9.7	270.713
806.28	-2.300	4.134	1.260	PW	806.29	245.755668	269:51:26	269.857	-1.990	4.444	1.354	Panne	0.310	9.4	300.850
905.99	-2.030	4.404	1.342	PW	906.28	276.234144	269:54:35	269.910	-1.415	5.019	1.530	PW	0.615	18.7	331.328
1005.70	-1.721	4.713	1.436	PW	1005.34	306.426108	269:55:41	269.928	-1.245	5.189	1.582	PW	0.476	14.5	361.520
1105.07	-1.588	4.846	1.477	PANNE	1105.39	336.921348	269:54:12	269.903	-1.835	4.599	1.402	EOPanne	-0.247	-7.5	392.015
1204.42	-1.879	4.555	1.388	PW	1204.66	367.178844	269:55:39	269.928	-1.490	4.944	1.507	PW (thin)	0.389	11.9	422.273
1303.29	-2.087	4.347	1.325	PW	1303.49	397.302228	269:54:56	269.916	-1.870	4.564	1.391	Panne	0.217	6.6	452.396
1402.61	-1.770	4.664	1.422	PW	1402.48	427.47438	269:55:24	269.923	-1.830	4.604	1.403	Panne	-0.060	-1.8	482.569
1601.07	-1.827	4.607	1.404	PW	1601.12	488.021376	269:56:33	269.943	-1.560	4.874	1.486	PW	0.267	8.1	543.116
1640.38	-1.916	4.518	1.377	EOPW	1640.49	500.019828	269:53:50	269.897	-2.905	3.529	1.076	MF (in main channel)	-0.989	-30.1	555.114
A21												0set			

Benchmark Elevations				
1980	6.434 ft NAVD88		OPEN	NA
2009	5.830 ft NAVD88		CLOSE	NA

3/31/2009 Topcon GPT-3002W

Brian Spear, Ron Eby, Ryan Bassett

1980 Survey							2009 Survey									RESULTS		
Sdist (ft)	Hdist (ft)	Hdist (m)	Vdist (ft)	Z (ft)	Z (m)	Description	Sdist (ft)	Hdist (ft)	Hdist (m)	Vangle	Dec Deg	Vdist (ft)	Z (ft)	Z (m)	Description	Z Diff (ft)	Z Diff (cm)	Graph Dist (m)
A25				10.866	3.312	A25							10.866	3.312	A25 BM			
35.16	34.93	10.65	-4.029	6.837	2.084	Toe	35.424	35.235	10.740	264:05:00	264.083	-3.650	7.216	2.199	PW (edge)	0.379	11.6	10.7
99.95	99.79	30.42	-5.703	5.163	1.574		99.985	99.865	30.439	267:11:42	267.195	-4.890	5.976	1.822	PW	0.813	24.8	30.4
134.15	134.00	40.84	-6.380	4.486	1.367	EOTCr	134.425	134.262	40.923	267:10:18	267.172	-6.620	4.246	1.294	TCr	-0.240	-7.3	40.9
162.84	162.74	49.60	-5.674	5.192	1.583	EOTCr	162.520	162.381	49.494	267:38:00	267.633	-6.710	4.156	1.267	Bank	-1.036	-31.6	49.5
199.68	199.57	60.83	-6.610	4.256	1.297		199.775	199.681	60.863	268:14:22	268.239	-6.140	4.726	1.441	Panne	0.470	14.3	60.9
310.28	310.23	94.56	-5.632	5.234	1.595	EOTCr	310.335	310.265	94.569	268:47:12	268.787	-6.570	4.296	1.309	EOBank	-0.938	-28.6	94.6
328.74	328.69	100.18	-5.942	4.924	1.501	EOTCr	328.920	328.853	100.235	268:50:45	268.846	-6.620	4.246	1.294	EOBank	-0.678	-20.7	100.2
407.06	407.02	124.06	-6.044	4.822	1.470		407.155	407.120	124.090	269:14:35	269.243	-5.375	5.491	1.674	PW	0.669	20.4	124.1
506.17	506.13	154.27	-5.989	4.877	1.487		505.975	505.948	154.213	269:24:07	269.402	-5.275	5.591	1.704	PW	0.714	21.8	154.2
613.03	613.00	186.84	-6.020	4.846	1.477	EOTCr	613.105	613.058	186.860	269:17:23	269.290	-7.595	3.271	0.997	TCr	-1.575	-48.0	186.9
627.38	627.35	191.22	-5.976	4.890	1.491	EOTCr	627.585	627.555	191.279	269:26:22	269.439	-6.130	4.736	1.444	PW	-0.154	-4.7	191.3
712.12	712.09	217.05	-6.107	4.759	1.451		712.325	712.304	217.110	269:33:41	269.561	-5.445	5.421	1.652	PW	0.662	20.2	217.1
811.72	811.70	247.41	-5.932	4.934	1.504		811.645	811.628	247.384	269:37:56	269.632	-5.195	5.671	1.729	PW	0.737	22.5	247.4
902.76	902.74	275.16	-5.903	4.963	1.513	EOPW	902.310	902.291	275.018	269:37:35	269.626	-5.865	5.001	1.524	EOBank	0.038	1.2	275.0
A26															0set			

