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Elkhorn Slough Tidal Wetland Project

Hydrodynamic Modeling and Morphologic Projections of Large-Scale Restoration Actions

FINAL REPORT

Prepared for

The Elkhorn Slough Tidal Wetlands Project

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EXECUTIVE SUMMARY

Elkhorn Slough, a shallow estuary approximately 10-km long located in Central Monterey Bay, California, hosts a diverse mosaic of habitats that support over 780 aquatic bird, marine invertebrate, marine mammal and fish species (Elkhorn Slough Tidal Wetland Project Team 2007). Following the construction of Moss Landing Harbor in 1947, which included dredging a new ocean inlet to replace the previous shoaling tidal inlet, local stakeholders and scientists began observing tidal erosion (deepening and widening) along Elkhorn Slough (Slough) and the loss of marshplain habitat (Oliver and others 1988; Philip Williams & Associates 1992; Van Dyke and Wasson 2005). Tidal erosion along the slough channel and the loss of vegetation in the marsh interior have been mainly attributed to construction and maintenance dredging of the Moss Landing Harbor entrance, which increased tidal flow to and from the estuary. In addition, historic sources of sediment supply to the Slough have been cut off reducing the Slough's resilience to the increased tidal flow. Other possible factors contributing to the erosion problems include intentional and unintentional levee breaching, subsidence of marsh areas, accelerating sea level rise, and changes to biological processes.

In November 2006 the Philip Williams and Associates, Ltd. (PWA) team was retained to investigate potential restoration alternatives to address these problems of tidal erosion and marsh loss. The alternatives considered in this study include existing conditions and three additional restoration alternatives:

- **Alternative 1 – No Action:** No intervention is taken, allowing existing conditions in the Slough to persist.
- **Alternative 2 – New Ocean Inlet:** A new inlet, located at the approximate location of the historic inlet, would be created and connected to the main Slough by a channel excavated to the north and east of Moss Landing Harbor. A new barrier would completely block tidal exchange between Elkhorn Slough and Moss Landing.
- **Alternative 3 – Tidal Barrier at Highway 1:** Tidal exchange between the Slough and Moss Landing Harbor would be restricted, but not eliminated, by a partial tidal barrier at the Highway 1 bridge. Two different barrier crest elevations are considered.
- **Alternative 4 – Restoration of Parsons Slough:** Restoration of subsided marsh within Parsons Slough, a tributary to Elkhorn Slough, would reduce tidal exchange within the main Slough channel downstream of the Parsons-Elkhorn confluence.

All four restoration alternatives are evaluated at Year 0 (immediately after implementation), Year 10 and Year 50 (10 and 50 years after project implementation, respectively). Year 10 corresponds to the short-term timescale when the proposed restoration alternatives are expected to exhibit clear differences in morphologic response. Year 50 corresponds to the long-term timescale, a time period likely near the limit at which meaningful morphologic predictions can be made.

The largest project task was the development of a hydrodynamic computer model of the Slough to provide a tool to predict the response of the system to possible restoration alternatives. Once developed and calibrated, the model provides predictions of the change in tidal flow regime in response to possible structural changes to the slough system. The predicted changes in flow regime, in conjunction with an assessment of the relationships between the flow regime and channel morphology allow an assessment of the likely effectiveness of various options in halting the erosion and restoring the slough to a more depositional environment. In addition to these site specific studies, a description of geomorphic changes occurring in similarly impacted estuaries elsewhere provides insight to the Elkhorn problems.

Overall, the hydrodynamic modeling and related studies on geomorphic and habitat change supports the conceptual models and observations of Elkhorn scientists over the past 20 years that describe the estuary to be on a trajectory of sustained erosion/sediment export, with ongoing scour of the main channel and conversion of the vegetated marshplain to mudflat. Without intervention, we expect the rate of main channel scour to continue (though at a progressively slower rate), while the remaining marshes will largely be converted to mudflats, and low mudflat will convert to subtidal habitat. Sea level rise of 30 cm (1 foot), which is predicted to occur within fifty years, will further impact the vegetated marshplain habitat by increasing inundation frequency. While the exact rate and final form of these processes are difficult to predict in detail, the trend and scale of both past changes and ongoing processes are clear, and provide no indication that the system is near equilibrium and that erosion will stop without significant intervention.

Unfortunately, there are no small-scale restoration approaches that have been identified that would halt this trajectory of habitat conversion. The human-induced impacts to Elkhorn Slough during the 20th century, coupled with future sea level rise, create an unfavorable future environment for vegetated marshplain habitat. If it is determined to be desirable, reversing these impacts would require restoration responses commensurate in scale. Engineering approaches such as relocating and reconstructing a shallow inlet to the north of the current harbor entrance (Alternative 2), or constructing a shallow tidal barrier at the Highway 1 Bridge (Alternative 3a/b) would reduce the rate of sediment loss from the estuary. Reducing the tidal prism contributed from the subsided Parsons Slough Complex, through either placement of fill material and / or limitation of tidal exchange via construction of water control structures, would reduce a portion of the increased tidal flushing occurring in the lower estuary. None of these alternatives would replace the loss of sediment supply to the system, created by the re-routing of the local rivers directly to the Bay. Sediment supply would be needed to rebuild intertidal areas, resupply the slough channels, and maintain intertidal areas against rising sea level. An artificial sediment supply, with periodic resupply to offset the inundation impacts of rising sea levels, would be required to restore an expansive marshplain, and replace the sediment volumes lost over the past 60 years.

If Slough managers and decision-makers decide to pursue action plans to reduce the ongoing erosion processes, we would recommend a phased program, using adaptive management and monitoring to assess the effectiveness of actions taken, adjust the facilities to maximize their effectiveness, and implement increasingly larger and more costly options only as necessary. Uncertainties in the environmental outcomes of the restoration alternatives exist, not only in terms of habitat response but also over issues such as water quality. While more detailed studies in the future can reduce some of the uncertainties, we recommend a phased approach to restoration with each subsequent action taking place under adaptive management approach. The management alternatives described in this report (restriction of tidal exchange from Parsons Slough, construction of a low sill at Highway 1 bridge, construction of a high sill at this location, and construction of a new ocean inlet), provide a sequence of projects with increasing cost and impacts that could also be implemented sequentially, based on a monitoring program and various pilot studies to demonstrate effectiveness and need for additional action. From an erosion reduction perspective, each step in this sequence would be beneficial individually, and would not represent unnecessary or significant duplicative costs and effort if implemented in a phased manner.

While the scale of intervention, estimated costs, and potential impacts of the Elkhorn restoration alternatives described in this report are large, they are comparable in level of effort and cost to other recent and ongoing significant wetlands restoration projects in California.

The information in this report provides local scientists and decision-makers with a basis for assessing the likely future evolution of the morphology and habitat functions provided by the slough in response to ongoing changes, and options for a range of actions to reduce or halt the ongoing erosional processes. It provides methodology for comparing the relative magnitude of change, and the scales of cost and intervention of the alternatives. Based on the direction selected by the Slough managers, future studies can refine both the assessment of impacts, system benefits/changes, and the design of the various alternatives to optimize design and costs while reducing adverse impacts.

1. INTRODUCTION

Elkhorn Slough, a shallow estuary approximately 10-km long located in Central Monterey Bay, provides a diverse mosaic of habitats that support over 780 aquatic bird, marine invertebrate, marine mammal and fish species (Elkhorn Slough Tidal Wetland Project Team 2007). Following the construction of Moss Landing Harbor in 1947, which included dredging a new ocean inlet to replace the previous shoaling tidal inlet, local stakeholders and scientists began observing tidal erosion (deepening and widening) along Elkhorn Slough (Slough) and expansion of marsh creek salt pans in the interior of the marshplain (Oliver and others 1988; Philip Williams & Associates 1992) (ABA Consultants 1989; Dean 2003; Sampey 2006; Van Dyke and Wasson 2005). Tidal erosion along the slough channel and the loss of vegetation in the marsh interior have been mainly attributed to construction and maintenance dredging of the Moss Landing Harbor, which increased tidal flow to and from the estuary. Other possible factors contributing to the problem include intentional and unintentional levee breaching, subsidence of marsh areas, decreases in sediment supply, accelerating sea level rise, and changes to biological processes.

In 2004 the Elkhorn Slough Tidal Wetlands Project (TWP) was initiated to develop and implement strategies to conserve and restore estuarine habitats in the Elkhorn Slough watershed. This collaboration, involves over 100 coastal resource managers, scientific experts, representatives from key regulatory and jurisdictional entities, leaders of conservation organizations, and community members. The TWP is supported by a Modeling Advisory Team (MAT) tasked with overseeing consulting efforts to evaluate the hydrodynamic, geomorphic, and ecosystem responses to a suite of large-scale restoration alternatives compared with a "no-action" alternative.

In November 2006 the Philip Williams and Associates, Ltd. (PWA) team was hired to provide modeling, geomorphic, engineering and ecological services. Guided by the MAT and TWP Coordinator, the primary focus of this investigation has been the development of a calibrated 2D numerical model describing existing conditions and three additional restoration alternatives:

- Alternative 1- the No Action Alternative;
- Alternative 2 - the New Ocean Inlet;
- Alternative 3 - a Tidal Barrier at Highway 1; and
- Alternative 4 - Restoration of Parsons Slough.

All four restoration alternatives are evaluated at Year 0 (immediately after implementation), Year 10 and Year 50 (10 and 50 years after project implementation, respectively). Year 10 corresponds to the short-term timescale when the proposed restoration alternatives are expected to exhibit clear differences in morphologic response. Year 50 corresponds to the long-term timescale, a time period likely near the limit at which meaningful morphologic predictions can be made. The methodology developed for the Year 10 and Year 50 morphologic projections of Elkhorn Slough is also presented.

This Final Report includes summaries of completed reports and memorandums including: the Literature Review Memorandum (Task A) (Philip Williams & Associates 2007c); the Restoration Concepts Memorandum (Task B) (Philip Williams & Associates 2007d); the Inlet Stability Memorandum (Task C) (Philip Williams & Associates 2007b, Appendix B); and the Hydrodynamic Modeling Calibration Report (Task D) (Philip Williams & Associates 2007a, Appendix A). This report also presents the hydrodynamic modeling results (Task D), future morphologic projections (Task E) and semi-quantified projections of habitat change (Task F) of the large-scale restoration actions. A brief engineers report (descriptions, drawings and preliminary cost estimates) is presented for two restoration alternatives selected by the TWP Advisory Team (Task G).

1.1 REPORT ORGANIZATION

The report is divided into six major sections describing the physical processes, an evaluation of the alternatives and the future morphologic projections:

- Section 2: Observed Habitat Changes at Elkhorn Slough – A brief description of the historic land-use and habitat changes. Concern about habitat change, in the form of tidal erosion and marsh loss, motivates the consideration of restoration alternatives.
- Section 3: Estuarine Geomorphology and Sediment Delivery – A brief description of the changes to sediment resources and the opportunities and constraints these place on the proposed restoration alternatives.
- Section 4: Descriptions of Proposed Restoration Alternatives – A summary of the physical characteristics of the proposed restoration alternatives.
- Section 5: Evaluation of Alternatives – An evaluation of the four alternatives using a hydrodynamic model coupled with the methodology for predicting long-term geomorphic change. This section comprises the bulk of technical analysis.
- Section 6: Discussion of Alternatives – The alternatives are compared with respect to hydraulic performance and habitat projections. The feasibility of implementing and managing the alternatives is also discussed.
- Section 7: Engineers Report (Conceptual Designs and COst Estimates) – Conceptual designs and cost estimates for two of the proposed restoration alternatives are presented.

2. OBSERVED HABITAT CHANGES AT ELKHORN SLOUGH

Elkhorn Slough has been subjected to a variety of natural and anthropogenic changes over the past 150 years. The changes have altered, and continue to impact, the tidal, freshwater, and sediment processes that support and sustain the Slough's rich habitat diversity and ecological significance as a National Marine Sanctuary, State Ecological Reserve and National Ecological Research Reserve (Elkhorn Slough Tidal Wetland Project Team 2007). One of the primary concerns is that approximately 50 percent, or 1000 acres, of Elkhorn Slough's tidal marsh have been lost since the mid 19th century (Van Dyke and Wasson 2005).

2.1 HISTORIC LAND USE CHANGES TO ELKHORN SLOUGH WATERSHED

Substantial land use changes since the mid 19th century have affected the morphology and tidal habitats of Elkhorn Slough (Van Dyke and Wasson 2005). Littoral sediment and riverine sediments inputs, as well as land-use changes such as deforestation in the 19th century, supplied excess sediment to the system resulting in infilling of the main slough channel and the establishment of a persistent sandbar at the mouth that limited tidal exchange (Van Dyke and Wasson 2005). The sandbar was likely a dynamic feature (similar to that of the Pajaro River's sandbar today) that changed seasonally as sediment availability and hydraulic flows varied. The most significant early changes to Slough habitats occurred in the late 1800s when the construction of the railroad tracks along the east bank of the Slough bisected North Marsh and Parsons Slough and isolated these areas from the main slough channel (Philip Williams & Associates 1992). Around the turn of the century, waterfowl hunters built dams and levees to impound freshwater, ranchers and farmers diked low-lying marsh lands to create pastures for cattle grazing, and additional salt marsh areas were diked to create solar salt evaporation ponds (Peichel and others 2005). These land use changes directly reduced the acreage of tidally-inundated salt marsh flanking Elkhorn Slough.

Records dating back to at least 1859 demonstrate that the Salinas River, Tembladero Slough, Moro Cojo Sloughs and Elkhorn Slough shared a common connection to Monterey Bay. At that time, sediments from these southerly channels were conveyed past the mouth of Elkhorn Slough. (Occasional exceptions to this connection occurred when high Salinas River flow breached the barrier sand dunes.) Some of this sediment could be conveyed up the slough during flood tides, and become available for marsh building. In 1909 or 1910, a breach was cut in the sand dunes seven kilometers south of the present-day Moss Landing Harbor entrance to allow the Salinas River to discharge directly to the ocean, decreasing both freshwater and sediment inputs to Elkhorn Slough (Gordon 1996; Philip Williams & Associates 1992). It is hypothesized that the Pajaro River to the north potentially sustained a similar connection to the Slough, although no publicized data is available to substantiate this claim. The potential connection between the Pajaro River and the Slough would have been cut off around the same time period when farmers, and subsequently the County, began maintaining a direct connection between the Pajaro River and Monterey Bay to reduce flooding of agricultural lands (Santa Cruz County Public Works Department 2006). Although the overall impacts of these diversions to the sediment budget, inlet stability and salinity regime of Elkhorn Slough have not been analyzed in detail, they were likely significant. The Salinas (and possibly the Pajaro River) provided a source of freshwater and sediment, and the variations in river flow would have created a dynamic hydraulic system (Philip Williams & Associates 1992). In addition to periodic floods conveying peak flows of 2,800 m^3/s (100,000 cfs) or more of fresh water, these large floods conveyed enormous quantities of sediment (Philip Williams & Associates 1992). Estimates of average annual sediment delivery along the Salinas River vary from 760,000 m^3/yr (1 million cubic yards) (McGrath 1987) to 1.6 x 10^6 m^3/yr (2 x 10^6 yd^3/yr) (Farnsworth 2000), with extreme floods on the Salinas River (> 2,200 m^3/s, 80,000 cfs) transporting millions of cubic meters of sediment daily (McGrath 1987). On any given year, climatic variability would have influenced the actual amount of sediment delivery by orders of magnitude (Farnsworth and Milliman 2003). Although sand-size sediments from the watershed delivery are sequestered in the main river channel and nearshore environments, finer material was likely to be dispersed throughout the Slough and far into Monterey Bay (Farnsworth 2000). Presumably, fine-grain material delivered by the rivers provided important inorganic marsh-building sediments to the marshes of Elkhorn Slough. Thus, from a geomorphic perspective, diversion of the rivers represented a significant change to the system.

Subsequent to the river diversions, tide gates were installed at Hudson's landing, Bennett Slough, Moro Cojo Slough, and the old Salinas River channel, which continue to restrict tidal flow to these areas (Peichel et al, 2005). It is estimated that diking and draining of salt mash areas for agricultural and salt production, which eliminated tidal circulation from extensive wetland areas, resulted in up to 1 m of subsidence in areas such as Parsons Slough and South Marsh (Oliver and others 1988; Philip Williams & Associates 1992; Van Dyke and Wasson 2005). Land subsidence may also result from the gradual effects of groundwater withdrawal or vertical movements associated with major earthquakes.

Although agricultural practices, railroad construction, diking and draining of tidal wetlands, and other anthropogenic activities resulted in direct modifications of the Slough and the natural wetland habitats, rapid erosion of the Slough and interior marsh loss was not observed until after construction of the Moss Landing Harbor in 1947. The construction of the Moss Landing Harbor created a new Slough opening at the mouth of Monterey Bay's submarine canyon. This new opening dramatically increased the tidal exchange with the Bay compared to pre-construction conditions, and initiated tidally-induced erosion in the Slough. Several researchers have studied the deepening and widening of the main channel and the accompanying loss of interior marsh vegetation (Dean 2003; Malzone and Kvitek 1994; Oliver and others 1988; Philip Williams & Associates 1992). Details of these two modes of environmental change – tidal erosion and interior marsh loss – are discussed below.

2.2 TIDAL EROSION

Oliver et al. (1988) were the first to collect post-1947 bathymetric data in Elkhorn Slough documenting that since the opening of the Moss Landing Harbor in 1947, increased tidal currents had substantially eroded the main channel of Elkhorn Slough. Harbor construction was confirmed to be the major cause of the observed changes to slough width and depth by PWA (Philip Williams & Associates 1992). Additionally, unintentional levee breaching at the mouth of Parsons Slough during the winter storms of

1982-1983 and planned restoration actions at South Marsh in 1983 were also determined to be substantial contributors to tidal prism and channel erosion along the Slough. In the first hydrodynamic modeling investigation of Elkhorn Slough, PWA quantified the bed shear stress under pre- and post-harbor conditions (Philip Williams & Associates 1992). The one-dimensional flow model was also applied to assess changes in tidal hydraulics due to levee breaching in South Marsh and Parsons Slough in 1982-83. The study indicated that the levee breaches had increased tidal prism in Elkhorn Slough by approximately one-third.

Over the past two decades, the Seafloor Mapping Laboratory (SFML) at California State University Monterey Bay (CSUMB) has performed detailed bathymetric surveys of Elkhorn Slough. Surveys performed in 1993, 2001 and 2003 reveal complex patterns of erosion and deposition (Dean 2003; Malzone and Kvitek 1994; Sampey 2006). SFML students and staff have estimated net erosion rates from the Slough of 8.0 x 10^4 m^3/yr (100,000 yd^3/yr) between 1988 and 1993; 5.6 x 10^4 m^3/yr (75,000 yd^3/yr) between 1993 and 2001; and 1.2 x 10^5 m^3/yr (150,000 yd^3/yr) between 2001 and 2003 (Sampey 2006). Over each period, the highest rates of tidal erosion have occurred downstream (west) of Parsons Slough. However, the 2001-2003 multi-beam dataset indicates that portions of the mudflats in this reach have experienced deposition. In the areas of the Slough landward of Kirby Park, bank failure has resulted in net deposition between 2001 and 2003. Additionally, recent modifications to the Union Pacific Railroad (UPRR) bridge crossing has been hypothesized as the cause for recent deposition at the mouth of Parsons Slough over the same period (Sampey 2006). Previously, the mouth of Parsons Slough had experienced substantial erosion and bank loss in response to the 1980's levee breaching.

Measurements of tidal currents along the main channel of Elkhorn Slough over the past 30 years confirm that current velocities are sufficiently high to scour sediment from the slough channel. Intermittent tidal current measurements collected near the Highway 1 Bridge reveal that peak velocities have increased from approximately 0.75 to 1.20 m/s (2.5 to 4 ft/s) over the past 30 years and are consistently ebb-dominated (Broenkow and Breaker 2005). Recent measurements and modeling by Stanford University have shown spatial variability in current velocities, with depth-averaged peak velocities diminishing from about 1.0 m/s (3.3 ft/s) at the Highway 1 Bridge to approximately 0.5 m/s (1.6 ft/s) near Kirby Park (Monismith and others 2005). Analysis of the critical shear stress of sediment cores collected near Seal Bend and Kirby Park suggest that velocities of this magnitude are sufficiently strong to mobilize channel and mudflat sediments (Sea Engineering Incorporated 2006). Sea Engineering Incorporated (2006) analyses suggest that velocities in the range of 0.25 to 0.45 m/s (0.8 to 1.5 ft/s) are capable of producing bed shear stresses sufficient to resuspend sediment (Sea Engineering Incorporated 2006).

2.3 MARSH LOSS

Van Dyke and Wasson (2005) applied detailed GIS tools to an extensive set of historic charts, maps and aerial photographs to quantify the rates and spatial patterns of vegetation loss and tidal creek widening over the past 150 years. Their results show complex patterns of marsh loss over space and time. Van Dyke and Wasson (2005) show that the major cause of marsh loss over the past 150 years was levee building and tidal restriction (e.g., decreased tidal exchange in marsh areas isolated from the Slough by water control structures). Although tidal exchange has been returned to many of these areas, marsh vegetation has not re-established because the former marshplains subsided during the diked period, and are no longer at corrected elevations to support marsh plants. In marsh areas along the main channel of Elkhorn Slough that have never been diked, a different type of marsh loss has been observed. There has been some marsh loss along the bank edges as the main Slough channel widens (slow and gradual), and major loss of vegetated cover in the marsh interior. The observed pattern of interior marsh loss generally begins with the formation of interior marsh ponds and expansion of marsh creeks (Elkhorn Slough Tidal Wetland Project Team 2007). Rates of vegetation loss were greatest along the lower Slough in the decade following construction of Moss Landing Harbor. While marsh loss accelerated in the upper Slough over the subsequent decades, marshes in the lower Slough experienced a temporary recovery before high rates of marsh loss returned. GIS analysis of aerial photographs between 1931 and 2003 also show an acceleration of marsh creek widening, with the most rapid widening occurring in the upper reaches of the Slough. Overall, vegetative cover decreased from an average of 90% cover to 40% cover in undiked regions between 1931 and 2003.

Although long-term tidal monitoring is not available to quantify changes to the duration of time that the marsh is inundated by high tides, it is hypothesized that increased tidal inundation is a major mechanism of marsh loss and pond formation (Elkhorn Slough Science Team 2007). This would be consistent with changes in major processes:

- elimination of the major sediment sources (i.e., diversion of the Salinas River, levee construction on the Pajaro River)
- land subsidence due to groundwater overdraft and tectonics
- improved agricultural practices that have reduced erosion from the local watershed when compared with previous agricultural practices
- accelerated sea level rise
- possible changes to the high tide water levels due to construction of the Moss Landing Harbor
- Increases in the tidal current velocities and the ebb dominance that favor a net export of sediment from the marshplain.

Recent radiocarbon-dated sediment cores collected from the Elkhorn Slough marshplains and analyzed by researchers at UC Berkeley suggest that long-term sediment accumulation rates have averaged approximately 1.1 mm/yr (0.04 in/yr) over the past 6,000 years (Burke Watson 2007). Preliminary results indicate that approximately one-quarter of the accumulated sediment is organic, and that episodic delivery from the local watershed, the Salinas River or the Pajaro River, may have accounted for the majority of imported inorganic sediment accumulation. These initial results are consistent with estimates of late Holocene rates of sea level rise of approximately 0.4 to 1.1 mm/yr (Fleming and others 1998; IPCC 2001), and indicate that Elkhorn Slough marshes had sufficient sediment sources to keep pace with sea level rise in the past.

Visual observations indicate that marsh degradation in Elkhorn Slough occur concurrently with the mortality of marsh vegetation, although the exact cause of the mortality is unknown. Marsh vegetation mortality can be caused by increased or decreased tidal inundation and decreased sedimentation, which area likely causes in Elkhorn Slough. (Marsh vegetation mortality can also be caused by biogeochemical changes, pathogens, fungi, insects, or other factors; however, these factors are not addressed in the current study.) The persistence of marsh vegetation acts to prevent erosion of the marshplain; however, as marsh vegetation dies and decays, exposed sediments are made available for subsequent erosion. In addition, in an erosional environment, this organic material is conveyed out of the system, and not incorporated as marsh building material.

3. ESTUARINE GEOMORPHOLOGY AND SEDIMENT DELIVERY

3.1 HISTORIC GEOMORPHOLOGY OF ELKHORN SLOUGH

Since the end of the most recent ice age (c. 20,000 years ago) Elkhorn Slough has continued to evolve under the influence of sea level rise, tidal and freshwater forcing, sediment delivery, and climatic variability. In recent history, the morphology of Elkhorn Slough has changed considerably due to anthropogenic causes, such as the diversion of Salinas River, the construction of Moss Landing Harbor, agricultural practices, railroad construction, and the diking and draining of tidal wetlands as discussed in Section 2. As a consequence of engineering activities and changes in sediment delivery, the morphology of Elkhorn Slough is changing from an estuary typified by extensive vegetated marsh areas towards a lagoonal system with limited areas of vegetated marsh and expansive areas of intertidal mudflat and open water.

Elkhorn Slough is comprised of several distinct habitats, or subunits, that are integral components of a dynamic evolving estuarine system that is itself, a single coherent landform. The subtidal channels, intertidal mudflats and tidal salt marshes that form on the estuarine margin are all components of the estuary that interact and evolve with each other over a range of spatial and temporal scales in response to physical and biological processes. These complex interactions at Elkhorn Slough are further complicated through the addition of the dredged harbor and ocean inlet. The form of the estuary at any given time is the current expression or ‘snapshot’ of the interaction and evolution of hydrodynamic, geomorphic, and biological processes within the estuary.

Estuaries adjust their form by the erosion and deposition of sediment. Sediment may be reworked from other parts of the estuary, or may enter the estuary from the tidal inlet downstream or the local watersheds upstream. Sediment circulates and moves between each of the components within the estuary, allowing the estuary as a whole to continually adjust towards an equilibrium form in response to changes in hydrodynamic or geomorphic processes. The interaction of the sediment supply with relative sea level rise ultimately determines how intertidal wetland habitats evolve within an estuary. Their extent and structure is also influenced by other physical processes that determine the distribution of sediments between the components of the estuary: the tidal range, the wind wave climate, flood flows, tidal circulation, and the presence of sediment sinks or sources within the system. For example, organic deposition from marsh plants occurs on the marshplain once vegetation has established, thereby increasing organic marshplain sediment accumulation. The presence of vegetation also increases the mineral sediment trapping efficiency of the marshplain.

Under historic conditions, the tidal inlet of Elkhorn Slough sustained an open connection to the ocean via a dynamic balance between deposition of wave-driven sand transport and scour by tidal currents and freshwater discharge. A tidal inlet is a restricted, relatively narrow channel developed across a barrier that provides exchange of water, energy, nutrients, sediment and organisms between the estuary and ocean.

Inlet morphology and stability largely depends upon the interactions of wave processes, that deposit beach sands at the inlet mouth and entrance channel, and tidal and fluvial flows, which scour away previously deposited material. Depending on the scale and interaction of these processes, tidal inlets may be stable and open year-round or subject to temporary closure. The Slough's historic inlet may have periodically closed, although clear evidence of that is not available.

As recently as 1880, the tidal inlet and the main slough channel were regularly navigated by steamships, suggesting a deeper channel (Van Dyke and Wasson 2005). However, the diversion of the Salinas River and increases in watershed delivery of sediment due to land clearing for cattle grazing and agriculture resulted in channel infilling and the potential for sustained inlet closure. The construction of Moss Landing Harbor in 1947, coupled with the relocation of the tidal inlet to the mouth of the submarine canyon creates a much larger and stable entrance, allowing Elkhorn Slough to exchange ocean water with Monterey Bay through the entrance channel at the harbor without risk of closure or navigation hazards.

The harbor and backwater areas landward of the current tidal inlet/harbor entrance are dredged to maintain navigable depths. The necessity for periodic dredging reflects the natural system response to foster sedimentation inboard, as well as outboard, of the tidal inlet. Typically, in a natural tidal inlet, coarse-grained sediments derived from alongshore littoral drift are captured within flood-tide and ebb-tide deltas inboard and outboard of the inlet, respectively. Fine-grained material is not commonly deposited in these shoals, but rather transported past in suspension to be deposited in more quiescent environments. At Elkhorn Slough, a flood-tide shoal tends to form from littoral sands; however, active dredging prevents its persistence. The formation of an ebb-tide shoal is impacted by the presence of the submarine canyon which acts as an irreversible sink. The absence of these shoals influences tidal flow patterns and potentially contributes to the ebb-dominance of Elkhorn Slough's tidal currents. Ebb dominance is important in that it results in the permanent removal of sediment eroded from the slough.

Prior to 1947, Elkhorn Slough's morphology reflected a tidally-influenced basin with fringing salt marshes created by mineral sediment supplied by a combination of supply from the local watershed and large seasonal contributions from the Salinas and Pajaro Rivers. The historic morphology was constrained by a natural beach barrier that limited tidal exchange that probably fostered a flood-dominant system with a net import of sediment. The combination of mineral and organic sediment accumulation within the Slough exceeded rates of sea level rise, allowing marshes to persist as sea level rose. Organic sediment contributions were predominantly derived from pickleweed marsh. The morphology of the Slough was characteristic of a river-mouth estuary in which sedimentation and accommodation space (the volume in which sediment could be deposited if sediment is available for deposition) was roughly in equilibrium with sea level rise and tidal processes. Sufficient sediment was available to maintain a stable channel-dominated system with extensive vegetated marsh areas.

The large-scale anthropogenic changes which occurred over the past century have reduced the natural sediment supply. This reduction in sediment delivery has altered the natural state of the system, shifting the Slough from a typical river-mouth estuary in equilibrium with its sediment supply to a sediment-starved lagoon. A lagoon is typified as a system with excess accommodation space that can not be met by sediment availability. The distinction between these large-scale landforms should be considered a morphological continuum of deltaic-estuarine-lagoonal morphology that can change as environmental conditions and sediment supply change. A marked increase in sediment supply to an estuary, be it mineral or organic, at a rate in excess of the hydraulic capacity to remove it will result in infilling and evolution towards a more deltaic form. Conversely, a decline in sediment supply to an estuary will result in an increase in accommodation space and evolution towards a lagoonal state.

3.2 CHANGES IN SEDIMENT DELIVERY

As discussed in Section 2.1, large-scale changes have occurred in and adjacent to Elkhorn Slough that have significantly impacted the sediment supply to the system, and therefore the overall estuarine morphology. The Salinas River likely provided a significant source of sediment to Elkhorn Slough prior to its diversion in 1909 or 1910, particularly during flood flows which conveyed large sediment loads (Gordon 1996; McGrath 1987). The construction of Moss Landing Harbor and the creation of a new ocean inlet at the Monterey Bay submarine canyon also decreased the amount of sediment entering Elkhorn Slough from long-shore currents as the submarine canyon acts as an efficient sediment sink (Peichel and others 2005). The dredged channel connecting Elkhorn Slough to the head of the submarine canyon has resulted in a sustained net export of sediment from Elkhorn Slough.

Historically, an additional source of sediment may have come from the Pajaro River. One mode of connection between the Pajaro River and Elkhorn Slough functioned similarly to the Salinas River. The mouth to the Pajaro River closed on a seasonal basis due to the formation of a sand bar during the summer, and winter flows would cause the formation of a large lagoon behind the sand bar. It is uncertain, but possibly overflows from the developing lagoon are hypothesized to have flowed southward through a channel that connected to Elkhorn Slough near the historic inlet – combining with similar flows from the Salinas River. However, published data is not available to confirm the Pajaro River – Elkhorn Slough connection. Winter storms and large flood flows on the Pajaro and Salinas Rivers would re-open their respective tidal inlets, re-establishing direct connections between the rivers and Monterey Bay. A second mode of connection between the Parjaro River and Elkhorn Slough occurs through Watsonville Creek. This creek connects the Pajaro River valley to the head of Elkhorn Slough at Hudson's Landing. This connection was active during flooding of the Pajaro River in 1995.

In addition to a potential direct fluvial connection, some fluvial sediment may have reached Elkhorn Slough via nearshore transport. Prior to 1949, the Pajaro River would regularly overtop its banks, sending flood flows and sediment-rich waters into Monterey Bay and Elkhorn Slough. In 1949, the U. S. Army Corps of Engineers completed construction of a network of levees along the Pajaro River and Salsipuedes and Corralitos Creeks to prevent fluvial flood flows from inundating the surrounding developed areas. The levee network also reduced the sediment load to Elkhorn Slough by reducing the sediment load carried by the Pajaro River into Monterey Bay and the Slough. The levee system has been intermittently breached and overtopped, and flood flows exceeded the design capacity of the levee system as early as 1955. In 2000, the Pajaro River levee system was estimated to provide protection from fluvial floods with a recurrence interval of 13 to 15 years (U.S. Army Corps of Engineers 2000), and efforts are currently underway to provide 100-year flood protection.

In the late 1800s and early 1900s, local watershed delivery of sediment to Elkhorn Slough was also likely significant due to local deforestation and the clearing of land for cattle grazing and row farming. Agricultural practices also led to significant topsoil erosion which increased the watershed-derived sediment supply; however, improved agricultural practices aimed to reduce erosion and conservation-based land acquisition activities over the past two decades have reduced (although not eliminated) these local watershed sediment loads.

3.3 PRELIMINARY SEDIMENT CORE INTEPRETATION

One of the key uncertainties facing the prediction of the future geomorphology and habitat distribution in Elkhorn Slough is defining the relative importance of mineral and organic sediment in maintaining the marshes against relative sea level rise. Specifically, as mineral sediment supply diminishes, at what point is organic supply from the remains of plant matter insufficient to keep pace with sea level rise?[1] It is possible to use the information from sediment cores to infer the contribution of mineral sediment supply in maintaining marsh elevations throughout the Late Holocene, or past 5000 years. In addition this information provides a basis for calculating the volume of sediment required to maintain marsh accumulation against 21st century increased rates of sea level rise.

This section summarizes the preliminary interpretation of sediment core data collected by the University of California at Davis (UCD) from the Yampah and Azevedo Marshes in Elkhorn Slough. These cores collected by UCD provide a record of mineral and organic sediment at each location extending to depths of -3.32 m and -5.96 m at Yampah and Azevedo Marshes, respectively. Such an accumulation of sediment represents sedimentation over several thousand years, potentially between 4000 and 6000 years.

As described in a memorandum by Burke Watson (Burke Watson 2007), three sets of data are available as part of the UCD dataset: 1) botanical determination of organic material; 2) x-radiographs of cores describing lamination structure with some supporting radiocarbon dates; and 3) various soil properties at

[1] The capacity for plants to accumulate organic deposits varies considerably dependant upon species and environmental conditions, particularly salinity. In freshwater settings such as the Sacramento – San Joaquin Delta Tule marsh has the capacity to accumulate organic deposits at over 10 mm / yr (Orr and others 2003). Pickleweed in saline conditions is far less productive than Tule species. The authors are not aware of any examples of mineral sediment-starved salt marshes keeping pace with sea level rise purely through organic sedimentation. Randall and Foote (2005), for example, document the elevations of impounded marshes with managed water levels to accrete at a lower rate of accretion than the rates of sea level rise outboard. Even under managed conditions, high rates of organic deposition did not occur in saline conditions. Further evidence of the importance of mineral sedimentation is apparent from a geomorphic examination of micro and meso-tidal estuaries. These estuaries consist of a tripartite system: barrier, inlet and flood tide shoal; deltaic sediments associated with fluvial deposits; and expansive shallows distal from sediment sources. Were salt tolerant plants capable of building marshes at a rate greater than the low rates of sea level rise seen over the past 5000 years (typically around 1 mm / yr: IPCC 2007) then these estuaries would have accumulated expansive marshes deposits where now open mudflats exist.

regular depth intervals, including bulk density, moisture content and loss on ignition (a measure of carbon content).

Though Watson's dataset is relatively small a broadly consistent history can be discerned from cores collected at sites in the both the outer and inner estuary.

From the botanical data, Burke Watson (Burke Watson 2007) describes that the cores consist of a mix of mineral and organic sediments. Plant material includes varying proportion of *Cyperaceae* (Sedges) and *Chenopodiaceae* (Goosefoot Genera including Pickleweed) with more of the salinity intolerant sedge found on the Azevedo Marsh than Yampah marsh. This salinity difference is reflected in the carbon content of the soils (Median LOI: Azevedo Marsh 25 %; Yampah marsh 10%).

The x-radiographic data identifies a stratigraphy sequence of organic rich sediments inter-bedded with occasional layers of relatively organic-poor, mineral-rich sediments. This sequence is consistent with sustained organic accumulation on a slowly accreting marshplain surface through time, occasionally punctuated by the influx of mineral deposits (such as during a high flow event or storm). Burke Watson (Burke Watson 2007) attributes these variations as the response to fluvial flood deposits. which account for 10 to 30% of the total stratigraphic column by volume.

The quantified soil characteristics provide a means to assess relative contributions of mineral and organics deposits. From the raw data the following parameters are available: mass of water (M_w)[2]; mass of dry sediment (M_s); mass of carbon (M_c); and mass of mineral sediment with carbon removed (M_m). From these data constituents, per unit volume per unit depth interval can be calculated[3].

An evaluation of the raw data shows that mineral sediment contributed between 22 to 28% of the accumulating marsh deposit, per unit volume. Carbon deposits contributions account for only about 3-6% and water 66-75% of the accumulated sediment, per unit volume; some of this water was bound within in plant matter. Using this information and assuming a rate of sea level during the late Holocene of 1.1 mm yr^{-1} (Burke Watson 2007), the average volume of particulate sediment brought into the estuary each year to maintain a marsh area of 9 Mm^2 against rising sea level can be calculated as a total a volume of 2,400 m^3. Subtidal and mudflat areas would have been accumulating sediment at similar, or greater, rates as well.

Consequently, the core data can be used to bound the time-averaged accumulation for the supply of sediment to Elkhorn Slough each year. In addition, it appears that this material was brought in to the system episodically during low-frequency, high-magnitude flow events. However it is unclear whether the sediment is derived from the Salinas River, the Pajaro River or the local Elkhorn Slough watershed, or a combination of sources.

2 M_s includes the mass of carbon plus mineral material

3 Volume of individual constituents was based upon the following densities: density of water ($\rho_w = 1.00$ g cm^{-3}); density of carbon ($\rho_c = 2.26$ g/cm^{-3}); density of mineral material ($\rho_w = 2.65$ g cm^{-3}).

The contemporary Salinas River discharges between approximately 3.3 x 10^6 Mg yr^{-1} (Farnsworth and Milliman 2003) to 1.7 x 10^6 Mg yr^{-1} (Inman and others 1998). This delivery rate is two orders of magnitude greater than the estimated delivery of 5.6 x 10^4 Mg yr^{-1} from the Pajaro River (Inman and others 1998) and 1.0 x 10^4 Mg yr^{-1} from the Carneros Creek (Watson, personal communication). With only 6.4 x 10^3 Mg yr^{-1} (based on 2.4 x 10^3 m^3 of mineral sediment of density 2.65 g cm^{-3}) required in conjunction with typical rates of organic sedimentation to keep pace with sea level rise, this volume equates to less than 1% of sediment output of the Salinas River, 11% of Pajaro River or 64% of Carneros Creek. All of these sources are therefore plausible significant sediment contributors to Elkhorn Slough. In historic times, the Salinas, along with smaller Tembladero Slough and Moro Cojo sloughs, flowed behind a spit running across the mouth Elkhorn Slough and so offered a likely source of sediment to the Slough.

Based on above data on sediment quantity it appears that sediment delivery from the Salinas River, and possibly the Pajaro River, would have allowed the marshes to keep pace with sea level rise over the past century if the Salinas Rivers had not been diverted and the Pajaro River had not been leveed. Following the diversion of the Salinas River in 1909 or 1910, no appreciable sediment from the Salinas River watershed has been delivered to Elkhorn Slough, although some minor contribution may come from the Gablian/Tembladero watershed through the old Salinas River channel. Since 1947, tidal scour has led to a net export of sediment from the Slough (although littoral sediments continue to accumulate in Moss Landing Harbor), with estimates of contemporary erosion rates between approximately 5.6 x 10^4 to 1.2 x 10^5 m^3 yr^{-1} (Dean 2003; Sampey 2006).

Assuming a 21st century rate of a low estimate of relative sea level rise of 3 mm yr^{-1} (IPCC, 2007) the approximately 6.4 Mm^2 of marshplain would require a sedimentation rate of about 1.9 x 10^4 m^3 yr^{-1} to sustain an equilibrium elevation relative to the tides[4]. However, as a consequence of tidal erosion and wetland loss over the past several decades, over 4 Mm^3 of sediment would be required to raise all of the intertidal marshplain to Mean Higher High Water.

3.4 OPPORTUNITIES AND CONSTRAINTS FOR RESTORING FLUVIAL SEDIMENT DELIVERY

Preliminary evaluation of the watersheds adjacent Elkhorn Slough does not reveal any clearly feasible source of sediment for restoring the historic rates of fluvial sediment delivery to Elkhorn Slough to reverse tidal erosion and marsh loss. This evaluation is constrained by the lack of data quantifying the inherently variable sediment loads of the adjacent watersheds. In addition to location and conveyance issues, most of the nearby fluvial sources contain contaminated sediments, reducing their potential value for marsh building.

[4] Approximately 6.3 x 10^3 m^3 of marsh sedimentation each year would balance each millimeter of sea level rise. Additional sediment would be required to raise the subsided marshplain areas at an elevation gain rate greater that sea level rise. The potential amount of sediment to raise subsided marsh areas to equilibrium marshplain elevations is estimated to be about 4 x 10^6 m^3.

3.4.1 Pajaro River

Historically, one mode of connection between the Pajaro River and Elkhorn Slough functioned similarly to the Salinas River. In the summer, the flow in the river was very low and the tidal inlet would close due to the development of a sand bar. In the winter, a lagoon would develop behind the closed inlet, and overflows from the lagoon would be directed southward, potentially connecting to Elkhorn Slough near the historic inlet just north of Moss Landing Harbor. However, no published data exist to confirm a direct connection between the Pajaro River and Elkhorn Slough at the slough mouth. When winter flood flows on the Pajaro River occurred, the Pajaro inlet would breach, re-establishing a direct connection with Monterey Bay.

For the past 75 to 100 years, the inlet has been bulldozed open to avoid agricultural flooding caused by the formation of the lagoon. However, for the past 20 years the river has been allowed to pool and meander, and the inlet is only bulldozed open if water levels within the lagoon endanger property or life. Although re-establishing or creating a connection between the lower Pajaro River and Elkhorn Slough could provide a potential source of sediment for Elkhorn Slough, this solution may not be desirable as it would increase the sediment loading to Moss Landing Harbor and increase the need for maintenance dredging. In addition, the sediment load transported by the Pajaro River is likely far below historic levels. The levee system constructed in 1949 reduced the overbank flood frequency of the Pajaro River, potentially decreasing the net downstream sediment transport during large flood events. Improved agricultural practices and sand mining have also decreased the Pajaro River's sediment load compared to the early and mid-1900s.

The Pajaro River upstream of Highway 1 presents an alternative opportunity for restoring sediment delivery to Elkhorn Slough. In 1995, a major flood event breached the Pajaro River levees when flows exceeded the design capacity. During this event, Watsonville Creek, , a channel between the upper Pajaro River and the Slough, conveyed flows from the Pajaro River to the Slough. The function of this channel could be enhanced in order to increase Elkhorn Slough's sediment supply. However, the nearly 3-mile long channel has a very low slope; therefore sediment deposition within the channel would likely occur, decreasing the conveyance capacity and increasing the likelihood of flooding of the adjacent agricultural lands. In addition, water and sediment quality within the Pajaro River are poor due to legacy contamination from agricultural practices. The impaired water and sediment quality could limit the value of this connection; however, this opportunity warrants further study as it presents a potentially feasible option for restoring natural sediment delivery upstream in Elkhorn Slough.

3.4.2 Salinas River

The Salinas River provides the largest source of sediment in the region. Estimates of sediment discharge range between 1.7×10^6 Mg yr^{-1} (Inman and others 1998) and 3.3×10^6 Mg yr^{-1} (Farnsworth and Milliman 2003). Although the exact nature and variability of the historic contribution from the Salinas River to Elkhorn Slough is not currently clear, it likely provided the major source of sediment to Elkhorn Slough. However, the diversion of the Salinas River in 1909 or 1910 dramatically decreased this potential sediment source. Presently, only the Gabilan/Tembladero watershed, a sub-watershed of the historic Salinas River watershed is still connected hydraulically to Elkhorn Slough through the Old Salinas River Channel and Moss Landing Harbor; however, flow rates are low, and the two systems are connected via culverts and tide gates which limit the transport of both water and sediment.

There are two major constraints associated with reconnecting the Salinas River sediment supply with Elkhorn Slough: sediment quality and the location of the historic connection. The use of agricultural chemicals in the Salinas Valley resulted in legacy pollution problems with pesticides such as DDT and other persistent pollutants. There is a high level of concern about the potential impact of these pollutions on Elkhorn Slough organisms should this connection be restored. Historically, sediment delivery from the Salinas River occurred along the Old Salinas River channel, through the South Moss Landing Harbor, to the mouth of Elkhorn Slough. In some years the Salinas River opened directly to Monterey Bay near its current location, limiting the connection with Elkhorn Slough. Reconnection of significant Salinas River flows to the Old Salinas River Channel would result in considerable deposition along the Old Salinas River channel, and especially in the South Harbor. This would impact agricultural operations and facilitate the need for more frequent dredging in the South Harbor.

3.4.3 Carneros Creek

Carneros Creek, which is within Elkhorn Slough's watershed, is estimated to have an annual sediment load of 1.0 x 10^4 Mg yr^{-1} (E. Watson, pers. comm.). However, much of the creek's sediment load has filled in the lower reach of the creek, augmenting a freshwater marsh and limiting sediment conveyance capacity to Elkhorn Slough (B. Largay, pers. comm.). Carneros Creek is connected to Elkhorn Slough by tide gates under Elkhorn Road in the Hudson's Landing area; and the tide gates likely affect sediment delivery to Elkhorn Slough. Activities within the Carneros Creek watershed have been underway to improve the water quality within the creek, including improving agricultural practices to reduce erosion and decrease sediment loadings and potential sources of pollution to the creek.

3.4.4 Imported Sediment

Imported sediment, or fill, could provide an additional source of sediment for Elkhorn Slough. Sediment could be imported via a barge, pipeline, train, or truck and either placed in the main Slough channel or on the marshplain. Additional analyses would be required to better determine the most effective use of fill along the Slough's main channel or on the marshplain.

Currently, the eroding main channel is a sediment sink because it removes sediment from Elkhorn Slough that may otherwise be available to the marshplain. The sediment sink of the main channel is not the final destination of sediment; sediment passes out of the main channel to Moss Landing Harbor and Monterey Bay. If restoration actions are successful at reducing tidal current velocities along Elkhorn Slough, sediment could be placed in the main Slough channel between Moss Landing Harbor and Parsons Slough to fill a sediment sink that may compete for the limited amount of marsh-building sediment available to the system. Because fill in the main channel would not be a substrate for vegetation, it could consist of larger-grained sand particles that are more resistant to erosion than the fine particles found on the marshplain. Fill placement may also have the additional benefits of further reducing tidal current velocities by increasing bed friction losses and improving water quality by reducing residence time. Estimates of fill requirements to raise the main channel bed thalweg to elevations between -8 ft NAVD and -12 ft NAVD are provided in Section 7.3.

Imported fill could also be placed on the marshplain to bring subsided and degraded marshes to a more sustainable elevation for marsh vegetation. Raising existing marsh areas (excluding Parsons Slough) by approximately 0.33 m (1 foot) would require approximately 1 Mm^3 (1.4 million cubic yards) of imported fill. This effort could be accomplished in several phases with early efforts focused on the more subsided and degraded marshes. It should be noted that with accelerated sea level rise, continued placement of imported fill material on the marshplain may be required at regular (e.g., decadal) intervals unless a local of source of natural supplied sediment can be identified to maintain marsh elevations as sea levels rise.

A study is currently underway to evaluate options for sediment supply to rebuild marsh habitat in the Parsons Slough, for which approximately 1.7 Mm^3 (2.2 million cubic yards) of sediment would be required to recreate historic marshplain elevations (Moffat and Nichol, 2008). This study has identified a number of land-based and marine-based sources and delivery opportunities. The most promising land-based source is the Graniterock quarry in Aromas, which generates 450,000 metric tons per year (500,000 short tons per year) of excess granitic dust (passing 200 sieve) at a cost of $7 per cubic yard (B. Largay, pers. comm.). Marine-based sources include: Moss Landing Harbor, Santa Cruz Harbor, Monterey Harbor, the Nearshore Ocean, and Offshore Ocean.

3.4.5 *Spartina* Introduction

The primary species of vegetation colonizing he marshplain of Elkhorn Slough is pickleweed. In tidal marshes to the north, another plant species, cordgrass (*Spartina foliosa*), occurs, which is adapted to colonizing lower elevations. Although not directly related to increasing fluvial sediment t delivery, the introduction of *Spartina* may increase the trapping efficiency of the marshes, allowing more of the existing sediment available within the system to be captured for marsh building. *Spartina*, which colonizes lower in the tidal frame than pickleweed, may locally increase sediment accretion and may slightly raise the marshplain elevation as a result of belowground organic matter accumulation. However, the introduction of *Spartina* would not address the major erosion factors: current erosive characteristics of the Slough and insufficient supply of sediment. Without a solution to address these core issues, the introduction of *Spartina* alone would not likely reduce marsh loss over the short-term in the face of longer-term increases in sea level and continued exposure to erosive tidal forces.

There is currently no evidence that *Spartina* occurred naturally within Elkhorn Slough. Therefore several factors should be considered before introducing a new species:

- If *Spartina foliosa* is introduced into Elkhorn Slough, the Elkhorn Slough National Estuarine Research would need to be prepared to accept the fact that if *S. alterniflora* or its hybrids should find its way into Elkhorn Slough, they may eventually end up with the hybrid as well. Since *S. alternifora* and its hybrid can occupy a much wider ecological niche along an elevation gradient (e.g., such as colonizing lower in the tidal frame), they would need to consider the effects of the introduction on areas higher in the marsh and lower in the intertidal zone. This could mean a reduction in habitats such as small intertidal channels and eel grass beds.

- While the goal would be to introduce a pure strain of *S. foliosa*, it is uncertain whether pure populations exist anymore in San Francisco Bay from which to collect parent material. If this does prove to be feasible through careful genetic testing, the Elkhorn Slough system could potentially provide a genetically pure bank of material for future restoration projects in San Francisco Bay.
- A look at the tidal currents along the coastline would be necessary to determine if *Spartina* might be transported to other outer bays/estuaries that currently do not support *Spartina* populations (e.g., Morro Bay).
- Species introductions have become increasingly controversial and the long-term effects of such an introduction require a thorough evaluation. *Spartina* was introduced in both San Francisco Bay and in Puget Sound for erosion control and bank stabilization. The Invasive *Spartina* Project in San Francisco Bay and the Washington State Department of Agriculture should be contacted to get a clear understand of the possible long-term effects of *Spartina* introduction on Elkhorn Slough.
- *Spartina* does form strips of vegetation along the outboard extent of marshes in San Francisco Bay. However, due to the erosional nature of the system, the bank morphology in Elkhorn Slough is different from most areas in San Francisco Bay where *S. foliosa* is present. For example, on the east shoreline of San Francisco Bay where a pronounced chenier ridge exists at the marsh edge due to higher wave action relative to other portions of the Bay, there is very little *S. foliosa*. Given these observations, we would expect *S. foliosa* to establish in the subsided marsh interiors of the Elkhorn Slough more so than along the marsh perimeter. Also, as stated above, the possibility exists that *S. alterniflora* and/or its hybrid could occur and would occupy a much broader niche than *S. foliosa*.

The introduction of *Spartina* into the Elkhorn Slough system would likely result in increased vegetated marsh and a slight reduction in the rate of decline of these marshes over the short-term. The beneficial effects of introduction could be greater if the erosive tidal forces were diminished and a greater amount of suspended sediments were available within the system. However, any expected short-term potential benefits need to be weighed carefully against the possibility for unintended consequences often associated with species introductions.

3.5 SEDIMENT SOURCES, DEFICITS, AND DEMANDS

Table 3-1 provides a scoping level estimate of the sediment budget for restoration of Elkhorn Slough. Sediment quantities are provided in terms of both mass and bulk volume of sediment (i.e. volume of deposited material including pore spaces). Included are estimates of sediment flux from local river systems, derived from previous studies.

Sediment demand to restore the Slough's marsh to pre-harbor conditions is considerable. The amount of sediment required depends upon the capacity to reduce exports from the Slough and the magnitude of future sea level rise. Historically the estuary was maintained in a relatively 'full' state, sequestering on average 6 x 10^3 Mg of mineral sediment each year from the more than 1.7 x 10^6 Mg that were delivered by the local rivers. For much of the 19th century, sea level rise was relatively slow (1.1 mm/yr). With harbor construction, tidal scour has resulted in 1.1 x 10^6 Mg or more of sediment being lost from the main channel system. Sediment has also been lost from the marsh plain both through marshplain erosion and expansion of internal channel networks. For all marsh areas, including Parsons Slough, the lost sediment is probably on the order of 1.9 x 10^6 Mg.

In absence of actions to reduce erosion sediment export will continue from the estuary. The volume of sediment loss from the main channel is estimated to be somewhere between 31 x 10^3 Mg/yr and 67 x 10^3 Mg/yr (Dean 2003; Sampey 2006). Our study suggests that over time the extent of sediment loss from the main channel will continue, although at a declining rate (see Section 6.2 and Table 6-4 below). Engineering actions at the mouth Elkhorn Slough and in Parsons Slough would reduce the export of sediment but not provide a supply of sediment to meet demands to maintain marshes in response to accelerating, sea level rise. Presently, under sea level rise conditions of 3 mm/yr, to maintain the existing marsh area (796 acres) against sea level rise requires supply of around 5 x 10^3 Mg/yr of sediment. This estimate does not account for sediment that will be required to maintain mudflat areas (1605 acres), an additional 10 x 10^3 Mg per year.

Application of sediment can, depending upon volume, forestall or reduce the rate of marsh loss. Examples of potential sediment sources include 5 x 10^5 Mg/yr of quarry sediment. This source would provide a significant contribution to maintaining or rebuilding a section of Elkhorn Slough's marshplain. However, this volume equates to the volume of sediment currently lost from Elkhorn Slough every five years. This short lifespan of placed fill points to the importance of reducing sediment loss from the system, taking a phased approach to restoration, and focusing the application of available sediment to key habitat areas. It is less clear at this time whether, along with construction of a sill, refilling the 2 x 10^6 Mg of lost from the main channel is necessary to reduce the rate of marsh conversion to mudflat. At this stage best available information suggests that by not filling the channel will sustain a sink competing with the marshplain for sediment. As a result, the marshplain would be less resilient to sea level rise. As part of a phased approach, the necessity to refill some or the entire channel could be assessed as an adaptive management requirement after sill construction.

Table 3-1. Components of Elkhorn Slough Sediment Budget

Sediment Budget Component	Sediment Mass	Units	Sediment Bulk Volume	Units	Source
Salinas River	1,700,000 to 3,300,000	Mg	3,000,000 to 6,000,000	m^3	Farnsworth and Milliman (2003); Inman and others (1998)
Pajaro River	56,000	Mg	100,000	m^3	Inman and others (1998)
Carneros Creek	10,000	Mg	17,900	m^3	Burke Watson, personal communication
Historic demand for sustaining marsh	6,100	Mg/yr	13,200	m^3	Estimated by PWA using Burke Watson (2007) cores.
Demand for sustaining remaining marsh area	4,900	Mg/yr	10,700	m^3/yr	Estimated by PWA using Burke Watson (2007) cores.
Demand for sustaining restored marsh, per acre	6	Mg/yr	14	m^3/yr	Estimated by PWA using Burke Watson (2007) cores.
Deficit on marshplain	1,850,000	Mg	4,000,000	m^3	Estimated by PWA as volume required to raise all of the marsh plain to MHHW.
Deficit from past channel erosion (1943 bathymetry - 2003 bathymetry)	1,100,000 to 1,700,000	Mg	2,000,000 to 3,000,000	m^3	Estimated order of magnitude
Channel erosion rate (2001-2003)	31,000	Mg/yr	56,000	m^3/yr	Dean (2003)
Channel erosion rate (2003-2005)	67,200	Mg/yr	120,000	m^3/yr	Sampey (2006)
Predicted channel erosion rate (Alternative 1 - No action, Year 0 – Year 10)	54,900	Mg/yr	98,000	m^3/yr	Table 6-4
Predicted channel erosion rate (Alternative 1 - No action, Year 10 – Year 50)	24,000	Mg/yr	43,000	m^3/yr	Table 6-4
Graniterock Quarry granitic dust (Potential off-site sediment supply)	500,000	Mg/yr	900,000	m^3/yr	Don Barret, Graniterock, personal communication

Assumptions

- Average density of sediment eroded from channels and placed on marshplain is 1.5 Mg/m3 (estimated from (Sea Engineering Incorporated 2006)
- Average density of natural marsh including organic contributions is 1.25 Mg/m^3 (Burke Watson 2007)
- Sediment bulk volume includes pore spaces
- Historic area of wetlands = 2965 acres; Existing Salt marsh area = 796 acres
- Current rate of sea level rise = 3 mm/yr; Late Holocene rate of sea level rise = 1.1 mm/yr
- Marsh deficit estimates including Parsons Slough, which is assumed to have subsided by 1 m.

4. DESCRIPTIONS OF PROPOSED RESTORATION ALTERNATIVES

The proposed restoration alternatives are similar to the large-scale alternatives presented in the Elkhorn Slough Tidal Wetland Strategic Plan (Elkhorn Slough Tidal Wetland Project Team 2007). These restoration alternatives were previously presented in the Restoration Concepts Memorandum dated July 17, 2007 (Philip Williams & Associates 2007e). The restoration alternatives are, in summary, defined as:

- Alternative 1: No Action
- Alternative 2: New Ocean Inlet
- Alternative 3: Tidal Barrier at Highway 1
- Alternative 4: Restoration at Parsons Slough

It should be noted that some of these actions could be combined, implemented in phases, and/or managed adaptively in order to improve restoration performance. For example, Alternative 4 (Restoration at Parsons Slough) could be combined with either of the other 'action' alternatives (Alternative 2 or 3). In the case of Alternative 3, the sill at Highway 1 could be designed to accommodate future increased elevations if additional reductions in tidal prism are warranted. In addition, instead of single sill at the Highway I bridge, multiple sills could be constructed upstream in Elkhorn Slough to further reduce tidal prism, velocities, and tidal scour. Multiple sills may also allow for better navigation opportunities within the Slough. Alternatively, the sill at Highway 1 could be raised to become a full tidal barrier if managers decide to implement Alternative 2 in the future. This would allow the managers to test the effectiveness of the sill before constructing a new ocean inlet.

Other adaptive management options are also available to reduce tidal erosion and/or marsh loss, including mechanical placement of sediment on the marshplain to raise marshplain elevations. Imported sediment could also be placed along the main channel of Elkhorn Slough. Assuming that the restoration alternatives described below are successful in reducing tidal current velocities along Elkhorn Slough, placing imported fill along the channel bed could potentially improve marsh sustainability by filling a sediment sink that would otherwise sequester the limited amount of marsh-building sediment available to the system. Filling deep portions of Elkhorn Slough may also, at least partially, mitigate adverse effects on water quality. The predicted long-term equilibrium dimensions of the slough under the restoration alternatives, combined with an iterative modeling approach, would be required to refine the extent and elevation of possible fill placement along the slough channel. This analysis has not been performed as part of the current study. An additional adaptive management option is the introduction of *Spartina*, which could increase the amount of vegetative cover and slow marsh loss. However, the introduction of species needs to be considered carefully, as discussed in Section 3.4.

4.1 ALTERNATIVE 1 – NO ACTION

Alternative 1 represents the No Action Alternative, which assumes that no intervention is taken to arrest the current patterns of tidal erosion and wetland loss. Hydrodynamic modeling results and projections of future morphology for this alternative provide a benchmark for evaluating the effectiveness of the proposed action alternatives.

Existing data on the slough bathymetry, distribution of tidal habitats, and hydrodynamic properties were used to specify model parameters for Alternative 1. The details of these data are described in the model calibration report (Appendix A). The hydrodynamic modeling results and methodology for projecting future morphology (see Section 5 below) are then used to predict future hydraulic and geomorphic conditions at Year 10 and Year 50.

4.2 ALTERNATIVE 2 – NEW OCEAN INLET

Alternative 2 would create a new ocean inlet and a new channel to reconfigure Elkhorn Slough's connection with Monterey Bay (Figure 4-1). The new ocean inlet would be located at approximately the historic location of the old Salinas River mouth in 1943, and extend into Lower Bennett Slough. The new channel would connect to the new inlet, extend along the north and east sides of the Department of Fish and Game (DFG) Wildlife Management Area, and join the Slough approximately 1 km east of the Highway 1 bridge. This alternative also requires both a barrier under the existing Highway 1 bridge to completely block tidal exchange between Elkhorn Slough and Moss Landing Harbor, as well as a new bridge where Highway 1 crosses the new channel.

Implementation of this alternative within the hydrodynamic model required specification of the following components:

- *Ocean inlet* – The new ocean inlet will be at the same location as the pre-harbor (e.g., 1943) location of the Salinas River. Currently, this location is occupied by beach and dunes. Based on the relationship between tidal prism and inlet area of other existing inlets (Jarrett 1976) and the 1943 USACE survey of the Salinas River inlet, the initial estimate for the inlet's narrowest point, the throat, was a cross-sectional area below mean sea level between 93 m^2 (1,000 ft^2) and 280 m^2 (3,000 ft^2). The initial throat geometry estimate, along with the remnant flood shoal channel structure evident in the LiDAR data set, were modified iteratively in the model bathymetry to remove sharp velocity gradients across the complex planform structure of the region. The final inlet cross–sectional area is 135 m^2 (1450 ft^2) below mean lower low water (MLLW), calculated based on the reduced tidal prism in the resulting simulations. The Inlet Stability Memorandum presents a cross-sectional area of 265 m^2 (2850 ft^2) which corresponds the existing tidal prism. An analysis of the stability of the new inlet is discussed in Appendix B (Inlet Stability Assessment).

- *Flood-tide shoal* – In addition to the inlet, soundings collected by the USACE in 1943 and historical photographs indicate that extensive intertidal flood-tide shoals were present prior to construction of Moss Landing Harbor. The proposed location for the flood-tide shoal coincides with the pre-harbor location of this shoal, known today as Lower Bennett Slough. The LiDAR elevation data for Lower Bennett Slough revealed indications of the historic flood-shoal structure. The planform structure of the historic channels was preserved and their bed elevation lowered such that the channels' total cross-sectional area was proportional to the new ocean inlet.

- *Connecting channel* – The planform location of the constructed tidal channel that connects Elkhorn Slough to the new ocean inlet is somewhat constrained by property ownership and existing infrastructure. The proposed location was selected to connect with the eastern boundary of the flood-tide shoal, cross under Highway 1 at the existing Lower Bennett Slough culvert, follow the existing Lower Bennett Slough channel along the north side of the DFG Wildlife Management Area, and turn south along the east side of the DFG area, following the existing marsh channel where possible (Figure 4-1). The channel's width was set to 100 m (330 ft) to remain within property boundaries. Its depth was set to 4.3 m (14 ft) below MLLW such that peak flow velocities in the channel remained below 1 m/s (3.3 ft/s). With these dimensions, the channel's cross-sectional area is less than the existing Elkhorn Slough channel, but greater than the 1943 entrance channel. Model testing of a channel whose depth is 2.3 m (7.5 ft) below MLLW produced peak flow velocities significantly above 1 m/s, possibly leading to excess erosion. At later stages in the planning process, this channel's dimensions could be further refined. Options include creating a shallower channel that may undergo some limited, but not harmful, erosion, or levee setbacks to expand the channel's width. It should be noted here that a number of other channel alignments are feasible, and can be considered in a future refinement phase. For example, the channel could be routed in different ways through the DF&G property, and could be use to create a physical barrier ("moat") to reduce disturbance by feral animals etc. to various parts of the system.

- *Highway 1 barrier* – For the hydrodynamic model, the proposed barrier under the existing Highway 1 bridge will be a dam with an elevation above the highest tide elevation. Hence, no tidal exchange would occur between Moss Landing Harbor and Elkhorn Slough.

- *New Highway 1 bridge* – The new bridge is assumed to span the new connecting channel's full width and would be above the channel's highest tide elevation. It is assumed that the bridge would be designed such that it would not affect flow in the channel, therefore the bridge is not included in the model domain.

A modified configuration for the new ocean inlet was proposed by PWA but not selected for further analysis because of its impacts on the harbor. This Alternative 2b (New Ocean Inlet – Extend North Jetty) is depicted in Figure 4-2. The alternative consists of a new inlet just north of the north jetty, and an extension of the north jetty eastward to the vicinity of the south abutment of the exiting Highway 1 Bridge. This alternative may be more consistent with coastal sand transport processes and therefore may be more "stable" in terms of closure potential and migration. (See Appendix B: Inlet Stability Assesement for a more complete discussion of the coastal processes affecting the new inlet.) The Highway 1 barrier and new bridge included in Alternative 2 (Figure 4-1) would not be necessary for Alternative 2b, reducing construction costs as compared with Alternative 2.

4.3 ALTERNATIVE 3 – TIDAL BARRIER AT HIGHWAY 1

Alternative 3 includes two scenarios for the construction of a partial tidal barrier, referred to as a sill, at the Highway 1 bridge (Figure 4-3). Implementation of this alternative would reduce tidal exchange between the Slough and Moss Landing Harbor but not eliminate this hydraulic connection. The sill would perform a similar function to the historic shoaling inlet by reducing tidal exchange.

Evaluation of this alternative with the numerical model required specification of the sill parameters. Alternatives 3a and 3b include sills with a crest elevation at 1.4 m (4.6 ft) and 0.1 m (0.3 ft) below MLLW, respectively. These crest elevation were selected after testing a range of sill elevations indicated that a lower sill has minimal impact on the Slough's water levels and bed shear stress. The lower sill (Alternative 3a) was included as a potential option to maintain boat navigation though reducing the available clearance at the low water levels to less than 1 m (3.3 ft). The higher sill elevation more substantially reduces tidal prism but with greater impact on navigation, and circulation related to water quality.

These configurations of a single sill provide an initial estimate of the Slough's hydraulic response to a partial tidal barrier at Highway 1. Additional analysis would be necessary during the conceptual design phase to better define the optimal barrier configuration. Additional design refinements are also possible, such as providing a 'notch' in a higher elevation sill that would allow for passage of small watercraft. Imported fill could also be placed upstream of the sill along the bed of the main Elkhorn Slough channel, as described in Section 3.4.4. This fill would eliminate a sediment sink that would otherwise sequester the limited amount of marsh-building sediment available to the system. Placement of fill along the main channel was not included in the hydrodynamic modeling of this alternative.

Modeling of a single sill provides an indication of the Slough's response to a constriction at Highway 1. For purposes of comparing the long-term Slough response to different large-scale restoration alternatives, consideration of a single sill is sufficient. If future consideration of this alternative is hampered by navigation concerns, then multiple sills east of Highway 1 may be a viable alternative. The number, location, and crest elevations of multiple sills can be analyzed and optimized to reduce current speeds and hydraulic discontinuities, i.e. "weir pour-over", while also providing a reduction in tidal prism.

4.4 ALTERNATIVE 4 – RESTORATION OF PARSONS SLOUGH

Unlike the other proposed restoration alternatives described above, Alternative 4 does not include direct modification of the tidal prism by changes to the ocean inlet or slough channel. Instead, Alternative 4 would reduce the erosion potential in the main slough channel downstream of the Parsons Slough mouth by reducing the tidal prism from Parsons Slough and South Marsh (Figure 4-4). Due to its relatively large size of 175 hectares (430 acres) and bed elevations which have subsided by approximately 1 m (3 ft) below MHHW, Parsons Slough and South Marsh represent approximately 1.8 million m^3 (1,500 ac-ft) of the overall flow, or 30% of the total tidal prism, of Elkhorn Slough (Broenkow and Breaker 2005).

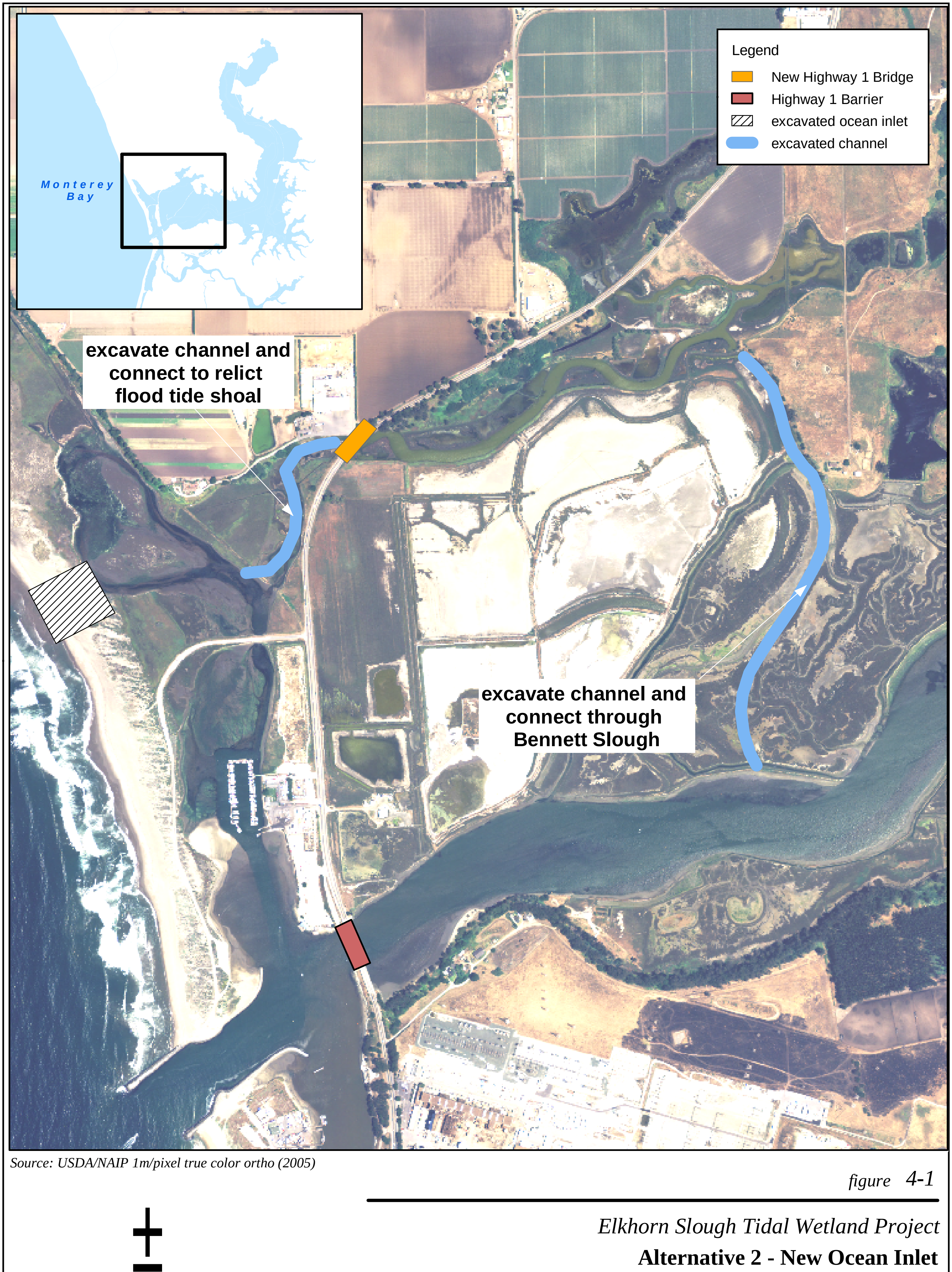
Philip Williams & Associates (1992) suggested that this reduction in tidal prism could be achieved in one of two ways (Figure 4-4). In the first approach, fill could be used to raise the bed of the Parsons Slough and South Marsh to elevations appropriate for a natural marsh (approximately MHHW), and the system would be subject to the full tidal range. This approach would likely require reconstruction of the opening under the UPRR bridge to prevent subsequent erosion of the placed sediment. The second approach would be to manage the hydrology of Parsons Slough and South Marsh with a new water control structure such that the inboard tidal inundation characteristics are appropriate to support marsh vegetation at the existing bed elevations. This new water control structure would be located along Parsons Slough at the UPRR trestle.

These two approaches would show comparable results on Elkhorn Slough outboard of Parsons Slough, assuming they mobilize the same tidal prism. The implementation of this alternative in the model is based on the former approach (e.g., placing fill to raise the bed elevation of Parsons Slough and South Marsh). Assuming that vegetated marsh would establish on top of the fill, hydraulic geometry relationships estimate that a diurnal tidal prism of 370,000 m^3 (300 acre feet) would be required to sustain this site (Philip Williams & Associates and others 1995). The bed elevation within Parsons Slough and South Marsh was therefore raised within the model. The appropriate increase in bed elevation (approximately 1.2 m, 3.9 ft) was determined through a sensitivity analysis. This increase yields a modeled tidal prism in close agreement with the target tidal prism of 370,000 m^3.

This alternative is now being evaluated in detail under a separate study being conducted for the Elkhorn Slough Foundation. Co-ordination between the separate Parsons Slough study and this report's larger scale study was initially established to allow the larger scale modeling of the impact of Parsons Slough restoration to represent the more detailed considerations of the Parsons Slough study.

Although it is recognized that Alternative 4 will be considered independently from the other proposed restoration alternatives, it can also be considered in combination with either Alternatives 2 or 3.

4.5 FIGURES



Source: USDA/NAIP 1m/pixel true color ortho (2005)

figure 4-1

Elkhorn Slough Tidal Wetland Project

Alternative 2 - New Ocean Inlet

Proj. # 1869

PWA

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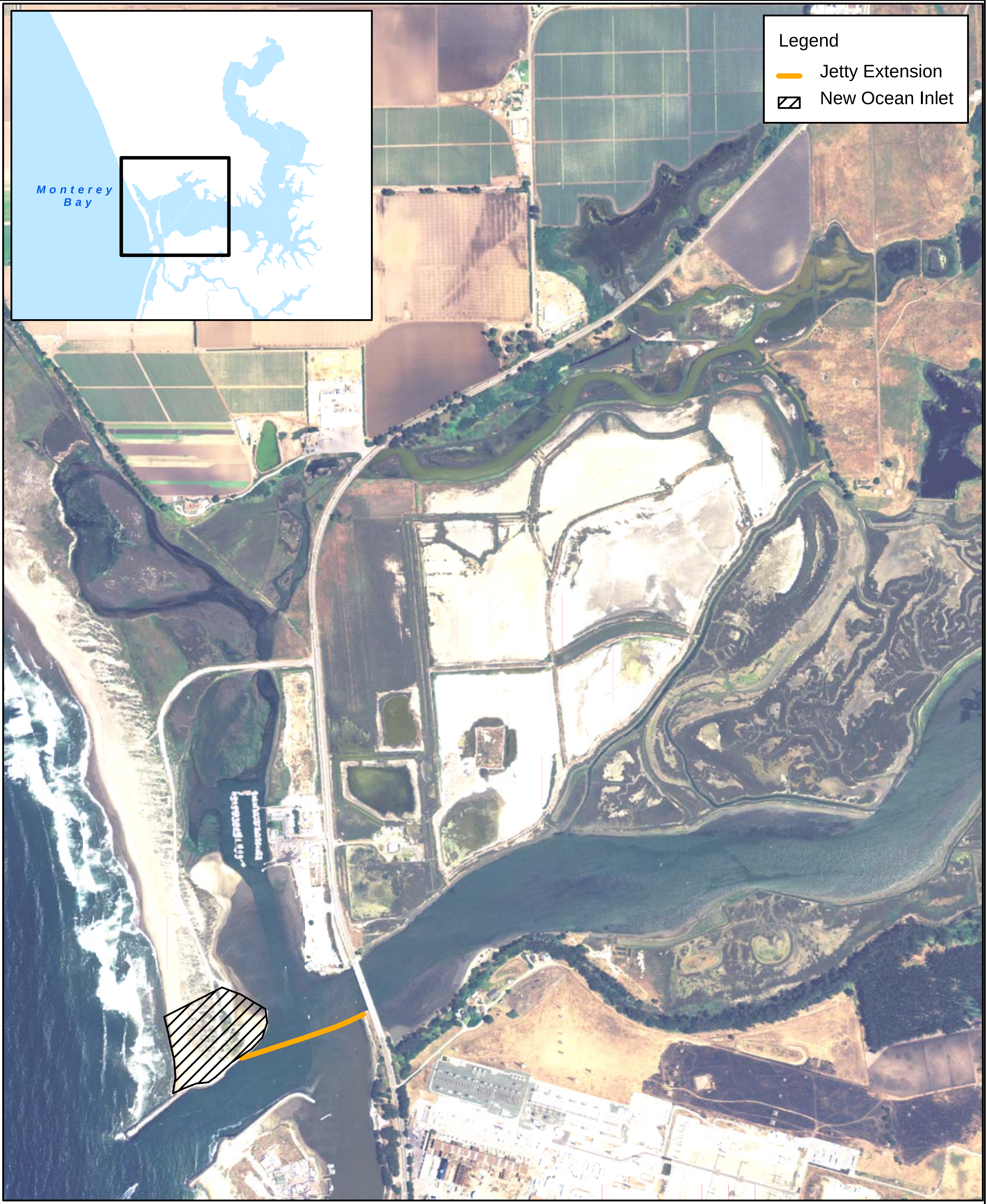


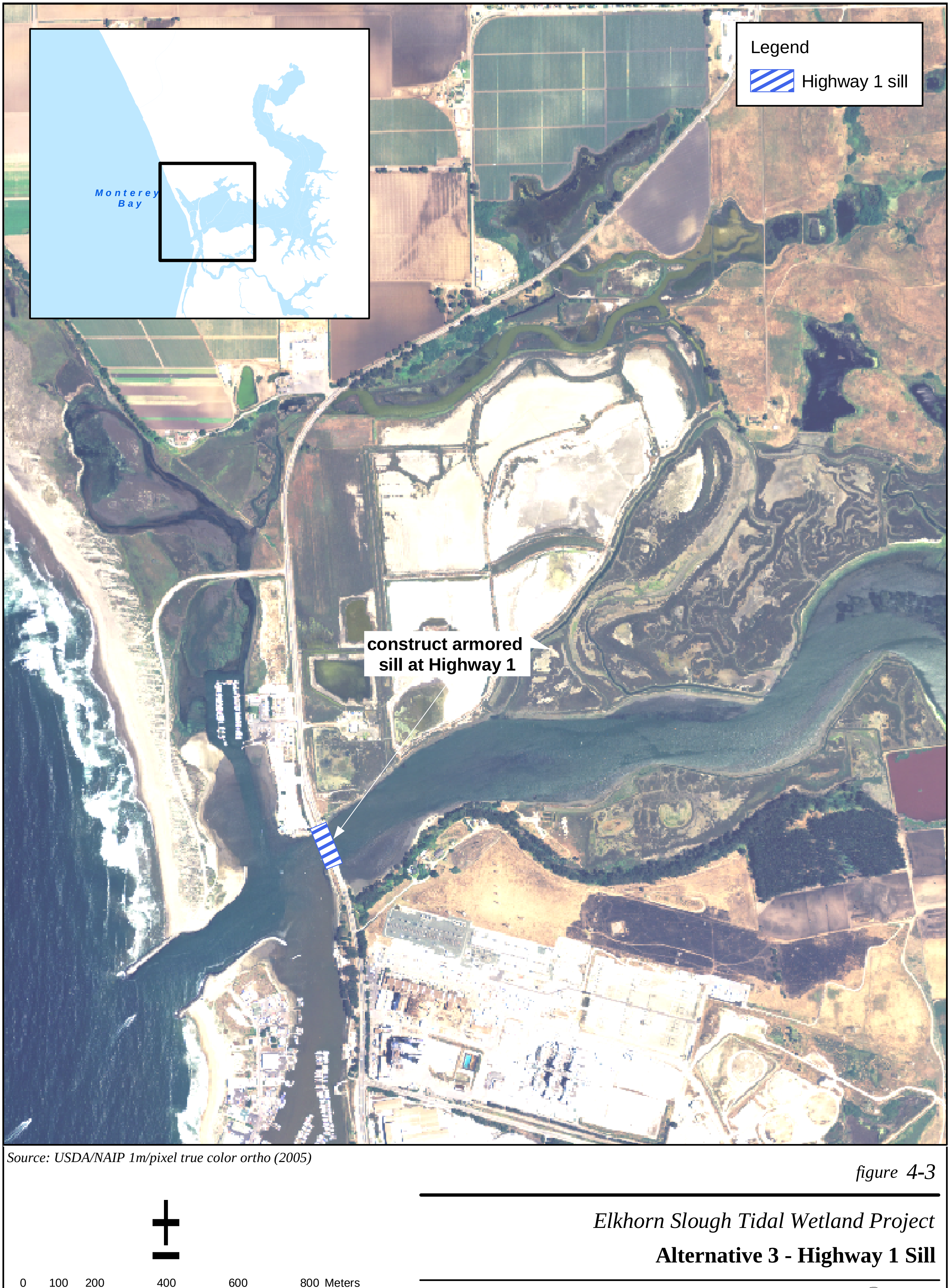
Source: USDA/NAIP 1m/pixel true color ortho (2005)

figure 4-2

Elkhorn Slough Tidal Wetland Project

Alternative 2b - New Ocean Inlet - Extend North Jetty

PWA



Source: USDA/NAIP 1m/pixel true color ortho (2005)

figure 4-3

Elkhorn Slough Tidal Wetland Project

Alternative 3 - Highway 1 Sill

Proj. # 1869

PWA

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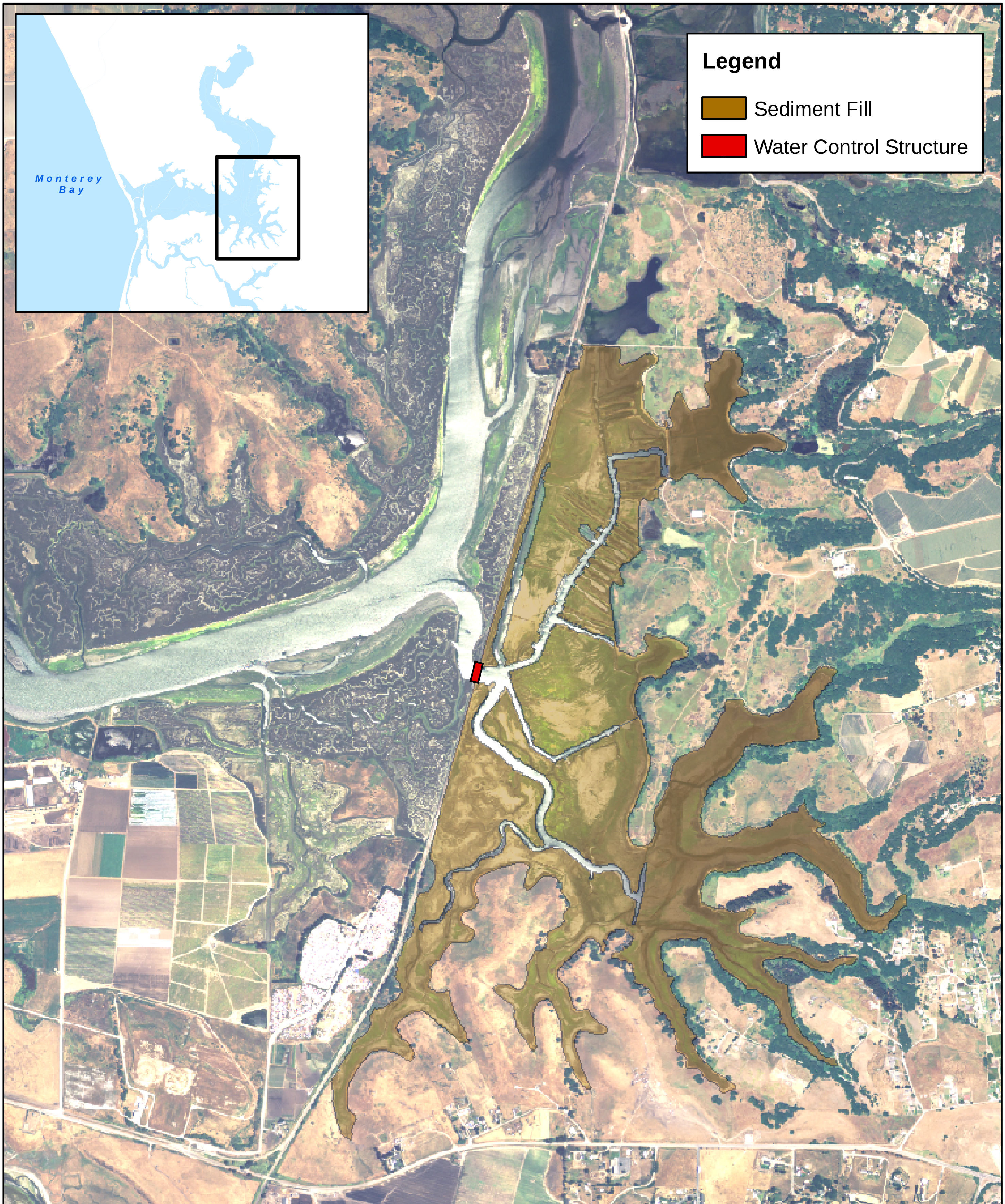

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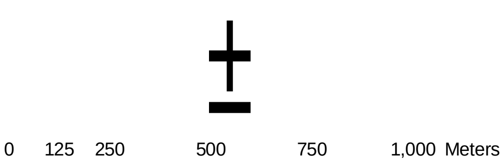

figure 4-4

Elkhorn Slough Tidal Wetland Project

Alternative 4 - Parsons Slough

Proj. # 1869

PWA

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5. EVALUATION OF ALTERNATIVES

This section presents an evaluation of the proposed restoration alternatives, outlined in Section 4, including the results of the geomorphic assessment and the DELFT3D hydrodynamic modeling. Before presenting the results, a summary of the development of the hydrodynamic model and the methodology developed for projecting the future Slough morphology is presented. The calibration and validation of the DELFT3D hydrodynamic model was described earlier (PWA (2007a) and Appendix A).

Alternative 1, the No Action Alternative, provides a baseline of comparison for the management alternatives. All alternatives are compared immediately after implementation (Year 0), at Year 10 and Year 50. The comparisons at Year 10 and Year 50 couple the Slough's geomorphic and hydrodynamic response to the restoration alternatives. The geomorphic response is evaluated by comparing thalweg depths and annual erosion rates; and the hydrodynamic response is evaluated by comparing the results with respect to water levels, current velocities, and bed shear stress.

5.1 DEVELOPMENT OF THE HYDRODYNAMIC MODEL

DELFT3D was selected as the primary hydrodynamic modeling tool for the Elkhorn Slough TWP restoration evaluation. DELFT3D was developed by WL | Delft Hydraulics in coordination with Delft University and consists of an integrated set of modules that simulate hydrodynamic flow. DELFT3D models unsteady tidal flows, flow through hydraulic structures, and drying and flooding of intertidal areas. The model employs a curvilinear flexible-mesh grid system, which provides the ability to fit the computation grid to the variable bathymetry of Elkhorn Slough.

Appendix A presents the details of the model calibration and validation. The calibration focused on comparing predicted and observed water levels and current speeds (Monismith and others 2005) at multiple stations in the main Elkhorn Slough channel. Water levels were analyzed at four stations using time series comparisons, statistical correlations and tidal harmonic analysis at the four stations. During the calibration period, the predicted water levels matched the observed water levels closely. The correlation coefficients squared (r^2) were greater than 0.99 for three of the four stations, with the largest differences ($r^2 = 0.98$) observed at a station with possible errors in the measured water levels. The model accurately reproduced estimates of aerial inundation extent produced by SFML from aerial photographs, providing confidence in the model's ability to represent hydrodynamics over the marshplain.

Predicted current speeds also matched closely with observed current speeds, with correlation coefficients squared (r^2) greater than 0.96 at three of five stations analyzed. At two of the stations, the data was inaccurate or limited in vertical extent. At the Parsons Slough station, the instrument location relative to the main tidal flows prevented it from properly measuring ebb tides. However, predicted and observed current speeds matched well on flood tide. At the fifth station, only a point velocity measurement was collected, therefore a logarithmic velocity profile had to be assumed to estimate the depth-averaged velocity from the point velocity measurement. Using this approach, the model tends to over predict current speeds at this station on the stronger flood tides. In general, the model accurately predicts the semi-diurnal pattern and spring-neap variability observed in the current speed field measurements, with the highest velocities occurring on ebb tides. The model also captures the relative decrease in current speed observed between the mouth and the head of Elkhorn Slough.

Observed bed shear stress measurements were collected at one station near the head of Elkhorn Slough (Monismith and others 2005), and the data obtained during this period exhibit a large degree of variability, limiting the ability to compare model predictions and field observations. However, despite the variability in the observed data, the model predictions capture the diurnal variability seen in the field measurements of bed shear stress.

Model validation also shows excellent agreement between predicted and observed water surface elevations and current speeds. The predicted water surface elevations match the observed water surface elevations in both amplitude and phase, with 1:1 correlation coefficient squared (r^2) greater than 0.99 for all three observation stations. Modeled current speeds also accurately reflect observed current speeds during the validation period. At a station near to the Monterey Bay inlet, the correlation coefficient squared is 0.92, and at an upstream station near the head of the Slough, the model predicts both the peak flood and ebb current speeds well, with a correlation coefficient squared of 0.94.

Overall, the model provides an accurate representation of the Slough hydrodynamics. The differences between observed and predicted parameters presented in the calibration report are not considered significant, especially when compared with changes observed in the Elkhorn Slough system since the completion of Moss Landing Harbor in 1947 and when compared with changes under the proposed restoration alternatives. Additionally, sensitivity analyses demonstrate that model predictions are relatively insensitive to typical freshwater discharges. Extreme storm events and the associated runoff were not evaluated as part of model calibration and validation. Ongoing, daily tidal exchange, rather than extreme events, is assumed to control long-term morphologic change.

5.2 METHODOLOGY FOR PROJECTING FUTURE MORPHOLOGY

Morphological change in Elkhorn Slough is evident through expansion of the main channel and conversion of the vegetated marshplain to mudflat. Predicting the future geomorphic response of the Slough to the proposed restoration alternatives requires a methodology for linking changes in the Slough's hydraulics to changes in the Slough's morphology. The methodology developed and implemented for this study combines predictions of bed shear stress from the DELFT3D hydrodynamic model with an assessment of past rates of geomorphic change using bathymetric data collected by SFML. For each alternative, the developed methodology is applied to predict the change in bed elevation in the main Slough channel between Year 0 and Year 10 and between Year 10 and Year 50. Note that this model only links bed shear stress directly to long term erosion rate; the actual erosion, transport, and deposition of sediment that occurs with each tide is not explicitly modeled. The methodology was used to assess past geomorphic change, and the geomorphic response was consistent with both the observed rates of total volumetric change and the observed spatial patterns of erosion. Additionally, the resulting geomorphic responses for Alternative 1, the No Action Alternative, are consistent with the 50-year predictions for habitat trends enumerated in the Elkhorn Slough Tidal Wetland Strategic Plan (Elkhorn Slough Tidal Wetland Project Team 2007).

The allocation of funding between the components in this report emphasized the development of a hydrodynamic model of Elkhorn Slough. As such, the resources available for developing and implementing these projections of future morphology were limited. Additional analysis may be appropriate to further enhance the reliability of long-term geomorphic predictions.

5.2.1 Conceptual Overview

Estuaries are dynamic systems; their form and function vary in response to changes in sediment supply and hydraulics, as described in Section 3. A change in the system, such as sea level rise or engineering activity, induces a geomorphic response in the system. This geomorphic response consists of an adjustment in the distribution of small-scale landforms such as channels, mudflats and marshes and ultimately results in the evolution of the estuarine system (Pethick and Crooks 2000). The intent of this study is to develop a methodology for projecting the future morphology of Elkhorn Slough in response to the proposed restoration alternatives. This requires an understanding of both past geomorphic change and the hydraulic response of the Slough to the proposed restoration alternatives. The relationship between the geomorphic and hydraulic responses should be coupled such that a restoration alternative's immediate effect on hydraulics will result in short-term morphological changes, which in turn will alter both the long-term hydraulics and morphology.

The approach developed for this study relies on linking geomorphic quantities (e.g., bed elevation) with hydrodynamic model predictions (e.g., bed shear stress), and provides a first approximation of morphological change. Developing morphological predictions is recognized as a relatively new applied science with a high degree of uncertainty given the number and complexity of the processes involved (Wilcox and Iverson 2003). The sediment transport processes which influence geomorphic change are complex and dynamic, spanning scales from sub-millimeter sediment grains to kilometers of slough circulation. Additionally, episodic events such as subsidence from earthquakes and extreme flood events play a role that is difficult to predict. In future studies, a more detailed understanding of Elkhorn Slough sediment dynamics might be obtained by incorporating a sediment transport module within the hydrodynamic modeling analysis. In addition, this approach could be further complemented with a model that fully integrates sediment dynamics and hydrodynamics to explicitly model long-term morphological change (Lesser and others 2004). However, both approaches would require significantly more resources compared with the present methodology, particularly in the form of field data collection, sediment parameters and computational expense. Considerable uncertainties will likely remain, given the large-scale changes in regional sediment supply. The benefit of applying such an approach may not outweigh the investment of limited resources. When these approaches have been applied to other estuarine modeling problems, uncertainties with respect to the model predictions of long-term geomorphic change remain substantial (EMPHASYS Consortium 2000; Gelfenbaum and others 2004; Haigh and others 2005; HR Wallingford and others 2002; Lesser and others 2004).

Through consultation with the Modeling Advisory Team (MAT), Year 10 and Year 50 were selected as appropriate points in time to evaluate the evolution of the Slough. Year 10 corresponds to the short-term timescale at which the different restoration alternatives are expected to exhibit clear differences in morphologic response. Year 50 corresponds to the long-term timescale, a time period likely near the limit at which meaningful morphologic predictions can be made. Year 50 does not necessarily represent the long-term equilibrium timescale within the Slough.

The impact of accelerated future sea level rise is only considered for the long-term Year 50 morphological projections when the effects of rising sea level would likely be considered significant. Estimates of sea level rise typically contain a large degree of uncertainty, both due to scientific uncertainties and uncertainties related to future carbon emissions scenarios. Over the last year, there have been major advances in the science (Church and White 2006; Huntington and others 2007; Meier and others 2007; Overpeck and others 2006; Rahmstorf 2007), suggesting that future sea level rise may be even higher than that predicted by recent references such as IPCC (2007). IPCC (2007) predicts a rise in mean sea level over the next fifty years on the order of 15 to 30 cm (0.5 to 1.0 ft). For this study, a sea level rise rate of 30 cm was chosen to provide a more conservative (upper bound) estimate regarding the potential long-term geomorphic response.

5.2.1.1 Predicting the Evolution of the Main Channel

The hydrodynamic modeling methodology focused only on predicting changes to the main Slough channel depth. This simplification of geomorphic change within the Slough is justified by several aspects of the Slough's hydrodynamics, geomorphology, and data availability. Sensitivity analysis (Appendix D,) indicates that channel bed erosion is the key parameter which changes tidal hydraulics within the estuary. Fortunately, this parameter also has the most extensive observations of historical rates of change. The sensitivity analysis reported in Appendix D reveals changes to the elevation of the marshplain to be secondary. For example, when changes to the main Slough channel depth expected on the 10-year timescale were implemented simultaneously with changes to the marshplain elevation expected on the 50- to 100-year timescale, the hydrodynamics responded more strongly to the changes to the main channel's depth. Although changes to the main channel's width were not modeled, the changes to the Slough's hydrodynamics as a result of channel widening would follow similar patterns to the changes from channel deepening. An additional difficulty with predicting changes to channel width and marshplain elevation is the lack of observation data to quantify the past and present rates of change of these variables. For example, the SFML data collected at the channel margins suggests accretion over a two-year interval, which is contrary to long-term trends indicate channel widening at a rate of approximately 30 cm/yr (Elkhorn Slough Tidal Wetland Project Team 2007). Similarly, detecting changes in marsh plain elevation has proven to be challenging given the current level of vertical datum accuracy; ongoing efforts aim to improve estimates of marshplain elevation changes (personal communication, E. van Dyke).

The primary limitation of the approach is the reliance on erosion rate data in the form of multiple, recent bathymetric surveys. It assumes that erosion rate as a function of bed shear stress is constant with time, which does not account for changes in sediment or bed properties with time or depth of erosion. In addition, because this approach relies on empirical data specific to Elkhorn Slough, it is not necessarily applicable to other systems.

In spite of these limitations, the methodology has several advantages. It incorporates hydraulic variability into the geomorphic projections and, because of its simplicity, it is offers capacity to assess multiple alternatives, with time and resource constraints. The methodology was used to assess past geomorphic change in the channel, and the geomorphic response was consistent with both the observed rates of total volumetric change and the observed spatial patterns of erosion. As such, the methodology is adequate to project differences in the channel geomorphic response to the proposed restoration alternatives. Although substantial uncertainty with respect to the future projections remains, the relative differences in geomorphic response provide a meaningful basis for comparing the proposed restoration alternatives in the capacity to reduce the major erosive forces.

5.2.1.2 Predicting the Evolution of the Marshplain

The evolution of the marshplain appears to be a response to the combination of a modified sediment budget and changed hydraulic conditions. There are a variety of individual mechanisms producing marshplain erosion (identified in the TWP conceptual model). The current modeling study and sediment supply discussions provide insights into several of these mechanisms: increased tidal range caused by the harbor dredging; conversion of the system to ebb-dominated hydraulics, with eroded sediment lost to the system. Predicating the geomorphic future of the marshplain is complicated by ecologic and geomorphic processes, thresholds, and by the limited availability of supporting data. Such uncertainties are common in dealing with coastal environments. The most effective approach to estimate likely future marshplain condition based on an assessment of monitored historic trends, available modeling data and comparison of documented cause and effecting relationships in similar estuaries. A record of observed changes in Elkhorn Slough is documented in Section 2, and the modeling analysis described in Section 5.

Elkhorn Slough is included in the class of a barrier (or bar-built) estuary. These estuaries form in micro- and meso-tidal settings where sands accumulate at the mouth of the estuary through longshore drift. Such estuaries exhibit broadly common distributions of habitat in response to interactions between combined tidal and fluvial flow and sediment supply. Knowing this helps us infer how changes in either or both of these parameters will affect the distribution of marshes and mudflats throughout the estuary into the future with under conditions of sea level rise.

Barrier estuaries tend to consist of a tripartite morphology, including: (1) a barrier, inlet and tidal delta complex; (2) a central estuary basin; and (3) an estuary head delta (Bird, 1967, Dalrymple and others, 1992, Cooper, 1994, 2001, 2002, Roy and others, 2001; Sloss and others, 2006). The formation of the barrier and head delta reflects direct supply and deposition of sediment. However, the central areas of the estuary tends may remain as broad shallow mudflats or subtidal muds rather than vegetated marsh because of limited sediment supply, in combination with a resuspension and export by waves of delivered sediment. Only under conditions of high sediment load, typically from the catchment, do mudflats build up to create vegetated marshes; this sediment typically is derived from catchment supplies (Cooper 1994, 2001, 2002). In absence of a mineral sediment supply salt marsh plants are incapable of building a marsh surface equivalent to more than 1 or 2 mm per year (Randall and Foote 2005; Turner and others 2006), and so with time if the supply of sediment decline the estuary central basin tends to revert to lagoonal habitat. A significant difference between Elkhorn Slough and other barrier estuaries is the current direct, jettied connection to a deep submarine canyon. Such a direct connection to a major sediment sink accentuates losses of sediment from Elkhorn Slough relative to other estuaries.

5.2.2 Methodology Implementation and Application

The methodology for projecting future channel morphologic change is depicted in the flow chart in Figure 5-1. At the center of the chart is the key link in the methodology: the relationship between bed shear stress and erosion rate. Bed shear stress, the independent variable, is determined from the hydrodynamic model results. The erosion rate, the dependent variable, is determined from repeated observations of Slough depth. Once established, this erosion-shear stress relationship is applied to existing bed elevation data to predict future bed elevations. The erosion-shear stress relationship was calibrated by comparing the predicted annual erosion rate for the entire Slough against observed values. The components of this methodology are described in more detail below.

Bed shear stress, the independent parameter shown in Figure 5-1, was chosen as the key hydrodynamic parameter since it represents the force per unit area exerted on the bed by the tidal currents. Although wind-wave-induced bed shear stress often plays an important role in resuspending sediments in larger systems with sufficient fetch lengths, wind-waves are less significant in Elkhorn Slough due to its existing size and geometry. Sufficient bed shear stress is required for sediment erosion and it also correlates directly with tidal currents, the flows that transport and remove eroded sediment from the Slough. Observations in Elkhorn Slough indicate that below an easily eroded surface layer, bed shear stresses greater than 0.2 N/m^2 are sufficient for sediment erosion from the main channel (Sea Engineering Incorporated 2006).

Although sediment transport plays an important role in shaping the estuarine geometry, as sediment is eroded, it is often deposited and eroded several times as it is reworked through the estuary. Sediment that was recently deposited has a much lower critical shear stress for erosion and is therefore subsequently easily eroded and transported through the system. Over longer timescales, particularly with a system that is a net-exporter of sediment, the current methodology neglects the shorter-term timescale processes such as ebb and flood tide transport and sediment settling times. Ganju and Schoellhamer (2007) found that small errors in these shorter timescale processes can accumulate to cause major errors in geomorphic predictions; therefore they recommend an intermediate step approach for predicting decadal change, similar to the approach used in this study.

For each grid cell in the model, the simulation's peak bed shear stress5 was selected as representative of the tidally-oscillating bed shear stress. The peak bed shear stress value from each grid cell was then assembled into a spatial map for the entire Slough. In general, sediment erosion is correlated with bed shear stress that exceeds a given threshold or critical value. Since the main channel was not actively eroding prior to construction of the new harbor entrance, the peak bed shear stress under 1943 conditions was selected as the threshold above which sediment erosion occurs. The 1943 peak bed shear stresses decrease from values at the mouth of approximately 1 N/m^2 to values in the upper Slough of approximately 0.5 N/m^2. This spatial change in the threshold roughly corresponds to the spatial variation in sediment composition. At the mouth, the bed is composed of sandy muds; in the upper Slough, the bed is composed of finer, more cohesive sediment. By subtracting the 1943 peak bed shear stress from each alternative's peak bed shear stress, the excess bed shear stress is defined. The 1943 model configuration is described in Section 5.2.3.

Tidal erosion rates, the dependent parameter shown in Figure 5-1, were derived from repeated measurements of the bed elevation in 2001, 2003, and 2005 by SFML. By differencing a pair of sequential bed elevation maps, changes in bed elevation for the period from 2001 to 2003 (Figure 5-2a) and from 2003 to 2005 (Figure 5-2b) were estimated for most of the Slough's main channel. These elevation changes are converted to erosion rates by dividing by the time interval between surveys. The elevation changes in Figure 5-2 demonstrate consistent magnitude between them and both exhibit trends of larger erosion rates near the mouth which decrease moving upstream in the Slough. The 2001 to 2003 erosion rates (Figure 5-2a) have negative values along the edges of the main channel and in the upper part of the Slough, indicating depositional regions.

By combining the excess bed shear stress with the erosion rate, a predictive relationship can be derived, as shown in the center box of Figure 5-1. A plot of the observed tidal erosion rates versus the excess bed shear stress is shown in Figure 5-3 for Alternative 1 (No Action) at Year 0. The considerable scatter in this data is consistent with both the underlying complexity of cohesive sediment transport and the limited accuracy of making point measurements of change over short geomorphic timescales. Aggregating the point data into summary statistics, in the form of the median for 0.1 N/m^2 bins along the horizontal axis, suggests an erosion-shear stress relationship that is linearly increasing from the origin and then becomes constant for larger excess bed shear stress values. The constant erosion rate may be indicative of the armoring process as fines are winnowed from the bed and the bed composition becomes sandier. The relationship suggested by the data was further refined by calibration to observed annual erosion rates.

Once the best estimate of the relationship between excess bed shear stress and erosion has been developed, it is used to alter the depth of each model grid cell. It is assumed that sediment removed from

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5 Bed shear stress is defined in the DELFT3D model as $\tau_b = \frac{\rho g \overline{U}\left|\overline{U}\right|}{C_{2D}^2}$ where τ_b=bed shear stress, ρ=density of water, g=acceleration due to gravity, $\overline{U}$=the magnitude of the depth-averaged horizontal velocity, and C_{2D}=2D Chezy coefficient.

the bed to increase the depth is exported from the Slough. This assumption is supported by the clear and consistent historic trend of main channel and marsh erosion over the past decades. This net flux of sediment out of the Slough occurs because the water exiting the Slough on each ebb tide has a higher suspended sediment concentration than the Monterey Bay water entering the Slough on each flood tide. Without sufficient fluvial sediment delivery to offset this tidal export, net impact on the Slough is erosion. Currently, tidal currents in the Slough are ebb dominant, which probably enhances net export of sediment. If a restoration scenario changes the tidal currents to flood dominance, net export will continue because of the disparity in suspended sediment concentration between ebb and flood tides.

