Elkhorn Slough Tidal Wetland Project

Elkhorn Slough National Estuarine Research Reserve
Elkhorn Slough Foundation

Management of Tidal Scour and Wetland Conversion in Elkhorn Slough:

Partial Synthesis of Technical Reports on Large-Scale Alternatives:

Hydrology, Geomorphology, Habitats and Engineering
Water Quality

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Note:

This is a living document.

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Overview

Project scope

Elkhorn Slough, one of the largest coastal estuaries in California and host to over 750 species of plants and animals, is undergoing rapid ecologic change: in 60 years the channel has deepened by 500 percent and hundreds of acres of salt marsh have died back or are deteriorating. The Elkhorn Slough Tidal Wetland Project, a collaborative effort of about 100 scientists, managers and key stakeholders, was established in 2004 to advance the understanding of the processes and potential solutions to these rapid habitat changes.

Ecosystem services provided by the slough and its watershed are threatened by water quality impairment, invasive species, watershed development, freshwater diversion and other stressors, which are the subject of coordinated parallel efforts to steward the resource. The Tidal Wetland Project is a planning process focused on the tidal portion of the ecosystem. Through consensus, this process established goals of preserving and restoring priority habitats including salt marsh, tidal creeks, tidal brackish marshes and soft sediment habitats.

The Tidal Wetland Project seeks to preserve and restore estuarine habitats by restoring the processes that sustain them. One strategy is to restrict the tidal exchange between the slough and Monterey Bay without compromising water quality. The soft sediments that build salt marshes and sustain diverse communities of invertebrates are removed from the estuary by the tidal exchange between the slough and Monterey Bay, which was substantially increased by the opening of Moss Landing Harbor Mouth in 1947 by the Army Corps of Engineers. The harbor mouth opening also increased the tidal range in the slough, which increases the flooding and dieback of salt marsh. But the tides bring in Monterey Bay water that is rich in oxygen and lower in nutrients and phytoplankton. They also export algae and materials that consume oxygen. This exchange may be essential to maintaining acceptable water quality in the slough.

The group identified several large scale management options that would restore the hydrologic conditions that sustain these habitats and called for more information about the effects of those actions on the ecosystem and the people that use it. The effort values collaboration and consensus because no single entity holds management authority over the slough and collaboration from multiple landowners would be required to implement any of these large scale alternatives.

This document reports on the series of technical investigations undertaken to answer those questions. The approach aims to consider multiple habitats and species, accommodate uncertainty, and accomplish ecosystem restoration without compromising the quality of life of people who rely on the resource. These investigations describe opportunities and constraints and evaluate the tradeoffs between choices, and are not intended to identify a preferred alternative but to inform decisions about whether to recommend specific alternatives for further evaluation or set them aside. Those decisions are to be made during the next year by the Tidal Wetland Project Strategic Planning Team, a group of stakeholders including representatives from local government, resource management agencies, non-profit organizations, commercial interests and landowners. If a specific course of action is recommended, that decision would be followed by further study to clarify remaining technical issues. If that work verifies that a project is both viable and desirable, the group will pursue its implementation. This Ecosystem Based

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The purpose of this document is to synthesize the technical findings briefly and clearly so stakeholders can access the information critical to developing wise restoration strategies. This document summarizes multiple investigations that describe how the estuarine ecosystem would respond to four large-scale management alternatives, in comparison with a "no action" alternative. The alternative concepts include: No Action, a New Ocean Inlet, a tidal barrier at Highway 1 in the form of either a Low Sill or a High Sill and the restoration of historic salt marsh and/or tidal exchange at Parsons Slough. Completed studies provide information on the influence of these large-scale actions on tidal circulation, channel scour, habitat change and cost. Ongoing work is examining the effects on water quality, key species, politics and socioeconomics. The original findings are detailed in technical reports, cited below.

These investigations are the result of collaboration between the Elkhorn Slough National Estuarine Research Reserve, the Elkhorn Slough Foundation, the Monterey Bay Aquarium Research Institute, Philip Williams and Associates (PWA), the Ocean Foundation and the Tidal Wetland Project Strategic Planning Team and Science Panel.

The analysis of the proposed management actions has identified and explored their strengths and limitations to the extent possible given their conceptual nature. The process of developing and implementing a robust management strategy is structured to adapt to these findings and adjust course. Two major limitations of the proposed large scale actions have been identified: they may exacerbate compromised water quality conditions, and their long term efficacy may be limited unless a supply of sediment to the estuary is also restored. Sustaining and restoring priority habitats will likely require actions in these areas as well.