Benchmark Elevations				
1980	10.866	ft NAVD88	OPEN	NA
2009	10.607	ft NAVD88	CLOSE	NA

3/31/2009 Topcon GPT-3002W

Brian Spear, Ron Eby, Ryan Bassett

1980 Survey							2009 Survey									RESULTS		
Sdist (ft)	Hdist (ft)	Hdist (m)	Vdist (ft)	Z (ft)	Z (m)	Description	Sdist (ft)	Hdist (ft)	Hdist (m)	Vangle	Dec Deg	Vdist (ft)	Z (ft)	Z (m)	Description	Z Diff (ft)	Z Diff (cm)	Graph Dist (m)
-60.42	-59.61	-18.17	9.879	16.326	4.976	Upland				Too Overgrown					Upland			
-30.51	-30.44	-9.28	2.084	8.531	2.600	Upland	-30.72	-30.62	-9.33	85:29:42	85.495	2.415	8.862	2.701	Upland	0.331	10.1	0.0
A29				6.447	1.965	A29							6.447	1.965	A29 BM			
99.32	99.30	30.27	-2.020	4.427	1.349	MF	99.04	99.02	30.18	269:58:11	269.970	-1.780	4.667	1.422	Panne	0.240	7.3	39.5
200.04	200.03	60.97	-2.147	4.300	1.311	MF	200.00	199.98	60.96	269:16:58	269.283	-2.505	3.942	1.201	Panne	-0.358	-10.9	70.3
234.39	234.39	71.44	-0.187	6.260	1.908	Levee	234.42	234.40	71.45	269:27:30	269.458	-2.215	4.232	1.290	Bank	-2.028	-61.8	80.8
253.22	253.21	77.18	-1.646	4.801	1.463	EOTCr	253.36	253.35	77.22	269:29:45	269.496	-2.230	4.217	1.285	EOBank	-0.584	-17.8	86.6
298.90	298.89	91.10	-1.860	4.587	1.398	PW	299.19	299.19	91.19	269:40:54	269.682	-1.660	4.787	1.459	EOTCr	0.200	6.1	100.5
325.20	325.20	99.12	-1.217	5.230	1.594	EOTCr	325.26	325.25	99.13	269:27:01	269.450	-3.120	3.327	1.014	EOBank	-1.903	-58.0	108.5
347.11	347.11	105.80	-1.550	4.897	1.493	EOTCr	347.52	347.50	105.92	269:22:27	269.374	-3.795	2.652	0.808	TCr	-2.245	-68.4	115.3
395.62	395.62	120.58	-1.634	4.813	1.467	PW	396.04	396.04	120.71	269:50:40	269.844	-1.075	5.372	1.637	PW	0.559	17.0	130.0
494.16	494.16	150.62	-1.639	4.808	1.465	PW	494.53	494.53	150.73	269:52:52	269.881	-1.020	5.427	1.654	PW	0.619	18.9	160.1
599.71	599.71	182.79	-1.786	4.661	1.421	PANNE	600.17	600.16	182.93	269:52:27	269.874	-1.310	5.137	1.566	Panne	0.476	14.5	192.3
650.26	650.26	198.20	-1.595	4.852	1.479	EOTCr	649.86	649.85	198.08	269:52:18	269.872	-1.445	5.002	1.525	EOBank	0.150	4.6	207.4
666.22	666.22	203.06	-1.662	4.785	1.458	EOTCr	666.07	666.05	203.01	269:41:00	269.683	-3.675	2.772	0.845	TCr	-2.013	-61.4	212.3
700.77	700.77	213.59	-1.907	4.540	1.384	PW	701.88	701.88	213.93	269:53:59	269.900	-1.270	5.177	1.578	PW	0.637	19.4	223.3
801.10	801.10	244.17	-1.835	4.612	1.406	PW	800.90	800.89	244.11	269:55:31	269.925	-1.030	5.417	1.651	PW	0.805	24.5	253.4
865.49	865.49	263.80	-2.021	4.426	1.349	EOTCr	866.43			269:50:49	269.847	NA			PW			
895.51	895.51	272.95	-1.241	5.206	1.587	EOTCr	895.74	895.74	273.02	269:58:49	269.980	-0.295	6.152	1.875	PW	0.946	28.8	282.4
995.49	995.49	303.42	-2.111	4.336	1.322	PW	995.42	995.42	303.40	269:55:08	269.919	-1.390	5.057	1.541	PW	0.721	22.0	312.7
1076.72	1076.72	328.18	-1.775	4.672	1.424	EOPW	1056.51	1056.50	322.02	269:47:03	269.784	-3.955	2.492	0.760	MF	-2.180	-66.4	331.4
A30															0set			