The implementation of this step is represented graphically on the right-hand side of Figure 5-1. Grid cells within the main Slough channel are identified as those cells with depths greater than 1 m (3.3 ft) below MLLW. The new depth is then calculated as the old depth plus the product of the erosion rate and the time period between the present year and future year under consideration (e.g., Year 10). Additionally, the new depth is constrained to not exceed 10 m (33 ft). This depth constraint was selected on the assumption that the Slough's depth would not exceed the nominal value of the dredged depth maintained in Moss Landing Harbor. The bed depths were evaluated twice for Year 10 and Year 50 conditions. Present-day excess bed shear stress was used to predict depths at Year 10. The model's bathymetry was updated and the model was re-run. The resulting Year 10 excess bed shear stresses were then used to predict depths at Year 50.

Several variations of the erosion-shear stress relationship were tested on the existing bed elevation and with the existing excess bed shear stress. The predicted annual erosion rates for the entire Slough were then compared to the observed annual erosion rates (Sampey 2006). After testing several different slopes for the linearly-increasing portion of the relationship, the relationship shown in Figure 5-3 was selected as it yields annual erosion rates of 98,000 m^3/yr (130,000 yd^3/yr) for the entire Slough. This rate falls in the middle of the observed range of erosion rates, 56,000-120,000 m^3/yr (73,000-160,000 yd^3/yr) reported in Sampey (2006).

To demonstrate the methodology, the intermediate steps for developing the Year 10 morphology for Alternative 1, the No Action Alternative, are shown in Figure 5-4, Figure 5-5, and Figure 5-6. The 2003 bathymetry is used to represent Year 0 (Figure 5-4). Predicted bed shear stress from the DELFT3D simulations using this bathymetry and the 1943 bathymetry are used to calculate the excess bed shear stress shown in Figure 5-5. When this excess bed shear stress is converted to spatially-varying erosion rates using the erosion-shear stress relationship shown in Figure 5-3 and the Year 0 depths are altered accordingly, the predicted depths at Year 10 are as shown in Figure 5-6a. The difference between the Year 0 and Year 10 depth maps is shown in Figure 5-6b to highlight the predicted changes over this time period. The largest changes occur in the lower portions of the Slough, below the confluence with Parsons Slough. Along the center line of this reach, the depth increases by 2 m (6.6 ft) over ten years. This magnitude of change corresponds to the maximum erosion rate of the erosion rate-shear stress relationship, 0.2 m/yr, integrated over the ten-year period. The predicted erosion rates decline upstream of Parsons Slough in response to the decreasing excess bed shear stress.

Summaries of the morphologic change for each alternative are presented in Section 5.3 in conjunction with the evaluation of tidal hydraulics.

5.2.3 1943 Model Configuration

Before the 1947 construction of Moss Landing Harbor and the jettied inlet to Monterey Bay, Elkhorn Slough geomorphology was relatively stable (e.g., the main slough channel was not actively eroding) (Philip Williams & Associates 1992). Therefore, model simulations of pre-harbor (e.g., 1943) conditions provide an alternative reference to compare against the hydrodynamics of restoration alternatives. The use of 1943 conditions for comparison purposes does not imply that pre-harbor conditions are a goal of the restoration efforts. Pre-harbor (e.g., 1943) conditions represent a point in time that are similar to existing conditions within the watershed (e.g., substantial marsh areas are diked off from the Slough and decreased fluvial sediment supply), and post large-scale and likely irreversible changes within the watershed that impacted the morphology and hydrodynamics of the Slough (e.g., increased sedimentation due to deforestation and land clearing that likely caused infilling of the Slough). In addition to the use of the 1943 bed shear stress to calculate the excess bed shear stress associated with the proposed alternatives, as described in Section 5.2.2, the water levels and current velocities from the 1943 conditions serve as a basis for comparing the response of the proposed restoration alternatives.

The modeled pre-harbor bathymetry was derived from a 1943 bathymetric survey conducted by U.S. Army Corps of Engineers. Cross sections from this survey extend from the original ocean inlet of the Slough to just west of Seal Bend. Between these cross sections, spaced approximately 100-200 m (330-660 ft) apart, DELFT3D's grid-generation and interpolation tools generated a continuous channel thalweg. Upstream of the last surveyed cross section, from Seal Bend to the head of the Slough, a trapezoidal channel was used to represent the main Slough channel. The centerline and width of the channel replicate the 2003 bathymetry. The depth of the trapezoidal channel linearly decreases from the upstream-most 1943 cross section to the 2003 depth at the head of the Slough. Use of the 2003 centerline, width and depth at head of the Slough were necessary due to the lack of historical data. Of these values, only the width is likely to have increased significantly between 1947 and 2003 (Van Dyke and Wasson 2005). The modeling indicates that the pre-harbor hydrodynamics are controlled by flow capacity at the inlet; therefore, an overstatement of the pre-harbor width in the upper two thirds of the Slough will likely have a relatively small impact on the overall hydrodynamics. Figure 5-7 displays the reconstructed pre-harbor bathymetry.

It should be noted that although the pre-harbor conditions are used as a basis of comparison for the alternatives, the hydrodynamics and resulting bed shear stress maps from this condition contain uncertainty due to some aspects of the bathymetry (lack of detailed data). The hydrodynamics associated with this alternative have been compared with available information regarding current velocities and water levels to show that they are reasonable; however, a comprehensive calibration of pre-harbor conditions is not feasible.

5.3 PREDICTIONS OF TIDAL HYDRAULICS AND GEOMORPHIC CHANGE

The DELFT3D model of Elkhorn Slough provides a tool for directly assessing the impact of the proposed restoration alternatives on the Slough's tidal hydraulics, and for indirectly inferring changes in the main channel's morphology. The physical configuration of each alternative at Year 0 was implemented in the model domain as described in Section 4. In addition, the future morphology under each scenario was projected for Year 10 and Year 50 as described in Section 5.2. This section presents model output selected to assess the response of the alternatives with respect to the two principal methods of habitat loss: tidal erosion of the main Slough channel and marsh loss. Tidal current velocities are the controlling factor for tidal erosion as the currents exert erosive shear stress on the bed and transport eroded sediment from the Slough (Section 2.2). Water levels are considered to be a significant factor affecting marsh loss through the drowning of marsh plants (Section 2.3).

The simulation period selected for evaluating the restoration alternatives coincides with the period used for model calibration. However, the alternative evaluation period was extended such that it spans an entire 28-day tidal month from April 5, 2003 to May 2, 2003. Observed water levels from NOAA's Monterey Bay station (ID 9413450) serve as the open boundary condition applied at the western edge of the model domain. Since there was no rainfall during this period, freshwater inflows were negligible and therefore not included in the model. Discharges to and from the Moss Landing Power Plant were included in the model. Bed roughness values were assigned based on bed elevation to differentiate between unvegetated subtidal areas and vegetated marshplain. Additional details of the model setup can be found in the calibration report (Appendix A).

Alternative 1, No Action, is described first and in relation to 1943 conditions to establish a reference frame for the remaining alternatives. For each alternative, the modeled water levels, current velocities and bed shear stress are presented and discussed. In addition, an assessment of the projected geomorphic change is made by comparing thalweg depths and annual erosion rates. The results are presented at two locations on the main Slough channel to represent the spatial variability in the Slough. As shown in Figure 5-4, the downstream location is situated near the Slough's mouth where currents are strongest and just upstream of the proposed connection with the Alternative 2 connecting channel so that results can be compared between alternatives. The upstream location is situated near Kirby Park, where current speeds are diminished and the tidal range is slightly amplified. Together, these two locations demonstrate the range of hydrodynamic conditions along the main Slough channel. For each location, the cross-sectional average of each parameter was calculated to reduce the influence of lateral variability.

5.3.1 Alternative 1 – No Action

Alternative 1, the No Action Alternative, provides a baseline for comparison for the 'action' alternatives. The high rates of present-day habitat loss are expected to continue under this alternative. To quantify the hydrodynamic factors contributing to habitat loss, model predictions of water levels, current velocities, and bed shear stress are presented. These hydrodynamic factors also serve as the basis for predicting

Slough geomorphology at Year 10 and Year 50. Model results from the 1943 conditions provide a basis for comparing the response of implementing this alternative.

5.3.1.1 Water Levels

Water levels, along with current velocities, are the key hydrodynamic response parameters to an alternative's physical configuration. By plotting the series of points whose coordinates are formed by these two parameters, the overall response and subsequent changes to these two parameters can be succinctly summarized on the same plot. These water level versus velocity plots for Alternative 1 are shown in Figure 5-8. At ten-minute intervals, model results for the cross-sectional average velocity and water level are plotted as a single point. Plotting these points for the entire Year 0 simulation creates a region of points that define this alternative's envelope of velocity and water level. This region can be summarized by drawing its outer boundary, as shown in Figure 5-8 for Year 10 and Year 50. The width of these regions represents peak velocities while the vertical extent represents the tidal range. This section presents a discussion of the water levels; velocities are discussed in the next section.

The vertical extent of the data points in Figure 5-8 indicate the range of water levels predicted for Alternative 1 at different times. At the downstream location (Figure 5-8a), water levels at Year 0 range from -0.3 m to 1.9 m NAVD (-1 ft to 6.2 ft). Because of the ample hydraulic connection through Moss Landing Harbor, this range is identical to the tide range in Monterey Bay. This Year 0 range exceeds the 1943 tide range by 0.4 m (1.3 ft) for high tides and by 1 m (3.3 ft) for low tides. Under 1943 conditions, the inlet between Monterey Bay and the Slough muted the tide range.

Based on the projections of future morphological change, water levels at Year 10 are expected to remain nearly identical to Year 0 water levels. This lack of response indicates that water levels are not sensitive to the tidal erosion predicted to occur between Year 0 and Year 10. At Year 50, water levels increase by approximately 0.3 m (1 ft), which corresponds to the assumed rate of sea level rise.

Upstream water levels exhibit slightly higher values, on the order of 5 cm (2 in) when compared to downstream water levels, due to tidal amplification (Figure 5-8b). This amplification is caused by the main Slough channel decreasing in cross-sectional area with distance from the mouth. As the flood tides funnel upstream into this decreasing cross-sectional area, water levels are slightly elevated in response.

In addition to the range of water levels, the delineation of Slough habitat depends on the inundation period. In systems with sufficient suspended sediment concentrations, increased inundation (such as that accompanying sea level rise), would lead to increased sedimentation and the marshes would build upwards in equilibrium with the tidal frame. However, in systems with limited sediment supply, such as Elkhorn Slough, it is unlikely that marshes would accrete sediment in response to an increased inundation period or sea level rise. Many marsh species can only tolerate limited periods of the reduced gas exchange and elevated salinity associated with inundation. Since inundation of a particular bed elevation occurs when the water level exceeds that elevation, the inundation period can be expressed for any time interval as the percentage time exceeded. For instance, the water level that is exceeded 10% of the time would coincide with an inundation period of 36 minutes per 6-hour tide, 2.4 hrs per day, or 3 days per month.

Figure 5-9 depicts the percent time exceeded curves for Alternative 1. In their vertical extent, the curves replicate the changes in time discussed above. The steeper slope at the ends of all the curves indicate that water levels are infrequent in these portions of the tidal range because these extremes only occur during spring tides. Because of the relatively short distance between the marshplain and the main channel, water levels on the marshplain are nearly identical to those in the main Slough channel (Philip Williams & Associates 2007a, Appendix B). However, the marshplain becomes dry once the water level drops below the marshplain bed elevation. Therefore, the intersection of the percent time exceeded curves with the typical marshplain bed elevation can be used to determine the inundation period for the marshplain under different conditions. For Elkhorn Slough's existing conditions, the typical marshplain elevation is 1.4 m (4.6 ft) (Elkhorn Slough Tidal Wetland Project Team 2007) and is shown in Figure 5-9. This bed elevation is exceeded 4% of the time under 1943 conditions, 11% of the time under Year 0 and Year 10 conditions, and 35% of the time under Year 50 conditions. Prolonged inundation can kill pickleweed (Zedler 1982), therefore influencing its lower limit of distribution. Pickleweed in a southern California marsh was found to be inundated 13% of the time (Sadro and others 2007). In San Francisco Bay, pickleweed distribution is limited to the upper, more exposed elevations of the marsh plain (Josselyn 1983). Pickleweed has also been shown to thrive in zones where the emergence period is greater than or equal to the period of submergence; pickleweed could not survive when the submergence period was four times greater than the emergence time (Josselyn 1983).

5.3.1.2 Velocity and Bed Shear Stress

Velocity, the primary hydrodynamic factor controlling tidal erosion, is represented along the horizontal axes of the water level versus velocity plots in Figure 5-8. At the downstream location, the Year 0 cross-sectional average velocity ranges from 0.75 m/s (2.5 ft/s) on ebb to 0.60 m/s (2.0 ft/s) on flood. The larger peak velocity during ebb tides is consistent with the ebb-dominant asymmetry observed in the Slough (Monismith and others 2005). Particularly since ebb-dominance is a reversal from 1943 conditions, the peak ebb velocity of Alternative 1 Year 0 is more than double the peak ebb velocity of 1943 conditions.

The predicted geomorphic changes in the Slough at Year 10 and Year 50 result in a decrease in velocities. Between Year 0 and Year 10, peak velocities at the downstream location decrease by 17%. This decrease occurs because the main Slough channel is projected to deepen in response to continuing tidal erosion. Deepening the channel increases the cross-sectional area and reduces the influence of bed friction. Together, these changes enable the same conveyance capacity with reduced current velocities. Between Year 10 and Year 50, peak velocities decrease an additional 19%, as tidal scour and channel deepening continue.

For all cases, velocities at the upstream location are lower than the corresponding velocity at the downstream location (Figure 5-8b). In contrast to the downstream stations, changes in velocity with time are relatively slight. For instance, between Year 0 and Year 10, changes in velocity at the upstream location are negligible and between Year 10 and Year 50, the decrease in velocity is approximately 10%. These negligible or small net changes in velocities are the result of counterbalancing mechanisms. Better conveyance from increased depths in the lower Slough enables slight increases in discharge to the upper Slough. However, deeper channels in the upper Slough distribute this increased discharge over a larger cross-sectional area, thereby reducing velocities.

Bed shear stress is a measure of the friction between the tidal currents and the bed. Its tidally-oscillating signal can be summarized as the percentage of time that specific flood or ebb bed shear stresses are exceeded by the cross-sectionally averaged bed shear stress time series. Figure 5-10 shows curves depicting this relationship for Alternative 1 at the downstream and upstream locations. The percent exceeded does not extend to 100% because the reference time period includes both flood and ebb tides. When the time series is split into flood and ebb, each tide is less than 100% but a flood and ebb pair together sum to 100%. The percent exceeded curves confirm the ebb-dominant nature of Year 0 conditions and indicate that geomorphic changes projected for Year 10 and Year 50 alter bed shear stresses on ebb tide more dramatically than on flood tide. Changes in the bed shear stress distribution are more pronounced at the downstream location, particularly for ebb tides between Year 0 and Year 10.

Modeled bed shear stress can also be compared with measured sediment properties. Sea Engineering Inc. extracted cores from the main Slough channel to evaluate the shear stress at which sediment was eroded from the cores (Sea Engineering Incorporated 2006). Below an easily eroded surface layer, critical bed shear stress was observed to be 0.2 N/m^2. Although these measured critical bed shear stresses are for a single point while the modeled bed shear stress percent exceeded curves are averaged for a cross-section, the measured values provide a reference point for assessing the alternatives.

At the downstream location, the Year 0 predicted bed shear stress exceeds this critical value for 5% of flood tides and 10% of ebb tides. In contrast, for 1943 conditions, predicted bed shear stress exceeds the critical value less for than 2% of the flood tides and not at all on ebb tides. This difference is consistent with a stable, or non-eroding, morphology for 1943 conditions and active tidal erosion for existing conditions. At Year 10, the predicted bed shear stress exceeds the critical value for less than 1% of flood tides and 4% on ebb tides. At Year 50, the predicted bed shear stress exceeds the critical value for less than 1% of flood tides and less than 3% on ebb tides.

5.3.1.3 Geomorphic Change

Main Channel Evolution

Hydrodynamic output from Alternative 1 was used to predict geomorphic change in the Slough channel at Year 10 and Year 50, as described in Section 5.2. Between Year 0 and Year 10, the projected annual erosion rate for the entire main channel is 98,000 m^3/yr. Since this erosion occurs in the main channel, the spatial distribution of the change can be depicted graphically by plotting the Slough's thalweg depth as a function of distance from the Highway 1 bridge, as shown in Figure 5-11. Between the construction of the harbor and existing conditions, depths in the main Slough channel have increased by up to 6 m (20 ft) at the mouth of the Slough. At Year 10, additional erosion of up to 2 m (6.6 ft) is projected for the Slough, based on Year 0 excess bed shear stress. Most of this erosion is expected to occur in the lower portion of the Slough.

Between Year 10 and Year 50, the projected annual erosion rate for the Slough is 43,000 m^3/yr, less than half of the rate predicted between Year 0 and Year 10. This decrease in the annual erosion rate occurs because of the decrease in excess bed shear stress at Year 10. Depths along much of the lower Slough are projected to reach the nominal depth of the harbor, 10 m (33 ft), and are not eroded further. By Year 50, much of the upper Slough is projected to have depths approximately twice that of the current (Year 0) depths.

Marshplain Evolution

The future evolution of the marshplain area is inferred by combining information from historic change assessment, evolution in the trend of the primary factors that control marsh expansion or contraction (loss), and comparison with erosive tidal marsh systems in similar estuaries. Based on these assessments, as described below, it appears that marshplain loss occurring in Elkhorn Slough reflects a morphological adjustment of ebb-dominated estuary subject to low available suspended sediment concentrations and marsh erosion will continue at the reported high rates in to the future.

A tidal wetland marshplain forms at an elevation close to that Mean Higher High Water (MHHW) in response to a balance of depositional and erosional processes. These were shown in a conceptual model format by the TWP advisory team:

- Those processes that support marshplain development and growth include the supply and deposition of mineral sediment and the production of organic sediment (from plant growth and decay) in a low energy environment.
- The processes that result in loss or erosion of marshplain can include:
    - A decrease in the relative elevation difference between the marshplain and tidal levels (i.e., the marshplain becomes lower, compared with the tidal levels.
    - An increase in the erosive forces exerted by the tidal water, either along the marsh edge, or in the interior of the marsh.

The supply of mineral sediment in the system can come from fluvial (upland) or coastal sources, as well as from erosion of local watersheds[6]. For Elkhorn Slough, the sediment sources and changes to these were described in Section 3. Overall, the supply of mineral sediment has probably decreased significantly in the past century.

[6] Volume unknown

The production of organic sediment relies on the ongoing sustainability of the marshplain vegetation. As this vegetation is lost during erosion, it creates a feedback loop where less organic sediment is then produced.

The relative elevation of the Elkhorn marshplain in relation to tidal waters can be affected by several factors:

- Global changes in sea level
- Local increases in maximum tidal elevation in response to expanded or more efficient hydraulic connections at the Slough mouth
- Possible tectonic changes (in response to earthquake or groundwater removal induced subsidence)

Global sea level has historically been rising at a rate of about 0.5 ft/century, and is expected to increase significantly in the next century. The hydraulic modeling conducted in this report shows that compared to preharbor conditions in the 1940's, the new harbor entrance creates a much more efficient tidal connection, and tidal exchange in the marsh has increased. (However, earlier maps of the slough show a larger mouth, so that at some point in the past, the slough may have naturally experienced a less damped tidal exchange). The third factor (possible tectonic changes) may have occurred at Elkhorn, though the data on this are not available.

While we are not able to quantify all of the specific rates of processes in the Marshplain Conceptual Model, it is clear that the trend in all of the key variables (i.e., decreased mineral sediment supply, decrease in the production of organic sediment, increased tidal flow velocities/erosive forces, net export of sediment, and increased inundation of the marshplain) is towards the observed and ongoing marshplain loss.

Unpublished data presented by K. Wasson tabulate the loss of vegetated marsh between 1931 and 2003. Over this timeframe the extent of vegetated marsh has declined from around 85-95 cover throughout the estuary to between 5 – 60 % (greatest rates of loss in the innermost estuary). In marsh areas with >60-70% cover extent of vegetated marsh appears to have declined at a near linear rate. However, once the extent of vegetation cover falls below 60% the rate of marsh loss appears to have accelerate dramatically (falling from 60% to 5% vegetated cover over less than a 30 year period). Though the mechanism causing of marsh loss is not described in Wasson's dataset the accelerated rate of marsh loss is consistent with an ecological or geomorphic threshold being crossed. We would expect the remaining marsh areas of Elkhorn Slough (which currently have a vegetation cover of 59-65%) will also undergo comparable and perhaps accelerated rates of vegetation loss in coming decades.

Sediment delivery and storage on the mudflats and marshes is a key parameter in maintaining health of these habitats. Data quantifying actual suspended sediment in Elkhorn Slough is limited; estimates by Monismith and others (2005) suggest possibly up to a maximum of 100 mg/l during peak tidal flows (inferred) and of the order of 30-40 mg/l on weaker tidal flows (measured). The Monismith study supports observations that due to ebb-dominance, eroded sediments are pumped downstream and ultimately out of the estuary. Under such conditions, while the estuary remains ebb-dominated and suspended sediment concentrations remain low it is reasonable to infer that marsh loss will continue.

Estuaries with similar tidal characteristics (ebb-dominated) and low sediment supply availability share a common morphology with the Elkhorn Slough marshes. The estuaries of Essex County, UK are undergoing similar change to those in Elkhorn Slough, with erosion occurring through internal channel erosion and marshplain breakdown and to a lesser degree marsh edge retreat. These estuaries are subject to ebb-dominated currents resulting in net sediment export (Postford Haskoning Environment, 2002), and limited supply sediment availability in circulation (HR Wallingford, 2002). They have lost between 14% and 59% of their vegetated marsh area over a 25 year period[7].

We predict that over the next fifty years, apart from the high intertidal fringes at the edge of the estuary, the remaining marshplain areas will mostly revert to mudflat. It is anticipated that the rate of erosion will accelerate for a period of time as marsh areas become devoid of vegetation, creating expansive mudflats. Potentially, the rate of sediment loss will decline as the mudflat surface elevation falls below mean tide elevation and erosional forces become more diffuse. However, with an ebb-dominated tidal system, the trend of sediment export will continue, and over time and with rising sea level the areas of subtidal habitat will increase.

5.3.2 Alternative 2 – New Ocean Inlet

Alternative 2 decreases tidal action by constructing a new smaller and shallower ocean inlet for the Slough and completely eliminating flow through the Slough's current expanded inlet through Moss Landing Harbor. The decreased tidal action resulting from this alternative is expected to attenuate habitat loss. To quantify the hydrodynamic factors contributing to habitat loss, model predictions of water levels, velocities, and bed shear stress are presented. These hydrodynamic factors also provide the basis for predicting Slough geomorphology at Year 10 and Year 50. Model results from existing conditions (Alternative 1, Year 0) and 1943 conditions provide a basis for comparing the response of implementing this alternative.

5.3.2.1 Water Levels

As shown in Figure 5-12a, predicted water levels for Alternative 2 (Year 0) at the downstream location range from 0.3 m to 1.7 m (1.0 ft to 5.6 ft). This range would be smaller that of Alternative 1 (Year 0); the mean tidal range would also be 0.1 m (0.3 ft) higher under Alternative 2 (Year 0) than observed under existing conditions. The decreased in tidal range indicates that the proposed reconfiguration of the

[7] Inventories by Burd, 1992; Cooper and others 2001, and Royal Haskoning Environment 2006 document high rates of salt marsh loss at rates ranging between 14% and 59% over the examined period between 1973 and 1998. Over this short period Essex lost around 1000 ha of salt marsh, or 33% of the total area existing in 1973. At these rates, several of these low lying estuaries will have lost most or all of their vegetated marsh area by year 2050. In the Stour and Orwell estuaries upstream of Harwich Harbor, marsh loss between 1973 and 1988 has averaged 55% and 33%, respectively.

Slough's inlet would limit tidal flow, thereby muting the tidal range inside the Slough. However, even with this decrease, Alternative 2's tidal range would remain greater than the 1943 tidal range. Although both Alternative 2 and 1943 conditions would have similar ocean inlet configurations, differences between the channels connecting the inlets to the Slough, as well as Alternative 2's deeper main Slough channel, likely contribute to the greater tidal range observed in Alternative 2. (Future refinement of this alternative may show that a smaller connecting channel between the ocean and Elkhorn Slough is feasible.)

Tidal range at the upstream section (Figure 5-12b) would be slightly amplified compared to the downstream section. The amount of tidal amplification at high water would be 3 cm (1 in), less than tidal amplification observed under existing conditions. This is consistent with the amplification resulting from flow convergence, since the decreased flow of Alternative 2 yields decreased tidal amplification.

Based on the projections of future morphological change, water levels at Year 10 are expected to remain nearly identical to Year 0 water levels. This lack of response indicates that water levels are not sensitive to the tidal erosion predicted to occur between Year 0 and Year 10. At Year 50, water levels increase by approximately 0.3 m (1 ft), which corresponds to the assumed rate of sea level rise.

Percent time exceeded curves, first described in Section 5.3.1.1, are shown for Alternative 2 in Figure 5-13. Compared to existing conditions, the Alternative 2 (Year 0) curve exhibits a flattened slope characteristic of a decreased tidal range. However, the decrease would not bring Alternative 2 in line with 1943 conditions. Alternative 2's curve departs from the 1943 curve by up to 0.3 m (1 ft) at the bottom of the tide range and by 0.1 m (0.3 ft) at the top of the tide range. At the nominal elevation of the marshplain, the percent time exceeded for Alternative 2 (Year 0) is 7%, approximately halfway between existing and 1943 conditions. This elevation would also exceeded 7% of the time under Year 10 conditions and 33% of the time under Year 50 conditions. Prolonged inundation can kill pickleweed (Zedler 1982), therefore influencing its lower limit of distribution. See Section 5.3.1.1 for more details.

5.3.2.2 Velocity and Bed Shear Stress

Predicted velocities for Alternative 2 are shown along the horizontal axes in Figure 5-12. At the downstream location, the horizontal extent of the Alternative 2 (Year 0) region indicates flood-dominance and muted tides, with peak flood velocities reaching nearly 0.4 m/s (1.2 ft/s) while peak ebb velocities reach less than 0.3 m/s (1 ft/s). Compared with existing conditions, this alternative reverses from ebb to flood dominance and experiences a factor of two decrease in peak velocity. The system switches from ebb to flood dominance because the shallow depths at the inlet mouth asymmetrically influence the ebb and flood tides. Water levels are lower during ebb tide; therefore the influence of friction is greater and more momentum is removed from the flow. For example, Figure 5-12 shows an inverse linear relationship between velocity and depth for both Alternative 2 and 1943 conditions. The peak ebb velocity under Alternative 2 is similar to 1943 conditions while peak flood velocity is slightly less than 1943 conditions. During falling ebb tides, both Alternative 2 (Year 0) and 1943 conditions have linearly decreasing velocities as a function of water level. This inverse relationship suggests that the flow is limited by declining cross-sectional area as the water level drops closer to the bed. This limitation on flow occurs within the relatively shallow channels of the new inlet and flood shoal.

The predicted geomorphic changes in the Slough at Year 10 and Year 50 are slight for Alternative 2. Therefore, peak flood velocities do not change significantly between Year 0 and Year 10. However, with the addition of mean sea level rise at Year 50, peak flood velocities increase by 1114% between Year 10 and Year 50.

Compared to the downstream location, velocities are damped at the upstream location (Figure 5-12b). The flood dominance persists, with peak flood velocity of 0.3 m/s (1 ft/s) surpassing peak ebb velocity of 0.2 m/s (0.6 ft/s). Alternative 2 (Year 0) peak velocity is similar on ebb tide and slightly lower on flood tide when compared with 1943 conditions. Similar trends to the downstream station are predicted for the upstream location at Year 10 and Year 50.

Figure 5-14 shows the distributions of bed shear stress as a function of percent time exceeded for Alternative 2. At both the downstream and upstream locations, Alternative 2 (Year 0) peak bed shear stress is significantly less than observed under existing conditions, and similar to 1943 conditions. At all times, the Alternative 2 (Year 0) bed shear stress does not exceed the critical bed shear stress for erosion of 0.2 N/m^2 (Sea Engineering Incorporated 2006). Because of minimal morphologic change predicted between Year 0 and Year 10, the bed shear stress distribution at Year 10 is identical to that of Year 0. The increase in mean sea level associated with Year 50 results in elevated bed shear stress as compared with Year 10. At Year 50, the predicted bed shear stress exceeds the critical value only on ebb tides, for 2% of the time.

5.3.2.3 Geomorphic Change

Main Channel Evolution

Profiles of projected thalweg depths for Alternative 2, Years 0, 10 and 50 are shown in Figure 5-15. Between Year 0 and Year 10, 1.5 meters of erosion is projected for the reach 1-2 km from Hwy 1. This region corresponds to the location where the new connector channel would enter the existing main channel. All other portions of the Slough experience only minimal change between Year 0 and Year 10. Between Year 10 and Year 50, erosion is predicted to continue in the vicinity of the confluence of the new connector channel and the existing main channel. The other portion of the Slough with projected erosion at Year 50 occurs in the vicinity of Parsons Slough's mouth. This reflects the continuing geomorphic adjustment to the reconnection of South Marsh and Parsons Slough in the 1980s.

Marshplain Evolution

Alternative 2 without application of a sediment source will probably not result in substantial mineral accretion on the marshplain. Potentially, with a lowering of water levels by 20-25 cm because of tidal muting by the new inlet, vegetation will initially recolonize degraded marsh areas. However, assuming continued rising sea level, this revegetation will likely be temporary and by Year 50 the vegetated marshes will have converted largely to mudflat. Because under alternative 1 tidal velocities are substantially reduced it is expected that conversion of marsh to mudflat will occur primarily though drowning rather than tidal channel incision. Application of sediment to the marshplain, in sufficient quantities to meet sea level rise could create vegetated marsh and in degraded areas can reverse vegetation loss.

5.3.3 Alternative 3 – Tidal Barrier at Highway 1

Alternative 3, constructing a partial tidal barrier (referred to as a sill) at the Highway 1 bridge reduces the tidal exchange between the Slough and Moss Landing Harbor. The decreased tidal exchange resulting from a sill is expected to reduce tidal erosion and attenuate habitat loss. Two different sill crest elevations were evaluated within this alternative – a low sill with a uniform crest elevation of 1.4 m (4.6 ft) below MLLW (Alternative 3a) and a high sill with a uniform crest elevation of 0.1 m (0.3 ft) below MLLW (Alternative 3b). To quantify the hydrodynamic factors contributing to habitat loss, model predictions of water levels, velocities, and bed shear stress are presented for both of these sill elevations. These hydrodynamic factors also serve as the basis for predicting slough geomorphology at Year 10 and Year 50. Model results from existing conditions (Alternative 1, Year 0) and 1943 conditions provide a basis for comparing the response of implementing this alternative.

As discussed in Section 4.3, Alternative 3a (Low Sill) was selected for initial consideration to minimize navigation impacts while still reducing tidal exchange. Alternative 3b (High Sill) further reduces the tidal exchange, but also limits navigation during all or part of the tidal cycle. An additional increase in the sill crest elevation or the construction of multiple sills could further reduce the tidal exchange under this alternative. A sensitivity analysis indicates that a more restrictive partial tidal barrier – or multiple partial barriers – could reduce the tidal prism in the Slough resulting in water levels and current velocities similar to those presented for Alternative 2. The sensitivity analysis relied on adjusting the modeled friction coefficient of the sill as a surrogate for a more restrictive tidal barrier. The results of this sensitivity analysis are presented in Appendix C. If further consideration of a higher sill height or multiple sills is warranted, the results from the sensitivity analysis can be translated into a physical design which optimizes the number, location, and dimensions of one or more sills.

5.3.3.1 Water Levels

Alternative 3a (Low Sill)

As shown in Figure 5-16a, predicted water levels for Alternative 3a (Year 0) at the downstream location range from -0.1 m to 1.8 m (-0.3 ft to 5.9 ft), a 15% reduction in tidal range from existing conditions. The low sill at the Highway 1 bridge damps both ends of the tidal range – low tides are not as low and high tides are not as high. This damping occurs because the sill limits the tidal exchange between the Slough and Monterey Bay, preventing the Slough from completely filling on high tide and from completely draining on low tide. The difference between the lowest tides is larger than that of the highest tides since the sill blocks the lower part of the tide regime more effectively. Peak high water levels under

Alternative 3a are 0.3 m (1 ft) greater than the 1943 levels, and 0.1 m (0.3 ft) below existing conditions. The tidal range at the upstream section (Figure 5-16b) follows a similar pattern, with the addition of slight amplification at high tide.

Based on the projections of future morphological change, water levels at Year 10 are expected to remain nearly identical to Year 0 water levels. This lack of response indicates that water levels are not sensitive to the tidal erosion predicted to occur between Year 0 and Year 10. At Year 50, water levels increase by approximately 0.3 m (1 ft), which corresponds to the assumed rate of sea level rise.

Percent time exceeded curves, first described in Section 5.3.1.1, are shown for Alternative 3a in Figure 5-17. Compared to existing conditions, the Alternative 3a (Year 0) curve exhibits a flattening of slope indicating a decreased tidal range. Alternative 3a differs from the 1943 curve. At the nominal elevation of the marshplain, the percent time exceeded for Alternative 3 (Year 0) is 9%. This elevation is also exceeded 9% of the time under Year 10 conditions and 33% of the time under Year 50 conditions.

Alternative 3b (High Sill)

Raising the sill crest elevation further reduces tidal exchange into and out of the Slough, yielding additional damping at both ends of the tidal range. Water levels at the downstream location range from 0.22 m (0.72 ft) to 1.7 m (5.6 ft) under Alternative 3b (Figure 5-20a), a 33% reduction in tidal range from existing conditions. Peak high water levels under Alternative 3b are 0.2 m (0.6 ft) greater than the 1943 levels, and 0.2 m (0.6 ft) below existing conditions. The tidal range at the upstream section (Figure 5-20b) follows a similar pattern, with the addition of slight amplification at high tide.

Based on the projections of future morphological change, water levels at Year 10 are expected to remain nearly identical to Year 0 water levels. This lack of response indicates that water levels are not sensitive to the tidal erosion predicted to occur between Year 0 and Year 10. At Year 50, water levels increase by approximately 0.3 m (1 ft), which corresponds to the assumed rate of sea level rise.

Percent time exceeded curves, first described in Section 5.3.1.1, are shown for Alternative 3b in Figure 5-21. Compared to existing conditions, the Alternative 3b (Year 0) curve flattens, indicating a decreased tidal. Alternative 3a differs from the 1943 curve. At the nominal elevation of the marshplain, the percent time exceeded for Alternative 3b (Year 0) is 7%. This elevation is also exceeded 7% of the time under Year 10 conditions and 30% of the time under Year 50 conditions.

5.3.3.2 Velocity and Bed Shear Stress

Alternative 3a (Low Sill)

Predicted velocities for Alternative 3a are shown along the horizontal axes in Figure 5-16. At the downstream location, the horizontal extent of the Alternative 3a (Year 0) region indicates ebb-dominance, with peak ebb velocities reaching more than 0.6 m/s (2 ft/s) while peak flood velocities are less than 0.5 m/s (1.6 ft/s). These velocities represent a 20% decrease from existing conditions, with a slightly larger relative decrease on ebb tide as compared to flood tide. The peak ebb velocities are more than twice 1943 conditions while peak flood velocities are similar to 1943 conditions. Similar relative changes in velocities are predicted for the upstream location (Figure 5-16b).

The presence of the sill at the mouth of the Slough, an active boating thoroughfare, raises concerns about decreased navigability. Because the sill reduces cross-sectional area, flow velocities increase over the top of the sill. During spring tides, predicted peak velocities in the vicinity of the sill are 0.8 m/s (2.6 ft/s) on flood tide and 1.3 m/s (3.9 ft/s) on ebb tide. For comparison, peak flood velocities for Alternative 1 (No Action) are 0.5 m/s (1.6 ft/s) and 0.6 m/s (2.0 ft/s) on flood and ebb, respectively. Since the model only resolves flows at the scale of depth-averaged, 10 m wide grid cells, local velocities in the immediate vicinity of the sill may be higher.

The predicted geomorphic changes in the Slough at Year 10 and Year 50 would result in a decrease in velocities. Between Year 0 and Year 10, peak velocities at the downstream location decrease by 10%. This decrease occurs because the main Slough channel is projected to expand in response to continuing tidal erosion. Deepening the channel increases the cross-sectional area and reduces the influence of bed friction. Together, these changes enable the same conveyance capacity with reduced current velocities. Between Year 10 and Year 50, peak velocities decrease an additional 7%, as tidal scour and channel deepening continue, although at decreased rates.

Figure 5-18 shows distributions of bed shear stress as a function of percent time exceeded for Alternative 3a. At the downstream location, Alternative 3a (Year 0) bed shear stresses decrease by 35% on ebb tide and 28% on flood when compared with existing conditions. Bed shear stress also decreases at the upstream station, but by a smaller relative amount. At the downstream location on ebb tides, the Alternative 3a (Year 0) bed shear stress exceeds the critical bed shear stress for erosion of 0.2 N/m^2 (Sea Engineering Incorporated 2006) 7% of the time. For the downstream flood tide and both upstream tides, the bed shear stress exceeds the critical bed shear stress less than 1% of the time. At Year 10 and Year 50, the predicted bed shear stress distributions are similar; they both exceed the critical value for less than 1% of flood tides and for less then 3% of ebb tides.

Alternative 3b (High Sill)

Predicted velocities for Alternative 3b are shown along the horizontal axes in Figure 5-20. At the downstream location, the horizontal extent of the Alternative 3b (Year 0) region indicates nominal ebb dominance, with peak ebb velocities reaching 0.46 m/s (1.5 ft/s) while peak flood velocities are approximately 0.42 m/s (1.4 ft/s). These velocities represent a 39% decrease from existing conditions on ebb tides and a 30% decrease on flood tides. The peak ebb velocities are nearly twice 1943 conditions while peak flood velocities are slightly less than 1943 conditions. Similar relative changes in velocities are predicted for the upstream location (Figure 5-20b).

The presence of the sill at the mouth of the Slough, an active boating thoroughfare, raises concerns about decreased navigability. Because the sill would reduce cross-sectional area, flow velocities would increase over the top of the sill. During spring tides, predicted peak velocities in the vicinity of the sill would be 1.0 m/s (3.3 ft/s) on flood tide and 1.6 m/s (5.2 ft/s) on ebb tide. For comparison, peak flood velocities for Alternative 1 (No Action) are 0.5 m/s (1.6 ft/s) and 0.6 m/s (2.0 ft/s) on flood and ebb, respectively. Since the model only resolves flows at the scale of depth-averaged, 10 m wide grid cells, local velocities in the immediate vicinity of the sill may be higher.

The predicted geomorphic changes in the Slough at Year 10 and Year 50 are slight for Alternative 3b. Therefore, peak flood velocities would not change between Year 0 and Year 10. However, with the addition of mean sea level rise at Year 50, peak velocities would increase by 9% between Year 10 and Year 50.

Figure 5-22 shows distributions of bed shear stress as a function of percent time exceeded for Alternative 3b. At the downstream location, Alternative 3b (Year 0) bed shear stresses would decrease by up to 64% on ebb tide and up to 46% on flood when compared with existing conditions. Bed shear stress also would decrease at the upstream station, but by a smaller relative amount. At the downstream location on ebb tides, the Alternative 3b (Year 0) bed shear stress exceeds the critical bed shear stress for erosion of 0.2 N/m^2 (Sea Engineering Incorporated 2006) less than 1% of the time. Because of minimal morphologic change predicted between Year 0 and Year 10, the bed shear stress distribution at Year 10 is identical to that of Year 0. The increase in mean sea level associated with Year 50 results in elevated bed shear stress as compared with Year 10. At Year 50, the predicted bed shear stress exceeds the critical value only on ebb tides, for 2% of the time.

5.3.3.3 Geomorphic Change

<u>Main Channel Evolution</u>

Profiles of projected thalweg depths for Alternative 3a, Years 0, 10 and 50 are shown in Figure 5-16. Between Year 0 and Year 10, one meter of erosion is projected for the downstream half of the Slough. In the upstream half of the Slough, projected erosion tapers off to near zero. Between Year 10 and Year 50, erosion of up to 5 m is predicted near the mouth of the Slough. Over 1 km of the Slough's length is expected to reach the 10 m depth limit incorporated into the geomorphic change model. In the upper Slough, erosion decreases from up to 2 m to minimal change. Any sediment leaving the estuary would be captured the canyon (Paull and others 2006) or dispersed downdrift. Some sediment eroded from the marsh and mudflat areas will settle into the channel to accumulate as erodible soft fluid mud behind the sill.

Profiles of projected thalweg depths for Alternative 3b, Years 0, 10 and 50 are shown in Figure 5-23. Between Year 0 and Year 10, one half meter of erosion is projected for a few locations along the downstream portion of the Slough. For the remainder of the Slough, predicted erosion is near zero. Between Year 10 and Year 50, erosion on the order of 2 m is predicted at several locations along the downstream portion of the Slough. Less than 1 km of the Slough's length is expected to reach the 10 m depth limit incorporated into the geomorphic change model. In the upper Slough, erosion ranges from one half meter to negligible. Net sediment loss will continue as any sediment leaving the estuary will be captured the canyon or dispersed. Unless filled with placed sediment, the channel will act as a sink for sediment eroded from marsh and mudflat areas.

Marshplain Evolution

Alternative 3a would result in lowering of water elevations by around 10 cm which would halt or reverse the loss of vegetated marshplain. With continued sea level rise the marshplain will progressively drown, resulting in expansive mudflat. Rate of channel expansion into the marsh will decrease under this scenario because of reduced flow velocities, relative to Alternative 1. The main channel would compete with the marshplain for sediment eroded from the mudflats and marshes.

Alternative 3b will result in lowering of water elevations by around 20 cm which would also halt or reverse the loss of vegetated marshplain. With continued sea level rise the marshplain would progressively drown, resulting in expansive mudflat. The rate of channel expansion into the marsh would substantial decrease under this scenario because of lowered flow velocities relative to Alternative 1. The main channel would compete with the marshplain for sediment and so filling the channel with sediment may increase the longevity of adjacent mudflats and, to a lesser degree, marsh. See Section 3.4.4 for a more complete description of using imported fill in the main channel. Placement of fill along the main channel was not included in the hydrodynamic modeling of this alternative.

While it is anticipated that vegetated marshplain loss would not be completely halted by these alternatives, the benefit of Alternative 3, particularly Alternative 3b, over Alternative 1 is that the rate of change can be slowed, providing time to implement project elements to retain wetlands. They would also provide a greater potential that the morphology of Elkhorn Slough will stabilize at dominantly expansive mudflats rather than continuing to erode to subtidal habitat.

In conjunction with the sill options, periodic direct application of sediment to the marshplain in sufficient quantities would allow restoration of vegetated marsh habitat. Because the rate of loss of sediment from the system is less under Alternative 3 that Alternative 1, lesser quantities of sediment over time would be required to maintain intertidal areas and placed sediment would not be eroded and conveyed out of the system.

5.3.4 Alternative 4 – Restoration of Parsons Slough

Alternative 4, restoration of Parsons Slough would decrease the tidal prism in Elkhorn Slough downstream of the Parsons Slough mouth using either an hydraulic control at the railroad bridge or placement of fill in the subsided wetlands to attenuate tidal erosion and habitat loss. To quantify the hydrodynamic factors contributing to habitat loss, model predictions of water levels, velocities, and bed shear stress are presented. These hydrodynamic factors also serve as the basis for predicting slough geomorphology at Year 10 and Year 50. Model results from existing conditions (Alternative 1, Year 0) and 1943 conditions provide a basis for comparing the response of implementing this alternative.

5.3.4.1 Water Levels

As shown in Figure 5-24a, predicted water levels for Alternative 4 (Year 0) at the downstream location range from -0.3 m to 1.9 m (-1 ft to 6.2 ft). This range is identical to that of existing conditions. This lack of change in water level is expected since the existing Slough water levels closely mimic Monterey Bay tides and Alternative 4 does not alter the incoming tide in the main slough channel. Peak water levels under Alternative 4 remain 0.4 m (1.3 ft) above the 1943 levels. The tidal range at the upstream section (Figure 5-24b) follows a similar pattern, with the addition of slight amplification at high tide.

Based on the projections of future morphological change, water levels at Year 10 are expected to remain nearly identical to Year 0 water levels. This lack of response indicates that water levels are not sensitive to the tidal erosion predicted to occur between Year 0 and Year 10. At Year 50, water levels increase by approximately 0.3 m (1 ft), which corresponds to the assumed rate of sea level rise.

Percent time exceeded curves, first described in Section 5.3.1.1, are shown for Alternative 4 in Figure 5-25. The Alternative 4 (Year 0) curve replicates predictions for existing conditions, and correspondingly, it is significantly different from the 1943 curve. At the nominal elevation of the marshplain, the percent time exceeded for Alternative 4 (Year 0) is 11%. This elevation is also exceeded 11% of the time under Year 10 conditions and 34% of the time under Year 50 conditions.

5.3.4.2 Velocity and Bed Shear Stress

Predicted velocities for Alternative 4 are shown along the horizontal axes in Figure 5-24. At the downstream location, the horizontal extent of the Alternative 4 (Year 0) region indicates ebb-dominance, with peak flood velocities reaching nearly 0.5 m/s (1.6 ft/s) while peak ebb velocity are approximately 0.65 m/s (2.1 ft/s). These velocities represent a 15% decrease from existing conditions. The peak velocities are nearly twice that of 1943 conditions. Only slight velocity changes are predicted for the upstream location (Figure 5-24b), indicating that the upper Slough is relatively insensitive to modifications of Parsons Slough.

The predicted geomorphic changes in the Slough at Year 10 and Year 50 result in a decrease in velocities. Between Year 0 and Year 10, peak velocities at the downstream location decrease by 10%. This decrease occurs because the main Slough channel is projected to deepen in response to continuing tidal erosion. Deepening the channel increases the cross-sectional area and reduces the influence of bed friction. Together, these changes enable the same conveyance capacity with reduced current velocities. Between Year 10 and Year 50, peak velocities decrease by up to 15%, as tidal scour and channel deepening continue.

For Alternative 4, distributions of bed shear stress as a function of percent time exceeded are shown in Figure 5-26. At the downstream location, Alternative 4 (Year 0) bed shear stresses decrease by up to 50% on both ebb and flood tide when compared with existing conditions. Bed shear stress also decreases at the upstream station, but by a smaller percentage. At the downstream location on ebb tides, the

Alternative 4 (Year 0) bed shear stress exceeds the critical bed shear stress for erosion of 0.2 N/m^2 (Sea Engineering Incorporated 2006) 4% of the time. For the downstream flood tide and both upstream tides, the bed shear stress exceeds the critical bed shear stress for erosion less than 2% of the time. At Year 10 and Year 50, the predicted bed shear stress distributions are similar; they both exceed the critical value for less than 1% of flood tides and 3% on ebb tides.

5.3.4.3 Geomorphic Change

Main Channel Evolution

Removing or substantially reducing the tidal prism of Parsons Slough would result in an immediate reduction in the rate of scour of the channel in the lower estuary. Profiles of projected thalweg depths for Alternative 4, Years 0, 10 and 50 are shown in Figure 5-27. Between Year 0 and Year 10, approximately one meter of erosion is projected for the downstream three quarters of the Slough. In the upper Slough, projected erosion tapers off to near zero. Between Year 10 and Year 50, erosion of up to 6 m is predicted near the mouth of the Slough. Nearly 2 km of the Slough's length is expected to reach the 10 m depth limit incorporated into the geomorphic change model. In the upper Slough, erosion decreases from up to 3 m to minimal change only at the head of the Slough.

The system will remain slightly ebb-dominated. With dredging continuing in the harbor it is not anticipated that the channel will acquire sediment from outboard of the estuary, but will act as a sink sequestering sediment eroded from mudflat and marsh areas. These sediments over time will migrate seawards, transported by catchment run-off and high flow tidal events.

Marshplain Evolution

Alternative 4 does not significantly influence either MHHW or MLLW elevations and as such will not directly impact immediate acreage of intertidal habitat outside Parsons Slough. Over time it is anticipated that the marshplain would fail to keep pace with rising sea level and largely covert to mudflat through internal dissection and marsh drowning. With reduced tidal currents there would be a reducing in the rate of sediment export from the tidal channel network. The main channel would act as a sink for sediment competing with the marsh surface for material eroded from the mudflats and marshes.

Periodic, direct application of sediment to the marshplain in sufficient quantities will foster restoration of vegetated marsh habitat. Because the rate of loss of sediment from the estuary is less under Alternative 4 that Alternative 1, lesser quantities of sediment over time would be required to maintain intertidal areas. With reduced hydraulic connectivity to Parsons Slough a potentially large sediment sink for sediment eroded from Elkhorn Slough is removed from the system.

5.4 PREDICTION OF FUTURE HABITAT CHANGES

Given predicted sea level rise and hydro-geomorphic changes due to the proposed restoration actions, tidal habitat composition will change. At Elkhorn Slough, changes in tidal habitat composition can be predicted by analyzing how tidal habitat processes might change; we do this by formulating "conceptual models." Using the conceptual models previously developed, we can estimate how alternative restoration actions may affect tidal habitat composition. Finally, given these predictions, advantages/disadvantages of the restoration alternatives can be discussed and evaluated, assuming that tidal habitat composition goals have been identified.

In our conceptual models of tidal habitat processes, we assume the following: (1) Channel widening and deepening will continue to cause direct loss of wetland habitat; (2) Because the tidal system is ebb-dominated, a net loss of sediment will also continue to occur; and (3) Due to the lack of sediment input, the existing marshes will continue to subside and convert to mudflat.

The allocation of funding between the components in this report emphasized the development of a hydrodynamic model of Elkhorn Slough. As such, the resources available for developing and implementing these predictions of future habitat changes were limited. Additional analysis may be appropriate to further enhance the reliability of long-term habitat predictions.

5.4.1 Habitat Processes Specific to Elkhorn Slough

The marshes at Elkhorn Slough are unique in that they are dominated by pickleweed with cordgrass absent. Presumably, this makes losses/gains of vegetated marshes more sensitive to alterations of hydroperiod and sedimentation rates.

Drainage and salinity are factors in pickleweed production and distribution. In a study of factors controlling primary productivity of perennial pickleweed (*Sarcocornia pacifica*, formerly *Salicornia virginica*) in San Francisco Bay, aboveground biomass was higher in plots closer to channels than in poorly drained plots away from channels (Parker and others 2007). However, salinity was also a controlling factor, having a strong negative effect on annual net primary productivity in the poorly drained plots (Parker and others 2007). Poor drainage was again determined to affect the distribution of pickleweed species, with pickleweed tending to favor highly saline, non-waterlogged areas (Brereton 1971). Pickleweed grows within a broad range of salinities in nearby South San Francisco Bay; it occurs in locations where soil salinities range from 6.9 ppt to 71.7 ppt, with mean interstitial salinities of 40.9 ppt (H. T. Harvey & Associates 2002).

Pickleweed typically occupies a tidal range between mean high water (MHW) and mean higher high water (MHHW) (Mahall and Park 1976). In Elkhorn Slough, pickleweed mean ranges occur between the lower elevation limit of 0.79 +/- 0.11 m above MHW, to an upper limit of 0.81 +/- 0.11 m above MHW (National Ocean Survey 1993; National Oceanic and Atmospheric Association 1978). In Estrada Marsh and North Marsh, pickleweed elevation ranges were similar. Pickleweed ranges may be wider depending on local site conditions, indicating that microtopography could play an important role in its distribution. For example, pickleweed elevation ranges were higher in Estrada Marsh and North Marsh when measured at different sites by another researcher (Finney 2004).

Other factors that may contribute to pickleweed distribution are surface soil plasticity, aeration, salinity, density (mutual protection between individual plants), and herbivory. In less waterlogged areas, higher plant density may contribute to more stable substrate; stable substrate would increase the survival of individual plants, which in turn would increase plant density. Thus, as pickleweed distribution in an area begins to decline, decreasing densities may actually increase mortality in an area (Brereton 1971). Herbivory by *Sphaeroma* could occur due to marsh loss and patchiness along the edges of Elkhorn Slough; the presence of *Sphaeroma* has been confirmed in mudflat areas.

Nutrient concentrations are also an important factor in Elkhorn Slough because pickleweed has been shown to be nitrogen limited (Boyer and others 2001); nutrient issues are being evaluated in a separate report.

5.4.2 Habitat Projection Considerations

A conceptual model was developed for Elkhorn Slough; various assumptions and boundary conditions were applied to the model, and hydrodynamic model results allowed us to estimate changes in tidal habitat composition. Recognized uncertainties in assumptions and boundary conditions were evaluated through sensitivity analyses; ranges in parameters were evaluated to "bracket" the potential habitat outcomes under the various alternatives. The model boundary conditions, parameter values, and assumptions considered were: sea level rise; accretion rates; channel widening and bank erosion; channel cross section form; and marsh elevation

5.4.2.1 Sea Level Rise

Without significant sediment input to the system, the Elkhorn marshes are likely not sustainable under sea level rise predictions. Over the long-term Year 50 morphological projections, the effects of sea level rise would likely be significant enough to detect, and the potential exists for localized effects on habitat between Year 0 and Year 50. Although not considered in the hydrodynamic model, Year 10 habitat predictions assumed a sea level rise rate of 3 mm/yr, resulting in a 3-cm increase in water levels.

5.4.2.2 Accretion Rates

In the Elkhorn Slough system, sedimentation and marsh accretion patterns have not been thoroughly documented. Preliminary Surface Elevation Table (SET) data from October 2006 to June 2007 indicate that for an 8-month period, accretion averaged between 3 mm and 5 mm for the upstream reach and approximately 5 mm for the downstream reach (unpublished data)[8]. Long-term sediment accumulation rates have averaged approximately 1.1 mm/yr over the past 6,000 years (Burke Watson 2007).

These preliminary data are useful in comparison to the results from additional accretion studies. In San Pablo Bay, vertical accretion modeling suggested that salt marshes in that area will be sustainable with sea level rise of 3 to 5 mm/yr and average sediment supply (Orr and others 2003).

While large areas of erosion have occurred in along the main channel and in tidal creek channels in Elkhorn Slough, localized processes also likely contribute to changes in the marsh morphology. Crampton (Crampton 1994) documented a decrease in marshplain elevation at Elkhorn Slough of approximately 12 cm from 1947 to 1994, which averages to approximately -2.5 mm/yr. In Willapa Bay, another west coast estuary, accretion among individual *Spartina* mounds ranged from +1.0 to +10.1 mm/yr while erosion on adjacent mudflats averaged –13.8 mm/yr, suggesting that the accreting *Spartina* mounds were likely "robbing" sediment from adjacent mudflat sites (Ball 2005). In addition, localized marsh loss from other factors such as herbivory (although likely playing a less significant role) may also be contributing factors apart from large-scale processes.

Therefore, a range of marsh accretion rates were assumed in Elkhorn Slough. At the low end, the strong ebb-dominated tide could result in scour not only from the channels, but also from the marshplain, therefore accretion rate of -2.5 mm/yr was used as a "worst case" scenario (based largely on Crampton (Crampton 1994)). Since the SET data at Elkhorn Slough represent a single measurement, they are considered quite unreliable. Therefore, on the high end, an accretion rate of +2 mm/yr was assumed, based on the average between the long-term rate of 1.1 mm/year and the preliminary SET results of ~3 mm/yr. Over a 50-year time period, this range of erosion/accretion rates results in a marsh elevation change of -12.5 cm to +10 cm. These marsh elevation changes were used with the modeled changes in water surface elevation, to estimate a range in tidal habitat projections. Given the lack of empirical data for sedimentation rates at Elkhorn Slough and how they might change under each restoration scenario, marsh accretion was treated uniformly across all alternatives.

5.4.2.3 Channel Widening and Bank Erosion

Bank erosion and marsh retreat were quantified along the main channel of Elkhorn Slough over a 72-yr time series, through GIS analysis (Van Dyke and Wasson 2005). Bank retreat of the main channel has been relatively constant at approximately 20 cm/yr over the last 72 years; the main channel width is predicted to increase by approximately 10 m in 50 years. Van Dyke and Wasson's analysis of 20 cm/yr was based on data collected from 73 cross sections along the main slough channel, and excluded degraded upper slough cross sections because determining the true channel edges was difficult in these severely degraded marshes. For the Year 50 habitat composition projections, a bank retreat rate of 20 cm/yr was

[8] Ongoing accretion has also been recorded in the eroding marshes of Essex. As the marshes erode, through internal breakdown, channel incision and marsh edge retreat, sediments are released into circulation some of which contribute to accretion of the remaining but diminishing area of vegetated marsh.

used. This rate was scaled proportionately for each of the action alternatives using the relative proportions found in Table 6.1 (Projected Erosion Rates).

For the purposes of projecting future shallow versus deep subtidal areas, it was assumed that as the channel widens, that the bathymetric profile would remain similar in form to the existing cross-sections (see Section 5.2). The assumption that the cross sectional geometry is consistent inherently assumes that some mudflats will be preserved. However, with a net export of sediment from Elkhorn Slough, some of these mudflats could become subtidal in the 50-year planning horizon. Predicting the bathymetric profile for each alternative was beyond the scope of this project and the assumption was made to facilitate relative comparisons.

5.4.2.4 Tidal Creek Widening

Tidal creek widening was not modeled for this report, but was considered qualitatively when developing the habitat estimates. In 2005, Van Dyke and Wasson analyzed data for 196 tidal creeks in 5 geographical areas of Elkhorn Slough and found that rates of marsh loss and tidal creek widening have increased dramatically in recent years (Wasson, unpublished data). These predictions assumed a linear trend for the processes of tidal creek widening, which may or may not be the case. Tidal creek widths in 2003 in the lower Slough ranged between 10-11 m, with a predicted increase of between 2-8 m between 2003 and 2050. Tidal creek widths for the upper Slough in 2003 ranged between 12-19 m, with predicted increased of between 13-21 m.

In comparing these tidal creek predictions with marsh cover predictions for the same areas, the lower Slough is predicted to lose 9-18% of the marsh cover that was present in 2003. The upper Slough is predicted to lose 5-21% of the cover that was present in 2003. Not reflected in that percent decrease however is the fact that the predicted marsh loss in some areas of the upper Slough will reach zero percent marsh cover prior to 2050. For example, remaining marsh cover in the most upstream area (Section 5) is very low (~5 acres) and is predicted to have no appreciable marsh vegetation prior to 2020.

It should be reiterated that these assumptions are based on a linear increase in tidal channel widening and a concurrent linear decrease in marsh vegetation cover. However, it appears that these relationships may not be linear. A closer examination of the data from the most upstream areas indicate that the vegetation declined in a linear manner and then reaches a threshold point, after which the decline becomes much more rapid. Therefore, their predictions should be considered conservative rates of marsh loss and actual rates could be higher.

The mechanisms of tidal creek widening are much the same as widening in the main channel. However, in areas where the surrounding vegetated marsh has largely converted to mudflat (as at Elkhorn Slough), it is difficult to define the edge of the tidal channel. If vegetation is used as a boundary condition for defining channel width, the rate of channel widening may be overestimated. Therefore, given the scale of the loss of vegetated marsh at Elkhorn Slough, channel widening on the marsh plain was treated uniformly across alternatives as marsh drowning from sea level rise and lack of marsh accretion likely dominate any affects from tidal channel widening.

5.4.2.5 Channel Cross Section

Elkhorn Slough's main channel has increased in both width and depth since 1946, resulting in a volume increase of over 200% (Malzone 1999). Cross sectional changes from Sampey (Sampey 2006) were examined to determine how these changes in channel bathymetry might influence the future distribution of shallow and deep subtidal habitats. The existing area < 2m deep was estimated from the cross section profiles along the slough. Under alternative scenarios where continued channel erosion is expected, similar bathymetric profile forms were assumed for the widened channel, and the values of shallow and deep subtidal areas were recalculated accordingly.

5.4.2.6 Marsh Elevation

Ground and vegetation elevations can be estimated by LIght Detection And Ranging (LIDAR) remote sensing, but LIDAR may be limited in its ability to discriminate between ground and vegetation. Taller vegetation such as trees are readily separated from surrounding surfaces, but discriminating low growing, dense vegetation can be difficult (Rosso and others 2006). Ground survey elevation data can quantify the accuracy of LIDAR, but a complete ground survey to verify LIDAR data was not performed for this analysis. Instead, 91 elevation points on the tidal wetland marsh were collected using both a survey-grade GPS and a total station; these elevations were compared against the LIDAR data. A 95% agreement was observed between the LIDAR and surveyed elevations, within 5 cm (Smith and others 2005).

In the conceptual model, the average positive bias due to vegetation was assumed to be 5 cm; this value was used when estimating changes in tidal habitat composition. Vegetation zones were categorized based on a random sampling of the LIDAR elevation data and related to specific habitat types (marsh, mudflat, and open water), as assessed from field verification and the aerial imagery. This analysis is consistent with the use of LIDAR in other studies to classify vegetation-based habitats (Sobocinski and others 2006).

5.4.3 Tidal Habitat Composition Projections

Tidal habitat composition was defined by four habitat categories: (1) vegetated marsh; (2) intertidal mudflats; (3) shallow subtidal areas that are < 2m deep; and (4) deep subtidal channels that are > 2m deep. These habitat type categories were selected based on the habitats as defined for the indicator species being analyzed simultaneously with this report (Wasson, pers. comm.). The habitat composition projections represent approximate and relative changes in the quantity of each habitat type, relative to the existing habitat areas for open water. The open water habitat areas were divided into shallow subtidal (210 acres) and deep subtidal (340 acres), intertidal mudflat (1,090 acres), and vegetated marsh (750 acres).

Under current management practice, several areas in Elkhorn Slough are restricted from full tidal inundation. For these analyses, the management of these tidally restricted areas were assumed to remain the same under the proposed alternatives. The marsh complexes excluded from this habitat projection analysis include: Blohm Porter and North Marshes, which are currently managed under restricted tidal conditions; the Salt Ponds Wetland Complex, which is managed primarily for nesting and breeding habitat for the western snowy plover (*Charadrius alexandrinus*); and Parson's Slough for which management is currently being evaluated under a separate restoration process.

Utilizing the morphological scenarios, hydrodynamic model outputs, conceptual models, and knowledge of processes that determine tidal habitats, we have projected changes to tidal habitats for the specified time periods (Year 0, Year 10, and Year 50), for each alternative. We used a combination of Light Detection and Ranging (LIDAR) data (National Geodetic Survey 2004) and a composite aerial photograph (National Agricultural Imagery Program 2005) to correlate elevation and existing habitat zones.

The tidal datum predictions from the hydrodynamic model results were combined with a range of marsh accretion and channel widening values, to calculate the spatial inundation regime for each alternative scenario. Modeled water level results are a response to the physical configuration of the marsh and proposed alternatives, and the results also consider the effects of sea level rise. The shifts in water level result in changes in the inundation regime for the marsh and mudflat, and some of the alternatives change the water surface elevations of MHHW and MLLW. Examples of how these changes influence the habitat predictions include decreasing MHHW, resulting in an increase in vegetated marsh area in degraded areas, while increasing MLLW displaces lower areas of the intertidal mudflats with shallow subtidal habitat.

Each alternative also causes shifts in the depth and duration of the marshplain inundation (Figure 6-2, Figure 6-5, and Figure 6-8). Prolonged inundation can kill pickleweed (Zedler 1982), therefore influencing its lower limit of distribution. Pickleweed in a southern California marsh was found to be inundated 13% of the time (Sadro and others 2007). In San Francisco Bay, pickleweed distribution is limited to the upper, more exposed elevations of the marsh plain (Josselyn 1983). Pickleweed has also been shown to thrive in zones where the emergence period is greater than or equal to the period of submergence; pickleweed could not survive when the submergence period was four times greater than the emergence time (Josselyn 1983). Under existing conditions, the hydrodynamic model indicates that the marshplain is inundated approximately 11% of the time to a maximum depth of approximately 0.5 m. The 1943 data indicate that the marshplain was inundated less than 5% of the time at depths of only about 0.1 m. Each alternative varies the trajectory of marshplain inundation; however, all alternatives result in dramatic increases in the depth and duration of flooding by Year 50 (Figure 6-8). These projected inundation values range from 30-35% while the maximum depth of flooding increases to 0.6-0.8 m.

However, these results assume no change in the elevation of the marshplain. Taking into account the range of accretion and erosion values discussed earlier, as well as the change in the percent time that the water level exceeds the current (and projected future) marshplain elevation, and also the marsh vegetation's ability to tolerate inundation, we calculated the area of each habitat type given the new tidal ranges.

Due to tidal amplification upstream of Parsons Slough, and indications from the LIDAR data that subtle elevation changes could be detected between the upstream and downstream areas of Parsons Slough, the study area was divided into two reaches (Upstream and Downstream) to correspond with the hydrologic modeling results and more accurately classify vegetation zones within these areas. Results were then combined to give an overview of the projected changes for the entire slough.

The projected acreages for each of the habitat types in the fully tidal areas of Elkhorn Slough are shown in Table 5-1 to Table 5-5. Note that the Year 0 numbers for the action alternatives include habitat shifts that are likely to occur within the first few years after project implementation. Therefore the only 'Existing Conditions' habitat acreages shown are for Year 0, Alternative 1 (No Action). For example, there are currently 695 acres of salt marsh habitat (Table 5-1, Year 0), whereas we are projecting over 800 acres of salt marsh for Alternative 2 (Table 5-2, Year 0). These projected changes in Year 0 for each alternative are a result of the changes to the water surface elevations, flow velocities and channel scour, etc. that are a result of the proposed actions for that alternative. It should also be noted that these projections carry a high degree of uncertainty given the lack of empirical data on factors such as plant distribution relative to microtopography, accretion rates, organic matter contribution, etc. For example, the ranges of projected habitat values for the 50-year scenario are narrow. This is a function of the projected sea-level rise and an increasingly narrow range of elevations that are appropriate to support marsh vegetation. Rather, these projections should be utilized in comparing the relative outcomes between alternatives.

5.4.3.1 Alternative 1 - No Action

Main Channel Evolution

Hydrodynamic output from Alternative 1 was used to predict geomorphic change in the Slough channel at Year 10 and Year 50, as described in Section 5.2. Between Year 0 and Year 10, the evolution of the main channel will continue to be similar to existing conditions with steady progression of scour and widening. Most of the projected erosion during this period will occur in the main channel, primarily in the lower portion of the Slough.

Between Year 10 and Year 50, the projected annual erosion rate for the Slough is less than half of the rate predicted between Year 0 and Year 10. Depths along much of the lower Slough are projected to reach a threshold that is equal to the nominal depth of the harbor, and not erode further. By Year 50, the upper Slough is projected to have depths approximately twice that of the current (Year 0) depths.

Marshplain Evolution

Sediment supply is a critical component in maintaining a vegetated marshplain and marsh development requires a sufficient supply of sediment and associated accretion to support and maintain marsh elevation, particularly in anticipation of sea level rise. In Elkhorn Slough, marshes in the lower sections of the slough are eroding primarily along the main channel with a larger portion of the marsh maintaining healthy vegetation cover than in the upper slough areas, where the interior marshes are degrading primarily from the results of tidal channel scour. The marshplain morphological change occurring in Elkhorn Slough appears to be consistent with a response of an ebb-dominated estuary subject to low available suspended sediment concentrations. As long as the estuary remains ebb-dominated and with low suspended sediment concentrations and an insufficient influx of sediment, it is likely that marsh loss will continue and will follow the projected trajectory described below.

Habitat Predictions

Under Alternative 1 (No Action), it is assumed that the main channel will continue to widen and deepen at current rates, resulting in an increase in subtidal habitats at the expense of the intertidal habitats. Sea level rise will increase water levels on the marshplain.

Deep subtidal habitat will remain relatively stable between Year 0 and Year 10, with slight acreage increases. Between Year 10 and Year 50, deep subtidal habitat will continue to steadily increase. Shallow subtidal habitats will continue to gradually increase between Year 0 and Year 10 and between Year 10 and Year 50.

The largest projected increase in habitats over the 50-Year period under Alternative 1 is the increase in intertidal mudflat area. While intertidal mudflat area will continue to steadily increase between Year 0 and Year 10, the largest increase in intertidal mudflat will occur between Year 10 and Year 50 with continued widening of the main channel and tidal channel areas, and increased water levels compounded by the effects of sea level rise. Export of sediment from the system, as indicated by the deepening of the main channel, would result in intertidal mudflat converting to subtidal habitat; however there is still a large net gain in intertidal mudflat from the loss of salt marsh.

Salt marsh habitat will diminish slightly between Year 0 and Year 10. However, between Year 10 and Year 50 as the main channel and tidal channel scour continues, salt marsh habitat will continue to decrease significantly, especially with the effects of sea level rise, and much of this area will eventually be replaced by intertidal mudflat. The narrow projected range (9-11%) of salt marsh assumes that the majority of the marshplain will be inundated beyond the tolerance of pickleweed in most places, thereby converting it to mudflat. However, we expect that there will still be a perimeter of marsh habitat, albeit shifted to a higher and more limited elevation range.

Table 5-1. Habitat Projections, Alternative 1 (No Action)

Habitats	Associated Species	Existing		Projected		
		Year 0 (acres)	Year 0 (%)	Year 10 (acres)	Year 50 (acres)	Year 50 (%)
Deep Subtidal (> 2m depth)	Flatfish (some flatfish use eelgrass as habitat)	345	15%	350 - 400	450 - 530	19 – 23%
Shallow Subtidal (< 2 m depth)	Eelgrass Oysters	209	9%	210 - 240	220 - 260	9 – 11%
Intertidal Mudflat	Shorebirds Invertebrates	1088	47%	1100 - 1150	1220 - 1440	52 – 61%
Salt Marsh	Pickleweed	695	30%	620 - 670	220 -260	9 – 11%

5.4.3.2 Alternative 2 - New Ocean Inlet

Main Channel Evolution

Creation of a new ocean inlet would largely halt the loss of sediment from Elkhorn Slough and weak, potentially slightly flood-dominated tidal currents will cease to erode channel sediments. Some subtidal areas at the mouth of the estuary may be partially filled with sand migrating from the inlet, but these inputs will only occur a limited distance into the estuary.

Marshplain Evolution

Under Alternative 2, marshplain accretion is unlikely without supplemental sediment additions to the estuary. A lowering of water levels at the upper end of the tidal range by some 20-25 cm from tidal muting would likely result in initial recolonization of vegetation in some degraded marsh areas. However, the recolonization by vegetation will likely be a temporary condition, and the vegetated marshes would less vegetated habitat (primarily mudflat) by Year 50. Marsh to mudflat conversion is expected to be a result of marsh drowning versus tidal channel incision.

Habitat Predictions

Alternative 2 (New Ocean Inlet) would result in a truncated tidal range at both the upper and lower ends of the tidal range compared with exiting conditions. This will result in an immediate increase in subtidal habitats and vegetated marsh area, with a corresponding decrease in intertidal mudflat areas. However, as sea levels rise, these gains in salt marsh area will diminish and by Year 50 the vegetated marshes would have begun conversion to mudflat resulting in less vegetated marsh than existing conditions.

Between Year 0 and Year 10, deep subtidal, shallow subtidal and intertidal mudflat areas habitats will gradually increase with a related loss of vegetated marsh. These increases in subtidal and intertidal mudflat habitat will continue from Year 10 through Year 50, with substantial losses of vegetated marsh during this same time period.

Table 5-2. Habitat Projections, Alternative 2 (New Ocean Inlet)

Habitats	**Associated Species**	**Projected**				
		Year 0 (acres)	**Year 0 (%)**	**Year 10 (acres)**	**Year 50 (acres)**	**Year 50 (%)**
Deep Subtidal (> 2m depth)	Flatfish (some flatfish use eelgrass as habitat)	530	23%	540 - 600	650 – 765	28 – 33%
Shallow Subtidal (< 2 m depth)	Eelgrass Oysters	320	14%	330 - 380	400 – 470	17 – 20%
Intertidal Mudflat	Shorebirds Invertebrates	660	28%	660 - 740	680 – 800	29 – 34%
Salt Marsh	Pickleweed	820	35%	700 - 770	385 - 455	16 – 20%

5.4.3.3 Alternative - Tidal Barrier Under Highway 1 (Sill)

<u>Main Channel Evolution</u>

Under Alternative 3a (Low Sill), reduced tidal flow velocities would result in reduced rates of channel scour and reduced sediment loss from the estuary. However, the net sediment loss would continue as most of the sediment leaving the estuary will be captured in the canyon or dispersed, rather than recycled back into the estuary. While net sediment export will continue, some sediment eroded from the marsh and mudflat areas would settle into the channel with the construction of a sill structure.

Under Alternative 3b (High Sill), tidal flow velocities will be substantially reduced effectively halting channel scour and substantially reducing sediment loss from the estuary. While the decreased opening would result in eroded marsh and mudflat sediments remaining in the estuary, net sediment loss would likely continue unless supplemental sediment is placed on the marshplain.

Marshplain Evolution

Alternatives 3a and 3b would result in decreasing water elevations by approximately 10 to 20 cm respectively, which may initially halt or reverse the loss of vegetated marshplain. However, continued sea level rise will progressively drown the marshplain, ultimately resulting in increased mudflat habitat.

Channel expansion rates would decrease as a result of lowered flow velocities relative to No Action. The main channel would act as a sink for sediment competing with the marsh surface for material eroded from the mudflats and marshes.

Habitat Predictions

Alternative 3a will result in a slightly truncated tidal range at both the upper and lower ends of the tidal range compared with existing conditions. Between Year 10 and Year 50 under Alternative 3a, subtidal and intertidal mudflat habitat will increase with the largest increase occurring in shallow subtidal habitat. Corresponding increases in vegetated marsh will occur during this period.

Similarly, Alternative 3b will substantially decrease the rate of channel expansion because of lowered flow velocities, keeping deep subtidal areas relatively stable. The main channel will act as a sink for sediment and so filling the channel with sediment will increase the longevity of adjacent mudflats, and to a lesser degree, marsh.

Under both Alternatives 3a and 3b, MLLW elevations will be raised by 20-50 cm, respectively, resulting in conversion of some mudflat areas to subtidal habitat, with substantial increases in shallow subtidal habitat.

The lowering of water surface elevations under either of the sill alternatives may, for a limited number of years, halt or reverse the loss of vegetated marshplain between Year 0 and Year 10. Shallow subtidal and intertidal mudflat will initially increase and will continue to increase through Year 50.

Between Year 10 and Year 50, continued sea level rise would progressively drown the marshplain, resulting in increases in mudflat habitat. It is anticipated that marsh conversion to mudflat would continue in the long term Under Alternative 3b potential exists for the morphology of Elkhorn Slough to stabilize with habitat dominated by expansive mudflats rather than continuing to erode to subtidal habitat.

Table 5-3. Habitat Projections, Alternative 3a (Low Sill at Highway 1)

Habitats	Associated Species	Projected				
		Year 0 (acres)	Year 0 (%)	Year 10 (acres)	Year 50 (acres)	Year 50 (%)
Deep Subtidal (> 2m depth)	Flatfish (some flatfish use eelgrass as habitat)	375	16%	370 - 400	390 - 440	16 – 19%
Shallow Subtidal (< 2 m depth)	Eelgrass Oysters	225	10%	240 - 270	330 - 390	14 – 17%
Intertidal Mudflat	Shorebirds Invertebrates	980	42%	1000 - 1100	1140 – 1340	49 – 57%
Salt Marsh	Pickleweed	760	33%	680 - 710	290- 340	12 - 15%

Table 5-4 . Habitat Projections, Alternative 3b (High Sill at Highway 1)

Habitats	Associated Species	Projected				
		Year 0 (acres)	Year 0 (%)	Year 10 (acres)	Year 50 (acres)	Year 50 (%)
Deep Subtidal (> 2m depth)	Flatfish (some flatfish use eelgrass as habitat)	480	21%	420 - 460	350 - 380	15 – 16%
Shallow Subtidal (< 2 m depth)	Eelgrass Oysters	290	12%	320 - 410	530 - 650	23 – 28%
Intertidal Mudflat	Shorebirds Invertebrates	720	31%	750 - 820	830 - 1000	36 – 43%
Salt Marsh	Pickleweed	850	36%	790 - 850	400 - 490	17 – 21%

5.4.3.4 Alternative - Reduce Parsons Slough Tidal Prism

<u>Main Channel Evolution</u>

Removing or substantially reducing the tidal prism of Parsons Slough will result in an immediate reduction in the rate of scour of the channel in the lower estuary. However, the system will remain slightly ebb-dominated.

<u>Marshplain Evolution</u>

Alternative 4 does not significantly influence either MHHW or MLLW elevations and as such will not immediately impact intertidal habitat acreage. The main channel will act as a sediment sink competing with the marsh surface for material eroded from the mudflats and marshes. The reduced exchange between Parsons Slough and Elkhorn Slough will eliminate a potential sediment sink from the system.

<u>Habitat Predictions</u>

Since Alternative 4 is not expected to significantly influence either MHHW or MLLW elevations, this action will not significantly change the acreage of intertidal habitat between Year 0 and Year 10. The loss of vegetated marsh habitat during this period will be only slightly less than No Action.

While reduced tidal currents will reduce the rate of sediment export from the tidal channel network, between Year 10 and Year 50, it is anticipated that the marshplain will fail to keep pace with rising sea level and largely covert to mudflat and intertidal habitat. Increased surface water levels will result in a substantial decrease in vegetated marsh, which will persist without periodic application of sediment to the marshplain.

Table 5-5. Habitat Projections, Alternative 4 (Reduce Parsons Slough Tidal Prism)

Habitats	**Associated Species**	**Projected**				
		Year 0 (acres)	**Year 0 (%)**	**Year 10 (acres)**	**Year 50 (acres)**	**Year 50 (%)**
Deep Subtidal (> 2m depth)	Flatfish (some flatfish use eelgrass as habitat)	350	15%	350 - 380	430 - 500	18 – 21%
Shallow Subtidal (< 2 m depth)	Eelgrass Oysters	210	9%	210 - 230	220 - 240	9 – 10%
Intertidal Mudflat	Shorebirds Invertebrates	1090	47%	1100 - 1150	1200 - 1400	51 – 60%
Salt Marsh	Pickleweed	690	30%	630 - 670	240 - 300	10 – 13%

5.5 FIGURES

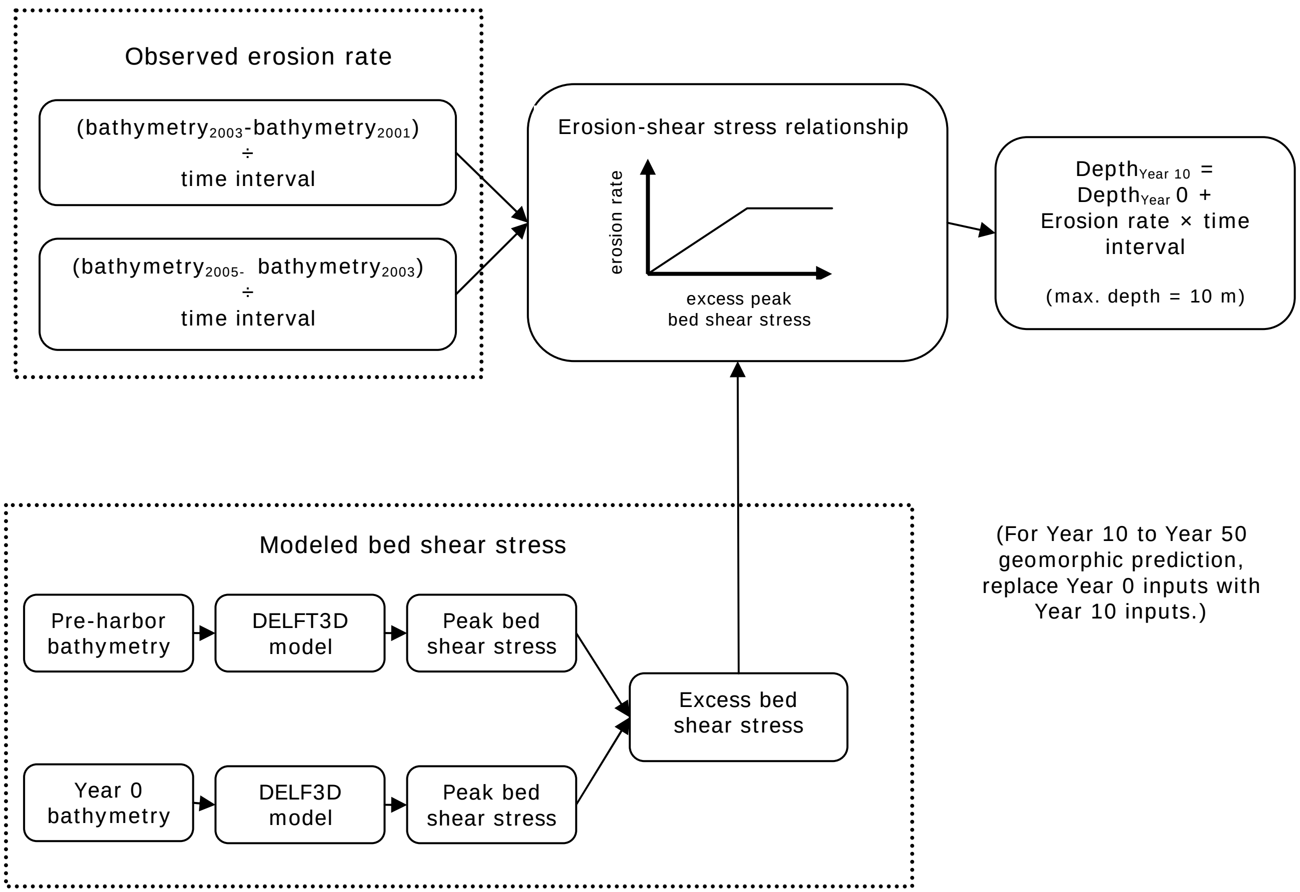

figure 5-1

Elkhorn Slough Tidal Wetlands Restoration

Methodology for Projecting Geomorphic Change

PWA Ref# 1869

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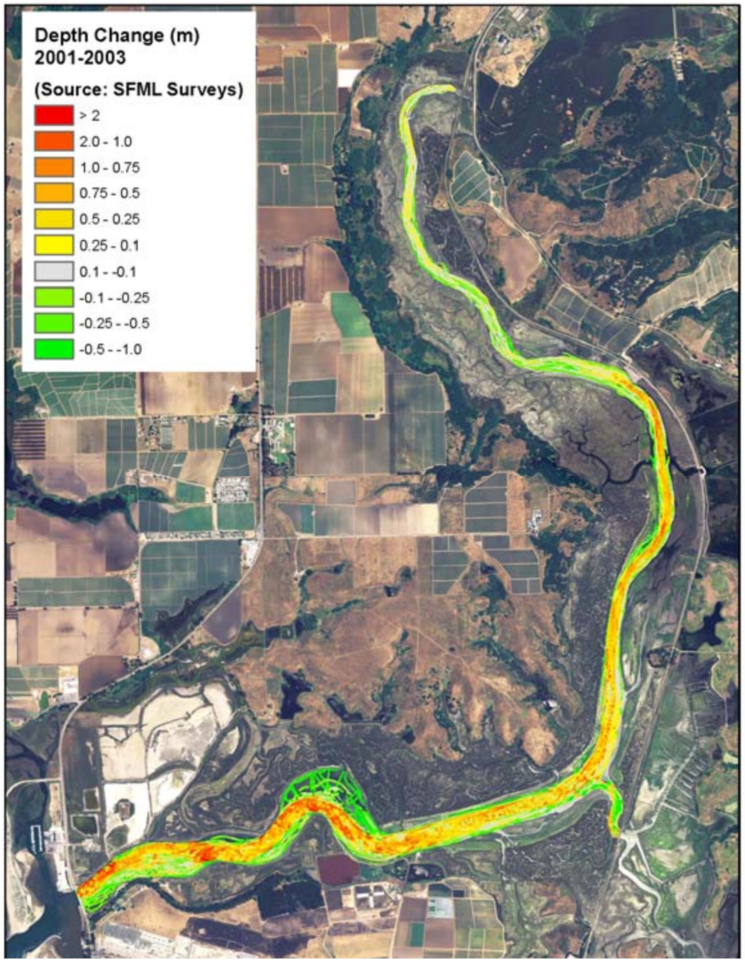
a) 2001-2003



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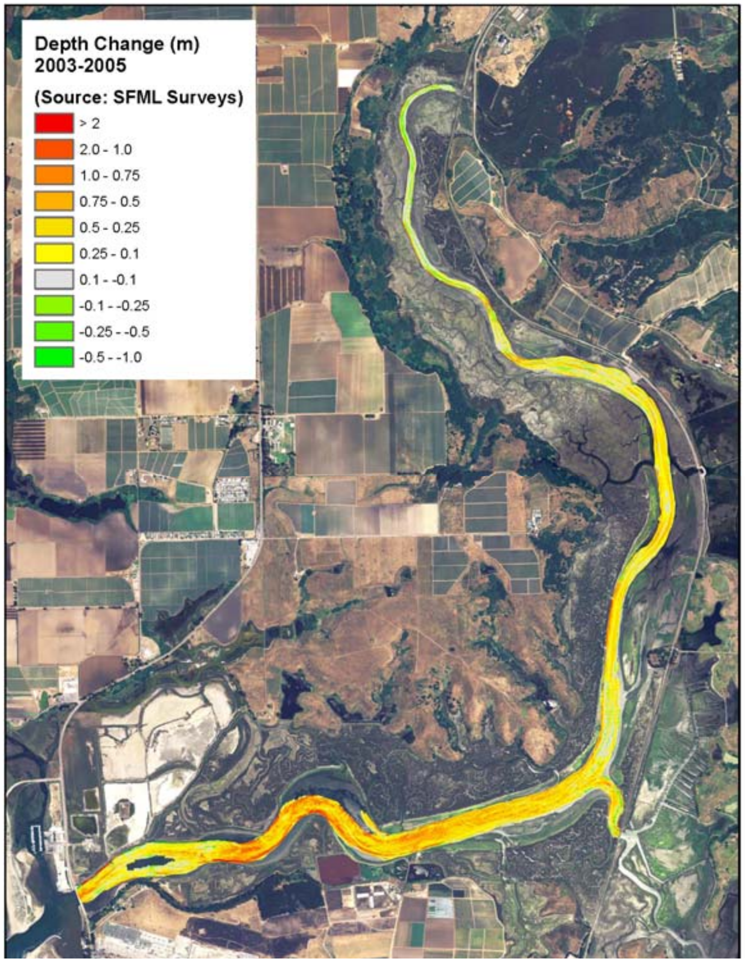


Source: SFML sidescan surveys

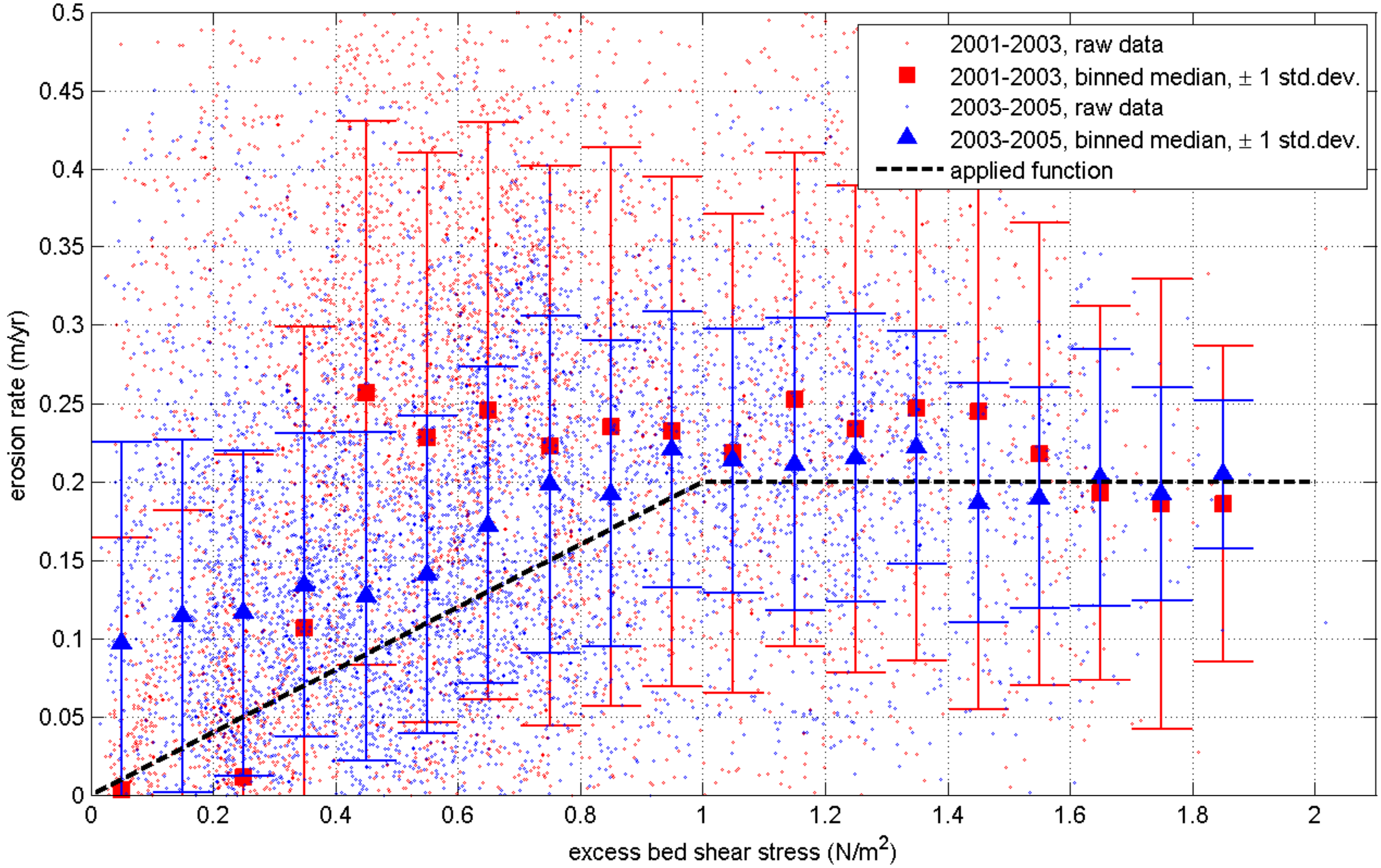
figure 5-2

Elkhorn Slough Tidal Wetlands Restoration

Observed Bathymetric Change

PWA Ref# 1869

PWA



Source: CSU-SFML batymetric surveys (2001, 2003, and 2005) & DELFT3D model results

Figure 5-3

Elkhorn Slough Tidal Wetlands Restoration

Erosion rate vs. excess bed shear stress

PWA Ref# 1869.5

PWA

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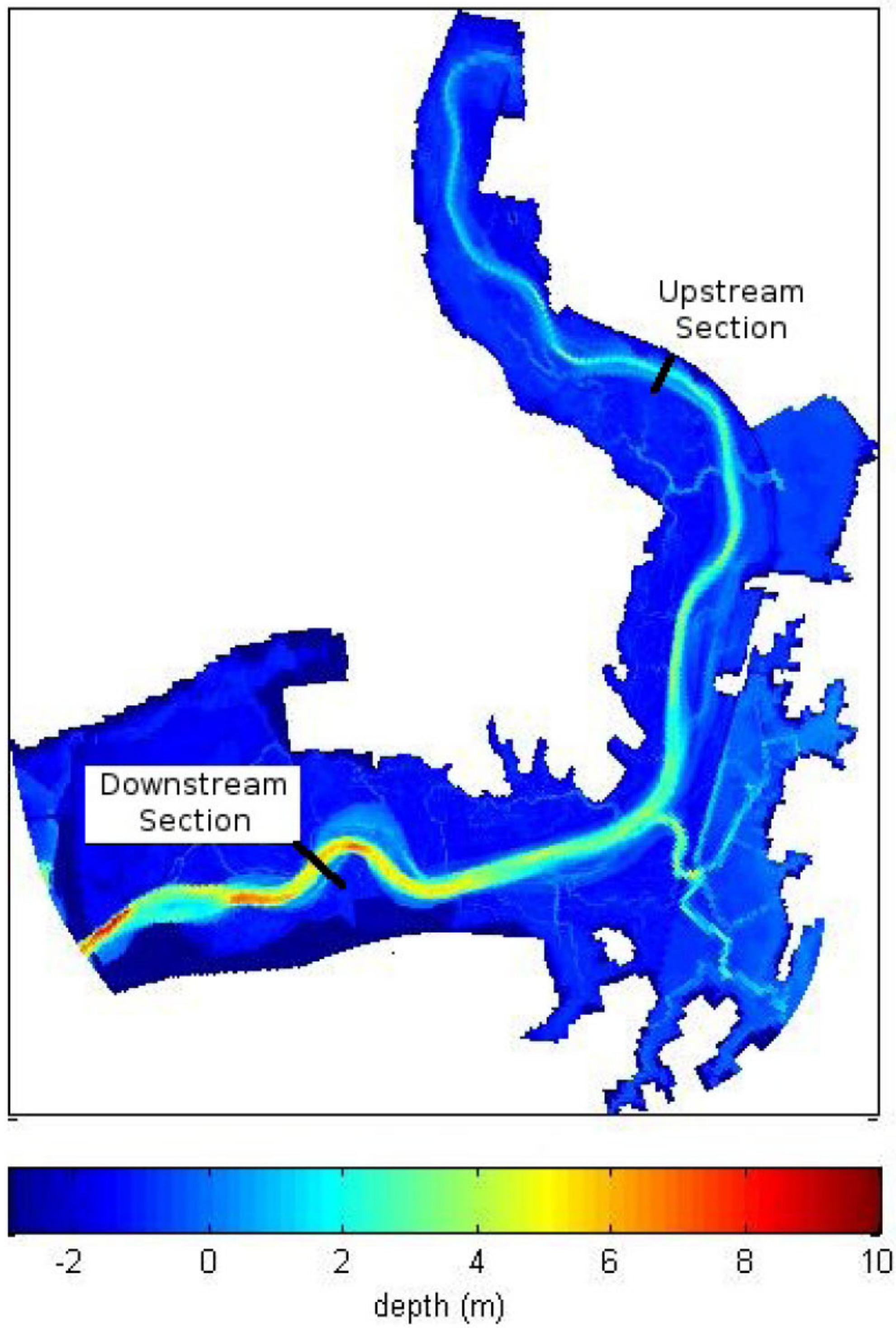


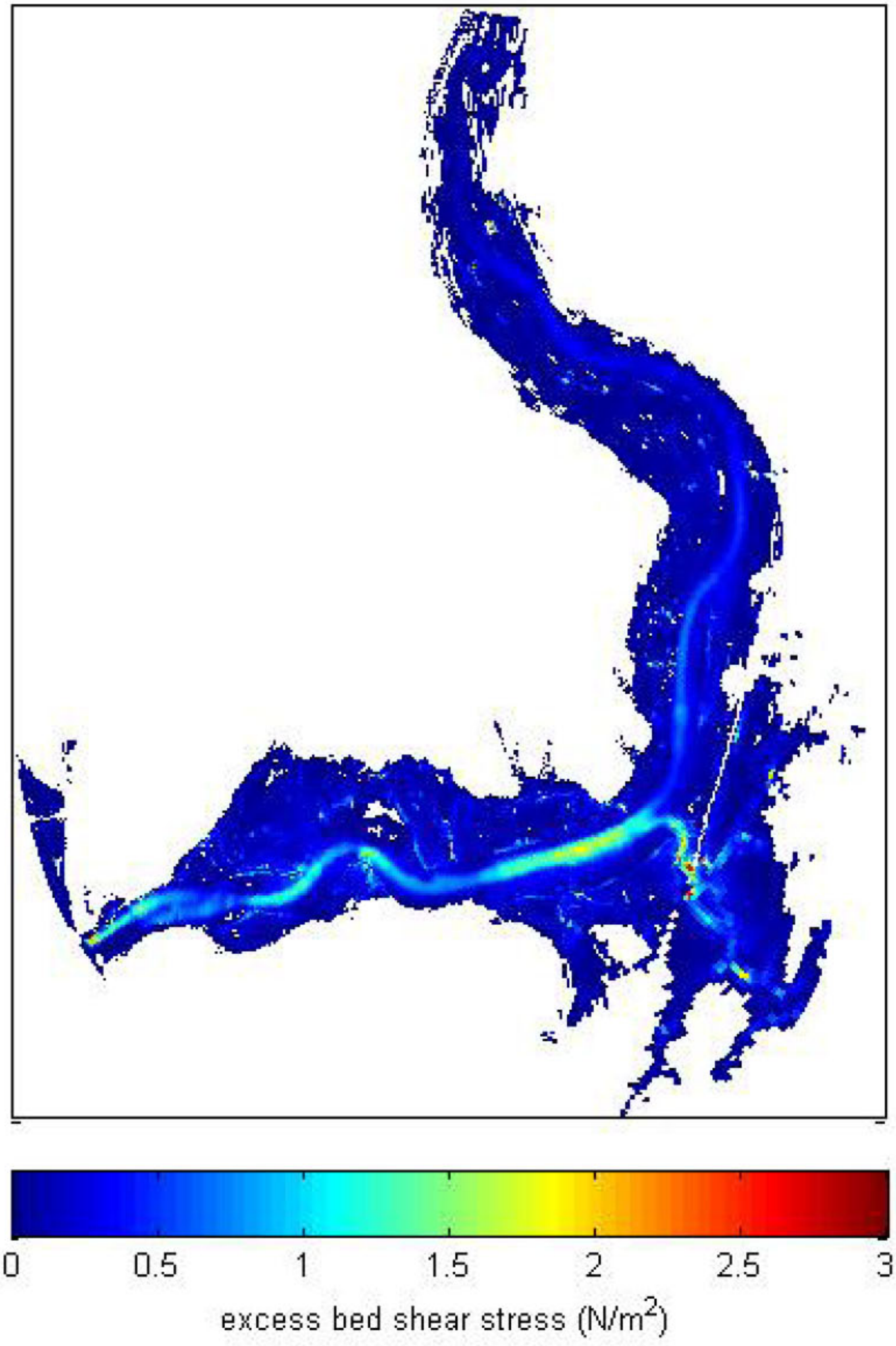
Source: CSU-MB SFML bathymetry (2003) and NOAA/NGS LiDAR (2004)

figure 5-4
Elkhorn Slough Tidal Wetlands Restoration

Alternative 1 Bathymetry, Year 0

PWA Ref# 1869

PWA

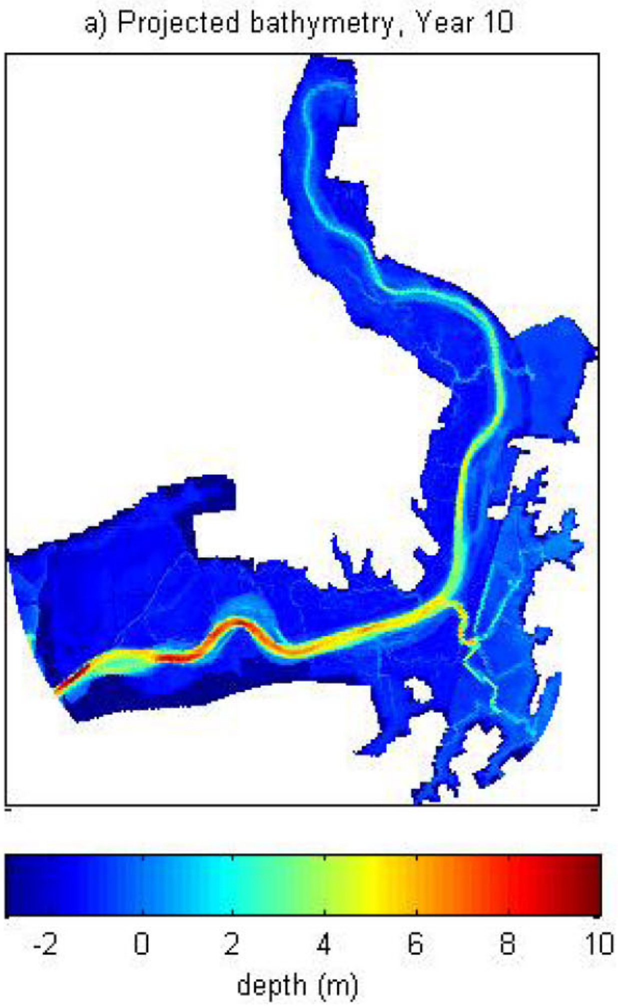


Source: DELFT3D model results

figure 5-5
Elkhorn Slough Tidal Wetlands Restoration

Alternative 1 Excess Bed Shear Stress, Year 0

PWA Ref# 1869

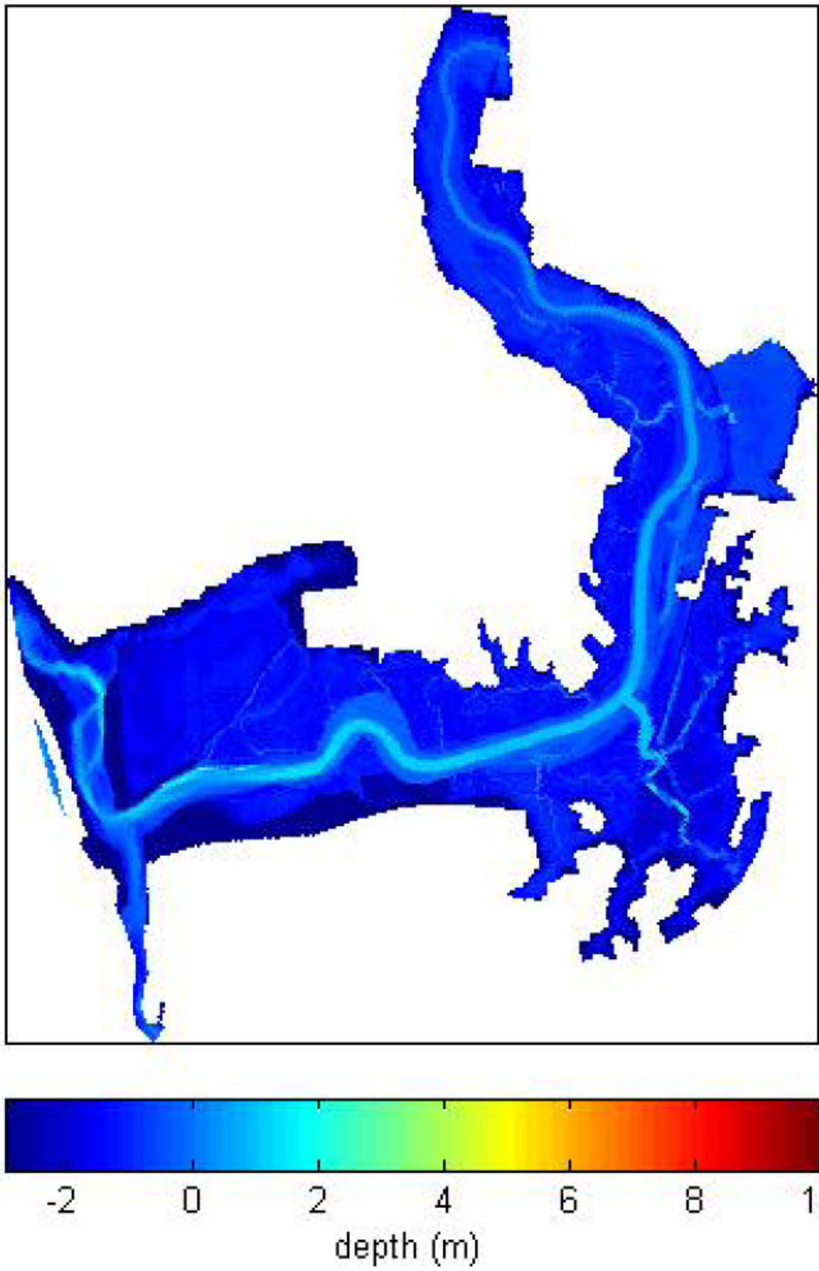


Source: CSU-MB SFML observations and DELFT3D model results

figure 5-6
Elkhorn Slough Tidal Wetlands Restoration

Alternative 1 Bathymetric Change, Year 0 to Year 10

PWA Ref# 1869

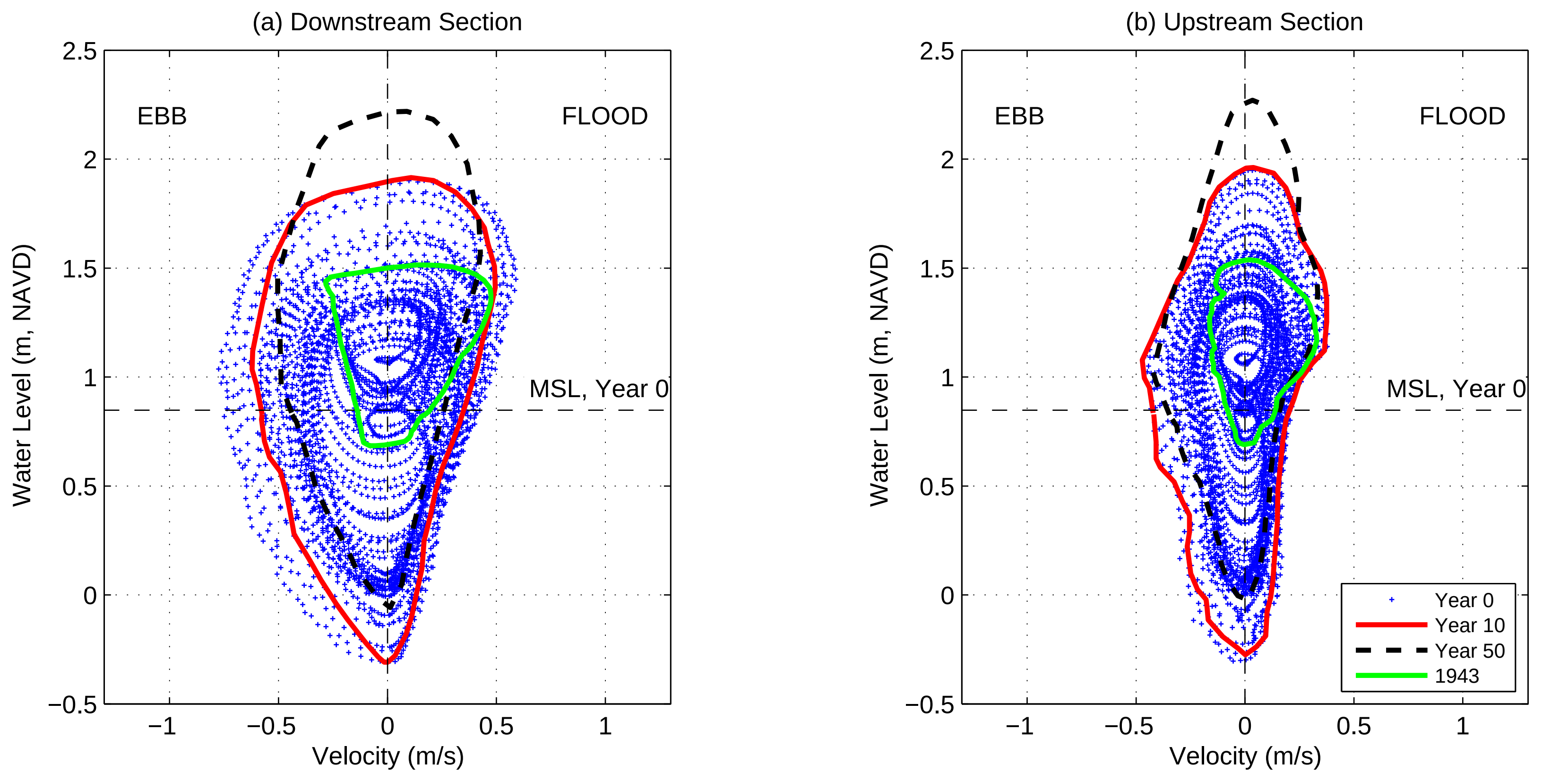


Source: U.S. Army Corps of Engineers survey (1943)

figure 5-7
Elkhorn Slough Tidal Wetlands Restoration

Estimated 1943 Slough Bathymetry

PWA Ref# 1869



Source: DELFT3D model results

Figure 5−8

Elkhorn Slough Tidal Wetlands Restoration

Alt. 1 (No Action) Water Level vs. Velocity – Year 0, Year 10, and Year 50

PWA Ref# 1869

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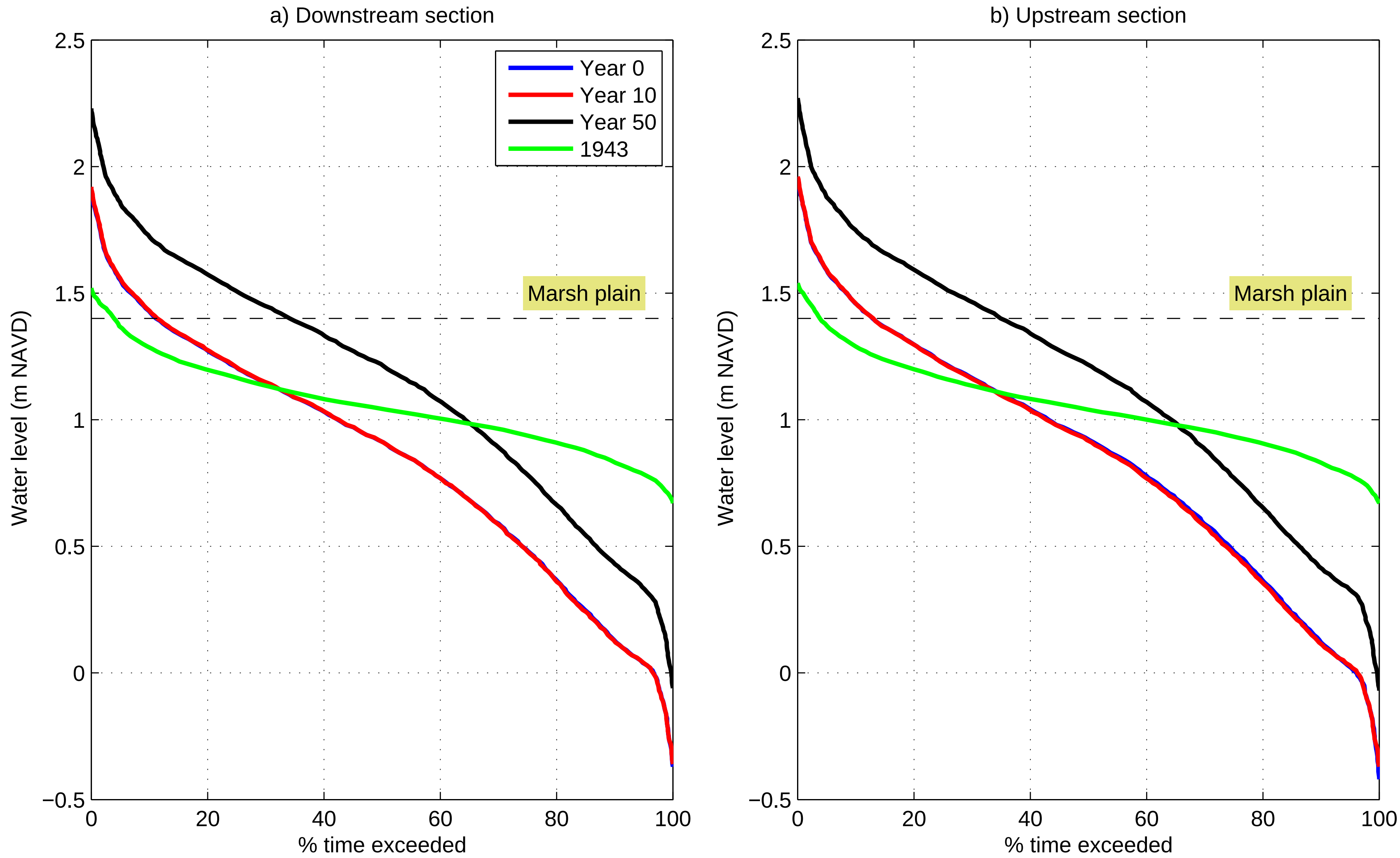