Hydrodynamics and habitats

Philip Williams and Associates and HT Harvey and Associates led an investigation of Elkhorn Slough hydrology, geomorphology and habitats. This investigation built on numerous preceding investigations. The analysis supported the hypothesis of the Tidal Wetland Strategic Plan: that the two dominant agents of change include an excess of tidal energy resulting from the opening of the Moss Landing Harbor, and a deficit of sediment resulting from the diversion of the Salinas River mouth.

The report predicted the extent of different habitats, the rate of channel scour and a variety of hydrologic parameters under the different management alternatives and at time periods of zero, 10 and 50 years following implementation. Those results are summarized in tables in this document.

The analysis found that the four alternatives considered would result in substantial effects on the estuary. The New Ocean Inlet, Low Sill and High Sill would reduce tidal range and current velocity, while the Parsons Slough Restoration would reduce current velocity compared to No Action. Each alternative would substantially reduce the rate of channel scour, increase the extent of salt marsh and decrease in the extent of mudflat. In order of increasing effect on tidal scour and habitats, the alternatives are: Parsons Slough Restoration, a Low Sill at the Highway 1 bridge, a New Ocean Inlet, and a High Sill at the Highway 1 bridge.

The investigation warned that the rate of sea level rise predicted to result from climate change will make salt marsh restoration unsustainable unless the supply of fine sediment to the estuary is also restored. A substantial sediment supply could offset tidal scour and the effects of sea level rise, sustaining marshes and mudflats into the future. With such a supply, the habitat distributions predicted for Year 0 could theoretically be sustained for many decades, with the amount of sediment required depending on the rate of sea level rise and the management alternative adopted.

Water quality

Ken Johnson and his team at the Monterey Bay Aquarium Research institute investigated biogeochemical processes related to dissolved oxygen and nitrate. This work built on nearly two decades of research led by the Elkhorn Slough National Estuarine Research Reserve. They found that dissolved oxygen concentrations fluctuate widely under present conditions related to extremely high rates of primary productivity related to external inputs of nitrogen. This analysis indicated that large portions of the slough are at risk of disruptive events where dissolved oxygen drops to levels that could kill invertebrates or cause avoidance behavior in fish.

They found that tidal exchange, which would be reduced by the large scale actions, does not play a major direct role in dissolved oxygen cycling in the slough. However, they cautioned that large scale actions could increase stratification or the residence time of water in the slough. Those changes could alter the ecologic communities in ways that also increase the risk of low dissolved oxygen events.

The work led to three main recommendations with respect to pursuing large scale actions to preserve the tidal wetlands of Elkhorn Slough:

1. We should better understand how any project would affect mixing in the slough mixes, and projects should be designed to facilitate mixing.
2. We will not be able to predict with certainty all the possible outcomes of a project in advance, so any project should allow for management that adapts to new information.
3. The key to improving water quality in Elkhorn Slough is reducing nutrient inputs from the watershed.

In response to these findings, the Tidal Wetland Project has engaged in ongoing efforts to reduce the load of nutrients, improve water quality through restoration projects and better understand the risks and processes of eutrophication.

Future Sections

This document will be expanded in the future to include additional sections providing overviews on:

Key Species, and

Policy and Socioeconomics.

Other sections may be added as well to compile information needed for an effective decision process and, following those decisions, to chart the path ahead.

Table of Contents

Introduction

Elkhorn Slough ecosystems

Elkhorn Slough is a rare estuarine ecosystem on the rugged California Coast, harboring some of the largest tracts of tidal salt marsh and intertidal mudflats outside San Francisco Bay. The tidal habitats here encompass extraordinary biological diversity, providing critical habitat for over 135 aquatic bird, 550 marine invertebrate, and 102 fish species (Caffrey et al. 2002). The Elkhorn Slough watershed hosts two dozen rare, threatened and endangered species.

Recognizing the value of these resources to the country, the National Oceanic and Atmospheric Administration designated areas of Elkhorn Slough as part of the Monterey Bay National Marine Sanctuary (MBNMS) and as a National Estuarine Research Reserve. The State of California Department of Fish and Game has also designated parts of Elkhorn Slough as a State Ecological Reserve and as a Wildlife Management Area. The National Audubon Society includes the Slough in its Globally Important Bird Areas and the Manomet Bird Observatory named the Slough a Western Hemisphere Shorebird Reserve. More than 50,000 people visit the Slough annually to view wildlife and enjoy nature.