Benchmark Elevations

1980	6.447	ft NAVD88
2009	5.957	ft NAVD88

OPEN NA

CLOSE NA

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Brian Spear, Ron Eby

1980 Survey							2009 Survey									RESULTS		
Sdist (ft)	Hdist (ft)	Hdist (m)	Vdist (ft)	Z (ft)	Z (m)	Description	Sdist (ft)	Hdist (ft)	Hdist (m)	Vangle	Dec Deg	Vdist (ft)	Z (ft)	Z (m)	Description	Z Diff (ft)	Z Diff (cm)	Graph Dist (m)
A33				22.195	6.765	A33							22.195	6.765	A33 BM			
62.24	59.90	18.26	-16.918	5.277	1.608	Toe	62.50	60.48	18.434	104:36:29	104.608	-15.760	6.435	1.961	PW	1.158	35.3	18.4
99.38	97.86	29.83	-17.291	4.904	1.495	PW	99.15	97.83	29.820	99:19:35	99.326	-16.065	6.130	1.868	PW	1.226	37.4	29.8
198.33	197.58	60.22	-17.282	4.913	1.497	PW	197.94	197.28	60.130	94:41:36	94.693	-16.200	5.995	1.827	PW	1.082	33.0	60.1
223.30	222.63	67.86	-17.253	4.942	1.506	EOTCr	223.70	223.08	67.994	94:15:40	94.261	-16.620	5.575	1.699	PW	0.633	19.3	68.0
246.99	246.39	75.10	-17.218	4.977	1.517	EOTCr	246.51	245.80	74.920	94:20:56	94.349	-18.690	3.505	1.068	Bank	-1.472	-44.9	74.9
294.45	293.94	89.59	-17.317	4.878	1.487	PW	294.50	294.05	89.626	93:09:14	93.154	-16.200	5.995	1.827	PW	1.117	34.0	89.6
352.91	352.49	107.44	-17.140	5.055	1.541	EOPW	352.94	352.56	107.460	92:39:59	92.666	-16.415	5.780	1.762	MF	0.725	22.1	107.5
A34															0set			

Benchmark Elevations

1980	22.195	ft NAVD88
2009	21.612	ft NAVD88

OPEN NA

CLOSE NA

*** Original 1980 benchmark lost, reset in 2009 using 1/2in pipe by MidCoast Engineers.

1/31/2009 Topcon GPT-3002W

Brian Spear, Ron Eby

1980 Survey						2009 Survey								RESULTS		
Sdist (ft)	Hdist (ft)	Hdist (m)	Vdist (ft)	Z (ft)	Description	Sdist (ft)	Hdist (ft)	Hdist (m)	Vangle	Dec Deg	Vdist (ft)	Z (ft)	Description	Z Diff (ft)	Z Diff (cm)	Graph Dist (m)
-76.63	-76.43	-23.30	5.49	11.390	Upland	-76.980	-76.345	-23.270			9.871	15.773	Upland (trail)	4.383	133.6	0.0
-26.20	-26.14	-7.97	-1.73	4.169	Upland	-26.065	-26.036	-7.936			1.226	7.128	Upland	2.959	90.2	15.3
A38			0.00	5.902	A38	0.000	0.000	0.000			0.000	5.902	A38 BM	0.000	0.0	23.3
99.94	99.86	30.44	-4.05	1.852	PW	99.890	99.888	30.446	No Vertical angle		-0.624	5.278	PW	3.426	104.4	53.7
192.43	192.38	58.64	-4.24	1.667	PW	NA			collected. Used				TCr	-1.667	-50.8	23.3
286.30	286.28	87.26	-3.73	2.169		NA			Backsight to collect NEZ				TCr	-2.169	-66.1	23.3
300.58	300.56	91.61	-3.67	2.232		299.615	299.615	91.323	coordinates		-0.274	5.628	TOB	3.396	103.5	114.6
399.76	399.74	121.84	-3.90	2.006	PW	399.545	399.544	121.781			-0.659	5.243	PW	3.237	98.7	145.1
499.33	499.32	152.19	-3.83	2.073	PW	499.830	499.829	152.348			-0.709	5.193	PW	3.120	95.1	175.6
584.38	584.37	178.11	-4.17	1.734	EOPW	583.545	583.543	177.864			-1.579	4.323	MF	2.589	78.9	201.1
A39												Backsight				