Source: DELFT3D model results

Figure 5−9
Elkhorn Slough Tidal Wetlands Restoration

Alt. 1 (No Action) Water Level vs. Percent Exceeded – Year 0, Year 10, and Year 50

PWA Ref# 1869

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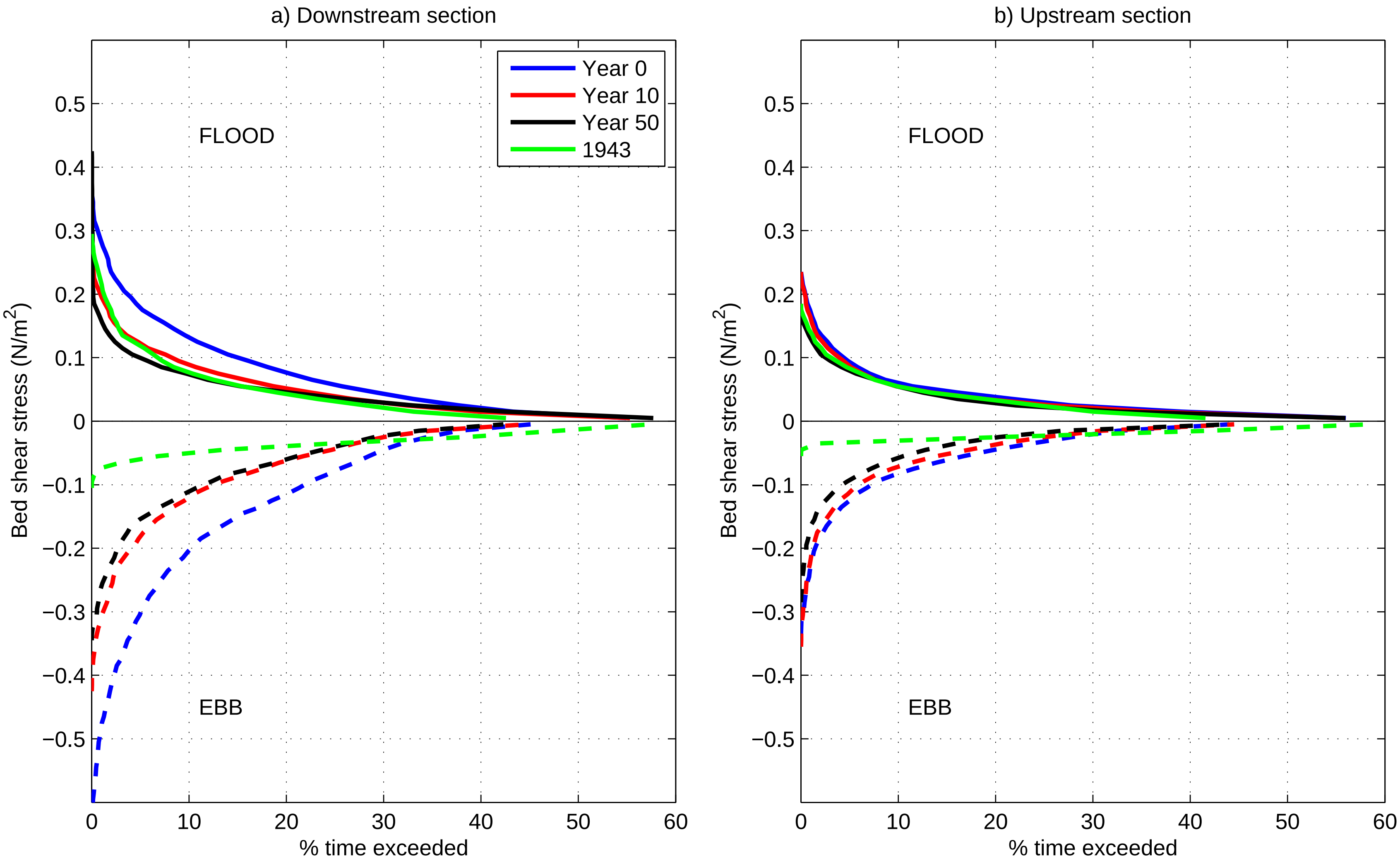

Source: DELFT3D model results

Figure 5−10
Elkhorn Slough Tidal Wetlands Restoration

Alt. 1 (No Action) Bed Shear Stress vs. Percent Exceeded – Year 0, Year 10, and Year 50

PWA Ref# 1869

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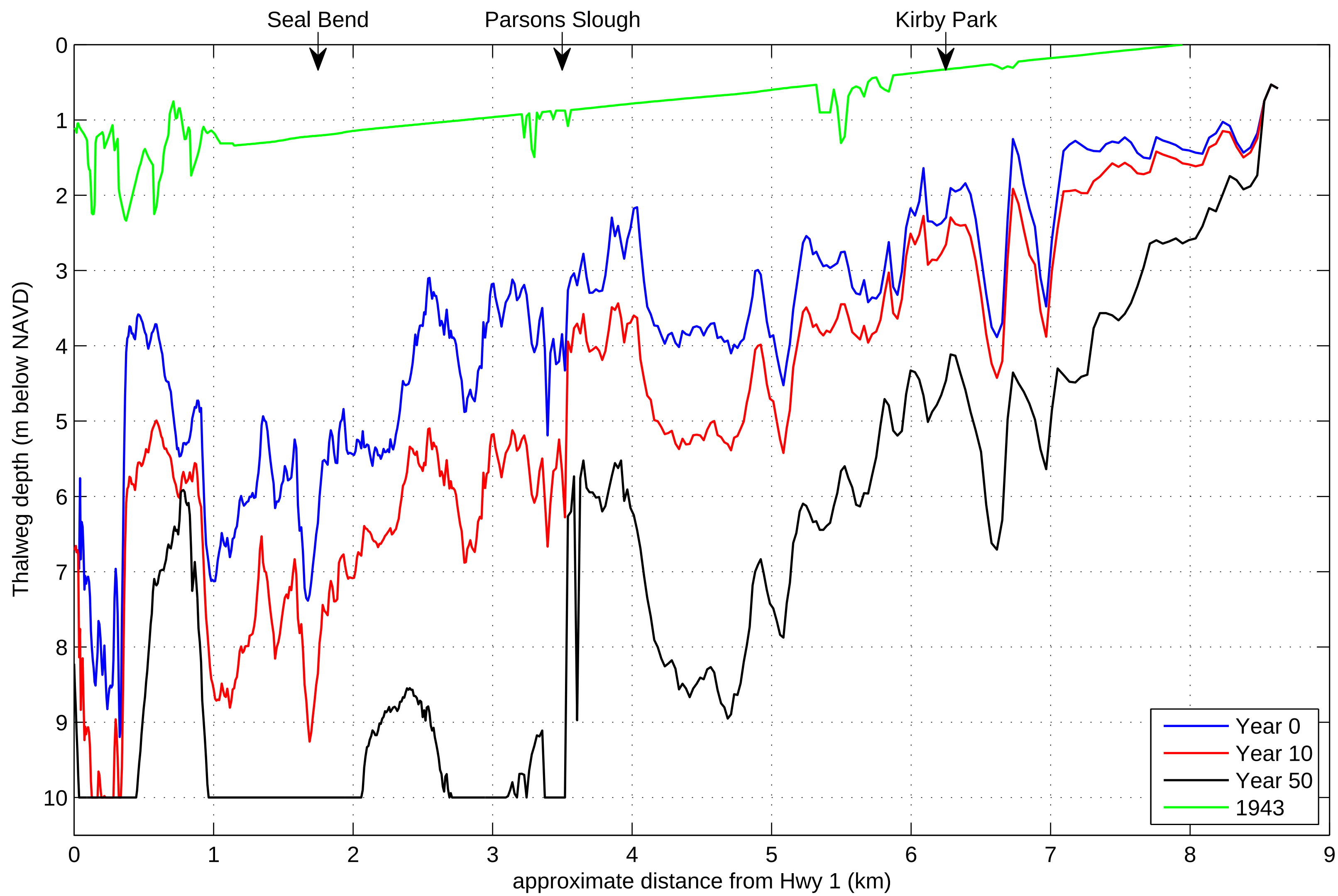

Source:USACE survey (1943), CSU−SFML batymetric survey (2003), and DELFT3D model results

Figure *5−11*
Elkhorn Slough Tidal Wetlands Restoration

Alt. 1 (No Action) Projected Thalweg Depths − Year 0, Year 10, and Year 50

PWA Ref# 1869

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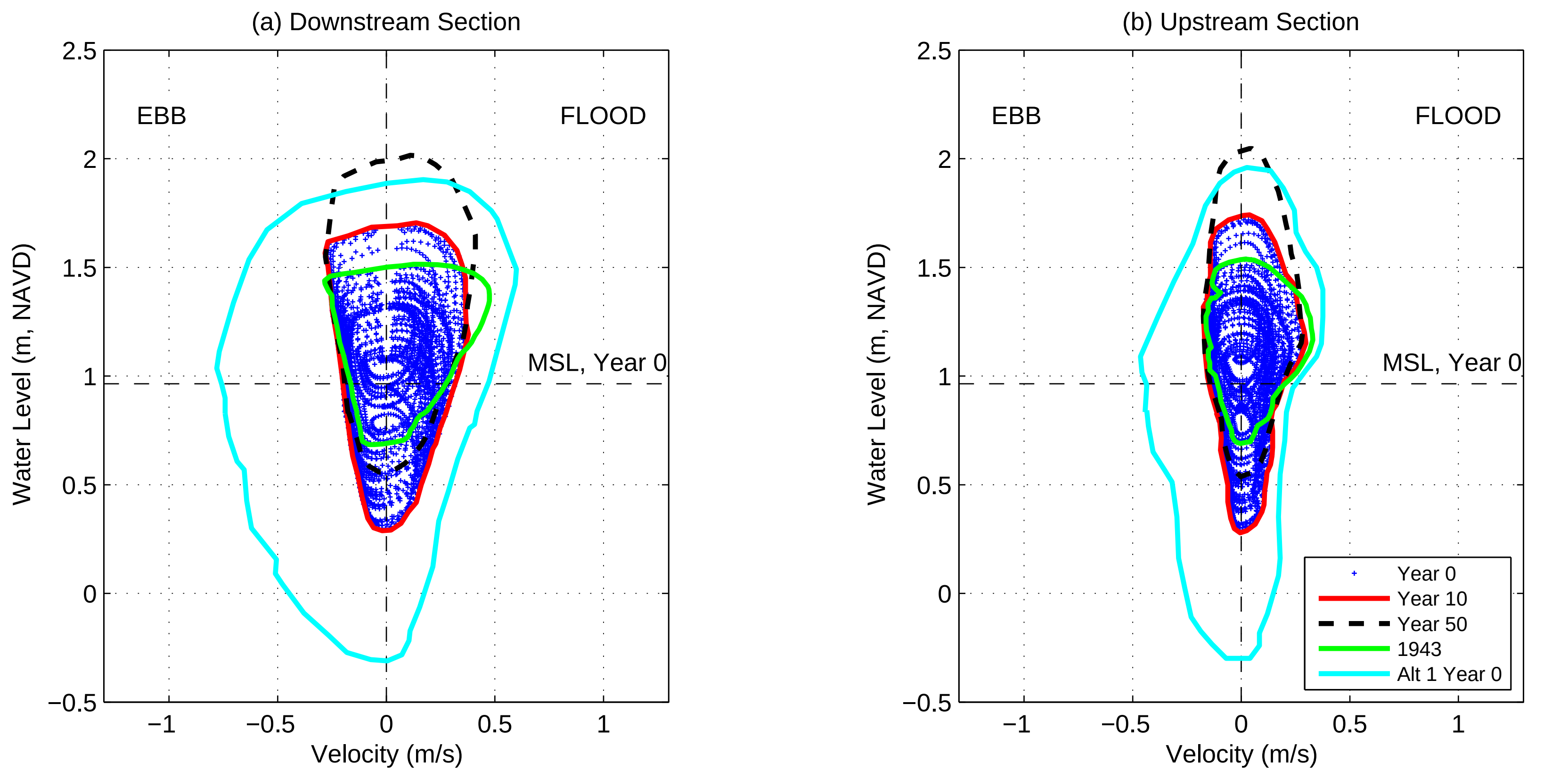

Source: DELFT3D model results

Figure *5−12*

Elkhorn Slough Tidal Wetlands Restoration

Alt. 2 (New Inlet) Water Level vs. Velocity – Year 0, Year 10, and Year 50

PWA Ref# 1869

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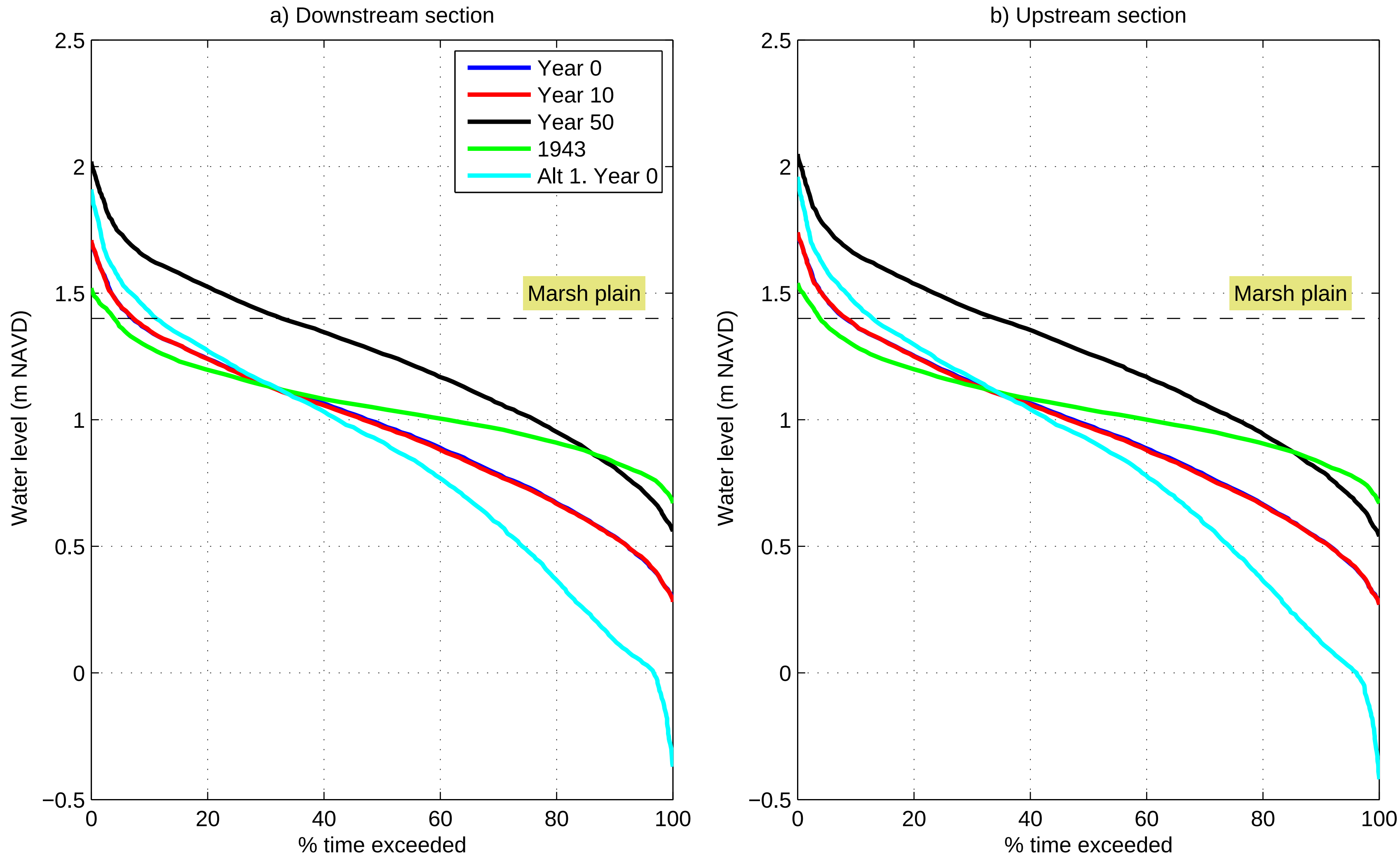

Source: DELFT3D model results

Figure 5−13
Elkhorn Slough Tidal Wetlands Restoration

Alt. 2 (New Inlet) Water Level vs. Percent Exceeded – Year 0, Year 10, and Year 50

PWA Ref# 1869

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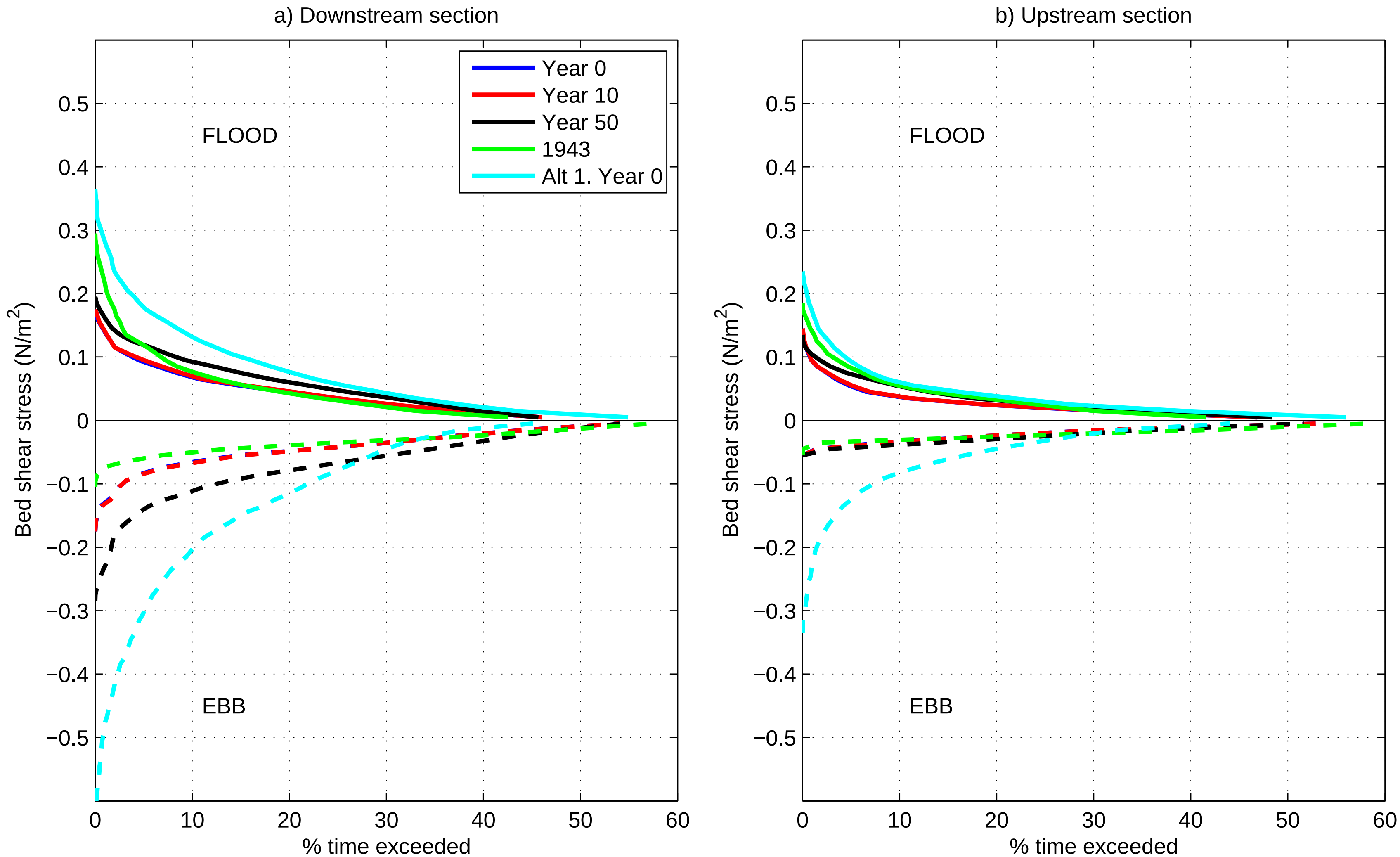

Source: DELFT3D model results

Figure 5−14
Elkhorn Slough Tidal Wetlands Restoration

Alt. 2 (New Inlet) Bed Shear Stress vs. Percent Exceeded – Year 0, Year 10, and Year 50

PWA Ref# 1869

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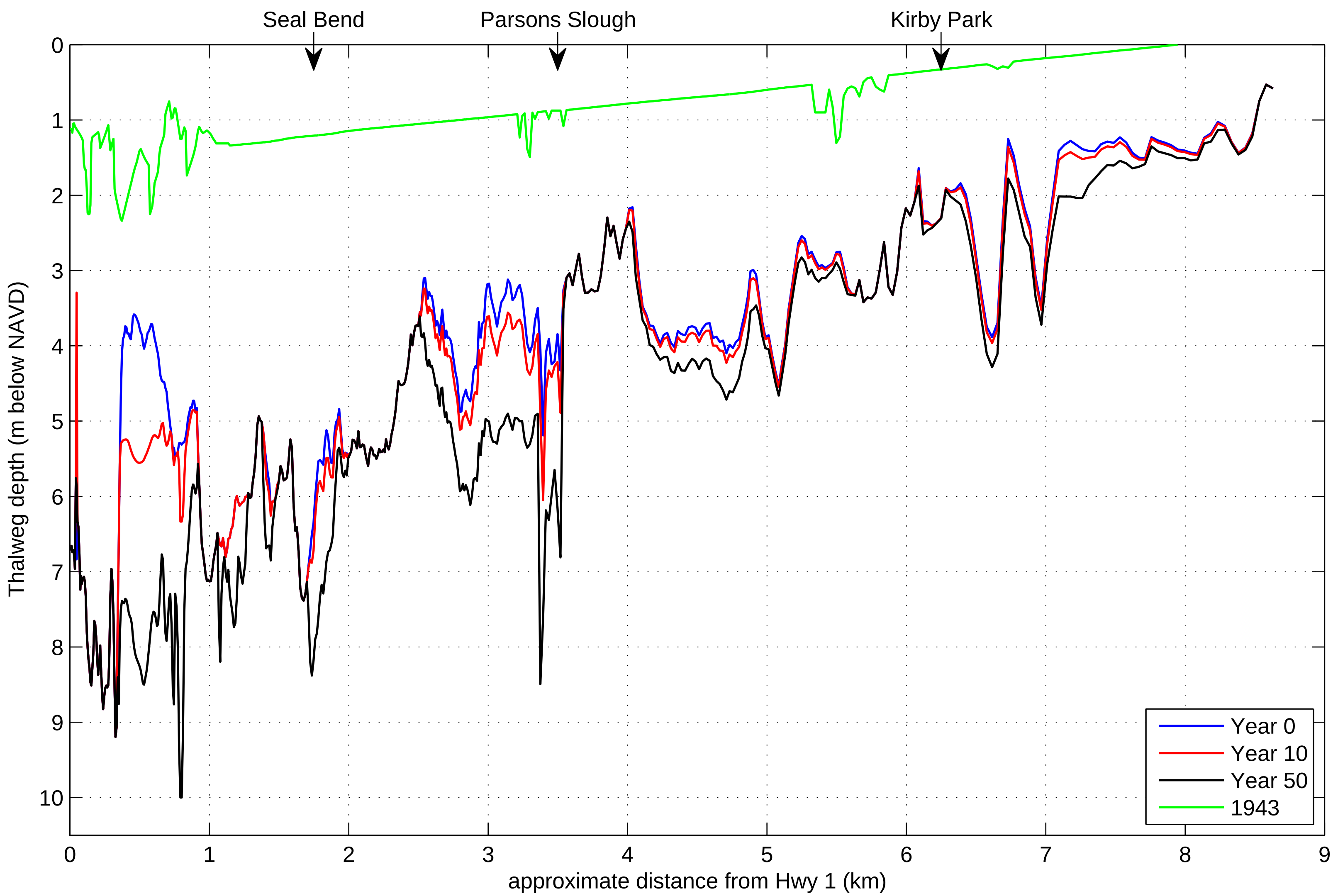

Source: USACE survey (1943), CSU−SFML batymetric survey (2003), & DELFT3D model results

Figure 5−15
Elkhorn Slough Tidal Wetlands Restoration

Alt. 2 (New Inlet) Projected Thalweg Depths − Year 0, Year 10, and Year 50

PWA Ref# 1869

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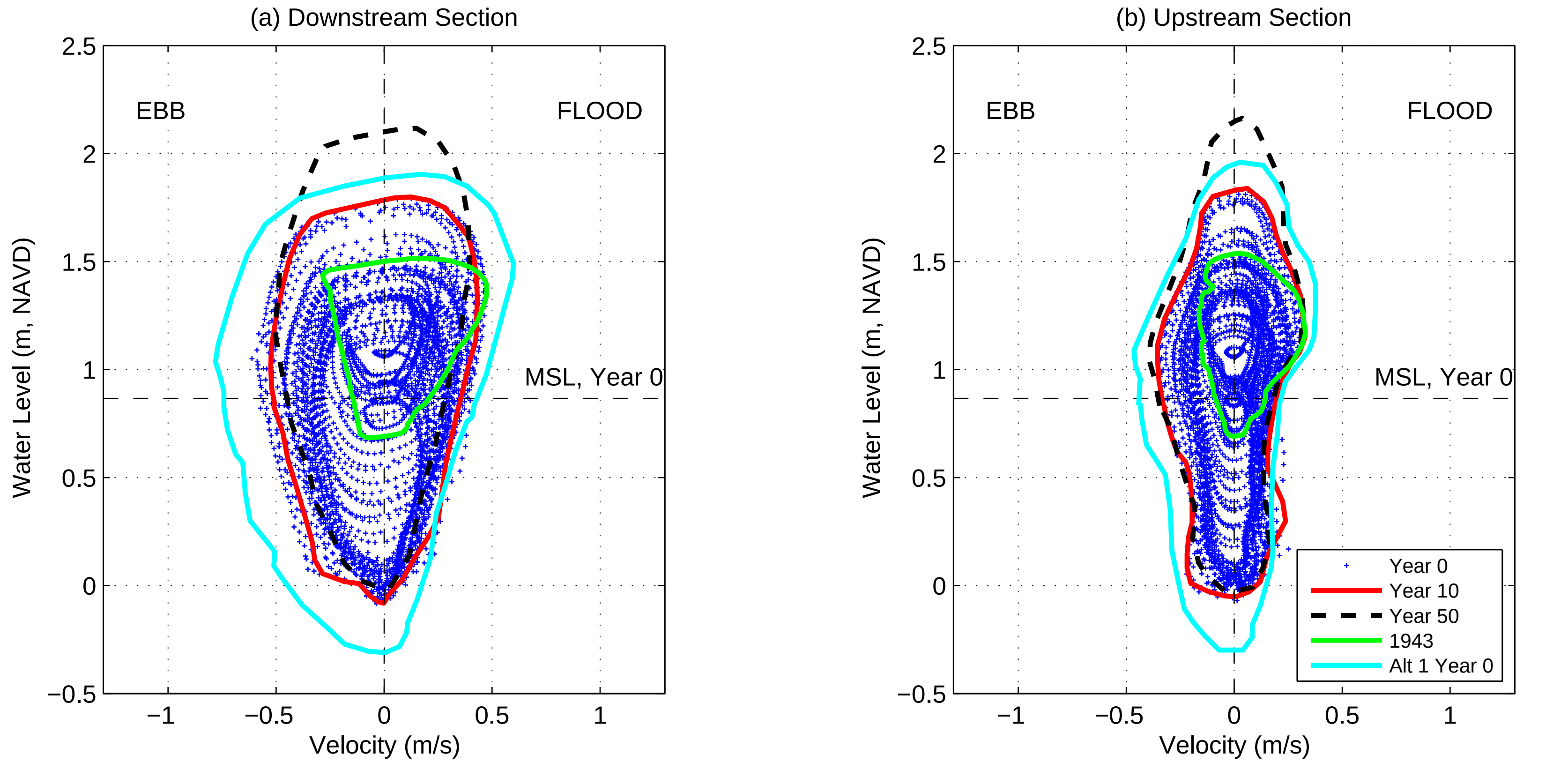

Source: DELFT3D model results

Figure 5−16
Elkhorn Slough Tidal Wetlands Restoration

Alt. 3a (Low Sill) Water Level vs. Velocity – Year 0, Year 10, and Year 50

PWA Ref# 1869

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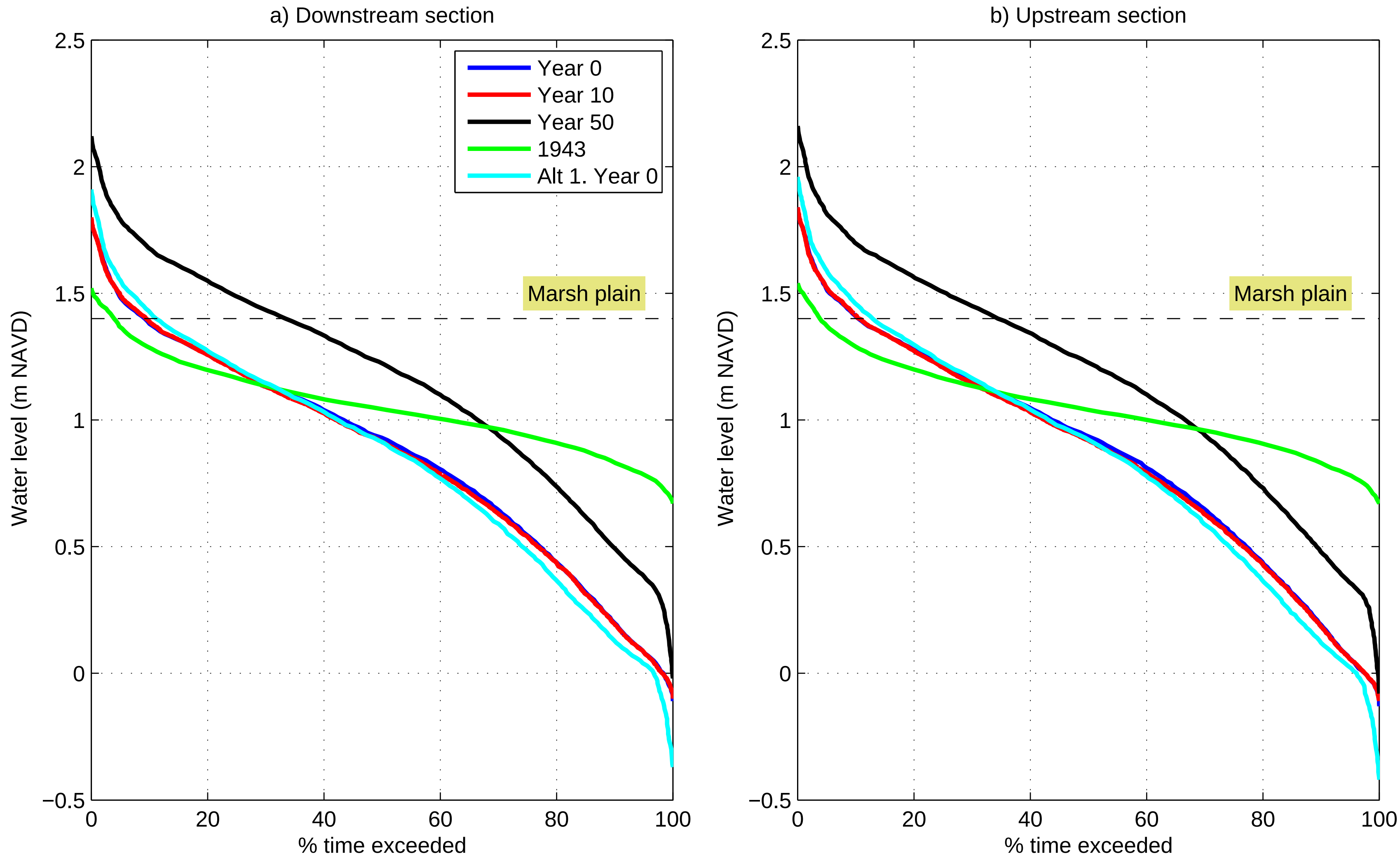

Source: DELFT3D model results

Figure 5−17
Elkhorn Slough Tidal Wetlands Restoration

Alt. 3a (Low Sill) Water Level vs. Percent Exceeded – Year 0, Year 10, and Year 50

PWA Ref# 1869

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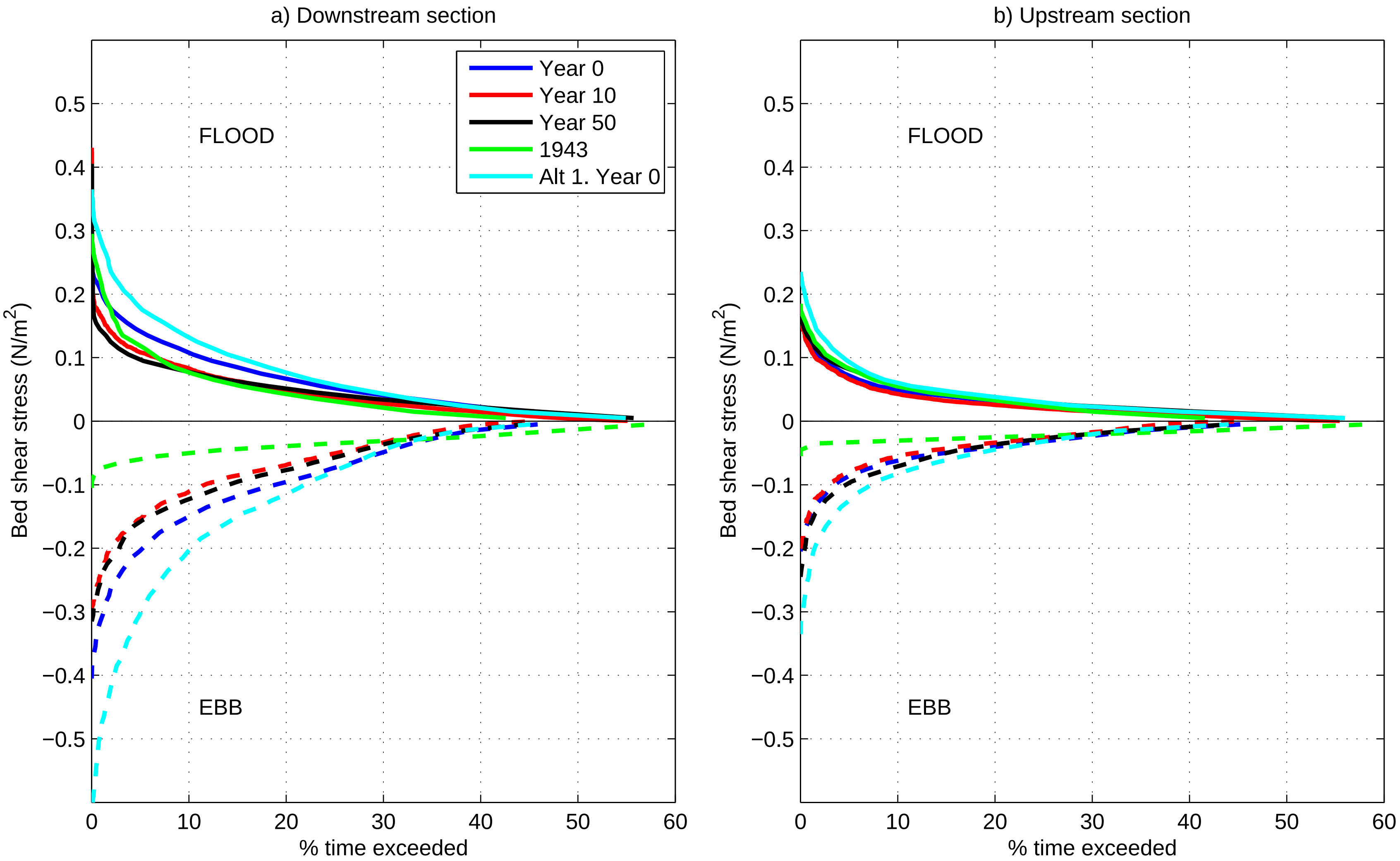

Source: DELFT3D model results

Figure 5−18
Elkhorn Slough Tidal Wetlands Restoration

Alt. 3a (Low Sill) Bed Shear Stress vs. Percent Exceeded – Year 0, Year 10, and Year 50

PWA Ref# 1869

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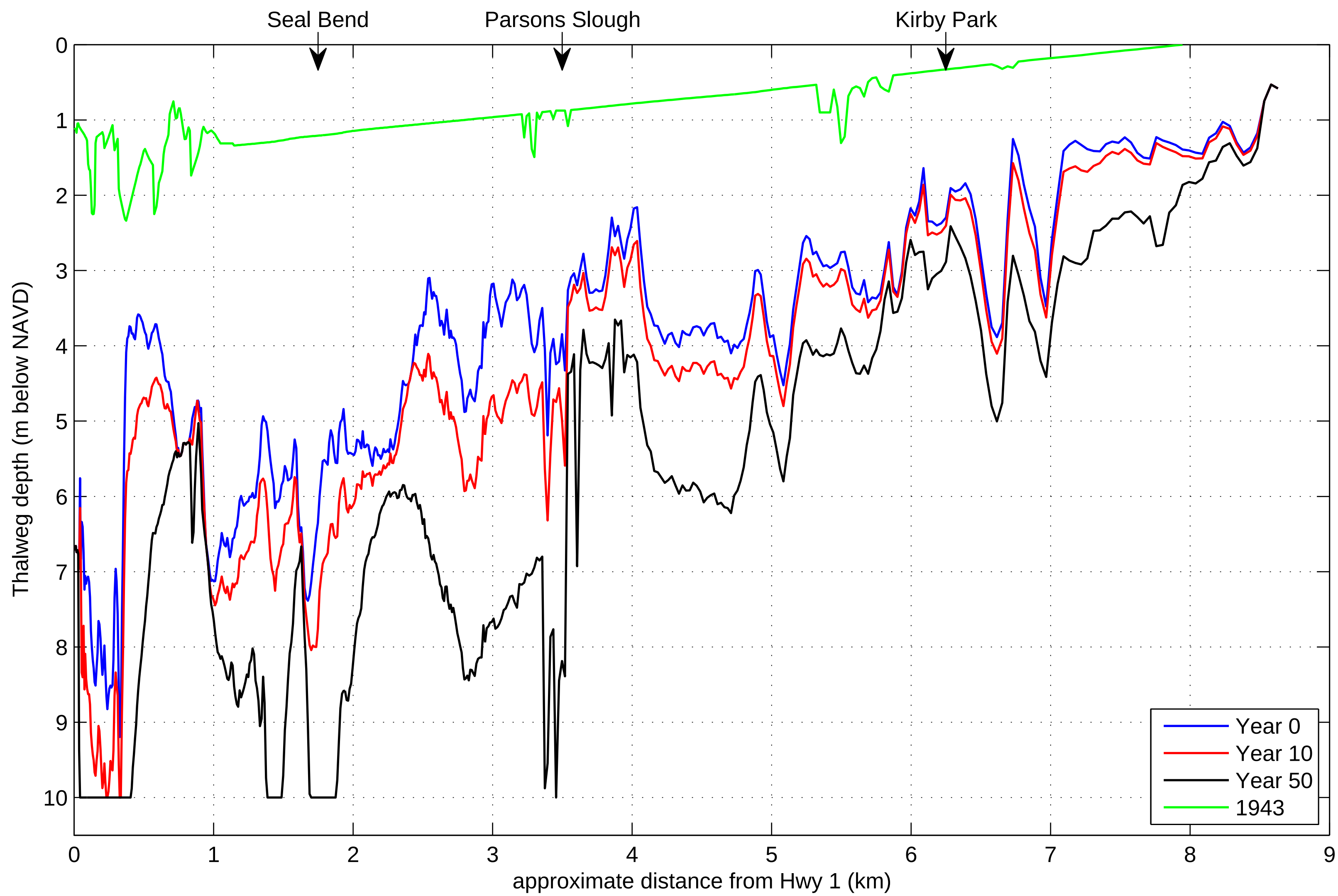

Source: USACE survey (1943), CSU−SFML batymetric survey (2003), & DELFT3D model results

Figure 5−19
Elkhorn Slough Tidal Wetlands Restoration

Alt. 3a (Low Sill) Projected Thalweg Depths − Year 0, Year 10, and Year 50

PWA Ref# 1869

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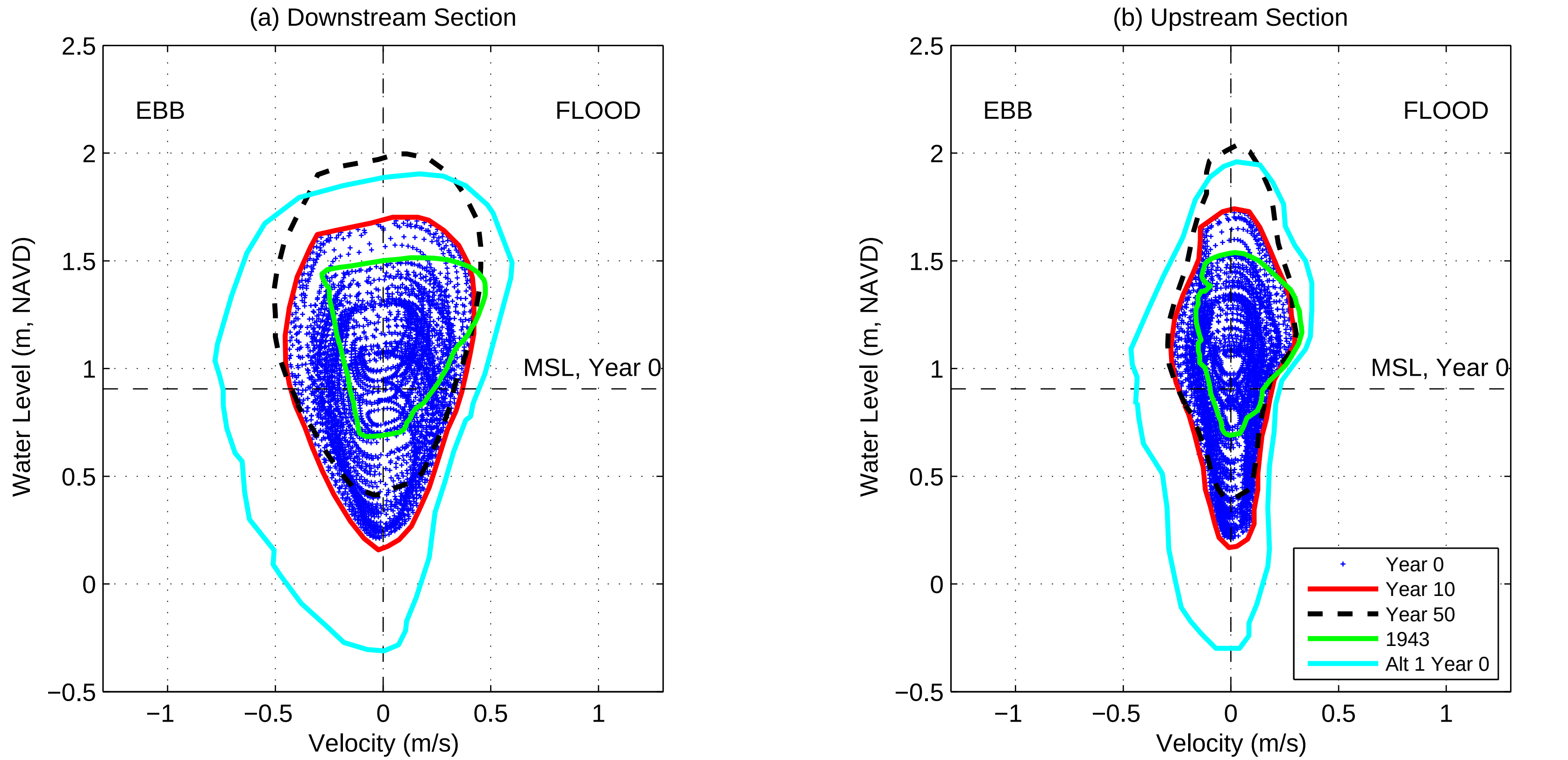

Source: DELFT3D model results

Figure 5−20
Elkhorn Slough Tidal Wetlands Restoration

Alt. 3b (High Sill) Water Level vs. Velocity – Year 0, Year 10, and Year 50

PWA Ref# 1869

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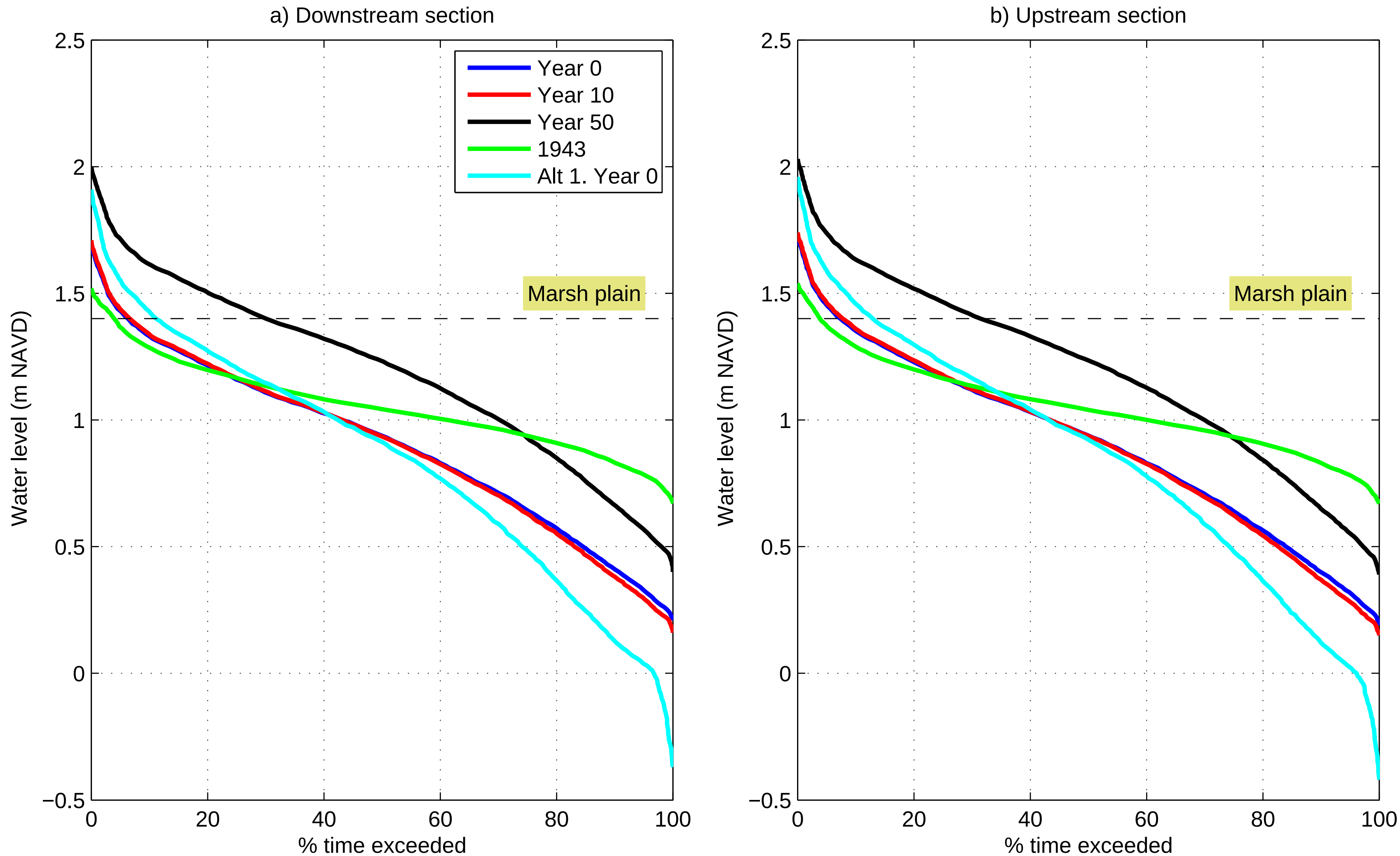

Source: DELFT3D model results

Figure 5−21
Elkhorn Slough Tidal Wetlands Restoration

Alt. 3b (High Sill) Water Level vs. Percent Exceeded – Year 0, Year 10, and Year 50

PWA Ref# 1869

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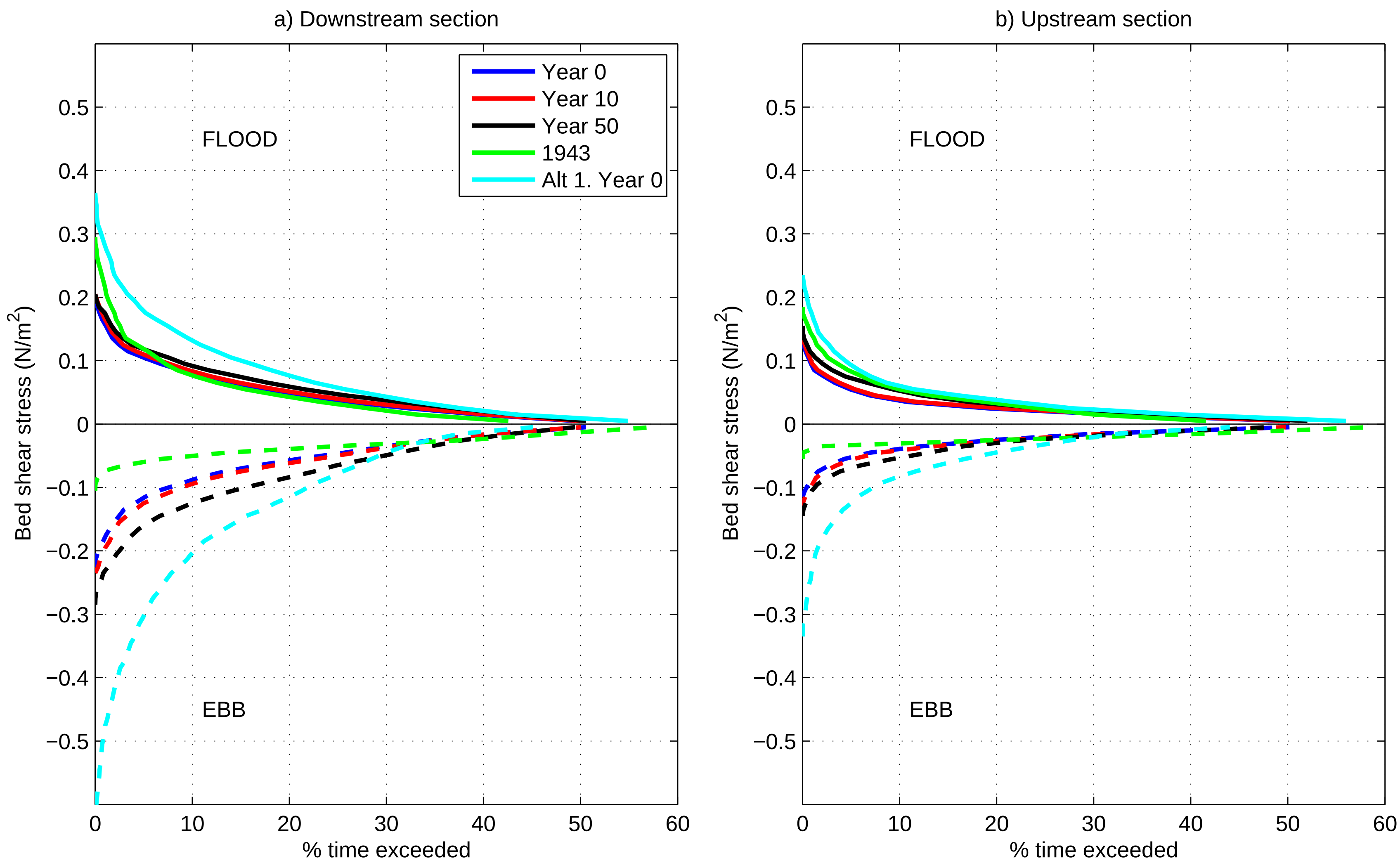

Source: DELFT3D model results

Figure 5−22
Elkhorn Slough Tidal Wetlands Restoration

Alt. 3b (High Sill) Bed Shear Stress vs. Percent Exceeded – Year 0, Year 10, and Year 50

PWA Ref# 1869

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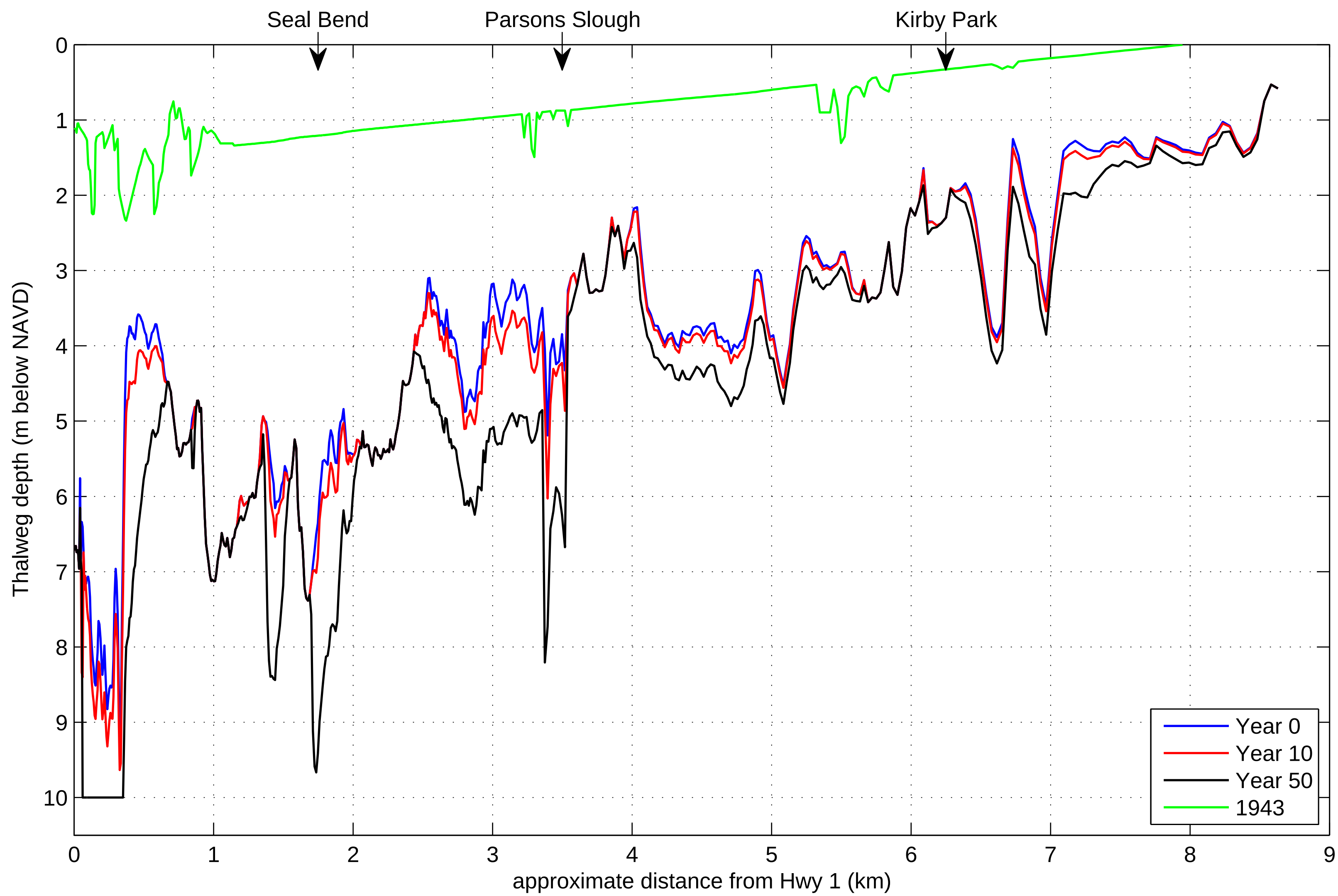

Source: USACE survey (1943), CSU−SFML batymetric survey (2003), & DELFT3D model results

Figure 5−23
Elkhorn Slough Tidal Wetlands Restoration

Alt. 3b (High Sill) Projected Thalweg Depths − Year 0, Year 10, and Year 50

PWA Ref# 1869

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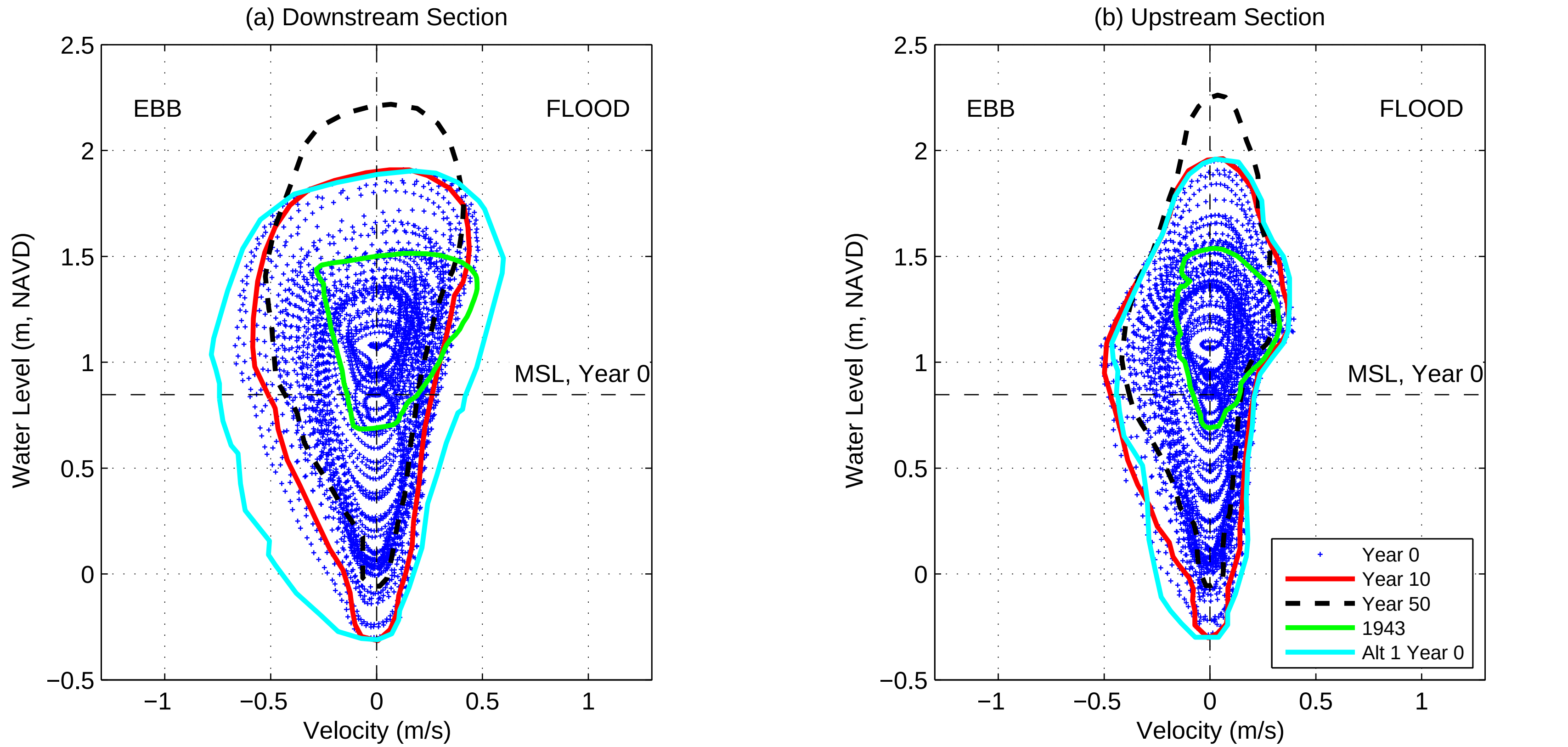

Source: DELFT3D model results

Figure *5−24*

Elkhorn Slough Tidal Wetlands Restoration

Alt. 4 (Parsons) Water Level vs. Velocity – Year 0, Year 10, and Year 50

PWA Ref# 1869

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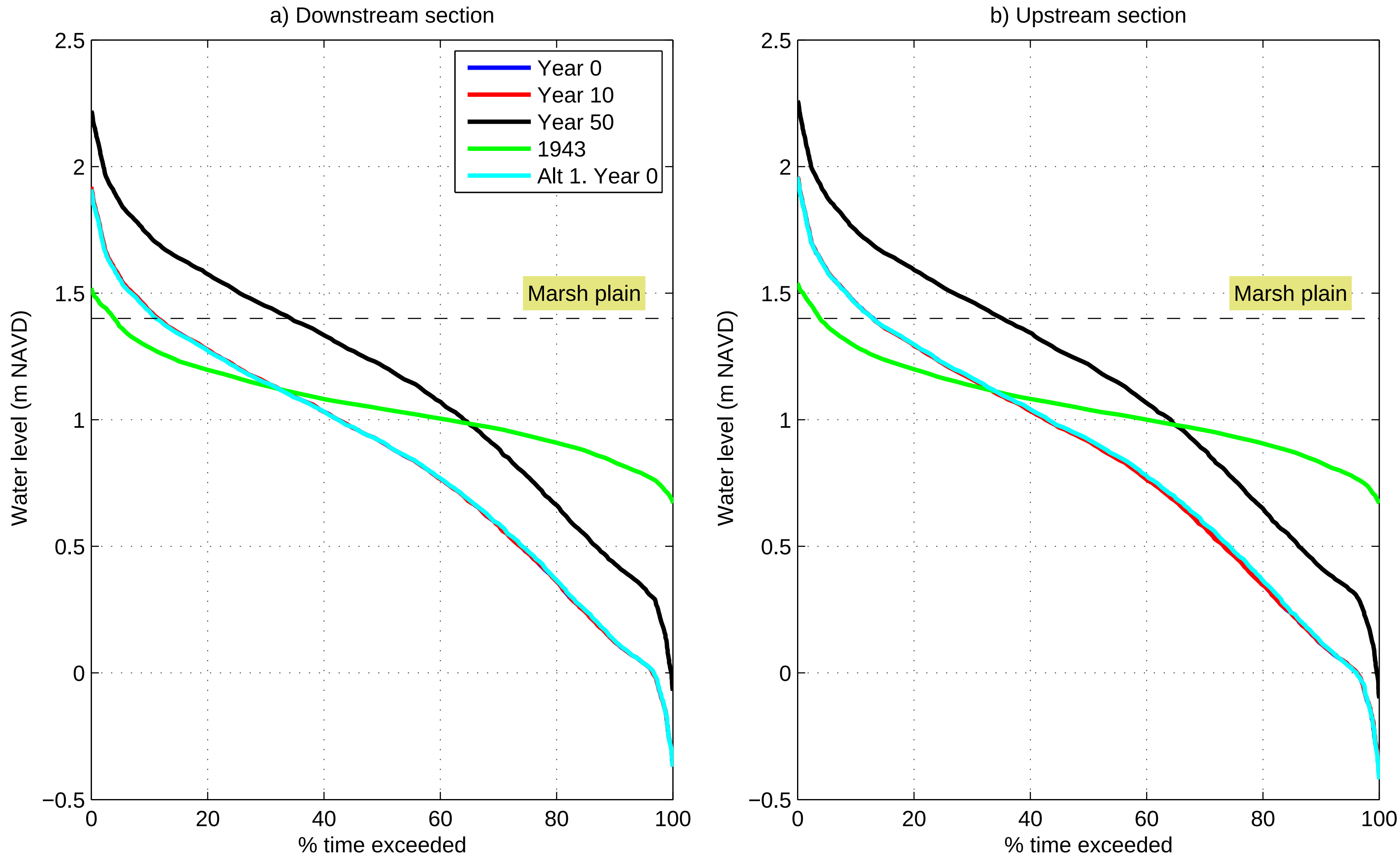

Source: DELFT3D model results

Figure 5−25
Elkhorn Slough Tidal Wetlands Restoration

Alt. 4 (Parsons) Water Level vs. Percent Exceeded – Year 0, Year 10, and Year 50

PWA Ref# 1869

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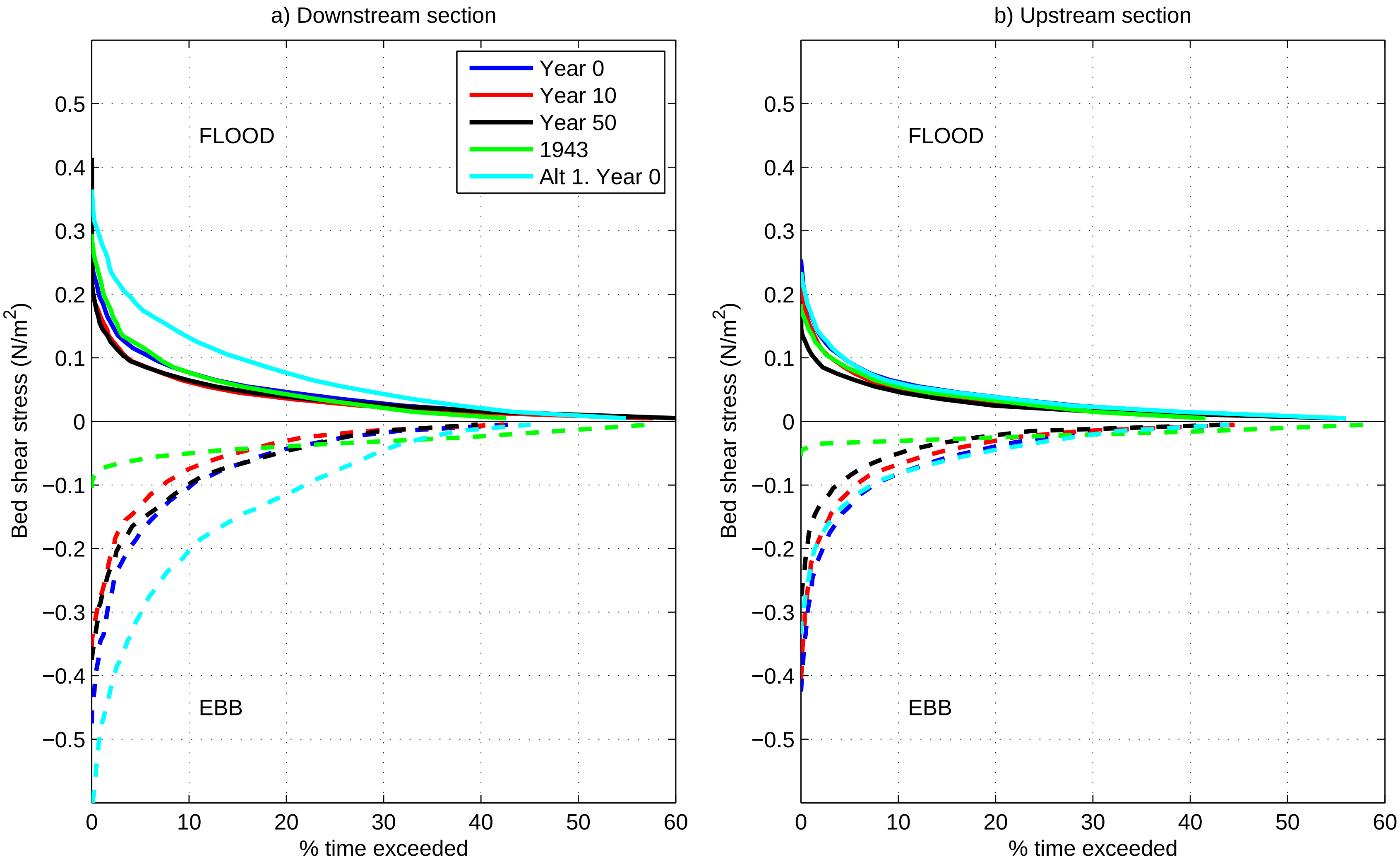

Source: DELFT3D model results

Figure 5−26
Elkhorn Slough Tidal Wetlands Restoration

Alt. 4 (Parsons) Bed Shear Stress vs. Percent Exceeded – Year 0, Year 10, and Year 50

PWA Ref# 1869

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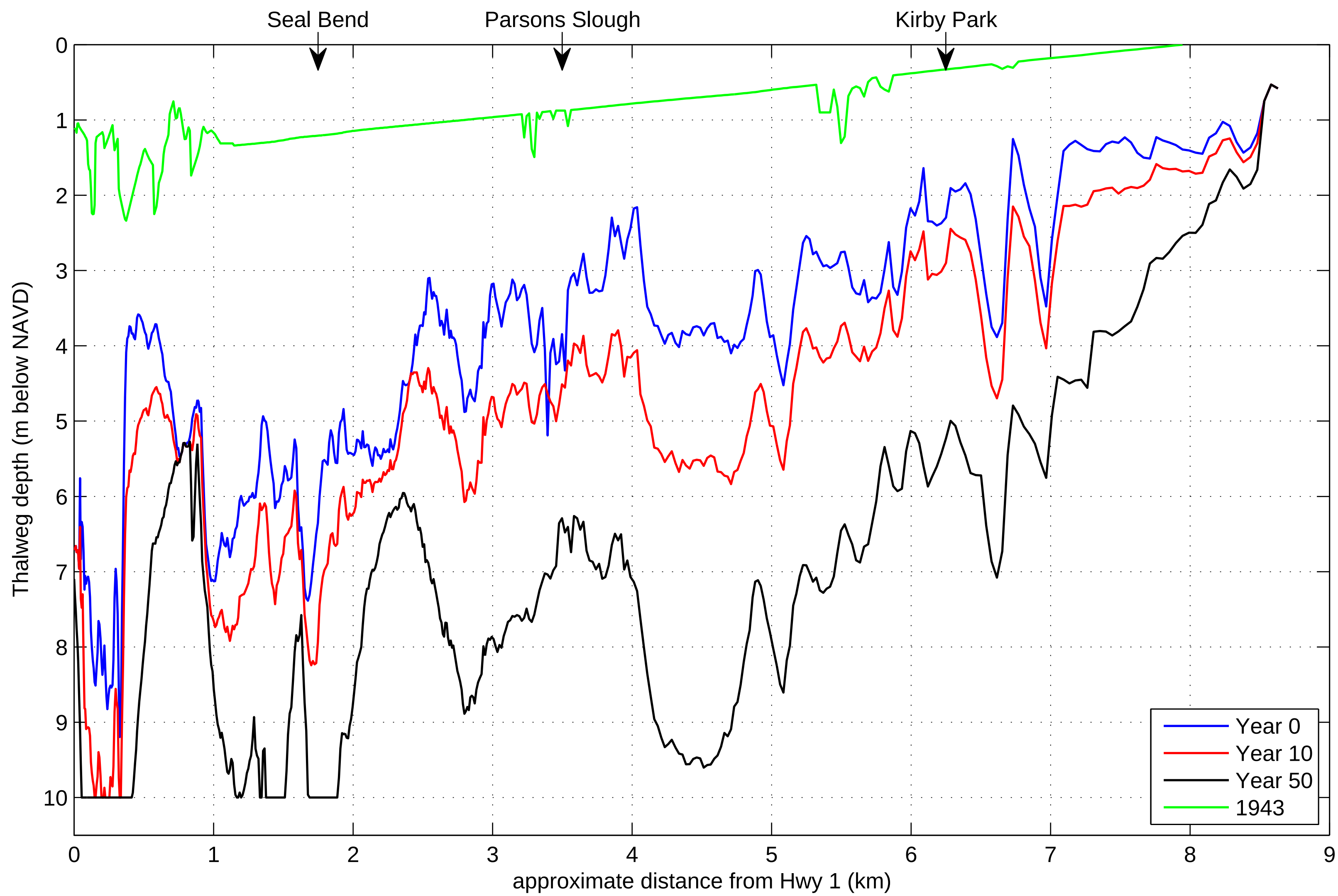

Source: USACE survey (1943), CSU−SFML batymetric survey (2003), & DELFT3D model results

Figure *5−27*

Elkhorn Slough Tidal Wetlands Restoration

Alt. 4 (Parsons) Projected Thalweg Depths − Year 0, Year 10, and Year 50

PWA Ref# 1869

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6. DISCUSSION OF ALTERNATIVES

This section presents a comparison of the four proposed restoration alternatives described in Section 4 and analyzed in Section 5. To facilitate the comparison, hydrodynamic and geomorphic predictions for the four proposed restoration alternatives are shown on the same figure for each geomorphic period – Year 0, Year 10, and Year 50. Additionally, feasibility considerations for each alternative are discussed and the uncertainty regarding the analysis is described. Using this information as background, the client team selected two alternatives for further evaluation.

6.1 HYDRAULIC COMPARISON

6.1.1 Year 0

Figure 6-1 presents a comparison of the water level versus velocity model results for the four proposed restoration alternatives at the downstream station (Figure 5-4) for Year 0. Figure 6-2 presents a similar comparison for water level versus percent time exceeded, and Figure 6-3 presents bed shear stress versus percent time exceeded. Conditions in 1943 are included in these figures as an additional basis of comparison. The primary modeling results for each proposed restoration alternative and their relationship to one another are summarized below and tabulated in Table 6-1.

Alternative 1 (No Action)

- Across all alternatives, this alternative provides the upper bound on both water levels and velocity.
- In contrast to 1943 flood dominance, this alternative exhibits ebb dominance in the form of larger peak velocity and bed shear stress on ebb tides.
- The nominal marshplain elevation of 1.4 m (4.6 ft) is exceeded 11% of the time.
- Bed shear stress exceeds the observed critical bed shear stress of 0.2 N/m^2 (Sea Engineering Incorporated 2006) on 11% of the time on ebb tides and 4% of the time on flood tides.

Alternative 2 (New Ocean Inlet)

- With the largest reduction in tidal range and velocity, this alternative most closely approaches 1943 conditions.
- This alternative reverses from ebb-dominance of existing conditions to flood-dominance of 1943 conditions.
- The nominal marshplain elevation of 1.4 m (4.6 ft) is exceeded 7% of the time.
- Bed shear stress falls below the observed critical bed shear stress of 0.2 N/m^2 for all times.

Alternative 3a (Highway 1 Low Sill)

- Compared to existing conditions, this alternative decreases the tide range by 15% and peak velocity by approximately 20%.
- This alternative retains the ebb-dominance of existing conditions.
- The nominal marshplain elevation of 1.4 m (4.6 ft) is exceeded 7% of the time.
- Bed shear stress exceeds critical bed shear stress 7% of the time on ebb tide and rarely on flood tide.

Alternative 3b (High Sill)

- Compared to existing conditions, this alternative decreases tide range by 33% and peak velocity by almost 40%.
- The peak velocities for all tides are similar to the peak velocity for 1943 and Alternative 2 (New Ocean Inlet). However, instead of being flood-dominant, Alternative 3b has flood and ebb tides that are nearly equal in magnitude.
- The nominal marshplain elevation of 1.4 m (4.6 ft) is exceeded 9% of the time.
- Bed shear stress exceeds critical bed shear stress less than 1% of the time on both ebb and flood tides.

Alternative 4 (Parsons Slough Restoration)

- Although this alternative reduces peak velocity by 15-20%, it produces no change in water levels as compared to Alternative 1.
- This alternative retains the ebb-dominance of existing conditions.
- The nominal marshplain elevation of 1.4 m (4.6 ft) is exceeded 11% of the time.
- Bed shear stress exceeds critical bed shear stress 4% of the time on ebb tide and rarely on flood tide.

Table 6-1. Summary of Hydrodynamic and Geomorphic Parameters, Year 0

	highest water level	lowest water level	peak velocity, flood	peak velocity, ebb	% tine inundation exceeded @ marshplain	% time bed shear stress exceeded @ 0.2 N/m^2, flood	% time bed shear stress exceeded @ 0.2 N/m^2, ebb	tidal prism	thalweg depth, downstream (0.25 km from HWY 1)	thalweg depth, upstream (4.5 km from HWY 1)
units	**m**	**m**	**m/s**	**m/s**	**%**	**%**	**%**	**Mm^3/tide**	**m**	**m**
1943	1.5	0.7	0.47	0.28	4	2	0	1.6	1.5	0.75
Alternative 1 (No action)	1.9	-0.3	0.59	0.75	11	3	10	5	8	4
Alternative 2 (New inlet)	1.7	0.3	0.37	0.27	7	0	0	3.7	8	4
Alternative 3a (Low sill)	1.8	-0.1	0.47	0.59	9	1	5	4.5	8	4
Alternative 3b (High sill)	1.7	0.22	0.42	0.46	7	0	1	3.8	8	4
Alternative 4 (Parsons)	1.9	-0.3	0.49	0.65	11	2	4	3.7	8	4

6.1.2 Year 10

Figure 6-4 presents a comparison of the water level versus velocity model results for the four proposed restoration alternatives at the downstream station for Year 10. Figure 6-5 presents a similar comparison for water level versus percent time exceeded, and Figure 6-6 presents bed shear stress versus percent time exceeded. Conditions in 1943 are included in these figures as an additional basis of comparison. The primary modeling results for each proposed restoration alternative and their relationship to one another are summarized below and tabulated in Table 6-2.

Alternative 1 (No Action)

- Across all alternatives, this alternative would continue to provide the upper bound on both water levels and velocity.
- This alternative would retain the ebb-dominance of existing conditions.
- The tide range would not change from Year 0 such that the nominal marshplain elevation of 1.4 m (4.6 ft) would continue to be exceeded 11% of the time.
- Bed shear stress would exceed the observed critical bed shear stress of 0.2 N/m^2 (Sea Engineering Incorporated 2006) on both ebb and flood tides.

Alternative 2 (New Ocean Inlet)

- This alternative would reduce tidal exchange at Year 0 to the extent that predicted geomorphic change between Year 0 and Year 10 is minimal. Therefore, the Slough's hydraulics would not significantly change from Year 0 conditions. With the largest reduction in tidal range and velocity, this alternative would continue to most closely approach 1943 conditions.

Alternative 3a (Low Sill)

- Predicted erosion between Year 0 and Year 10 would result in reduced velocities that are intermediate between Alternative 1 (No Action) and Alternative 3b (High Sill).
- This alternative would retain the ebb-dominance of existing conditions.
- The tide range would not change from Year 0 such that the nominal marshplain elevation of 1.4 m (4.6 ft) would continue to be exceeded 7% of the time.
- Bed shear stress would exceed critical bed shear stress 7% of the time on ebb tide and rarely on flood tide.

Alternative 3b (High Sill)

- This alternative would reduce tidal exchange at Year 0 to the extent that predicted geomorphic change between Year 0 and Year 10 is minimal. Therefore, the Slough's hydraulics would not significantly change from Year 0 conditions. Its peak currents would remain similar to 1943, although they are nearly equal between flood and ebb rather than flood-dominant.

Alternative 4 (Parsons Slough Restoration)

- Predicted erosion between Year 0 and Year 10 would result in reduced velocities that are similar to Alternative 1 (No Action) at this same time.
- This alternative would retain the ebb-dominance of existing conditions.
- The tide range would not change from Year 0 such that the nominal marshplain elevation of 1.4 m (4.6 ft) would continue to be exceeded 11% of the time.
- Bed shear stress would exceed critical bed shear stress 4% of the time on ebb tide and rarely on flood tide.

Table 6-2. Summary of Hydrodynamic and Geomorphic Parameters, Year 10; Percent change calculated as relative increase (positive) or decrease (negative) from Year 0

	highest water level	lowest water level	peak velocity, flood	peak velocity, ebb	% tine inundation exceeded @ marshplain	% time bed shear stress exceeded @ 0.2 N/m^2, flood	% time bed shear stress exceeded @ 0.2 N/m^2, ebb	thalweg depth, downstream (0.25 km from HWY 1)	thalweg depth, upstream (4.5 km from HWY 1)
units	**m**	**m**	**m/s (% change)**	**m/s (% change)**	**% (% change)**	**% (% change)**	**% (% change)**	**m (% change)**	**m (% change)**
Alternative 1 (No action)	1.9	-0.3	0.5 (-15%)	0.62 (-17%)	11 (0%)	1 (-80%)	4 (-60%)	10 (25%)	5.2 (30%)
Alternative 2 (New inlet)	1.7	0.3	0.36 (-3%)	0.28 (4%)	7 (0%)	0 (0%)	0 (0%)	8 (0%)	4 (0%)
Alternative 3a (Low sill)	1.8	-0.1	0.43 (-9%)	0.53 (-10%)	9 (0%)	1 (0%)	3 (-57%)	9.3 (16%)	4.25 (6%)
Alternative 3b (High sill)	1.7	0.22	0.42 (0%)	0.46 (0%)	7 (0%)	0 (0%)	1 (0%)	8.5 (6%)	4 (0%)
Alternative 4 (Parsons)	1.9	-0.3	0.44 (-10%)	0.59 (-9%)	11 (0%)	1 (-50%)	3 (-25%)	9.5 (19%)	5.5 (38%)

6.1.3 Year 50

Figure 6-7 presents a comparison of the water level versus velocity model results for the four proposed restoration alternatives at the downstream station for Year 50. Figure 6-8 presents a similar comparison for water level versus percent time exceeded, and Figure 6-9 presents bed shear stress versus percent time exceeded. Conditions in 1943 are included in these figures as an additional basis of comparison. Because of the similarity between the alternatives at Year 50, the summary of the hydraulics at this time are grouped according to the hydraulic parameters of water levels, velocity, and bed shear stress. The primary modeling results for each proposed restoration alternative and their relationship to one another are tabulated in Table 6-3.

Water Levels

- All water levels would be shifted up by 30 cm in accordance with the change in mean sea level at the model's ocean boundary.
- As a result of mean sea level rise, the nominal marshplain elevation of 1.4 m (4.6 ft) would be exceeded 30-35% of the time for all alternatives.
- Tidal range is the most significant difference between alternatives. Because they provide the largest reduction in tidal exchange, Alternative 2 (New Ocean Inlet) and Alternative 3b (High Sill) would have the smallest tidal ranges. Alternative 1 (No Action) and Alternative 4 (Parsons Slough) would have nearly identical tidal ranges to oceanic tides. Alternative 3b (Low Sill) damps high tides by approximately 10 cm.

Velocity and Bed Shear Stress

- At Year 50, the peak velocities of all the alternatives would converge to approximately 0.5 m/s. This is the peak velocity predicted under 1943 conditions. However, only Alternative 2 (New Ocean Inlet) would exhibit the flood dominance in agreement with 1943 conditions. The other alternatives would have peak flood and ebb velocities of nearly equal magnitude.
- The bed shear stress distributions for all alternatives would be similar. The observed critical bed shear stress of 0.2 N/m^2 (Sea Engineering Incorporated 2006) would rarely be exceeded.

Table 6-3. Summary of Hydrodynamic and Geomorphic Parameters, Year 50; Percent change calculated as relative increase (positive) or decrease (negative) from Year 10

	highest water level	lowest water level	peak velocity, flood	peak velocity, ebb	% time inundation exceeded @ marshplain	% time bed shear stress exceeded @ 0.2 N/m^2, flood	% time bed shear stress exceeded @ 0.2 N/m^2, ebb	tidal prism	thalweg depth, downstream (0.25 km from HWY 1)	thalweg depth, upstream (4.5 km from HWY 1)
units	**m**	**m**	**m/s (% change)**	**m/s (% change)**	**% (% change)**	**% (% change)**	**% (% change)**	**Mm^3/tide (% change)**	**m (% change)**	**m (% change)**
Alternative 1 (No action)	2.2	0	0.43 (-14%)	0.5 (-19%)	35 (218%)	1 (0%)	3 (-25%)	6.3 (26%)	10 (0%)	8.5 (63%)
Alternative 2 (New inlet)	2.0	0.6	0.41 (14%)	0.28 (0%)	33 (371%)	0 (0%)	2 (0%)	4.7 (27%)	8 (0%)	4.25 (6%)
Alternative 3a (Low sill)	2.1	0.0	0.4 (-7%)	0.5 (-6%)	33 (267%)	1 (0%)	3 (0%)	5.9 (31%)	10 (8%)	6 (41%)
Alternative 3b (High sill)	2	0.4	0.45 (7%)	0.5 (9%)	30 (329%)	0 (0%)	2 (100%)	4.9 (29%)	10 (18%)	4.3 (8%)
Alternative 4 (Parsons)	2.2	0	0.41 (-7%)	0.5 (-15%)	34 (209%)	1 (0%)	3 (0%)	5 (35%)	10 (5%)	9.5 (73%)

6.2 GEOMORPHIC CHANGE

Reduced sediment supply (by rerouting the flow of adjacent rivers and reduced inflow of coastal sediment) and modification of the tidal hydraulics (increasing the strength of the ebb-tide flow) by relocation, construction and maintenance dredging the harbor mouth are the primary causes of morphological change in Elkhorn Slough. Throughout the past four to six millennia, Elkhorn Slough has been a sink for sediment supplied by adjacent catchments and has built expansive marshes. The estuary is now eroding and exporting sediment, a process which accelerated in the decades after the harbor was built, and again after Parsons Slough was breached. As significant channel expansion continues, tidal flow velocities and the rate of sediment export are predicted to slow in coming decades. However, as ongoing erosion continues on the marshplain, and without a replacement of fluvial sediment supply, we expect the area of intertidal marsh to continue to decrease. The combination these erosion forces with anticipated sea level rise will eliminate most marsh area within 50 years.

Under Alternative 1, we anticipate that the channel will continue to deepen and widen but that the rate of deepening will decline with time. The typical depth of the thalweg is set by the depth of dredging at the harbor. There may be locations at constrictions in the channel where this depth will be deeper than the harbor (10 m). With deepening of the channel we anticipate that the channel edge will widen, at a rate currently estimated to be about 20 cm per year (Van Dyke, Pers. Comms March, 2008). Erosion of the marshplain is likely to continue, most likely at an accelerated rate. We anticipate conversion of expansive areas of currently vegetated marsh to mudflat, with remnant marsh restricted to transitional high ground areas. By year 50 we expect that little of the former marsh extent will remain. With a continued connection to the Monterey Canyon, sediment loss from Elkhorn Slough is likely to continue, resulting in long-term progressive conversion of mudflat to subtidal habitat. The rate of marsh loss could be reduced by actively supplying sediment to the marsh surface.

Construction of a new ocean inlet, outlined in Alternative 2, would reduce the loss of sediment from Elkhorn Slough, and possibly result in an import of limited amount of sediments, (mainly sands) into the outer estuary. Erosion of the main channel will cease, though this area will remain a sink for sediments displaced from higher intertidal areas, unless filled with imported sediments. In the absence of a sediment supply the extent of marsh will decrease as vegetated areas convert to mudflat, and lower mudflat areas convert to subtidal habitat. Actively supplying sediment would reduce the rate or even reverse vegetated marshes loss; the volume of sediment required to build wetlands areas would be less than that required for Alternative 1 as tidally driven sediment export from Elkhorn Slough will be significantly reduced.

The sill options outlined under Alternative 3 act to reduce the velocities of the ebb tide and so reduce the sediment export. The low sill (Alternative 3a) would have a reduced effect on tidal hydraulics and sediment flux but would limit the downward scour of the main channel. The higher sill (Alternative 3b) would substantially reduces the velocity of ebb tide currents and would significantly reduce but not fully halt sediment export from the estuary. Unless sediment is placed to fill the accommodation space behind the sill the channel will act as a sediment sink competing for sediments mobilized from marsh and mudflat areas. The low and high sill will immediately reduce high water levels by approximately 10 and 20 cm, respectively. This would allow degraded marsh areas to re-colonize with vegetation. However, this effect would be temporary if rising sea level reverses this benefit. Low water levels will also be raised by each sill alternative by 20 – 50 cm resulting in a conversion of some mudflat to subtidal areas. Supply of sediment to marsh areas could assist in sustaining these areas of the estuary against rising sea level; amounts required will be less than under Alternative 1 and more than Alternative 2.

Reducing the tidal prism of Parsons Slough (Alternative 4) would have a direct affect on the tidal hydraulics of the estuary and would reduce the rate of estuary scour, and a potential sink of sediment circulating in the estuary. The lower Elkhorn Slough channel would act as a sink for sediment displaced from the intertidal areas and without a sill this sediment will progressively move down estuary and be eventually exported.

None of the modeled alternatives address the issue of insufficient sediment supply to balance ongoing sea level rise. Each management alternative lowers the rate of tidal export of sediment from the estuary, with the rate proportional to the extent of hydraulic control. Even with reduction of rate of export it is likely that there will over time be a redistribution of sediment from high intertidal areas to subtidal areas either within the Slough or in Monterey Bay. As described in Section 3.4.4, one possible action to reduce the competition for sediment would entail filling either the main channel or the subsided marshplain with placed sediment. It should be recognized that all tidal wetlands along the California coast will be faced with the same problem of accelerated sea level rise. Only those with high sediment supply and/or a spatial configuration that allows inland and upward migration will persist; others will be converted to mudflats, and subsequently, sub-tidal habitat.

While it is difficult to accurately predict the rate of long-term evolution of existing marshplain areas (the conversion from vegetated to unvegetated areas may occur at non-linear rates). It appears highly likely that these areas will convert to expansive mudflat, either through drowning and or mechanical erosion and breakdown of the marshplain by tidal currents and waves.

Table 6-4. Projected Annual Erosion Rate from the Main channel for Alternatives 1-4 in Years 0-10 and Years 10-50

	Years 0-10	**Years 10-50**
Alternative 1 – No action	98	48
Alternative 2 – New inlet	15	11
Alternative 3a – Low sill	43	28
Alternative 3b – High sill	11	11
Alternative 4 – Parsons Slough	61	35

Note: all quantities in thousands of cubic meters per year. Quantities do not include potential sediment (sand) influx from nearshore.

6.3 HABITAT COMPARISON

Table 6-5 outlines the general trends that can be expected from each alternative at Year 50 when compared to existing conditions. The habitat predictions represent the quantity of each habitat based on an approximate percent change from the existing habitat area for open water. Open water was divided into shallow subtidal (210 acres) and deep subtidal (340 acres), intertidal mudflat (1,090 acres), and vegetated marsh (750 acres). These habitat projections to not include any assessment of the change in habitat quality associated with the alternatives.

Under Alternative 1 (No Action), the main channel is assumed to continue widen and deepen at current rates, resulting in an increase in subtidal habitats at the expense of the intertidal habitats. Increased water levels resulting from sea level rise would increase water depths on the marshplain. Salt marsh habitat would continue to diminish significantly and would be replaced by intertidal mudflat.

Alternative 2 (New Ocean Inlet) would result in a truncated tidal range at both the upper and lower ends of the tidal cycle compared with exiting conditions. This would result in an immediate increase in subtidal habitat and vegetated marsh area, with a corresponding decrease in intertidal mudflat areas. However, with sea level rise, these gains in salt marsh area would diminish and by Year 50 the vegetated marshes would have begun converting to mudflat, resulting in less vegetated marsh than existing conditions.

Alternative 3a (Low Sill at Highway 1) would also result in a slightly truncated tidal range at both the upper and lower ends of the tidal cycle compared with exiting conditions. With reduced tidal velocities the rate of erosion along the main channel will decrease. This would also result in an increase in subtidal habitat and an initial increase vegetated marsh area, with a corresponding decrease in intertidal mudflat areas. Alternative 3b (High Sill at Highway 1) would have similar results, but would more substantially curtail the rate of channel expansion because of more dramatic reductions on flow velocities. Under both alternatives the main channel would act as a sediment sink. Actively filling the channel with sediment would fill this sink and increase the longevity of adjacent mudflats, and to a lesser degree, marsh. The decrease in water surface elevations under either of the sill alternatives may, for a limited number of years, halt or reverse the loss of vegetated marshplain.

Finally, in Alternative 4 (Restoration at Parsons Slough), removing or substantially reducing the tidal prism of Parsons Slough would result in immediately reducing the rate of scour of the channel in the lower estuary. However, Alternative 4 does not significantly influence either MHHW or MLLW elevations and as such would not directly impact immediate acreage of intertidal habitat. Alternative 4 is expected to result in only minimal differences in habitat distributions along the main channel when compared to the No Action alternative.

It should be noted that the percent changes shown in Table 6-5 should be utilized in comparing the relative effects of each alternative. We recognize that there are wide uncertainties surrounding these projections. For example, we have more confidence in the anticipated changes in the subtidal areas than rates of conversion of marsh to mudflat projections. There are poorly defined thresholds that separate mudflat and vegetated marsh habitats; these are difficult quantify with the available data as discussed previously in the report. However, we feel the tabulated results provide a means to broadly compare across alternatives.

All management alternatives act to reduce flow velocities in the main channel and so act to reduce rates of sediment export. No alternative results in a substantial import of sediment. Under Alternatives 1, 3a and 4 sediment export will continue; under Alternative 3B and particularly Alternative 2, sediment loss is substantially reduced. Reducing the rate of sediment loss would extend the existence of intertidal areas. By Year 50 rates of sediment loss would decline for all alternatives, though because of infinite sink capacity of the Monterey Canyon we anticipate a continued net export of sediment to occur, to varying degrees, with all alternatives except Alternative 2. Should the canyon extend in to the harbor then potentially the rate of sediment export would increase.

Because of limited availability of sediment to sustain intertidal areas, and assuming ongoing sea level rise, the marsh areas will eventually convert to mudflat. Alternatives, 2, 3a and 3b act to lower the high water elevations and so, for a period of time, reverse some of the of the marsh vegetation loss.

Applying sediment to the marshplain and channel would act to reduce the rate of habitat conversion. The volumes of sediment required to maintain existing habitats would be less for alternatives 2 and 3b because of lower rates of ongoing sediment export from the estuary.

Table 6-5 . Relative Estimates of Habitat Changes by Alternative, Year 50

Habitat Types	Alternative 1: No Action	Alternative 2: New Ocean Inlet	Alternative 3a: Tidal Barrier at Highway 1 (Low Sill)	Alternative 3b. Tidal Barrier at Highway 1 (High Sill)	Alternative 4: Restoration of Parsons Slough
Deep Subtidal	⇧ +40%	⇧ +100%	⇧ +10%	⇔ <5%	⇧ +35%
Shallow Subtidal	⇧ +15%	⇧ +100%	⇧ +60%	⇧ +100%	⇧ +10%
Intertidal Mudflat	⇧ +25%	⇩ -30%	⇧ +15%	⇩ -15%	⇧ +20%
Salt Marsh	⇩ -65%	⇩ -40%	⇩ -55%	⇩ -35%	⇩ -60%

⇧ = Increase

⇔ = No Substantial Change

⇩ = Decrease

6.4 FEASIBILITY DISCUSSION

Hydrodynamic modeling results predicted geomorphic evolution, and predicted habitat response inform the assessment of the proposed restoration alternatives. In addition to the effectiveness of the proposed restoration alternatives at reducing Slough scour and stopping or slowing marsh loss, the following implications should be considered during the alternatives evaluation.

6.4.1 Alternative 2 - Implications for Management Decisions

Alternative 2 proposes the most dramatic changes to the physical landscape, including the creation of a new ocean inlet and connecting slough channel. As such, its direct cost is likely to be substantially larger than the other alternatives. In addition, Alternative 2 has the greatest potential risk of undesirable impacts. Specific feasibility considerations of this alternative include:

- *Feasibility of Bridge Construction*. Construction and future maintenance of a new Highway 1 bridge presents significant cost implications and a high level of construction-related impacts.

- *Inlet Stability and Changes to the Shoreline*. A stability assessment of the new ocean inlet is presented in Appendix B. Coastal inlets of small embayments are extremely dynamic, especially those without a major fluvial source of flow to periodically force sand out of the inlet mouth. The new ocean inlet may be susceptible to periodic or permanent closure, especially when strong ocean waves coincide with weak neap tides. Closure potential may change over time as the effective tidal prism of Elkhorn Slough adjusts to future erosion and marsh loss. Inlet closure would substantially affect water quality within the Slough and require mechanical intervention (breaching) since no significant source of freshwater discharge is available to naturally re-open the inlet as occurred historically with the Salinas River. The new ocean inlet may also result in short- and long-term changes to the shoreline due to the temporary sediment demand required to form flood- and ebb-tide shoals and long-term changes in the nearshore wave climate.

- *Disturbance to Managed Ponds*. The new tidal connection between Elkhorn Slough and Bennett Slough could affect existing habitats within at the DFG Moss Landing Wildlife Area, such as the former salt ponds currently managed for Snowy Plover. If a narrow channel is required, it may be necessary to construct levees to confine the newly excavated channel. As noted above, a number of channel alignments may be feasible, and optimization of these will reduce potential impacts.

- *Water Quality in Elkhorn Slough*. Diminished tidal current velocities and modification of circulation patterns in the Slough could negatively affect water quality by increasing residence times. However, the proposed tidal barrier would reduce the input of high nutrients loads since discharge from the old Salinas River channel into Elkhorn Slough would be eliminated.

- *Recreational Navigation*. The complete tidal barrier at Highway 1 would require a lock component if boat access between Elkhorn Slough and Moss Landing Harbor were to be maintained. Alternatively, a new boat launch facility may be feasible adjacent to the Highway 1 bridge at the downstream end of the Slough.

- *Dredging at Moss Landing Harbor*. Diversion of the Elkhorn Slough tidal flows that presently pass through the Moss Landing Harbor will decrease the scouring potential that currently removes a portion of the littoral sediment deposited in the harbor, particularly beach sands that accumulate within the navigation channel between the two jetties. This change in tidal hydraulics will likely increase the dredging requirements at the Federal Channel at Moss Landing. Currently, channel dredging is required approximately every other year to maintain navigable depths. Conversely, the annual sediment yield of the Slough may represent a considerable portion of the sediment source currently accumulating in the Harbor. This alternative's re-direction of the tidal flow would eliminate this source.