Estuarine wetlands, such as salt marsh, mudflats and soft bottom subtidal habitats form where the energy of tidal currents, rivers and waves is dissipated by landforms and sediment accumulates. The geometry of tidal channels results from the balance of hydraulic energy and the supply and texture of sediment, responding to excess energy by deepening or widening, and to excess sediment by shoaling and narrowing.

Sediment typically deposits across salt marshes because the vegetation slows currents and dampens waves. The vegetation then grows up through these fine deposits. But estuarine sediments consolidate and oxidize over time, resulting in the gradual subsidence or lowering of the marsh plain unless these processes are offset by new mineral sediment and the accumulation of organic material. With a sufficient sediment supply, salt marsh will gradually rise to keep pace with moderate rates of sea level rise, but without it the marsh surface gradually becomes lower in the tidal frame. The plants can tolerate only limited inundation, and below a certain threshold, the marsh vegetation dies back. Absent vegetation, former marsh sediments are then vulnerable to erosion by waves. This lowers the land surface further such that reversing this marsh loss by natural processes requires long periods of time and large quantities of sediment, and may be irreversible.

Elkhorn Slough is out of balance. Excess tidal energy in the channel is resulting in widespread tidal scour and bank erosion. Soft mud bottom sediments have been removed, resulting in a channel bed armored with hard substrates. Salt marshes that have persisted for perhaps 3000 years are dying back. The mean percent cover of salt marsh vegetation in un-diked marshes of the Slough decreased 41 percent between 1931 and 2003 (Van Dyke and Wasson 2005). Tidal creek banks are being undercut by higher current velocities and collapsing into the channels. The width of 196 tidal creeks measured throughout the Slough increased by 80 percent during this same time period (Van Dyke and Wasson 2005). The main channel of Elkhorn Slough has likewise been eroding. Dean (2003) found that the mean cross-sectional area of the main channel increased by 24 percent in only eight years (1993-2001). These trends contrast dramatically with the geological history of the Slough that showed it as a depositional environment up to 1947 (Schwartz 1983).

The Tidal Wetland Project

The Elkhorn Slough Tidal Wetland Strategic Plan, developed between 2004 and 2007 by the Tidal Wetland Project Strategic Planning Team, Science Panel and staff, identified goals, objectives and planning principals. The goals prioritize the preservation and restoration of estuarine wetlands and the processes that sustain them. The plan outlines two strategies to address habitat change in the estuary. Strategy A, the focus of this document, calls for the investigation of large- scale actions to manage the dominant physical processes in the estuary-tidal energy and sediment supply. Strategy B calls for projects to directly restore habitat.

Evaluating large-scale hydrological management alternatives

Large scale management actions were selected for consideration by the Elkhorn Slough Tidal Wetland Project Strategic Planning Team with guidance from the Science Panel, as described in the Tidal Wetland Strategic Plan (Elkhorn Slough Tidal Wetland Project, 2007). The alternatives considered operate on the hydrology of the slough, since past management of hydrology appears to have led to the most obvious and dramatic changes to Elkhorn Slough ecosystems during the historical record.

Two primary strategies were used to develop the action alternatives, which were based on a conceptual model of the processes governing habitat change in Elkhorn Slough:

1. Reduce the tidal prism to slow current velocities and in turn reduce tidal scour. Small changes in velocity can have a large effect on scour.
2. Reduce the height of mean higher high water (MHHW) to reduce the amount of time that the marsh plain is inundated. This will make a larger area suitable for salt marsh, as the duration of inundation limits the viability of marsh vegetation.

The effort has considered five alternatives:

- No Action: Maintain existing infrastructure but make no other major changes to management of the slough (Alternative 1).
- New Inlet: Create a new ocean inlet for Elkhorn Slough, separate from and north of the Moss Landing Harbor mouth (Alternative 2).
- Low Sill: Construct a tidal barrier near the Highway 1 Bridge consisting of a rock armored sill shaped like a dam and with a crest 4.6 feet below mean lower low water (MLLW) (Alternative 3a).
- High Sill: Similar to the Low Sill but with a crest 0.3 feet below MLLW. (Alternative 3b).
- Parsons Slough Project: Reduce tidal prism in Parsons Slough by adding sediment and/or restricting tidal exchange to restore the 430 acres of Parsons Slough, currently mudflats, to salt marsh (Alternative 4). The analysis assumed that the project would reduce the Parsons Slough tidal prism by half. The actual restoration design will be determined in a

process currently underway. The combined effects of the Parsons Slough Project and the Low Sill were considered for certain parameters.