OPEN	12244.160	14489.035	4.435	
CLOSE	12244.190	14489.065	4.435	
			0.000	ft

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Brian Spear, Ron Eby

1980 Survey						2009 Survey								RESULTS		
Sdist (ft)	Hdist (ft)	Hdist (m)	Vdist (ft)	Z (ft)	Description	Sdist (ft)	Hdist (ft)	Hdist (m)	Vangle	Dec Deg	Vdist (ft)	Z (ft)	Description	Z Diff (ft)	Z Diff (cm)	Graph Dist (m)
-36.79	-35.27	-10.75	10.47	17.095	Upland	-36.670	-34.139	-10.406			13.386	20.013	Upland	2.918	0.9	0
A43	0.00	0.00	0.00	6.627	A43	0.000	0.000	0.000			0.000	6.627	A43 BM			
5.02	3.25	0.99	-3.83	2.800	PW	4.730	4.673	1.424			-0.734	5.893	PW	3.093	0.9	11.830
33.84	33.53	10.22	-4.56	2.067	MF	33.660	33.571	10.232			-2.449	4.178	MF	2.111	0.6	20.638
143.54	143.48	43.73	-4.25	2.381	MF	141.960	141.937	43.262			-2.569	4.058	MF	1.677	0.5	53.668
150.62	150.56	45.89	-4.34	2.292	MF	149.910	149.897	45.689			-1.944	4.683	MF	2.391	0.7	56.094
182.06	182.02	55.48	-3.95	2.675	EOTCr	183.255	183.236	55.850			-2.664	3.963	MF/EOB	1.288	0.4	66.256
239.32	239.28	72.93	-4.10	2.524	TCr	239.365	239.318	72.944			-4.754	1.873	MF	-0.651	-0.2	83.350
270.38	270.35	82.40	-4.09	2.539	TCr	270.450	270.432	82.428	No Vertical angle		-3.139	3.488	MF	0.949	0.3	92.833
300.89	300.86	91.70	-4.05	2.582	PW	300.485	300.483	91.587	collected. Used		-1.029	5.598	PW	3.016	0.9	101.993
400.32	400.29	122.01	-4.62	2.005	PW	400.325	400.320	122.018	Backsight to		-1.899	4.728	PANNE	2.723	0.8	132.423
498.93	498.91	152.07	-4.37	2.262	PW	498.920	498.918	152.070	collect NEZ		-1.309	5.318	PW	3.056	0.9	162.476
531.20	531.19	161.91	-3.93	2.696	EOTCr	531.415	531.400	161.971	coordinates		-3.994	2.633	MF	-0.063	0.0	172.376
554.81	554.79	169.10	-4.23	2.395	PW	554.530	554.507	169.014			-5.079	1.548	MF/TCr	-0.847	-0.3	179.419
593.29	593.28	180.83	-4.18	2.446	PW	593.315	593.314	180.842			-1.014	5.613	PW	3.167	1.0	191.248
692.99	692.98	211.22	-4.49	2.142	PW	692.755	692.754	211.151			-1.164	5.463	PW	3.321	1.0	221.557
792.53	792.52	241.56	-4.59	2.040	PW	792.000	791.999	241.401			-1.179	5.448	PW	3.408	1.0	251.807
892.17	892.16	271.93	-4.84	1.785	PW	891.960	891.959	271.869			-1.474	5.153	PW (hard mud/thin PW)	3.368	1.0	282.275
997.72	997.71	304.10	-4.48	2.145	PANNE	997.235	997.234	303.957			-1.384	5.243	EOPANNE	3.098	0.9	314.363
1097.72	1097.71	334.58	-4.06	2.568	PW	1097.550	1097.550	334.533			-0.684	5.943	PW	3.375	1.0	344.939
1153.13	1153.12	351.47	-4.05	2.581	EOPW	1153.000	1152.998	351.434			-2.134	4.493	MF	1.912	0.6	361.840
A44													Backsight			
						OPEN	12030.005	12709.185	4.460							
						CLOSE	12030.015	12709.160	4.460							
									0.000							