- *Fluvial Sediment Delivery*. Construction of a barrier at Highway 1 would eliminate any remaining fluvial sediment delivery to Elkhorn Slough from old Salinas River channel (OSRC), this term in the sediment budget has yet to be quantified but is expected to be relatively small. While the OSRC does also convey runoff from a considerable watershed area (Gabilan/Tembladero and Moro Coho watersheds) it appears that they convey relatively low sediment levels to the Slough. An additional management implication may be that a tidal barrier at Highway 1 would preclude actions to restore fluvial sediment delivery from the old Salinas River channel in the future, if the ever became possible.

- *Access for Marine Mammals and Fish*. Access between Monterey Bay and the estuarine habitats of Elkhorn Slough for fish and marine mammals would be affected if inlet closure were to occur, or if the equilibrium size of the inlet throat provided inadequate depths.

6.4.2 Alternative 3 - Implications for Management Decisions

Construction of a partial tidal barrier at Highway 1 also presents substantial construction and cost implications, which require consideration of the effectiveness and risks of this alternative. However, the costs and risks would be considerably less than those for Alternative 2. Additional analysis would be necessary during the conceptual design phase to better define the optimal barrier configuration. Optimization would take into account the following specific feasibility considerations:

- *Dredging at Moss Landing Harbor*. Reduction of the effective tidal prism of Elkhorn Slough will diminish the scouring potential currently provided by strong ebb tide currents. This is expected to increase dredging requirements at Moss Landing Harbor, particularly the navigation channel between the two jetties. The impact of this alternative will be less than Alternative 2 since some of the Slough's tidal prism will continue to pass through the Harbor.

- *Water Quality in Elkhorn Slough*. Water quality implications associated with a damped tidal range and longer residence time would likely be similar to those described under Alternative 2. However, the reduction of high nutrient loads would not be as great as that for the full barrier / new entrance proposed under Alternative 2. Therefore, water quality in the slough would likely be worse under this alternative.

- *Recreational Navigation*. Navigation implications are also an issue with this alternative. Modeling conducted for this study indicates that current speeds would increase in the vicinity of both the low sill and the high sill. This increase may negatively impact navigation. Since the model's resolution relative to the sill is relatively coarse (depth-averaged and 10 m horizontal grid cell size), a more detailed examination flow in the immediate vicinity of the sill is recommended at further planning stages. It is possible that these constraints could be reduced by constructing multiple sills.

- *Fluvial Sediment Delivery*. Construction of a barrier at the Highway 1 bridge would significantly reduce – but not eliminate – fluvial sediment delivery from old Salinas River.

- *Access for Marine Mammals and Fish*. Access between Monterey Bay and the estuarine habitats of Elkhorn Slough for fish and marine mammals may be affected by either the low sill or the high sill.

6.4.3 Alternative 4 - Implications for Management Decisions

Alternative 4 could be implemented either by placing fill on the subsided marshplain of Parsons Slough, or through the use of water control structures to reduce the effective tidal prism, as described in Section 4. Many of the details regarding fill placement (e.g., sources, methods) or construction of water control structures (e.g., type, size and geometry of structure) are expected to be developed as part of the Parsons Slough Restoration Project. However, due to the relatively large fill requirements of the first approach, the two approaches described above would likely differ substantially with respect to costs and ease of permitting. Although implementation of the 'fill' approach is anticipated to be significantly more difficult and expensive, it would promote a more natural and likely sustainable marshplain. Other potential implications for management decisions include:

- *Fluvial Sediment Delivery*. Implementation of Alternative 4 would not affect the existing fluvial sediment delivery from old Salinas River.

- *Access for Marine Mammals and Fish*. Access to existing estuarine habitats within the Parsons Slough marsh complex for fish and marine mammals, particularly sharks and rays, could be affected depending on the restoration approach pursued. This will be evaluated as part of the Parsons Slough Restoration Project.

6.5 PROJECT ASSUMPTIONS AND UNCERTAINTIES

This section describes several assumptions and uncertainties associated with the hydrodynamic modeling.

6.5.1 Level of Detail

The alternatives are described at the conceptual level of detail, e.g., the alternatives are not specified at a project or detailed-design level of detail. Location and dimensions of the design elements are based on preliminary recognizance, local experience professional judgment; these designs would be refined in later stages based on modeling results and additional engineering analysis. Future project-level modeling may be used to assess the importance of design features (e.g., the need for levee and/or channel bank armoring along the new channel in Alternative 2, and the impact of the sill dimensions and fill placement on peak velocities and navigability in Alternative 3). The use of conceptual design levels in the alternative simulations does not introduce substantial uncertainty on the model results since the model is designed to be run using this scale of elements. However, model refinements would be required to address site-specific questions such as the impact of the sill on navigation hazards.

6.5.2 Non-tidal Areas

The model domain extends from the coastal ocean to the head of the Slough at Elkhorn Road, and includes areas that contribute significant portions of tidal prism to the inlet-slough-wetland system (Philip Williams & Associates 2007a). Additionally, regions connected to the slough via hydraulic structures were included in the grid if their typical tidal range exceeded 5 cm (K. Wasson, personal communication). Several regions that were historically connected to the Slough but currently are not presently tidally connected were excluded from the domain. These excluded regions include: Barn Pond, Cattail Pond, the Rookery Ponds, and the Packard Ponds. In addition, regions that are only minimally connected (typical tide range less than 5 cm) are also excluded from the model domain. These excluded minimally-tidal regions include: Struve Pond, Estrada Marsh, South and Middle Azevedo Ponds, and Porter-Blohm Marsh.

The exclusion of these regions is not expected to introduce substantial uncertainty on the model results. Additional modeling in the future may require the inclusion of these areas if restoration or management actions would alter their tidal connection to the Slough.

6.5.3 Grid Resolution

One of the uncertainties affecting the Year 0 model results is the accuracy and resolution of the available bathymetry and the grid resolution used to resolve this bathymetry. To the extent possible, the models have made use of the most recent and best available bathymetric data which minimizes the uncertainty introduced by bathymetry. However, when the bathymetric data is sampled onto the model grids, additional filtering of the bathymetric data occurs which limits the capacity of the model to resolve small-scale bathymetric features. To reduce this effect, the grid resolution was selected to be as fine as possible (~10 m) to resolve the primary features of interest, such as the main Elkhorn Slough channel and the larger marsh channels. The grid resolution would need to be an order-of-magnitude finer to resolve the majority of the smaller marsh creeks in the marsh-channel drainage network. However, a grid resolution of this scale would result in a model that was computationally inefficient. Therefore, the smaller marsh creeks are not explicitly resolved because (i) they cannot be fully resolved with the nominal 10-m grid; (ii) the available data to characterize the smaller marsh creeks is sparse; and (iii) initial results show that the model can be showing flows on the marshplain without the detailed channel network included (i.e. the marshplain is wetting and drying and it's contributing to the overall tidal prism).

6.5.4 Marshplain Elevation Data

A key data uncertainty is the marshplain elevation along the gradient from areas dominated by healthy marsh vegetation to areas of vegetation dieback to mudflats. As discussed in PWA (2007a), a limited accuracy assessment of the 2004 LIDAR data was performed, but this assessment has not yet been used to post-process the LIDAR data to remove vegetation bias (VanDyke, pers. comm.). Post-processing of the LIDAR data would be required to remove any vegetation bias by ground-cover type (i.e., dominant vegetation type). Investigations are underway regarding post-processing algorithms to produce a bare earth elevation model, but this work is not yet ready for distribution (VanDyke, pers. comm.). For statistically characterizing relatively broad areas of marshplain, the 2004 LIDAR data set is the best overall source of elevation data available for the Slough and is generally considered accurate to plus or minus 5 cm, with isolated regions containing somewhat larger errors (VanDyke, pers. comm.).

Also, the assumption that long term average marsh accretion is bounded to -2.5 to + 2.5 mm/year is a major uncertainty (see Section 5.4.2.2 for further details). The preliminary SET and marker horizon data at Elkhorn Slough show a marsh accretion rate of 3-5 mm/year. Since the data represent only a single measurement, they are considered quite unreliable. However, if the upper bounds of marsh accretion at Elkhorn Slough did indeed approach 5 mm/year, then over a 50-year time period there would be substantially more vegetated marshes in the system and less mudflat under all alternatives. Additional processes such as tidal channel expansion and marsh panne development may also influence the quantity and quality of tidal marsh habitat, but modeling these habitat components was beyond the scope of this project.

6.5.5 Two-dimensional Model Approach

The model solves the 2D depth-averaged approximation of the hydrodynamic flow equations (that is the model simulates horizontal flow, but not vertical flow at various depths). The use of 2D simulations (versus fully 3-dimensional as occurs in nature) significantly reduces the computational time required for the model simulations, but prevents vertical variations of the true flow field from being captured. However, velocities of the secondary flows measured by Stanford University within the main slough channel are much smaller than velocities of the primary flows directed along the Slough (Monismith and others 2005). 2D model simulations also assume a logarithmic velocity profile which affects the model's calculation of bottom shear stress. In the actual flow field, the vertical velocity structure may not be logarithmic as the structure would be influenced by stratification and interactions with the bed. However, the bottom bed shear stress calculated from a 2D model formulation allows for a reasonable comparison of the change in bed shear stress between alternatives when evaluated relative to baseline conditions. In addition, the model calibration and validation showed excellent agreement with respect to water levels and current speeds (Philip Williams & Associates 2007a).

6.5.6 Long-term Bathymetric Change Predictions

Bathymetric changes over time were estimated by comparing hydrodynamics results (flow velocity/shear stress) with measured historic rates of channel change and using these to predict future channel evolution. Actual sediment transport and geomorphic modeling was not performed.

The development of a sediment transport and geomorphic model of Elkhorn Slough would be a much more extensive effort requiring additional data collection efforts and greater levels of effort and cost. The effort involved in setting up this type of model is not practical or appropriate for analyses at the planning and feasibility assessment level. However, such a model could be useful for informing future restoration phases and adaptive management decisions if sufficient resources are available. Potential impacts to sediment erosion and deposition patterns is estimated based on comparisons of the changes in calculated bed shear stress for the alternatives. Potential changes to the slough in response to the increased tidal prism are estimated based on hydraulic geometry relationships (Williams and others 2002), as discussed in PWA (2005). These methods have been used successfully for previous restoration studies (Jones & Stokes 2004a; Jones & Stokes 2004b; U.S. Fish and Wildlife Service and others 2004; U.S. Fish and Wildlife Service and others 2007).

There is considerably more uncertainty in the geomorphic assessment and predictions of future morphology, compared with the hydrodynamic modeling, including uncertainties relating to: the sediment budget components, sediment dynamics and the major sediment transport pathways, the morphologic response to sediment surpluses and deficits, the spatial variability of the physical properties of the soil, and future rates of sea-level rise. There is, therefore, considerable uncertainty inherent in the predictions of long-term geomorphic change both for the no project alternative and in response to the alternatives.

It is recognized that developing long-term morphologic predictions is a relatively new applied science (Wilcock and Iverson 2003), and based on the available information, a more complex approach may not necessarily yield more certain results. The Year 10 morphology is estimated based upon current conditions and then used to predict the Year 50 condition. These future modeling results represent the estimated future conditions, based on the best available information to evaluate the potential long-term changes in Slough hydrodynamics. It should be noted that additional analyses which rely on the results of the geomorphic assessment and hydrodynamic modeling, such as the long-term predictions of habitat change, will also contain the same uncertainty, if not greater uncertainty. These follow on studies should therefore be evaluated in the correct context and not be viewed as an absolute prediction of future conditions. Although the uncertainties are additive at each step in an alternatives evaluation process, the analyses all rely on the same available information and the same underlying assumptions. Therefore the results do allow for a meaningful comparison of the alternatives.

While there is considerable uncertainty regarding the actual rates of change, or the final morphological configuration, the long term trends in both the key variables driving erosional processes, and the observed response of the system over the past 60 years has been consistent, and shows no sign of reaching equilibrium. The modeling methodology reflects this long term perspective and does not attempt to explain shorter term events which may include local accretion. Our predictions indicate a future ecosystem with a larger, deeper main channel, relatively little vegetated marshplain in the fully tidal areas, and a combination of intertidal and subtidal mud flats fringing the channel.

The relative effectiveness of the various alternatives in slowing or halting these erosional processes are also clear: the new slough mouth (Alternative 2) as modeled has the largest controlling effect on erosional processes, followed by the "high" sill, then the "low" sill, and then the Parson's slough (Alternative 4). Given the lack of certainty on two other controlling parameters (future sea level rise and sediment supply) combined with the modeling uncertainty described above, it is not possible to specify accurately what the exact effect of each alternative would be on the final morphology of the system.

6.5.7 Physical Processes

To simplify the complex natural system such that hydrodynamic and geomorphic modeling became tractable, a number of assumptions about the system's physical processes were made. For each process in a section below, the assumption is stated, explained, and possible impacts on results discussed.

6.5.7.1 Freshwater Inputs

The hydrodynamic model neglects freshwater inputs during simulations of the restoration alternatives. If sufficiently large, these inputs can alter water levels and current speeds. However, Elkhorn Slough has a relatively small watershed which limits freshwater inputs to the Slough. Additionally, although the Slough falls between the two large watersheds of the Pajaro and Salinas Rivers, connectivity with these watersheds is limited to only the largest flow events in these watersheds and not well quantified. In the case of freshwater inputs associated with typical winter storms, sensitivity analysis with the hydrodynamic model shows minimal impacts on current speeds ands water levels (Appendix A). More extreme freshwater inputs, such as flooding from the Pajaro or Salinas River watersheds, may increase water levels and currents speeds within the Slough. These extreme events were not simulated for this study, as we do not think they have a significant impact on the erosional processes.

6.5.7.2 Sediment Inputs

The geomorphic model does not incorporate sediment inputs to Elkhorn Slough. Limited data exists for quantifying these inputs. Analysis of the Slough's sediment budget indicates that the primary sources of sediment to the Slough have been re-routed directly to Monterey Bay. By relying on observed, present-day erosion rates, the geomorphic model presumably captures the net decrease in erosion resulting from sediment inputs. Actual sediment inputs may be episodic in nature and therefore not captured by the recent bathymetry observations. However, the erosional rates measured since the harbor opening include the net effect (if any) of sediment input.

6.5.7.3 Sediment Redistribution

The geomorphic model use to evaluate the restoration alternatives only makes predictions of sediment erosion, and therefore does allow for sediment redistribution via transport and deposition. The geomorphic model used hydrodynamics to determine an erosion rate as a function of peak bed shear stress. This method is consistent with observations indicating that the Slough has been an erosional environment for the last six decades. Neglecting transport and deposition may fail to predict localized regions of deposition within the Slough. However, given the observed trends, the extent of any potential deposition areas appears to be small, and likely temporary.

6.5.7.4 Maximum Main Channel Depth

The methodology for predicting geomorphic change constrained the maximum depth of 10 m NAVD on the main channel. This depth was selected as the nominal dredging depth for Moss Landing Harbor. It is unlikely that the Slough would erode deeper than the Harbor since the Harbor serves as the downstream boundary to the Slough. We expect the harbor entrance dredging depth to act somwhat as a “grade control” for the upstream channel depth. While some localized erosion can occur to greater depths (for example, at constrictions such as the Highway 1 bridge), we expect the overall channel to equilibrate near the harbor depth.

6.5.7.5 Main Channel Widening

The geomorphic approach only increases the main channel’s depth, while main channel widening is not explicitly modeled. While we recognize that the actual channel expansion will include both, for modeling purposes, we assume all cross-sectional increase by depth. This is an important simplification to make the model process tractable.

6.5.7.6 Marshplain Elevation

Modeling future scenarios was simplified by not including the effect marshplain elevation changes on tidal velocity. Changes to marshplain elevation affect the tidal prism, which could affect velocities. The importance of this effect was tested by sensitivity analysis that included modeling the system after lowering the marshplain to the elevation of mudflat (See Appendix D). These results show a minor effect on peak velocity compared to deepening the main channel. This simplification is justified under most likely future scenarios.

6.5.7.7 Tidal Creek Expansion

The geomorphic approach does not alter the dimensions of tidal creeks. Increasing these creek dimensions, as has been observed over time (Elkhorn Slough Tidal Wetland Project Team 2007), would increase flow to marshes. However, the increase in flow as compared to the overall Slough circulation is assumed to be small. The hydrodynamic model supports this assumption by demonstrating that the Slough's marshes, which are arranged in a narrow strip alongside the main channel, receive most via overtopping of the marshplain rather then being conveyed through the marsh channels. Secondly, changes to the tidal creeks can be evaluated in context of the changes in marshplain elevation of the marshplain discussed in the paragraph above. Sensitivity analysis demonstrated that changes in marshplain elevation are overshadowed by main channel erosion. Therefore, changes to the tidal creeks, which are a smaller fraction of the total marsh area than the marshplain, would be even less significant. While marsh creek extension does occur, it primarily results in local changes to tidal flow within the marsh creeks themselves, but has minimal impact on flows in the main channel.

6.5.7.8 Sediment Accretion Rates

The habitat prediction approach assumes the maximum organic sediment accretion to be +2 mm/year. This rate was based on the average between the long-term rate of 1.1 mm/year and the preliminary SET results of ~3 mm/yr. Since at this time, the SET data at Elkhorn Slough represent a single measurement, they are considered unreliable. The selected rate of +2 mm/yr is consistent with rates observed at other salt marshes. If actual sediment accretion rates are higher, the rate at which marshplain is converted to mudflat would be reduced.

6.5.7.9 Channel Cross Section

The habitat approach assumes that changes to the Slough's cross section profiles preserve consistent proportions to present day profiles. This assumption is used to make predictions of shallow and deep subtidal habitat. This assumption is based on the consistent relationship between geometry and hydrodynamics for tidal channels (Williams and others 2002).

6.5.7.10 Marshplain Vegetation

The habitat approach considers processes directly related to hydrodynamics and geomorphology, neglecting influences on marshplain vegetation such as herbivory, disease, nutrient loading, and competition by algal mats. Current understanding of these biologic processes is not sufficient to quantify and include in the habitat prediction model. Many of these processes are believed to be detrimental to salt marsh vegetation, and therefore could accelerate the salt marsh habitat loss, compared with the predicted levels.

6.5.8 Recommendations for Future Work

Elkhorn Slough is a complex, continually evolving, natural system with multiple interconnected processes affecting habitat. In light of the uncertainties, below are recommendations for future data collection and studies to further inform management decisions.

- Sediment
    - An ongoing suspended sediment monitoring program would leverage the existing LOBO network to provide better understanding of tidal and seasonal variations in sediment erosion, deposition, transport and fluxes. For example, neap tides can be thought of as a naturally occurring muting of the tide range on the same order as the proposed restoration alternatives. How do sediment fluxes within the Slough and from the Slough change between spring and neap tides?
    - Compile better spatial resolution of bed sediment composition and physical properties (e.g. grain size, erosion rate as a function of bed shear stress, and consolidation rate) to support future sediment transport modeling efforts.
    - Refine the sediment budget through better quantification of the inputs (especially Caneros Creek at the head of the Slough and the Gabilan/Tembledero watershed via the Old Salinas River channel) and outputs (tidal export at Highway 1).
    - Develop a sediment transport model for the Slough to improve understanding of existing conditions and likely impacts of restoration alternatives.

- Geomorphology
    - Monitor changes in marsh plain elevations relative to the tides in space and time through an expanded set of SET stations.
    - Prepare for focused geomorphic observations and assessment in response to extreme events such as Pajaro River flooding from Watsonville Creek or tectonic elevation changes.
    - Continue the biannual main channel bathymetric surveys by SFML and expand it to include coincident measurements of the larger marsh plain and tidal regions of the Slough. Regular monitoring of the entire Slough will enable a better understanding of inter-connected changes between the geomorphic units such as main channel width transgressions that alter mudflat extent and bank stability changes between mudflat and marsh.
    - Evaluate alternative methods for predicting geomorphic change that complement and enhance the methodology used in this study.

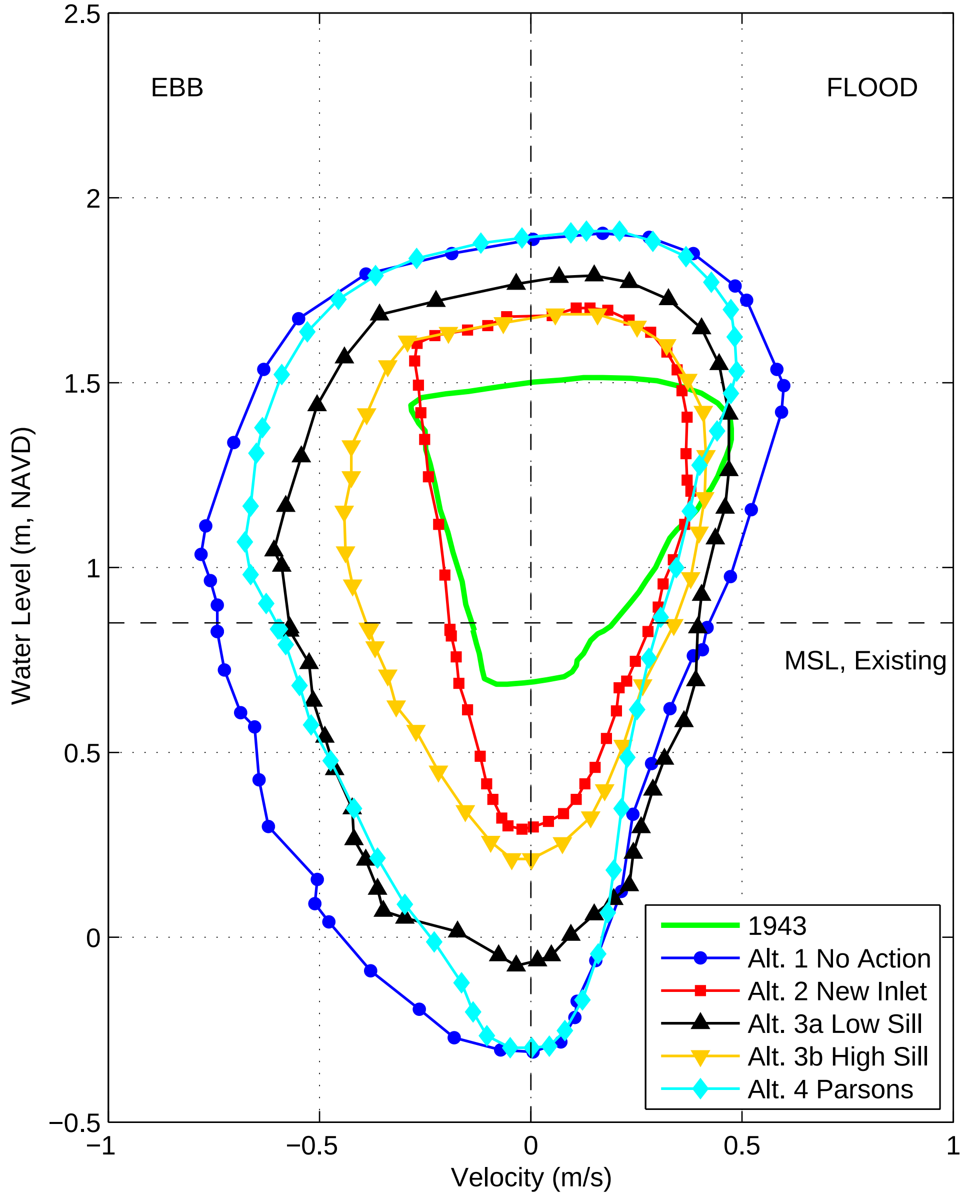
- Marshplain
  - Develop a greater understanding of the impacts of tidal water level elevations and sediment supply on marsh vegetation loss.
  - Monitor changes to the marsh channel network, particularly with regard to the internal "cannibalization" of marshplain to create higher channel network density seen in numerous British marshes.
  - Test different configurations of fill placement on the marshplain with regards to location within the Slough, grain size, bed elevation stability, vegetation recruitment success.
  - Initiate and monitor pilot restoration efforts within the existing main Slough marshes, Parsons Slough and muted tidal areas to evaluate which conditions and practices facilitate restoration.

- Restoration Design
  - Extend the conceptual design of the present alternatives by developing a refined understanding of the strengths and weaknesses of different sill configurations, e.g. multiple sills, notched sill, upstream channel fill.
  - Test an inlet control feature and raising subsided marsh on a smaller sub-region of the Slough, e.g. Parsons Slough.
  - Monitor and assess water quality within the muted tidal regions of the Slough, particular as different management strategies are applied to different regions.

6.6 ADAPTIVE MANAGEMENT AND PROJECT PHASING

In response to the assumptions and uncertainties discussed above, we would recommend a phased implementation of any of the action alternatives, as well as use of the modeling tool developed in the current study to refine the design approaches. The phased implementation should be developed to allow "adaptive management" of the alternatives as they are implemented, and the system response to implemented alternatives can actually be measured. So, for example, the wetland restoration project at Parsons Slough (Alternative 4) could be the first "Phase 1" constructed project. Subsequently (or concurrently), a low sill at Highway 1 could be designed so that the level of hydraulic control can changed (increased or decreased) following initial construction. A initially constructed low Highway 1 sill design (Alternative 3a) would allow for subsequent raising to the "high" sill configuration (Alternative 3b) if necessary. It could also be raised above the tide level to prevent any circulation under the current bridge as part of the construction of a new mouth to the north (Alternative 2).

6.7 FIGURES



Source: DELFT3D model results, downstream section

Figure 6−1

Elkhorn Slough Tidal Wetlands Restoration

Alternatives 1−4 Water Level vs. Velocity – Year 0

PWA Ref# 1869

PWA

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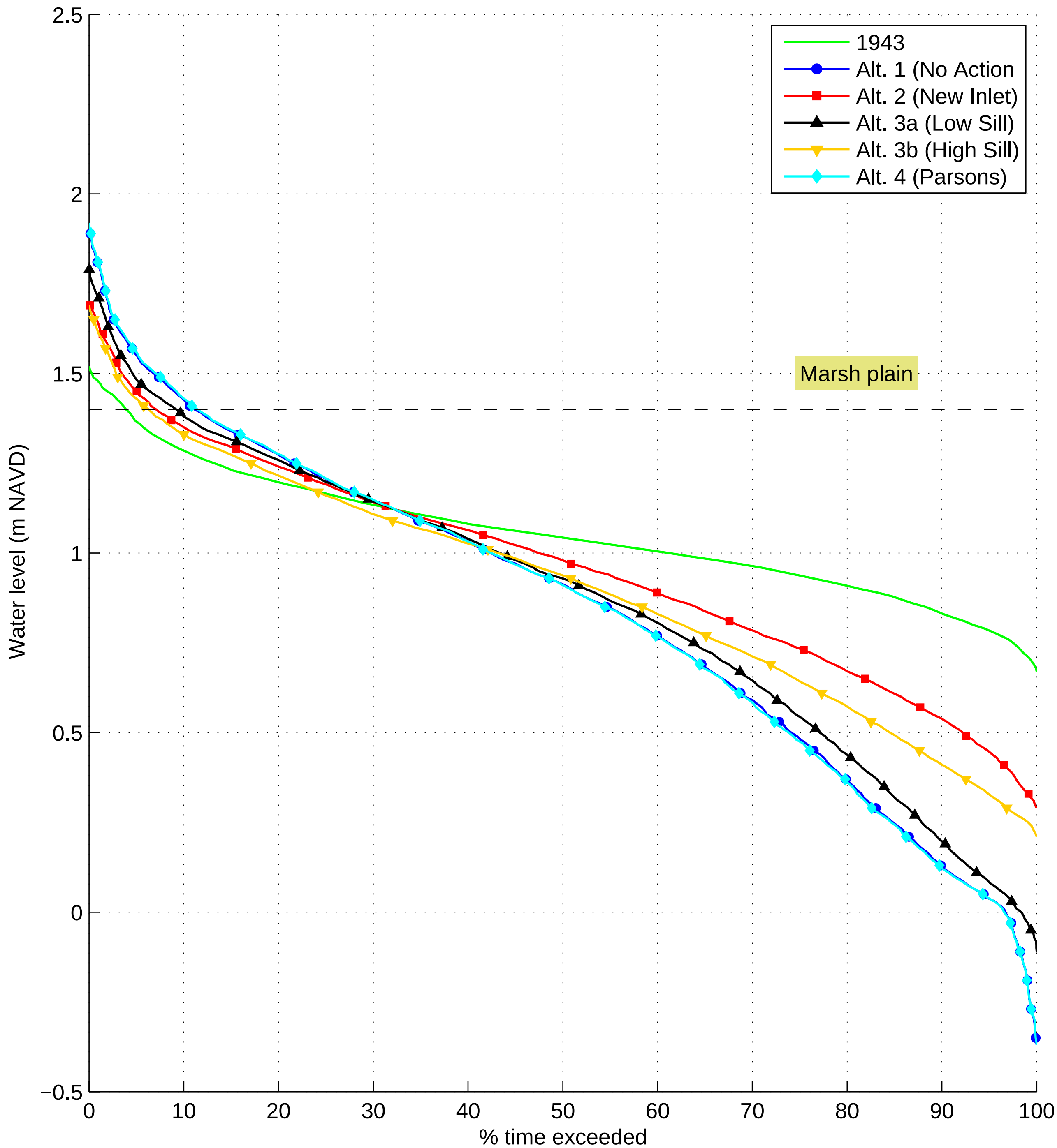

Source: DELFT3D model results, downstream section

Figure 6−2

Elkhorn Slough Tidal Wetlands Restoration

Alternatives 1−4 Water Level vs. Percent Exceeded – Year 0

PWA Ref# 1869

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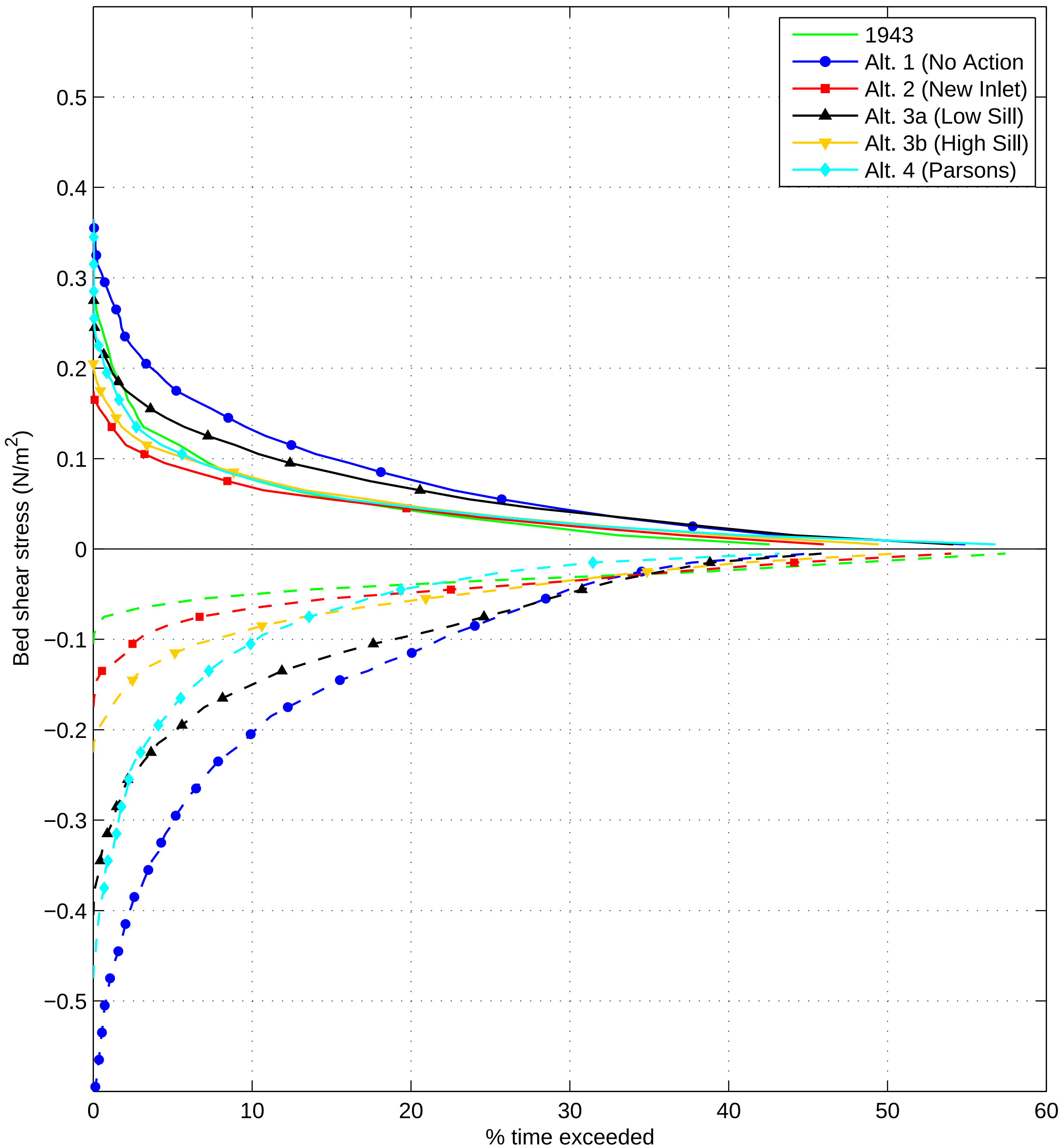

Source: DELFT3D model results, downstream section

Figure *6−3*

Elkhorn Slough Tidal Wetlands Restoration

Alternatives 1−4 Bed Shear Stress vs. Percent Exceeded − Year 0

PWA Ref# 1869

PWA

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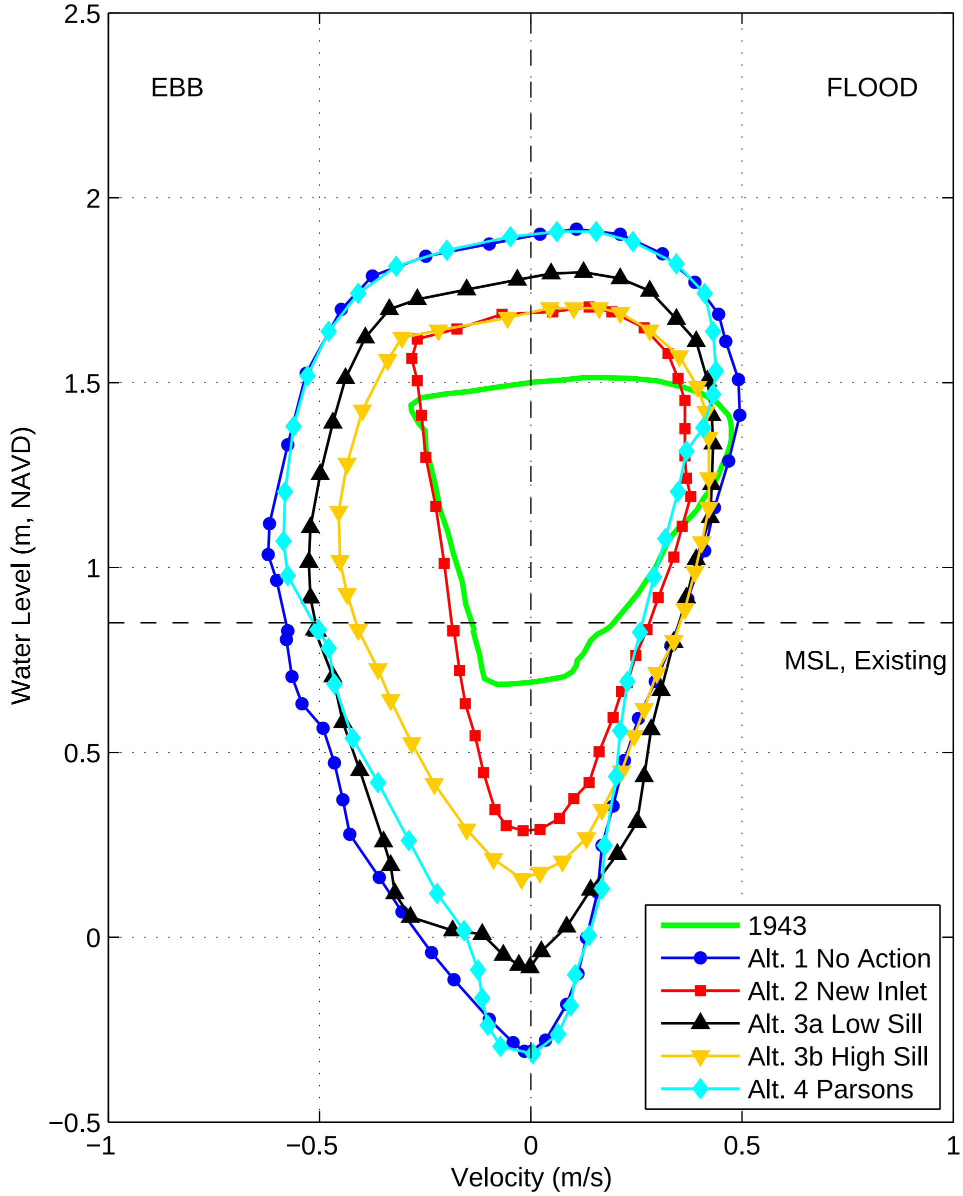

Source: DELFT3D model results, downstream section

Figure 6−4

Elkhorn Slough Tidal Wetlands Restoration

Alternatives 1−4 Water Level vs. Velocity – Year 10

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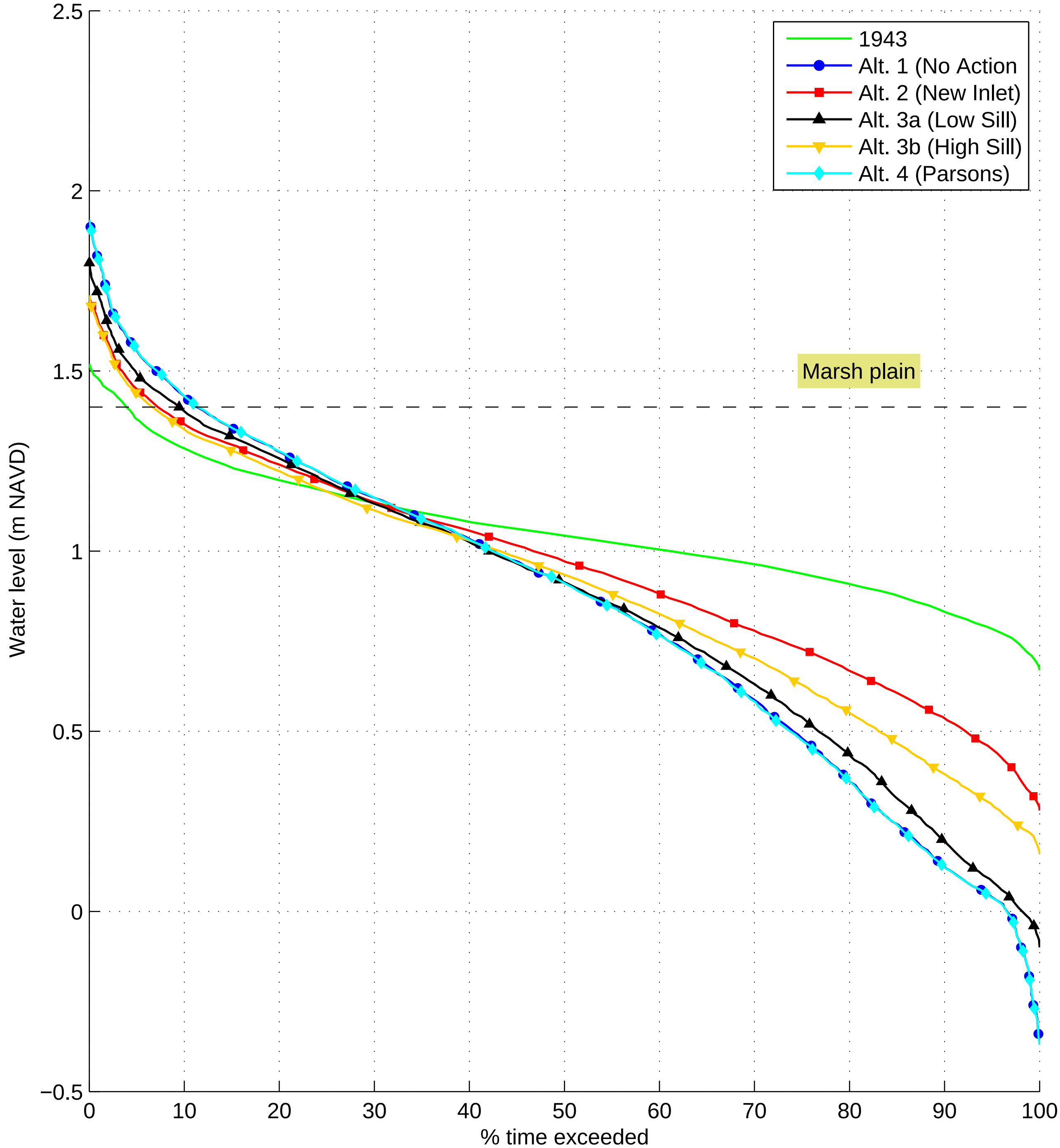

Source: DELFT3D model results, downstream section

Figure 6−5

Elkhorn Slough Tidal Wetlands Restoration

Alternatives 1−4 Water Level vs. Percent Exceeded – Year 10

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PWA

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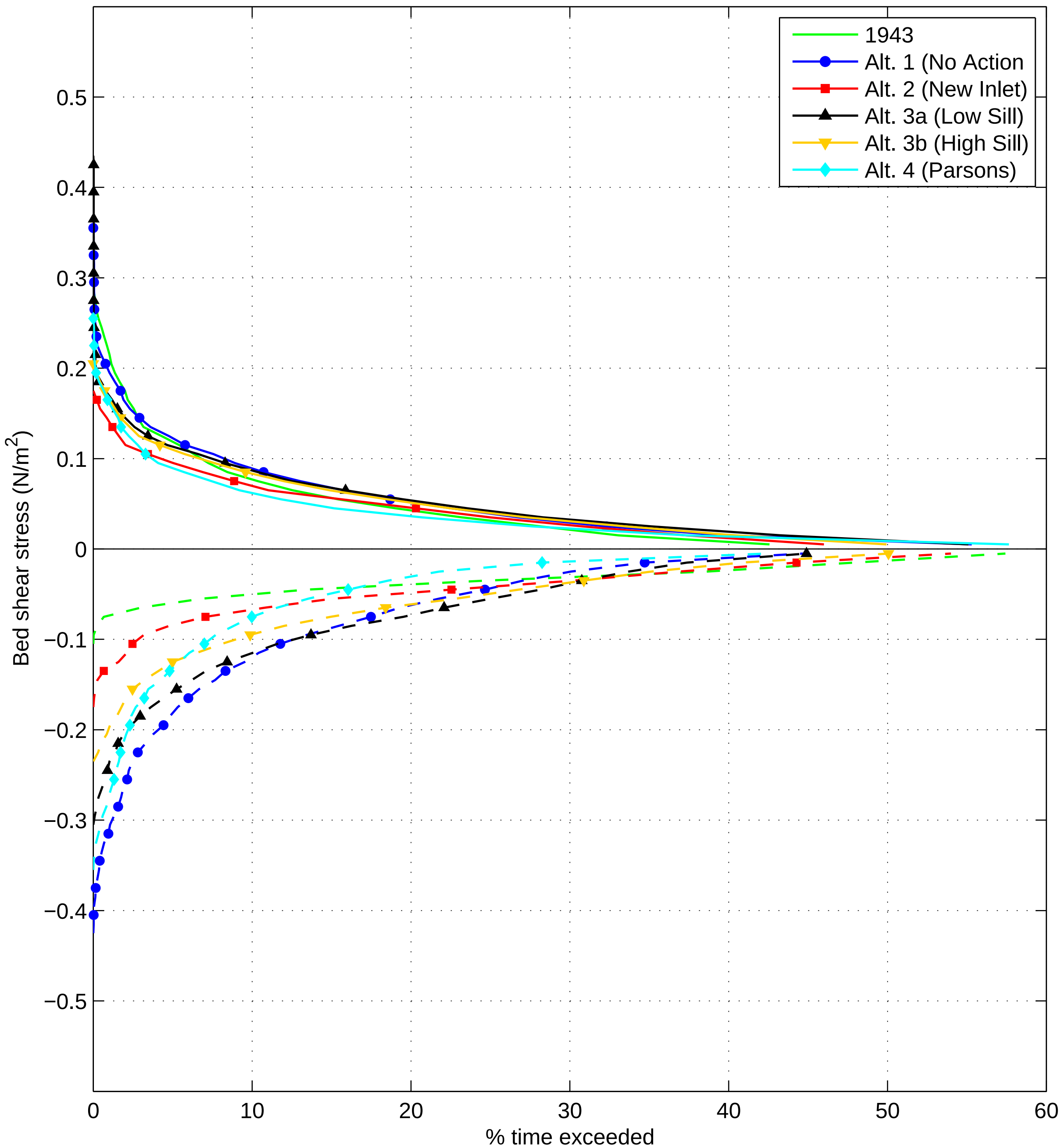

Source: DELFT3D model results, downstream section

Figure 6−6

Elkhorn Slough Tidal Wetlands Restoration

Alternatives 1−4 Bed Shear Stress vs. Percent Exceeded – Year 10

PWA Ref# 1869

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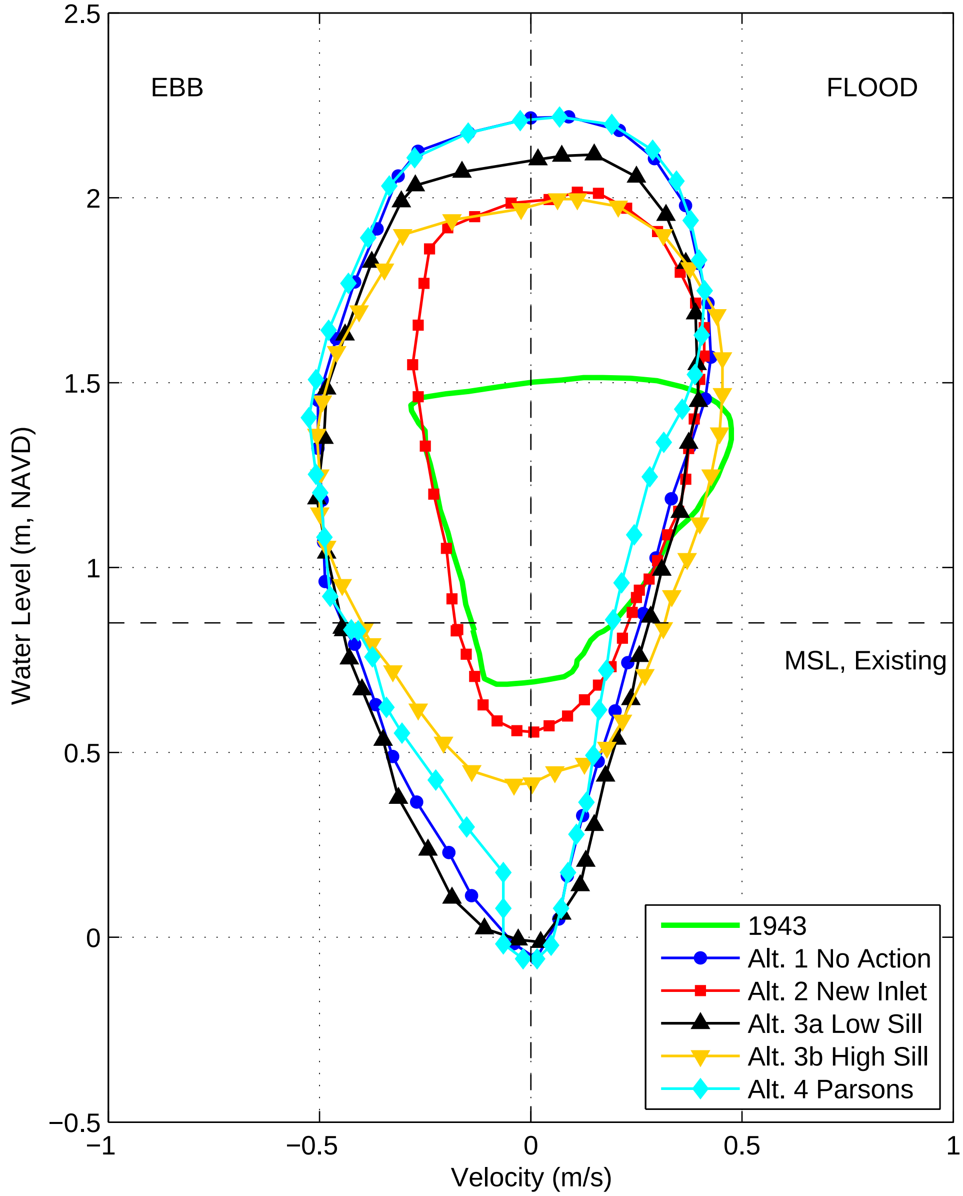

Source: DELFT3D model results, downstream section

Figure 6−7

Elkhorn Slough Tidal Wetlands Restoration

Alternatives 1−4 Water Level vs. Velocity – Year 50

PWA Ref# 1869

PWA

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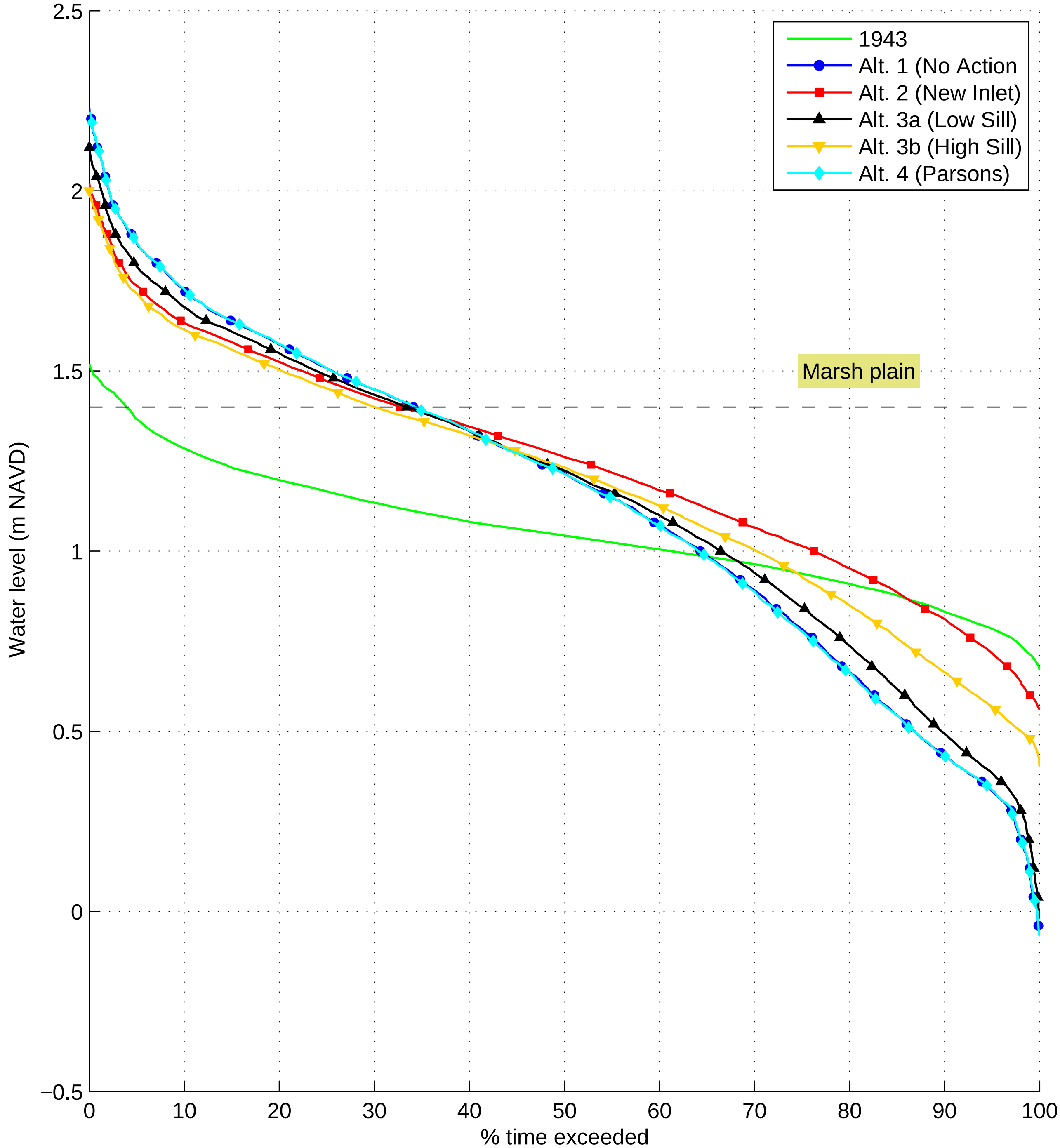

Source: DELFT3D model results, downstream section

Figure 6−8

Elkhorn Slough Tidal Wetlands Restoration

Alternatives 1−4 Water Level vs. Percent Exceeded – Year 50

PWA Ref# 1869

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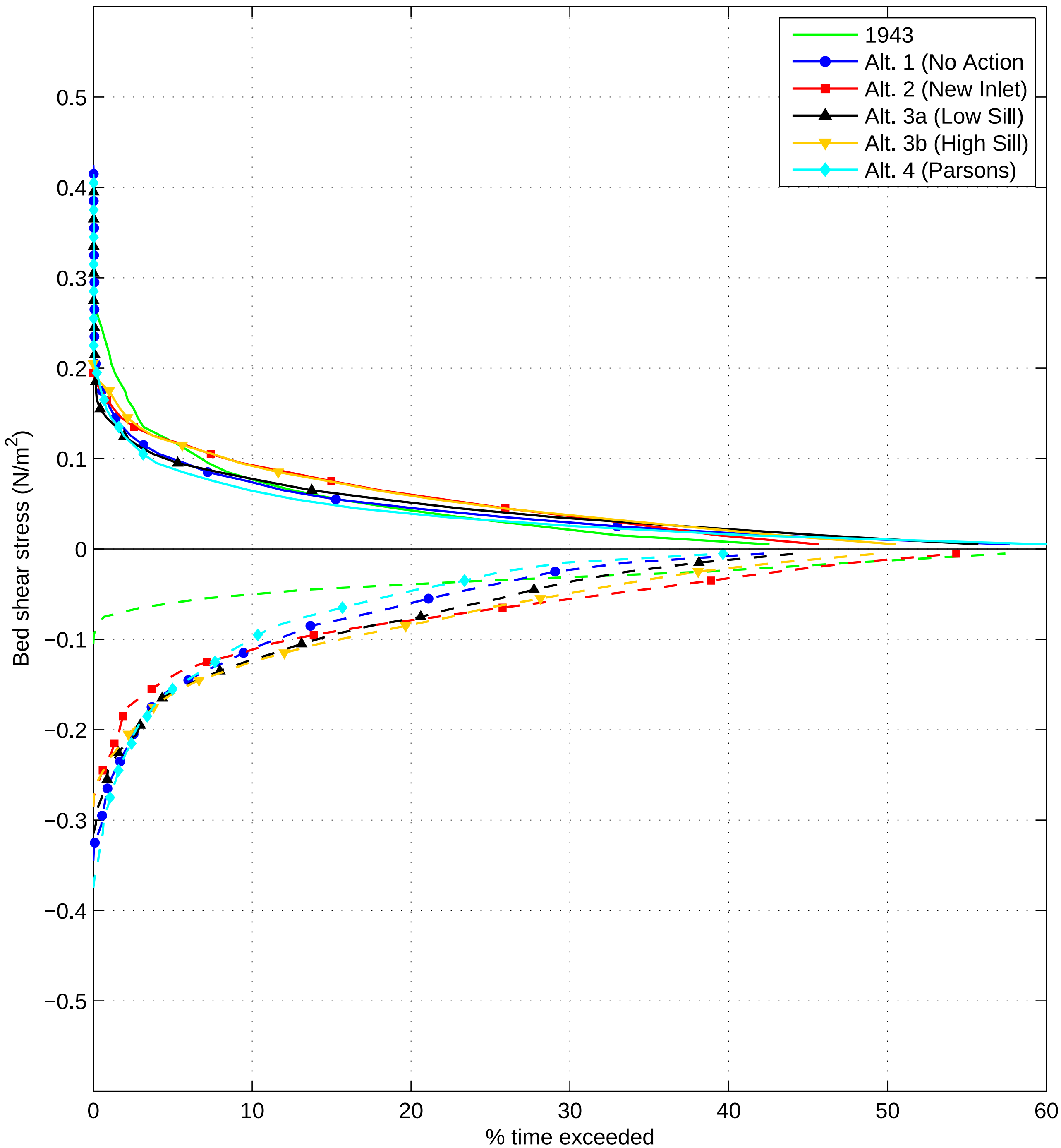

Source: DELFT3D model results, downstream section

Figure 6−9

Elkhorn Slough Tidal Wetlands Restoration

Alternatives 1−4 Bed Shear Stress vs. Percent Exceeded – Year 50

PWA Ref# 1869

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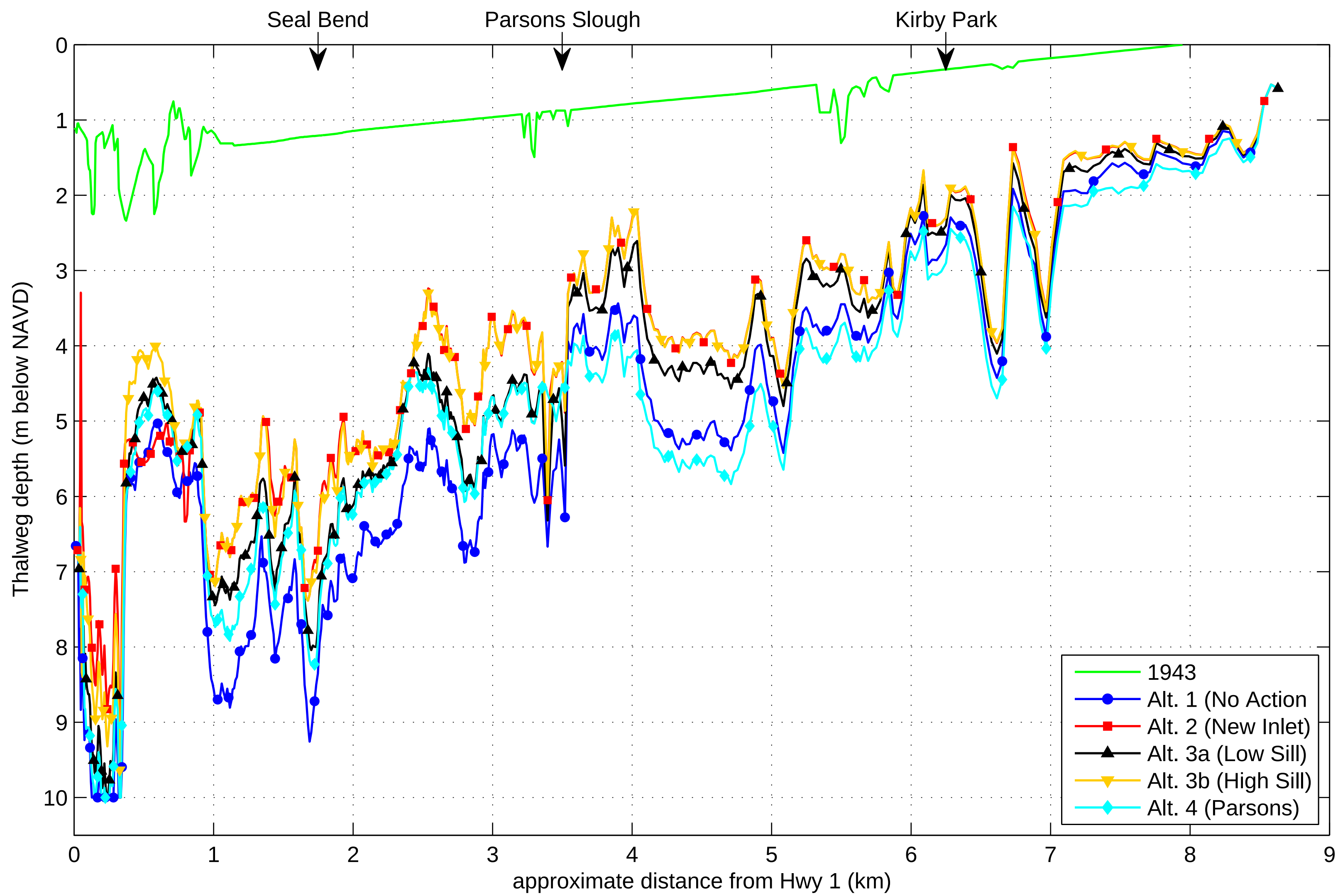

Source: USACE survey (1943), CSU−SFML batymetric survey (2003), & DELFT3D model results

Figure 6−10
Elkhorn Slough Tidal Wetlands Restoration

Alternatives 1−4 Projected Thalweg Depths − Year 10

PWA Ref# 1869

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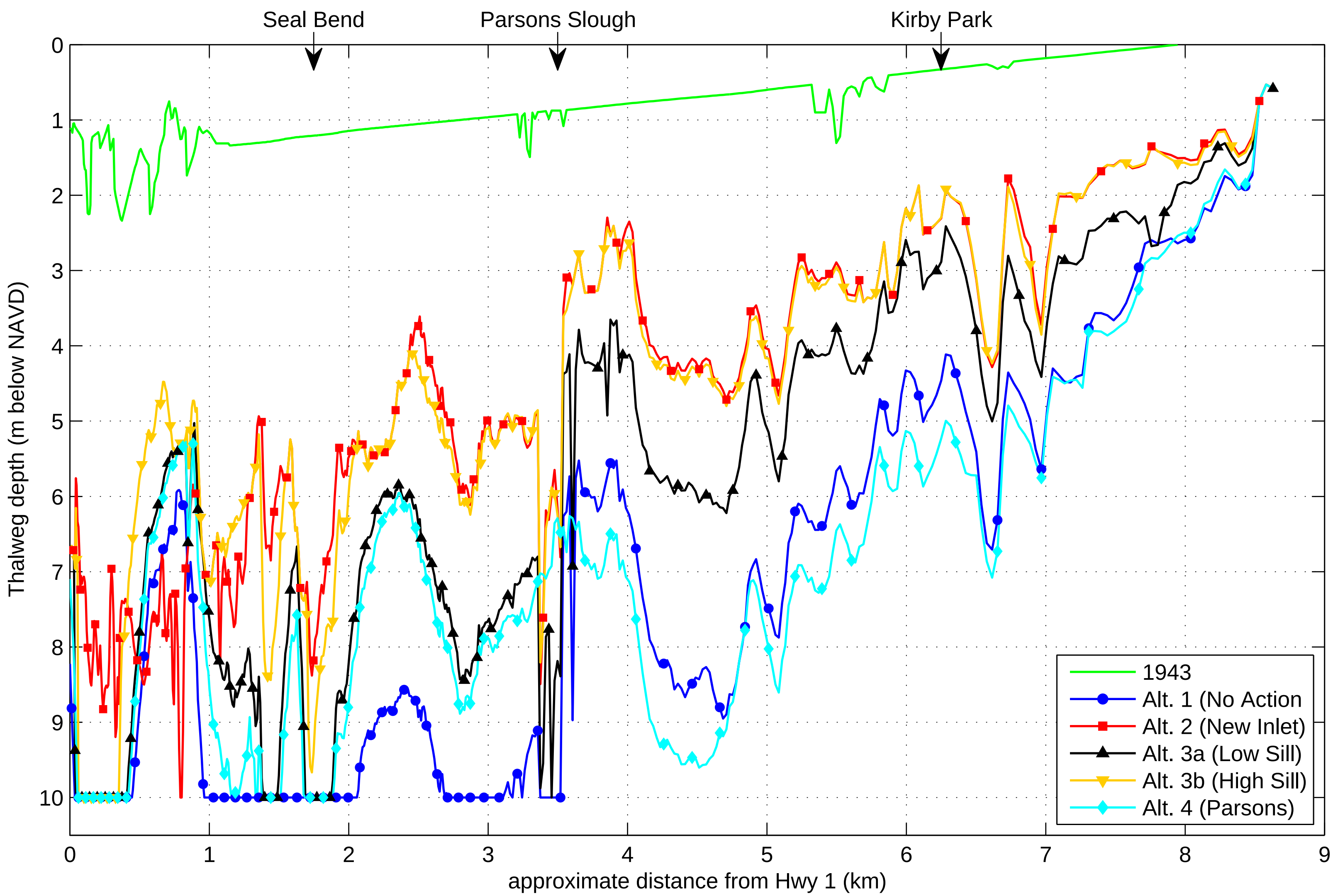

Source: USACE survey (1943), CSU−SFML batymetric survey (2003), & DELFT3D model results

Figure 6−11
Elkhorn Slough Tidal Wetlands Restoration

Alternatives 1−4 Projected Thalweg Depths − Year 50

PWA Ref# 1869

PWA

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7. ENGINEERS REPORT (CONCEPTUAL DESIGNS AND COST ESTIMATES)

This section describes the conceptual design and cost estimate for two selected alternatives selected by the client team for more detailed assessment: Alternative 2 – New Ocean Inlet, and Alternative 3a – Low Sill at the Highway 1 Bridge. Both of these alternatives include one sub-alternative, or optional element, that is additive in construction scope: the placement of fill in the existing Elkhorn Slough channel from the Highway 1 bridge up to Parson's Slough. This sub-alternative would replace some of the material eroded from the main channel during the past 60 years since the opening of the new harbor mouth. In addition to the option to place fill, which is described from a cost and construction perspective, there are a variety of refinements and variations that could be applied to either of the two selected alternatives. Some of these are suggested in the Alternatives descriptions, while others would be identified as part of the next phase of refinements in a selected project.

Alternatives 2 and 3a are briefly described below. The descriptions address engineering considerations, including geometry, methods and materials. Conceptual engineering drawings of plan and typical section views are included at the end of this section. Full size drawings of these figures are also provided. The content of each figure is summarized as follows:

- Figure 7-1 - key map and site plan;
- Figure 7-2 - detail of Alternative 2, the New Ocean Inlet, also in plan and section;
- Figure 7-3 - detail of Alternative 3a, the Low Sill at the Highway 1 Bridge, in plan and section;
- Figure 7-4 - potential extents of fill placement in the existing Elkhorn Slough channel.

Also, the "estimates of probable costs" are summarized in a table for each alternative. It is important to note that these are large scale construction projects and that the alternatives involve significant intervention, and hence would require further detailed analysis and engineering design that would likely lead to major provide additional refinements. Consequently, at this preliminary design phase, a cost contingency of 35% is included. We anticipate that actual construction costs could be reduced significantly through more detailed engineering. This is particularly true of the unit costs identified for fill placement; if a major fill element is included in the project, there is an opportunity to develop a construction methodology with a lower cost. Also, land costs are not included – at this stage, it is anticipated that all construction can be accomplished on publicly-owned land, and land and easement purchase costs are not included. Also, costs associated with environmental restrictions of construction including timing and phasing are not explicitly treated.

These estimates are subject to refinement and revisions as the design is developed in future stages of the project. The cost tables summarize the cost of construction, and do not include estimated project costs for additional studies, permitting, detailed design, construction observation, monitoring and ongoing maintenance. Estimated costs are presented in 2008 dollars, and would need to be adjusted to account for price escalation for implementation in future years. This opinion of probable construction costs is based on: PWA's prior experience, prices from similar projects, and consultation with contractors and others involved in comparable projects.

Please note that these estimates of probable construction costs and the actual costs at the time of construction may vary. The cost of construction will be impacted by the availability of construction equipment and crews and fluctuation of supply prices at the time the work is bid. PWA makes no warranty, expressed or implied, as to the accuracy of such opinions as compared to bids or actual costs.

7.1 ALTERNATIVE 2 – NEW OCEAN INLET

7.1.1 Conceptual Design

Conceptual design drawings of the New Ocean Inlet are provided in the site plan and keymap (Figure 7-1) and in the detailed plan and sections (Figure 7-2). The New Ocean Inlet alternative comprises several large-scale construction components, including:

- Channel excavation - New Tidal Channel: A new tidal channel would be excavated from the ocean to a junction with the existing Elkhorn Slough at location roughly between the existing inlet and the junction with Parsons Slough (Figure 7-1). Approximately 2.5 million cubic yards of material is proposed for excavation. A variety of fill placement locations are feasible. As shown in our initial design and included in the cost estimate, some of the material would be placed in the lower 2 miles of Elkhorn Slough up to about elevation -10' NAVD (about 500,000 cy). The remainder of fill could be placed in Parsons Slough or other subsided former salt marshes. We also recommend closing the existing culverts under Jetty Road to the North Harbor basin, and placing a small amount of fill around those to maintain separation between the North Harbor and the new Slough mouth and channel.

- Dredge Ocean Inlet: A new ocean inlet would be dredged and the sand used to create an offshore ebb bar outside the inlet. This will create a historical and natural feature of an inlet at this location, and result in the least costly placement of the excavated fill. The width of the inlet was selected to be 500', which is comparable, though slightly narrower than the historic inlet based on old maps.

- Jetties: We show two rubble mound jetties constructed in the nearshore zone at the new inlet to prevent inlet migration. Under optimal conditions, no jetties would be required as a natural morphology is preferable. However, as discussed in the inlet stability memo (Appendix B), the natural inlet dynamic morphology would likely include migration toward the south, which may not be compatible with present land use. Subsequent design analysis may indicate only one jetty maybe acceptable.

- Tidal Dam at Highway 1 Bridge: A rubble mound dam is included to block tidal flow between Elkhorn Slough and the existing inlet. This feature is similar to the low sill (Alternative 3a) in geometry and materials, except that the entire crest elevation is above the tidal range. Our initial design proposes a rubble mound structure. Other structural approaches may be feasible, such as a cellular coffer dam. An engineering feasibility analysis of various alternative structures would be conducted in the design phase. The dam will prevent navigation from the harbor to Elkhorn Slough unless an operable lock is included in the sill structure. The addition of a lock with a navigable depth of 7 ft to accommodate small boats is roughly estimated to cost on the order of $1,000,000 to $5,000,000, depending on a number of factors that require further evaluation.

- New Highway 1 Bridge and Approaches: A reinforced concrete highway bridge similar to the existing one across Elkhorn Slough is assumed. Some reconfiguration of the Highway and the channel would be required to allow the new bridge to be constructed perpendicular to the channel at this location. A perpendicular crossing is desired, resulting in the shortest length of bridge and reducing the potential for transverse flow directions and erosion. Costs were based on a review of the actual construction costs of the Elkhorn Slough and Carmel River bridges, using information provided by Caltrans to scale the new bridge based on size and updated to current costs. The bridge costs include a new bridge, abutments, new roadway sections, and transitions with the existing roadways. Bank armoring is also included in the vicinity of the bridge. (These estimated costs have not been reviewed by Caltrans or a transportation engineer and are therefore provisional.)

7.1.2 Estimate of Probable Costs

The engineer's estimate of likely construction costs is shown in Table 7-1.

Table 7-1. Engineer's Estimate for Alternative 2 - New Ocean Inlet

Item	Description	Estimated Cost
1	Mobilization	$ 4,000,000
2	New Channel and Reuse	$ 39,000,000
3	Dredge Ocean Inlet	$ 6,000,000
4	Jetties	$ 8,200,000
5	Tidal Dam at Highway 1 Bridge	$ 3,800,000
6	New Highway 1 Bridge and Approaches	$ 8,700,000
	SUBTOTAL	**$ 69,600,000**
	CONTINGENCY (35%)	**$ 24,400,000**
	TOTAL	**$ 94,000,000**

7.1.3 Additional Considerations and Potential Refinements

A review of the preliminary cost estimate identifies some of the primary cost items that may be reduced in future design refinement phases:

1. The New Tidal Channel: The planform location of the constructed tidal channel connecting Elkhorn Slough to the new ocean inlet is constrained by property ownership and existing infrastructure. The proposed location was selected to connect with the eastern boundary of the flood-tide shoal, cross under Highway 1 at the existing Lower Bennett Slough culvert, follow the existing Lower Bennett Slough channel along the north side of the DFG Wildlife Management Area, and turn south along the east side of the DFG area, following the existing marsh channel where possible (Figure 7-4). The channel's width was set to 100 m (330 ft) to remain within property boundaries. Its depth was set to 4.3 m (14 ft) below MLLW such that peak flow velocities in the channel remained below 1.1 m/s (3.6 ft/s). The channel's cross-sectional area is less than the existing Elkhorn Slough channel, but greater than the pre-harbor entrance channel, located adjacent to DF&G property, and has a relatively narrow corridor. Initially, a shallower channel, about 2m (6 ft) below MLLW, was considered. However, the velocity estimates from the hydrodynamic model indicated that velocities would still be relatively high, and the channel would likely widen and deepen (this is in response to the currently large tidal prism). A deeper channel was then developed and tested, to identify a non-erosive cross-section. In a future refinement phase, a corridor that can allow some erosion (width and depth) may allow an initially shallower channel to be constructed. Excavating to a shallower depth would reduce the project cost significantly, For example, excavating to -5' NAVD, which is the elevation across the flood shoal, would save about $20 million, or about 1/5 of the total project cost. In this case the channel would be allowed to naturally scour to reach an equilibrium cross-section. Another consideration is the effect of filling Elkhorn Slough with excavated material. This will reduce the potential tidal prism and allow a smaller equilibrium channel. Further modeling would help optimize the desired amount of earthwork. As noted in the discussion of alternatives, various other channel alignments may be feasible as well.

2. Dredge Ocean Inlet: We have assumed that an ebb tide bar would be constructed to limit erosion of adjacent beaches. Often called "pre-filling," this approach is recommended to mitigate potential erosion. Without pre-filling, the initial formation of this bar may trap some of the littoral sand movement along the shoreline, and result in temporary erosion of the adjacent beaches until the sand transport equilibrium is re-established. An alternative approach would be to breach the inlet and let it scour and feed the offshore bar, if subsequent research were to show that the potential for significant beach erosion was slight. Also, since much of the sand transported along shore is believed to move into the Monterey Canyon and is considered a "loss" to the beaches, pre-filling may not be required.

3. Jetties and Dredge Ocean Inlet: We have initially assumed that two jetties are required to prevent the new inlet from migrating. The concern is that the inlet stability analysis has shown a tendency

for lateral migration. Since the existing jetties inhibit northward sand transport, we anticipate the inlet would migrate southward until it reaches a more stable location just north of the existing north jetty. Further evaluation of inlet stability may result in smaller jetties or a single jetty.

The channel fill sub-alternative may also included as an additional element of this alternative. See Section 7.3 for a description of this sub-alternative and its associated costs.

7.2 ALTERNATIVE 3A – LOW SILL AT HIGHWAY 1 BRIDGE

7.2.1 Conceptual Design

Conceptual design drawings of the Low Sill at the Highway 1 Bridge are provided in the site plan and keymap (Figure 7-1) and in the detailed plan and sections (Figure 7-3). Alternative 3A – Low Sill at Highway 1 Bridge includes the following elements:

- Tidal Barrier: A tidal barrier with a low sill (nominal elevation of -4.5 ft NAVD) would be constructed on the west side of the existing Highway 1 Bridge. This location would require the shortest width of sill, and allows a tie-in to the existing extent of fill supporting the bridge abutments. The location (tied to the Highway 1 abutments) will prevent the potential for "outflanking" or "end-around cutting," which refers to erosion around the ends of the sill which would render it ineffective. The proposed location will require an encroachment permit from Caltrans since it is adjacent to the Highway 1 Bridge and in the right-of-way. However, other locations would require a greater amount of fill. The sill would be constructed of quarry stone. The quantities include an allowance for 3' of settlement owing to a compressible mud layer shown in soil borings. However, the drawings show the finished, settled grades. Further engineering is required to determine whether culverts are needed or desired to mitigate currents during construction and to affect water quality in the deeper sections of Elkhorn Slough.

- Fill Placement in Elkhorn Slough: We have assumed that fill will be placed upstream of the sill to increase hydraulic friction and to limit the depth where water quality could deteriorate under low-circulation conditions. However, this assumption has not been tested with the hydrodynamic model. A fill elevation of -10' NAVD was identified among the variety of fill options presented in Section 7.3 and included in this alternative's cost estimate. The elevation of -10' NAVD was selected to be slightly below the proposed elevation of the barrier core. This core would likely block sand migration due to its rock gradation and lower permeability. Depending on availability of sediment, a variety of fill elevations could be considered. Table 7-3 provides a range of fill volumes for a range of fill elevations.

7.2.2 Estimate of Probable Costs

The engineer's estimate of likely construction costs for Alternative 3a is included in Table 7-2.

Table 7-2. Engineer's Estimate for Alternative 3a - Low Sill at Highway 1 Bridge

Item	Description	Estimated Cost
1	Mobilization	$ 1,500,000
2	Fill Placement in Elkhorn Slough Channel	$ 15,000,000
3	Low Sill and Tidal Barrier	$ 3,500,000
	SUBTOTAL	**$ 20,000,000**
	CONTINGENCY (35%)	**$ 7,000,000**
	TOTAL	**$ 27,000,000**

7.2.3 Additional Considerations and Potential Refinements

A review of the preliminary cost estimate identifies some of the primary cost items that may be reduced in future design refinement phases:

- Other structural alternatives are possible, such as a cellular coffer dam constructed with sheet piles.
- In the conceptual design, a single sill, with a uniform crest elevation is shown. However, a variety of variations on this design are feasible to explore in subsequent steps.
    - The sill cross-section could include a deep notch in the middle, with higher sill sections on either side. This may allow the same level of hydraulic control, but perhaps have less influence on navigation. A notch may also affect the three-dimensional circulation of water, perhaps allowing a more efficient vertical mixing of the slough water behind the sill. Likewise, it could affect the influx of water from the harbor into the slough; during winter rainstorms, freshwater from the Salinas River, Tembladero, and Moro Coho Sloughs enters the harbor from the Old Salinas River Channel, and may be conveyed up Elkhorn Slough on a flood tide. This freshwater (containing nutrients and other runoff constituents from the agricultural operations in the area) is more buoyant that the sea water, and there is concern that it would be differentially transported up the Slough, further exacerbating water quality problems associated with the restrictions on tidal circulation created by the sill. The notch may facilitate sediment transport, which would be counter-productive. These types of assessments would require a combination of 3-dimensional hydraulic modeling linked with water quality modeling.
    - The sill would be designed so that the crest elevation could be made higher or lower by placing or removing additional rock. This would allow some level of adaptive

management of the effect of the sill on both hydraulic characteristics as well as sediment trapping behind the sill.

- For the single sill shown, all of the hydraulic control occurs at the sill. This results in significant change in current velocity and a relatively larger difference in up- and downstream water surface elevation across the sill. This differential, and the subsequent impacts on navigation, etc., become more pronounced as the sill crest gets higher (closer or into the tidal range). One alternative to reduce the magnitude of these changes would be to create a series of sills extending from the Highway 1 Bridge up stream across the main Slough channel. So for instance, 2, 3, or 4 sills could be constructed, set perhaps 500 or 1000 feet apart. These additional sills would be more challenging to construct, as they would not have the existing bridge abutments to tie into, and would have to be wider to span the full channel width.

- As an alternative to multiple sills, it may be feasible to constrict the channel width and depth for some distance upstream of Highway 1 behind the sill, creating a longer, narrower "throat" section that accomplishes many of the beneficial effects of the new entrance (i.e., switches the tidal regime from an "ebb" back to a "flood" tide dominance).

- Another sub option that was brought up in discussions was the possibility of an operable sill that could be mechanically raised or lowered on a regular basis throughout the tidal cycle. This would allow differential hydraulic conditions at various times within the daily tidal cycle, and allow the manipulation of the net tidal exchange to be converted from an ebb-dominated to a flood-dominated system. Conceivably, this could be accomplished with some type of adjustable series of vertical gates, a mechanical tidal barrier, or an inflatable "bladder" type dam. This would require a much higher level of construction costs, ongoing operation and maintenance, and present additional navigation hazards. We are unaware of this type or scale of structure in current use for wetland restoration and have not pursued it further at this preliminary assessment phase.

- Navigation across the low sill would continue to allow some access from the harbor into the slough (the proposed sill height would allow about 5-feet of water depth above the proposed sill crest at MLLW and perhaps more, if a notched sill were constructed). However, navigation may not be safe across the sill at all times (for example, the maximum velocities across the sill at the peak tidal ebb may be excessive). If the more detailed assessment shows this to be a significant concern, other navigation facilities may be desired. One approach would be to provide a launch and landing facility on either side of the Highway 1 Bridge, so that hand-carried vessels could be removed and launched on the other side. Another approach would be to include an operable, navigation lock to allow safe passage of vessels. The addition of a lock with a navigable depth of 7 ft to accommodate small boats is roughly estimated to cost on the order of $1,000,000 to $5,000,000, depending on a number of factors that require further evaluation.

7.3 CHANNEL FILL SUB-ALTERNATIVE

Placement of fill in the existing Elkhorn Slough channel is a sub-alternative of both Alternative 2 and 3a. The hydrodynamics resulting from this sub-alternative were not modeled as part of this study. This sub-alternative is included because of its potential to fill in a sediment source which competes with the marshplain, reduce tidal current velocities through added bed friction, and decrease residence time. Additional analysis is required to assess the impact of this sub-alternative on the Slough's physical processes and habitats. For Alternative 2, the excavated channel is a source of a large volume of sediment, and placement in the Elkhorn Slough channel provides a beneficial solution to the sediment surplus. Sediment sources are more limited for Alternative 3a, however, and additional operations would be required to obtain and place the required material. The preliminary sediment report options for the concurrent Parson's Slough study provides a comprehensive look at sediment availability in the area (Moffatt and Nichol, 2008). Considering the relatively good marine access to the main Elkhorn Channel, it appears that dredging from offshore near the submarine canyon may be a viable potential source of sediment. In this case, material would be pumped hydraulically and placed in the slough channel. Table 7-3 presents a range of fill volumes for different target fill elevations and the associated cost of construction. The costs in Table 7-3 assume that material is dredged from near the submarine canyon offshore and pumped to the slough at a unit cost of $30/CY. This unit cost includes mobilization and setup with pipes and booster stations to deliver the sand to Parsons Slough.

Table 7-3. Fill Volumes for a Variety of Target Fill Elevations in the Existing Elkhorn Slough Channel

Fill Elevation (Ft NAVD)	Volume (Cy)	Estimated Cost
-8	700,000	$ 21,000,000
-10	500,000	$ 15,000,000
-12	330,000	$ 9,900,000

7.4 NOTES ON COST ESTIMATE ASSUMPTIONS

In determining an opinion of probable construction costs appropriate to conceptual level design, several assumptions were required. These assumptions included:

- construction methods
- unit costs
- project sequencing and phasing
- permitting
- property acquisition

Table 7-4 is included to illustrate the level of accuracy and amount of contingency which is typically included in cost estimation for construction projects at various levels of design. This table is from the Cost Estimate Classification System, developed by the Association for the Advancement of Cost Estimating (AACE 1997). As shown in the table below, a particularly wide range in accuracy is assumed inherent for project design at the conceptual level. In addition, contingency is a large percentage of the estimated project costs, decreasing as the level of design is increased.

Table 7-4. Levels of Cost Estimate Accuracy and Contingency for Different Levels of Design

Design Completion Level	Cost Estimate Accuracy	Contingency
Conceptual (order of magnitude costs)	-30% to +50%	35–50%
Preliminary (30%)	-15% to +30%	20-25%
40 to 70% complete	-15% to +30%	15-20%
70 to 100% complete	-5% to +15%	10-15%

The detailed cost estimates for Alternative 2 (the New Ocean Inlet) and Alternative 3a (Low Sill at Highway 1 Bridge) are provided in Table 7-5 and Table 7-6, respectively. Quantities were estimated conservatively: for the new inlet channel, we assumed that the channel would be excavated to its modeled, equilibrium dimensions; quantities of quarry stone and quarry run were increased to account for settlement of the sill and the jetties. Unit price of construction for the various elements were determined from analysis of detailed plans and bid results, market price of materials, and PWA experience.

Construction of the low sill or tidal dam involves dredging weak soils and placing quarry run and quarry stone. The unit costs below assume that the rock material is delivered from a nearby quarry and is easily available.

Dredging and fill placement costs were assumed to vary with source and location of placement. Excavated material from the new channel for Alternative 2 could be used as fill for the Elkhorn Slough channel and for Parson's Slough. This material could be pumped via slurry pipeline or trucked. Another source of material could be from dredging in the offshore submarine canyon, and pumping the material up the slough. These different options incur different costs, and it is presently difficult to determine the method most likely to be used.

Bridge costs were determined from analyzing the detailed as-built drawings and bid results for the Elkhorn Slough Bridge (Caltrans 1985) and from the Carmel River Bridge (Caltrans 1995). All components of the deck and pilings were lumped, and a unit cost for these elements was determined based on the area of bridge. In addition, cost of approaches and abutments were also considered. These costs were escalated to the present year at a 3% interest rate, resulting in a unit cost of about $120/SF for deck and pilings, and $1000/LF for approaches and abutments. However, the preliminary nature of these estimates might easily fail to include a localized and key aspect of the design, and therefore the unit cost for deck and pilings was increased by 100%.

Additional cost information on comparable projects has been requested. Table 7-7 summarizes the estimated costs for large-scale tidal wetland restoration projects planned or recently completed in San Francisco bay.

Table 7-5. Detailed Cost Estimate for Alternative 2

Item	Description	Quantity	Unit	Unit Price	Estimated Cost
1	**Mobilization**	**1**	**LS**		**$ 4,000,000**
1a	Mobilization	1	LS	$ 4,000,000	$ 4,000,000
2	**New Channel and Reuse**	**1**	**LS**		**$ 39,000,000**
2a	Excavation	2,000,000	CY	$ 10	$ 20,000,000
2b	Transport and Place at Parsons Slough	1,490,000	CY	$ 10	$ 14,900,000
2c	Transport and Place to Block Channel at Jetty Road	10,000	CY	$ 10	$ 100,000
2d	Transport and Place in Elkhorn Slough Channel	500,000	CY	$ 8	$ 4,000,000
3	**Dredge Ocean Inlet**	**1**	**LS**		**$ 6,000,000**
3a	Dredge Inlet	300,000	CY	$ 10	$ 3,000,000
3b	Form Ebb Shoal	300,000	CY	$ 10	$ 3,000,000
4	**Jetties**	**1**	**LS**		**$ 8,200,000**
4a	Bedding	25,750	TON	$ 50	$ 1,287,500
4b	Core - Quarry Run	13,600	TON	$ 50	$ 680,000
4c	Armor Rock	61,600	TON	$ 100	$ 6,160,000
5	**Tidal Dam at Highway 1 Bridge**	**1**	**LS**		**$ 3,800,000**
5a	Extend Existing Abutment	80	LF	$ 10,000	$ 800,000
5b	Dredging	7,930	CY	$ 20	$ 158,600
5c	Bedding - Quarry Run	17,847	TON	$ 50	$ 892,350
5d	Core - Quarry Run	19,404	TON	$ 50	$ 970,200
5e	Quarry Stone	9,278	TON	$ 100	$ 927,800

Item	Description	Quantity	Unit	Unit Price	Estimated Cost
6	**New Highway 1 Bridge and Approaches**	**1**	**LS**		**$ 8,700,000**
6a	Deck and Pilings	25,000	SF	$ 250	$ 6,250,000
6b	Concrete Abutment	2	EA	$ 150,000	$ 300,000
6c	Approaches	2	EA	$ 300,000	$ 600,000
6d	Transition	2	EA	$ 150,000	$ 300,000
6e	Armoring	1,000	LF	$ 1,200	$ 1,200,000
	SUBTOTAL				**$ 69,600,000**
	CONTINGENCY	**35%**			**$ 24,400,000**
	TOTAL				**$ 94,000,000**

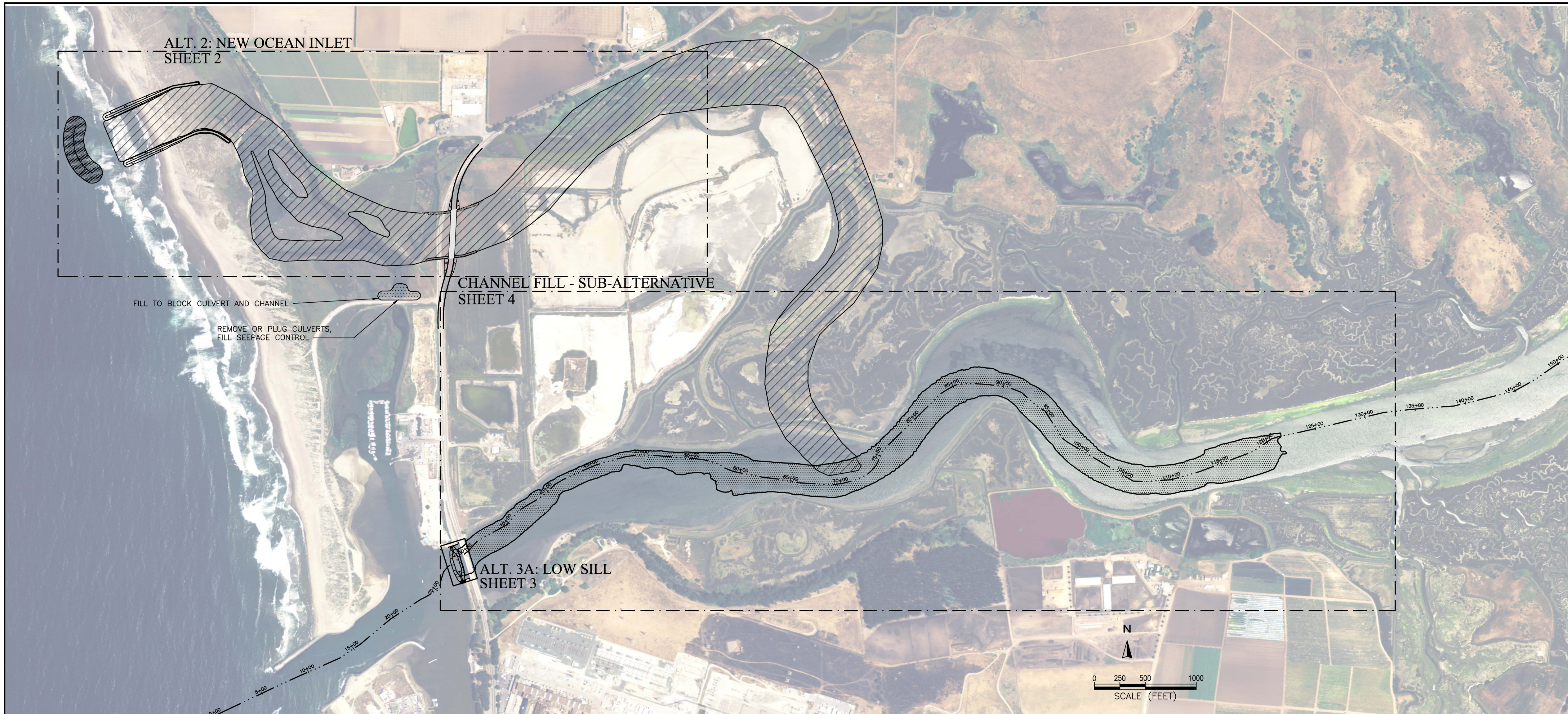
Table 7-6. Detailed Cost Estimate for Alternative 3a

Item	Description	Quantity	Unit	Unit Price	Estimated Cost
1	**Mobilization**	**1**	**LS**		**$ 1,500,000**
1a	Mobilization	1	LS	$ 1,500,000	$ 1,500,000
2	**Fill Placement in Elkhorn Slough Channel**	**1**	**LS**		**$ 15,000,000**
2a	Placement of Material from New Channel	0	CY	$ 0	$ -
2b	Placement of Dredged Material from New Inlet	0	CY	$ 30	$ -
2c	Dredge and Place Material from Submarine Canyon	500,000	CY	$ 30	$ 15,000,000
3	**Low Sill at Highway 1 Bridge**	**1**	**LS**		**$ 3,500,000**
3a	Extend Existing Abutment	80	LF	$ 10,000	$ 800,000
3b	Dredging	7,930	CY	$ 20	$ 158,600
3c	Bedding - Quarry Run	17,847	TON	$ 50	$ 892,350
3d	Core - Quarry Run	13,896	TON	$ 50	$ 694,800
3e	Quarry Stone	8,663	TON	$ 100	$ 866,300
	SUBTOTAL				**$ 20,000,000**
	CONTINGENCY	**35%**			**$ 7,000,000**
	TOTAL				**$ 27,000,000**

Table 7-7. Approximate Costs of Existing and Planned Large Scale Tidal Wetlands Restoration Projects in San Francisco Bay

Tidal Wetlands Restoration Projects	Acres	Approx Costs
Napa – Sonoma Marsh	3,000	$5,000,000
Hamilton / Bel Marin Keys	2,400	$175,000,000
Eden Landing	722	$5,000,000
Napa Plant Site	1,400	$7,000,000
Bair Island	1.400	$11,000,000
Bahia	418	$4,200,000
South Bay Salt Ponds	13,000	$980,000,000
Sears Point	970	$21,000,000
Dutch Slough	1,166	$35,000,000
Cullinan Ranch	1,564	$22,000,000

7.5 FIGURES



KEY MAP & SITE PLAN

LEGEND

- EXISTING GRADE (PWA TOPOGRAPHIC SURVEY)
- DESIGN GRADE
- (E) THALWEG
- RIP-RAP
- CORE
- BEDDING
- EXISTING GROUND
- EXCAVATION (PLAN & SECTION)
- EARTHWORK FILL (PLAN & SECTION)
- TOP OF SLOPE
- TOE OF SLOPE

ABBREVIATIONS

(E)	EXISTING
(N)	NEW
EL.	ELEVATION
TYP.	TYPICAL
MHHW	MEAN HIGHER HIGH WATER
MLLW	MEAN LOWER LOW WATER
NAVD	NORTH AMERICAN VERTICAL DATUM OF 1988
HWY-1	HIGHWAY 1

GENERAL NOTES:

1. TOPOGRAPHIC MAPPING GENERATED FROM LIDAR DATA COLLECTED BY THE NATIONAL GEODETIC SURVEY, FLOWN AT LOW WATER ON APRIL 13, 2004.
2. BATHYMETRIC MAPPING GENERATED FROM SONAR SOUNDINGS COLLECTED BY THE CSU SEA FLOOR MAPPING LAB IN 2003.
3. ELEVATIONS ARE REFERENCED TO NORTH AMERICAN VERTICAL DATUM OF 1988 (NAVD 88). HORIZONTAL CONTROL IS CALIFORNIA STATE PLANE COORDINATE SYSTEM, ZONE 4, IN FEET (NAD 83). ALL ELEVATIONS AND HORIZONTAL COORDINATES ARE IN FEET.

VERIFY SCALE
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0" ——— 1"
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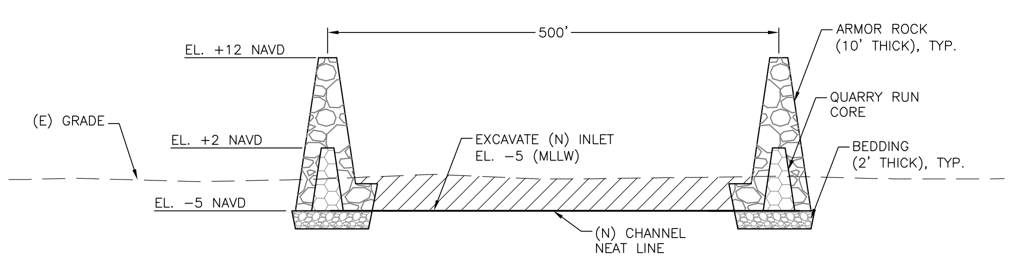
SHEET TITLE
KEY MAP

ELKHORN SLOUGH CONCEPTUAL DESIGN
ELKHORN SLOUGH TIDAL WETLAND PROJECT
BUILDING OR PROJECT

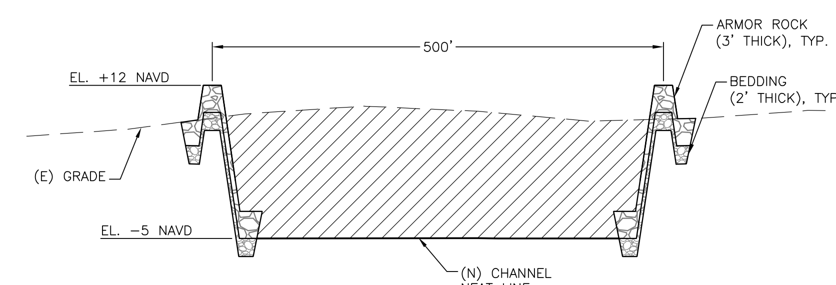
PREPARED FOR:
ELKHORN SLOUGH FOUNDATION

APPROVED	
DESIGNED	L. WHITE
DRAWN	L. WHITE
INCHARGE	B. BATTALIO C41785
LOCATION	
SCALE	AS SHOWN
FILE NO.	1869.00
DATE	MAR 26, 2008
SHEET	7-1

1 ALTERNATIVE 2 - NEW TIDAL INLET
DETAIL PLAN
SCALE: 1"=200'



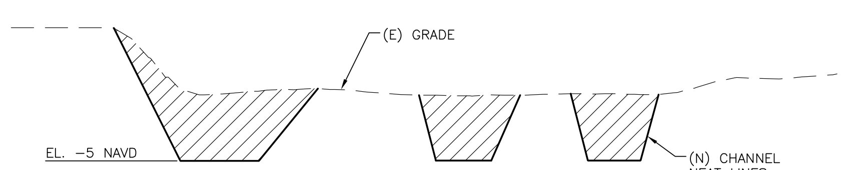
A INLET CHANNEL AND JETTIES
TYPICAL SECTION
SCALE: HORIZ: 1"=100' VERT: 1"=10'



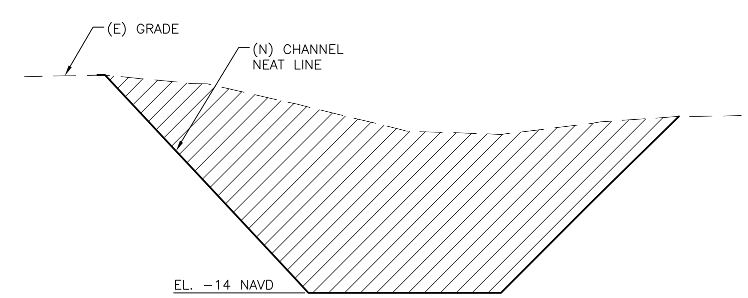
B INLET CHANNEL AT THROAT
TYPICAL SECTION
SCALE: HORIZ: 1"=100' VERT: 1"=10'

NOTES:

1. ALT. 2 REQUIRES BARRIER AT SILL LOCATION. (SEE SHEET 2).



C FLOOD SHOAL AND CHANNELS
TYPICAL SECTION
SCALE: HORIZ: 1"=100' VERT: 1"=10'



D NEW CHANNEL
TYPICAL SECTION
SCALE: HORIZ: 1"=100' VERT: 1"=10'

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SHEET TITLE
ALT.2 : NEW OCEAN INLET - PLAN & SECTIONS

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SHEET	7-2

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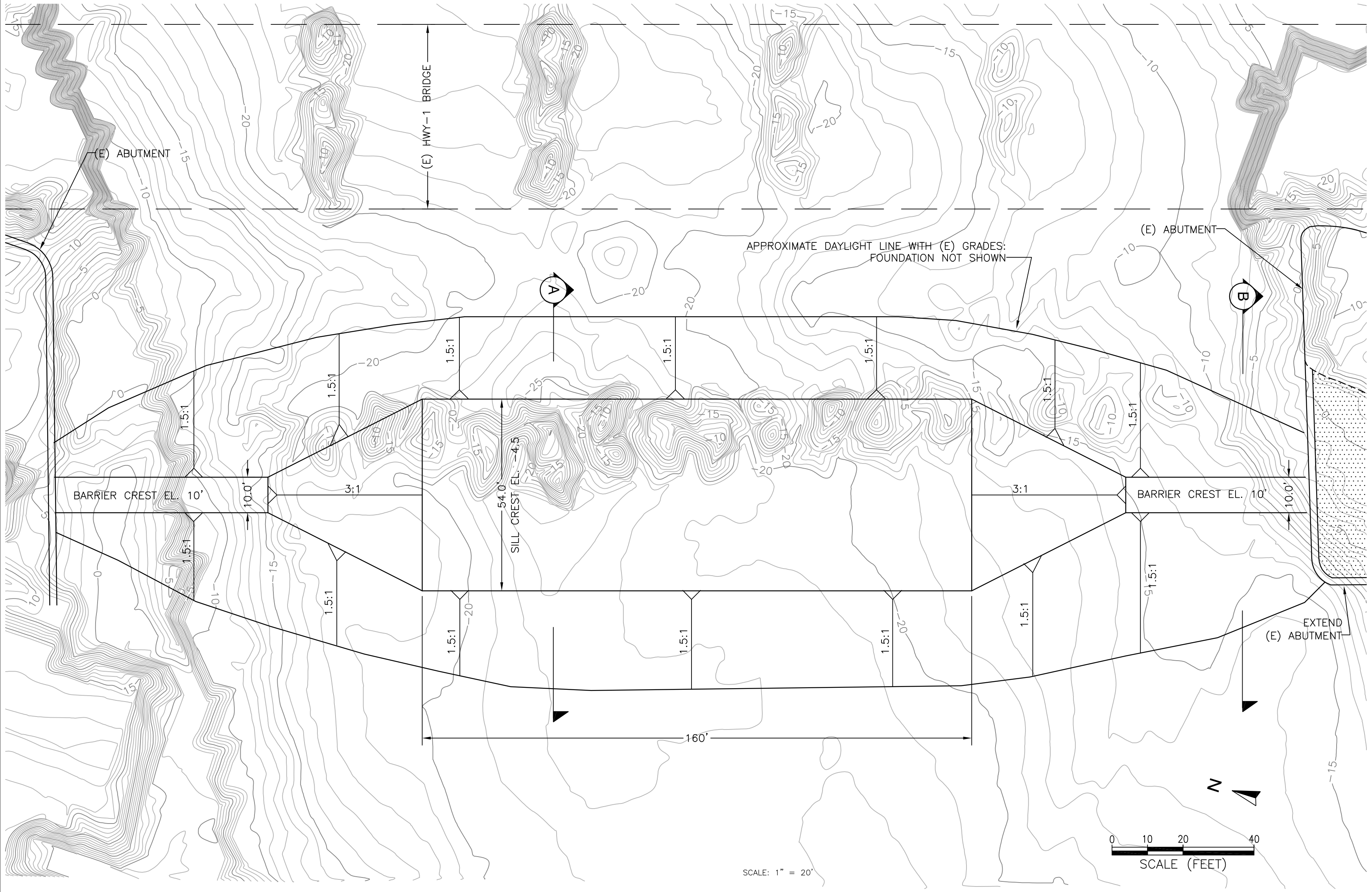
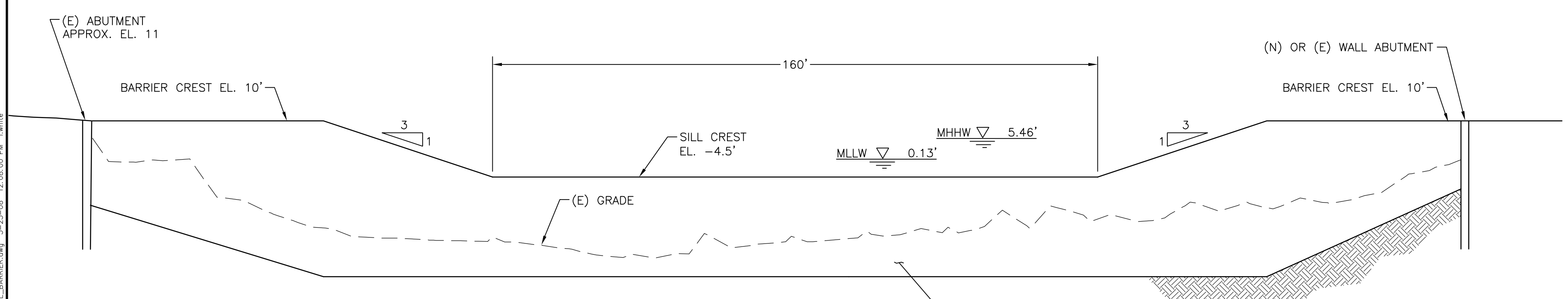
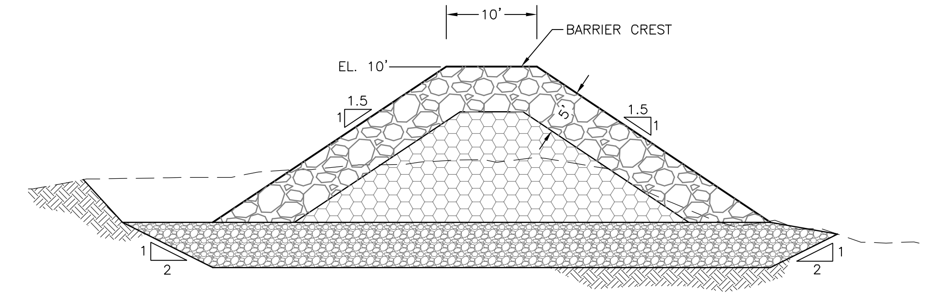


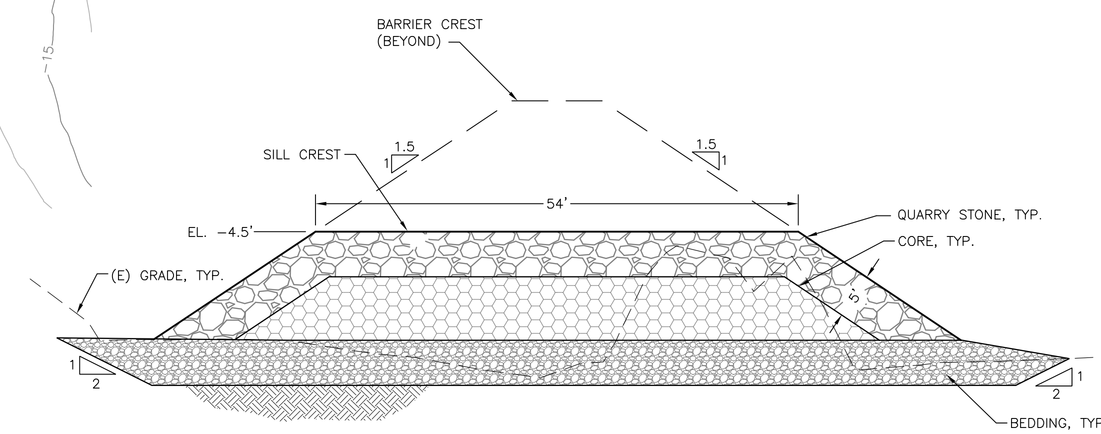
LOW SILL AT HWY-1 BRIDGE
DETAIL PLAN



LOW SILL AT HWY-1 BRIDGE
ELEVATION SCALE: 1" = 20'



B - BARRIER AT HWY-1 BRIDGE
SECTION SCALE: 1" = 10'



A - LOW SILL AT HWY-1 BRIDGE
SECTION SCALE: 1" = 10'

NOTES:

1. DEBRIS FROM OLD BRIDGE SHALL BE REMOVED BY CONTRACTOR PRIOR TO ROCK PLACEMENT.
2. HYDRAULIC BYPASS FACILITIES NOT SHOWN.