Each alternative was analyzed at three time intervals:

- Year 0 represents the effects of the project shortly after implementation. This scenario assumes that the project has changed the hydrology of the slough and shifted habitats but has not yet affected the morphology or shape of the slough.
- Year 10 represents the effects of the projects after 10 years of erosion and morphologic change. The Year 10 habitat projections incorporate the assumption of 3 cm (0.1 feet) of sea level rise.
- Year 50 represents the long term effects of the projects after several decades of erosion and morphologic change. The Year 50 scenario incorporates an assumed sea level rise of 30 cm (1 foot).

An interdisciplinary team characterized how Elkhorn Slough ecosystems would respond to these five alternatives. The analysis yielded a wealth of information, as described below in the sections summarizing each investigation.

The goal in evaluating these alternatives was not to choose one alternative over another or to design an alternative for implementation but to evaluate whether these concepts are good candidates for further consideration. Promising alternatives will require substantial refinement and the design specifics will likely be changed to improve performance or reduce undesirable effects. The primary objective was to characterize the effects of each alternative on the broader Elkhorn Slough ecosystem rather than in the area of the construction footprint. For recommended alternatives, those impacts would be considered in a subsequent round of review.

Descriptions of alternatives

Each alternative considered implements the restoration strategy to a different degree and with different tradeoffs in terms of cost, feasibility, and the effects on habitats, water quality, key species and users of the slough. The configuration of each alternative considered is very preliminary. The goal here was to evaluate whether the general approach offered by each alternative would produce satisfactory results. Recommended alternatives would necessarily undergo substantial revision and refinement during subsequent rounds of analysis.

No Action (Alternative 1)

The No Action Alternative would take no major action to reduce tidal scour and wetland loss (see Section 4.1). Existing bathymetry and topography was used in the development of the model.

New Ocean Inlet (Alternative 2)

The New Inlet would entail closing the current connection between Elkhorn Slough and Moss Landing Harbor and creating a new inlet to the north of the North Harbor at the location of the mouth of the slough prior to 1947. Bennett Slough would be widened and deepened along the north and east sides of the Department of Fish and Game Wildlife Management Area, serving as the connecting channel between the new inlet and the rest of Elkhorn Slough. The inlet would likely require one or more jetties and a new bridge over Highway 1. See Figure 1. (PWA Report Section 4.2)

The concept behind this alternative is as follows: The flood shoals and long sinuous channel associated with a new inlet would slow the flow of water into and out of the slough, reducing the tidal prism (the volume of water exchanged between Monterey Bay and the Slough during each tidal cycle). The alternative would reduce the velocity of tidal currents and tidal scour. Compared to Monterey Bay and to existing conditions, the high tides would be lower and low tides would be higher. Lowering high tide would increase the extent of salt marsh by decreasing the duration of flooding on the marsh plain.

Tidal Barrier at Highway 1: Low Sill (Alternative 3a) and High Sill (Alternative 3b)

The Low Sill and High Sill would each consist of a subtidal structure blocking a portion of the channel to act as a partial tidal barrier near the Highway 1 Bridge. The configurations examined would be built of rock lining the channel banks and bed. The Low Sill would have a crest elevation at 1.4 m (4.6 ft) below today's mean lower low water (MLLW). The High Sill would have a crest elevation at 0.1 m (0.3 ft) below MLLW. See Figure 1. (See PWA Report, Section 4.3)

The concept behind these alternatives is as follows: By constricting the channel at this point, the sill would reduce the channel depth in a manner similar to the flood shoals that occurred near the mouth prior to harbor construction. Like the New Ocean Inlet, a sill would restrict the flow of water, producing a lag between the tides in Elkhorn Slough and the tides in the Bay. This would reduce the tidal range and the tidal prism, the current velocity and tidal scour of the channel.