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Brian Spear, Ron Eby

1980 Survey					2009 Survey								RESULTS		
Sdist (ft)	Hdist (ft)	Hdist (m)	Z (ft)	Description	Sdist (ft)	Hdist (ft)	Hdist (m)	Vangle	Dec Deg	Vdist (ft)	Z (ft)	Description	Z Diff (ft)	Z Diff (cm)	Graph Dist (m)
A48			8.612	A48							8.612	A48 BM			
24.12	23.48	7.16	3.098	Toe	24.380	24.345	7.431	260:56:09	260.936	-1.305	7.307	PW			
148.70	148.56	45.28	2.223	EOTCr	148.615	148.541	45.298	268:11:11	268.186	-4.705	3.907	TCr			
174.70	174.61	53.22	2.861	EOTCr	174.745	174.666	53.262	268:16:38	268.277	-5.255	3.357	TCr			
267.82	267.75	81.61	2.646		267.780	267.774	81.619	269:36:21	269.606	-1.840	6.772	PW			
349.59	349.55	106.54	3.068	EOTCr	349.525	349.495	106.535	269:14:36	269.243	-4.610	4.002	TCr			
385.20	385.15	117.39	2.668	EOTCr	385.310	385.292	117.442	269:26:58	269.449	-3.700	4.912	vertical bank, TCr			
398.88	398.84	121.57	2.917	EOTCr	398.960	398.926	121.603	269:15:20	269.256	-5.180	3.432	TCr bank			
466.46	466.41	142.16	1.632	EOTCr	467.245	467.217	142.416	269:22:11	269.370	-5.135	3.477	TCr			
572.99	572.96	174.64	2.491		573.215	573.212	174.716	269:48:14	269.804	-1.955	6.657	PW			
688.95	688.92	209.98	2.432	EOPW	689.205	689.193	210.070	269:40:03	269.668	-3.990	4.622	MF			
A47												0set			

Not compared to 1980 due to reset benchmark in 2009 using 1/2 inch pipe by MidCoast Engineers.

OPEN	24.380	7.431	260:56:09	260.936	-1.305
CLOSE	24.410	7.440	266:49:53	266.831	-1.350
					-0.045

*** Original 1980 benchmark lost, reset in 2009 using 1/2in pipe by MidCoast Engineers.

APPENDIX C

BENCHMARK AND BACKSIGHT LOCATIONS

DEFINITIONS:

BM ID – Benchmark reference ID

Northing and Easting in **UTM NAD83 Zone 10N (meters)** coordinate system

Decription – either transect benchmark (BM) or reference backsight (BS)

Deflection Angle – angle turned when setting instrument on BM and facing BS

Direction - direction of deflection angle right (RT) or left (LT)

BM ID	Northing	Easting	Description	Deflection Angle	Direction
A1	4079975.548	610943.579	BM	84:50:00	RT
A2	4080008.357	610858.172	BS		
A8	4079094.956	610341.821	BM	87:51:00	RT
A9	4078912.708	610339.645	BS		
A14	4078169.834	610640.335	BM	78:15:00	LT
A15	4077996.363	610823.370	BS		
A17	4077669.233	611013.336	BM	64:17:33	RT
A15	4077996.363	610823.370	BS		
A20	4077363.735	611528.162	BM	82:40:00	RT
A21	4077323.652	611603.817	BS		
A25	4076800.875	611746.992	BM	86:00:00	RT
A26	4076682.542	611633.998	BS		
A29	4076297.050	611544.806	BM	60:25:00	LT
A30	4076114.584	611609.326	BS		
A33	4075709.316	611687.928	BM	67:20:00	RT
A34	4075445.274	611552.375	BS		
A38	4075377.900	611347.346	BM	37:55:00	RT
A39	4075471.807	611192.721	BS		
A43	4075365.988	610699.628	BM	59:50:00	RT
A44	4075383.824	610653.763	BS		
A47	4075613.999	610254.474	BS	46:45:00	LT
A48	4075536.489	610103.936	BM		