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SHEET TITLE
ALT 3A LOW SILL - PLAN AND SECTIONS

ELKHORN SLOUGH CONCEPTUAL DESIGN
ELKHORN SLOUGH TIDAL WETLAND PROJECT
BUILDING OR PROJECT

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DATE	MAR 26, 2008
SHEET	7-3

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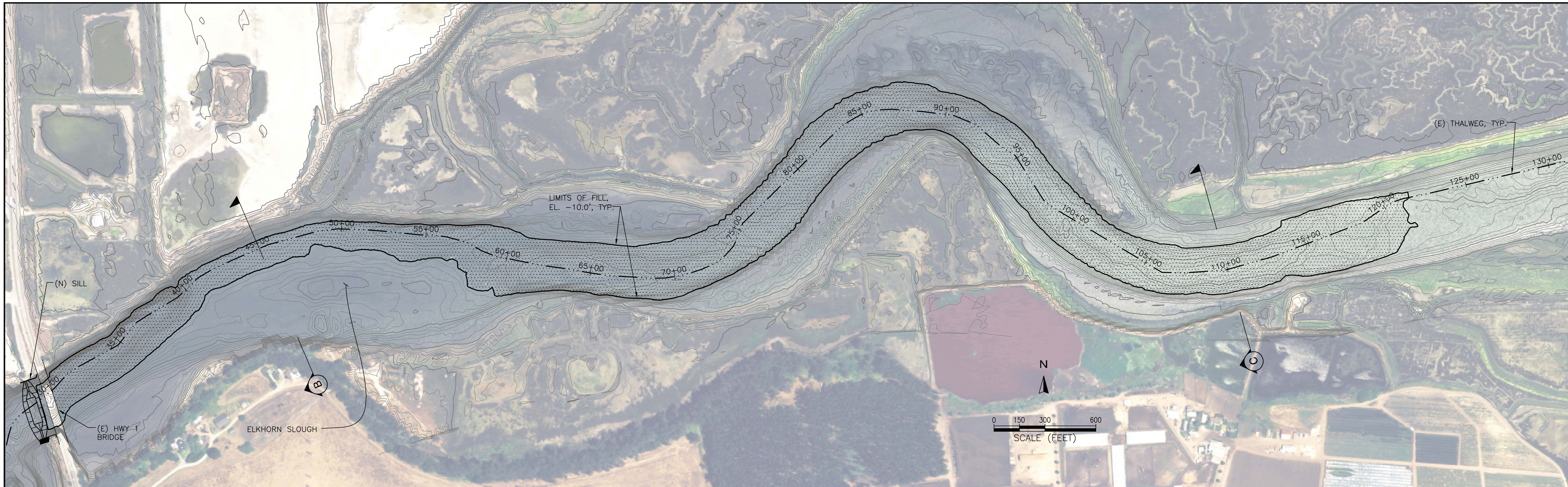
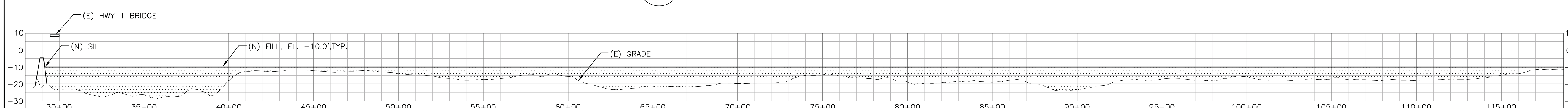
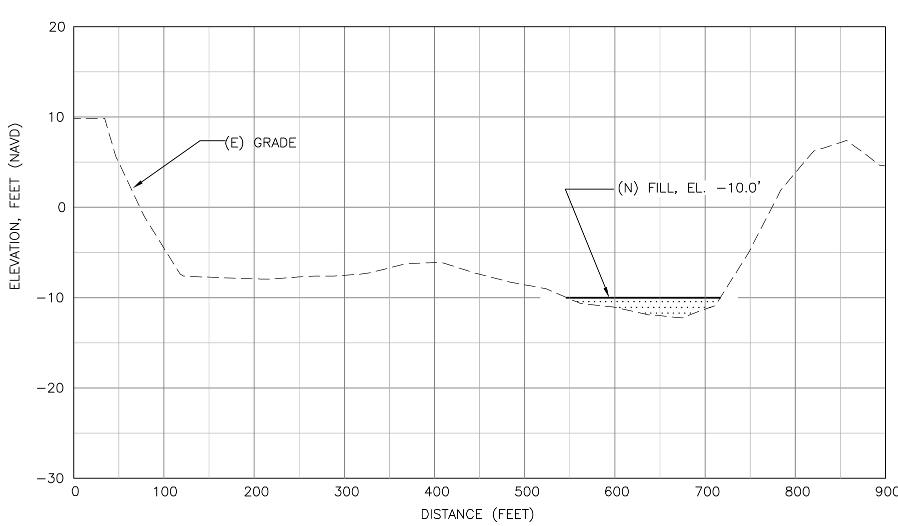


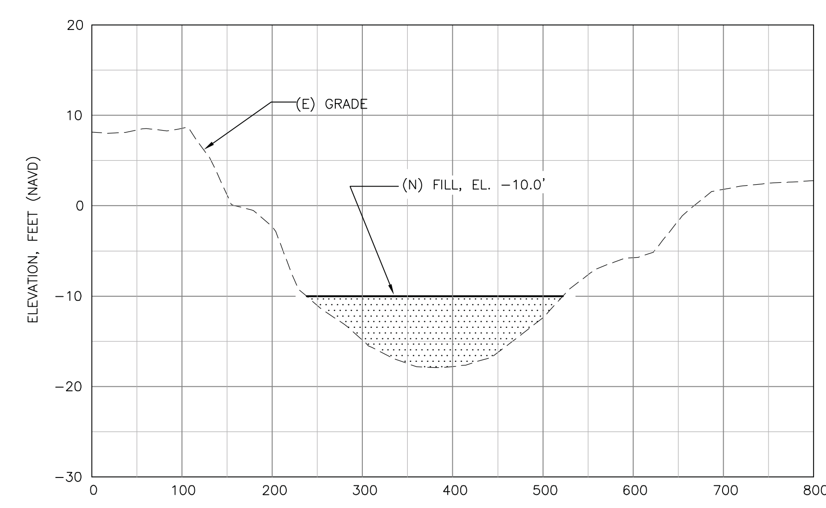
1 CHANNEL FILL SUB-ALTERNATIVE
PLAN



A PROFILE
ALONG THALWEG
SCALE HORIZ: 1" = 300' VERT: 1" = 30'



B CHANNEL SECTION
STA. 45+00
SCALE HORIZ: 1" = 100' VERT: 1" = 10'



C CHANNEL SECTION
STA. 110+00
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SHEET TITLE
CHANNEL FILL - PLAN, PROFILE, SECTIONS

ELKHORN SLOUGH CONCEPTUAL DESIGN
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8. SUMMARY / OVERVIEW

As described in the Request for Proposals for this project:

> *"The Elkhorn Slough estuary, containing California's second largest tract of salt marsh, is currently facing unprecedented rates of estuarine habitat loss and degradation. Over the past 150 years, human actions have altered the tidal, freshwater, and sediment processes which are essential to support and sustain Elkhorn Slough's estuarine habitats. This has led to substantial changes in the extent and distribution of tidal marsh, mudflat, creek, and channel habitats."*

8.1.1 Historic Changes in Elkhorn Slough

Over the past 4000-6000 years Elkhorn Slough has evolved as part of a network of river and tidally-influenced slough channels that drained regional watersheds and circulated tidal waters from Monterey Bay. Sediments were conveyed from the watersheds to fill coastal valleys. Over time sand built up along the shore creating the beach and dune barrier which connected the Salinas River, Tembladero Slough, Moro Cojo and Elkhorn Slough to the Bay through a common tidal inlet north of present day Moss Landing. The supply of sediment conveyed through this network was sufficient to fill Elkhorn Slough and create an expanse of tidal marshplains and a network of tidal channels. Periodic high flows flushed excess sediment through the system to the continental shelf and deep ocean.

Over the past century, a range of human activities, including the relocation, deepening and maintenance dredging of the Moss Landing Harbor (1940's), redirection of sediment from adjacent watersheds, most notably the Salinas River (1909-1910) and the re-opening of subsided, diked wetlands (Parsons and South Slough in the 1980's) has converted the hydraulic and sediment regime in Elkhorn Slough from a depositional to an erosional system. The main slough channel and fringing wetlands have been eroding on a progressive, large-scale basis over the past 60 years. The deeper, maintained harbor/slough inlet has expanded the tidal range and hydraulic efficiency in the Slough, with a net ebb tide (outflowing) dominant flow regime. In response, sediments are scouring from Elkhorn Slough and conveyed down the estuary to the Ocean, resulting in enlargement of main channel and expansion of creeks in to the marshplain. Other related processes, including higher water levels, result in marsh "drowning", killing marsh vegetation and exacerbating the rates of vegetated marshplain loss. Sediments transported out of the Slough are lost from the system, through the direct connection to nearby Monterey Submarine Canyon. Since the primary sediment supplies to Elkhorn Slough have been cutoff, insufficient sediment reaches the Slough and wetlands to sustain marshplain areas against rising sea level, and to balance the sediment exported from the estuary by increased tidal currents.

8.1.2 Modeling of Restoration Alternatives

The purpose of this investigation was to predict the evolution of the Slough over the next 50 years if no actions are taken to halt the current erosional process, and to develop and estimate the hydrodynamic and ecosystem response to several proposed restoration alternatives designed to reduce tidal habitat loss and degradation.

The development of a hydrodynamic computer simulation model of the Slough to provide a tool to predict the response of the system to possible restoration alternatives was the central focus of the project. Once developed and calibrated, the model provides predictions of the change in tidal flow regime in response to possible engineered changes to the slough system. These changes in flow regime, in conjunction with an assessment of potential cause and effect relationships between the flow regime and channel morphology (erosion and deposition) allow an assessment of the likely effectiveness of various options in halting the erosion and restoring the slough to a more depositional environment. In addition to these site specific studies, an examination of changes occurring in similarly impacted estuaries elsewhere provides insights to the Elkhorn setting.

The hydrodynamic model characterizes the tidal flows in present day Elkhorn Slough and, by modifying the expected future bathymetry, a means of assessing tidal flows in the future (Year 10 and Year 50). While predicting the future bathymetry is undertaken recognizing a high level of uncertainty the information developed from the modeling exercise provides an appropriate scoping-level assessment of the likely future of Elkhorn Slough and the potential hydraulic and geomorphic impacts of restoration alternatives.

Overall, the hydrodynamic modeling and ancillary studies on geomorphic and habitat change supports the conceptual models and observations of Elkhorn scientists over the past 20 years that describe the estuary to be on a trajectory of sustained sediment export, with ongoing scour of the main channel and conversion of the marshplain to mudflat. Without intervention, we expect the rate of main channel scour to continue (though at a progressively slower rate), while the remaining marshes will largely convert to mudflats, and low mudflat will convert to subtidal habitat. While the exact rate and final form of these processes are difficult to predict in detail, the trend and scale of both past changes and ongoing processes are clear, and provide no indication that the system is near equilibrium and that erosion will stop without significant intervention.

8.1.3 Restoration Considerations

Unfortunately, there are no small-scale restoration approaches that have been identified that would halt this trajectory of habitat conversion. The human-induced impacts to Elkhorn Slough during the 20th century have been considerable, and correspondingly, reversing these impacts will require restoration responses commensurate in scale. Engineering approaches such as relocating and reconstructing a shallow inlet to the north of the current harbor entrance (Alternative 2), or constructing a shallow tidal barrier at the Highway 1 Bridge (Alternative 3a/b) would reduce the rate of sediment loss from the estuary. Reducing the tidal prism contributed from the subsided Parsons Slough Complex, through either placement of fill material and / or limitation of tidal exchange via construction of water control structures, will reduce a portion of the increased tidal flushing occurring in the lower estuary. None of these alternatives would replace the loss of sediment supply to the system, created by the re-routing of the local rivers directly to the Bay. Sediment supply would be needed rebuild intertidal areas, resupply the slough channels, and maintain intertidal areas against rising sea level. An artificial sediment supply would be required to restore an expansive marshplain, replace the sediment volumes lost over the past 60 years, with periodic resupply to offset rising sea levels.

Initially, a decision is required to determine whether to accept the predicted future condition of the Slough with the No Action alternative or to pursue action alternatives. The next steps in the current planning study by TWP will include an evaluation of the possible impacts of the various alternatives described in this report. If Slough managers and decision-makers decide to pursue action plans to reduce the ongoing erosion processes, we would recommend a phased program, using adaptive management and monitoring to assess the effectiveness of actions taken, adjust the facilities to maximize their effectiveness, and implement increasingly larger and more costly options only as necessary. Uncertainties in the environmental outcomes of the restoration alternatives exist, not only in terms of habitat response but also over issues such as water quality. While future more detailed studies can reduce some of the uncertainties, we recommend a phased approach to restoration with each subsequent actions taking place under adaptive management approach. The management alternatives described in this report (Restriction of tidal exchange from Parsons Slough, construction of a low sill at Highway 1 bridge, construction of a high sill at this location, and construction of a new ocean inlet), provide a sequence of projects with increasing cost and impacts that could also be implemented sequentially, based on a monitoring program and various pilot studies to demonstrate effectiveness and need for additional action. Each step in this sequence would be beneficial individually, and would not represent unnecessary or significant duplicative costs and effort if implemented in a phased manner.

While the scale of intervention, estimated costs, and potential impacts of the Elkhorn restoration alternatives described in this report are large, they are comparable in level of effort and cost to other recent and ongoing restoration projects on significant wetlands in California:

- The recently completed Bolsa Chica wetland restoration project restored an 880 acre site in Southern California, with a cost of $147 million dollars (the project was similar in some elements to Alternative 2 for Elkhorn, and included a new ocean entrance with jetties, construction of a new bridge on Highway 1, and excavation/placement of 2 million cubic yards of sediment).
- The 300 acre Sonoma Baylands site (a subsided wetland similar to the Parsons Slough area) was restored using the placement of dredge spoils at a cost of about $20 million.
- The South Bay Salt Ponds in south San Francisco Bay (restoration of approximately 13,000 acres, with a purchase cost of $96 million and estimated implementation costs of about $980 million),
- The Napa Salt Ponds in North San Francisco Bay (3,000 acres; restoration cost of about $5 million),

- The Ballona Wetlands Project in Santa Monica Bay (restoration of 560 acres; purchase price of $60 million dollars, possible restoration costs of $15+million).

A key element in the above restoration projects has been the development of support and funding sources at the regional, state and federal government scale. Large projects require resources and support well beyond the capacity of most local entities. In many cases, successful restoration projects involve funding from both restoration agencies as well as from entities requiring mitigation credit for ongoing or past projects.

The information in this report provides local scientists and decision-makers with a basis for assessing the likely future evolution of the morphology and habitat functions provided by the slough in response to ongoing changes, and options for a range of actions to reduce or halt the ongoing erosional processes. It provides methodology for comparing the relative magnitude of change, and the scales of cost and intervention of the alternatives. Based on the direction selected by the Slough managers, future studies can refine both the assessment of impacts, system benefits/changes, and the design of the various alternatives to optimize design and costs while reducing adverse impacts.

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APPENDIX A.
MODEL CALIBRATION REPORT

Elkhorn Slough Tidal Wetland Project
Hydrodynamic Modeling Calibration Report

Final Report

Prepared for

The Elkhorn Slough Foundation

Prepared by

Philip Williams & Associates, Ltd.

May 14, 2007

PWA REF. 1869

Services provided pursuant to this Agreement are intended solely for the use and benefit of the Elkhorn Slough Foundation. No other person or entity shall be entitled to rely on the services, opinions, recommendations, plans or specifications provided pursuant to this agreement without the express written consent of Philip Williams & Associates, Ltd., 550 Kearny Street, 9th Floor, San Francisco, CA 94108.

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1. INTRODUCTION

This document presents the calibration and validation for the DELFT3D hydrodynamic model developed for the Elkhorn Slough Tidal Wetland Project (TWP). DELFT3D was selected by the Modeling Advisory Team and PWA as the primary hydrodynamic modeling tool for evaluation of the TWP restoration alternatives. This report presents the model construction (e.g., grid development and input and boundary condition data), a discussion of the calibration and validation approach, and the results of the model calibration and validation efforts. The calibrated model will be used during later stages of the TWP for restoration scenario modeling.

The goals of the modeling effort are to: (i) characterize the hydrodynamic response of the tidally-affected portions of the Elkhorn Slough system to various restoration actions; and (ii) inform the projection of future slough evolution and morphology. A concurrent modeling study will be conducted by Stanford University and will utilize the TRIM3D model described by Monismith et al. (2005).

The report is divided into four major sections describing the important aspects of the hydrodynamic model calibration and validation:

- **Section 2. Model Overview**. This section provides an introduction to the modeling effort for the Elkhorn Slough Tidal Wetland Project and a summary of the model set-up, including assumptions, grid development, and input and boundary condition data.
- **Section 3. Calibration.** This section presents the calibration approach and results for the April 2003 calibration period. All simulation results presented were made using the final calibrated model.
- **Section 4. Validation.** This section presents the validation approach and results for the December 2005 validation period. All simulation results presented were made using the final calibrated model.
- **Section 5. Summary of Model Calibration and Validation.** This section provides a brief summary of the model calibration and validation.

2. MODEL OVERVIEW

Elkhorn Slough is a tidal embayment approximately 10-km long located in Central Monterey Bay. The Slough is comprised primarily of a main subtidal channel flanked by intertidal wetland areas. Planned and unintentional levee breaching has restored tidal exchange to formerly diked areas over the past few decades. The Slough is connected to the ocean via Moss Landing Harbor, which was completed in 1947 and replaced the natural inlet. Water depths in the slough channel diminish from approximately 8 to 9 m near Moss Landing to less than 0.5 m at the head of the Slough near Elkhorn Road (Broenkow and Breaker 2005). Tides in the Slough are mixed semi-diurnal and closely coupled to those in Monterey Bay with current direction and velocities exhibiting strong ebb dominance (Monismith et al. 2005).

The present modeling effort provides a calibrated and validated hydrodynamic model that will serve as a tool for a variety of future studies. Of primary initial importance is the evaluation of restoration alternatives and quantification of various hydraulic characteristics of the proposed management actions. Conceptual models developed by the Science Panel will help refine both the computer-based hydrodynamic modeling efforts and the geomorphic assessment. Specifically, the model will quantify changes to some of the primary physically-based cause-and-effect pathways, which include:

- **Channel Scour.** Modifications to the tidal inlet that decrease bed shear stress along the main channel and result in slower rates of channel deepening and widening.
- **Loss of Marsh Edge (Bank Erosion).** Modifications to the tidal inlet that decrease current velocities and bed shear stress and result in slower rates of marsh loss (edges).
- **Loss of Marsh Interior (Marsh Dieback).** Modifications to the tidal inlet and/or placement of sediment on the marsh plain that decrease tidal inundation and result in slower rates of marsh loss (interior).

In addition to evaluating how these conceptual model linkages respond to proposed restoration actions, the hydrodynamic modeling will also inform future design refinements of the restoration alternatives. These may include the optimal geometry of a barrier under Highway 1, the appropriate size of a natural tidal inlet mouth, or channel dimensions. Results from the hydrodynamic model will also provide input to the long-term stability assessment of new ocean inlets by quantifying the effective tidal prism under restored conditions.

2.1 MODEL DESCRIPTION

DELFT3D was selected as the primary hydrodynamic modeling tool for the Elkhorn Slough TWP restoration evaluation. DELFT3D was developed by WL | Delft Hydraulics in coordination with

Delft University and consists of an integrated set of modules that simulate hydrodynamic flow. DELFT3D models unsteady tidal flows, flow through hydraulic structures, and drying and flooding of intertidal areas. The model employs a curvilinear flexible-mesh grid system, which provides the ability to fit the computation grid to the variable bathymetry of Elkhorn Slough.

The Navier-Stokes equations for an incompressible fluid, under the shallow water and Boussinesq assumptions, are solved on a staggered, finite-difference grid (WL | Delft Hydraulics 2003). The model may be applied in either two-dimensional (2D) depth-averaged mode or three-dimensional (3D) mode. For the purposes of this study, the 2D formulation is utilized. A complete description of the model assumptions, governing equations and approximations, including the space discretization[1], time integration and numerical solution methods is presented in WL | Delft Hydraulics (2003).

2.2 MODEL DOMAIN

2.2.1 Model Extent

The extent of the baseline Elkhorn Slough Model is shown in Figure 1. The domain extends from the coastal ocean to the head of the Slough at Elkhorn Road, and includes areas that contribute significant portions of tidal prism to the inlet-slough-wetland system. Additionally, regions connected to the slough via hydraulic structures were included in the grid if their typical tidal range exceeded 5 cm (K. Wasson, personal communication). The grid also covers the region to the north of Elkhorn Slough along the coastline in anticipation of modeling a new ocean inlet at the historic mouth of old Salinas River.

Seaward of the Slough, the model domain includes Moss Landing Harbor, adjacent sloughs and wetlands, and a portion of the open coastal zone approximately 4 km alongshore and 1.5 km cross-shore. Within the harbor, the model extends from Jetty Road to the north, to Moss Landing Road in the southeast, and to Sandholt Road in the southwest. Areas to the north (Lower Bennett Slough and Bennett Slough) and south (Old Salinas River Channel Marsh, Moro Cojo, and Crazy Cow Marsh) are included in the active grid. Lower Bennett Slough is connected to the north harbor through culverts. Moro Cojo connects to the eastern side of the south harbor through one-way flap gates which only allow flow from Moro Cojo to the harbor.

Within the Slough, the model domain includes the main Elkhorn Slough channel and the adjacent marsh plains. The edge of the model boundary is defined by either the uplands break or levees. Parsons Slough and the adjacent South Marsh are included in the model domain. Whistlestop Lagoon is included in the grid and connects to South Marsh through a bank of culverts. To the

[1] Discretization is defined as the process of replacing a continuous system of differential equations by a finite discrete approximation that can be solved numerically.

east of the railroad track levee, Hidden Pond, North Marsh and North Azevedo Pond are included in the model domain and connected to the slough through culverts.

Several regions that were historically connected to the Slough but currently are not tidally connected to the Slough were excluded from the domain. These excluded regions include: Barn Pond, Cattail Pond, the Rookery Ponds, and the Packard Ponds. In addition, regions that are only minimally connected (typical tide range less than 5 cm) are also excluded from the model domain. These excluded minimally-tidal regions include: Struve Pond, Estrada Marsh, South and Middle Azevedo Ponds, and Porter-Blohm Marsh. The West Salt Ponds are included in the model domain, but are disconnected from tidal action by levees.

2.2.2 Grid Sizing

DELFT3D employs a curvilinear orthogonal grid to represent the physical domain, which can be visualized as a rubber sheet of graph paper. Its curvilinear aspect allows the grid to be stretched and transformed so that it aligns with the sinuous topographic features of Elkhorn Slough. Orthogonality requirements dictate that the grid cannot be stretched too far from its original perpendicular intersections; therefore, although the grid follows the sinuous alignment of Elkhorn Slough, the grid cannot be stretched to also follow the complex alignments of the smaller marsh creeks. Instead, the grid resolution in the vicinity of the marsh channel networks is selected to capture the primary marsh channels. The orthogonality requirements constrain the ability to fit the grid to highly irregular topographic features. However, these features are not common when modeling large wetland areas.

The grid of the Elkhorn Slough Model was created using tools incorporated into the DELFT3D modeling environment. The underlying shape of the grid is defined by a series of user-specified complex curves defined by two or more points (spline curves). The tools then automate the creation of grid cells between the spline curves, allow for further grid refinement, and assist in maintaining grid orthogonalization. Figure 2 presents the model's grid resolution. Along Elkhorn Slough and the adjacent marshes the grid resolution is approximately 10 to 25 m with the grid resolution expanding to 250 m in Monterey Bay. The model domain currently contains 58,000 active grid cells. Typically, ten to fifteen cells span the channel width along the main stem of Elkhorn Slough, as shown in Figure 4 which provides a zoomed in view of the grid in the vicinity of Rubis Creek. This grid resolution captures the primary marsh creeks; however, the smaller marsh creeks are not well resolved.

2.2.3 Bathymetry

The most important component associated with developing a model that correctly represents a system's physical boundaries is the bathymetry. Multiple sources and forms of bathymetric and topographic data were integrated to represent the tidally-affected domain of Elkhorn Slough.

Figure 3 displays the compilation of the multiple data sources into a bathymetric surface for the Slough. The bathymetric data utilized in the model include:

- **Aerial photographs** - Aerial photographs enable delineation of distinct hydrologic units and of important boundaries such as the wet/dry boundary. The Seafloor Mapping Lab (SFML) at California State University at Monterey Bay (CSUMB) produced three composite aerial photographs for three different times on July 2, 2003. The times roughly corresponded to mean lower low water (MLLW), mean tide level (MTL), and mean lower high water (MLHW). A second composite aerial photograph was produced in 2005 by the U.S. Department of Agriculture's National Agricultural Imagery Program.
- **SFML 2003 sonar soundings** - This survey was conducted during high water and includes the main stem of the Slough, the reach of Parsons Slough from the mouth to the railroad bridge, and most of Moss Landing Harbor and the inlet. This data was collected at a resolution of l m in the horizontal.
- **National Geodetic Survey (NGS) 2004 LIDAR** – Airplane-based LIDAR provides measurements of the ground surface elevation. The NGS survey was flown at low water on April 13, 2004 so that much of the intertidal area was exposed and its elevation could be measured at 1-m horizontal resolution. In regions with marsh plants, the observed elevations are distorted by vegetation and do not precisely represent the elevation of the true marsh plain. Raw LIDAR data typically contains multiple returns, including the top of vegetation (the canopy), mid-level vegetation, and "bare earth" or ground elevation. Interpreting the LIDAR returns over vegetated areas typically requires some level of ground truthing in order to understand the returned LIDAR signal and remove vegetation bias. If vegetation is not adequately removed, the ground elevations will be overestimated in the LIDAR data covering densely vegetated regions. In this data set, no vegetation removal was performed and the data set represents a "first return," meaning the average return likely falls somewhere within the vegetation canopy (VanDyke, pers comm.). Preliminary validation of the LIDAR data was performed using an RTK-GPS and laser total station at 91 locations (Smith et al. 2004). This validation assessment showed that the LIDAR data was within ± 1 m, however, most locations had differences close to 0 m. The average positive bias due to vegetation was 5 cm, although the exact amount of the bias depends on vegetation type. A detailed validation and error analysis by ground-cover type has not yet been performed on this data set. Investigations are underway regarding post-processing algorithms to produce a bare earth elevation model, but this work is not yet ready for distribution (VanDyke, pers. comm.).
- **Monterey Bay bathymetry** - Bathymetry data at 30-m resolution for Monterey Bay adjacent to Elkhorn Slough was downloaded from NOAA's Estuarine Bathymetry website (http://estuarinebathymetry.noaa.gov/).

All topographic and bathymetric data was converted to the same horizontal datum (UTM Zone 10N, WGS84) and vertical datum (NAVD88). The 2004 LIDAR dataset covering the Slough was merged with the 2003 SFML sonar sounding dataset by SMFL staff. The compiled data set was then imported into DELFT3D.

2.3 INITIAL AND BOUNDARY CONDITION DATA

2.3.1 Tidal Boundaries

The influence of tides is introduced to the model by imposing an open tidal boundary condition in the coastal region of the model domain. Verified measured tides (e.g., water surface elevations) reported by NOAA at Monterey Bay (Station ID 9413450) are applied along the western boundary in the coastal zone. NOAA's published tide corrections for Moss Landing support this transfer of the Monterey Bay observations to the model boundary 20 km away. The tide corrections for Moss Landing Harbor indicate lags of only 1 minute and tide ranges which differ by 3 cm or less. To remove the influence of ocean swell and instrument noise, NOAA's Monterey Bay observations were filtered with a fifth-order Butterworth filter with a cut-off frequency of 2 hours. Along the north and south boundaries of the coastal zone, the water surface gradient is set to zero, thereby allowing the water surface to freely slip up and down these boundaries as prescribed by the western boundary condition.

2.3.2 Power Plant Discharges

Cooling water discharge from the Moss Landing Power Plant was incorporated into the model as an intake in the south harbor and a discharge in the coastal zone. Although electric output at the power plant varies with energy demand, the cooling water discharge remains relatively constant (LSP Moss Landing LLC 2002-2006). Since discharges are relatively constant, the monthly mean discharge, as reported in the Quarterly Reports submitted to the California Regional Water Quality Control Board, were used for each simulation period (LSP Moss Landing LLC 2002-2006). Typical mean monthly discharge values are in the range of 15 to 40 m^3/s. A sensitivity analysis (Appendix A) was performed to assess the affect of the peak power plant discharge capacity on the Elkhorn Slough system. A comparison between model results with and without the peak power plant discharge indicates that the power plant discharge significantly alters flow in the south harbor, slightly alters flow through the harbor inlet to Monterey Bay, and negligibly alters flow in Elkhorn Slough landward of the Highway 1 Bridge.

2.3.3 Freshwater Inflows

The major components of freshwater inflow to Elkhorn Slough were eliminated when the Salinas River was diverted directly to Monterey Bay. However, local freshwater runoff occurs from the surrounding watershed during rainfall events. A sensitivity analysis was performed to assess the importance of freshwater inputs on water levels and current speeds within Elkhorn Slough (see Appendix A). The sensitivity analyses evaluated inflows typical of the calibration and validation periods and did not address peak values associated with large storm events and/or extreme runoff events associated with localized flooding. The freshwater inflows were small when compared with the tidal flow and they did not alter the flow characteristics that drive geomorphic change (e.g., current velocity in the slough channel and/or tidal inundation of the marsh plain). As a result of this assessment, no freshwater inputs were included in the calibration and validation runs. However, freshwater inflows can be included in future simulations for evaluating water quality and/or salinity.

2.3.4 Other Parameters

Bed roughness

A variable Chezy friction coefficient was applied in the calibrated model. This parameter was adjusted during model calibration in order to match tidal propagation speed and observed current velocities. For subtidal regions (bed elevations below 1.0 m NAVD88) a Chezy coefficient of 80 $m^{1/2}/s$ was applied. For intertidal and marshplain regions (bed elevations above 1.2 m NAVD88), a Chezy coefficient of 40 $m^{1/2}/s$ was applied. The Chezy coefficient was linearly interpolated for bed elevations between 1.0 and 1.2 m. This region represents the transition zone between unvegetated mudflats and vegetated marsh based on an examination of aerial photos and the LIDAR data set. Results from the sensitivity analysis indicate that application of this depth-dependent Chezy coefficient reduces peak current velocities (by approximately 50%) and increases peak bed shear stress (by about 40%) on the marsh plain, as expected. Predicted water levels on the marsh plain are not significantly affected, nor are the results from marsh creeks or the main slough channel.

The use of a depth-dependant Manning's n roughness was investigated as part of the model calibration effort and the early calibration results were discussed with the Modeling Advisory Team. Although the use of a depth-dependent Manning's n roughness has been successfully applied in previous TRIM3D Elkhorn Slough modeling studies (Monismith et al. 2005), the DELFT3D model achieved a greater level of calibration utilizing the Chezy formulation.

Horizontal eddy viscosity

A constant horizontal eddy viscosity of 1 m^2/s was applied across the model domain. Previous estuarine DELFT3D applications have found this to be an appropriate choice. In addition, water surface elevations and current velocities have proven relatively insensitive to this model parameter (PWA 2006).

Wetting and drying criteria

The model was configured such that once the water depth in a grid cell falls below 0.5 cm, the cell is considered to be dry and no longer part of the active flow region. When a dry cell's water depth subsequently exceeds 1 cm as a result of inflow from adjacent, active cells, it returns to an active, wetted state.

Specification of Hydraulic Structures

Several culverts and other hydraulic structures connect the fully tidal portions of Elkhorn Slough and the Parsons Slough / South Marsh complex to muted tidal areas. Information regarding the type, location and size of these structures was provided by Bryan Largay (pers. comm.) and incorporated into the numerical model. These structures were adjusted to approximately provide the expected amount of tidal muting, but the culverts were not thoroughly calibrated. Modification of these hydraulic structures would be required if accurate water level predictions were required in the muted tidal areas during future projects. Since inaccuracies in the amount of tidal muting do not affect the predicted tidal currents or water levels in the Elkhorn Slough channel or fringing marsh plain, the implementation of hydraulic structures is sufficient for the purposes of the present modeling effort.

2.3.5 Initial Conditions

Observations along the length of the Slough indicate that water levels move nearly in unison throughout the Slough and slack water occurs at the minimum and maximum water levels of each tide. Therefore, the simulation start time was chosen to correspond to slack tide so that initial water velocities were approximated as zero throughout the Slough. Initial water levels within the Slough were set to the corresponding open tidal boundary condition. The model was run for several days to remove initial transients from the model results and enable water levels and velocities to equilibrate to the prescribed boundary conditions. This period, referred to as the "spin up period," was not included in the analysis of model results.

2.4 MODEL EXECUTION

One challenge of the hydrodynamic modeling effort is balancing the grid resolution and time step with the simulation time to ensure that the project's critical questions can be answered in a timely manner. Preliminary model runs were conducted utilizing time steps of 60, 30, 15 and 7.5 seconds. The model results indicated that sufficient convergence was achieved with a time step of 30 seconds utilizing the grid described in Section 2.2.2 and presented in Figure 2. With this time step, simulations execute on a 3.6 Ghz PC workstation at speeds approximately twenty times faster than real time. Using this hardware configuration, spin up and simulation of one tidal month can be completed in approximately 1.5 days.

The results from the 2D depth-averaged model are adequate to simulate the primary flow characteristics which determine water levels and bed shear stress distributions. These two parameters are fundamental to assessing marsh restoration as outlined in the scope of work. A 3D model may provide additional insight into constituent transport, particularly as it relates to water quality. If future alternative evaluation requires a more detailed water-quality assessment, the depth-averaged model can be expanded to three dimensions for constituent transport modeling.

2.5 MODEL UNCERTAINTY

DELFT3D is a widely used modeling tool for estuarine simulations and has been validated in numerous studies (WL | Delft Hydraulics 2003). However, all numerical models rely on approximations which introduce sources of uncertainty in the model results. Uncertainties may be present both spatially and temporally, and may result from a variety of factors, including physical characteristics of the model domain, specification of boundary conditions, or limitations in the model's numerical formulation. For the specific application of a hydrodynamic model of Elkhorn Slough, it is important to assess the modeling uncertainties and assumptions made in applying the model to understand the extent to which these uncertainties could affect model predictions.

The largest uncertainties affecting the hydrodynamic performance of the Elkhorn Slough Model are the accuracy and resolution of available bathymetry and the grid resolution used to resolve this bathymetry. The model has made use of the most recent and best available bathymetric data (Section 2.2.3) which minimizes uncertainty introduced by bathymetry. However, when the bathymetric data is sampled onto the model grids, additional filtering of the bathymetric data occurs which limits the capacity of the model to resolve small-scale bathymetric features. To reduce this effect, the grid resolution was selected to be as fine as possible (~10 m) to resolve the primary features of interest, such as the main Elkhorn Slough channel and the larger marsh channels. The grid resolution would need to be an order-of-magnitude finer to resolve the majority of the smaller marsh creeks in the marsh-channel drainage network. However, a grid resolution of this scale would result in a model that was computationally inefficient. Therefore, the smaller marsh creeks are not explicitly resolved because (i) they cannot be fully resolved with the nominal 10-m grid; (ii) the available data to characterize the smaller marsh creeks is sparse; and (iii) initial results show that the marsh plain is wetting and drying (i.e., it's contributing to the overall tidal prism).

An additional data gap relates to the validation of marsh plain elevations in areas dominated by vegetation. As discussed in Section 2.2.3, a limited accuracy assessment of the LIDAR data was performed, but this assessment has not yet been used to post-process the LIDAR data to remove vegetation bias (VanDyke, pers. comm.) Post-processing of the LIDAR data would be required to remove vegetation bias by ground-cover type (i.e., dominant vegetation type). Investigations are underway regarding post-processing algorithms to produce a bare earth elevation model, but this work is not yet ready for distribution (VanDyke, pers. comm.).

As described above, the grid resolution was selected to be as fine as possible, subject to the computational resources currently available. However, the use of 10-m grid resolution in the Slough still limits the capacity of the model to accurately resolve the bathymetry in the subtidal portions of the marsh creeks. Previous applications of DELFT3D in estuarine environments have indicated that the solution scheme used in the matrix solver may result in substantial energy dissipation in channels which are not aligned in the primary direction of the grid (i.e. "stair-step" channels) and are only one cell wide (PWA 2006). In Elkhorn Slough, the relatively short length of the marsh channels mitigates the impact of this dissipation on model results. See the calibration results presented in Section 3.

The model solves the 2D depth-averaged approximation of the hydrodynamic flow equations. The use of 2D simulations significantly reduces the computational time required for the model simulations, but prevents vertical variations of the true flow field from being captured. However, velocities of the secondary flows measured by Stanford University within the main slough channel are much smaller than velocities of the primary flows directed along the Slough (Monismith et al. 2005). 2D model simulations also assume a logarithmic velocity profile which affects the model's calculation of bottom shear stress. In the actual flow field, the vertical velocity structure may not be logarithmic as the structure would be influenced by stratification and interactions with the bed. However, the bottom bed shear stress calculated from a 2D model formulation allows for a reasonable comparison of the change in bed shear stress between alternatives when evaluated relative to baseline conditions.

Additional model uncertainties are introduced through the specification of boundary conditions and model parameterizations, such as bed roughness. Any field data used either to force the model or calibrate and validate the model has some associated uncertainty due to instrument calibration and errors, instrument location, field corrections and data noise. The calibration and validation process will provide feedback regarding which parameters have the largest influence on model results and therefore assist in reducing or clarifying the level of uncertainty.

3. CALIBRATION

Model calibration is an essential component of setting up a numerical model. Calibration is performed by forcing the model with prescribed boundary conditions (e.g., tides at the open boundary) and other input data (e.g., initial conditions), and comparing the predicted model results with field observations made during the simulation period. The Elkhorn Slough Model was calibrated using data collected by Stanford University over a three week period in April 2003. Differences between observed and predicted values provide guidance on which aspects of the model need to be improved and which model parameters or boundary conditions need to be adjusted.

The following sections outline the calibration approach for the Elkhorn Slough Model and present the final calibration results. All of the simulation results presented were made using the final calibrated model.

3.1 CALIBRATION APPROACH

Calibrating a model involves adjusting model parameters or model formulation in order to match model predictions and field observations at known locations. Most current hydrodynamic models, including DELFT3D, produce physically reasonable results with little required calibration. However, the calibration process can verify that each of the specified model inputs and boundary conditions are working properly. Generally, calibration is an iterative process. The model is run for a known set of input conditions, and its output is compared to a known set of observations. The discrepancies between the model predictions and the observation data help determine which aspects of the model are not adequately capturing the physical processes. This may lead to adjusting some calibration parameters, such as bed roughness.

For control purposes, usually only one parameter is changed at a time before re-running the model. Over the course of a few adjustments and runs, the model’s response to changes in the control parameter becomes evident. These adjustments are made until the model’s response to the specified inputs replicates the field measurements as closely as possible. The process of adjusting and re-running requires both experience and intuition – it is rare that a large-scale model can accurately reproduce every feature under examination, and a model adjustment that is beneficial for one set of outputs may be detrimental for others. The goal of the calibration process is to identify the areas and processes of highest interest, and maximize the model’s predictive capability in those areas, while ensuring reasonable behavior in the rest of the model predictions.

Model calibration was conducted using data collected between April 7 and April 25, 2003. Instruments were deployed by Stanford University at five locations along the main slough channel shown, as shown in Figure 1 (Monismith et al. 2005). These data provide the most extensive observational coverage of the flow field in the main channel of Elkhorn Slough. The data successfully collected at each of the five stations are summarized in Table 1. The full profiles of velocity collected by Stanford University were depth-averaged to correspond to the model formulation and output.

Table 1. Observed Quantities Collected During Stanford's April 7-25 2003 Deployment

Station	Observed Quantities
S1	Velocity profile
S2	Water depth, velocity profile
S3	Water depth, velocity profile
S4	Water depth, velocity profile
S5	Water depth, point velocity, bed shear stress

A comparison between the observed water levels within the Slough near Highway 1 (Stanford Station S1, Figure 1) and at NOAA's Monterey Bay station show close agreement during this period (Figure 5). This indicates that the Monterey Bay observation data can be used as the tidal boundary condition for the calibration run. The high frequency oscillations visible in the Monterey Bay observations were removed using a fifth-order Butterworth filter with a cut-off frequency of two hours. The filtered ocean boundary condition is shown in Figure 6.

The USGS gauging station (11152650) in the Reclamation Ditch (which connects to the Old Salinas River channel) approximately 15 km upstream from the South Harbor recorded limited freshwater inflows during this period, with peak discharges on the order of 1 m^3/s (Figure 7). A sensitivity analysis was performed assessing the importance of including typical freshwater discharges (see Appendix A). As a result of this assessment, no freshwater discharges were included in the calibration simulation. The mean monthly Moss Landing Power Plant intake and discharge of 14.5 m^3/s was included in the calibration simulation (LSP Moss Landing LLC 2002-2006).

Comparisons of predicted and observed water surface elevations, tidal harmonics, current speed and bed shear stress for the April 2003 calibration period are presented in the following sections.

3.2 WATER SURFACE ELEVATIONS

Comparisons of predicted and observed water surface elevations at four stations are presented in Figures 8 through 11. The figures for each station show the entire time series of the analysis period, a five-day segment of the time series for closer inspection, and a scatter plot of measured versus modeled data along with the corresponding correlation to the 1:1 line. At Station S2, data was successfully collected between April 7 and April 18. On April 18 the instrument turned onto its side (Monismith et al. 2005), and data collected after this period was not utilized. At Station S4, data collected prior to April 11 was suspect as water levels did not correlate with water levels collected Stations S2, S3 or S5. Analysis at Stations S4 was therefore truncated to span April 11 to April 25. At Stations S3 and 5, data was successfully collected from April 7 through April 25. It should also be noted that the data collected at Stations S3 and S4 appear to be limited by the instruments resolution and data was only collected at 10 cm intervals.

The water level data collected by Stanford University were not collected relative to a reference vertical datum (e.g., NAVD88), but rather the water surface elevation relative to the bed was collected (i.e., the water depth). Since the DELFT3D model calculates the water surface elevation relative to NAVD88, correlating these two quantities for comparison requires moving one data set into the same reference frame as the other. Although the water depth relative to the bed could be exported from a DELFT3D simulation, this quantity contains a degree of uncertainty due to the grid size. The grid resolution along the Slough is on the order of 10 m, and each grid cell is associated with a single bottom elevation value. The actual bathymetry of the Slough is likely variable within this grid cell (i.e., the bathymetry is not flat). Therefore the water depth estimated from the model would not represent the water depth at a specific point in space (e.g., an instrument location), but rather, the average water depth over the grid cell. Uncertainties also exist with respect to the exact location of the instrument due to the accuracy of the surface latitude and longitude measurements and/or other errors that hinder a direct correlation between the field observations and the model predictions. Therefore, the average water depth over a grid cell and the water depth collected by the instrument are unlikely to match within an acceptable degree of accuracy.

In light of these considerations, the water depth field observations were transformed in order to place them within the NAVD88 reference frame so that they are suitable for model calibration. The mean of both time series was calculated, and the difference between the two means was used to convert the water depth field observations into water surface elevations. The result of this transformation is shown on Figures 8 through 11. This transformation does not affect comparisons with respect to tidal amplitude or phase. The water surface elevation associated with the observed Monterey Bay ocean boundary condition was reported by NOAA relative to NAVD88, and this time series is also shown in the bottom panels of Figures 8 through 11. As can be seen, the Stanford University field observations compare reasonably well with the Monterey Bay data, although the transformed water surface elevations associated with the Stanford University field observations tend to be 5 to 10 cm lower than the Monterey Bay field observations.

It is important to note that the NOAA's Monterey Bay observations are reported in the same vertical datum as the bathymetric data (NAVD88) and no transformations are necessary to relate the NOAA reported water surface elevations to the bed. The Monterey Bay observations are used to drive the Elkhorn Slough model, therefore, the simulated water surface elevations within Elkhorn Slough are likely more representative of the actual water surface elevations (relative to the NAVD88 reference datum) than the transformed Stanford University field observations. Because the Monterey Bay field observations are 5 to 10 cm higher than the transformed Stanford University field observations, the simulations results are also expected to be 5 to 10 cm higher than the Stanford University field observations. Comparisons among alternatives will analyze relative differences between existing and with-project conditions, thus reducing the propagation of uncertainties with respect to water levels. In addition, the deployment of additional tide gages by the Elkhorn Slough National Estuarine Research Reserve will provide additional information with respect to water levels within the Slough as these tide gages will have vertical control.

3.2.1 Time Series Analysis

The predicted water surface elevations match the observed water surface elevations closely in both amplitude and phase at Stations S2 through S5, with a correlation coefficient squared (r^2) greater than 0.99 at Stations S2, S3 and S5, and a correlation coefficient squared of 0.98 at Station S4. The high correlation at Station S2 shows that the ocean boundary condition used to drive the model (the NOAA Monterey Bay data) is an appropriate choice (Figure 8).

In general, the model tends to slightly over predict the tidal range as expected based on the transformation applied to the Stanford University field observations. The largest over prediction occurs at Station S4 (Figure 10). However, the Station S4 field measurements appear to exhibit an anomaly with respect to the pattern of tidal amplification. Figure 12a presents the observed water depths at all four stations for a 12-hour period on April 15. The tide range increases from the mouth to the head of the Slough for Stations S2, S3 and S5. However, the observed tide range at Station S4 is smaller than observed at the other three stations by more than 30 cm. This may suggest that the pressure sensor for this station had an erroneous gain setting; therefore, the calibration at this station is likely greater than shown on Figure 10. Figure 12b presents the predicted water levels at the four stations for the same 12-hour period, and as can be seen, the modeled tide range steadily increases from Station S2 to Station S5, with no decrease in tide range associated with Station S4. In addition, the predicted increase in tide range between Stations S2 and S5 matches closely with the increase observed in the field measurements.

A comparison was made to assess the connectivity of the tidal marshes with the main stem of the Slough. Figure 13 displays the simulated water levels at Station S4, as well as the simulated water levels in a marsh channel in Big T marsh near Station S4 and on the adjacent Big T marsh plain (see Figure 1 for station locations). The simulated water levels in Big T marsh move nearly in concert with the water levels in the Slough, and as a result, the period of inundation is largely controlled by the bed elevation. However, the increase in simulated marsh water levels is slightly delayed when compared with simulated slough water levels at the beginning of a rising tide.

During these brief periods, the restricted cross-sectional area created by the shallow water depth limits flow rates.

The aerial photograph produced by SFML at approximately MLHW on July 2, 2003 was used to compare the observed aerial extent of marsh plain inundation with model predictions. It should be noted that the aerial photograph is a composite photograph containing a series of photos taken at slightly different time stamps, therefore the inundated areas delineated by SFML based on the aerial photographs are only an approximation of the area inundated at MLHW. In order to develop a meaningful comparison, the NOAA Monterey Bay tide records on July 2, 2003 were compared with the tide records from the calibration period, and an inundation map was produced from the model results at a tide level that corresponded with the mean time stamp from the aerial photos. Figure 14 shows the predicted marsh plain inundation, as well as SFML's delineated extent of inundation. The model accurately represents the aerial extent of inundation throughout the Elkhorn Slough system, providing confidence that the marsh drainage systems are well connected in the model and the model is performing as expected.

3.2.2 Harmonic Analysis

Tidal harmonic analysis of water levels provides another method of calibration and validation. In a tidally-driven system such as Elkhorn Slough, the ability to propagate the tidal signal accurately is often a better calibration tool than only correlating time series of water levels. Harmonic analysis of water levels involves decomposing a time series into its harmonic constituents. Any tidal signal consists of a combination of harmonic constituents, each with a known phase shift. Breaking down the overall signal into its constituents allows a comparison between the modeled and measured constituents. Since different tidal constituents result from different forcing mechanisms, the results of such a comparison can help identify which aspects of the model need further adjustment. Typically, only three to five of the major tidal constituents account for a large fraction of the tidal signal, such that examining these major constituents provides a good check of the tidal behavior of the model.

Tidal harmonic analysis was performed on both predicted and observed water levels at each station. Analysis at Station S2 spanned a 12-day period (April 7 to 18) corresponding to the period of successful data collection. The time period of analysis at Station S5 matches that at Station 2 to facilitate calculations of propagation time from constituent phases. At Stations S4, harmonic analysis spanned a 15-day period (April 11 to 25), and at Stations S3, harmonic analysis was performed over a 19-day period (April 7 to 25). Typically, a longer tidal record (i.e., at least 29 days) would be used for harmonic analysis; however, the present analysis was limited due to the length of the field measurement records.

The phase and amplitude of the M_2, K_1, O_1, S_2, P_1, and N_2 tidal constituents were analyzed.[2] These constituents represent the six most significant contributors, by amplitude, to the tidal forcing within Monterey Bay and Elkhorn Slough (Broenkow and Breaker 2005). Tables 2 through 4 present the phase and amplitude of the modeled and observed tidal constituents, as well as the tidal propagation time between Stations S2 and S5. The tables show the four major tidal constituents in order of decreasing amplitude, with M_2 being the dominant tidal constituent in Elkhorn Slough.

Table 2 shows that modeled water levels are generally within 4 degrees of phase with respect to the dominant tidal constituent (M_2) and within 1.3 degrees of phase with respect to K_1 when compared with measured field data. One degree of phase error corresponds to a two-minute difference in arrival time of high tide for a semi-diurnal constituent and an error of four minutes for a diurnal constituent.

Currently, the length of the record is too short to separate out components of comparable frequencies, therefore an inference method was used relating the relative historic magnitudes of the constituents (i.e., K_1:O_1, M_2:S_2, P_1:K_1, N_2:M_2). Amplitude ratios and phase offsets for the inference method were obtained for each Stanford University station based on the closest station reported in Broenkow and Breaker (2005). The stations used were either historical National Ocean Service tidal constituents (Stanford University stations S2 and S4) or tidal constituents derived from 2002-2003 observations by Broenkow and Breaker (2005) (Stanford stations S3 and S5). It should be noted that the inference procedure influences not only the amplitudes of the inferred constituents (O_1, S_2, P_1, and N_2), but also the amplitudes of the constituents on which the inference is based (K_1 and M_2). Additionally, since the inferred estimates are based on historical ratios between constituents, the harmonic analysis yields only two truly independent estimates for comparison between modeled and measured tidal constituents at Stanford stations S2 and S5, and four and three independent estimates at S3 and S4, respectively.

Harmonic analysis was also used to assess if the dominant tidal properties were being properly represented in Elkhorn Slough. Table 3 presents both the absolute and relative propagation error of the phase along the axis of the Slough between Station S2 and Station S5. The M_2 tidal constituent has a propagation error of approximately 0.5 minutes, which means that the M_2 tide propagates upstream from Station S2 to Station S5 approximately 0.5 minutes faster in the model when compared with field observations. The K_1 tidal constituent propagates upstream approximately 0.6 minutes faster than field observations.

[2] The letters refer to the principal astronomical driver of the cycle, such as M and O for lunar, S for solar, and K for lunar-solar interactions. The subscripts of the constituents refer to the number of cycles per day, with 1 referring to one cycle per day (diurnal), 2 to two cycles per day (semidiurnal), and so forth.

Table 4 shows that predicted tidal amplitudes are within 1 cm of the observed tidal amplitudes for three of the four stations. Station S4 exhibits the poorest fit with respect to both phase and amplitude, and this can be attributed to the potential equipment error associated with this station, as noted in Section 3.2.1.

Table 2. Phase Differences between Modeled and Measured Tidal Constituents, Calibration Run, April 2003

All values are in degrees; shading denotes inferred constituent; Negative values correspond to a faster arrival time in the model, whereas positive values correspond to the model lagging behind measured data

	S2			S3			S4			S5		
	Obs.	**Pred.**	**Diff.**	**Obs.**	**Pred.**	**Diff.**	**Obs.**	**Pred.**	**Diff.**	**Obs.**	**Pred.**	**Diff.**
M_2	185.4	189.5	4.1	186.7	189.7	3.0	184.5	188.9	4.4	192.6	196.5	3.9
K_1	239.0	240.3	1.3	229.6	230.5	0.9	233.5	233.5	0.0	241.9	243.1	1.2
O_1	255.3	256.6	1.3	207.8	208.7	0.9	211.9	212.1	0.2	259.8	261.0	1.2
S_2	184.9	189.0	4.1	187.8	187.8	0.0	183.9	188.3	4.4	187.6	191.6	4.0

Table 3. Tidal Propagation Differences from Station S2 to S5 between Modeled and Measured Tidal Constituents, Calibration Run, April 2003

All times are in minutes; shading denotes inferred constituent; Negative values correspond to a faster arrival time in the model, whereas positive values correspond to the model lagging behind measured data

	Observed	**Predicted**	**Difference**	**% Error**
M_2	14.9	14.4	-0.5	-3.1
K_1	11.6	11.0	-0.6	-4.8
O_1	18.8	18.8	-0.6	-3.1
S_2	5.2	5.2	-0.2	-4.4

Table 4. Amplitude Differences between Modeled and Measured Tidal Constituents, Calibration Run, April 2003

All values are in cm; shading denotes inferred constituents; Positive values represent larger modeled amplitudes, and negative values represent smaller modeled amplitudes

	S2			S3			S4			S5		
	Obs.	**Pred.**	**Diff.**	**Obs.**	**Pred.**	**Diff.**	**Obs.**	**Pred.**	**Diff.**	**Obs.**	**Pred.**	**Diff.**
M_2	44.7	44.7	0.0	50.9	50.9	0.0	50.3	53.6	3.3	48.5	47.2	-1.3
K_1	36.0	36.6	0.6	38.2	38.9	0.7	34.7	39.0	4.3	36.7	36.4	-0.3
O_1	21.8	22.1	0.3	22.7	22.8	0.1	21.5	23.6	2.1	22.6	22.4	-0.2
S_2	11.1	11.1	0.0	15.4	16.3	0.9	13.4	14.3	0.9	13.7	13.3	-0.4

3.3 CURRENT SPEED

Comparisons of predicted and observed current speeds at five stations are presented in Figures 15 through 19. The figures for each station show the entire time series of the analysis period, a five-day segment of the time series for closer inspection, and a scatter plot of measured versus modeled data along with the corresponding correlation to the 1:1 line.

Water depth has a significant effect on the predicted current speed and some uncertainty exists with respect to the location of the underwater instruments based on the precision of the surface latitude and longitude measurements. The model grid cell corresponding to the velocity profiling locations was identified based on the reported instrument positions. If the depth in the specified grid cell differed from the reported instrument depth, the observation data was compared with predicted velocities in an adjacent grid cell if the cell depth was more consistent with the reported instrument depth.

The model accurately predicts the semi-diurnal pattern and spring-neap variability, with the highest velocities occurring on ebb tides. The model also captures the relative decrease in current speed observed between Stations S1 and S5. Figure 15 displays a comparison of predicted and observed current speeds at Station S1 located nearest to the inlet to Monterey Bay. Predicted and observed current speeds correspond well, with a correlation coefficient squared (r^2) greater than 0.98. At Station S2 (Figure 16), model predictions also match well with field measurements and the correlation coefficient squared is greater than 0.97. The model slightly under predicts flood current speeds and over predicts ebb current speeds, with somewhat larger differences observed on spring tide. This tendency means that the model slightly overstates ebb dominance.

At Station S3 (Figure 17), the instrument was situated within Parsons Slough at a location that exhibited extreme flood-ebb asymmetry. In fact, during ebb tides the instrument recorded very low current speeds. Monismith et al (2005) hypothesize that although the instrument was near the center of the channel, this cross section experiences large lateral flow variability. During flood tides when observations and predictions are comparable, the model slightly over predicts current speed. In addition to the lateral variability of currents in this channel, there is uncertainty with respect to the bathymetry in this region. This location lies just within the extent of the SFML sonar soundings, and adjacent LIDAR-derived bathymetry data underneath and landward of the railroad bridge does not precisely match the sonar soundings. Although the predicted and observed current speeds at Station S3 only agree well on flood tides, the model does behave as expected in this region. The model predicts that the tidal prism of Parsons Slough is approximately 30% of the tidal prism of Elkhorn Slough. This agrees with previous estimates of Parson Slough’s contribution to the overall tidal prism of the system (Broenkow and Breaker 2005; Philip Williams & Associates 1992)

Predicted and observed current speeds at Station S4 (Figure 18) agree well with a correlation coefficient squared greater than 0.97. It should be noted that Monismith et al (2005) observed some irregularities in the lower 0.85 m of the Station S4 velocity profiles. It was hypothesized that the frame and/or the instrument may have influenced the flow. The lower 0.85 m of the velocity profile was therefore removed from the observed data and not included in the depth-averaged velocity profile. Although omitting this data may lead to an overestimation of the model's performance (i.e., true depth-averaged speeds may be less than suggested in Figure 18), this difference substantively effects the model's calibration because of the relatively large water depths within the slough channel.

Station S5 (Figure 19) exhibits slightly worse agreement with a correlation coefficient squared of 0.90. However, only a point velocity measurement at 0.4 m above the bed was recorded at Station S5 rather than the full velocity profile collected at the other stations. For comparison purposes, a logarithmic velocity profile was assumed to estimate the depth-averaged velocity from the point velocity measurement. Using this approach, the observed and predicted current speeds agree relatively well, although the model tends to over predict current speeds on the stronger flood tides.

Table 5 summarizes the root mean squared (RMS) error between predicted current speeds over the calibration period at each of the five stations. In general, the RMS errors are between approximately 5% to 10% of the peak tidal current speeds. The one exception is the RMS error at Station S3, presumably due to the problems with the observed data at this location (see discussion above).

Table 5. Root Mean Squared (RMS) Error between Predicted and Observed Current Speeds, Calibration Run, April 2003

Station	RMS Error, Current Speed (m/s)
S1	0.039
S2	0.057
S3	0.317
S4	0.040
S5	0.066

3.4 BED SHEAR STRESS

Bed shear stress is a key parameter for assessing the geomorphic evolution of Elkhorn Slough. The caveat noted in Section 3.3 regarding instrument position and the most appropriate grid cell for comparison also applies to comparisons of observed and predicted bed shear stress. Figure 20 presents a comparison of predicted and observed bed shear stress at Station S5 near the head of Elkhorn Slough. The figure shows the entire time series of the analysis period and a five-day segment of the time series for closer inspection. The predicted bed shear stress captures the diurnal cycle of the observed bed shear stress well on both flood and ebb tides. However, the observed bed shear stress exhibits a large degree of noise and Stanford University cautioned use of the data (Monismith, pers. comm.). The source of the noise is uncertain and could be associated with instrumentation problems or fouling.

4. VALIDATION

Once satisfactory agreement was achieved for the calibration data set, the calibrated hydrodynamic model was validated using two independent sets of prescribed boundary condition and input data, and the results were compared with observations made during the validation periods. If the model results compare favorably with the observation data during the validation period, the calibrated model is considered to adequately represent the system's baseline conditions. The Elkhorn Slough Model was validated using data collected by Stanford University in September 2002 (Appendix B), and data collected in December 2005 as part of the Land/Ocean Biogeochemical Observatory in Elkhorn Slough (LOBO) by the Monterey Bay Aquarium Research Institute (MBARI).

The following sections outline the validation approach for the Elkhorn Slough Model and present the validation results for both validation periods. All of the simulation results presented were made using the final calibrated model.

4.1 VALIDATION APPROACH

Once the calibration of the Elkhorn Slough Model was complete, the model was used to simulate two independent time periods in order to verify that the model calibration is robust. The overall goal was to develop a model that will be capable of predicting behaviors in response to a variety of external conditions, and the intent of the validation process is to subject the model to conditions not previously encountered during the calibration process.

For the validation phase, two independent sets of input data and boundary conditions were considered. The first validation simulation lasted from September 5 to September 25, 2002. Intuitively, the model should perform well for this validation period as the conditions were similar to the calibration period. However, in contrast to the April 2003 calibration period (Figure 5), the observed water levels in the Bay and the Slough exhibit differences of nearly 30 cm on some phases of the tide (Figure 21). The differences are most prevalent during spring tides between September 7 and 14 and occur on every other flood-ebb pair. Differences between the NOAA and Stanford University observation data for this period are expected to limit the usefulness of the September 2002 validation comparison between predicted and observed water levels and current velocities. The results of this effort are therefore presented in Appendix B.

Because of the discrepancies between the NOAA and Stanford University water levels during the September 2002, the model was validated utilizing a second independent data set collected as part of the LOBO/MBARI program in December 2005. This validation simulation utilizes filtered NOAA Monterey Bay observations for the ocean boundary condition, as shown in Figure 22.

This period was chosen because it contains a two-week period with relatively minimal precipitation and therefore low freshwater tributary inputs, and a two-week period of heavy rainfall when the recorded discharge in the Reclamation Ditch at USGS gauging station (11152650) exceeds 2 m^3/s (Figure 23).

A sensitivity analysis was performed to determine the net effect of the typical freshwater discharges on water levels and current speeds within Elkhorn Slough (see Appendix A). Based on the results of the sensitivity runs, freshwater inflows were not included. The mean monthly Moss Landing Power Plant intake and discharge for December of 15.3 m^3/s was included in the validation simulation (LSP Moss Landing LLC 2002-2006).

Table 6 summarizes the data successfully collected at the LOBO stations during December 2005. The stations locations are shown on Figure 1.

Table 6. Observed Quantities Collected at LOBO Stations During December 2005

Station	**Observed Quantities**
L01	Water depth, depth-averaged velocity
L02	Water depth, depth-averaged velocity
L04	Water depth

The same methods of analysis used in the calibration period were used to assess model performance. The validation results for the December 2005 period are presented in the following sections.

4.2 DECEMBER 2005 VALIDATION RESULTS

This section presents the Elkhorn Slough Model validation results for the December 2005 validation period. The analysis was conducted over a 28-day period extending from December 4 to December 31. Comparisons of predicted and observed water surface elevations, tidal harmonics and current speed are presented in the following sections.

4.2.1 Water Surface Elevations

4.2.1.1 Time Series Analysis

Comparisons of predicted and observed water surface elevations at three stations are presented in Figures 24 through 26. The figures for each station show the entire time series of the analysis period, a five-day segment of the time series for closer inspection, and a scatter plot of measured versus modeled data along with the corresponding correlation to the 1:1 line.

As with the Stanford University field measurements, the LOBOS observations were not collected relative to a reference vertical datum (e.g., NAVD88), but rather the water surface elevation relative to the bed was collected (e.g., the water depth). The same transformation was applied to shift the LOBOS water depths into the NAVD88 reference frame for comparison purposes (see Section 3.2). The mean of both time series was calculated, and the difference between the two means was used to convert the water depth field observations into water surface elevations. The result of this transformation is shown on Figures 24 through 26. This transformation does not affect comparisons with respect to tidal amplitude or phase.

The predicted water surface elevations match the observed water surface elevations closely in both amplitude and phase, with a correlation coefficient squared (r^2) greater than 0.99 at all three stations. The high correlation at Station LO1 shows that the ocean boundary condition used to drive the model (the NOAA Monterey Bay data) is an appropriate choice (Figure 24). As with the calibration period, the model tends to slightly over predict the tide range, particular during spring tide.

4.2.1.2 Harmonic Analysis

Tidal harmonic analysis was performed on both predicted and observed water levels over a 28-day analysis period between December 4 and 31 for Station LO1 and LO2. At Station LO4, tidal harmonic analysis was performed over a 16-day period between December 16 and 31 due to a gap in the observation record. Tables 7 through 9 present the phase and amplitude of the modeled and observed tidal constituents, as well as the tidal propagation time between Stations LO1 and LO2. The tables show the four major tidal constituents in order of decreasing amplitude, with M_2 being the dominant tidal constituent in Elkhorn Slough.

Table 7 shows that modeled water levels are within 1 degree of phase with respect to the diurnal tidal constituents and within 4 degrees of phase for the semi-diurnal tidal constituents when compared with measured field data. The largest phase differences between modeled and measured tidal constituents are associated with the M_2 tidal constituent.

Harmonic analysis was also used to assess if the dominant tidal properties were being properly represented in Elkhorn Slough. Table 8 presents the propagation error of the phase along the axis of the Slough from Station LO1 to Station LO2. The model propagates the M_2 tidal constituent upstream from Station LO1 to Station LO2 approximately 1.8 minutes slower than field observations, and the K_1 tidal constituent is propagated upstream approximately 0.9 minutes slower. Larger absolute differences in propagation errors are observed for the O_1 and S_2 tidal constituents, which propagate upstream faster than field observations.

Table 9 shows that predicted tidal amplitudes are within 2 cm of the observed tidal amplitude with respect to the four dominant tidal constituents. As with the phase errors, the largest amplitude differences between modeled and measured tidal harmonics are associated with the M_2 tidal constituent at Stations LO4 and LO2.

Table 7. Phase Differences between Modeled and Measured Tidal Constituents, Validation Run, December 2005

All values are in degrees; Negative correspond to a faster arrival time in the model, whereas positive values correspond to the model lagging behind measured data

	LO1			**LO4**			**LO2**		
	Obs.	**Pred.**	**Diff.**	**Obs.**	**Pred.**	**Diff.**	**Obs.**	**Pred.**	**Diff.**
M_2	185.1	188.2	3.1	193.1	196.6	3.5	193.1	197.1	4.0
K_1	221.2	221.3	0.1	223.9	224.4	0.5	226.8	227.1	0.3
O_1	207.8	208.3	0.5	207.9	208.3	0.4	214.6	214.5	-0.1
S_2	188.9	191.4	2.5	195.2	197.6	0.0	202.8	204.1	1.3

Table 8. Tidal Propagation Differences from Station LO1 to LO2 between Modeled and Measured Tidal Constituents, Validation Run, December 2005

All times are in minutes; Negative values correspond to a faster arrival time in the model, whereas positive values correspond to the model lagging behind measured data

	Observed	**Predicted**	**Difference**	**% Error**
M_2	16.6	18.4	1.8	10.7
K_1	22.2	23.1	0.9	4.1
O_1	29.3	26.7	-2.6	-8.8
S_2	27.7	25.4	-2.3	-8.4

Table 9. Amplitude Differences between Modeled and Measured Tidal Constituents, Validation Run, December 2005

All values are in cm; Positive values represent larger modeled amplitudes, and negative values represent smaller modeled amplitudes

	LO1			**LO4**			**LO2**		
	Obs.	**Pred.**	**Diff.**	**Obs.**	**Pred.**	**Diff.**	**Obs.**	**Pred.**	**Diff.**
M_2	48.9	49.7	0.8	47.4	49.2	0.2	50.6	52.3	1.7
K_1	37.3	37.1	-0.2	35.0	35.1	0.1	36.4	36.8	0.4
O_1	21.6	21.6	0.0	20.2	20.5	0.3	20.6	21.1	0.5
S_2	9.0	8.6	-0.4	8.3	7.3	-1.0	10.1	9.5	-0.6

4.2.2 Current Speed

Comparisons of predicted and observed current speeds at Stations LO1 and LO2 are presented in Figures 27 and 28, respectively. The figures show the entire time series of the analysis period, a five-day segment of the time series for closer inspection, and a scatter plot of measured versus modeled data along with the corresponding correlation to the 1:1 line.

Model predictions and field observations exhibit close agreement, with a correlation coefficient squared greater than 0.97 at Station LO1 and 0.94 at Station LO2. The model accurately predicts the semi-diurnal pattern and spring-neap variability, with the highest velocities occurring on ebb tides. The model also captures the relative decrease in current speed observed between Stations LO1 and LO2. At Station LO1, the model captures the peak magnitude of the ebb currents well, and tends to over predict the peak flood current speeds (Figure 27). The instrument at Station LO1 may be located in the peak current on ebb tide, but not on flood tide, which may explain some of the discrepancy between predicted and observed current speeds on flood tide. At Station LO2, the model represents the peak magnitude of the ebb and flood currents well.

Table 10 summarizes the RMS error between predicted current speeds over the validation period at the two locations were field data were available, Stations LO1 and LO2. The RMS errors are slightly higher than those computed for the calibration period, although they remain approximately 5% of the peak spring current speeds during ebb tides at the down-estuary location (Station LO1) and roughly 10% of the peak current speeds at the up-estuary location (Station LO2). Note that the RMS error for Station LO1 includes the differences in peak flood current speeds that are may be due to instrumentation placement, as discussed above.

Table 10. Root Mean Squared (RMS) Error between Predicted and Observed Current Speeds, Validation Run, December 2005

Station	**RMS Error, Current Speed (m/s)**
LO1	0.053
LO2	0.040

5. SUMMARY AND CONCLUSIONS

This section provides a brief summary of the calibration and validation results for the Elkhorn Slough Model.

5.1 CALIBRATION SUMMARY

Model calibration was conducted using data collected by Stanford University during April 2003. Specifically, the 19-day period extending from April 7 to April 25 was used, which corresponds to the period of field data collection. The calibration focused on comparing predicted and observed water levels and current speeds in the main Elkhorn Slough channel.

Water level analyses were conducted over the period from April 7 to April 18 for Station S2, from April 11 to April 25 for Station S4, and from April 7 to April 25 for Stations S3 and S5 based on the availability of successfully collected data (see Figure 1 for station locations). Water levels were analyzed using time series comparisons, statistical correlations and tidal harmonic analysis at the four stations. During the calibration period, the predicted water levels matched the observed water levels closely at three of the four stations. The correlation coefficients squared (r^2) were greater than 0.99 for Stations S2, S3 and S5. The largest differences between model predictions and field measurements were observed at Station S4, which had a correlation coefficient squared of 0.98. However, a closer inspection of the field measurements point to a possible error in the measured water levels at this station.

The model accurately reproduced estimates of aerial inundation extent produced by the Seafloor Mapping Laboratory from aerial photographs, providing confidence in the model's ability to represent hydrodynamics over the marsh plain.

Harmonic analyses were conducted over the calibration period to assess if the dominant tidal properties were properly resolved. Measurement of absolute and relative propagation error also provided an additional quantitative comparison between predicted and observed water levels. In general, the model propagates the tidal wave from Station S2 to Station S5 within one minute of the observations. Predicted tidal amplitudes are within 1 cm of the observed tidal amplitudes for three of the four stations.

Predicted current speeds also matched closely with observed current speeds, with a correlation coefficient squared greater than 0.98 at Station S1, 0.96 at Station S2, and 0.97 at Station S4. At Station S3 in Parsons Slough, the instrument location relative to the main tidal flows prevented capturing ebb tides. However, predicted and observed current speeds matched well on flood tide. At Station S5, only a point velocity measurement was collected. For comparison purposes, a logarithmic velocity profile was assumed to estimate the depth-averaged velocity from the point velocity measurement. Using this approach, the model tends to over predict current speeds on the stronger flood tides.

In general, the model accurately predicts the semi-diurnal pattern and spring-neap variability observed in the current speed field measurements, with the highest velocities occurring on ebb tides. The model also captures the relative decrease in current speed observed between Stations S1 and S5.

Observed bed shear stress measurements were only collected at Station S5 near the head of Elkhorn Slough, and the data obtained during this period exhibit a large degree of noise limiting the ability to compare model predictions and field observations. However, despite the noise in the observed data, the model predictions do capture the diurnal variability seen in the field measurements of bed shear stress.

A sensitivity analysis (Appendix C) was conducted to investigate the influence of depth-dependent Chezy coefficient relative to a spatially uniform specification of bed roughness. This analysis indicates that the current velocities and bed shear stress on the marsh plain are more sensitive to variations in the Chezy coefficients than marsh plain water levels or the predicted velocities, bed shear stress and water levels in the main slough channel.

5.2 VALIDATION SUMMARY

The Elkhorn Slough Model was validated using data collected by MBARI in December 2005 as part of LOBO. The analysis was conducted over a 28-day period extending from December 4 to December 31.

The December 2005 validation period shows excellent agreement between predicted and observed water surface elevations and current speeds. The predicted water surface elevations match the observed water surface elevations in both amplitude and phase, with 1:1 correlation coefficient squared (r^2) greater than 0.99 for all three observation stations (see Figure 1 for station locations).

Harmonic analyses were conducted over the validation period and reveal propagation errors slightly greater compared to the calibration period, although the differences in travel time between Station LO1 to Station LO2 for the two most dominant tidal constituents remain less than 2 minutes. Predicted tidal amplitudes are within 2 cm of the observed tidal amplitude with respect to the four dominant tidal constituents.

Modeled current speeds also accurately predicts current speeds during the validation period. At Station LO1, closest to the Monterey Bay inlet, the correlation coefficient squared is 0.92. The model captures the peak magnitude of the ebb current but tends to over predict the peak flood current speed. This may be attributable to the location of the instrument in the channel (e.g., it may be located in the peak current on ebb tide, but not on flood tide). At Station LO2 nearer to the head of the Slough, the model predicts both the peak flood and ebb current speeds well, with a correlation coefficient squared of 0.94.

5.3 CONCLUSIONS

The iterative calibration / validation process has resulted in an optimal comparison of predicted and observed water levels and current velocities at multiple stations along Elkhorn Slough. Differences between observed and predicted values are relatively small compared to absolute values. Additionally, sensitivity analyses demonstrate the model's ability to accurately predict these quantities is insensitive to typical freshwater discharges to the system, although cooling water intake to power plant is included in the model setup. Extreme events, such as large storms and the associated storm runoff, were not evaluated as part of model calibration and validation.

Results from the April 2003 calibration and December 2005 validation periods show that the model accurately predicts water levels and current speeds within Elkhorn Slough, demonstrating model fidelity. The relatively small differences between observed and predicted parameters presented in this report are not considered significant when compared with changes observed in the Elkhorn Slough system since the Moss Landing Harbor was completed in 1947. Peak current speeds have doubled over the past 30 years in response to this large-scale perturbation of the system (Broenkow and Breaker 2005). A response of similar magnitude could occur under restoration scenarios, as is evident in previous studies evaluating restoration of Elkhorn Slough. PWA (1992) predicted that bed shear stress may more than halve under 'restored' conditions,

It should be noted that although the model accurately represents existing conditions within an acceptable degree of uncertainty, additional uncertainties are associated with modeling restored conditions. For example, any modifications to the model bathymetry (i.e., restoring the historic tidal inlet) will represent an approximation of potential future conditions. Given the generally high degree of accuracy reported in this document, the uncertainties associated with this approximation are expected to be greater than the uncertainties inherent in the model's calibration. However, given the magnitude of change we expect under 'restored' conditions, as discussed above, the model will remain a valuable tool for comparing and contrasting the relative effectiveness of the proposed large-scale restoration alternatives.

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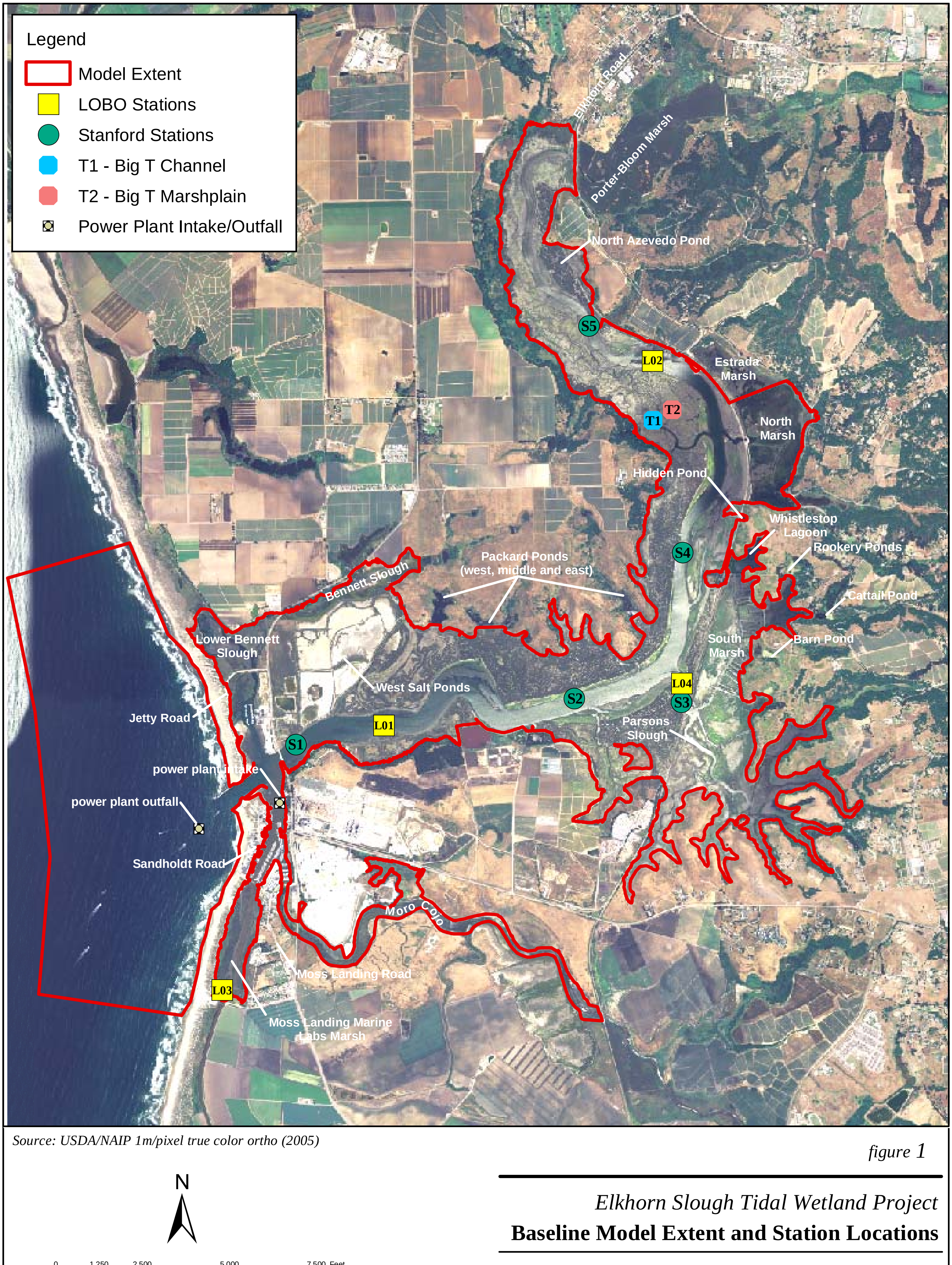

Source: USDA/NAIP 1m/pixel true color ortho (2005)

figure 1

Elkhorn Slough Tidal Wetland Project

Baseline Model Extent and Station Locations

Proj. # 1869

PWA

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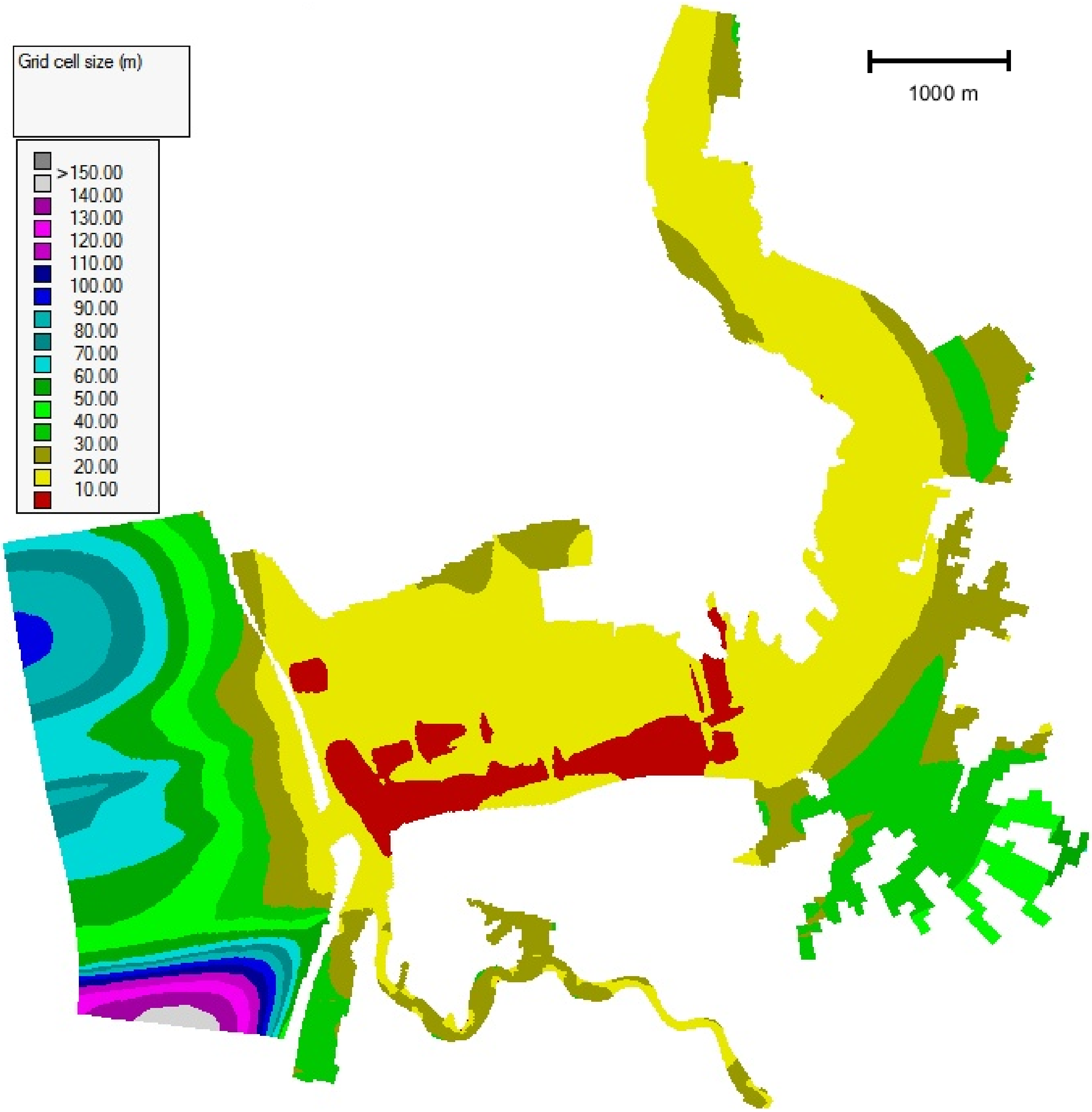

Note: Depths are positive downwards.

figure 2

Elkhorn Slough Tidal Wetlands Restoration

Elkhorn Slough Model Grid Resolution

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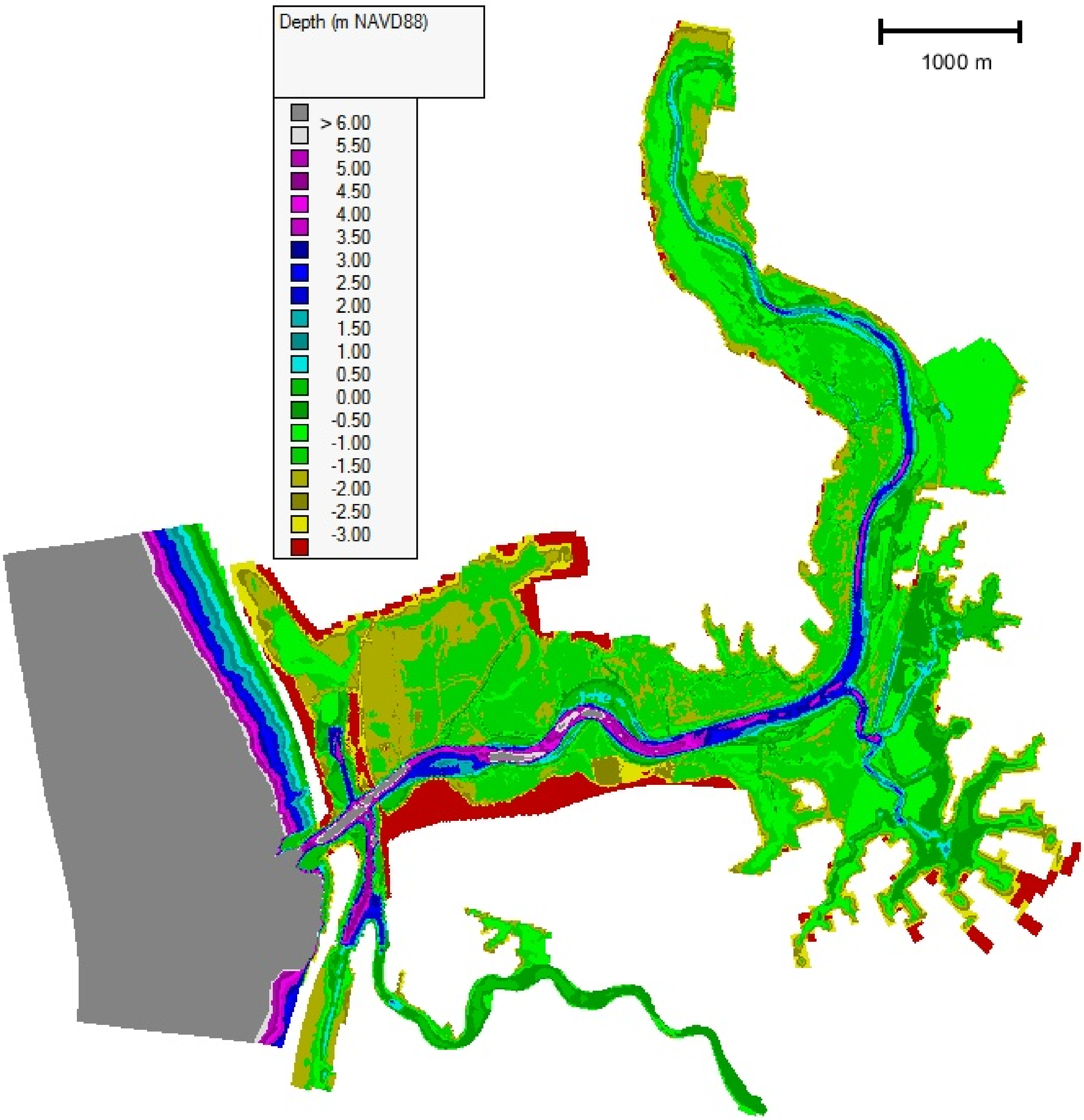

Note: Depths are positive downwards.

figure 3

Elkhorn Slough Tidal Wetlands Restoration

Elkhorn Slough Model Bathymetry

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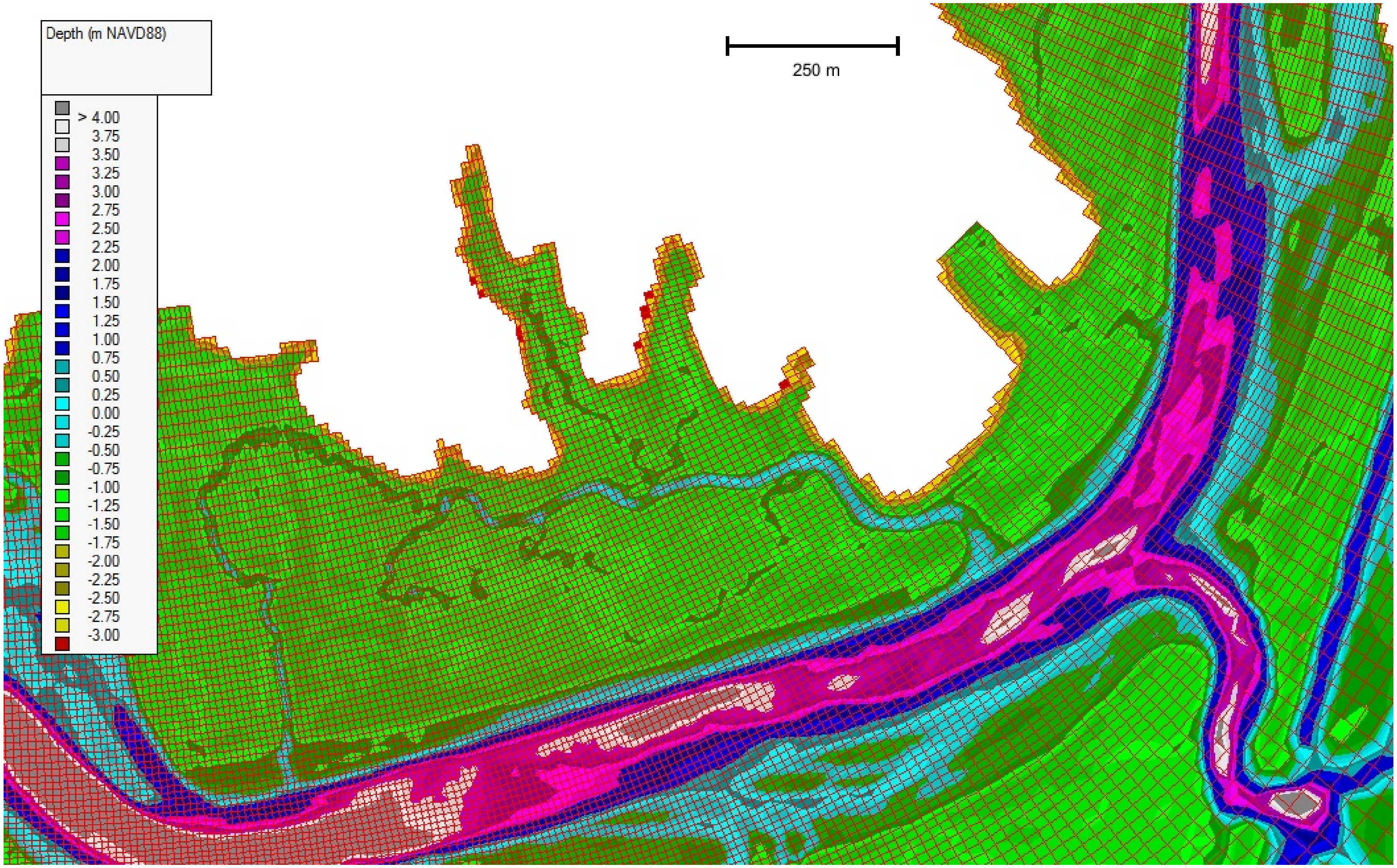

Note: Depths are positive downwards.

figure 4

Elkhorn Slough Tidal Wetlands Restoration

Zoomed View of Rubis Marsh Grid and Bathymetry

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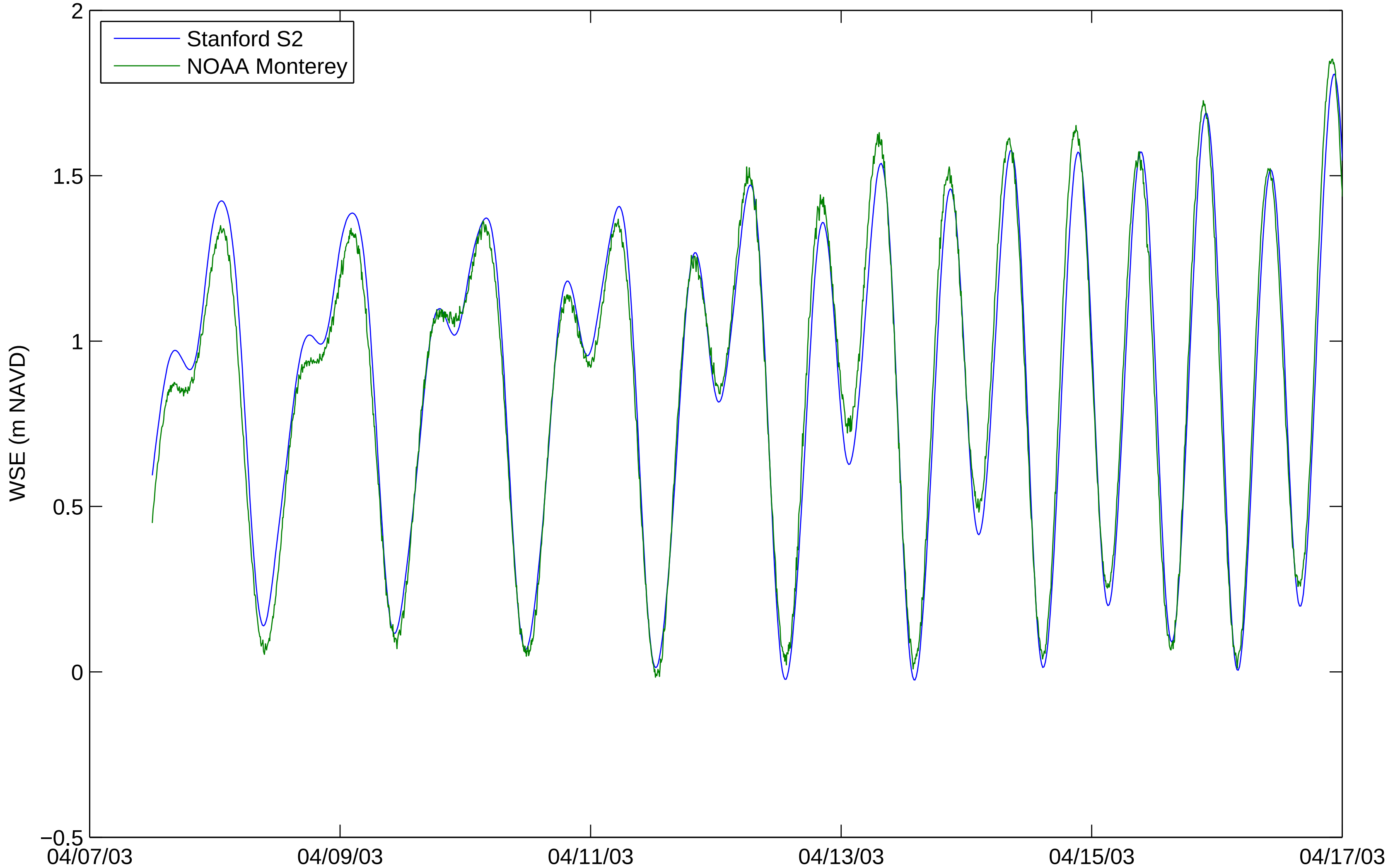

Source: Stanford University observations and NOAA observations (Station ID 9413450)

Figure 5

Elkhorn Slough Tidal Wetlands Restoration

April 2003 Observed Water Levels in Elkhorn Slough and Monterey Bay

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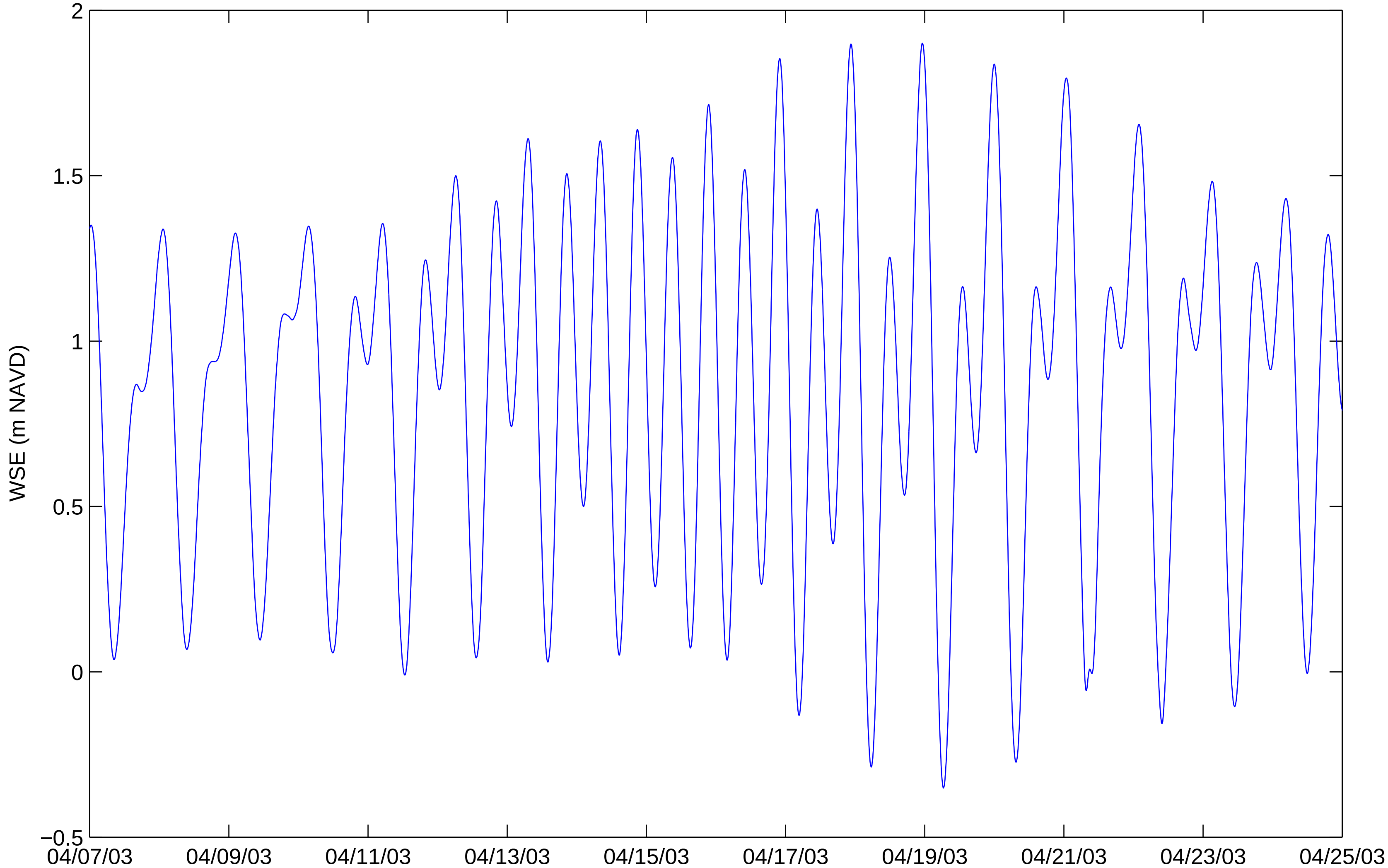

Source: NOAA observations (Station ID 9413450)

Figure 6
Elkhorn Slough Tidal Wetlands Restoration

April 2003 Ocean Boundary Condition

PWA Ref# 1869.5

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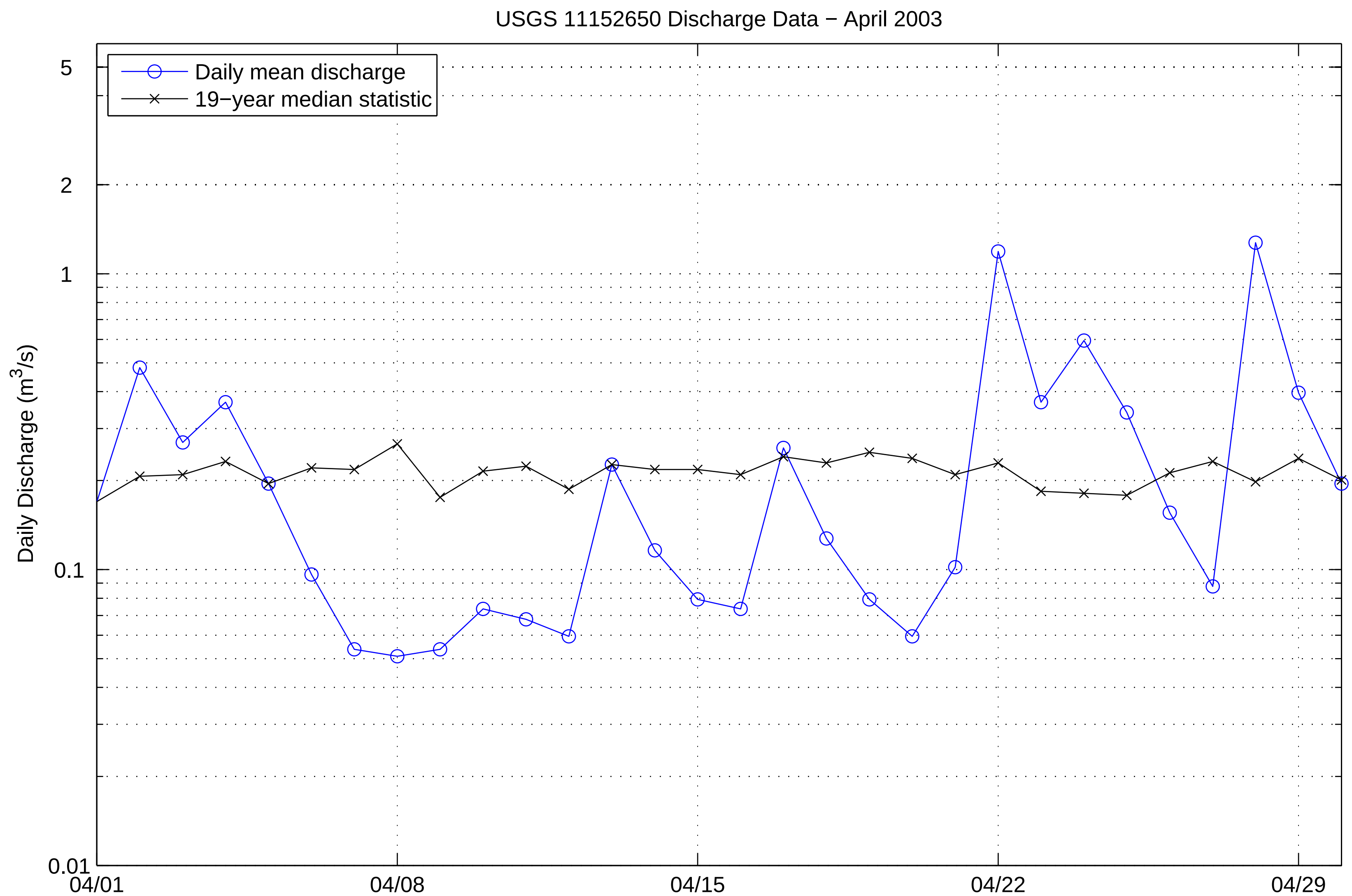

Source: USGS observations (Station ID 1152650)

Figure 7
Elkhorn Slough Tidal Wetlands Restoration

April 2003 Freshwater Discharge

PWA Ref# 1869.5

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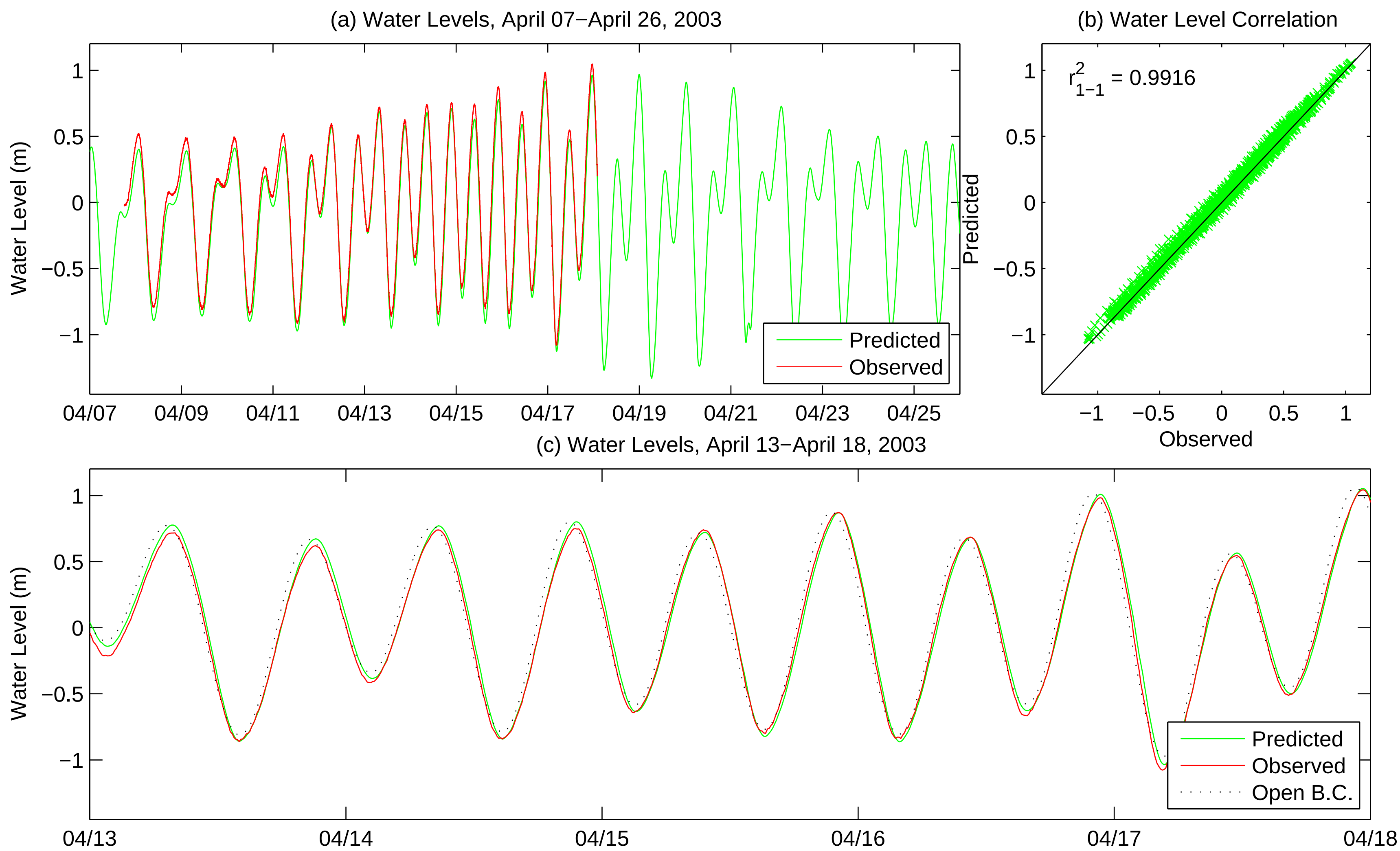

Source: Stanford University observations and DELFT3D model predictions. Observation data ends on April 18 because the instrument package fell over.