Restoration of Parsons Slough (Alternative 4)

The alternative assumes that extensive portions of Parsons Slough and South Marsh are restored to salt marsh from their current condition of subsided mudflats. This would reduce the tidal prism of Parsons Slough by about 50 percent. Restoration of Parsons Slough would reduce the tidal prism of Elkhorn Slough by 25 percent, and would reduce tidal currents and tidal scour in the main channel of the Lower Slough.

Restoring salt marsh in Parsons Slough would require adding sediment to raise the subsided areas to the elevation of salt marsh and/or the construction of a water control structure near the Union Pacific Railroad trestle bridge to restrict tidal exchange. For modeling purposes it was assumed that the tidal prism following restoration would be typical for a healthy salt marsh with a typical density of tidal creeks. See Figure 2 (See Section 4.3).

Note: For consistency, none of the habitat projections include the area in Parsons Slough.

Sediment Additions

The report recommended a substantial investment in placing sediment in portions of Elkhorn Slough to reduce the likelihood of water quality problems related to stratification of the water column near the tidal barrier near Highway 1, and to supplement the sediment supply to the estuary. This element was included as part of both the New Ocean Inlet and the Tidal Barrier alternatives.

Philip Williams and Associates initially recommended consideration of large scale sediment additions to subsided former marsh areas as a large scale action alternative. At the time a supply of sediment of sufficient size had not been located, and that alternative was not advanced. Since then, new options have become available, and sediment additions are now being considered in greater detail as a separate investigation.

Project diagrams

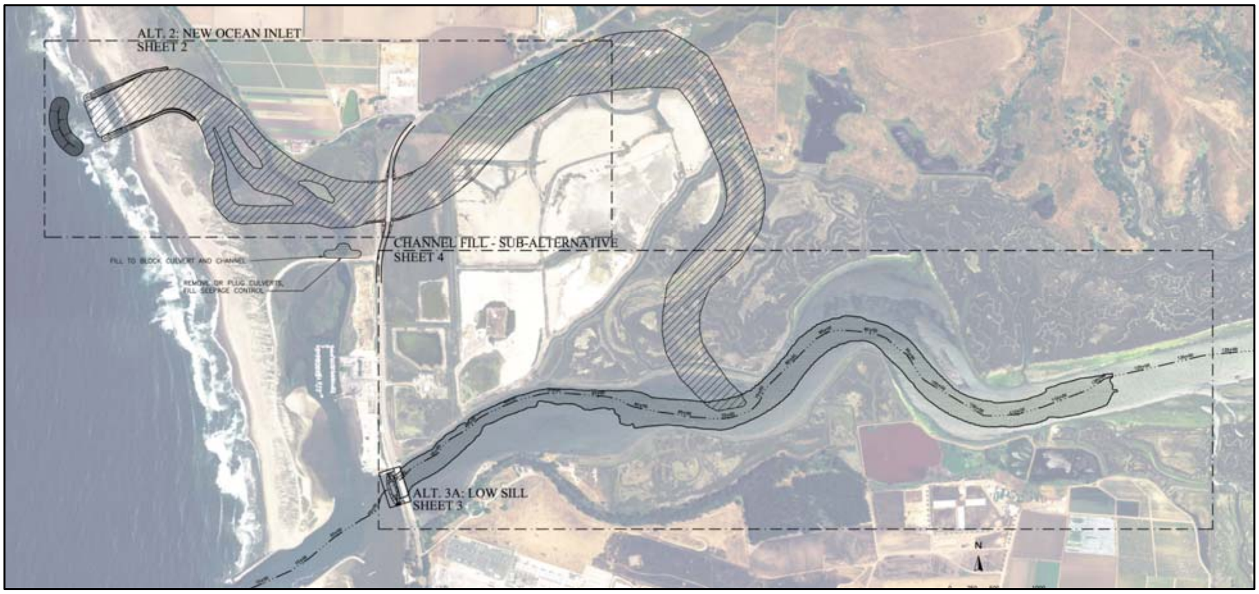
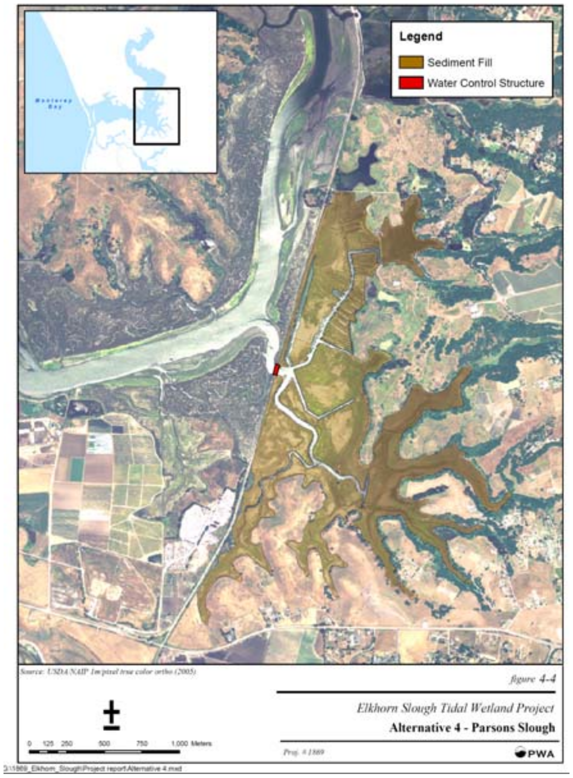