Figure 8
Elkhorn Slough Tidal Wetlands Restoration

April 2003 Water Levels, Station S2

PWA Ref# 1869.5

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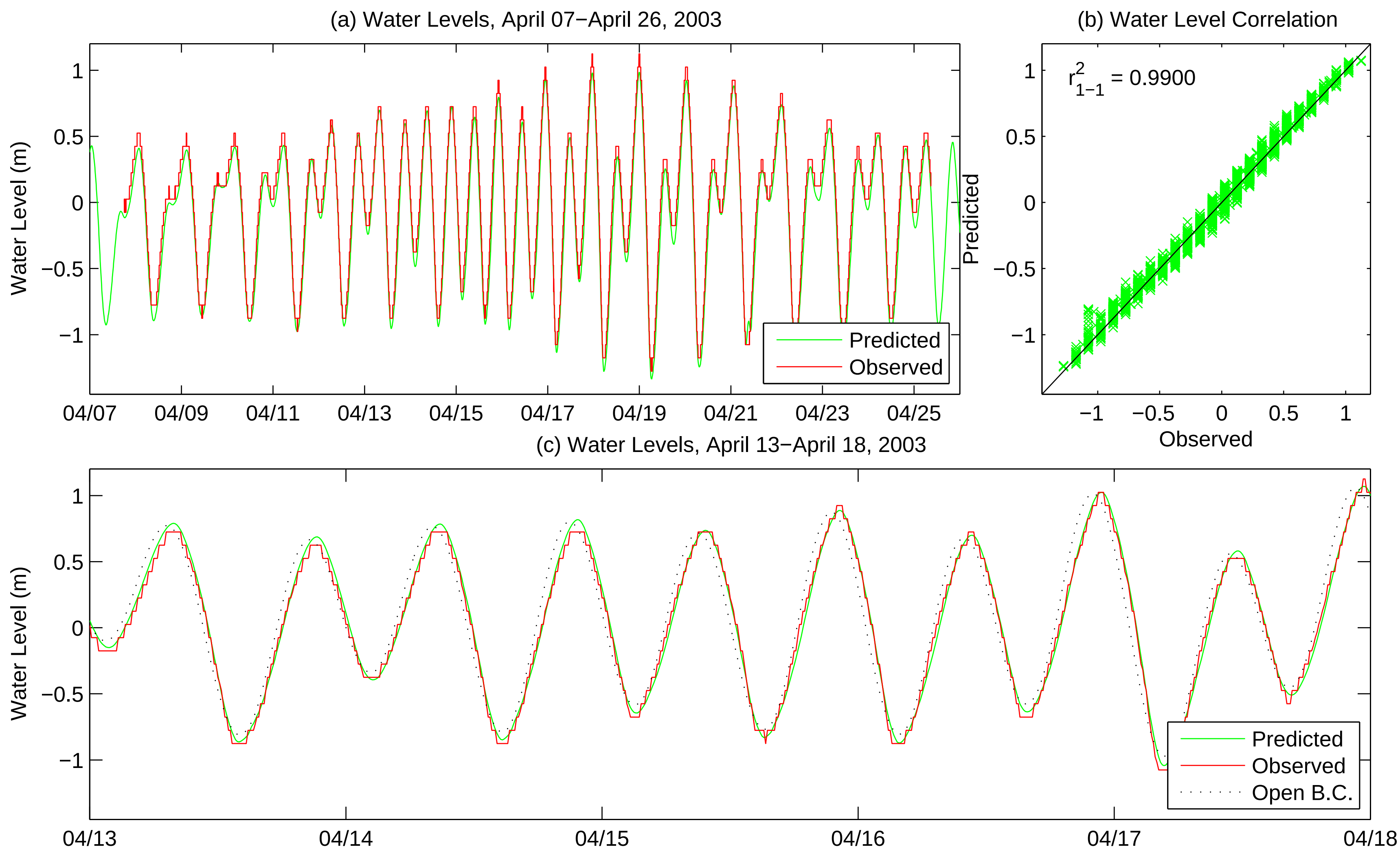

Source: Stanford University observations and DELFT3D model predictions

Figure 9
Elkhorn Slough Tidal Wetlands Restoration

April 2003 Water Levels, Station S3

PWA Ref# 1869.5

PWA

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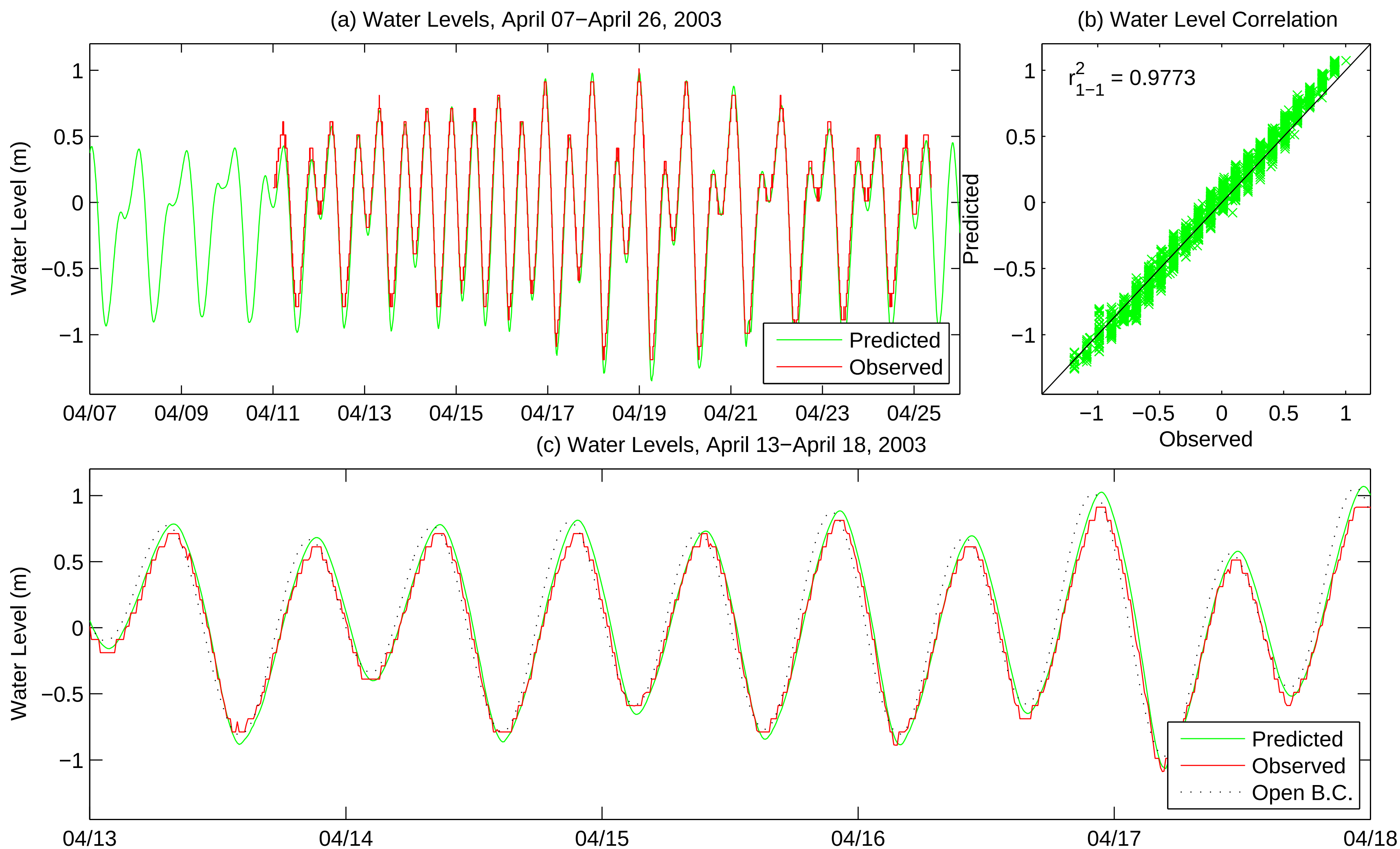

Source: Stanford University observations and DELFT3D model predictions. Observations collected before April 11, 2003 have been removed since they are not consistent with observations collected at the same time in other locations in the Slough.

Figure 10
Elkhorn Slough Tidal Wetlands Restoration

April 2003 Water Levels, Station S4

PWA Ref# 1869.5

PWA

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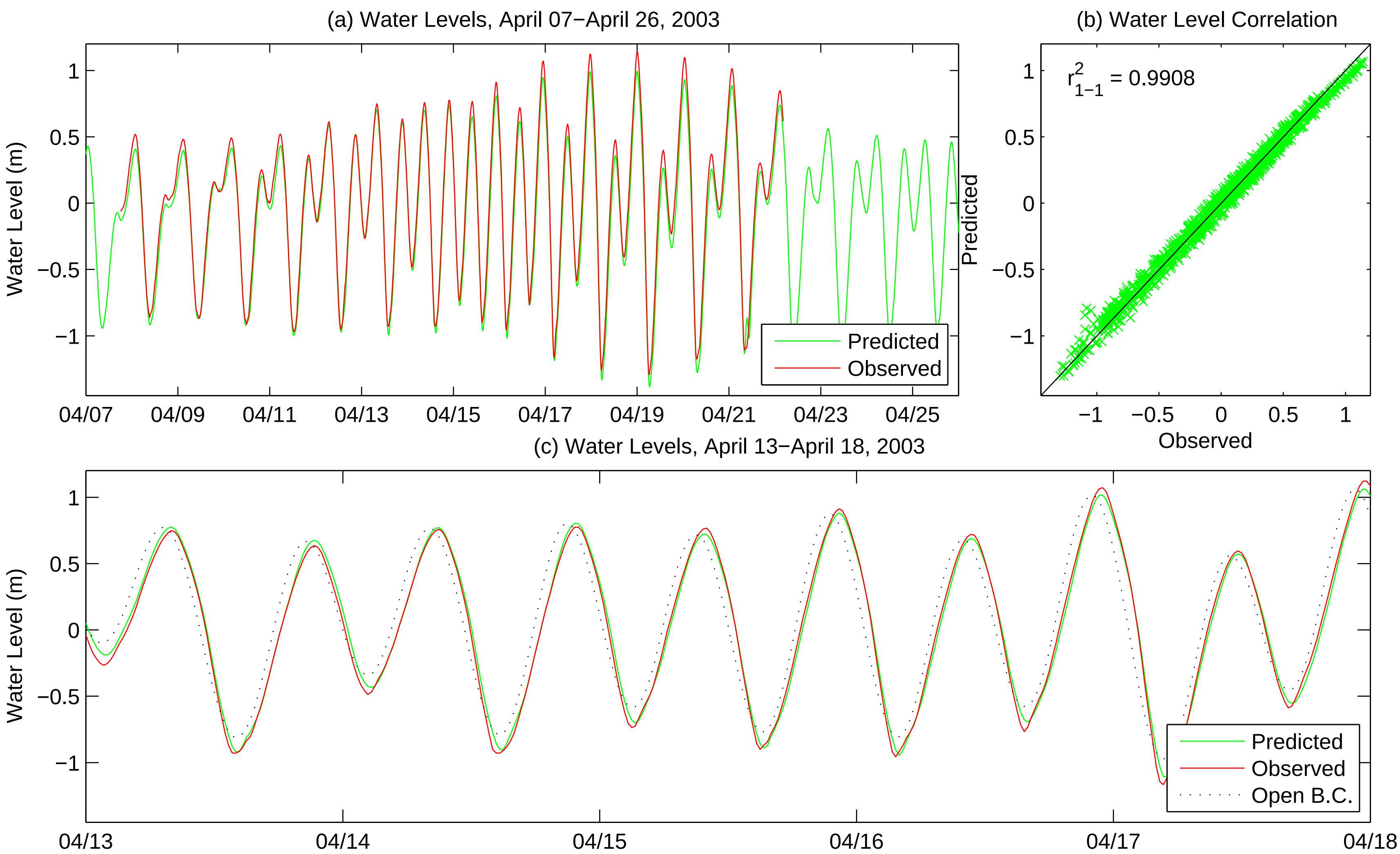

Source: Stanford University observations and DELFT3D model predictions. The instrument stopped recording data after April 22.

Figure *11*

Elkhorn Slough Tidal Wetlands Restoration

April 2003 Water Levels, Station S5

PWA Ref# 1869.5

PWA

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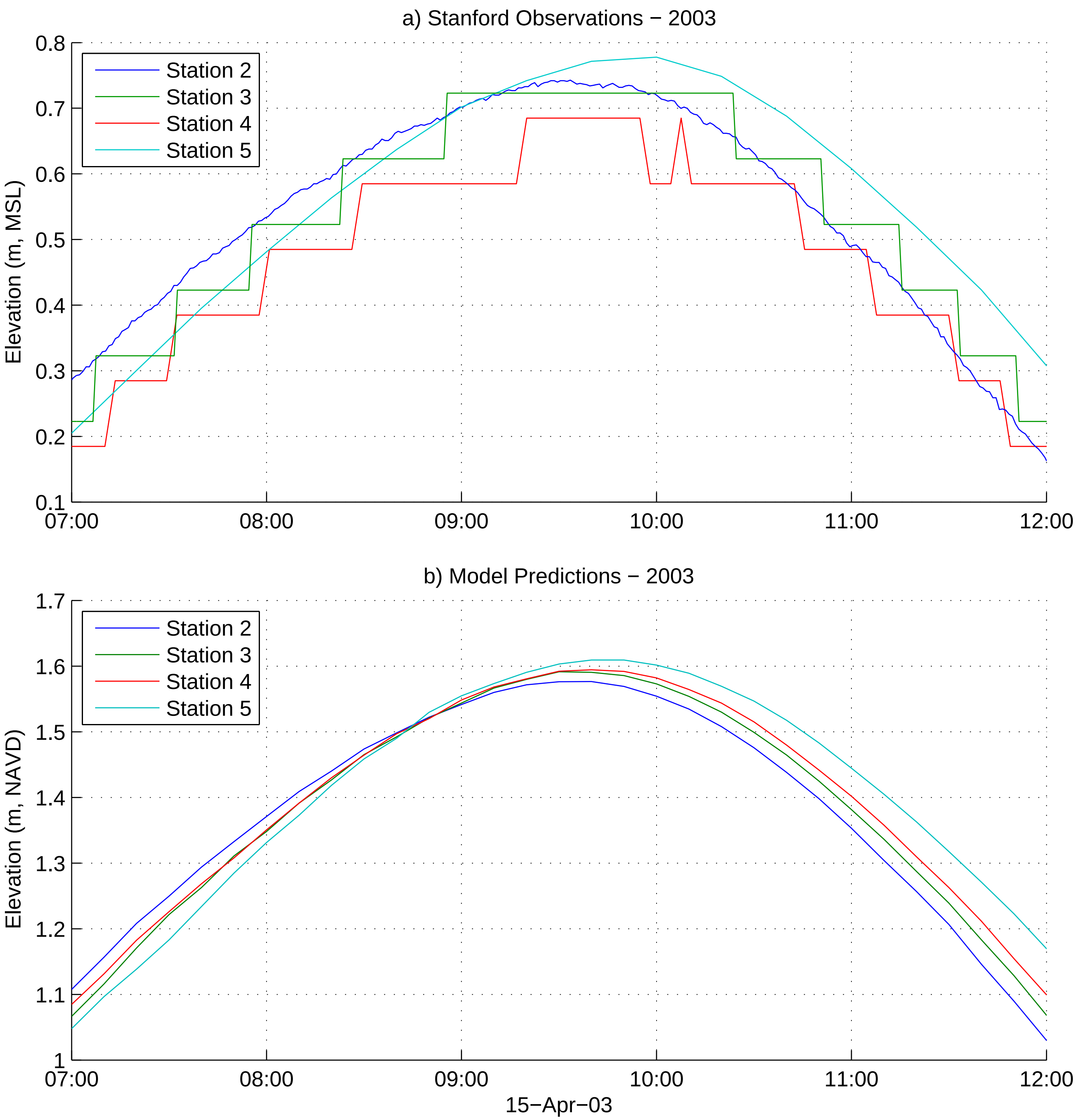

Source: Stanford University observations and DELFT3D model predictions. View has been zoomed to show water surface elevations from four stations along the Slough during higher high water.

Figure 12

Elkhorn Slough Tidal Wetlands Restoration

April 2003 Observed and Predicted Tidal Amplification

PWA Ref# 1869.5

PWA

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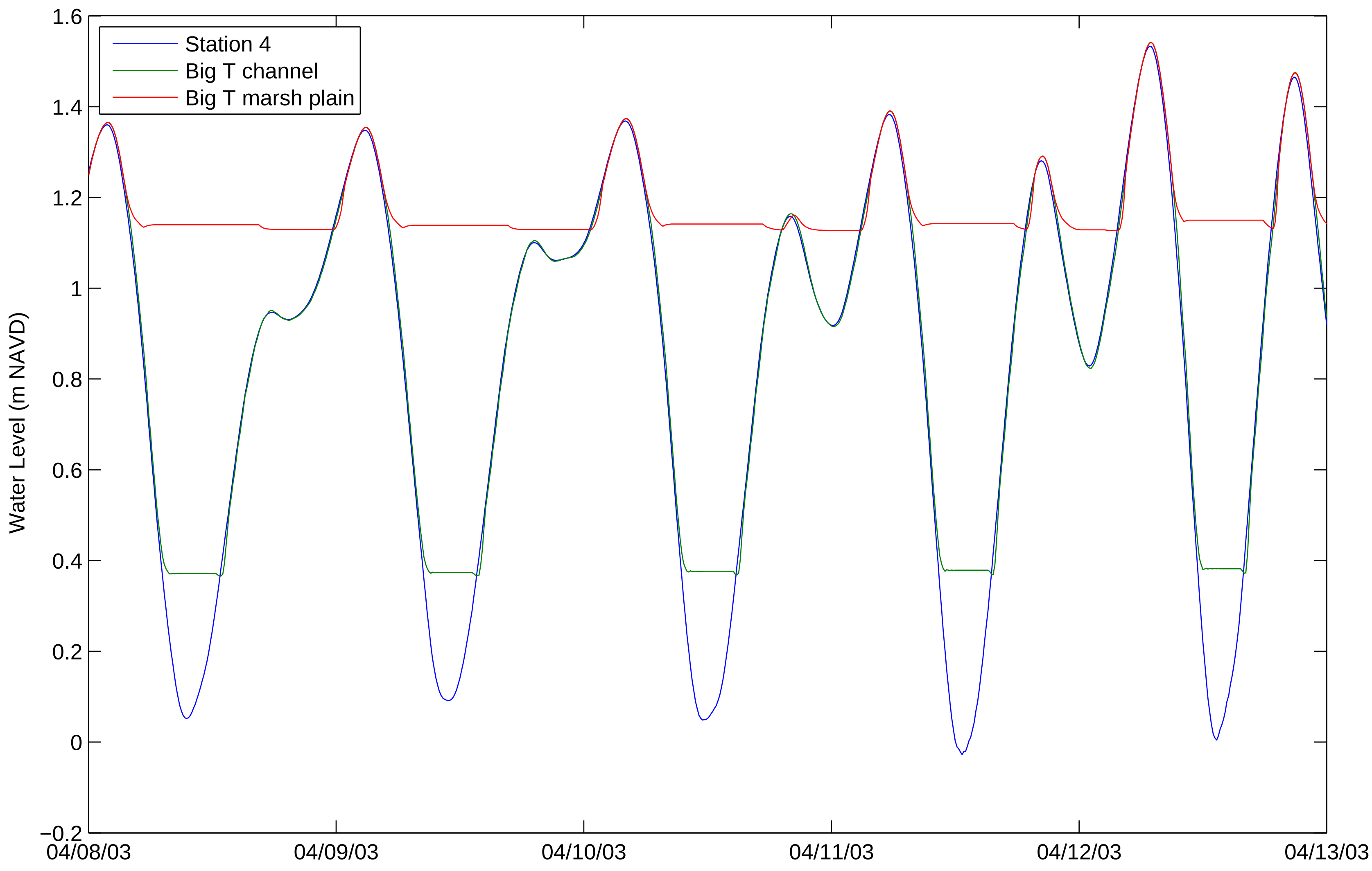

Source: DELFT3D model predictions

Figure 13

Elkhorn Slough Tidal Wetlands Restoration

April 2003 Water Levels, Channel and Marsh Connectivity

PWA Ref# 1869.5

PWA

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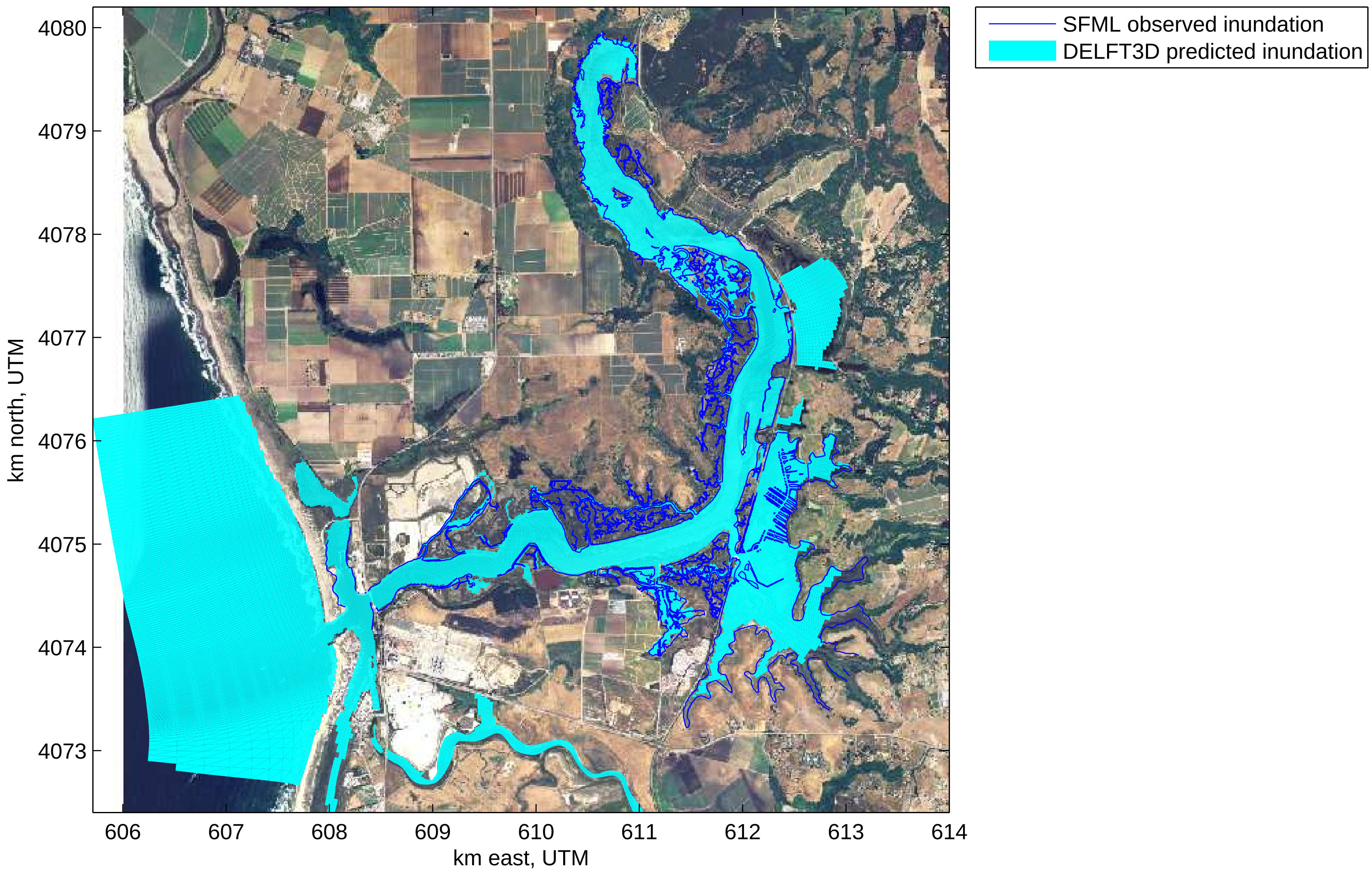

Source: April 2003 DELFT3D model predictions and July 2003 SFML inundation extent from aerial photographs

Figure 14
Elkhorn Slough Tidal Wetlands Restoration

April 2003 and July 2003 Marsh Plain Inundation

PWA Ref# 1869.5

PWA

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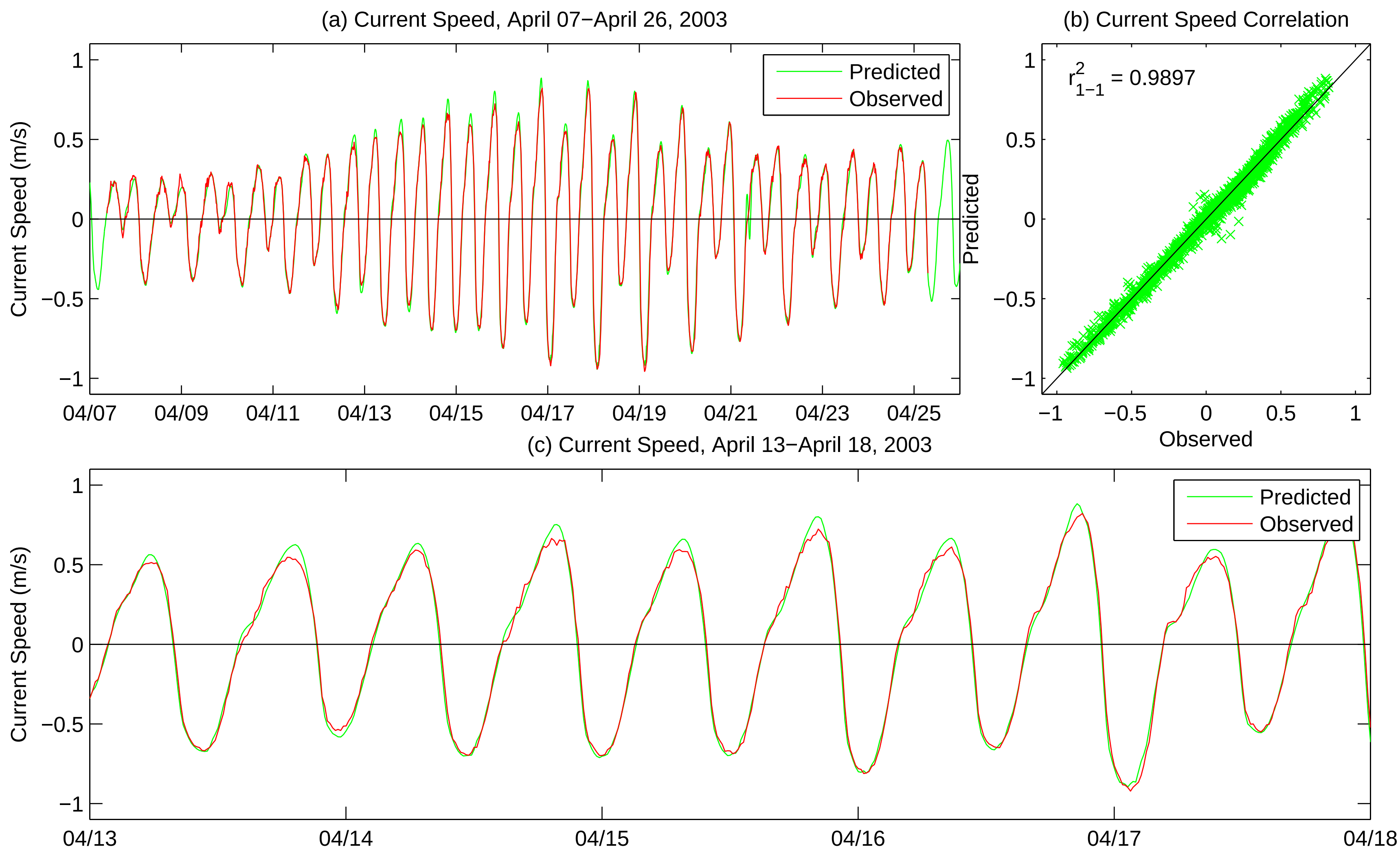

Source: Stanford University observations and DELFT3D model predictions

Figure 15

Elkhorn Slough Tidal Wetlands Restoration

April 2003 Current Speed, Station S1

PWA Ref# 1869.5

PWA

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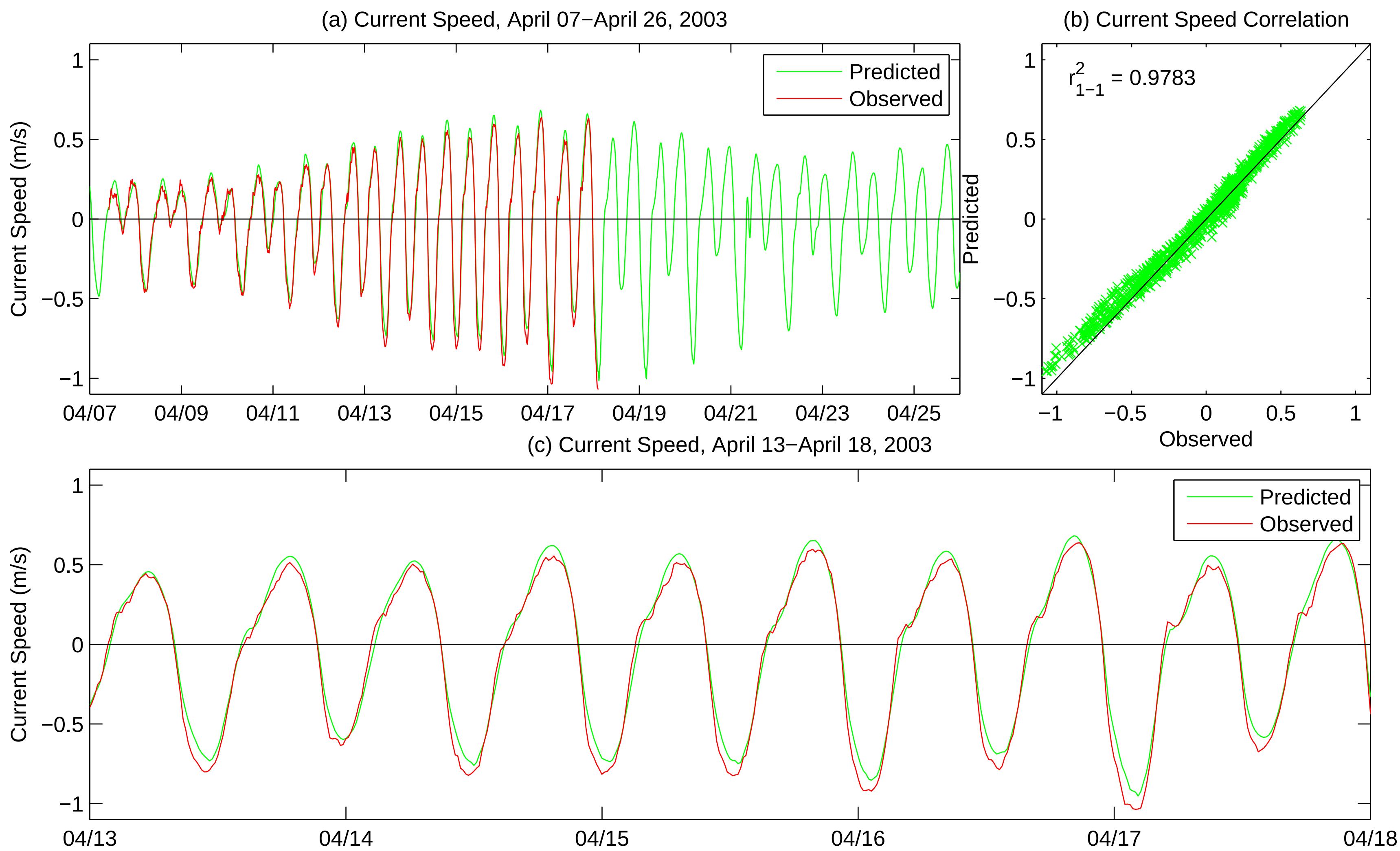


Source: Stanford University observations and DELFT3D model predictions. Observation data ends on April 18 because the instrument package fell over.

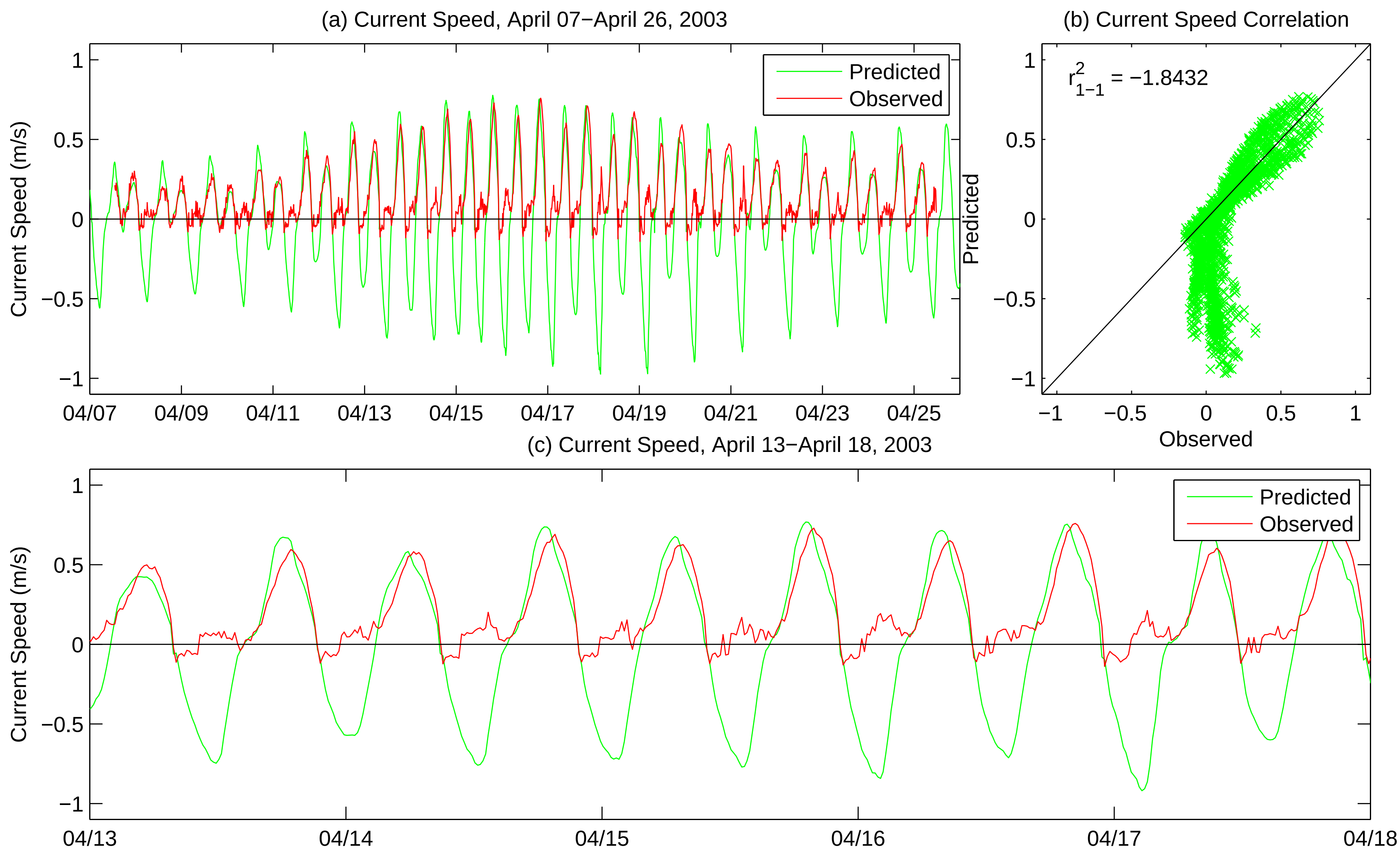
Figure 16
Elkhorn Slough Tidal Wetlands Restoration

April 2003 Current Speed, Station S2

PWA Ref# 1869.5

PWA

\\Orca\PWA\Projects\1869_ElkhornSlough\Task D HydroModeling\Reporting\Final calibration report\figs\matlab figs\output_ek6−4c−station2_vel.fig



Source: Stanford University observations and DELFT3D model predictions. Instrument located in flood−only point of channel cross section.

Figure 17
Elkhorn Slough Tidal Wetlands Restoration

April 2003 Current Speed, Station S3

PWA Ref# 1869.5

PWA

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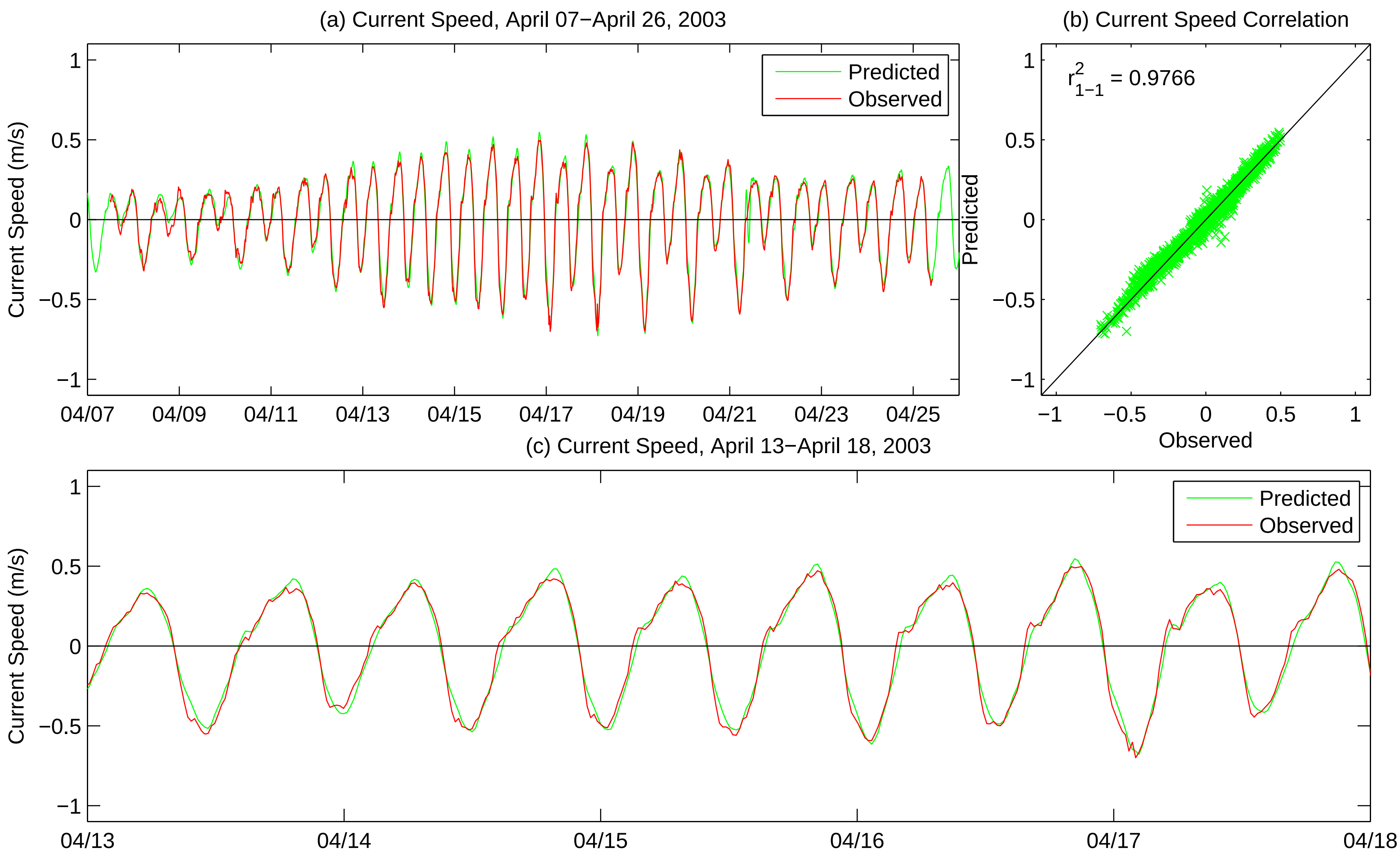

Source: Stanford University observations and DELFT3D model predictions

Figure 18

Elkhorn Slough Tidal Wetlands Restoration

April 2003 Current Speed, Station S4

PWA Ref# 1869.5

PWA

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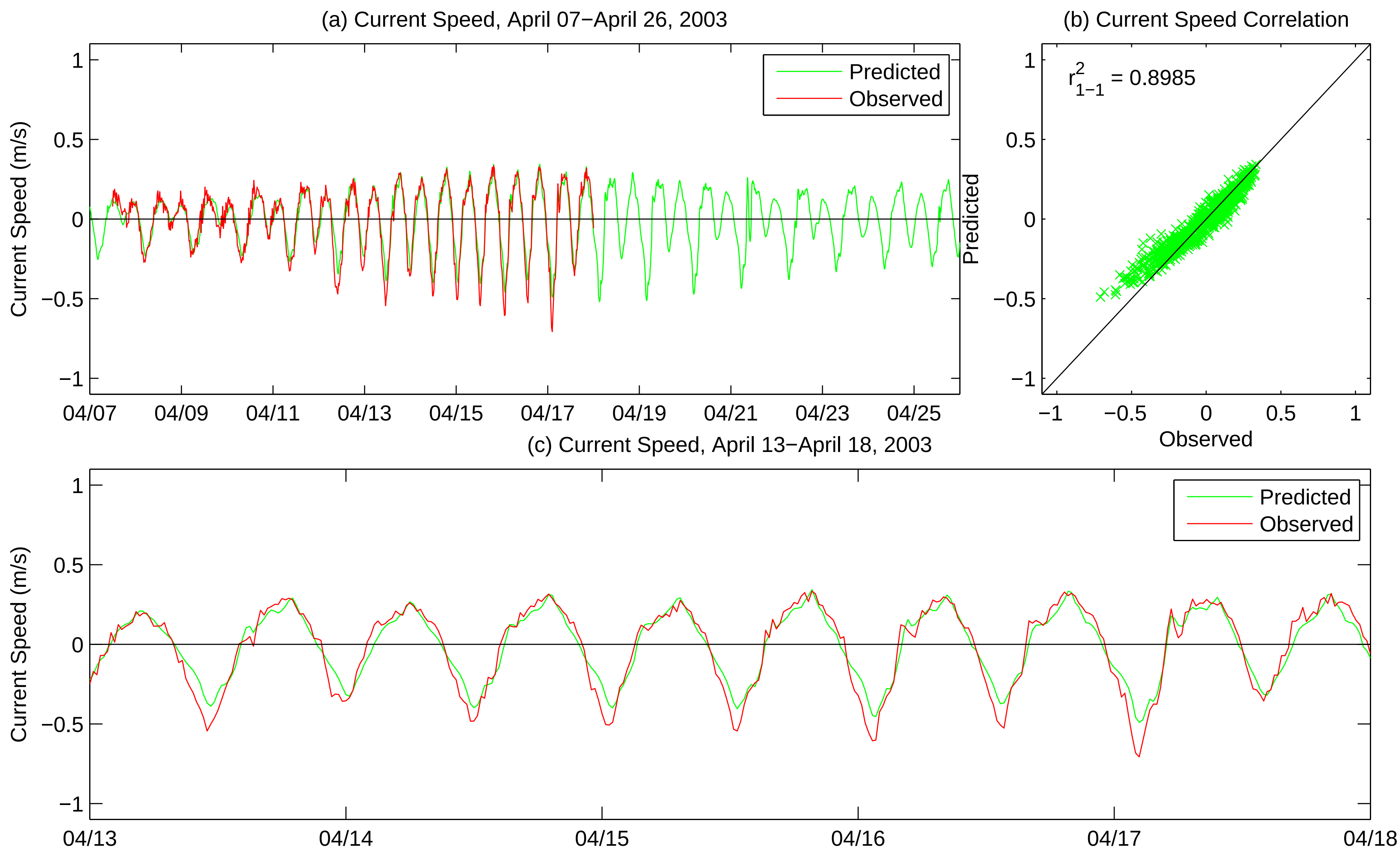

Source: Stanford University observations and DELFT3D model predictions

Figure 19
Elkhorn Slough Tidal Wetlands Restoration

April 2003 Current Speed, Station S5

PWA Ref# 1869.5

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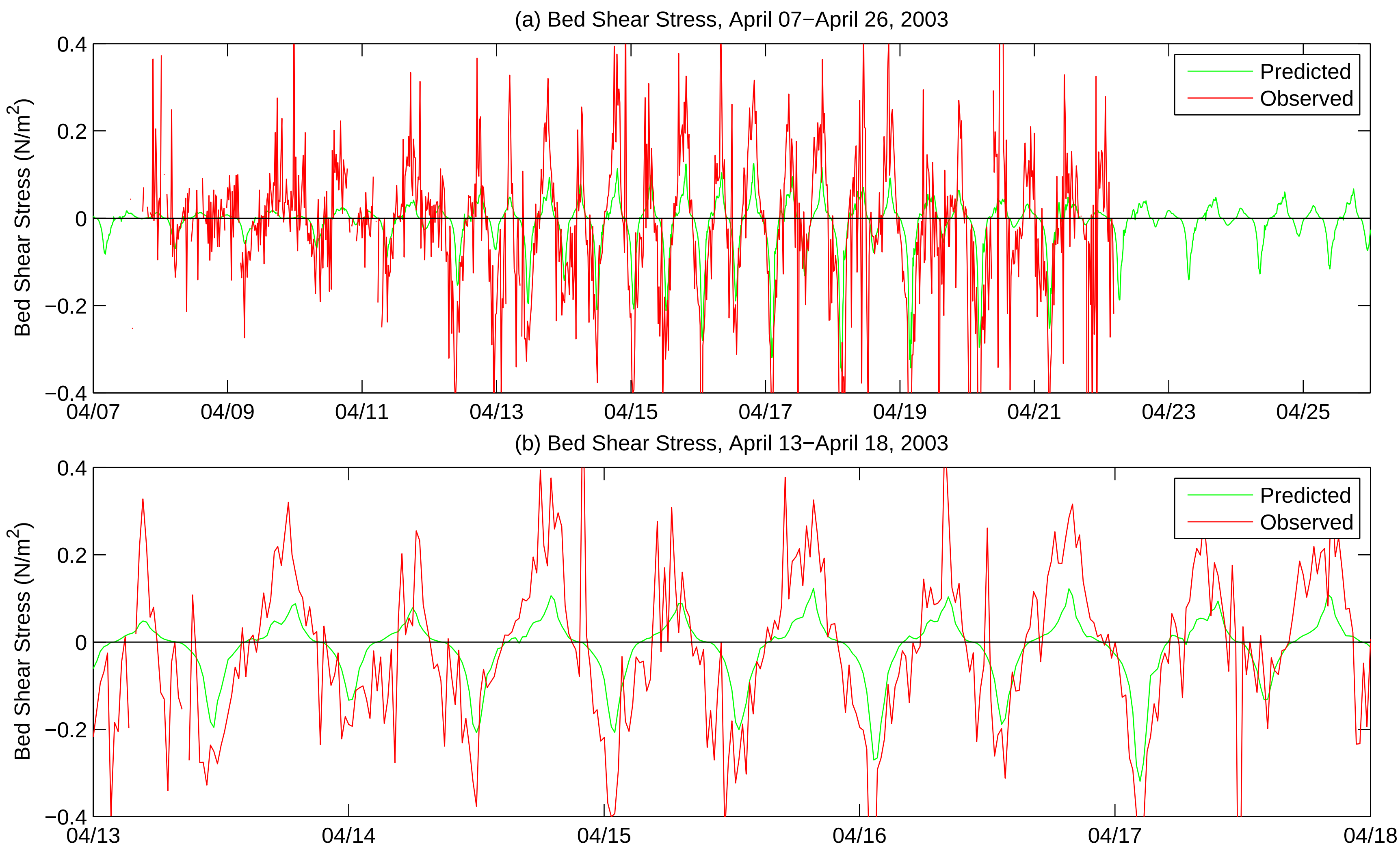

Source: Stanford University observations and DELFT3D model predictions

Figure 20
Elkhorn Slough Tidal Wetlands Restoration

April 2003 Bed Shear Stress, Station S5

PWA Ref# 1869.5

PWA

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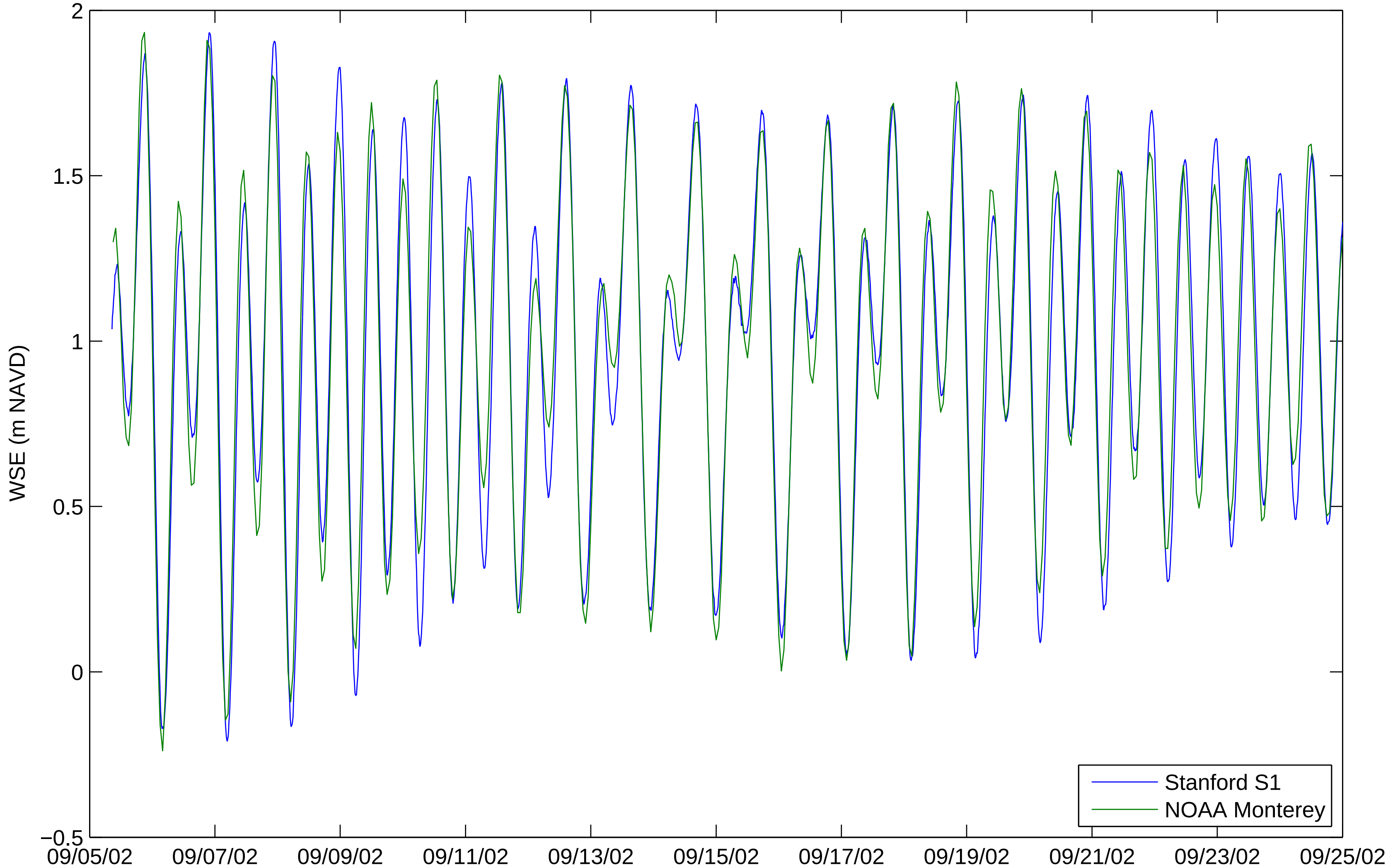

Source: Stanford University observations and NOAA observations (Station ID 9413450)

Figure 21
Elkhorn Slough Tidal Wetlands Restoration

Sept 2002 Observed Water Levels in Elkhorn Slough and Monterey Bay

PWA Ref# 1869.5

PWA

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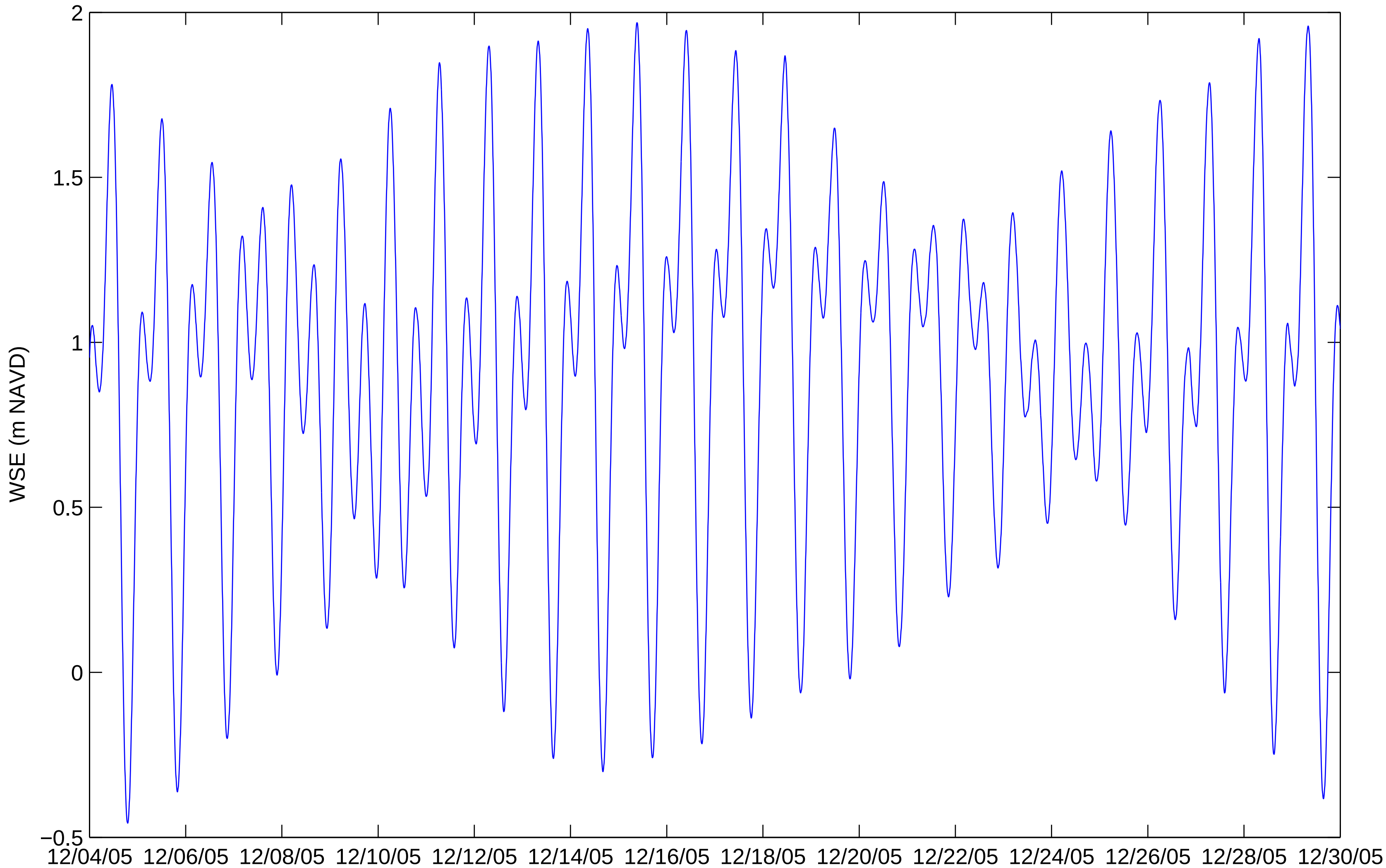


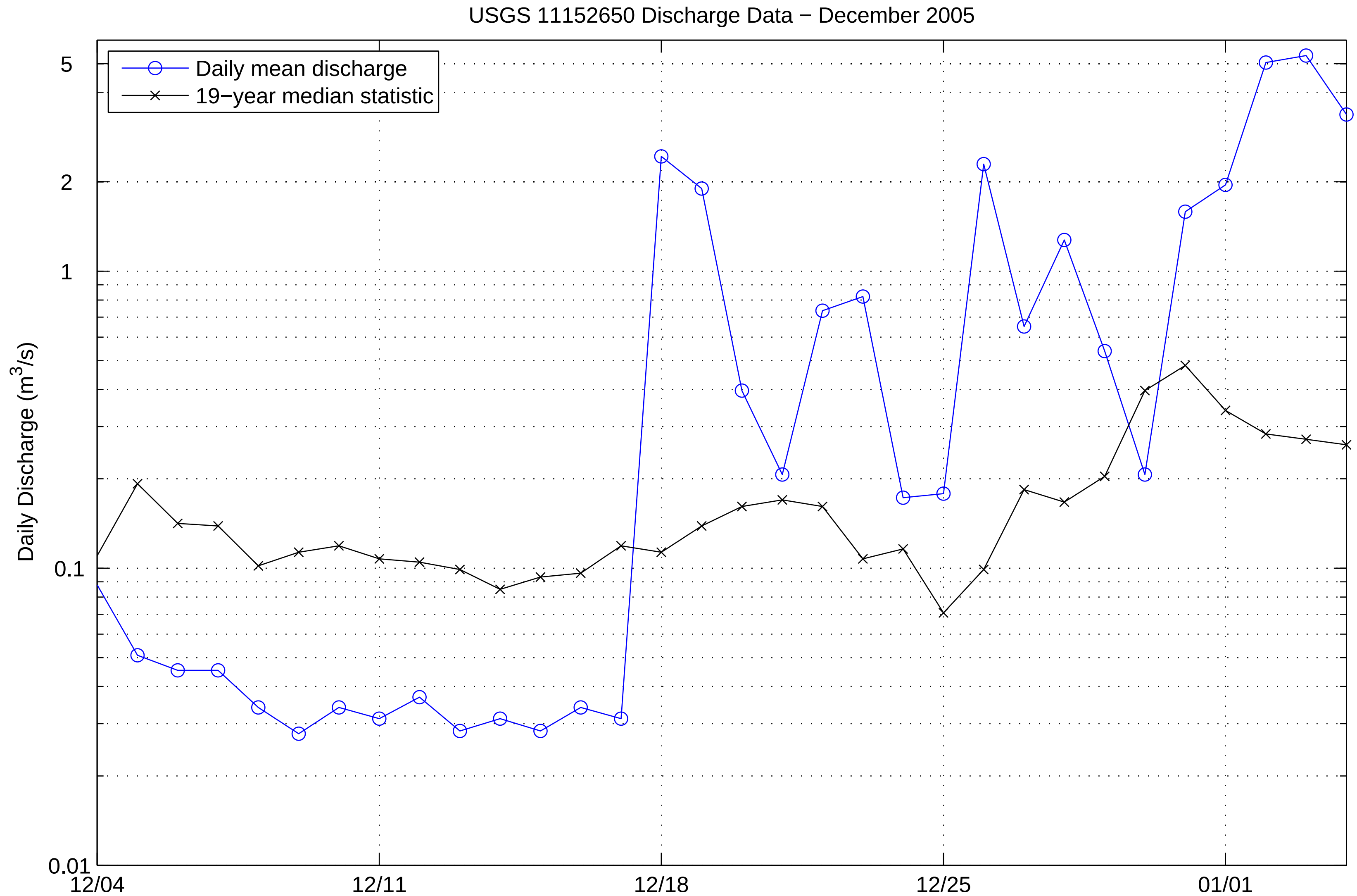
Source: NOAA observations (Station ID 9413450)

Figure 22
Elkhorn Slough Tidal Wetlands Restoration

December 2005 Ocean Boundary Condition

PWA Ref# 1869.5

PWA



Source: USGS observations (Station ID 1152650)

Figure 23
Elkhorn Slough Tidal Wetlands Restoration

December 2005 Freshwater Discharge

PWA Ref# 1869.5

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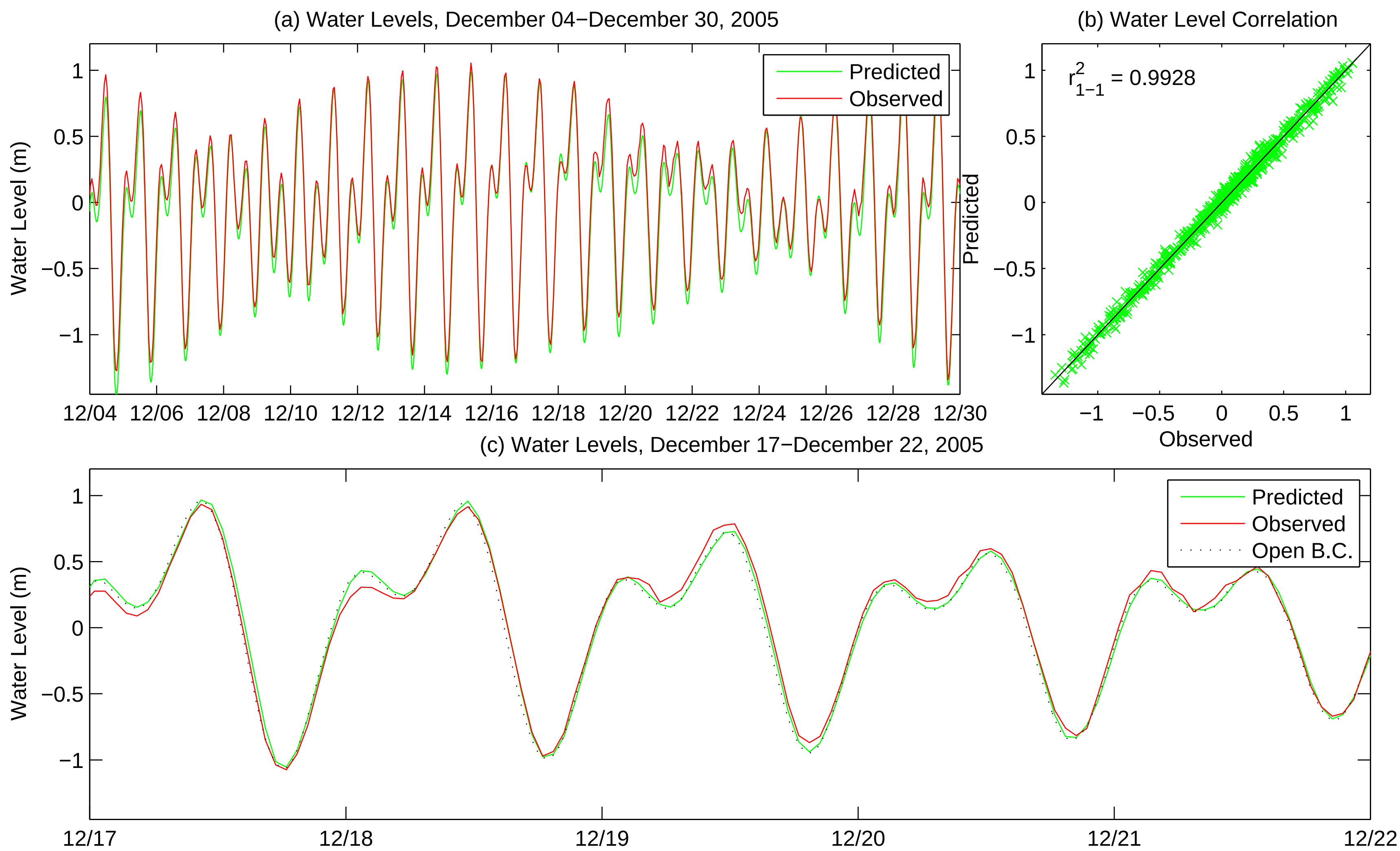

Source: LOBO observations and DELFT3D model predictions

Figure 24
Elkhorn Slough Tidal Wetlands Restoration

December 2005 Water Levels, Station LO1

PWA Ref# 1869.5

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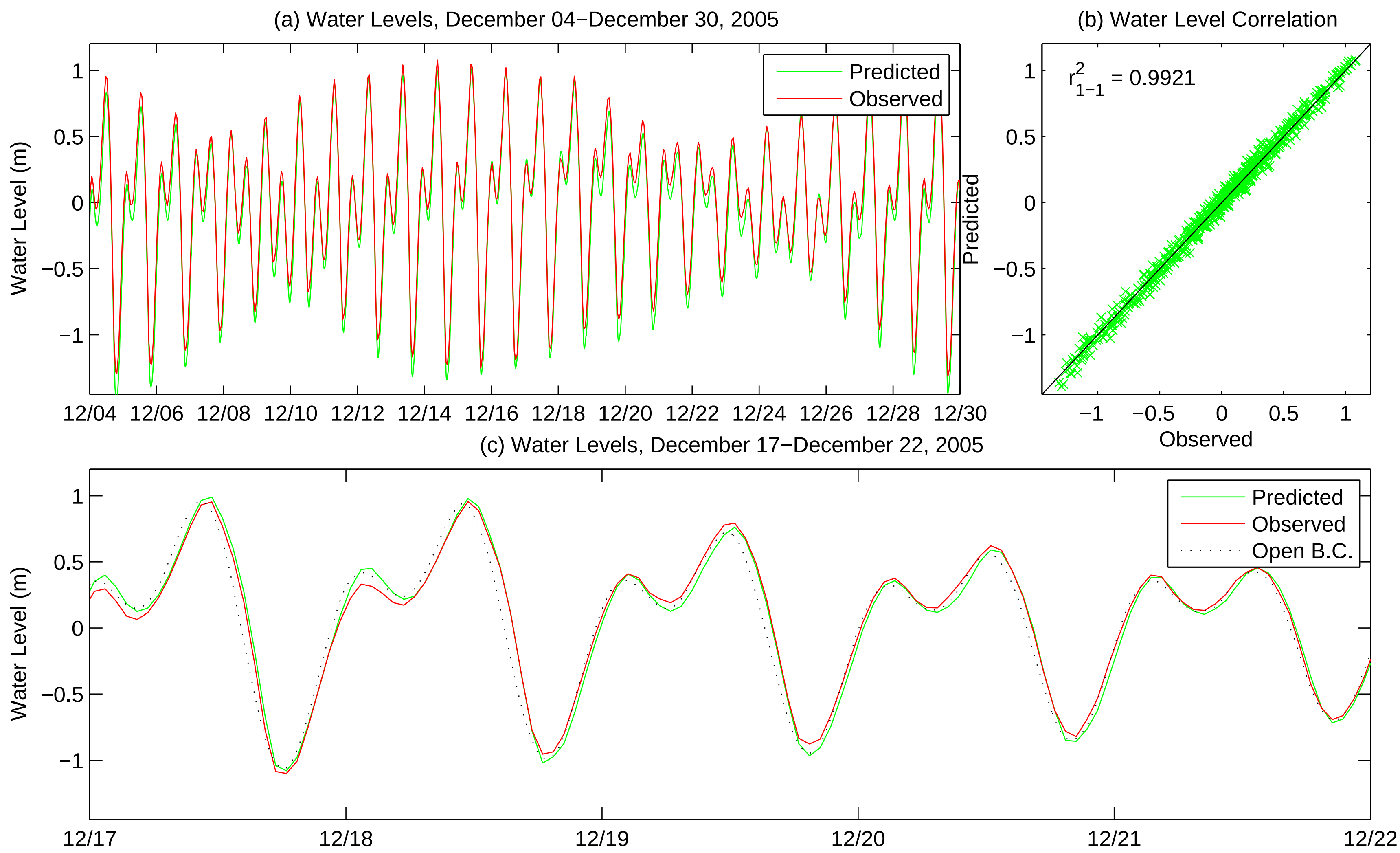

Source: LOBO observations and DELFT3D model predictions

Figure 25
Elkhorn Slough Tidal Wetlands Restoration

December 2005 Water Levels, Station LO2

PWA Ref# 1869.5

PWA

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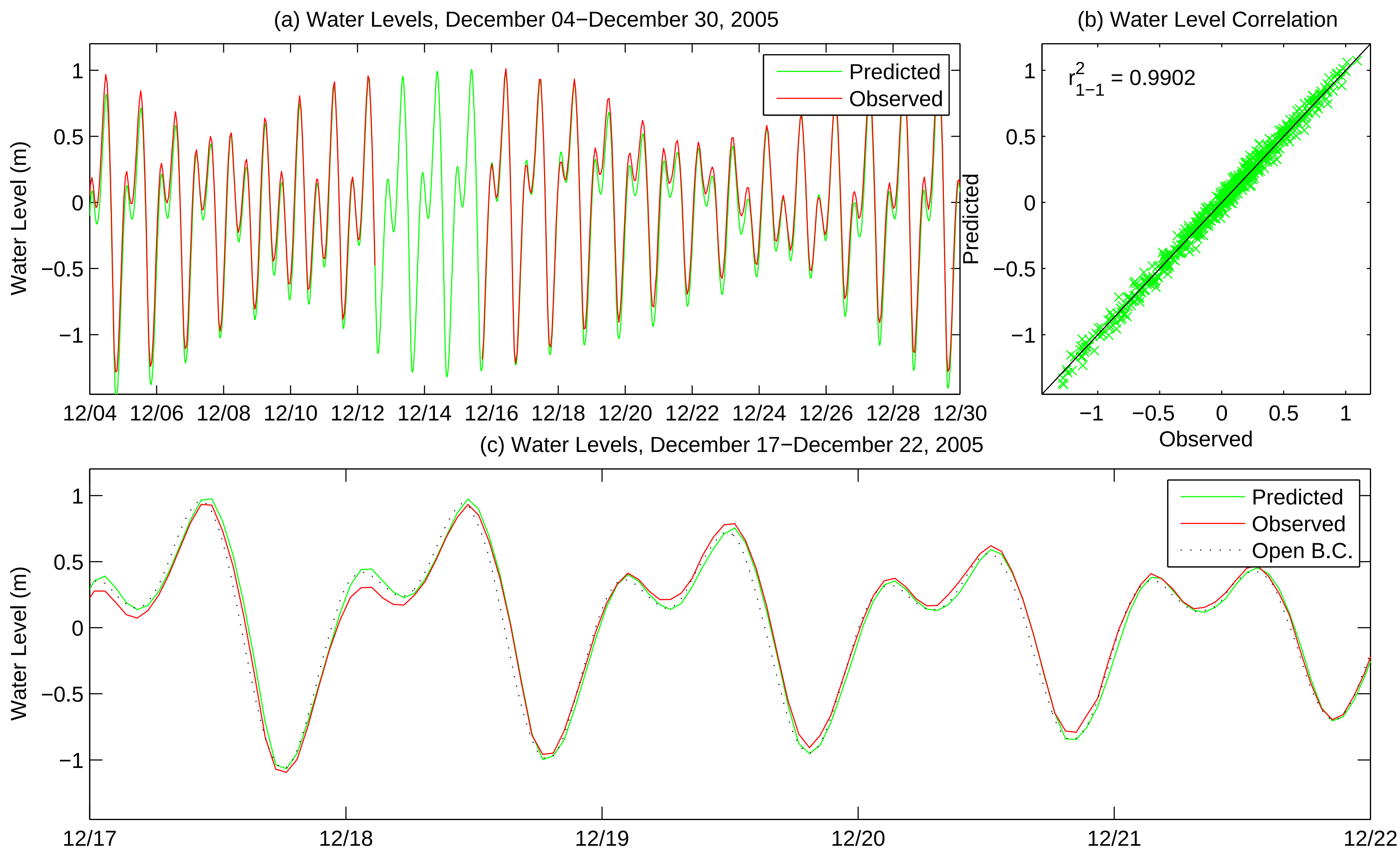

Source: LOBO observations and DELFT3D model predictions

Figure 26
Elkhorn Slough Tidal Wetlands Restoration

December 2005 Water Levels, Station LO4

PWA Ref# 1869.5

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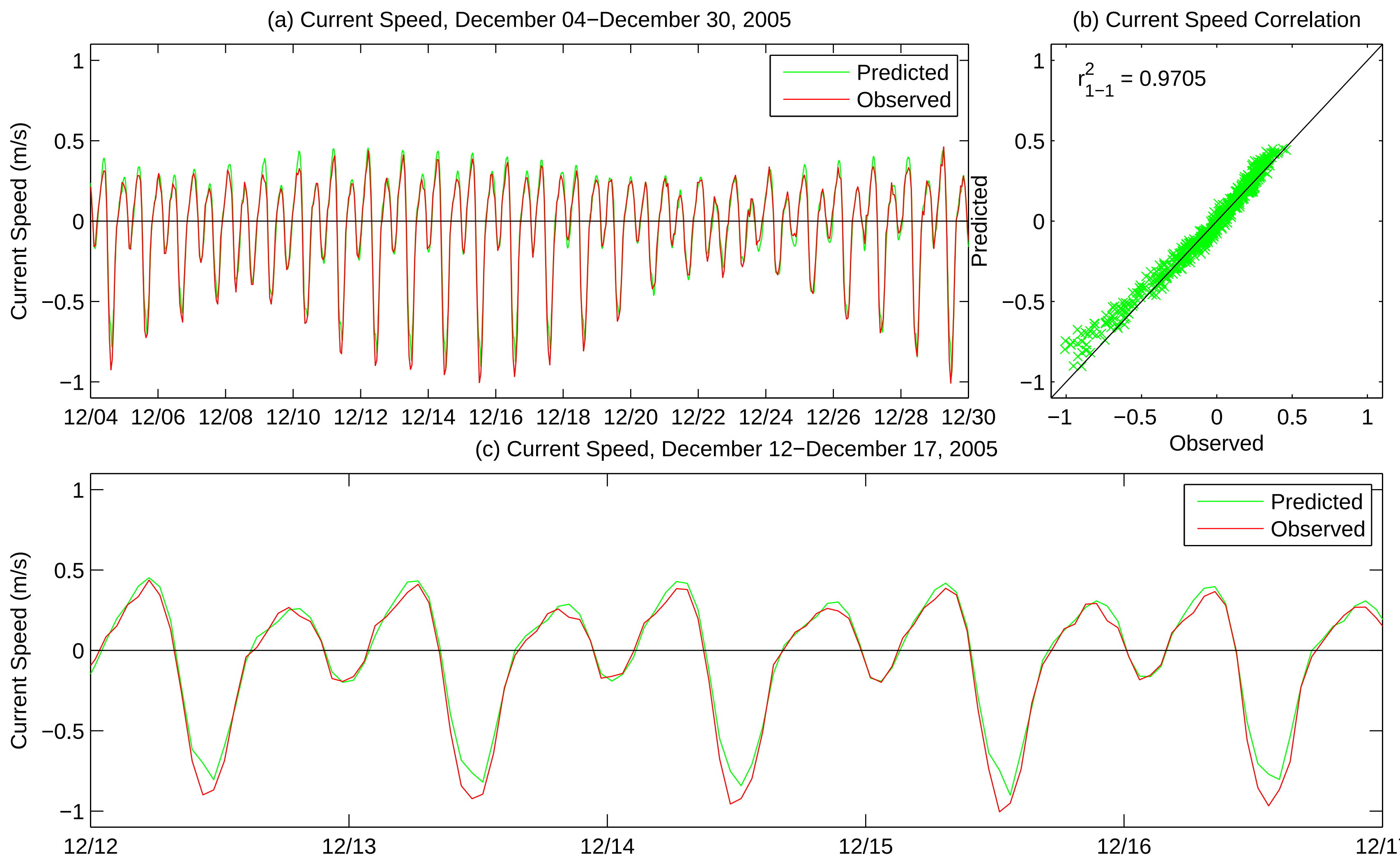

Source: LOBO observations and DELFT3D model predictions

Figure 27
Elkhorn Slough Tidal Wetlands Restoration

December 2005 Current Speed, Station LO1

PWA Ref# 1869.5

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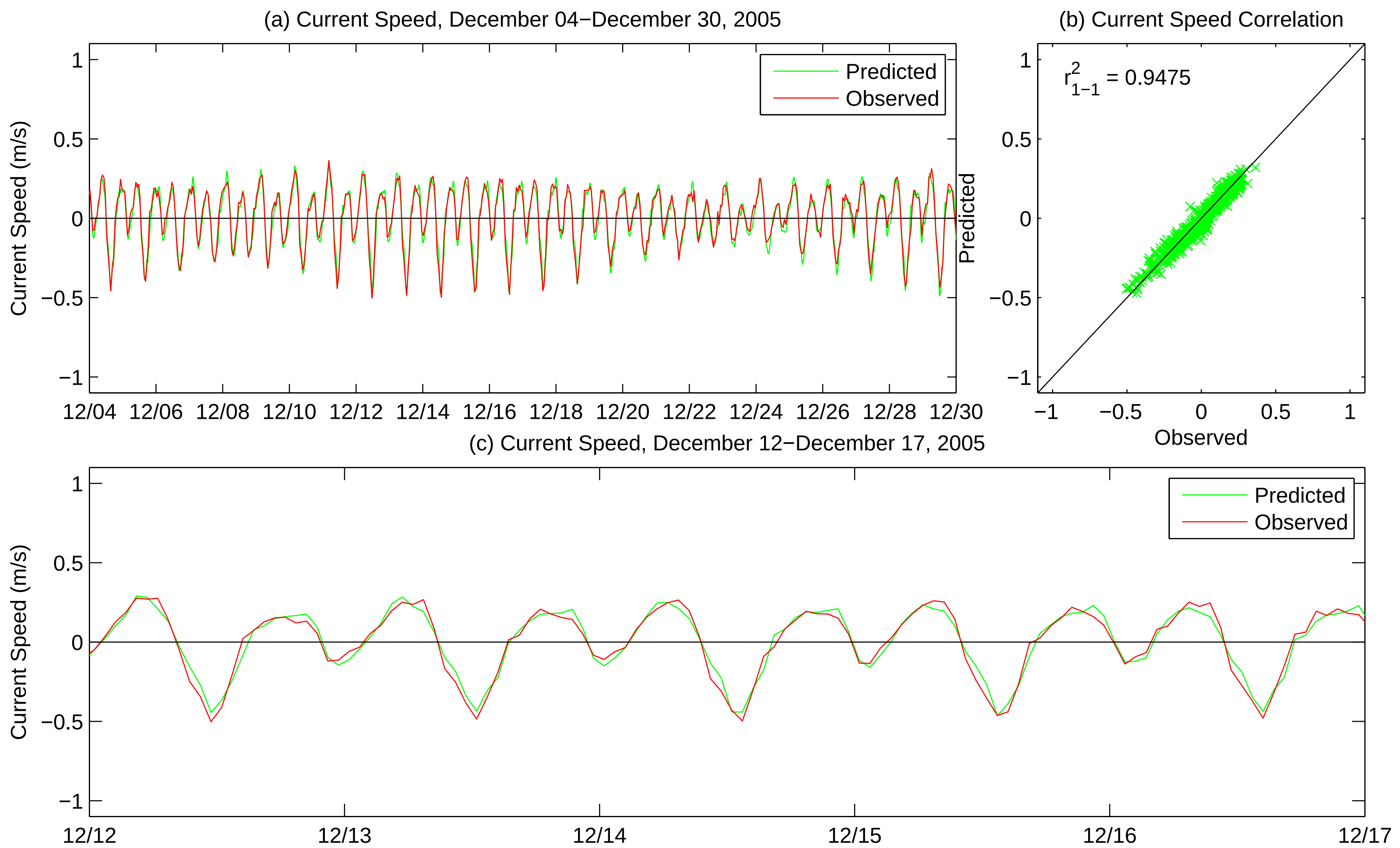

Source: LOBO observations and DELFT3D model predictions

Figure 28
Elkhorn Slough Tidal Wetlands Restoration

December 2005 Current Speed, Station LO2

PWA Ref# 1869.5

PWA

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APPENDIX A.
SENSITIVITY TO FRESHWATER DISCHARGE

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SENSITIVITY TO FRESHWATER DISCHARGE

A sensitivity analysis was performed to address the effect of freshwater discharge on water levels and current speeds within the Elkhorn Slough system. The December 2005 validation period was used for the sensitivity analysis. This period was chosen because it contains a two-week period with relatively minimal precipitation and therefore low freshwater tributary inputs, and a two-week period of heavy rainfall and therefore measurable freshwater tributary inputs would be anticipated. Figure A1 displays the recorded discharge at the USGS gauging station (11152650) in the reclamation ditch near Salinas over this time period. Prior to December 18, very low discharge is reported. The peak discharge of 2.4 m^3/s recorded on December 18 is 16% of the largest recorded daily discharge at this station between 1970 and 2006.

Three simulations were performed to assess the importance of the freshwater discharge:

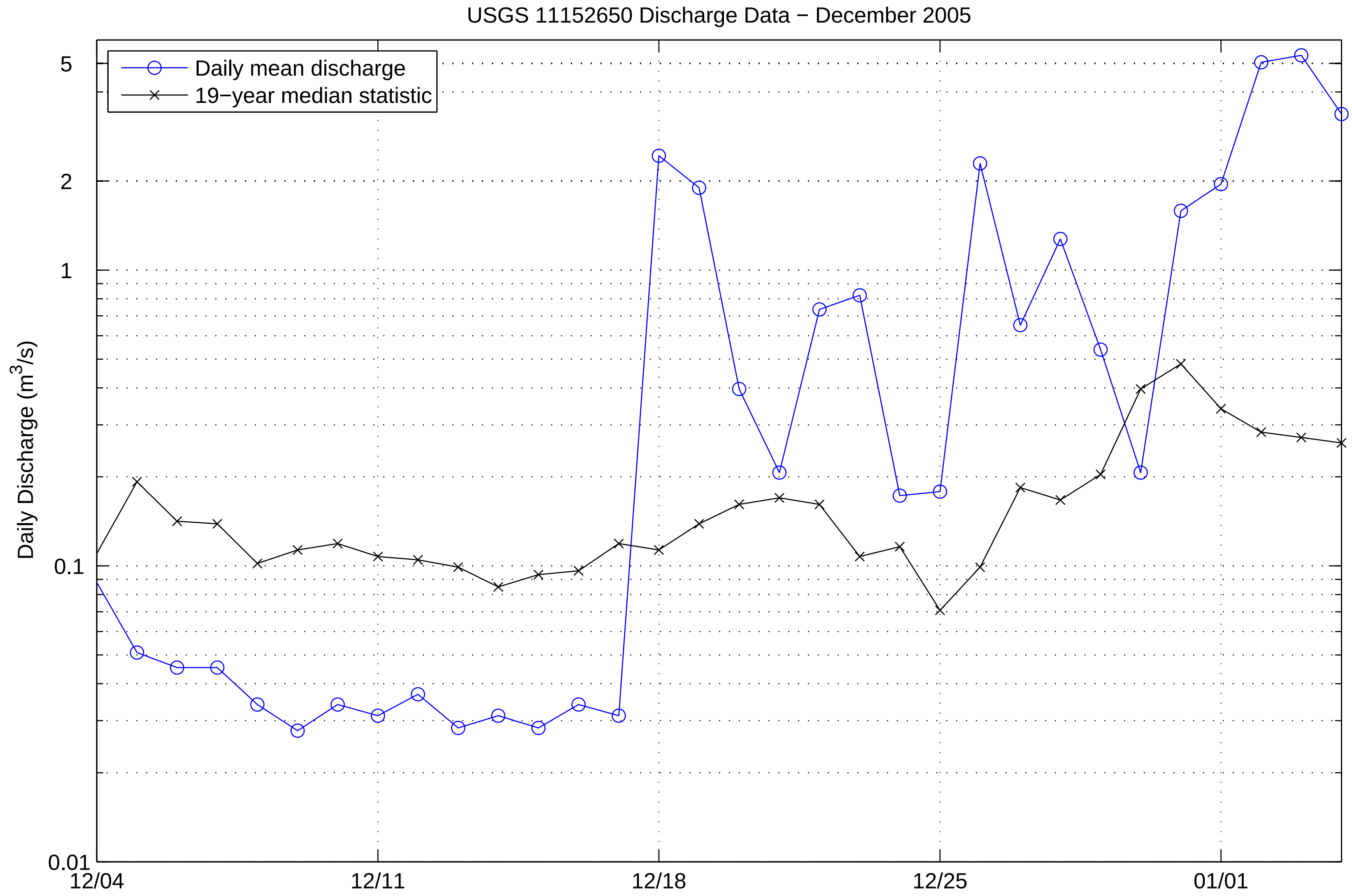
- No freshwater discharge (‘No q_f’): No freshwater discharge into the model domain.
- Discharge to South Harbor (‘Harbor q_f’): Twice the reported USGS gauging station discharge from the reclamation ditch input into the model at the South Harbor.
- Discharge to South Harbor and Head of Slough (‘Harbor & head q_f’): Twice the reported USGS gauging station discharge from the reclamation ditch input into the model at both the South Harbor and at the head of Elkhorn Slough.

The USGS gauging station (11152650) discharge displayed in Figure A1 was doubled to account for additional inflows to the reclamation ditch along the approximately 15 river kilometers between the gauging station and the South Harbor. Discharge observations were not available for the head of the Slough, so the USGS data was applied to the head of the slough as well. Twice the USGS gauging station discharge was used as a conservative estimate. The drainage area upstream of the USGS gauging station is 53.2 square miles while the drainage area of Carneros Creek watershed is only 30.6 square miles (B. Largay, personal communication).

Figure A2 presents the modeled water levels and current speeds at Station S1 for the three simulations. As can be seen, no apparent difference is observed between the three simulations. Figure A3 presents the modeled water levels and current speeds at Station S5. No difference in water levels is observed at Station S5. Small velocity differences are observed.

Figures

Figure A1. December 2005, Recorded Freshwater Discharge
Figure A2. December 2005, Freshwater Discharge Sensitivity, Station S1
Figure A3. December 2005, Freshwater Discharge Sensitivity, Station S5



Source: Stanford University observations and NOAA observations (Station ID 9413450)

Figure A1
Elkhorn Slough Tidal Wetlands Restoration

Dec. 2005, Recorded Freshwater Discharge

PWA Ref# 1869.5

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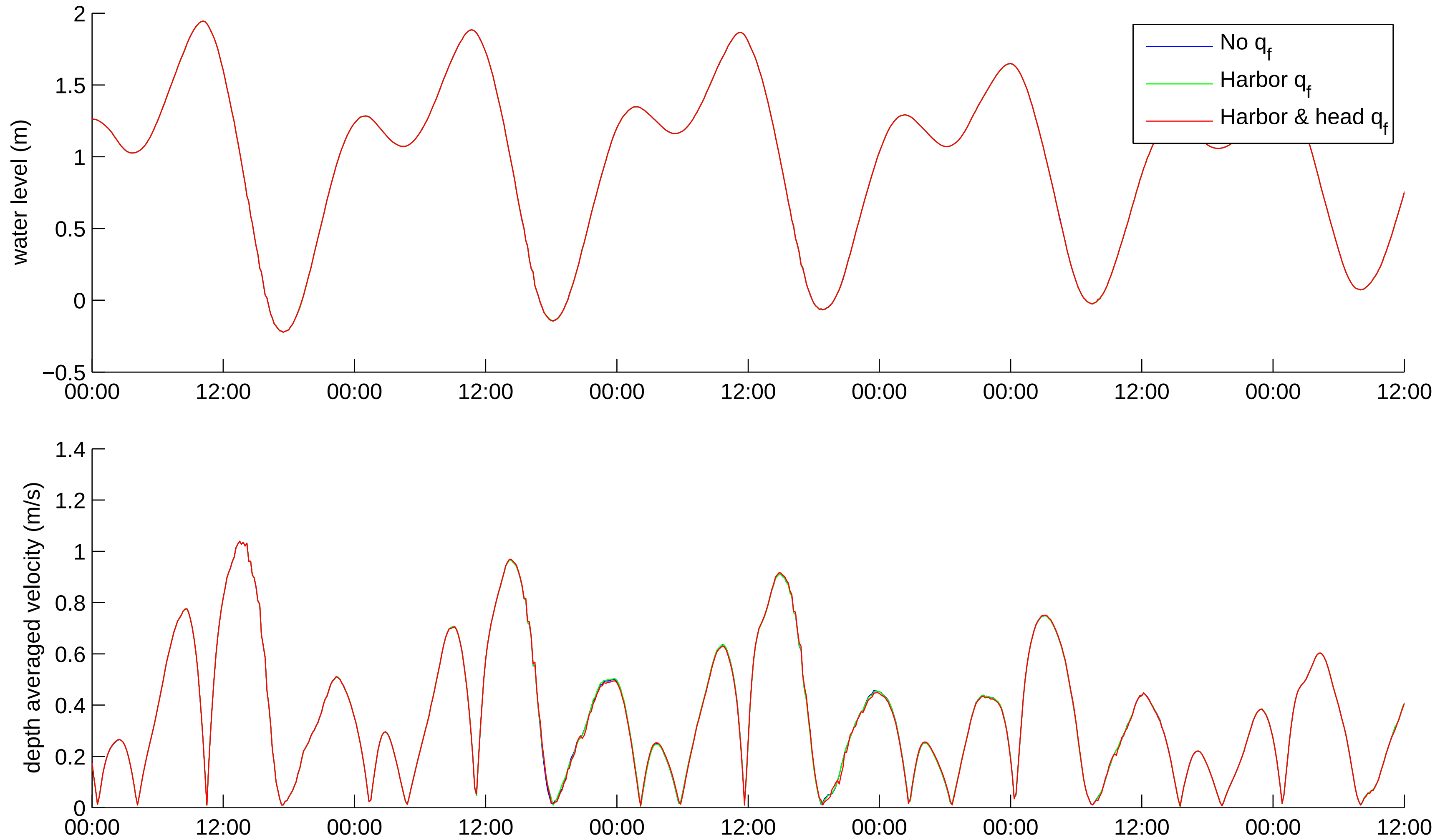

Source: DELFT3D model results

Figure A2
Elkhorn Slough Tidal Wetlands Restoration

Dec. 2005, Freshwater Discharge Sensitivity, Station S1

PWA Ref# 1869.5

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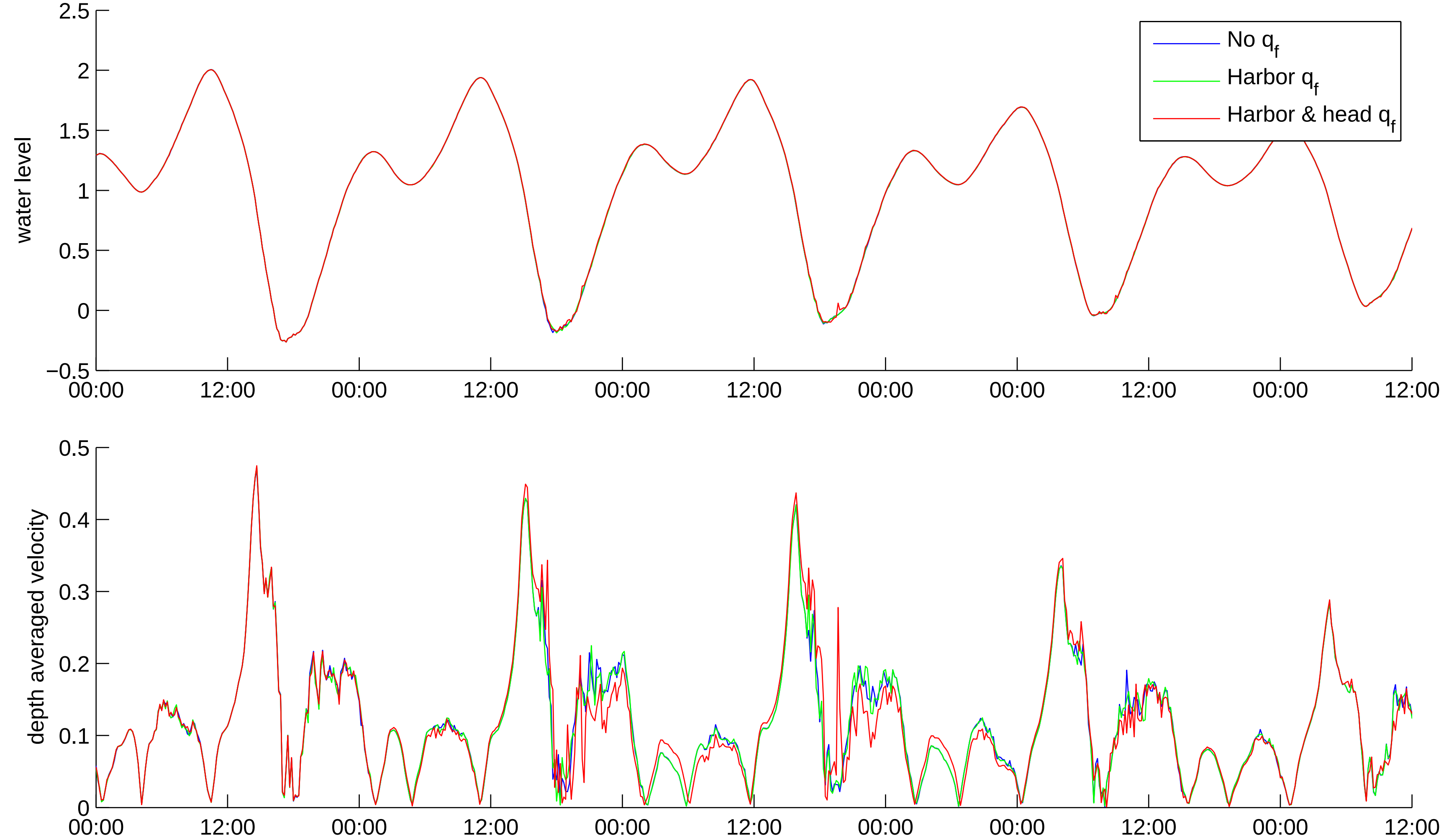

Source: DELFT3D model results

Figure A3

Elkhorn Slough Tidal Wetlands Restoration

Dec. 2005, Freshwater Discharge Sensitivity, Station S5

PWA Ref# 1869.5

PWA

\\Orca\PWA\Projects\1869_ElkhornSlough\Task D HydroModeling\Reporting\Final calibration report\app_a_figs\Station 5 WSE U q_f comparison.fig

APPENDIX B.
SEPTEMBER 2002 SIMULATION RESULTS

APPENDIX B.
SEPTEMBER 2002 SIMULATION RESULTS

This appendix presents the Elkhorn Slough Model simulation results for the September 2002 period. The analysis was conducted over a 19-day period extending from September 5 to September 25, which corresponds to the period of field data collection. Comparisons of predicted and observed water surface elevations, tidal harmonics, current speed and bed shear stress are presented in the following sections. As noted previously, discrepancies between observation data (NOAA Monterey Bay and Stanford University data, see Figure B1) are expected to lead to relatively poor agreement between the comparisons of predicted and observed water levels and current velocities for this period; therefore, a second independent set of data was used to validate the model (see Section 4 of the main report).

In order to remain consistent with the calibration period, the September 2002 simulation utilized the NOAA Monterey Bay observations for the ocean boundary condition. The high frequency oscillations were removed using a fifth-order Butterworth filter with a cut-off frequency of two hours, and the filtered ocean boundary condition used to drive the model is shown in Figure B2. In order to test the effects of the poor agreement between the NOAA and Stanford University water levels during September 2002, an additional simulation was performed utilizing the water level data collected at Station S1 as the ocean boundary condition. Use of this data to drive the model is consistent with the past Stanford University TRIM3D modeling effort (Monismith et al. 2005).

As with the calibration period, the USGS gauging station (11152650) in Old Salinas River Channel approximately 15 km upstream from the South Harbor recorded very limited freshwater inflows, with peak recorded discharges less than 0.1 m^3/s (Figure B4). Freshwater discharges were not included in this validation simulation. The mean monthly Moss Landing Power Plant intake and discharge for September of 39.9 m^3/s was included in the validation simulation (LSP Moss Landing LLC 2002-2006).

The September 2002 field observations were collected at approximately the same stations as the April 2003 deployment (Figure B3). The data successfully collected at each of the five stations are summarized in Table B1. The same methods of analysis used in the calibration period were used to assess model performance.

Table B1. Observed Quantities Collected During Stanford's September 4-24 2002 Deployment

Station	Observed Quantities
S1	Water depth, velocity profile
S2	Water depth, velocity profile
S3	Water depth
S5	Water depth, point velocity, bed shear stress

B1. WATER SURFACE ELEVATIONS

B1.1 Time Series Analysis

Comparisons of predicted and observed water surface elevations at four stations are presented in Figures B5 through B8. These results utilize the filtered NOAA Monterey Bay observations as the ocean boundary condition. The figures for each station show the entire time series of the analysis period, a five-day segment of the time series for closer inspection, and a scatter plot of measured versus modeled data along with the corresponding correlation to the 1:1 line.

The predicted water surface elevations for Station S1 match the NOAA Monterey Bay ocean boundary condition well with respect to amplitude and phase (Figure B5). When compared with the Stanford University observations, the model tends to both over predict and under predict the water levels. The correlation coefficients (r^2) for Stations S1, S2 and S3 are approximately 0.94, with slightly reduced agreement observed at Station S5 with a correlation coefficient of 0.93.

The model is capturing the tidal amplification observed between the mouth and the head of the estuary (i.e., water levels increase with distance from the mouth). Figure B9a presents the observed water depths at all four stations for a 12-hour period on September 18. The tide range increases from the mouth to the head of the Slough for all stations. Figure B9b presents the predicted water levels at the four stations for the same 12-hour period, and as can be seen, the tide range steadily increases from Station S1 to Station S5. However, the predicted increase in tide range between Stations S1 and S5 is smaller than observed in the field measurements by 3 cm.

As expected, the agreement between predicted and observed water levels improves when the model is forced using the Stanford University observations from Station S1 as the ocean boundary condition. Figure B10 displays the predicted and observed water surface elevations for Stations S1, and the model predictions are virtually identical to the field measurements, with a correlation coefficient greater than 0.99. At Station S5, the model predictions also match the field observations closely with respect to amplitude and phase, and a correlation coefficient approaching 0.97 is achieved (Figure B11).

B1.2 Harmonic Analysis

Tidal harmonic analysis was performed on both predicted (using NOAA boundary conditions) and observed water levels over a 21-day analysis period between September 5 and 25. Typically, a longer tidal record (i.e., at least 29 days) would be used for harmonic analysis; however, the present analysis was limited due to the length of the field measurement records.

Table B2 and Table B3 present the phase and amplitudes associated with the modeled and observed tidal constituents, as well as the tidal propagation times between Station S2 and S5. Table B2 shows that modeled water levels are largely within 3 degrees of phase with respect to the dominant tidal constituent (M_2). Phase differences larger than 10 degrees are observed for the K_1, O_1 and S_2 tidal constituents during this validation period. These larger differences are due to the disagreement between the NOAA Monterey Bay observation data used to drive the ocean boundary condition and the Stanford University field measurements use to derive the "measured tidal constituents".

As shown in
Table B2, the M_2 tidal constituent propagates upstream from Station S2 to S5 approximately 0.4 minutes slower than observed in the field measurements, and the K_1 tidal constituent propagates upstream approximately 4.6 minutes faster than the observed tidal constituent.

Table B3 shows that predicted tidal amplitudes are within 1 cm of the observed tidal amplitude with respect to M_2, O_1 and S_2. Positive values represent larger modeled amplitudes, and negative values represent smaller modeled amplitudes. The largest difference between modeled and measured tidal harmonics is associated with the K_1 tidal constituent. K_1 is slightly over predicted at Station S2 and S4, and under predicted at Station S3 and S5.

Table B2. Phase Differences between Modeled and Measured Tidal Constituents, Validation Run, September 2002

All values are in degrees

	S2	**S3**	**S4**	**S5**	**Propagation Error**	
					[min]	**% Error**
M_2	-0.8	-2.0	3.4	-0.6	0.4	1.7
K_1	-15.1	-14.8	-10.8	-16.2	-4.6	-14.0
O_1	11.6	10.1	14.9	11.7	0.6	1.8
S_2	-29.0	-31.0	-27.8	-28.9	0.2	0.7

Table B3. Amplitude Differences between Modeled and Measured Tidal Constituents, Validation Run, September 2002

	S2		**S3**		**S4**		**S5**	
	(cm)	**% Diff**	**(cm)**	**% Diff**	**(cm)**	**% Diff**	**(cm)**	**% Diff**
M_2	0.0	0.0	0.4	0.7	0.2	0.4	-0.7	-1.2
K_1	1.7	-4.4	-0.8	-2.0	0.5	1.3	-2.1	-5.2
O_1	-0.3	-1.3	0.1	0.4	0.9	4.1	-0.5	-2.1
S_2	0.1	0.6	0.5	3.1	0.4	2.4	0.5	3.0

B2. CURRENT SPEED

Comparisons of predicted and observed current speeds at three stations are presented in Figures B12 through B14. The figures for each station show the entire time series of the analysis period, a five-day segment of the time series for closer inspection, and a scatter plot of measured versus modeled data along with the corresponding correlation to the 1:1 line.

The model accurately predicts the semi-diurnal pattern and spring-neap variability, with the highest velocities occurring on ebb tides. The model also captures the relative decrease in current speed observed between Stations S1 and S5. As expected, the match between model predictions and field observations for this validation simulation is not as good as shown for the calibration period.

Figure B12 displays a comparison of predicted and observed current speeds at Station S1 located nearest to the inlet to Monterey Bay. Predicted and observed current speeds correspond well, with a correlation coefficient squared (r^2) greater than 0.95. As can be seen, the model tends to under predict flood current speeds and over predicts ebb current speeds. The same trend is observed at Station S2 (Figure B13), with a correlation coefficient squared greater than 0.94. Station S5 exhibits the poorest fit between model predictions and field measurements, with a correlation coefficient squared of approximately 0.87 (Figure B14). One reason for the lower agreement at this station is the reduced variability in current speeds – the range in current speeds is smaller than that observed at the other stations.

B3. BED SHEAR STRESS

Figure B15 presents a comparison of predicted and observed bed shear stress at Station S5 near the head of Elkhorn Slough. The figure shows the entire time series of the analysis period, a five-day segment of the time series for closer inspection, and a scatter plot of measured versus modeled data along with the corresponding correlation to the 1:1 line. Given that predicted bed shear is a derived value and proportional to the square of the current speed, the predicted bed shear stress matches the observed bed shear stress well on both flood and ebb tides. The agreement between predicted and measured bed stress is better after September 14 when NOAA Monterey Bay and Stanford University field measurements show better agreement.

Figures

Figure B1. September 2002 Observed Water Levels in Elkhorn Slough and Monterey Bay
Figure B2. September 2002 Ocean Boundary Condition
Figure B3. Station Locations
Figure B4. September 2002 Freshwater Discharge
Figure B5. September 2002 Water Levels, Station S1
Figure B6. September 2002 Water Levels, Station S2
Figure B7. September 2002 Water Levels, Station S3
Figure B8. September 2002 Water Levels, Station S5
Figure B9. September 2002 Observed and Predicted Tidal Amplification
Figure B10. September 2002 Water Levels, Station S1 (w/ Stanford BC)
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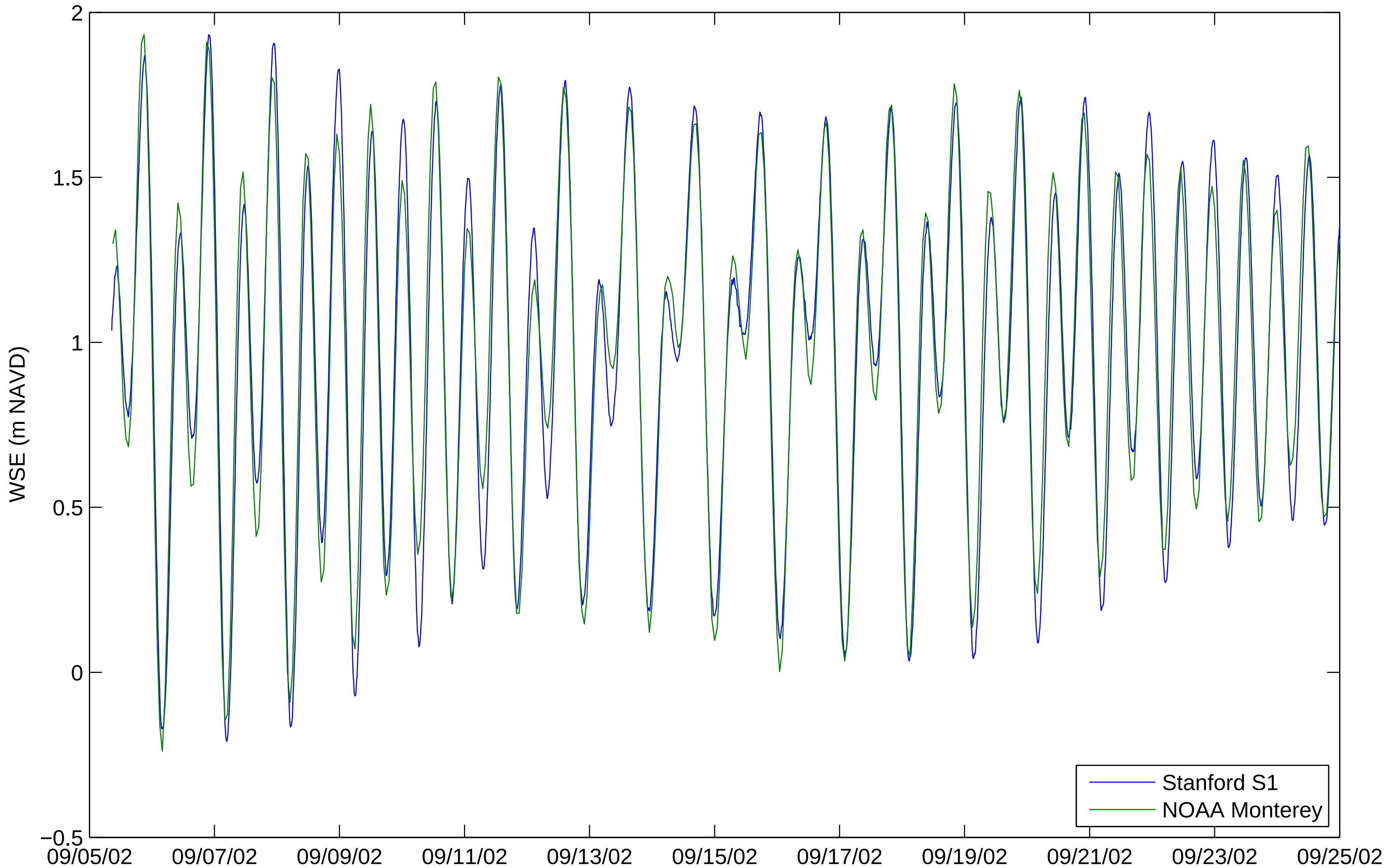
Figure B12. September 2002 Current Speed, Station S1
Figure B13. September 2002 Current Speed, Station S2
Figure B14. September 2002 Current Speed, Station S5
Figure B15. September 2002 Bed Shear Stress, Station S5



Source: Stanford University observations and NOAA observations (Station ID 9413450)

Figure *B1*

Elkhorn Slough Tidal Wetlands Restoration

Sept. 2002 Observed Water Levels in Elkhorn Slough and Monterey Bay

PWA Ref# 1869.5

PWA

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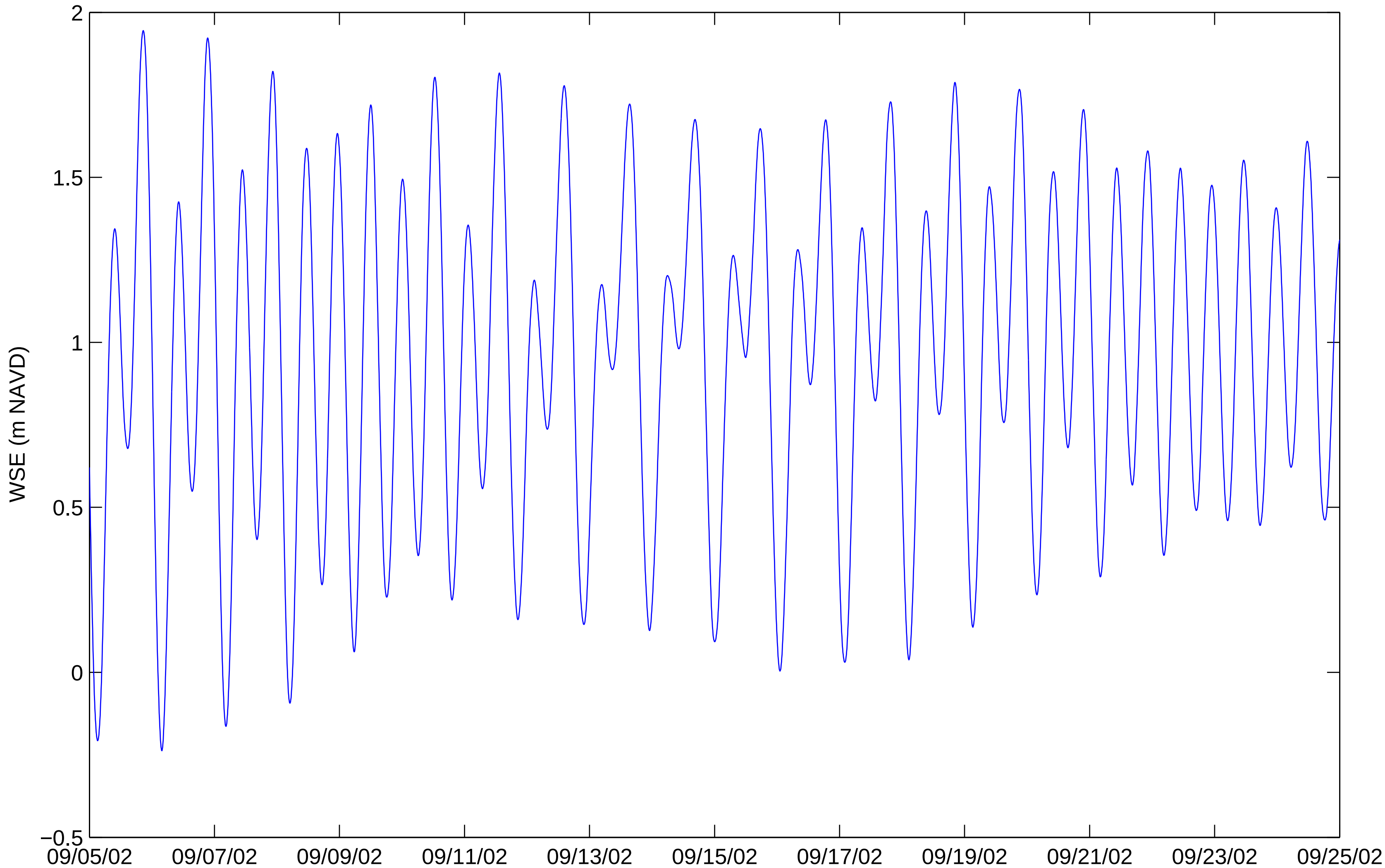

Source: NOAA observations (Station ID 9413450)

Figure *B2*

Elkhorn Slough Tidal Wetlands Restoration

September 2002 Ocean Boundary Condition

PWA Ref# 1869.5

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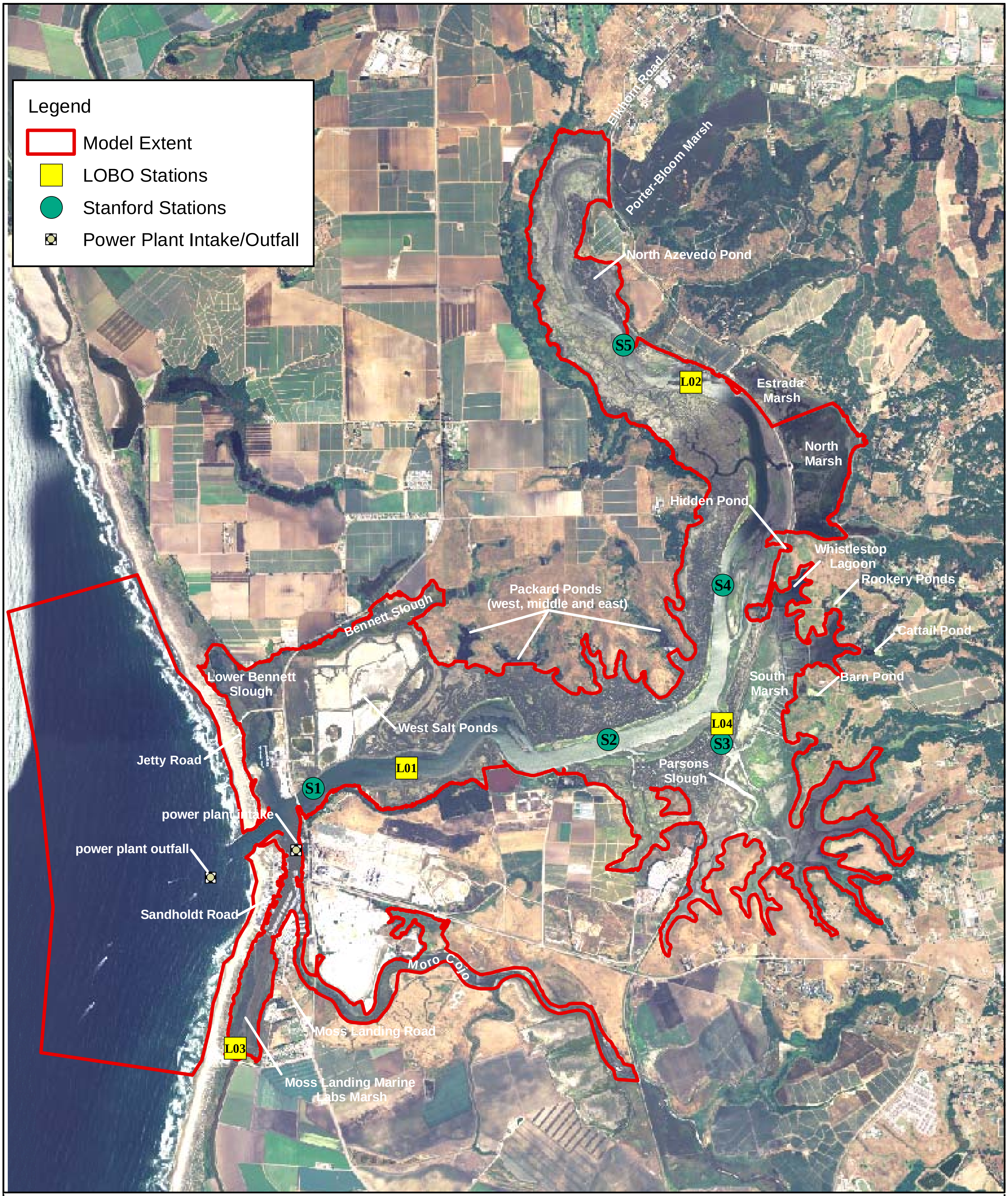

Source: USDA/NAIP 1m/pixel true color ortho (2005)

N

0 1,250 2,500 5,000 7,500 Feet

figure B3

Elkhorn Slough Tidal Wetland Project

Station Locations

Proj. # 1869

PWA

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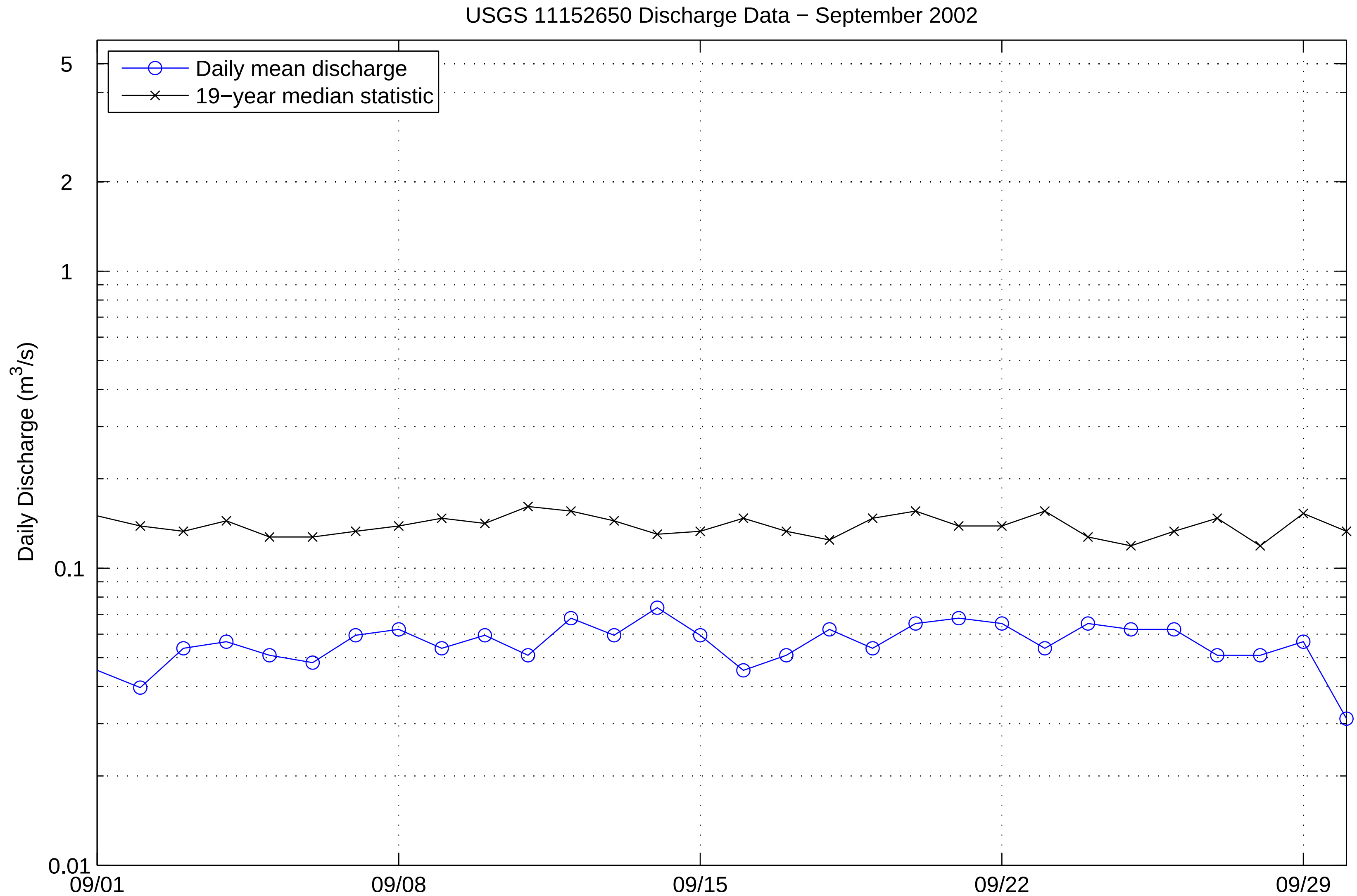

Source: USGS observations (Station ID 1152650)

Figure *B4*
Elkhorn Slough Tidal Wetlands Restoration

September 2002 Freshwater Discharge

PWA Ref# 1869.5

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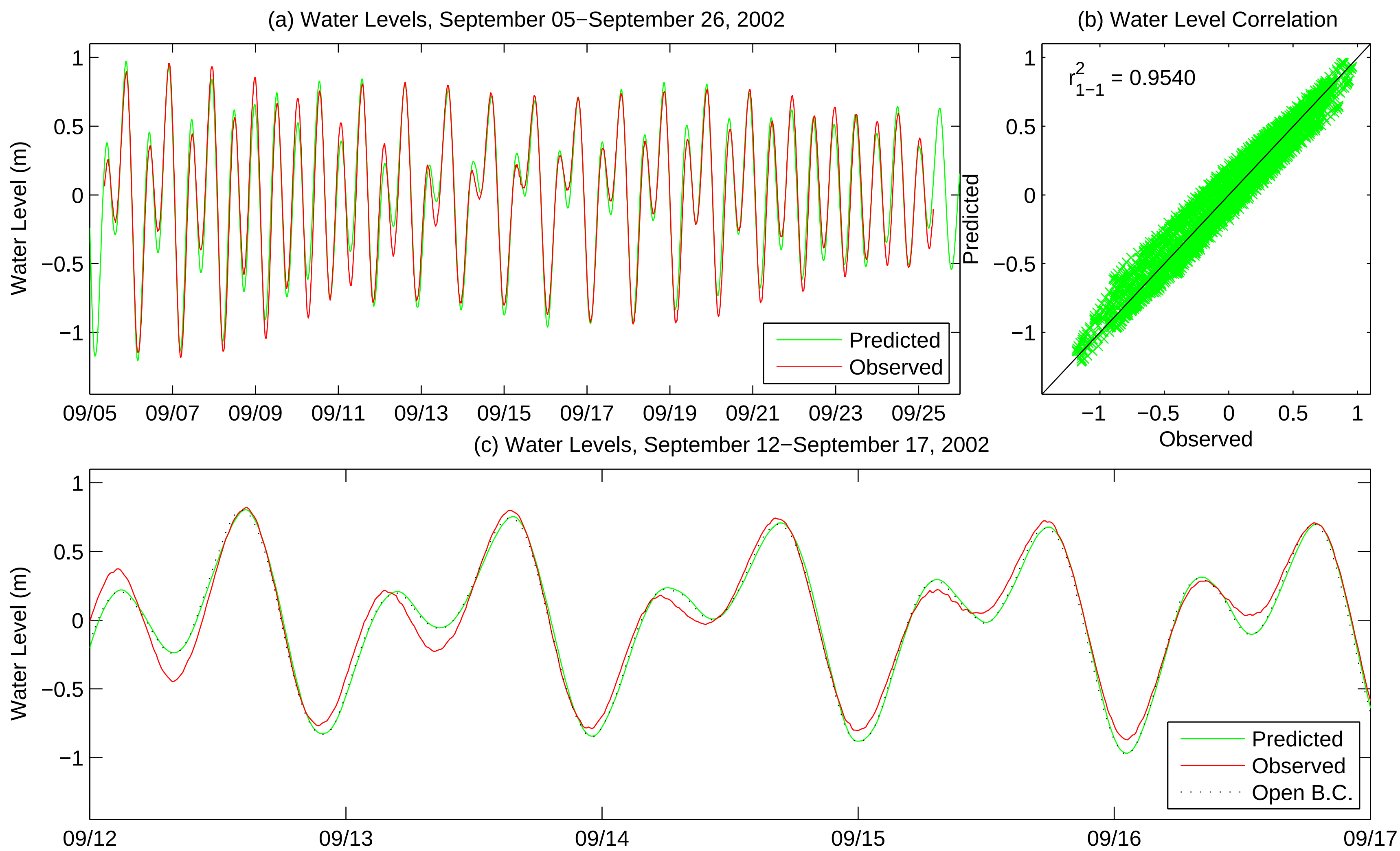

Source: Stanford University observations and DELFT3D model predictions. NOAA observations for Monterey Bay (Station ID 9413450) used as the tidal boundary condition.

Figure *B5*
Elkhorn Slough Tidal Wetlands Restoration

September 2002 Water Levels, Station S1

PWA Ref# 1869.5

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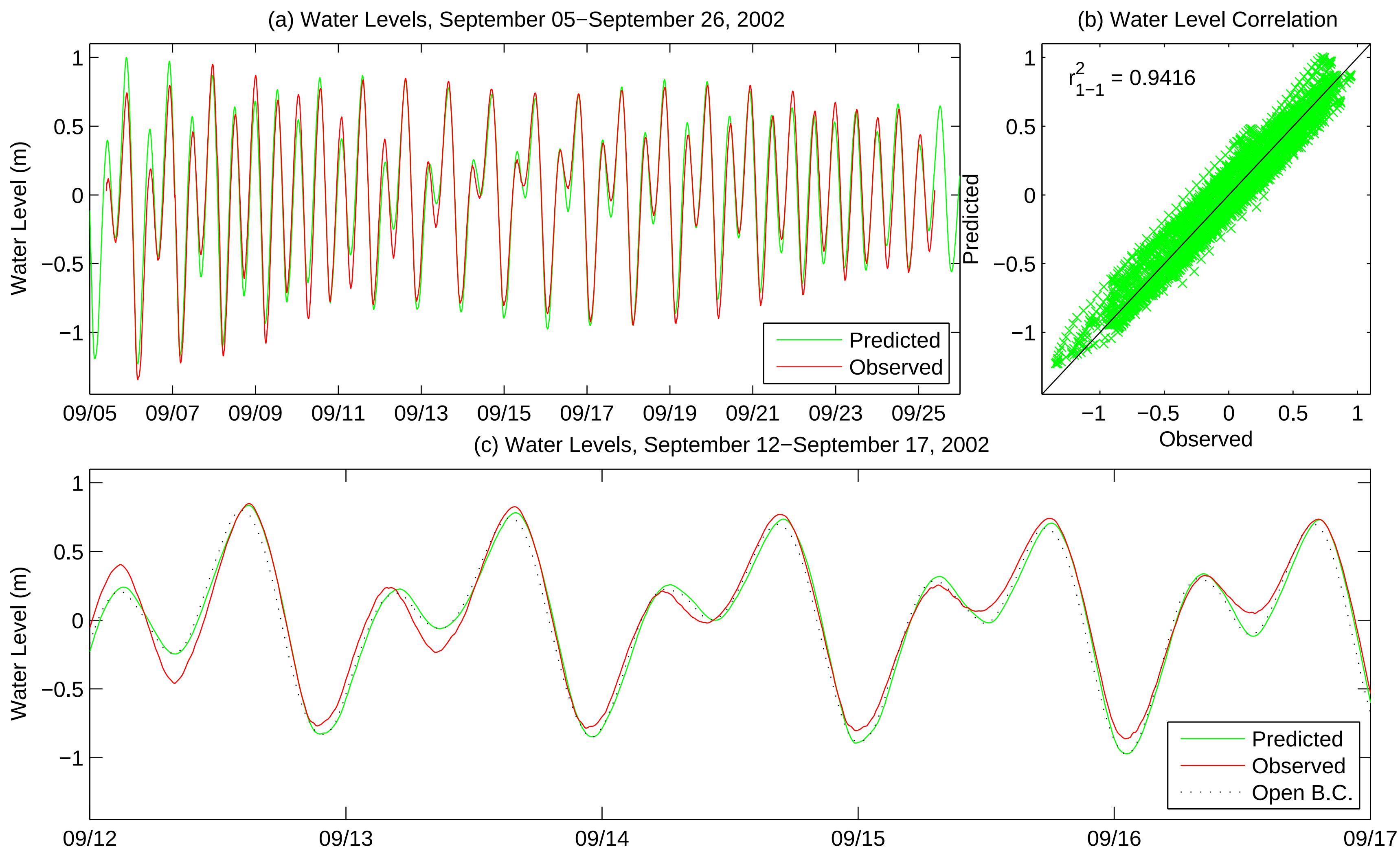

Source: Stanford University observations and DELFT3D model predictions. NOAA observations for Monterey Bay (Station ID 9413450) used as the tidal boundary condition.

Figure *B6*
Elkhorn Slough Tidal Wetlands Restoration

September 2002 Water Levels, Station S2

PWA Ref# 1869.5

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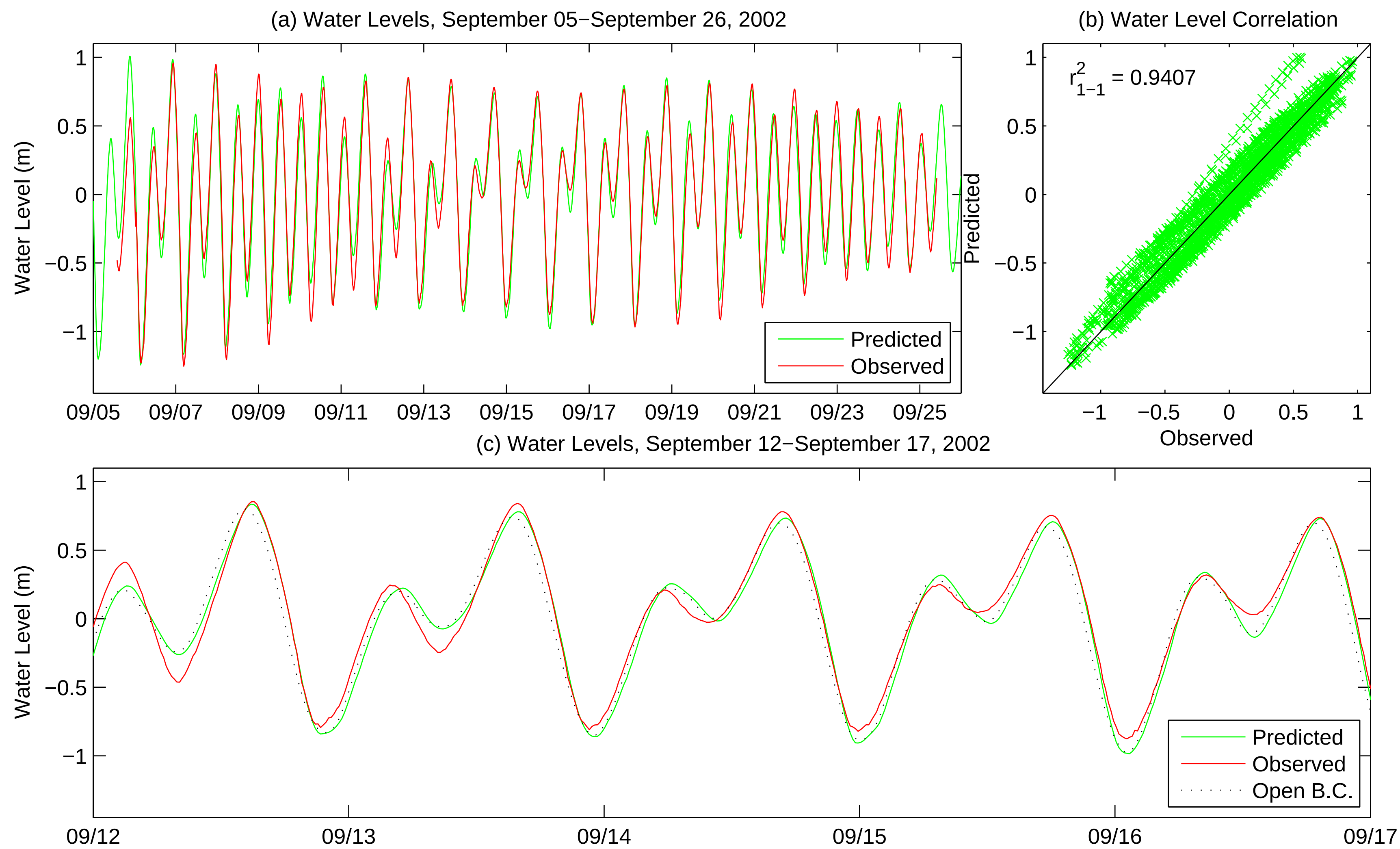

Source: Stanford University observations and DELFT3D model predictions. NOAA observations for Monterey Bay (Station ID 9413450) used as the tidal boundary condition.

Figure B7
Elkhorn Slough Tidal Wetlands Restoration

September 2002 Water Levels, Station S3

PWA Ref# 1869.5

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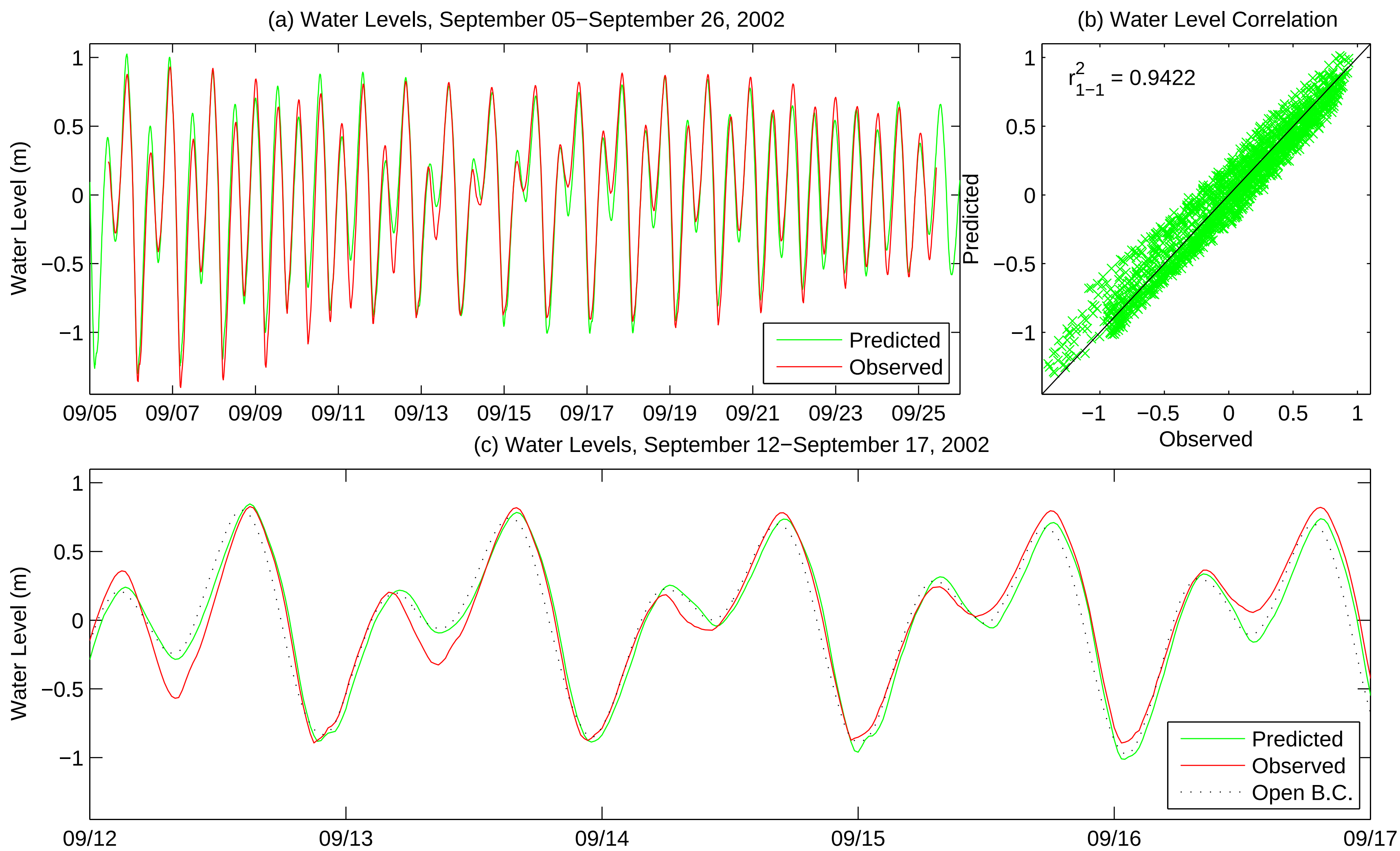

Source: Stanford University observations and DELFT3D model predictions. NOAA observations for Monterey Bay (Station ID 9413450) used as the tidal boundary condition.

Figure *B8*
Elkhorn Slough Tidal Wetlands Restoration

September 2002 Water Levels, Station S5

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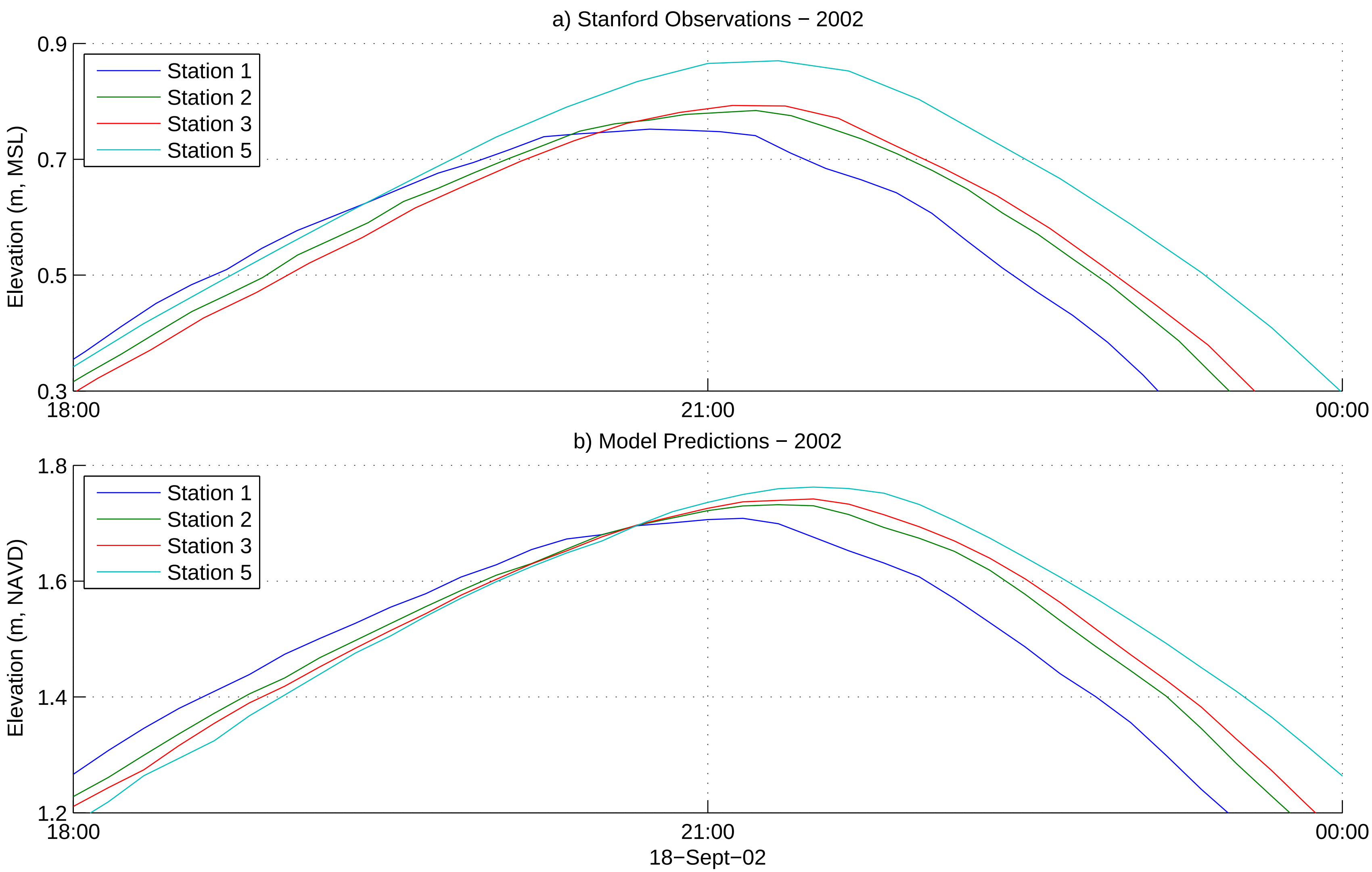

Source: Stanford University observations and DELFT3D model predictions. View has been zoomed to show water surface elevations from four stations along the Slough during higher high water.

Figure *B9*
Elkhorn Slough Tidal Wetlands Restoration

September 2002 Observed and Predicted Tidal Amplification

PWA Ref# 1869.5

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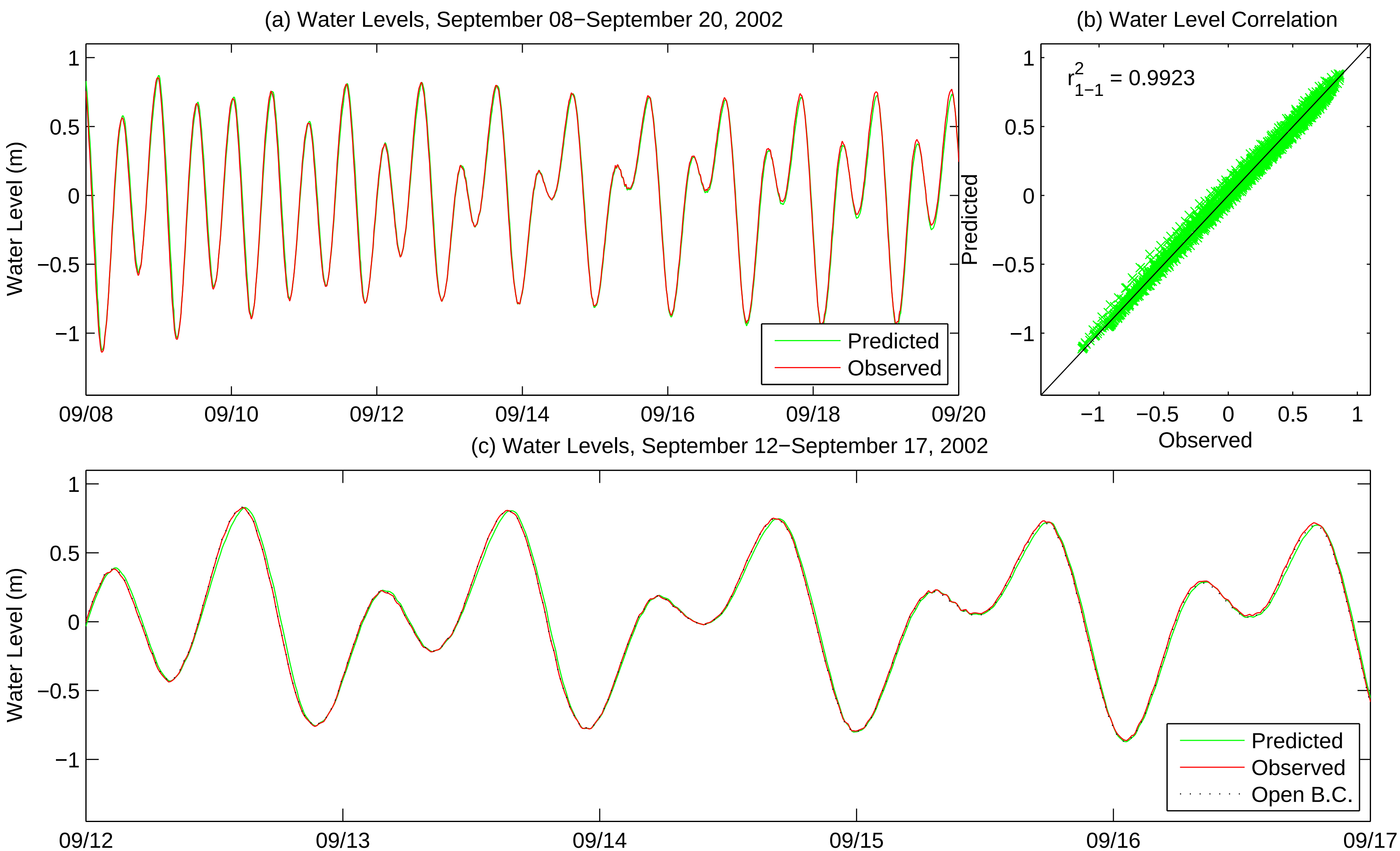

Source: Stanford University observations and DELFT3D model predictions. Stanford University observations at Station S1, lagged in time, was used as the tidal boundary condition.

Figure B10
Elkhorn Slough Tidal Wetlands Restoration

September 2002 Water Levels, Station S1 (w/ Stanford BC)

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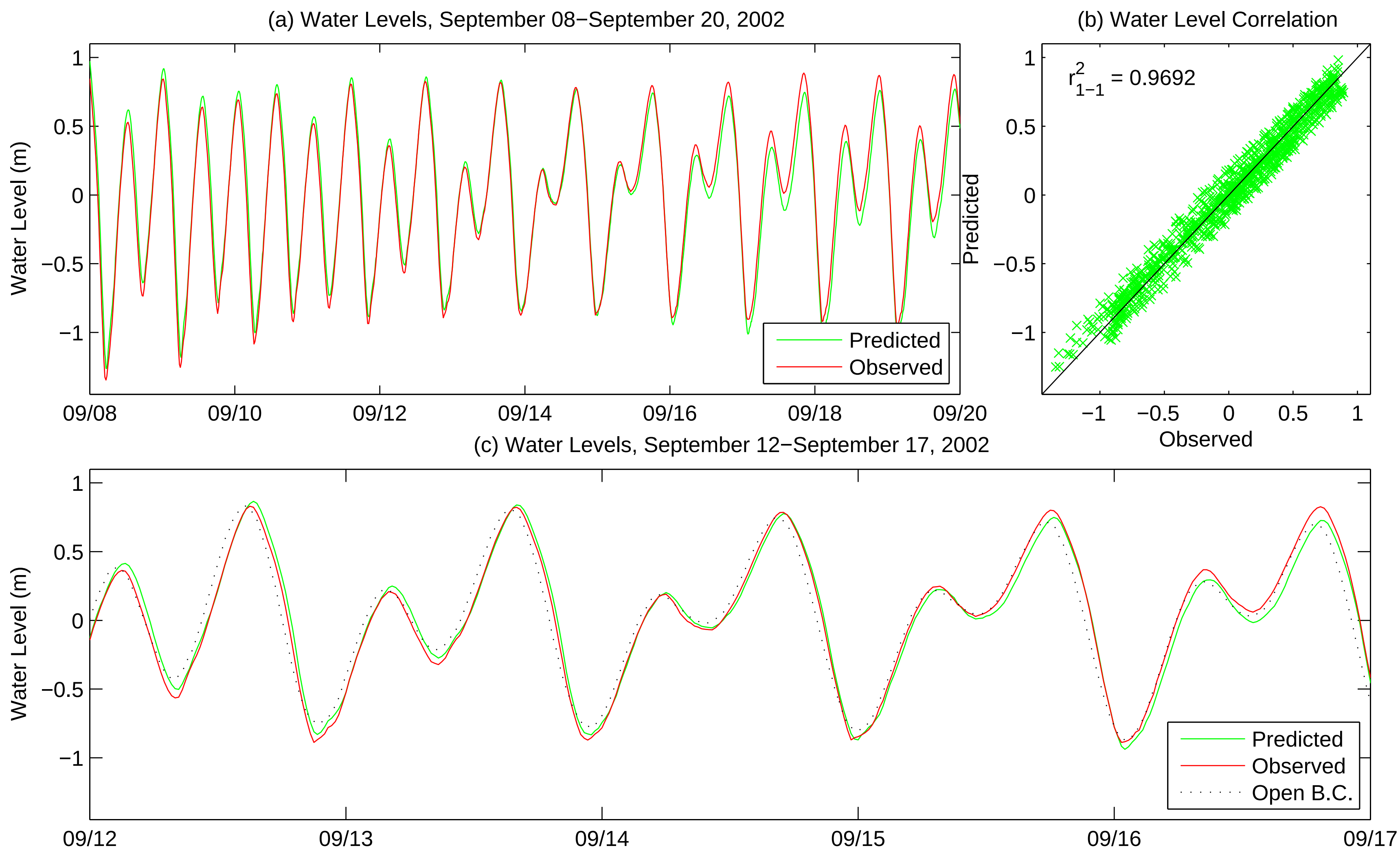

Source: Stanford University observations and DELFT3D model predictions. Stanford University observations at Station S1, lagged in time, was used as the tidal boundary condition.

Figure *B11*

Elkhorn Slough Tidal Wetlands Restoration

September 2002 Water Levels, Station S5 (w/ Stanford BC)

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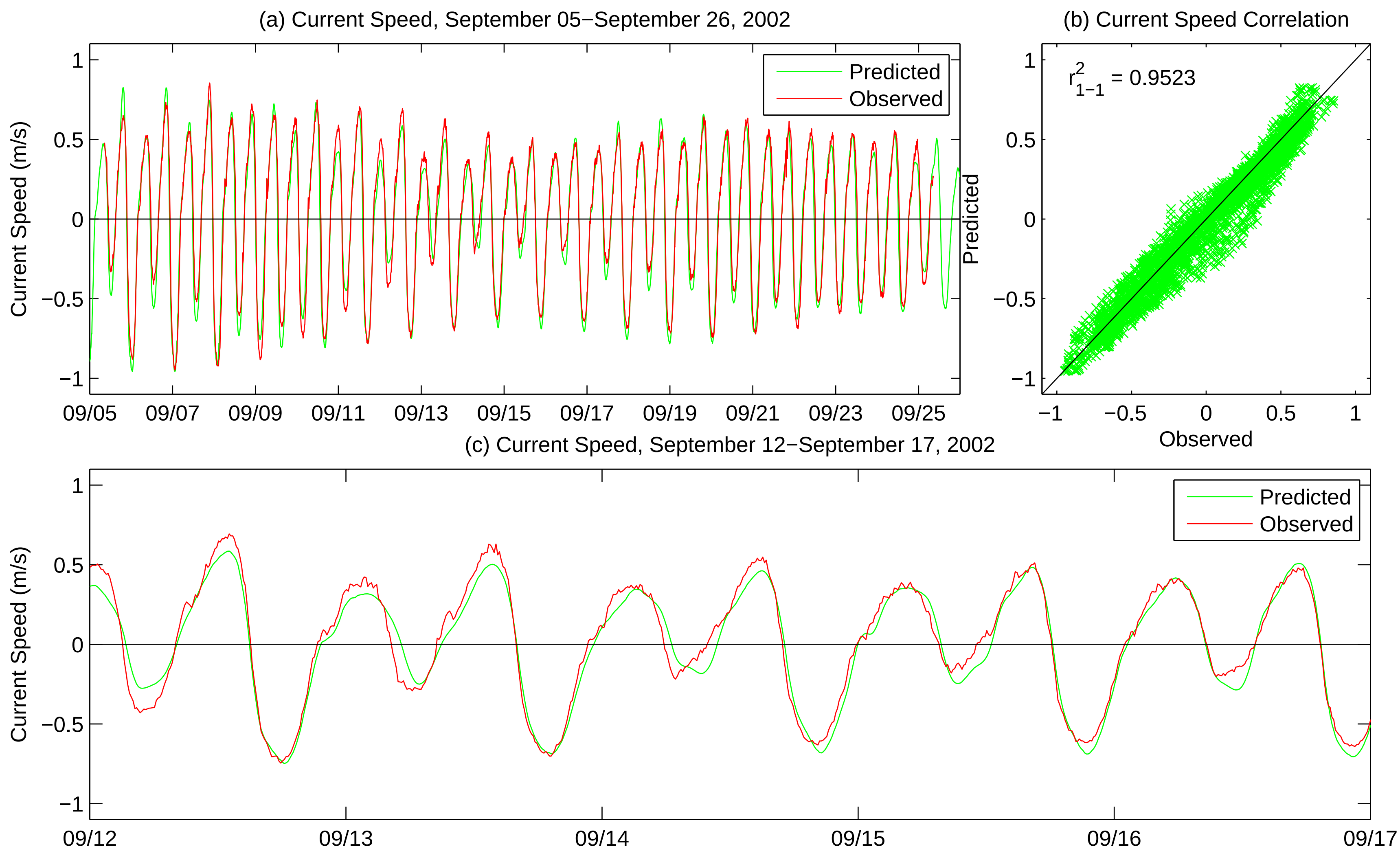

Source: Stanford University observations and DELFT3D model predictions. NOAA observations for Monterey Bay (Station ID 9413450) used as the tidal boundary condition.

Figure B12
Elkhorn Slough Tidal Wetlands Restoration

September 2002 Current Speed, Station S1

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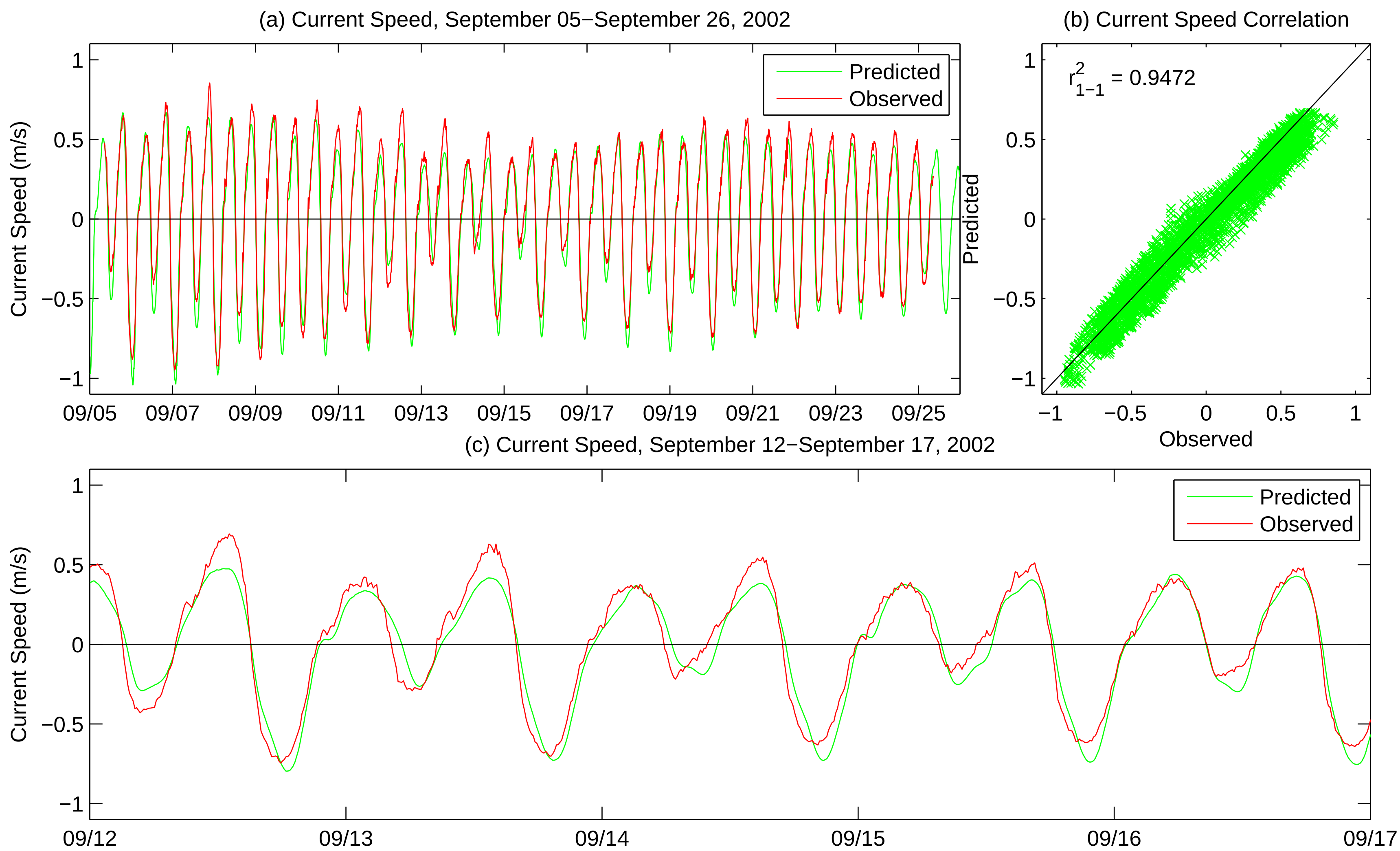

Source: Stanford University observations and DELFT3D model predictions. NOAA observations for Monterey Bay (Station ID 9413450) used as the tidal boundary condition.

Figure B13
Elkhorn Slough Tidal Wetlands Restoration

September 2002 Current Speed, Station S2

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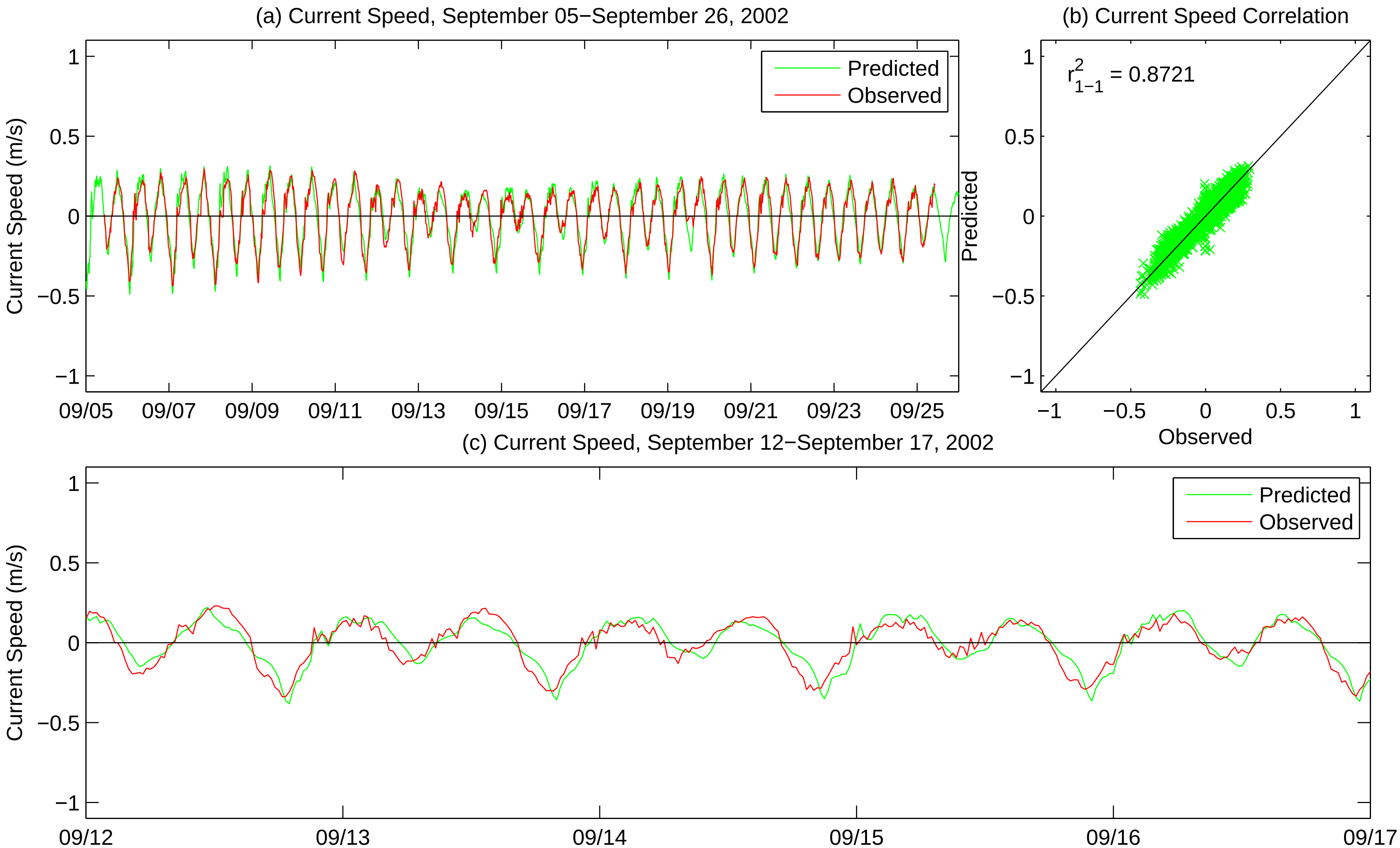

Source: Stanford University observations and DELFT3D model predictions. NOAA observations for Monterey Bay (Station ID 9413450) used as the tidal boundary condition.

Figure *B14*
Elkhorn Slough Tidal Wetlands Restoration

September 2002 Current Speed, Station S5

PWA Ref# 1869.5

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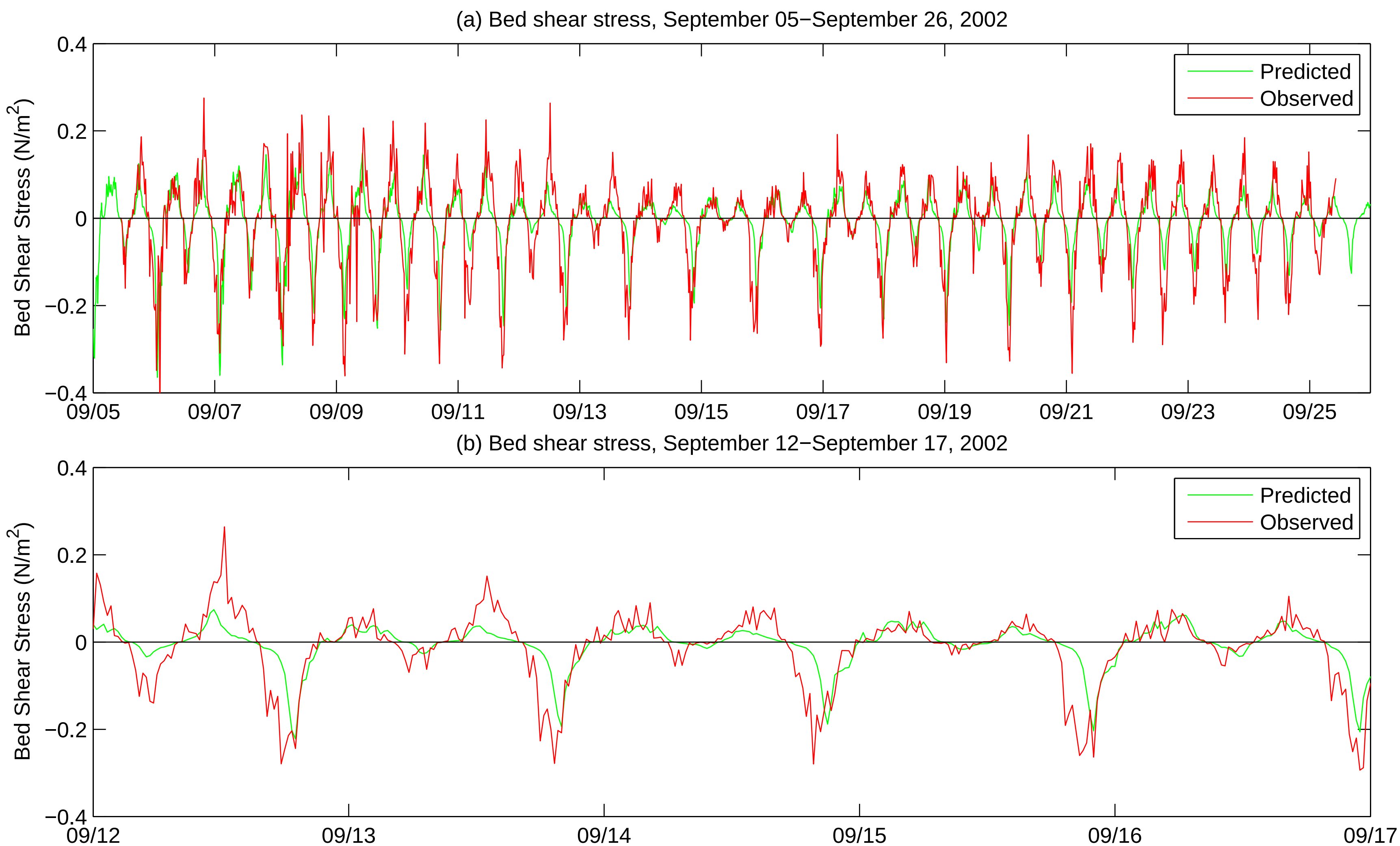

Source: Stanford University observations and DELFT3D model predictions. NOAA observations for Monterey Bay (Station ID 9413450) used as the tidal boundary condition.

Figure B15
Elkhorn Slough Tidal Wetlands Restoration

September 2002 Bed Shear Stress, Station S5

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APPENDIX C.
DEPTH-DEPENDENT CHEZY COEFFICIENT

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DEPTH-DEPENDENT CHEZY COEFFICIENT

Application of a constant Chezy coefficient, the parameter used to calibrate the friction between the water flow and the underlying bed, produces model results which closely replicate observed water levels and current speeds in the main channel of Elkhorn Slough. However, large portions of the adjacent marsh plain are vegetated, which increases friction loss over these areas. A depth-dependent Chezy coefficient can account for vegetation by reducing its value (friction is inversely proportional to the Chezy coefficient) based on bed elevation.

This appendix compares model results from a model run with a constant Chezy coefficient and a model run with the depth-dependent Chezy coefficient to evaluate the sensitivity of water levels, current speeds, and bed shear stress to these two different configurations. The comparison indicates that the use of a depth-dependent Chezy coefficient has a negligible impact on water levels through out the Slough, marsh channels and marsh plain. For approximately 90% of the tidal day, the depth-dependent Chezy coefficient has negligible impact on the current speeds and bed shear stresses of the main channel and marsh channels. During the remaining 10% of the tidal day, when the marsh plain is submerged, the depth-dependent Chezy coefficient configuration causes small to moderate changes in the predicted current speeds and bed shear stresses of the main channel and marsh channels. On the marsh plain, where the local value of the Chezy coefficient actually differs between the two configurations, current speeds are reduced by approximately 50% and bed shear stresses correspondingly increase during high tides of the depth-dependent Chezy coefficient run. Details of this sensitivity analysis are presented below.

C1. SELECTION OF DEPTH DEPENDENT CHEZY COEFFICIENT

Initial model calibration was conducted by adjusting a single Chezy coefficient applied throughout the entire model domain. Based on comparison with water surface and velocity observations in the Slough's main channel, a value of 80 $m^{1/2}/s$ was selected to optimize the agreement between predictions and observations during the April 2003 calibration period. The resulting agreement between observations and prediction for both the calibration and validation period indicate that this single value of the Chezy coefficient results in a well-calibrated model for the main slough. However, a single Chezy coefficient, which is partly a function of bed physical roughness, is not necessarily consistent with the additional roughness of vegetation on the marsh plain. Therefore, a depth-dependent Chezy coefficient was implemented which accounts for the greater roughness found on the marsh plain. Although there are no data to confirm the choice of this depth-dependent Chezy coefficient, this implementation is more consistent with the known physical condition of the bed on the marsh plain.

In the absence of recommendations for the choice of Chezy coefficient for vegetated marsh plain, estimates for Manning's n based on the physical bed properties were reviewed. Recommended values for Manning's n are approximately twice as large for vegetated as compared to earth-lined channels (Chow, 1959). Since the Chezy coefficient and Manning's n are inversely related, a Chezy value of 40 $m^{1/2}/s$, half of the main channel calibration value, was selected for the marsh plain. The Chezy coefficient can be thought of a conductance coefficient, with the lower value of the Chezy coefficient reducing current speeds as a result of correspondingly higher bed shear stresses.

For the depth-dependent Chezy model run discussed in this appendix, the dependence of the Chezy coefficient on depth was assigned based on an initial estimate of vegetation roughness. Grid cells with a bed elevation below 0.8 m NAVD were assigned a Chezy value of 80 $m^{1/2}/s$. Grid cells with a bed elevation above 0.9 m NAVD were assigned a Chezy value of 40 $m^{1/2}/s$. Grid cells with bed elevations between these two break points were assigned a Chezy value linearly interpolated between the two endpoints. The resulting spatial distribution of Chezy coefficients is shown in Figure C1.

For the actual model runs discussed in the main section of this report, the depth to apply the vegetated Chezy value was selected by inspection of aerial photographs and the LIDAR bathymetry of the Slough's marshes. Regions with bed elevations below 1.0 m NAVD were observed to be largely free of vegetation and regions with bed elevations above 1.2 m NAVD were observed to be well vegetated. Hence, the Chezy coefficient for grid cells with bed elevations below 1.0 m NAVD was set to the calibration value of 80 $m^{1/2}/s$. Grid cells with bed elevations above 1.2 m NAVD had their Chezy coefficient set to 40 $m^{1/2}/s$. The Chezy coefficient was linearly interpolated between 40 $m^{1/2}/s$ and 80 $m^{1/2}/s$ for bed elevations between 1.0 m and 1.2 m NAVD.

C2. COMPARISON BETWEEN CONSTANT AND DEPTH-DEPENDENT CHEZY COEFFICIENT

By comparing two model runs that were identical except for specification of the Chezy coefficient, the effect of this parameter on the various regions of the model domain can be assessed. A station characteristic of each of the major regions in the Slough – the main channel, the marsh channels, and the marsh plain – was selected to demonstrate the impact of the depth-dependent Chezy coefficient on the modeled hydraulic response. These stations, located at Stanford University's Station S4, within Rubis Creek, and within Rubis Marsh, are shown in Figure C1.

C2.1 Main Channel

Within the main channel, the Chezy coefficient was unchanged between the two runs. Because of this consistent value of the Chezy coefficient and the relative dominance of the main channel in determining water levels, water levels exhibited no significant difference between runs (Figure C2). For most of the tidal cycle, the depth-dependent Chezy coefficient also produced little difference in current speeds (Figure C3) and bed shear stresses (Figure C4). However, the depth-dependent Chezy coefficient produced slightly larger current speeds and bed shear stresses during the flood tide before the higher high tide (tides just before 4/18 and 4/19 in Figure C3 and Figure C4). During these flood tides, the marsh plain is inundated, such that the additional roughness (lower Chezy value) slows water wetting the marsh plain. To balance this loss of conveyance over the marsh plain, the current speed and corresponding bed shear stress in the main channel increase by up to 5% on the flood tides preceding higher high tide.

C2.2 Marsh Creek Channels

The bed elevation of the marsh creek channel selected for this sensitivity analysis was below the elevation break point at which the Chezy coefficient was decreased. Therefore, the value of the Chezy coefficient within the marsh channels was unchanged between runs. As a result, changes in flow were minimal except for brief periods when flow in the marsh channels was linked to the adjacent marsh plain.

For most time periods, the depth-dependent Chezy coefficient produced no significant change in water surface elevation in the marsh channels, as shown for Rubis Creek in Figure C5. The only exception is during the period after the strong ebb when the water level in the marsh channel is constant, indicating that this station has dried out. In this dry period after the strong ebb, the water level is 1.5 cm less under the depth-dependent Chezy configuration. This difference is less than this run's drying criteria of 5 cm, and therefore is within the model uncertainty for this run configuration. The drying criteria were subsequently lowered to 0.5 cm in the final calibration and validation runs.

Within Rubis Creek, current speeds (Figure C6) and bed shear stresses (Figure C7) are also minimally affected by the change to a depth-dependent Chezy coefficient. The only exception to this minimal difference between runs occurs for a few hours at the beginning of each new calendar day, when water levels exceed 1.75 m NAVD (Figure C5). For this brief period, the marsh plain adjacent to the marsh channel is inundated with more than 30 cm of water (Figure C8) and flow in the channel is closely linked to flow on the marsh plain. Because of this linkage, the lower, depth-dependent Chezy values on the marsh plain also lessen current speeds in the marsh channel. The concurrent reduction in bed shear stresses during this high water period confirm that the decrease in current speed results from non-local changes in the Chezy coefficient. A decrease in current speeds caused by a local decrease in the Chezy coefficient would be accompanied by higher bed shear stress.

C2.3 Marsh Plain

For most time periods, the depth-dependent Chezy coefficient produced small changes in water levels on the marsh plain, as shown for Rubis Marsh in Figure C8. Peak water level predicted with a depth-dependent Chezy coefficient is 1 cm higher than for the constant Chezy case, which is approximately 2% of the peak water depth. The inundation period both begins and ends ten minutes[1] sooner for the depth-dependent Chezy coefficient case. However, the duration of the inundation period is nearly identical[2].

The response of the current speed and bed shear stress demonstrate a clear response to the depth-dependent change in Chezy coefficient on the marsh plain. Current speeds are reduced by approximately 40-50% for the depth-dependent Chezy coefficient case as compared to the constant Chezy coefficient case (Figure C9). The peak bed shear stresses correspondingly increase from 0.1 N/m^2 to nearly 0.14 N/m^2 (Figure C10). The bed shear stresses at the beginning of the inundation period exhibit complex behavior, e.g. a spike in bed shear stress for the depth-dependent Chezy case, followed by nearly equal bed shear stress between the two runs even though current speeds are larger for the constant Chezy case. This complex behavior suggests that flow at these times, when the marsh plain is just beginning to be flooded, is driven more by the small scale bathymetric features than local bed roughness.

C3. REFERENCES

Chow, V. T. 1959. Open-Channel Hydraulics. McGraw-Hill, Inc.

[1] Model output was only saved every ten minutes, so this minimum observable difference for this run configuration. The actual difference could vary between 1 and 19 minutes.

[2] To within the resolution of the model's saved output. See footnote 1.

Figures

Figure C1. Depth-dependent Chezy Coefficients and Station Locations
Figure C2. Chezy Sensitivity Analysis, Station S4 Water Levels
Figure C3. Chezy Sensitivity Analysis, Station S4 Current Speeds
Figure C4. Chezy Sensitivity Analysis, Station S4 Bed Shear Stress
Figure C5. Chezy Sensitivity Analysis, Rubis Creek Water Levels
Figure C6. Chezy Sensitivity Analysis, Rubis Creek Current Speeds
Figure C7. Chezy Sensitivity Analysis, Rubis Creek Bed Shear Stress
Figure C8. Chezy Sensitivity Analysis, Rubis Marsh Water Levels
Figure C9. Chezy Sensitivity Analysis, Rubis Marsh Current Speeds
Figure C10. Chezy Sensitivity Analysis, Rubis Marsh Bed Shear Stress

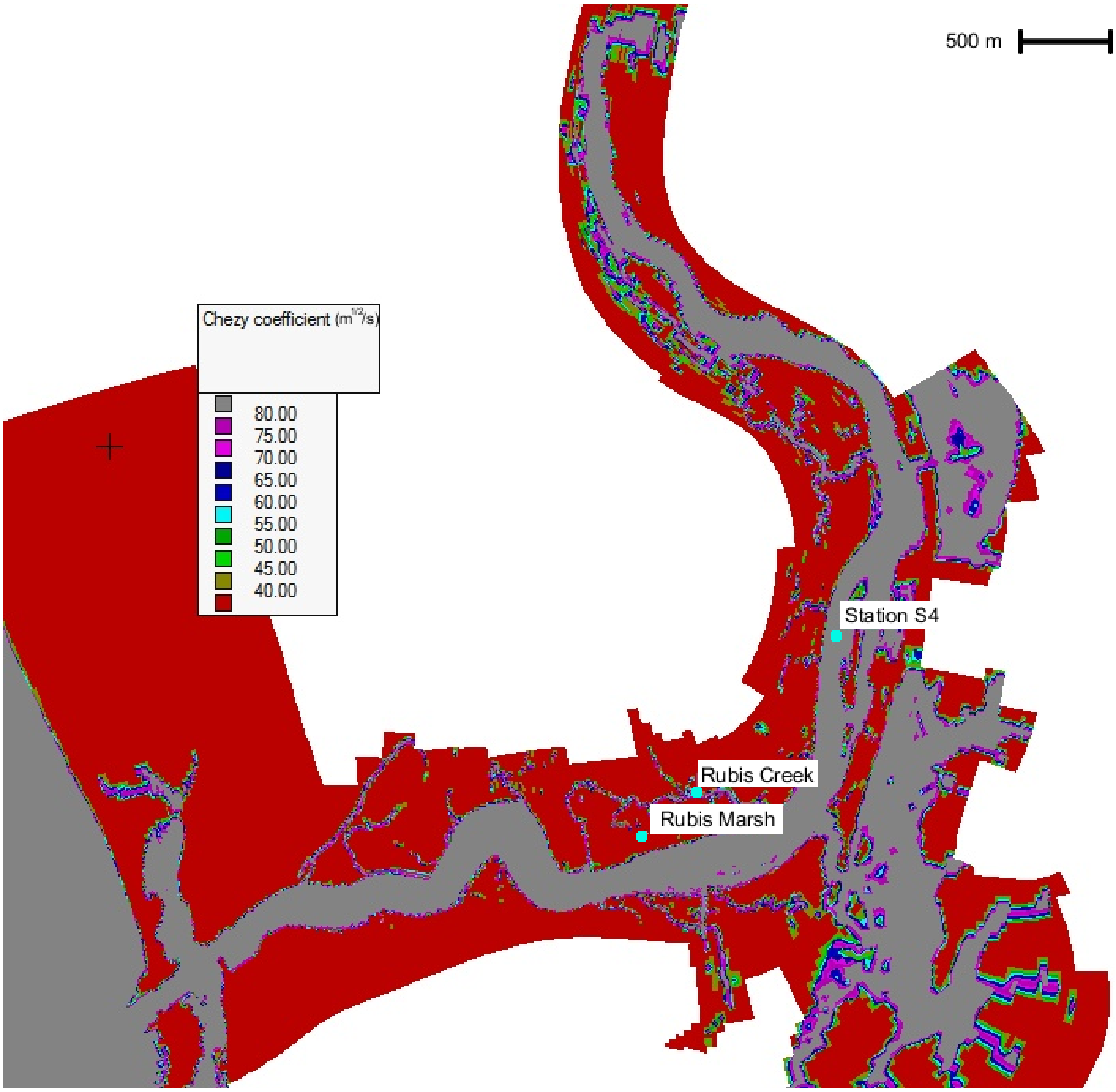


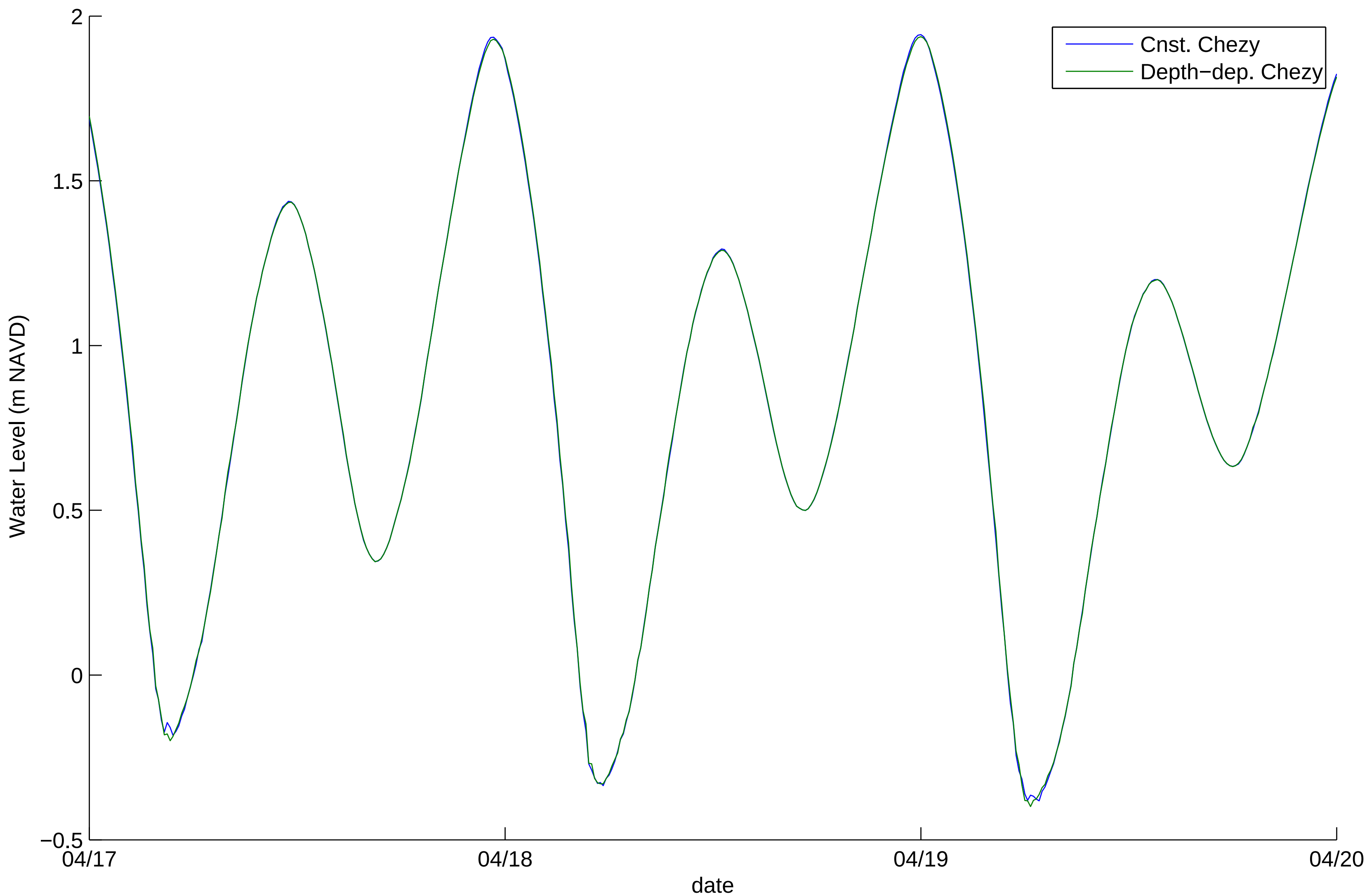
figure *C1*

Elkhorn Slough Tidal Wetlands Restoration

Depth-dependent Chezy Coefficients and Station Locations

PWA Ref# 1869.5

PWA



Source: DELFT3D model results

Figure *C2*
Elkhorn Slough Tidal Wetlands Restoration

Chezy Sensitivity Analysis, Station S4 Water Levels

PWA Ref# 1869.5

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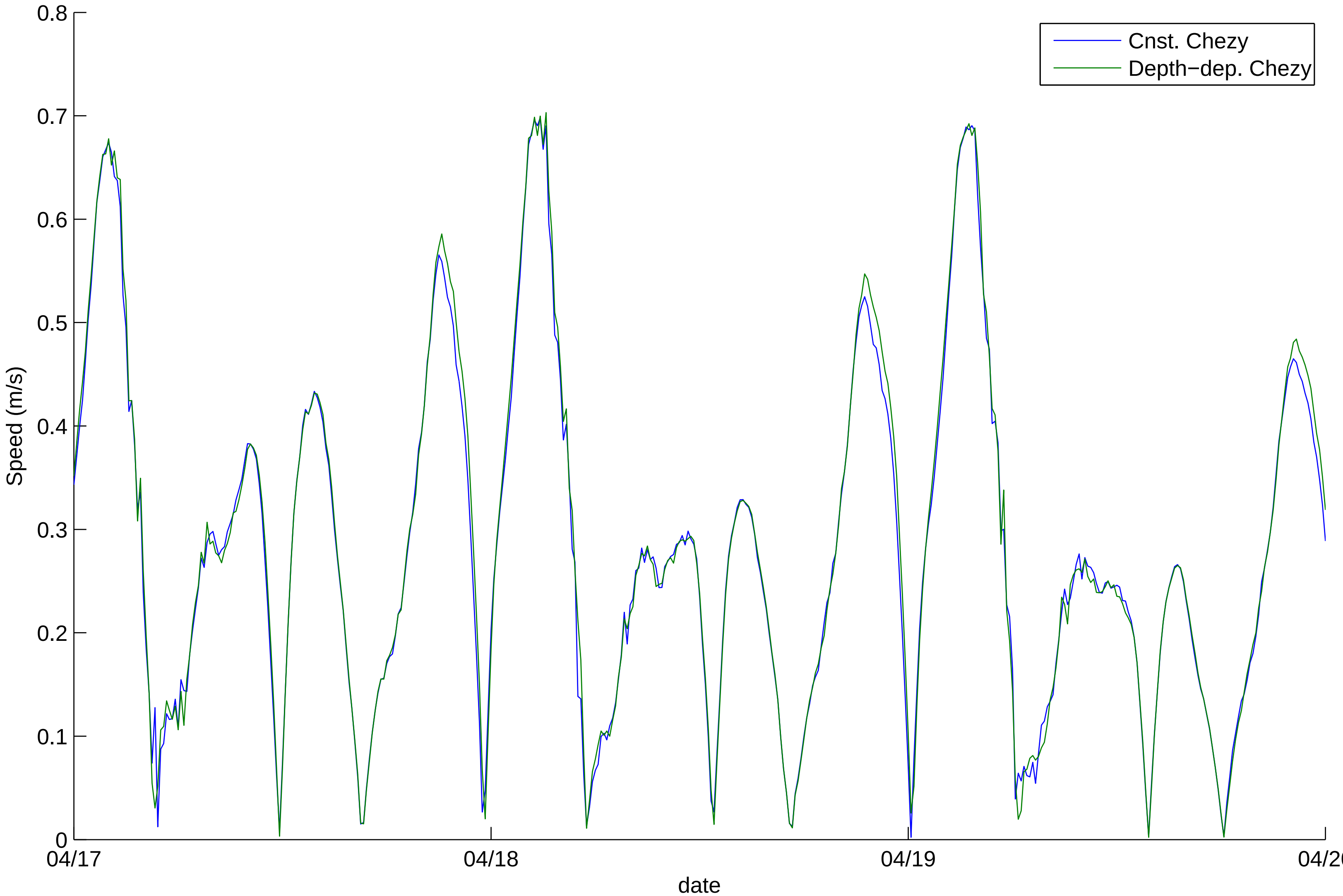

Source: DELFT3D model results

Figure C3
Elkhorn Slough Tidal Wetlands Restoration

Chezy Sensitivity Analysis, Station S4 Current Speeds

PWA Ref# 1869.5

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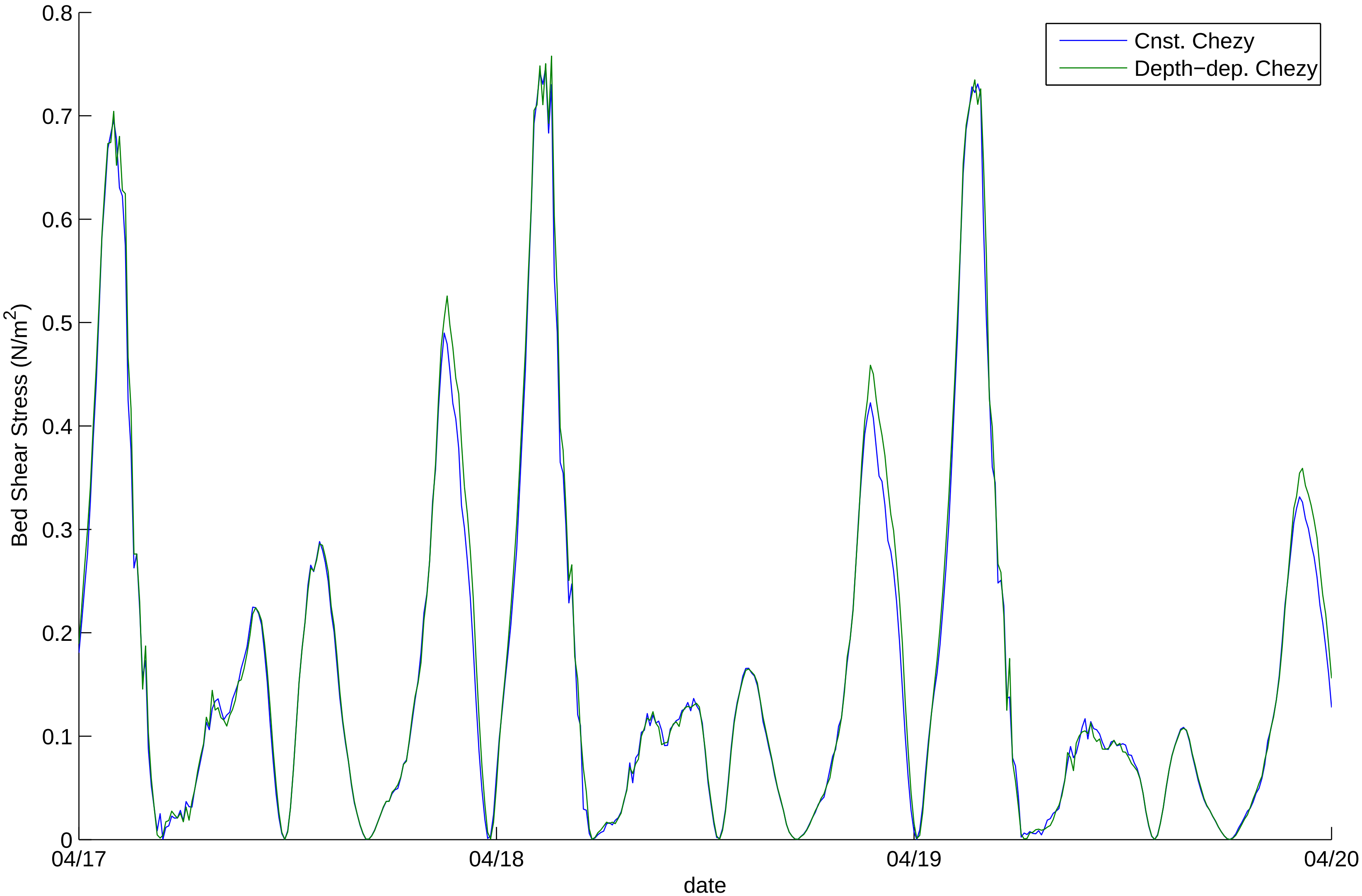

Source: DELFT3D model results

Figure C4

Elkhorn Slough Tidal Wetlands Restoration

Chezy Sensitivity Analysis, Station S4 Bed Shear Stress

PWA Ref# 1869.5

PWA

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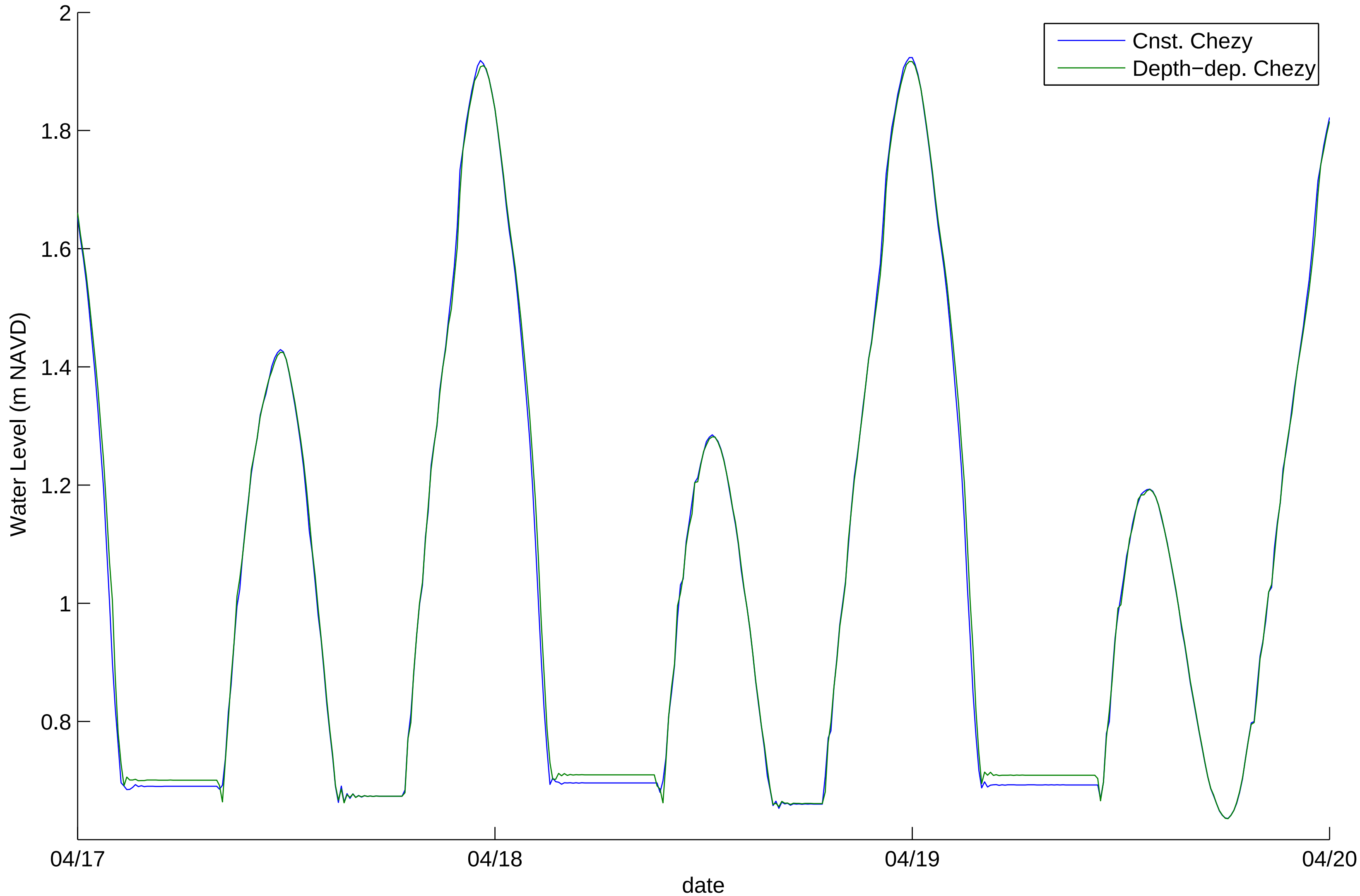

Source: DELFT3D model results

Figure C5

Elkhorn Slough Tidal Wetlands Restoration

Chezy Sensitivity Analysis, Rubis Creek Water Levels

PWA Ref# 1869.5

PWA

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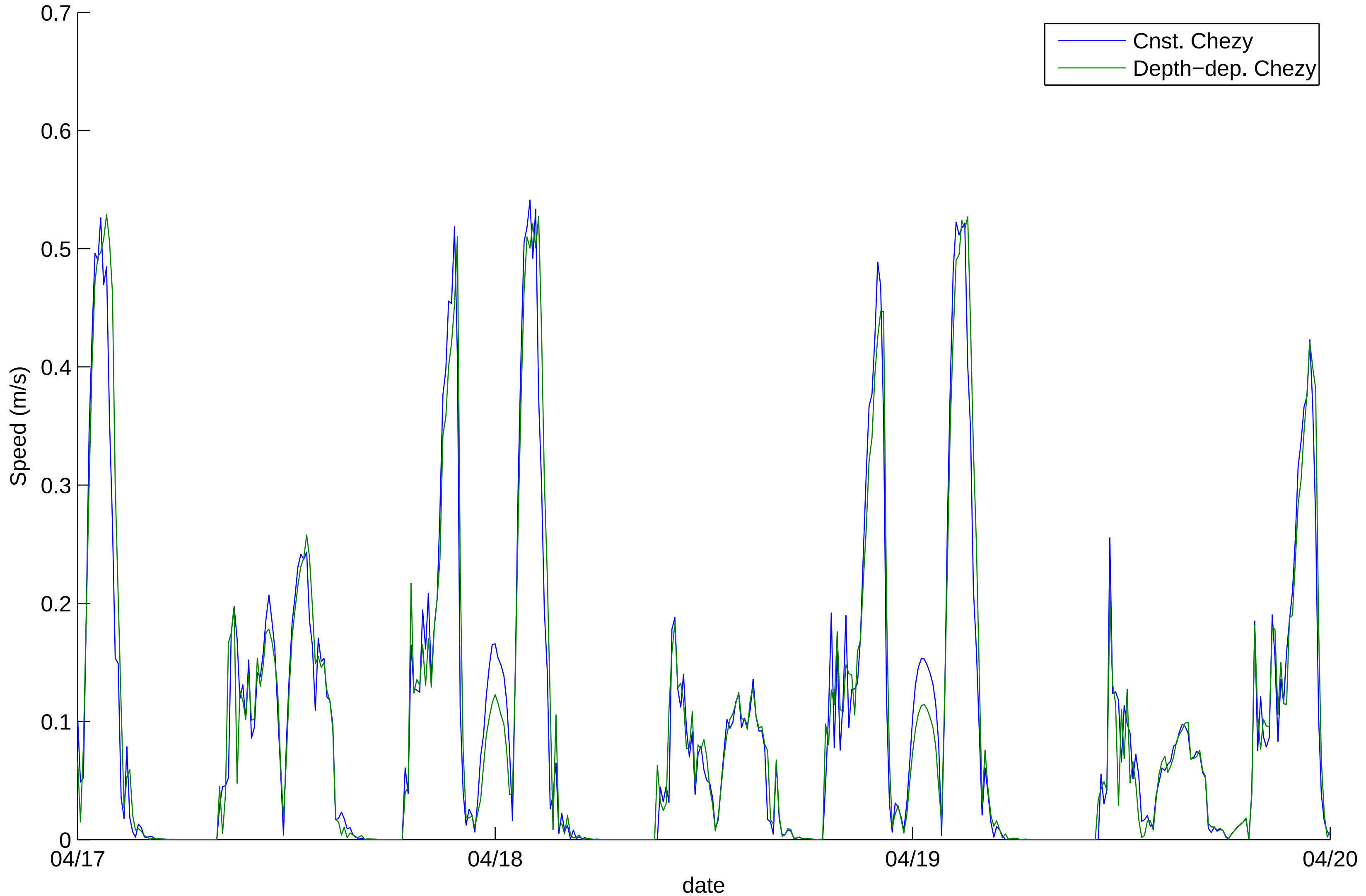

Source: DELFT3D model results

Figure *C6*
Elkhorn Slough Tidal Wetlands Restoration

Chezy Sensitivity Analysis, Rubis Creek Current Speeds

PWA Ref# 1869.5

PWA

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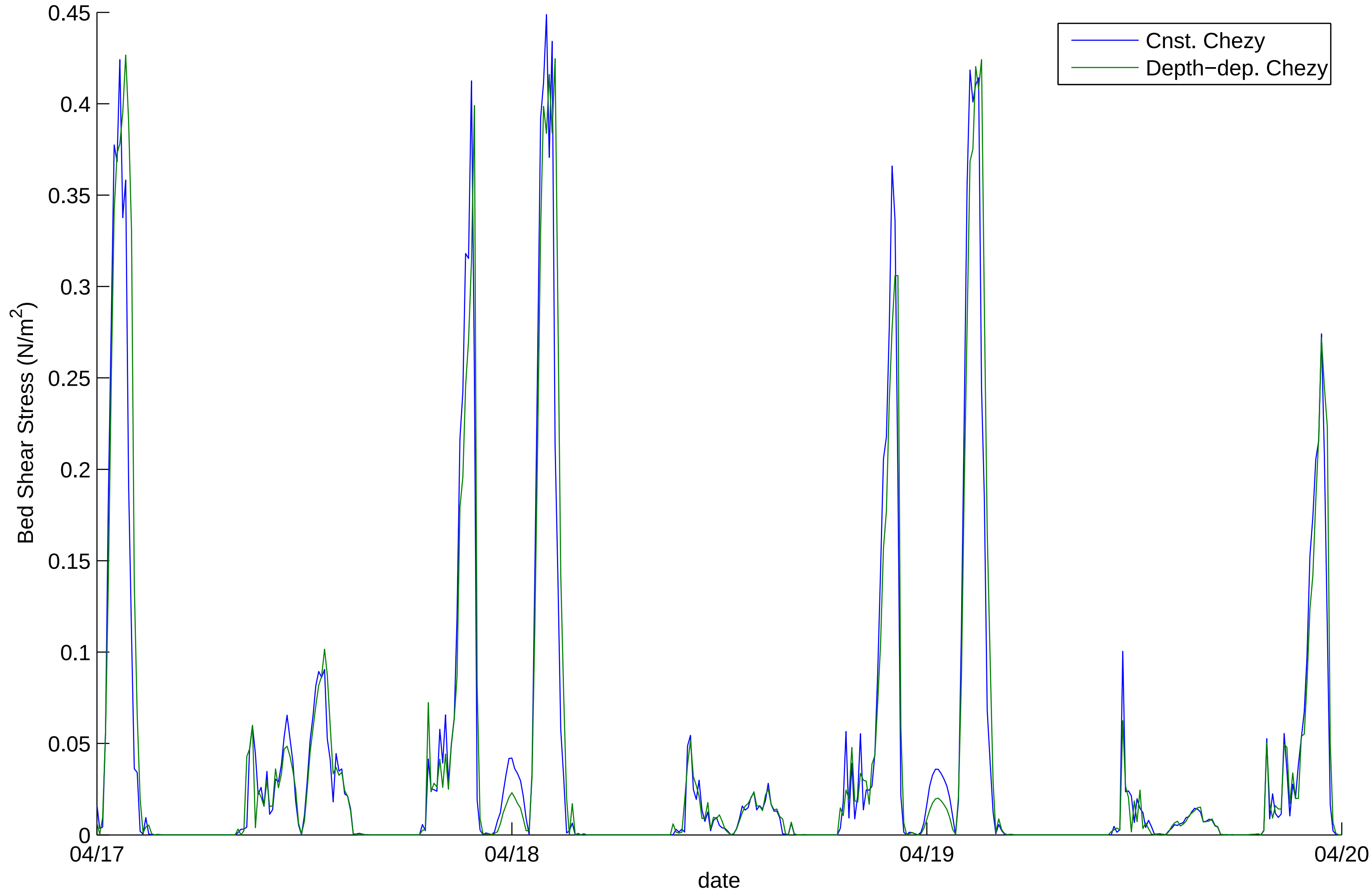

Source: DELFT3D model results

Figure C7
Elkhorn Slough Tidal Wetlands Restoration

Chezy Sensitivity Analysis, Rubis Creek Bed Shear Stress

PWA Ref# 1869.5

PWA

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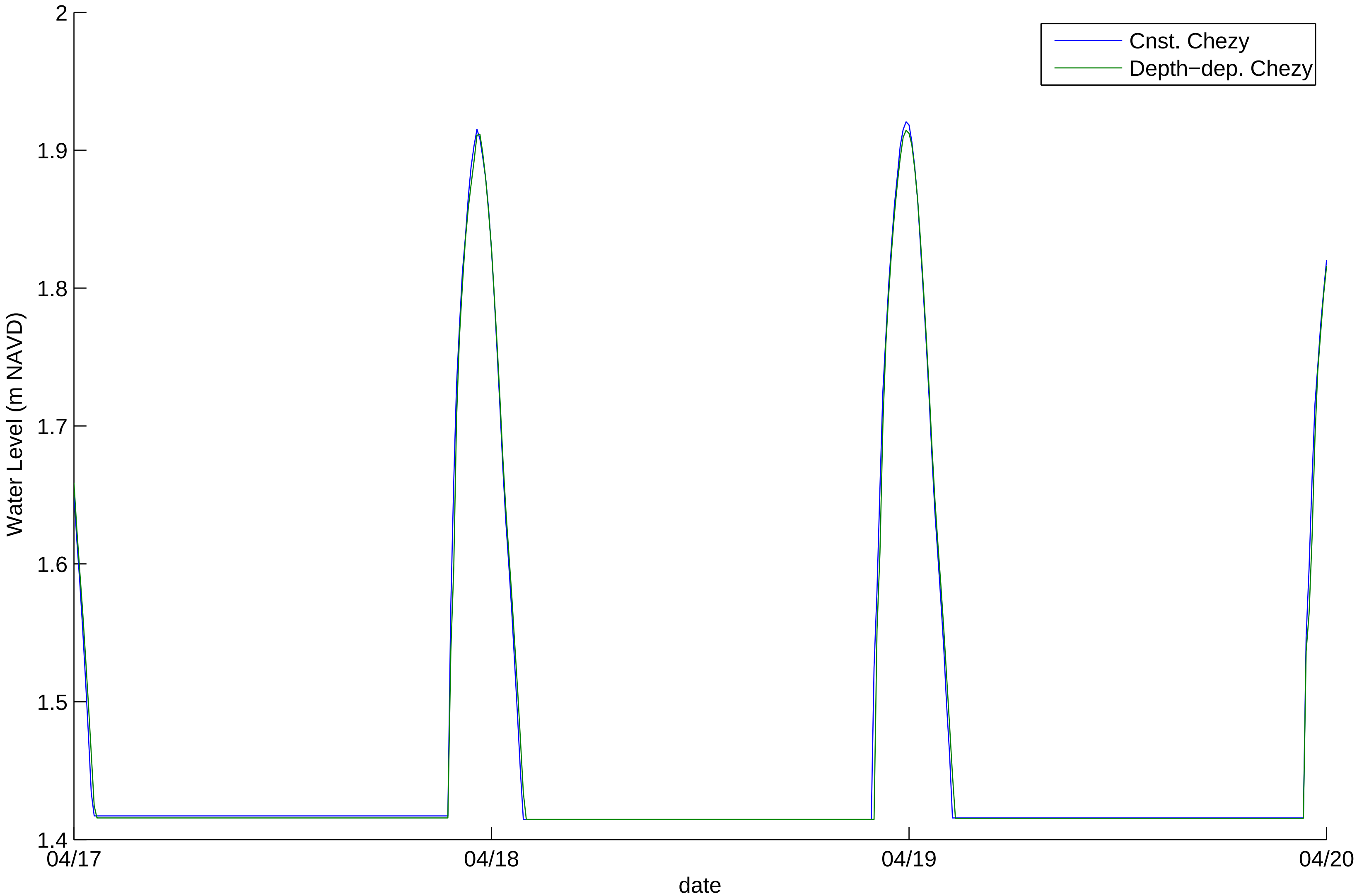

Source: DELFT3D model results

Figure C8

Elkhorn Slough Tidal Wetlands Restoration

Chezy Sensitivity Analysis, Rubis Marsh Water Levels

PWA Ref# 1869.5

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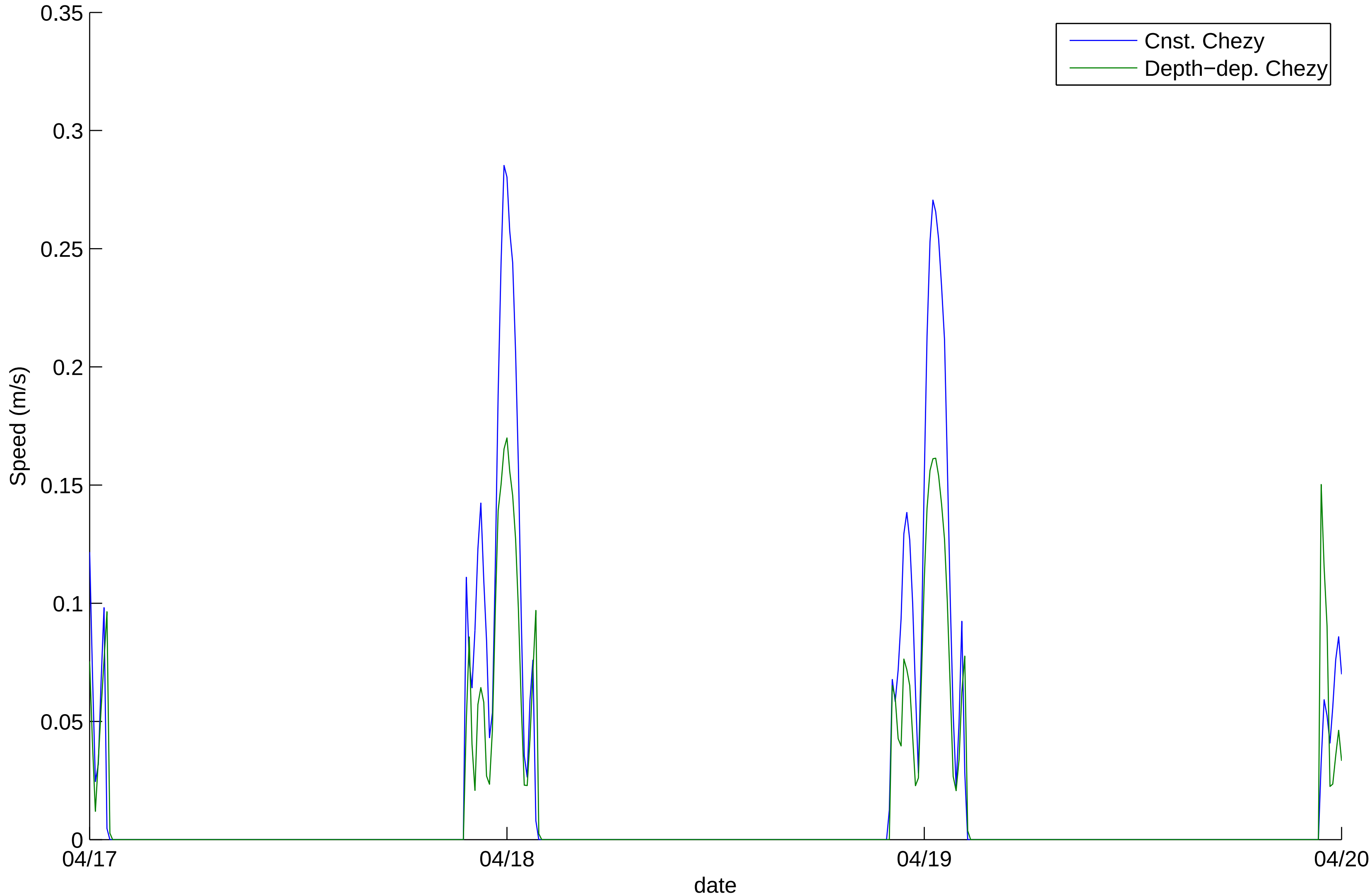

Source: DELFT3D model results

Figure *C9*
Elkhorn Slough Tidal Wetlands Restoration

Chezy Sensitivity Analysis, Rubis Marsh Current Speeds

PWA Ref# 1869.5

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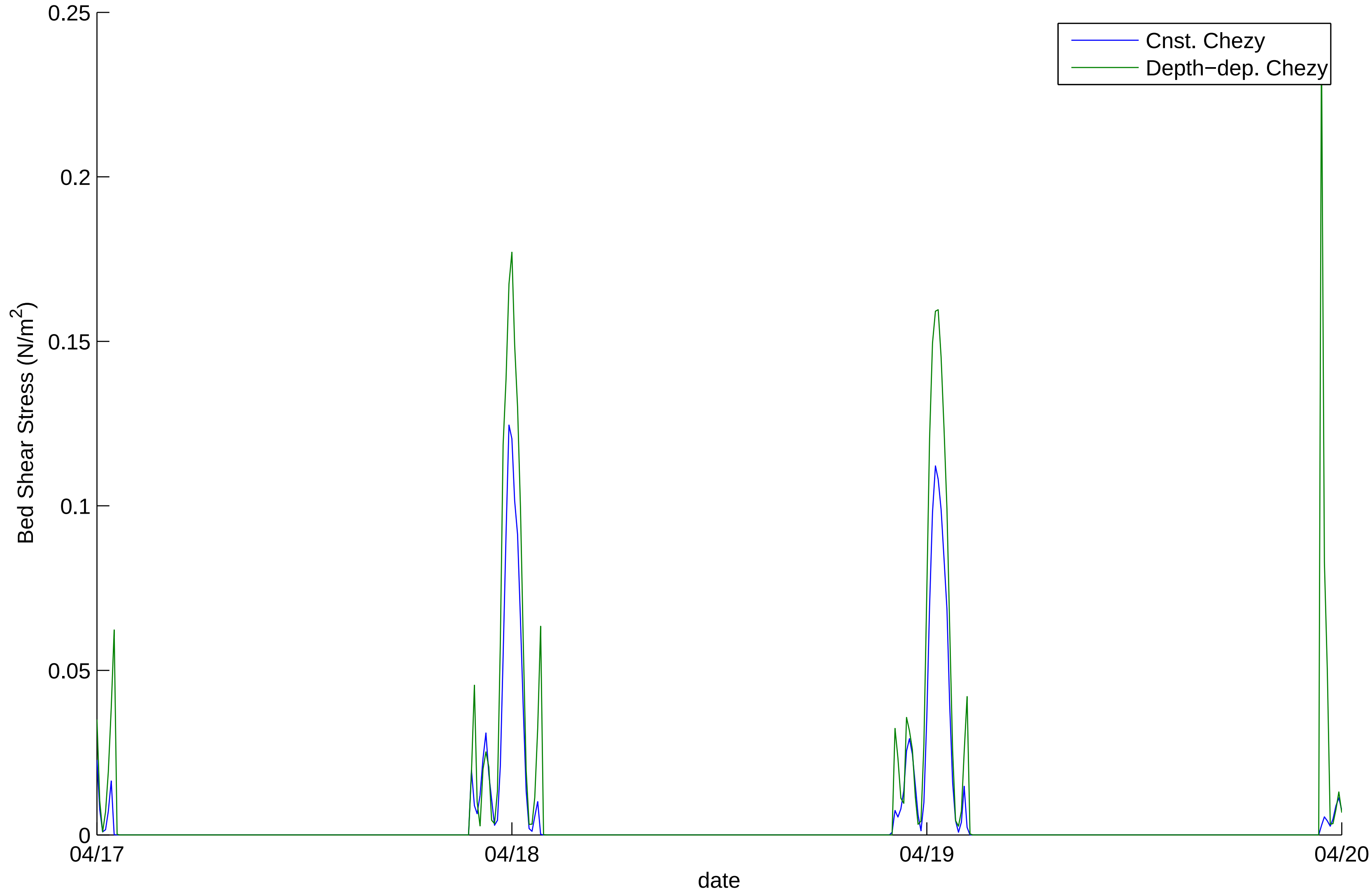

Source: DELFT3D model results

Figure C10
Elkhorn Slough Tidal Wetlands Restoration

Chezy Sensitivity Analysis, Rubis Marsh Bed Shear Stress

PWA Ref# 1869.5

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APPENDIX B.
INLET STABILITY ASSESSMENT

D R A F T
M E M O R A N D U M
(FOR DISCUSSION PURPOSES ONLY)

Date:	May 21, 2008
To:	Bryan Largay
Organization:	Elkhorn Slough Foundation
From:	Justin Vandever, Don Danmeier, and Bob Battalio
PWA Project #:	1869
PWA Project Name:	Elkhorn Slough Tidal Wetland Project
Subject:	Inlet Stability Assessment

1 INTRODUCTION

1.1 OVERVIEW OF MEMORANDUM

Alternative 2 of the Elkhorn Slough Tidal Wetland Project proposes to restore a self-shoaling tidal inlet north of Moss Landing Harbor. Implementation of this alternative would create the potential for inlet closure, since the connection between Elkhorn Slough and ocean would no longer be sheltered from wave-driven sand transport currently provided by the two-jetty entrance of Moss Landing Harbor. This memorandum presents information required to evaluate inlet stability of the proposed new ocean inlet, including the following:

- characterization of the nearshore wave climate;
- estimated rates of littoral drift in the vicinity of Moss Landing;
- an evaluation of historical closure potential; and
- our initial appraisal of closure potential under Alternative 2.