Figure 1. Conceptual design locations of large scale actions at the mouth of the estuary.

> The New Inlet (Alternative 2) would open to the ocean north of Jetty Road at the location of the historic mouth of the Old Salinas River Channel. Two jetties (shown) may be necessary to stabilize the inlet in this location. An ebb shoal (dark gray) and remnant flood shoals would be located near the new inlet. A new Highway 1 Bridge would be required for the connecting channel, which would be routed along Bennett Slough to the north and east of the Department of Fish and Game (DFG) Wildlife Management Area.
>
> Both the Low Sill (Alternative 3a) and the High Sill (Alternative 3b) would be located near the current Highway 1 Bridge. The Low Sill would have a crest elevation of 4.6 feet below mean lower low water, while the High Sill would have a crest elevation of 0.3 feet below mean lower low water. Cost estimates for both alternatives include backfilling the main channel of the slough to an elevation of -10 feet to reduce the likelihood of water quality problems and add sediment to the system.
>
> Different configurations for each of these alternatives are possible as discussed in the report.

Figure 2. Parsons Slough restoration project.

The Parsons Slough restoration project (Alternative 4) would entail sediment placement on the subsided former marsh plain and/or a sill or other water control structure near the railroad bridge (at the entrance to Parson's Slough). This would reduce the tidal prism and current velocities in the main channel while directly restoring tidal marsh habitat.



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

Hydrodynamics, tidal scour, habitat change and cost

Summary

The Elkhorn Slough National Estuarine Research Reserve and the Elkhorn Slough Foundation contracted with Philip Williams and Associates, Ltd. (PWA) to lead a team of scientists and engineers in the investigation of large-scale actions to reduce tidal energy and add sediment to the system. Team members included H.T. Harvey and Associates, 2nd Nature, Edward Thornton, Ph.D., and Stephen Monismith, Ph.D. A Modeling Advisory Team including members of the Elkhorn Slough Tidal Wetland Project Science Panel was established to advise on the project.

This team considered the effects of the alternatives on tidal exchange, channel scour and habitats, and then developed conceptual engineering designs for two of the alternatives. No-Action was considered along with four alternatives that would alter the estuary mouth or a major branch of the estuary, Parsons Slough. Effects were characterized for conditions shortly following project implementation and 10 and 50 years later. The report, released in June 2008, is available at the Tidal Wetland Project home page at www.ElkhornSlough.org.

The configuration of specific alternatives was developed by Philip Williams and Associates with review by the Modeling Advisory Team, a subset of the Science Panel. These designs should be considered to be in the conceptual stage of development.

The investigation supported the hypothesis of presented in the Tidal Wetland Project Strategic Plan that two agents of change played dominant roles in changing Elkhorn Slough habitats: an excess of tidal energy resulting from the opening of the Moss Landing Harbor, and a deficit of sediment resulting from the diversion of the Salinas River mouth.

The analysis found that the four alternatives considered would reduce tidal range and current velocity compared to no action. Each alternative would substantially reduce the rate of channel scour, increase the extent of salt marsh and a decrease in the extent of mudflat. In order of increasing effect on tidal scour and habitats, the alternatives are: Parsons Slough Restoration, a Low Sill at the Highway 1 bridge, the combination of the Parsons Slough Restoration and the Low Sill, a New Ocean Inlet, and a High Sill at the Highway 1 bridge.