1.2 HISTORY OF THE ELKHORN SLOUGH TIDAL INLET

Under natural conditions, the tidal inlet of Elkhorn Slough sustained an open connection to the ocean via a delicate balance between deposition of wave-driven sand transport and scour by tidal currents and freshwater discharge. Although recent paleoecological analysis of sediment cores suggests the inlet may have closed for some period of time, freshwater discharge from the Salinas River during winter rainstorms was presumably sufficiently large to naturally re-open the tidal inlet if closure did occur. After the diversion of the Salinas River in c. 1910, the potential for a sustained inlet closure increased due to the loss of the winter river flows required for natural re-opening. Since construction of Moss Landing Harbor in 1946, Elkhorn Slough has exchanged ocean water with Monterey Bay through the two-jetty entrance channel at the harbor without risk of closure.

Implementation of Alternative 2 would eliminate exchange between Elkhorn Slough and Moss Landing Harbor and route tidal flows north of the California Department of Fish & Game (CDFG) Wildlife Area and through a new ocean inlet immediately north of Jetty Road (Figure 1). This alternative is intended to restore the littoral and tidal processes required to shape and maintain a self-shoaling tidal inlet; a portion of the beach sands deposited along the entrance channel and flood-tide shoals would be scoured by ebb-tide currents until these two processes reach a balance and a dynamic equilibrium is achieved. As described below, we anticipate that the wave exposure under Alternative 2 would result in a substantially shallower inlet than the existing two-jetty entrance channel at Moss Landing Harbor. Preliminary results from the DELFT modeling indicate that this new tidal inlet would result in a substantial reduction of the effective tidal prism and tidal range of Elkhorn Slough with less up-estuary tidal scour.

2 CHARACTERIZATION OF NEARSHORE PROCESSES

An understanding of the nearshore processes in the vicinity of the proposed new ocean inlet is required to evaluate its stability and closure potential. In this section we present our analysis of the wave climate at Moss Landing and summarize the patterns and rates of littoral drift based on readily available information. In subsequent sections, we use these estimates of wave power and littoral drift to assess closure potential. Before the estimates of wave power and littoral drift are presented, we briefly described the wave characteristics of Monterey Bay.

2.1 WAVE CHARACTERISTICS OF MONTEREY BAY

The waves that approach Moss Landing are characterized by four dominant modes. Winter storms (November-March) in the northern hemisphere generate swell with deepwater significant wave heights up to 11 m (Wyland and Thornton, 1991) which approach from northwest to west-southwest. During the summer months (July-August), persistent offshore high pressure systems generate relatively short period waves from the northwest while distant storms in the southern hemisphere generate swell of low height but long periods. Locally generated wind-waves develop rapidly, in response to low offshore pressure systems during the winter months or strong summertime sea breezes that result from heating of interior land. Moss Landing has strong sea breezes as it is located at the head of the Salinas Valley.

Wave crests that approach bottom contours at an oblique angle will tend to bend parallel to the bottom contours as the result of wave refraction. An area where rays come together is a region of convergence (increased wave energy), and an area where rays separate is a region of energy divergence (decreased wave energy). In Monterey Bay, wave heights are diminished at Moss Landing owing to refraction over the Monterey submarine canyon. Swell at Moss Landing arriving from the northwest is highly refracted, but waves from the west and west-southwest are less refracted and more of their deepwater energy remains incident to the shore.

2.2 WAVE POWER AT MOSS LANDING HARBOR

Wave power (energy flux) is an important parameter for quantifying the potential for sediment transport in the nearshore region. PWA computed the mean annual deepwater wave power observations at the Monterey Bay Buoy (NOAA Buoy 46042) from 1987 to 2004[1]. To assess the potential for inlet closure at Elkhorn Slough, deepwater wave power estimates were transformed to nearshore values using refraction coefficients (K_r) for Moss Landing Harbor entrance obtained from various sources (Johnson, 1953; Wiegel, 1964; Ippen, 1966; Thornton, 2007; USACE). A refraction coefficient of 0 was assigned to incident wave directions beyond the range of 210-300° to account for the wave shadowing effect of Monterey Bay. Snell's Law was used to estimate refraction coefficients for shorter period wind waves with periods below 6 seconds. A bi-linear interpolation scheme was used to estimate refraction coefficients at frequencies and directions where direct values were not available. We used linear wave theory to determine the shoaling coefficients (K_s) from deepwater to the 10-m isobath. The square of the product of these two variables represents the energy transformation matrix (E/E_0). The resulting energy transformation matrix covered a frequency and direction range of 0.04-0.25 Hz (4-25 seconds) in 0.01 Hz increments and 205-330 degrees in 5 degree increments, respectively (Figure 2). Deepwater spectral wave energy beyond these frequency and direction limits was neglected in the nearshore energy transformation.

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1 Archived data from 1987 through 1997 were obtained on CD-ROM from the NOAA National Oceanographic Data Center (NODC). Data for 1998-2004 were downloaded from the NOAA National Data Buoy Center (NDBC) website.

The resulting estimates of deepwater (P_0), shallow water (P_S), and equivalent unrefracted deepwater ($P_0^{'}$) wave power are listed in Table 1. Note that the shallow water and deepwater equivalent wave power are equal due to conservation of power. Both are computed to verify the calculations. Figure 3 shows the mean annual equivalent unrefracted deepwater wave power with error bars indicating one standard deviation. The equivalent unrefracted deepwater wave power was obtained by deshoaling the estimated shallow water wave power (i.e., dividing by K_s). The deepwater wave power typically exceeds the shallow water wave power by a factor of approximately four on a yearly time scale. This is attributed primarily to the wave refraction of incident waves by the Monterey submarine canyon and secondarily to the effects of the shoreline geometry at the northern and southern ends of the Bay and the resulting wave shadow. We estimate that the mean equivalent unrefracted deepwater wave power over the 1987-2004 period of record was 2.1 x 10^{11} N-m/yr per meter wave crest (4.8 x 10^{10} lb-ft/yr per foot wave crest).

Table 1. Mean annual wave power at Moss Landing Harbor (10 m isobath)

Year	Number of hours in record	Percent yearly data coverage (%)	P_0 (10^{11} N-m/yr/m)	P_0', P_s (10^{11} N-m/yr/m)	P_0', P_s (10^{10} lb-ft/yr/ft)
1987	854	9.7	17.2	3.94	8.85
1988	8258	94.3	8.14	1.89	4.25
1989	7126	81.3	5.48	1.46	3.29
1990	8648	98.7	7.86	2.03	4.57
1991	8675	99.0	8.15	2.11	4.75
1992	8441	96.4	7.61	2.09	4.69
1993	8143	93.0	7.76	2.07	4.65
1994	8419	96.1	8.10	1.90	4.28
1995	8668	98.9	8.84	2.55	5.73
1996	8696	99.3	7.44	2.22	4.98
1997	7056	80.5	7.47	2.04	4.60
1998	4615	52.7	9.18	1.90	4.27
1999	5707	65.1	1.17	2.51	5.63
2000	8382	95.7	8.76	1.88	4.23
2001	7933	90.6	1.05	2.49	5.60
2002	8702	99.3	8.79	2.29	5.15
2003	8665	98.9	7.58	1.98	4.46
2004	2176	24.8	1.17	3.35	7.53
Average			**8.38**	**2.13**	**4.79**

2.3 SAND TRANSPORT AT MOSS LANDING

Construction of the coastal structures and modifications to Salinas River during the 20th century have substantially altered the patterns and rates of sand transport along the Moss Landing shoreline. These changes have implications to the potential inlet closure and migration under Alternative 2 and need to be considered when comparing the expected future stability of this proposed inlet to historic conditions. The paragraphs below summarize our understanding of changes to the littoral transport at Moss Landing and discuss potential implications for the stability of the proposed new ocean inlet.

During large rainstorms, the Salinas and Pajaro Rivers deliver large amounts of sediment to Monterey Bay through suspended transport and bed load. Willis and Griggs (2003) estimate that land-use modifications, alterations of the stream hydrograph, and upstream barriers to sediment transport have diminished the historical rates of stream-borne sand and gravel from the Salinas and Pajaro Rivers by 33% and 6% to approximately 550,000 and 46,200 m^3/yr, respectively. It should be noted that much of the fluvial sediment discharge is finer than beach sand, and therefore the contribution of regional fluvial discharges to littoral sand budgets is probably significantly smaller than indicated by these numbers. In addition to altering the rate at which beach-building sediments are delivered to the coast of Monterey Bay, human activities have also affected the patterns of littoral transport and the amount of sediment lost to the Monterey Submarine Canyon.

The permanent diversion of the Salinas River c. 1910 and construction of jetties at Moss Landing Harbor in 1946-47 has virtually eliminated the transport of stream-borne sediments from the Salinas River and the northward transport of beach sands to Moss Landing. Given its proximity to the nearshore zone, the head of the Monterey Submarine Canyon is effective at capturing littoral sediments that are diverted offshore by the harbor jetties. These jetties also divert littoral transport from the north, including fluvial delivery from Pajaro River. Patsch and Griggs (2006) estimate that the canyon captures approximately 230,000 m^3 of sand per year. Smith et al. (2005) estimate the rate of sediment loss to the canyon to be roughly 300,000-485,000 m^3/yr and comprised of the following components: 50,000-150,000 m^3/yr from the south (Dingler et al., 1985; Watson et al., 2003); 200,000-250,000 m^3/yr from the north (Best and Griggs, 1991); and 55,000-85,000 m^3/yr from Elkhorn Slough (Brantner, 2001; Dean, 2003). Another source of permanent loss of sediment is the maintenance dredging at Moss Landing Harbor. On average, this activity removes approximately 72,100 m^3/yr from the federally maintained entrance channel (22,900 m^3/yr) and locally maintained berthing areas and North Harbor (49,200 m^3/yr) (California Coastal Commission Permit No. 3-01-049). Although a portion of the sediment dredged from the harbor is derived from scour in Elkhorn Slough, we presume that the majority of this material is littoral sediments that are swept in during flood tides.

3 INLET STABILITY

The dynamics of tidal inlets vary greatly, from sites which are continually open with relatively small changes in location and shape, to inlets that are ephemeral or subject to intermittent opening and closing. Inlet stability is primarily a function of the opposing forces of waves that move sediment into the mouth of the inlet and tidal action that scours deposited material from the channel. Empirically-based criteria used to assess inlet closure potential directly or indirectly incorporate these two opposing forces.

3.1 METHODS USED TO ASSESS CLOSURE POTENTIAL

The paragraphs below summarize empirically-based criteria used to determine the potential for inlet closure. Along with the summary of each criterion, its applicability to the present study is discussed.

Tidal Prism Relationships. Hydraulic geometry relationships between tidal prism and the cross-sectional area of the inlet channel are perhaps the most common criteria applied to predict the stability of tidal inlets. These are empirical relationships based on surveys of stable inlets, and take the form:

$$A_e = C\,\Sigma^n$$

where A_e is the minimum cross-sectional area, Σ is the tidal prism, and C and n are empirically derived parameters. Jarrett (1976) examined earlier work by O'Brien (1931) for Pacific Coast inlets, and established relationships for sites along the Gulf and Atlantic coasts. The scatter in the data indicates that not all of the relevant processes are included in these simple relationships. Therefore, they should only be used as an approximation and interpreted as representative of long-term average conditions. Note that estimates of tidal prism and throat area at Moss Landing Harbor for 1971 conditions were used by Jarrett to establish the Pacific Coast two-jetty relationships.

Escoffier Analysis. Escoffier analysis is an engineering tool used to predict inlet stability and equilibrium cross sectional area and peak velocity. The equilibrium concept is based on the balance between wave energy, which acts to move sand into the inlet, and tidal scour, which acts to remove sediment from the channel. As depicted in Figure 4, Escoffier curves, which plot the maximum velocity (U_{MAX}) vs. cross sectional area (A_C), suggest the following three possible scenarios:

1. *Inlet normally closed*. If U_{MAX} is less than the velocity required to remove sediment from the previous tidal cycle (U_{CRIT}) the inlet will close.

2. *Unstable Inlet*. If U_{CRIT} intersects the curve, there are two possible solutions. The first solution (the lower value of A_C) is "unstable" since an initial reduction in flow area is accentuated by a reduction in velocity and the inlet will continuously shoal until closure. Similarly, an initial increase in flow area is accentuated by an increase in velocity and the inlet will scour until critical flow area is attained.
3. *Stable Inlet*. The second intersect of U_{MAX} and U_{CRIT} (the larger value of A_C) indicates a stable inlet since any induced changes in the cross-sectional area will result in a change of velocity that returns the inlet to its original size by deposition or scour.

Johnson's Stability Criterion. Johnson (1973) proposed a simplified approach of comparing the estimated average annual deep-water wave power with the potential tidal prism. Johnson concluded that for a given wave power, there appears to be a tidal prism that must be exceeded if the inlet is to remain open. After graphically presenting his results, Johnson identified a line that separates inlets that have closed or are usually closed and those that stay open. Like the hydraulic geometry relationships, this criterion gives a general indication of the long-term stability of the inlet, but cannot provide more than a qualitative indication of the frequency of closure. PWA has extended Johnson's stability criteria to address closure frequency and timing for inlets with marginal "stability" (Battalio et al., 2006; Goodwin, 1996). This method requires analysis that is beyond the scope of this study.

Bruun's Stability Criterion. The ratio of tidal prism to total littoral sediment drift has been used extensively in the literature as an indicator of inlet stability (Bruun and Gerritsen, 1959) (Bruun 1966; Bruun 1978). Inlets with ratios of tidal prism to annual gross littoral drift less than 20 are typically considered unstable, non-permanent coastal features (USACE, 2002). The usefulness of the Bruun criteria is limited by its qualitative description of inlet stability and ability to quantify littoral drift at the proposed location of the new ocean inlet.

PWA applied the tools described above to inform our assessment of closure potential under Alternative 2 as well as historic (i.e., pre-harbor) conditions. Application to historic conditions allows for an appraisal of the tools' usefulness by comparing the results to anecdotal information.

3.2 HISTORIC CONDITIONS

PWA assessed the closure potential of the c. 1940 (pre-harbor) inlet using the Johnson, Escoffier and Bruun methods. These results are consistent with historical accounts of the pre-harbor inlet, which describe a sluggish estuary and shoaling inlet mouth. Results from the specific analyses are presented below.

- Escoffier Analysis. The Escoffier Analysis was carried out with the U.S. Army Corps of Engineers Channel Equilibrium Area Software (Seabergh and Kraus, 1997). The typical approach involves calibrating the model before executing the full inlet stability analysis. Model parameters for the calibration and analysis are presented in Table 2. For this pre-harbor condition, the predicted unstable and stable equilibrium throat areas are 32 m^2 and 420 m^2, respectively. Given that the measured pre-harbor throat area was approximately 50 m^2, the results show that the historical inlet persisted on the "unstable" portion of the stability curve (Figure 5). Therefore, while the c. 1940 inlet did maintain an open connection to Monterey Bay, it was relatively unstable.

Table 2. Summary of Escoffier Analysis Parameters.

Tides	
Ocean Tide Amplitude (m)	1.0
Ocean Overtide Amplitude (m)	0.0
Tidal Period (hrs)	12.42
Basin Surface Area (Mm^2)[1]	3.0
Inlet Geometry[2]	
Hydraulic Radius (m)	1
Channel Length (m)	900
Channel Width (m)	80
Channel Area (m^2)	51
Frictional Parameters	
Entrance Loss, K_{en}	0.1
Exit Loss, K_{ex}	0.2
Manning's n	0.025

[1] Estimated as the area of subtidal saltwater channel from Van Dyke and Wasson (2005), Figure 3.
[2] Inlet geometry estimated from 1940 USACE survey of inlet throat and aerial photographs.

- Bruun Analysis. PWA constructed a numerical model of c. 1940 conditions using survey data collected prior to the construction of Moss Landing Harbor. Model results for the pre-harbor condition suggest that the relatively shallow throat substantially damped the tide range within the Slough and indicate that the mean diurnal tidal prism was approximately 2.2 Mm^3. Assuming this value and a (gross) littoral drift of 250,000 m^3/yr, the Bruun ratio is approximately 9 and suggests an unstable, non-permanent inlet.

- Johnson Analysis. Figure 6 displays the historical mean diurnal tidal prism predicted by the pre-harbor (e.g., 1943) model (2.2×10^6 m^3) (left Elkhorn Slough point on Figure 6) against annual wave power (21.3 x 10^^{10} N-m/yr/m) on Johnson's curve along with points for various coastal inlets of California. An additional Elkhorn Slough reference point is shown for existing conditions (right Elkhorn Slough point on Figure 6). An estimate of the closure threshold is shown as a wide solid band to indicate the qualitative nature of the criterion. The results indicate that while the inlet has historically plotted in the "open" region, Elkhorn Slough is near the threshold between stable and unstable inlets and a potential for closure may have existed historically in the absence of jetties and harbor dredging.

Although the inlet stability analysis presented above includes several approximations (i.e., parameters that are relatively simple to quantify are used as surrogates for complex wave-tidal-sediment transport analysis), the results from the three independent criteria suggest that the tidal inlet was only marginally stable immediatly prior to construction of the two-jetty inlet at Moss Landing. These results are generally consistent with anecdotal accounts of Elkhorn Slough which Van Dyke and Wasson (2005) summarize as a "sluggish lagoon with limited tidal exchange for much of the year due to a persistent sandbar at the mouth."

4 ASSESSMENT OF STABILITY THRESHOLD

The progression from pre-harbor (pre-1947) to present day conditions is clearly evident as Elkhorn Slough transformed from a sluggish lagoon susceptible to closure to a hydraulically efficient, stabilized dual jetty system. Figure 6 shows a qualitative assessment of the historic and present day stability of Elkhorn Slough based on the magnitude of deepwater wave power and potential tidal prism relative to other California lagoons. A qualitative estimate of the closure threshold is shown as a solid line. The results indicate that while the inlet has historically plotted in the "open" region, Elkhorn Slough is near the threshold between stable and unstable inlets and a potential for closure may have existed historically in the absence of jetties and harbor dredging. This finding is consistent with the results of the Escoffier analysis for the historic inlet, which indicate that the historic inlet existed on the unstable portion of the closure curve. For the calculated mean annual deepwater wave power of 2.13×10^{11} N-m/yr/m, the Johnson stability threshold predicts a minimum required *potential* tidal prism of roughly 3 million m^3 to maintain a stable inlet.

The equilibrium area vs. tidal prism relationship from Jarrett (1976) for two jetty Pacific coast inlets is shown on Figure 7. The conditions for the existing dual jetty system at Moss Landing Harbor Entrance ($A = 405$ m^2, $P = 6.79$ million m^3) are shown for reference. Figure 8 shows the equilibrium area vs. tidal prism relationship from Jarrett (1976) for unjettied and one jetty Pacific coast inlets. The existing cross-sectional area at the harbor entrance is substantially oversized (by approximately 40%) relative to a natural inlet given the existing tidal prism at the HWY 1 Bridge (6.2 million m^3). The expected conditions ($A = 265$ m^2) for the new ocean inlet alternative north of Moss Landing Harbor are represented as "Elkhorn Slough – Year 0." The existing tidal prism at the HWY 1 Bridge was used since the additional tidal prism due to Moss Landing Harbor will be bypassed by the proposed alternative. It is expected that in time the tidal prism will reduce in response to deposition of littoral sands. The evolving flood shoal will limit the tidal prism of Elkhorn Slough and the equilibrium point will shift along the Jarrett curve to a smaller equilibrium cross sectional area (indicated by arrows in the figure).

The ratio of tidal prism to total littoral sediment drift has been used extensively in the literature as an indicator of inlet stability (Bruun and Gerritsen, 1959). A tidal prism of approximately 2.2 million m^3 (pre-harbor numerical model) and littoral drift of 250,000 m^3/yr results in a stability index of 9 for historic (pre-harbor) Elkhorn Slough. Inlets with indices less than 20 are typically unstable, non-permanent coastal features. While anecdotal evidence suggests that the historic inlet was indeed a persistent feature, the low stability index confirms the hypothesis that a potential for closure may have existed historically. For comparison, the contemporary Moss Landing inlet tidal prism of 6.8 million m^3 yields a stability index of approximately 27. This indicates that in the absence of engineering structures and dredging, the inlet would be a relatively stable bar-bypassing inlet. Based on a stability threshold of 20 and littoral drift of 250,000 m^3/yr, the Bruun ratio predicts that a threshold *effective* tidal prism of 5 million m^3 would be required to maintain a stable inlet.

It should be noted that the consequences of an inlet closure for contemporary conditions could potentially be more severe than for historic conditions. Historically, freshwater discharge from the Salinas River aided tidal scour in maintaining an open ocean inlet and episodic winter floods could act to breach seasonal or occasional inlet closures. With the diversion of the Salinas River in the early 1900s, the ability of the system to recover from periodic closures has been substantially reduced.

5 DISCUSSION

Inlet stability is a term partly derived from the engineering perspective of an open inlet being stable and functional for navigation. This definition is not really appropriate for a restoration project, but is used herein for context with the available analysis methods. It should be noted that intermittent closure is not unusual and intermittently closed lagoons occur naturally in California and can provide valuable habitat (Goodwin, 1996). Another aspect of "instability" is migration of the inlet. The Bruun Analysis can provide some indication of the likelihood for an inlet to move up and down the coast. Downcoast movement is likely where the longshore sand transport is nearly unidirectional (i.e., the net transport is nearly equal to the gross) (Battalio et al., 2006). Oscillating migration is most likely where the net longshore transport rate is small relative to the gross transport rate but where the net is strong seasonally (i.e., the inlet may migrate due to seasonal changes in wave climate, storms, or other short term oscillations).

Historically, the Elkhorn Slough Inlet may have migrated up and down coast locally, and may have breached in a range of locations after closures, if these occurred. A future inlet may behave differently, however, owing to changes in river discharge and the change in longshore sand movement due to the harbor jetties. The jetties essentially prevent northward sand supply and therefore limit the northward sand transport at the proposed new inlet location. Therefore, we believe it is likely that the new inlet will tend to migrate southward toward the existing harbor inlet. Once at the north jetty, the inlet would stabilize, meaning that it would not be prone to as much migration and would likely remain open. Therefore, it seems that an alternative location for the new inlet potentially more consistent with the existing conditions is just north of the present day harbor entrance (Alternative 2b, Figure 9). This alternative was developed based on consideration of the coastal processes discussed above. The alternative consists of a new inlet just north of the north jetty, and an extension of the north jetty eastward to the vicinity of the south abutment of the exiting Highway 1 Bridge. The Highway 1 barrier and new bridge included in Alternative 2 (Figure 1) would not be necessary. Alternative 2b would be more "stable" in terms of closure potential and migration. Further analysis, including evaluation of land use and other costs are required to assess the best new inlet alternative and to compare alternatives.

6 CONCLUSIONS

The results presented above suggest that historically a potential for closure existed, and that the inlet persisted in a regime where episodic depositional events could have resulted in significant morphologic changes over seasonal and annual time scales. The stability thresholds of Bruun and Johnson indicate a minimum required tidal prism of 3.0 – 6.0 million m^3 to maintain a stable inlet. This corresponds to an equilibrium cross sectional area of 165-255 m^2 based on Jarrett's relationships for unjettied inlets. Strong littoral sediment transport (~250,000 m^3/yr) relative to the existing tidal prism may result in inlet migration along the shoreline towards the present-day Moss Landing Harbor. This migration could be managed by the construction of one or more jetties to limit shoaling within the inlet throat and inhibit lateral migration.

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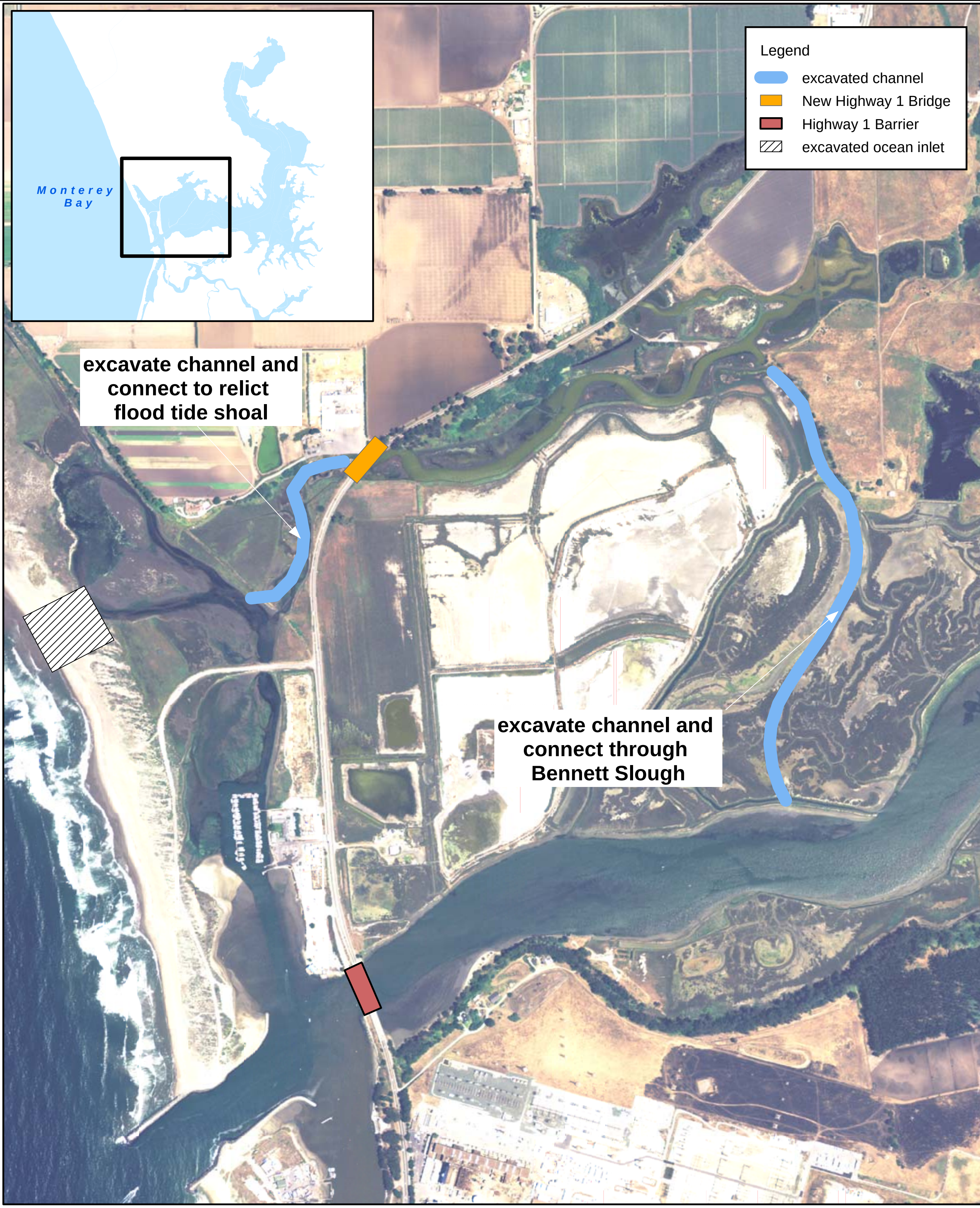

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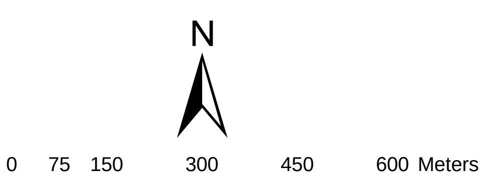

figure 1

Elkhorn Slough Tidal Wetland Project

Alternative 2 - Restore the Pre-Harbor (1945) Ocean Inlet

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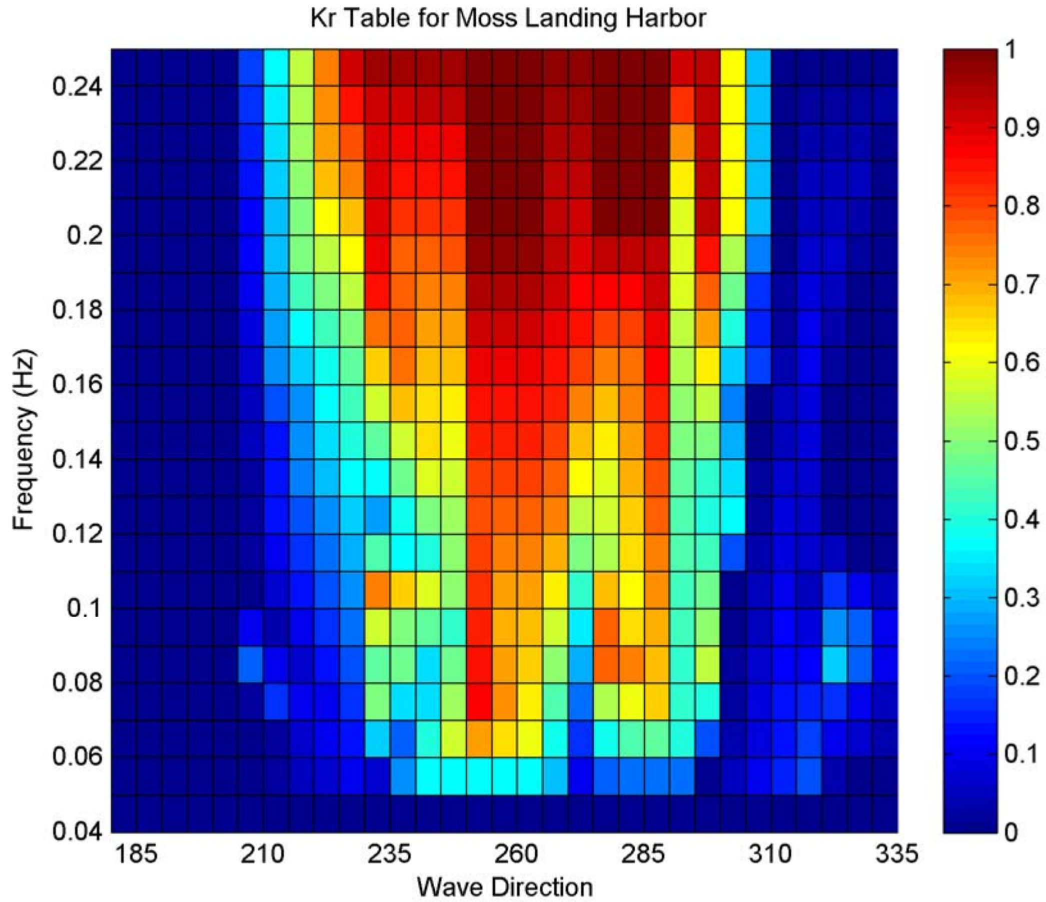

figure 2
Elkhorn Slough Tidal Wetland Project

Refraction Coefficients for Moss Landing Harbor

PWA Ref# 1869 Task C Inlet Stability Analysis

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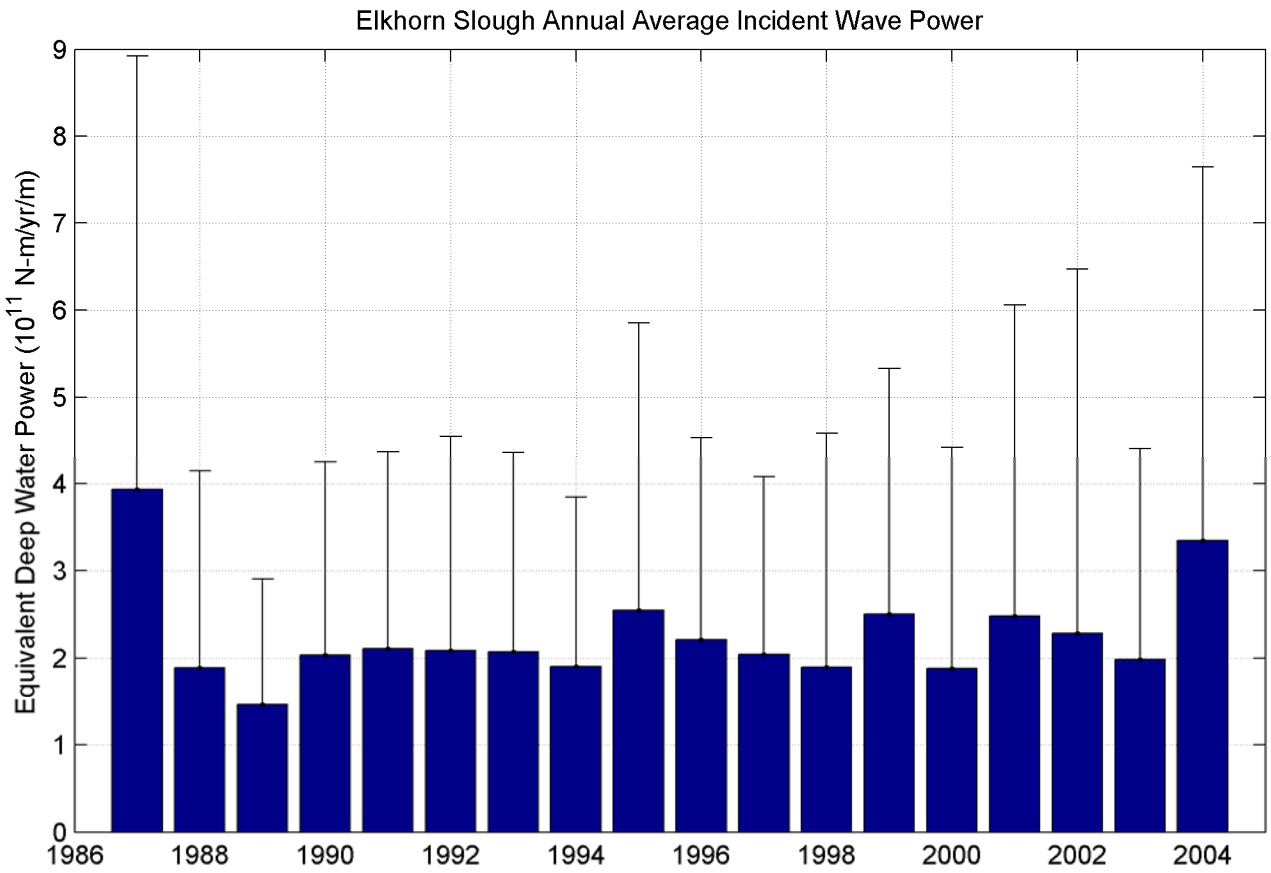

figure 3
Elkhorn Slough Tidal Wetland Project

Annual Average Incident Wave Power

PWA Ref# 1869 Task C Inlet Stability Analysis

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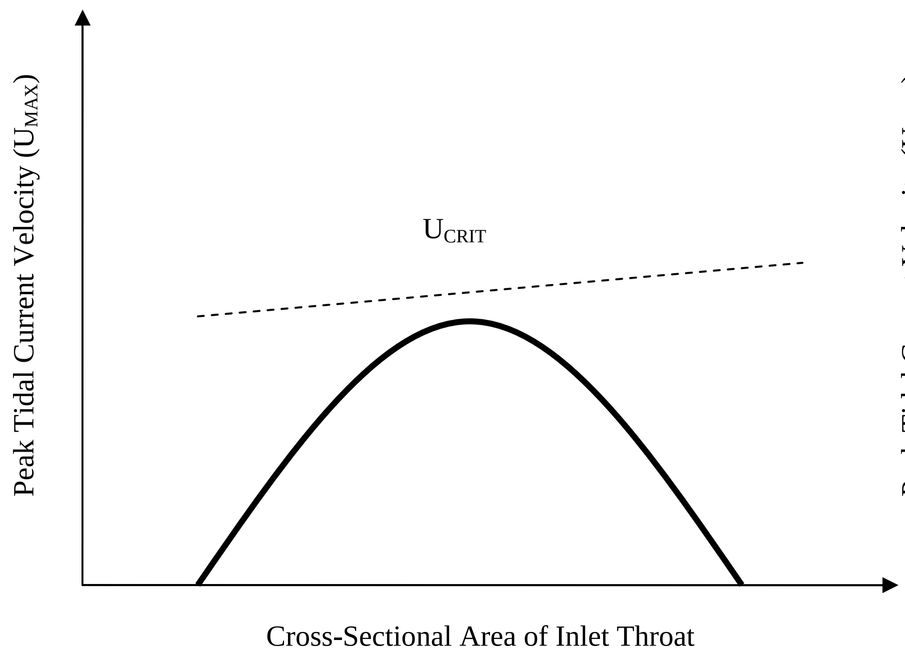
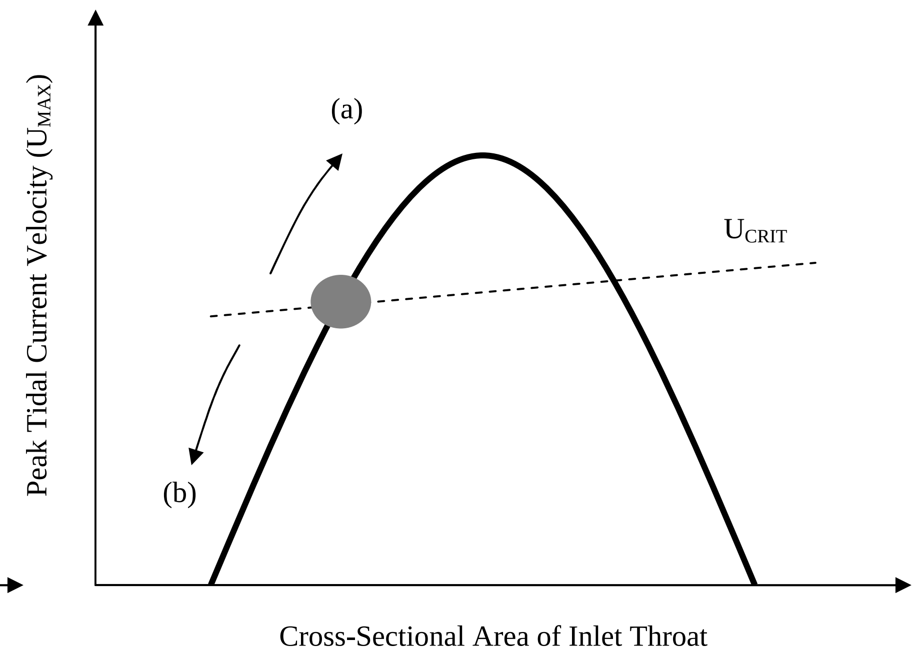
$U_{CRIT} > U_{MAX}$. Peak velocity through the inlet is insufficient to maintain an open inlet. Breaching may occur during high rainfall events if stream power is sufficiently large, but beach-building processes soon close inlet when streamflow diminishes.



Case 1: Inlet normally closed

(a) Initial scour increases velocity, which induces additional scour until inlet reaches new equilibrium with larger mouth.

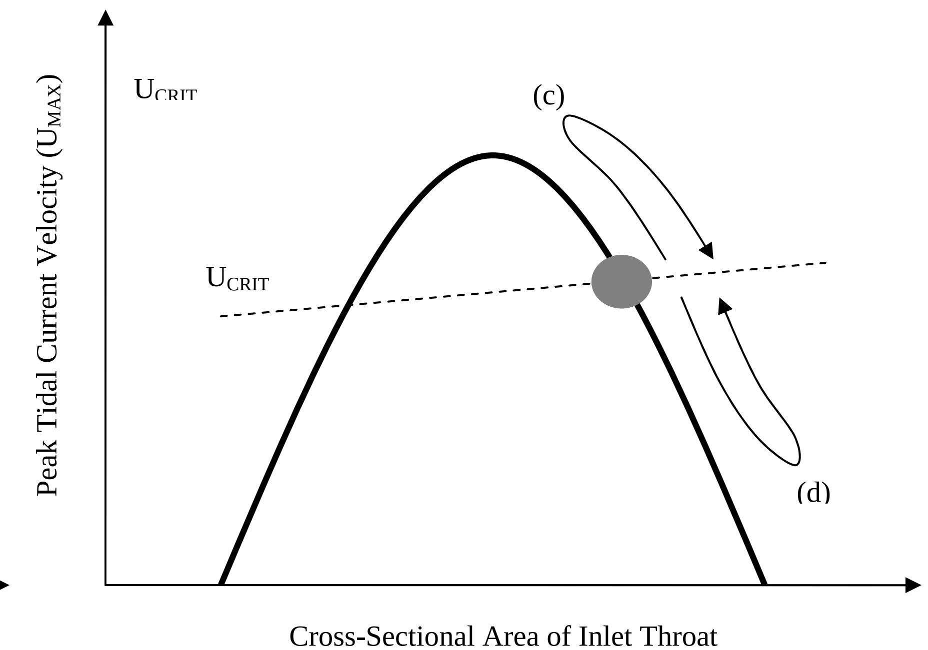
(b) Initial shoaling decreases velocity, which induces additional deposition until inlet closes.



Case 2: Unstable inlet

(c) Initial shoaling increases velocity, which induces scour that returns inlet to stable equilibrium.

(d) Initial scour decreases velocity, which induces deposition that returns inlet to stable equilibrium.



Case 3: Stable inlet

figure 4

Elkhorn Slough Tidal Wetland Project

Possible Outcomes of Open Inlets from Escoffier Analysis

PWA Ref #1869

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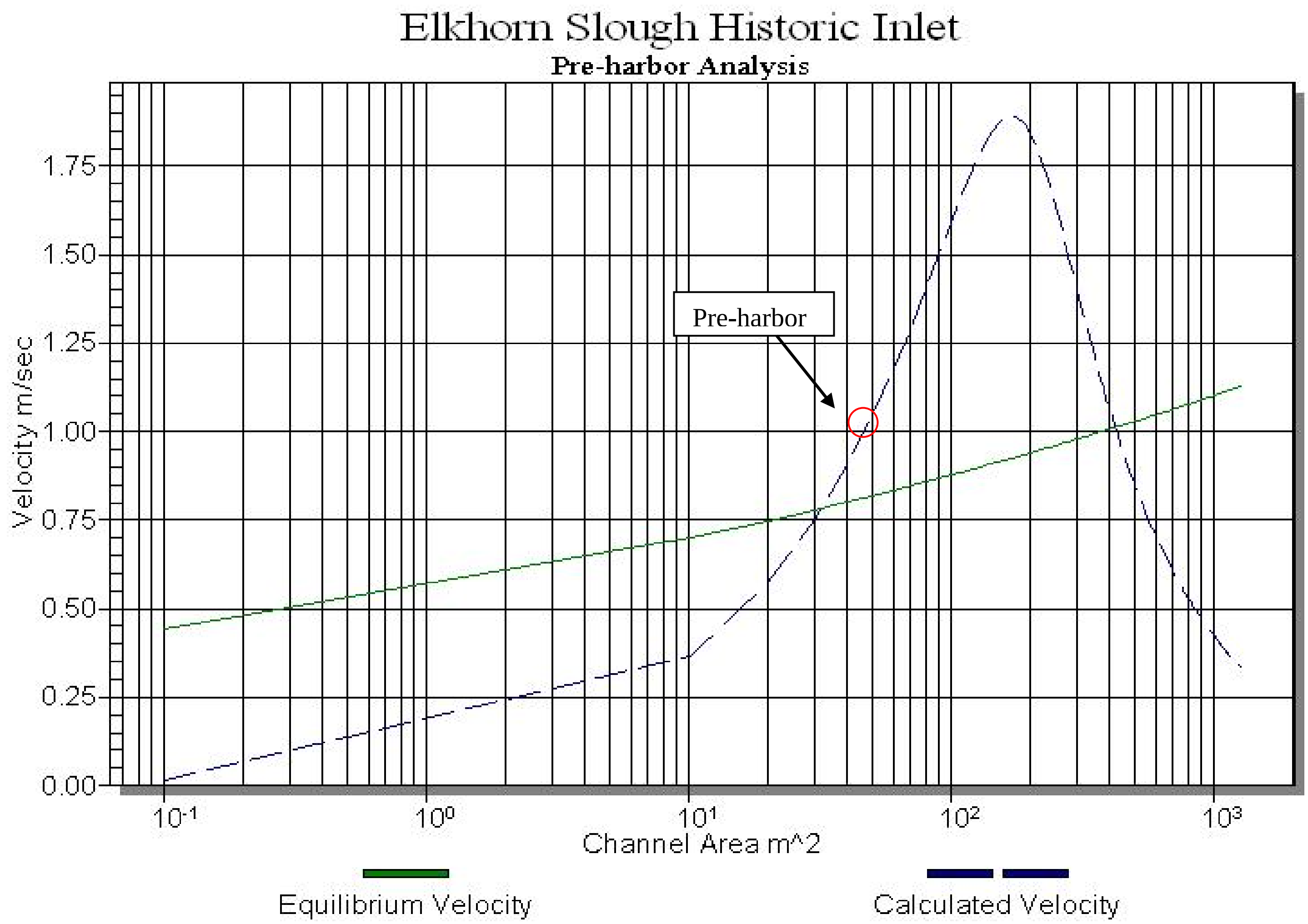

Source: USACE Channel Equilibrium Area Software

figure 5

Elkhorn Slough Tidal Wetland Project

Escoffier Curve for Pre-harbor Conditions

PWA Ref# 1869 Task C Inlet Stability Analysis

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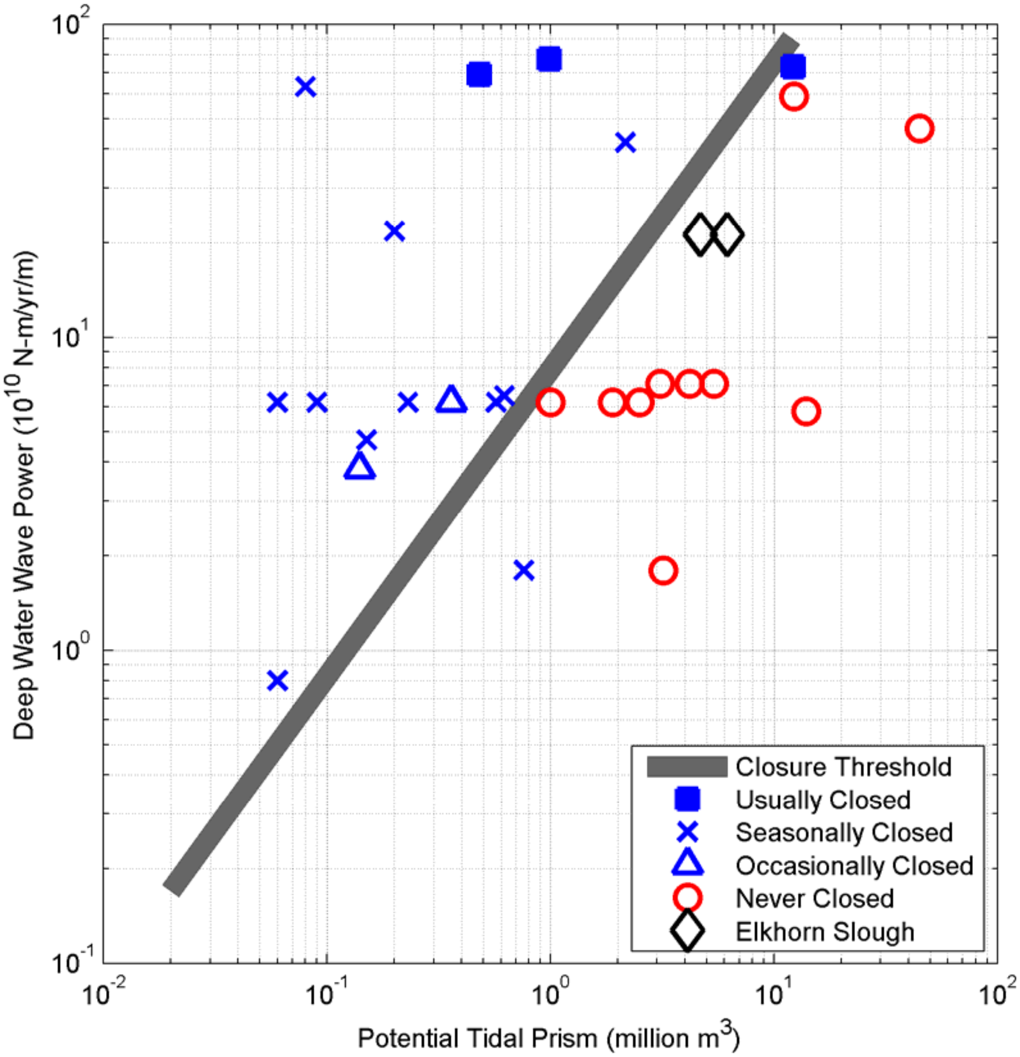

figure 6

Elkhorn Slough Tidal Wetland Project

Johnson-type plot of tidal inlet stability

PWA Ref# 1869 Task C Inlet Stability Analysis

PWA

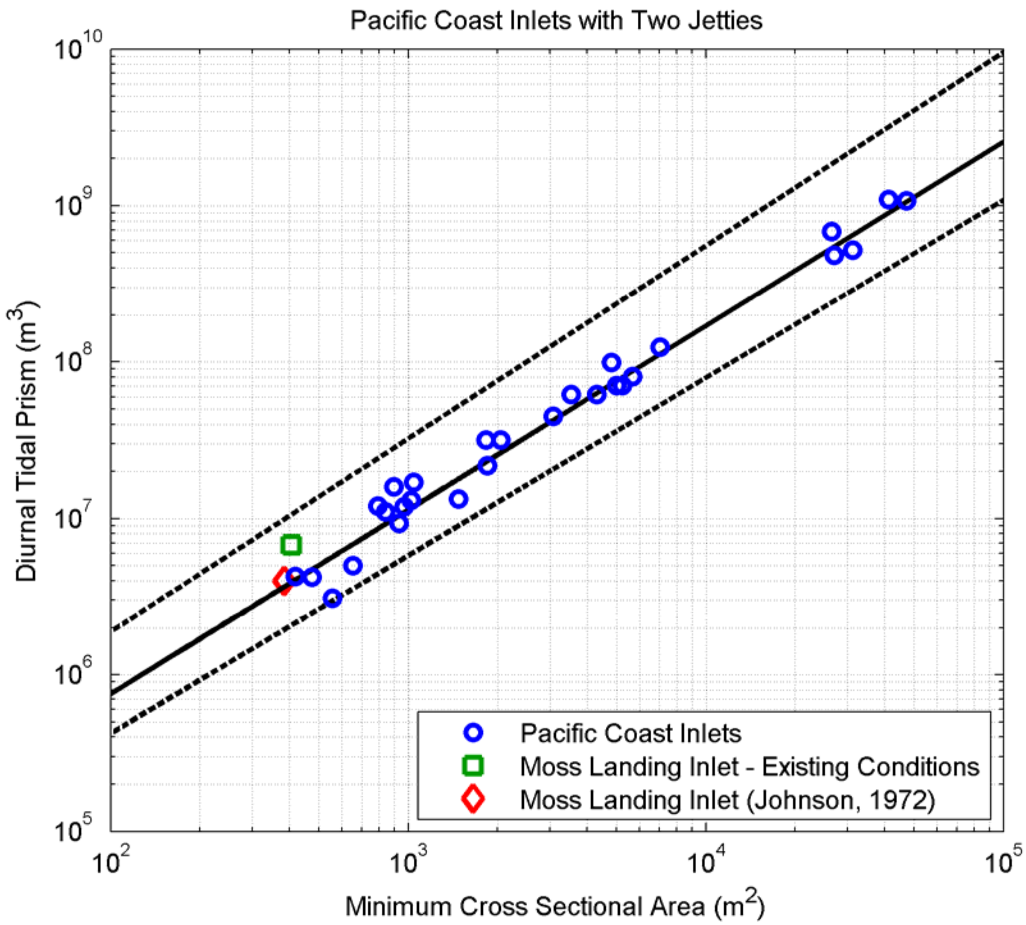

figure 7
Elkhorn Slough Tidal Wetland Project

Jarrett (1976) Tidal Prism-Area Relationship for Pacific Coast Two Jetty Inlets

PWA Ref# 1869 Task C Inlet Stability Analysis

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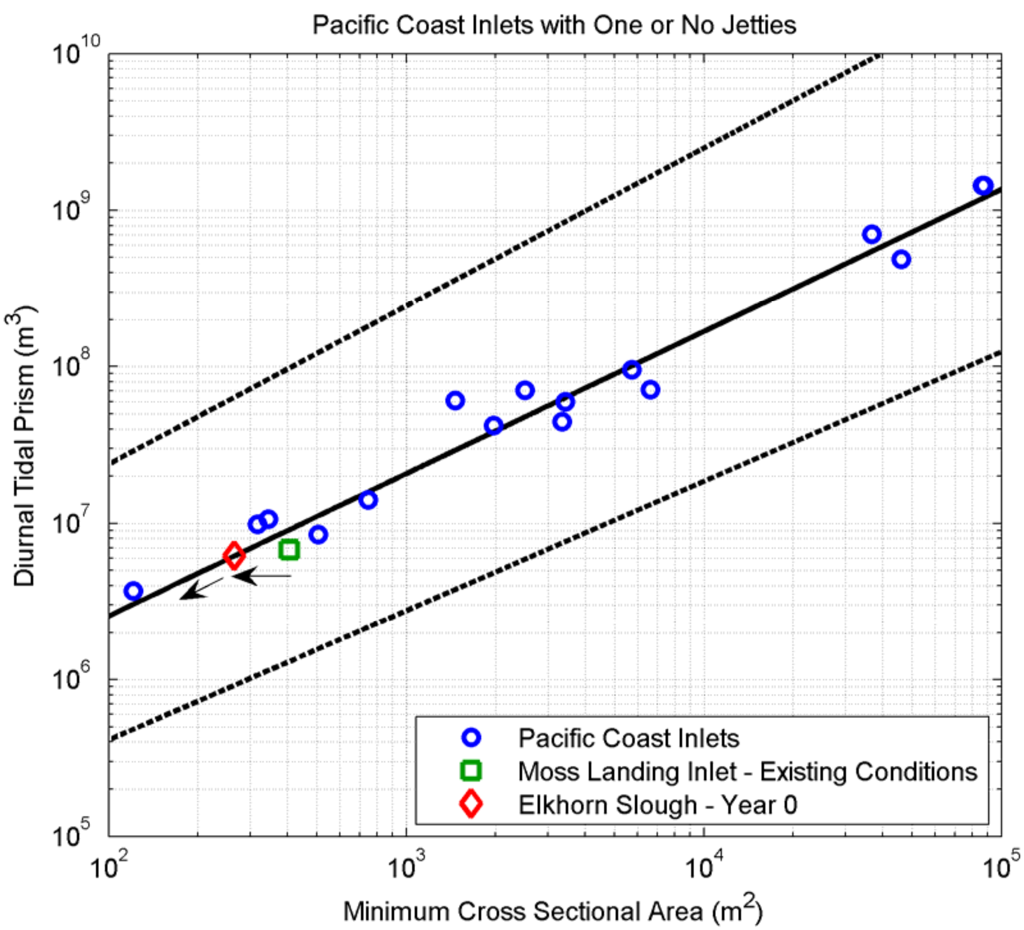


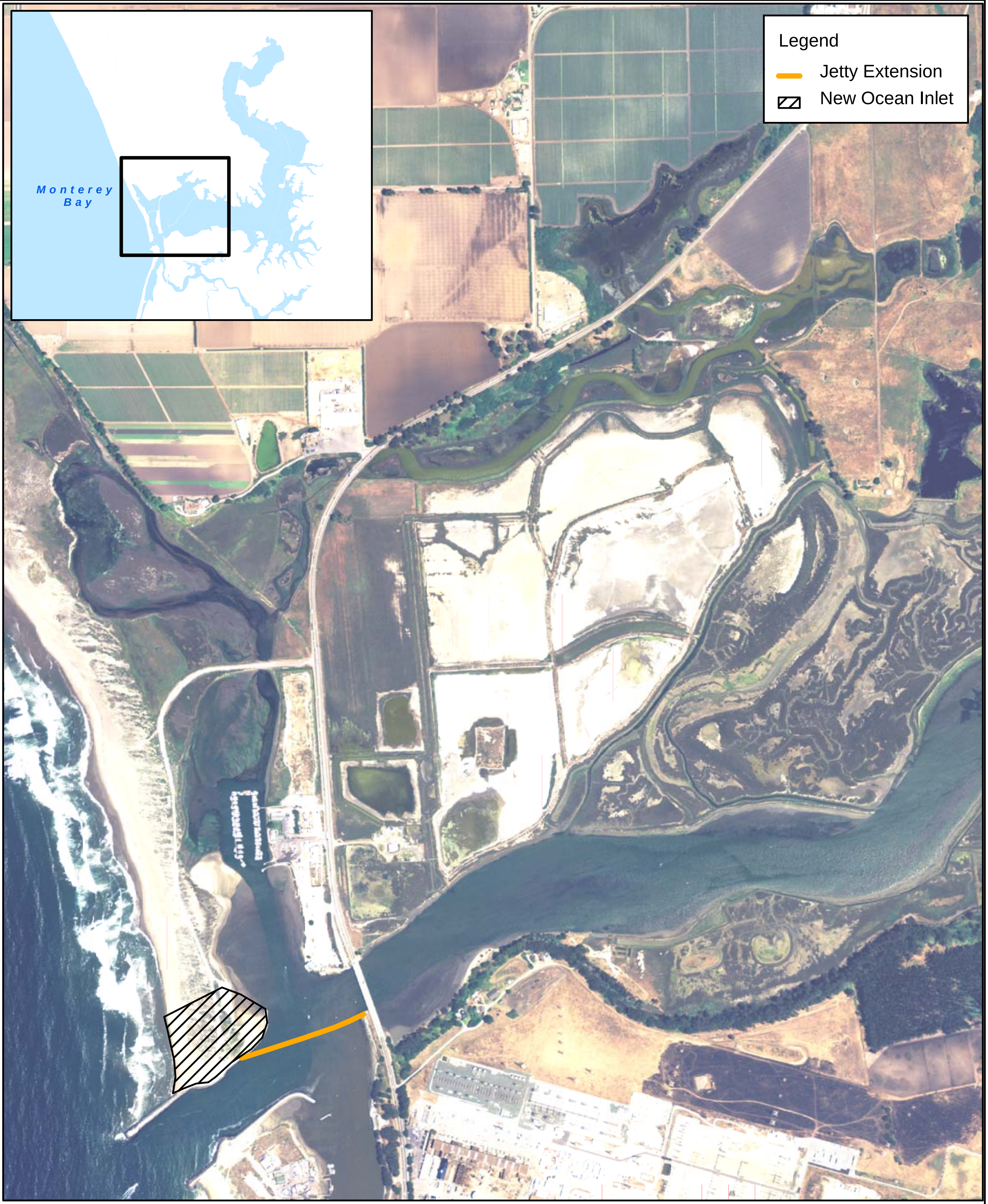
figure 8

Elkhorn Slough Tidal Wetland Project

Jarrett (1976) Tidal Prism-Area Relationship for Pacific Coast Unjettied and One Jetty Inlets

PWA Ref# 1869 Task C Inlet Stability Analysis

PWA



Source: USDA/NAIP 1m/pixel true color ortho (2005)

figure 9

Elkhorn Slough Tidal Wetland Project

Alternative 2b - New Ocean Inlet - Extend North Jetty

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APPENDIX C.
THE RESPONSE OF TIDAL HYDRAULICS TO REDUCTIONS IN HIGHWAY 1 TIDAL PRISM

APPENDIX C. THE RESPONSE OF TIDAL HYDRAULICS TO REDUCTIONS IN HIGHWAY 1 TIDAL PRISM

As part of the initial refinement of the Elkhorn Slough restoration alternatives, a sensitivity analysis was conducted to assess different configurations to reduce the tidal prism entering the Slough at Highway 1. The purpose of this analysis was to develop an understanding of the response of the Slough's hydraulics as the tidal prism at the mouth was reduced. In addition, the mechanism used for restricting tidal prism in this analysis is similar to the implementation of the partial tidal barrier proposed for Alternative 3. Therefore, this sensitivity analysis provides an indication of how tidal hydraulics are likely to respond to different configurations (e.g., higher sill elevations and/or multiple sills) of the partial tidal barrier proposed for Alternative 3.

Reductions in tidal prism were attained by placing a sill just downstream of where Highway 1 crosses the mouth of the Slough. To vary the amount of tidal prism entering the Slough, the crest elevation of this sill was varied from 4.4 m below MLLW (2 m above the thalweg) to 1.4 m below MLLW (5 m above the thalweg). Elevations higher than 1.4 m below MLLW were not explicitly analyzed since higher elevations would reduce boat clearance during low water to less than 1 m. However, higher sill elevations were implicitly analyzed through adjustments to the modeled sill friction coefficient. The friction coefficient is an empirical parameter that accounts for the energy losses generated by the complex flows over the sill. The default friction coefficient of one (1) was increased by a factor of 2, 4, 8, and 16 to further reduce tidal prism. Alternative 3 model predictions described in the main report (e.g. Sections 4.3, Section 5.3.3) correspond to the 1.4 m below MLLW sill with the default friction coefficient of one.

Increasing the friction coefficient was a rapid way to test different degrees of flow reduction, but does not necessarily correlate with realistic physical modifications to a single sill. The method was appropriate for the initial alternative refinement and was termed a 'black box' analysis in recognition that the exact mechanism used to reduce tidal prism was not as important as the response in the Slough's hydraulics. However, to translate from a particular friction coefficient to a physical sill configuration requires additional analysis to optimize the number, dimensions and location of one or more sills to achieve a similar reduction in tidal prism.

Results from these different sill configurations are displayed in the figures below. In each figure, the percent reduction in tidal prism, the independent variable, is compared against the corresponding percent reduction of a key hydraulic parameter that influences habitat loss – peak water level (Figure C-1), peak current speed (Figure C-2), or peak bed shear stress (Figure C-3).

Results from the 'black box' analysis described above, with variable sill elevations and friction coefficients, are shown as a dashed blue trend line in the figures. A dotted black 1-to-1 slope provides a reference to evaluate the relative response of the hydraulic variable to the tidal prism. The percent reduction of peak water level is approximately half that of the percent reduction in tidal prism (Figure C-1). In contrast, the percent reduction in peak current speed scales nearly identically to the percent reduction in the tidal prism (Figure C-2). As shown in Figure C-3, the peak bed shear stress, which decreases in proportion to the square of current speed, exhibits the largest dependence on reduction of tidal prism.

The individual colored points on this figure indicate results from the proposed restoration alternatives. It should be noted that the results from the proposed restoration alternatives are from an early iteration of the alterative modeling and may differ slightly from the more recent model results in presented in the main report. For most combinations of the alternatives and the hydraulic response variable, the alternatives fall close to the trend line established by the 'black box' analysis. The one exception is water levels predicted for Alternative 4. In this case, reducing the tidal prism associated with Parson Slough and South Marsh does not significantly alter the main Slough's water levels.

Alternative 3, a partial tidal barrier at Highway 1, falls on the 'black box' trend line since it is one of the configurations tested to create the trend line. Alternative 2, the new tidal inlet, lies just beyond the upper end of the 'black box' trend line. Since the trend line was created by varying sill friction coefficient characteristics, further reductions in tidal prism by altering the number, dimension and/or location of Alternative 3's sill configuration is likely to produce responses to Slough hydraulic variables that trend toward Alternative 2's conditions.

Figure C-1: Percent Reduction in Peak Water Level vs. Percent Reduction in Tidal Prism

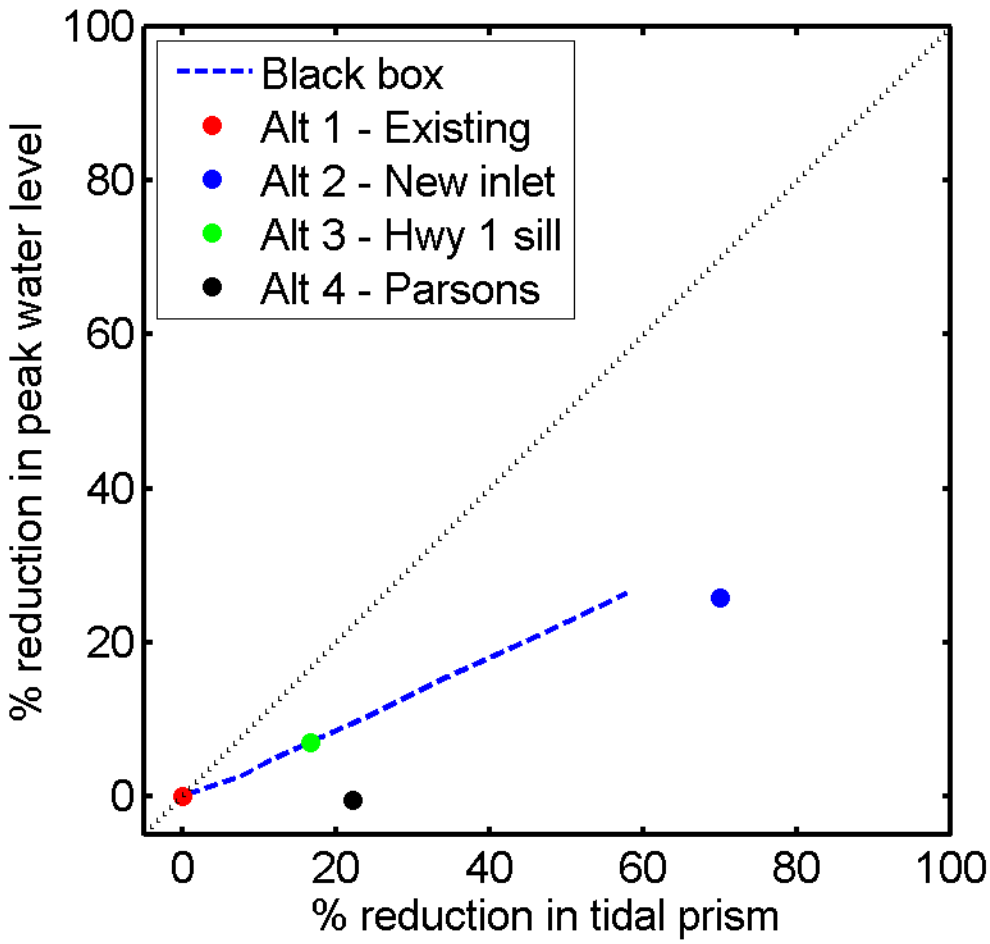


Figure C-2: Percent Reduction in Peak Current Speed vs. Percent Reduction in Tidal Prism

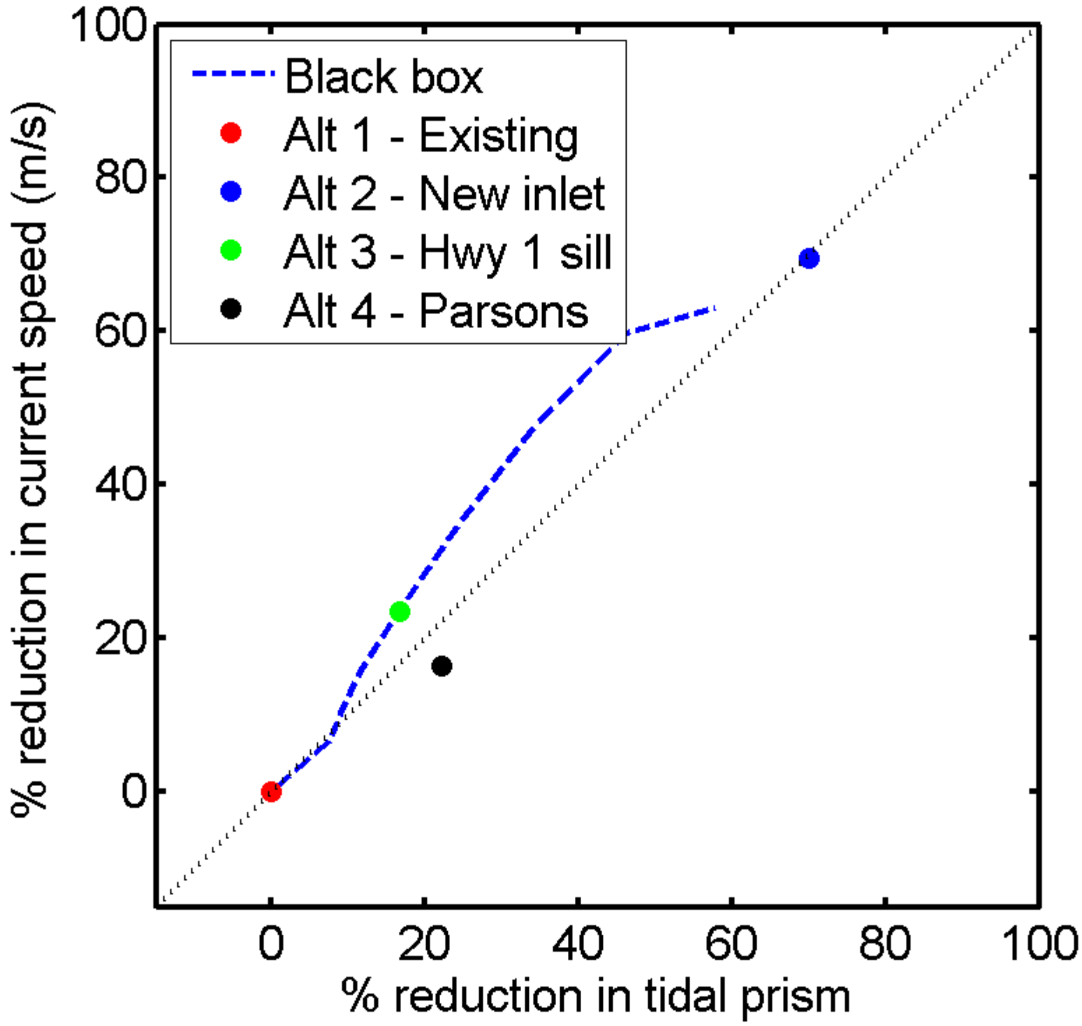
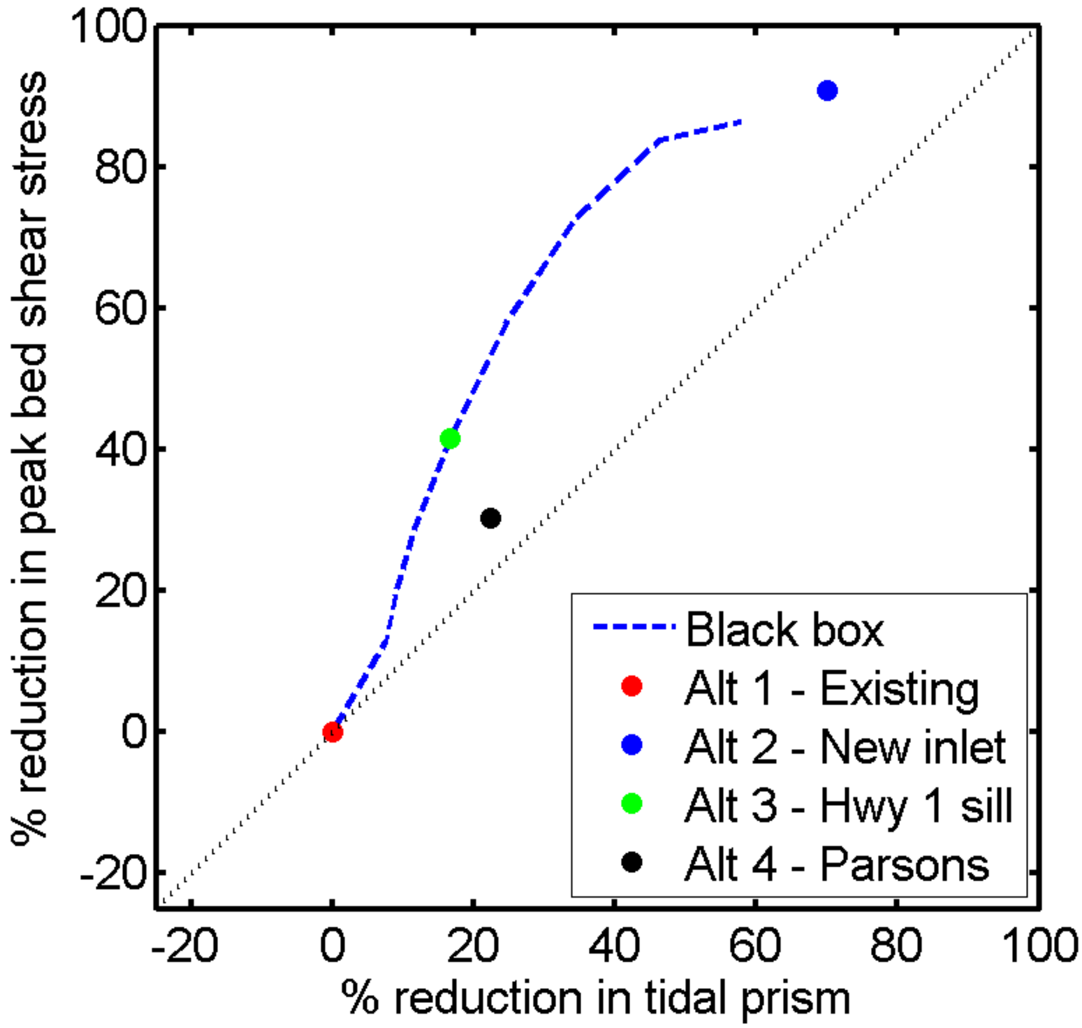


Figure C-3: Percent Reduction in Peak Bed Shear Stress vs. Percent Reduction in Tidal Prism



APPENDIX D.
SENSITIVITY ANALYSIS OF ELKHORN SLOUGH HYDRAULICS TO TIDAL EROSION AND MARSH LOSS

Appendix D: Sensitivity Analysis of Elkhorn Slough Hydraulics to Tidal Erosion and Marsh Loss

D.1 Introduction

Habitat loss in Elkhorn Slough has been associated with changes to two geomorphic units: tidal erosion in the main channel and (TWP, 2007) and loss of vegetation and conversion to mudflat of the marsh plain (Van Dyke and Wasson, 2005). These geomorphic changes to the elevation of the bed surface produce corresponding changes in the Slough's hydrodynamics. A sensitivity analysis of lowered bed elevation indicates that Elkhorn Slough's hydraulics respond more strongly to tidal erosion in the main channel than marsh loss. The main channel experiences a negative feedback (tidal currents decrease in response to main channel erosion) larger than the positive feedback (tidal current increase in response to marshplain erosion). By increasing the depth of the bed elevation of the main channel, the marsh plain, or both simultaneously, the hydrodynamic response of the Slough was assessed using the DELFT3D model.

D.2 Method

To test which parameters are dominant in defining the hydraulic characteristics of Elkhorn Slough, a sensitivity analysis was conducted with the calibrated existing conditions model. The five assessed scenarios are:

1. *Channel erosion* – Bed elevations less than -1 m[*], which includes only the Slough's main channel, were lowered by 50% of the difference between -1 m and the 2003 bed elevation. For example, bed elevations near the mouth of -8 m were changed to -11.5 m and bed elevations near Kirby Park of -3 m were changed to -4 m.
2. *Marshplain lowering method 1* – Marshplain between elevations of 1.7 m and 1.2 m was lowered to an elevation of 1.2 m to simulate loss of marsh vegetation and conversion to high mudflat. These elevations are representative of the breakpoint between vegetated marshplain and unvegetated mudflat as indicated by the LiDAR elevation data and aerial photographs. This method alters the bed elevation of 225 hectares (555 acres) of marshplain adjacent to the Slough.
3. *Marshplain lowering method 2* – Marshplain between an elevation of 1.7 m and 1.2 m was lowered by 0.3 m and marshplain between an elevation of 1.2 m and 0.9 m was lowered to an elevation of 0.9 m to simulate loss of marsh vegetation and conversion to high mudflat. This method alters the bed elevation of 355 hectares (877 acres) of marshplain adjacent to the Slough.
4. *Channel erosion and marshplain lowering* – Changes to both the main channel and marshplain, as described Scenario 1 and Scenario 3, were implemented simultaneously.

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[*] The vertical datum for all elevations is NAVD, which is within centimeters of MLLW.

5. *Mean sea level rise* – The water surface elevation at the open boundary in Monterey Bay was raised by 30 centimeters. Bed elevations remained unchanged from existing conditions.

Figure D-1 shows the hypsometry of Scenarios 1-4, as well as for Alternative 1 (No Action), which corresponds to existing conditions. The hypsometry curves in this figure overlap at numerous points, thereby requiring symbols to differentiate between the curves. Bed elevation changes were enacted for two distinct elevation ranges, below -1 m and above 1.2 m. In between, bed elevation is not the sole determinant as to whether a point lies within the main channel, within a marsh channel, or on the mudflat. Therefore, bed elevations within this interval were not altered. These hypsometry curves demonstrate that changes in main channel elevation were larger in vertical magnitude, but smaller in areal extent than changes to the marshplain.

Simulation periods for the scenarios listed above lasted for four days during spring tides of the calibration period (April 15-19, 2003). Model results are reported as water level versus current velocity curves. These curves depict the envelope of predicted simultaneous water level-velocity pairs. The predicted water level and depth-averaged velocity time series were averaged across a cross section near the mouth of the Slough.

D.3 Results

Figure D-3 presents a comparison of water level versus velocity curves for existing conditions (Alternative 1 Year 0), as well as the five sensitivity analysis scenarios at a cross section near the downstream end of the Slough (see Figure 5-4). The range of water levels only change under Scenario 5, in which mean sea level was explicitly altered. As indicated by Scenarios 1-4, water levels are insensitive to lowering the bed elevation of either the main channel or the marshplain.

Deepening the main channel, Scenarios 1 and 4, results in a decrease in velocity, as indicated by the narrowing of these curves' width (Figure D-3). Deepening only the marshplain, as in Scenario 2 and Scenario 3, generates increases in peak velocity of less than 10%. The difference between the marshplain lowering methods, Scenario 2 and Scenario 3, is minimal, indicating that the model results are not sensitive to the specific topographic changes induced by the marsh lowering method, but rather the characteristic magnitude of marshplain elevation change.

When both the main channel and the marshplain are altered in Scenario 4, the main channel lowering dominates the overall response, resulting in a velocity reduction at nearly all points of the tide. The one exception is at peak flood tides, located in the upper left quadrant of Figure D-3. The peak flood velocity occurs at the elevation of the marshplain because the flow area increases rapidly as water levels crest onto the marshplain. In this elevation during flood tide, lowering the marshplain offsets the effect of the deeper main channel to produce minimal difference between existing conditions and Scenario 4. Because of the reduction of peak ebb velocity but maintenance of peak flood velocity, Scenario 4 reduces the asymmetry between these velocity peaks.

For comparison, the impact of sea level rise on the unchanged bathymetry is also included in the sensitivity analysis. This change to the external system creates a corresponding linear offset on water levels. The relative change between sea level and marshplain is similar between Scenario 5 and Scenarios 2 and 3. Hence, the increase in velocity for Scenario 5 is similar, but slightly larger than, Scenarios 2 and 3. Scenario 5's increase is slightly larger because rather than limiting the lowering of bed elevation to a narrow range, i.e. 1.2-1.7 m of existing elevation, Scenario 5 alters relative elevations uniformly across the Slough.

Figure D-4 shows the water level versus velocity curves for Alternative 1 (No Action) and Scenarios 1-5 at the upstream cross section (Figure 5-4). Compared to the downstream station, at this location the Scenarios generate more similar hydraulic response. Water levels in Scenarios 1-4 span an identical tide range while Scenario 5 water levels are offset by the same 30 cm applied at the ocean boundary. Peak velocities agree to within 10% for all the Scenarios. Scenarios 2-4, which include marsh lowering, all produce a downward shift in the elevations at which the peak ebb velocities occur.

D.4 Discussion

Based on present rates, the magnitude and extent of marshplain lowering represents a larger change to existing conditions than then the magnitude and extent of channel erosion. Changes to bed elevation in the main channel are consistent with erosion expected in the 10 year time frame whereas changes to bed elevation on the marshplain are consistent with marsh loss in the 50-100 year time frame.

A comparison of thalweg elevations provide a sense of scale for the magnitude and extent of channel erosion implemented in Scenarios 1 and 4. Figure D-2 shows the thalweg elevations for Scenario 1/4 and Alternative 1 (No Action) at Year 0, Year 10, and Year 50. This comparison indicates that the Scenario 1 and Scenario 4 main channel bathymetry is similar to the predicted Year 10 bathymetry if no action is taken in the Slough.

Similarly, the present rate of marshplain loss provides a sense of scale for the magnitude and extent of marsh lowering implemented in Scenarios 2-4. Under Scenarios 2-4, all of the Slough's remaining marshplain is converted to intertidal mudflat. Elkhorn Slough Tidal Wetland Project Team (2007) estimates the present rate of marshplain loss at 1.2 hectares per year. In the absence of sea level rise, this rate would need to be sustained for more than 100 years to convert the all of the existing marshplain as is the case in Scenarios 2-4. However, present rates of marsh loss may accelerate with the predicted increase in mean sea level. If the marshplain is not able to maintain its position in the tidal frame in the face of sea level rise, then the entire marshplain could be converted to mudflat in a shorter period of time. The magnitude of marsh lowering, 30 cm, is consistent with the amount of sea level rise projected for 50 years into the future (IPCC 2007). Considering both the time scale based on present rates of marsh loss and the time scale of sea level rise, the magnitude and extent of marsh lowering in Scenarios 2-4 corresponds to expected changes at the 50-100 year time horizon.

By establishing time scales for the implemented channel erosion and marsh lowering, Scenario 4, which includes both of these geomorphic changes, indicates the relative importance of these two processes. Tidal velocities predicted for Scenario 4 (Figure D-3) exhibit an overall decrease as compared to existing conditions. This decrease can be attributed to channel erosion (Scenario 1), which generates negative feedback by increasing the cross-sectional area, enabling similar conveyance capacity at lower current speeds. This decrease in tidal velocities overwhelms the positive feedback of increasing velocity caused by marsh lowering (Scenarios 2 and 3). This sensitivity analysis supports the contention that the high rates of channel erosion in Elkhorn slough is the dominant morphodynamic feedback response that will influence slough tidal hydrology and sediment dynamics over the past and coming 50 year time frame.

D.5 References

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IPCC. 2007. Climate Change 2007: The Physical Science Basis. Contribution of Working Group I to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change. Solomon S, Qin D, Manning M, Marquis M, Averyt K, Tignor MMB, Miller HL, Chen Z, editors. Cambridge, United Kingdom and New York, NY, USA: Cambridge University Press. 996 p.

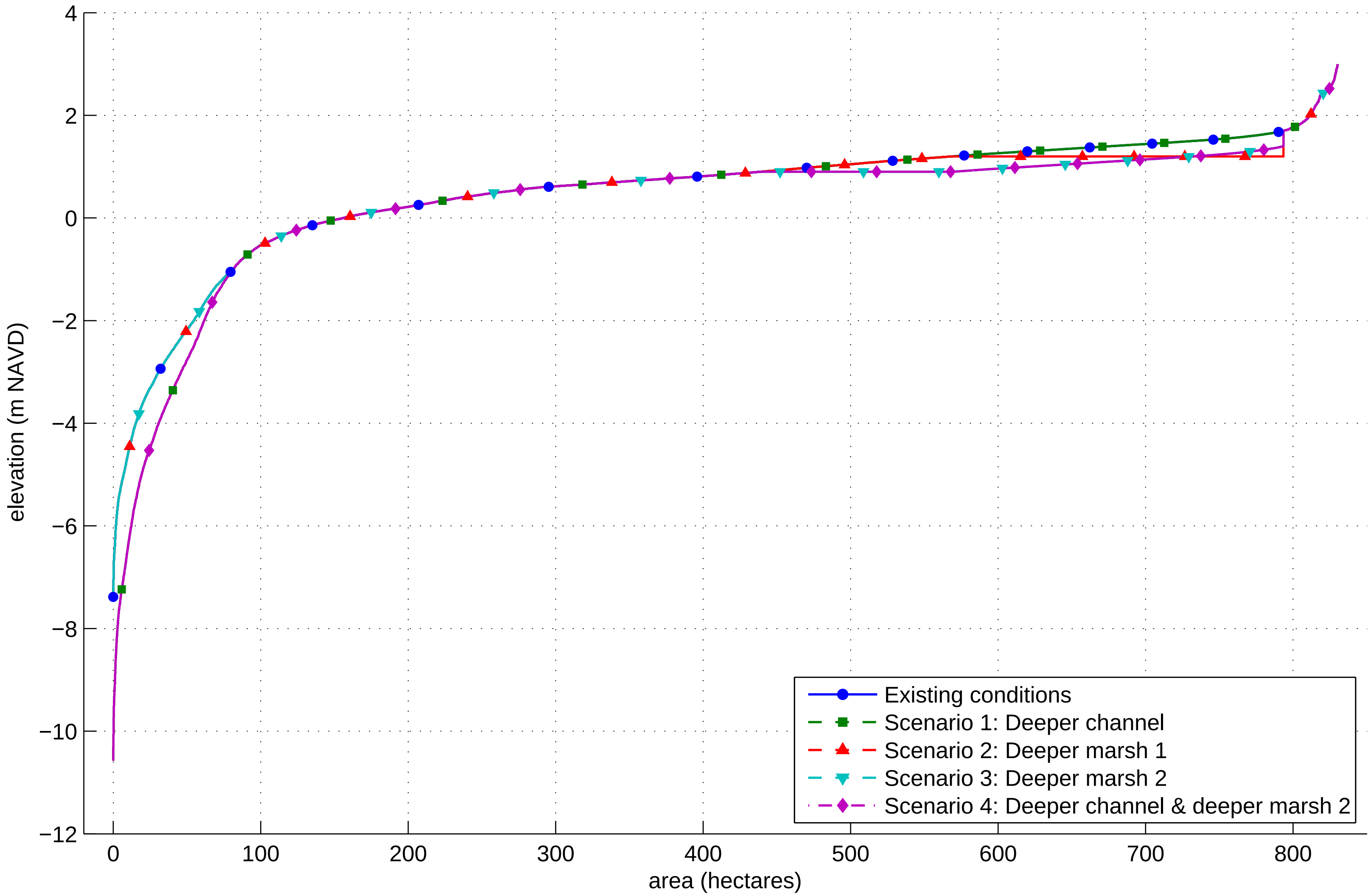
D.6 Figures

Figure D-1: Alternative 1 (No Action) and Depth Sensitivity Scenarios Hypsometry

Figure D-2: Alternative 1 (No Action) and Depth Sensitivity Scenario 1 Thalweg Depth

Figure D-3: Alternative 1 (No Action) and Depth Sensitivity Scenario Water level vs. Velocity – Downstream

Figure D-4: Alt 1 Alternative 1 (No Action) and Depth Sensitivity Scenario Water level vs. Velocity – Upstream



Source: CSU−SFML batymetric survey (2003) and NGS LiDAR (2004).

Figure D−1

Elkhorn Slough Tidal Wetlands Restoration

Depth Sensitivity Scenarios Hypsometry

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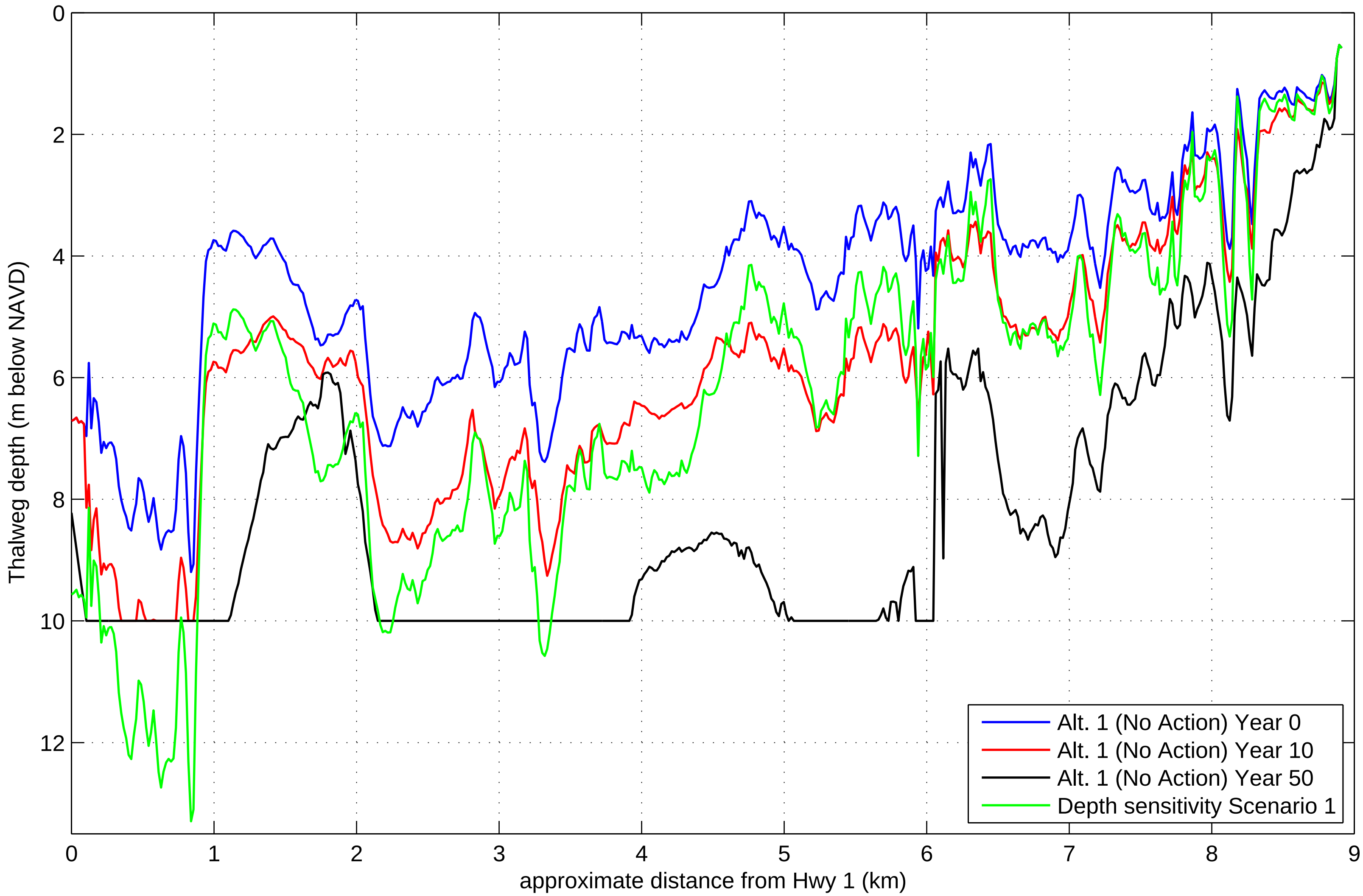

Source: CSU−SFML batymetric survey (2003) and DELFT3D model results

Figure D−2
Elkhorn Slough Tidal Wetlands Restoration

Alternative 1 (No Action) and Depth Sensitivity Scenario 1 Thalweg Depths

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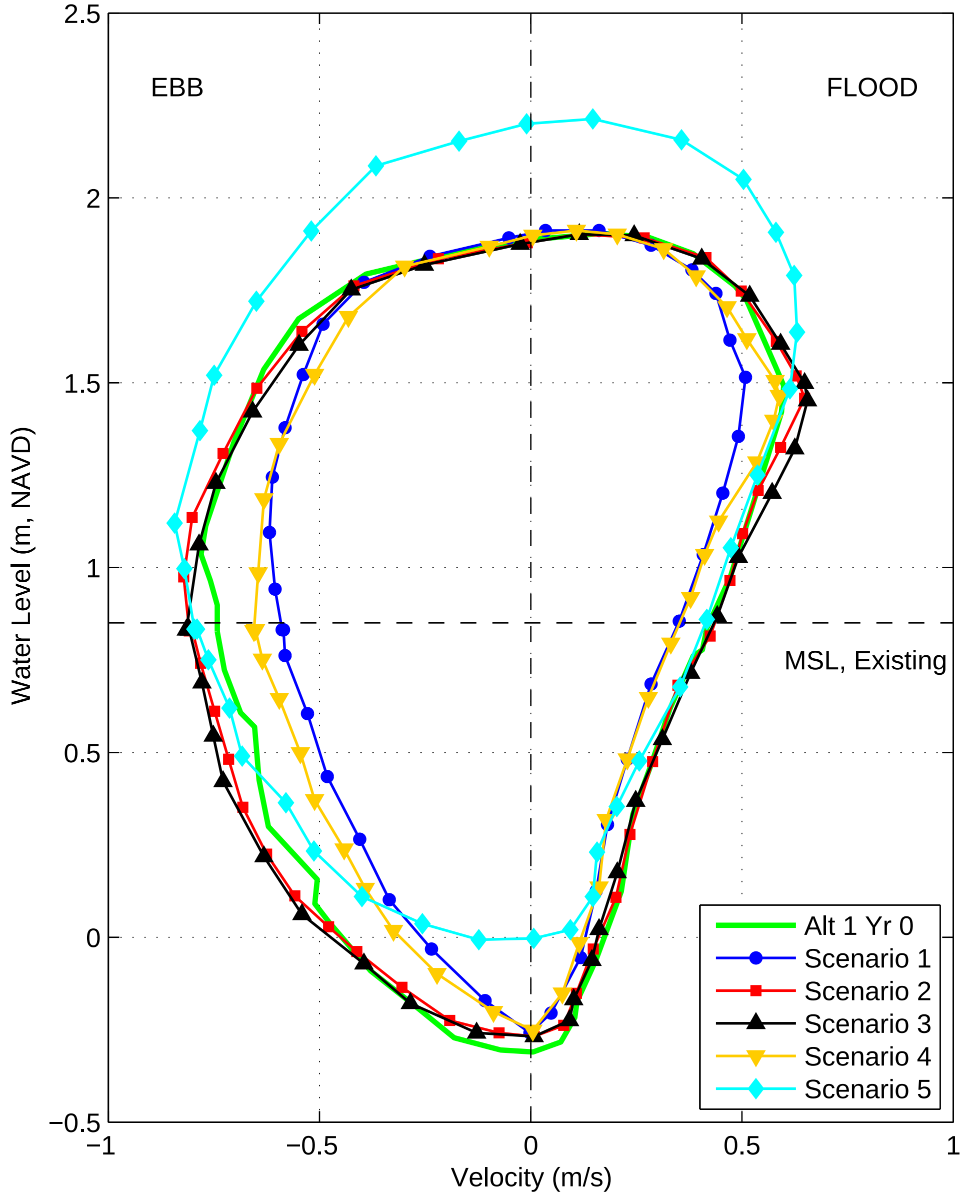

Source: DELFT Modeling Results

Figure D−3

Elkhorn Slough Tidal Wetland Project

Depth Sensitivity Velocity Stage Curves − Downstream Station

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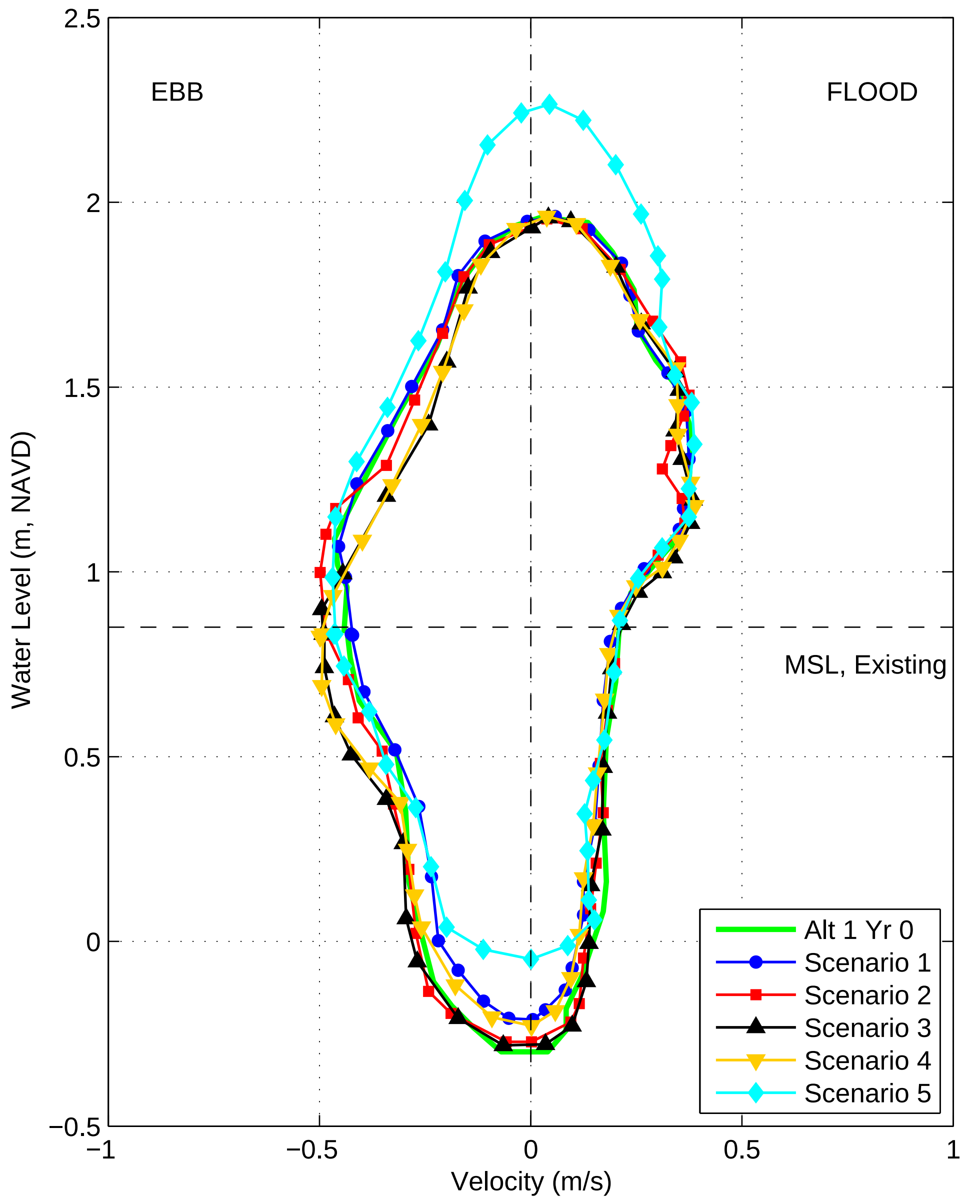

Source: DELFT Modeling Results

Figure *D−4*

Elkhorn Slough Tidal Wetland Project

Depth Sensitivity Velocity Stage Curves − Upstream Station

PWA Ref# 1869

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