A greater effect is not necessarily better. For example, decreasing current velocity reduces tidal scour, but it may increase water quality problems. The optimal point for the resources as a whole may not lie at the extreme. Other parts of this effort are considering those trade-offs.

The investigation warned that the rate of sea level rise predicted to result from climate change will make salt marsh restoration unsustainable unless the supply of fine sediment to the estuary is also restored.

Major Findings

Tides and currents

The action alternatives were predicted to have a substantial effect on tides and currents in the slough. Compared to present conditions tidal range would be reduced by the 15 percent by the Low Sill, 15 percent by the combination of the Low Sill and Parsons Slough Project, 30 percent by the High Sill and 35 percent by the New Ocean Inlet. The Parsons Slough Project would not affect tidal range. By comparison, 1943 conditions exhibited a tidal range 65 percent smaller than present conditions (Table 1).

The erosion of slough channels was not predicted to change the tidal range in future scenarios. Tidal range was predicted to remain unchanged from Year 0 to Year 10 (table 2). The analysis assumed that the entire tidal frame would rise by 1 foot (30 cm) in Year 50 as a result of sea level rise accelerated by climate change (Table 3).

Ebb tide currents, which erode the channel and export sediment from Elkhorn Slough, would slow by 15 percent by the Parsons Slough Project, 20 percent by the Low Sill, 30 percent by the combination of the Low Sill and Parsons Slough Project, 40 percent by the High Sill and 50 percent by the New Ocean Inlet Table 1). Over time peak current velocity was predicted to slow as the channel grows larger.

The Low Sill would reduce the tidal prism (the volume of water exchanged on each tidal cycle) by 10 percent, the High Sill, New Ocean Inlet or the Parsons Slough Project would each reduce it by 25 percent, and the combination of the Low Sill and the Parsons Slough Project would reduce it by 30 percent. The analysis predicted that by Year 50 the tidal prism would be equal or greater than it is now for all of the scenarios considered Table 3), largely as a result of sea level rise. Management actions leading to sediment accumulation on salt marshes and mudflats would counter this effect of rising sea level.

Tidal scour

Each of the alternatives would have substantial effects on the rate of tidal scour or channel erosion. The analysis predicted that the main channel would continue to deepen and widen under the No Action alternative at a rate of about 130,000 cubic yards (100,000 cubic meters) per year. This rate of scour would be reduced by about 40 percent by a Parsons Slough project, 60 percent by the Low Sill, 70 percent by the combination of the Low Sill and the Parsons Slough Project, 85 percent by the New Ocean Inlet and 90 percent by the High Sill (table 4). Compared to the No Action alternative, between Year 10 and Year 50 tidal scour would be reduced by 25 percent by the Parsons Slough project, 40 percent by the Low Sill, 75 percent by the New Ocean Inlet and 75 percent by the High Sill Table 4).

The analysis predicted changes to channel depth and the report includes plots of the maximum depth along the length of the slough for Year 10 and Year 50 for each alternative. Over time, tidal scour would slow for all alternatives along with peak current velocity, as the channel size increased faster than the tidal flow rates.

By Year 10 at a reference point by Hummingbird Island, near the center of the Slough, the main channel would deepen by 4 feet (1.2 meters) under the No Action scenario, by 1 foot (0.3 meters) under the Low Sill, and not at all under the High Sill or New Ocean Inlet alternatives. The Parsons Slough Project would deepen the channel in this area by 5 feet (1.5 meters) during this period. That Parsons Slough Project would *increase* tidal scour upstream of Parsons Slough compared to No Action, apparently by directing tidal energy now dissipated in Parsons Slough into upstream areas. The Parsons Slough Project would substantially reduce tidal scour in the main channel downstream of Parsons Slough. The combination of the Low Sill and Parsons Slough Project would deepen the channel there by 2.5 feet (0.8 meters).

Between Year 10 and Year 50, the main channel near Hummingbird Island was predicted to deepen further by 11 feet (3.3 meters) under the No Action scenario, by 6 feet (1.7 meters) under the Low Sill, and by 1 foot (0.3 meters) under either the High Sill or New Ocean Inlet alternatives. During this period, the Parsons Slough Project was predicted to deepen the channel there by an additional 13 feet (4.0 meters) (Table 5). The combination of the Low Sill and Parsons Slough project was not evaluated for Year 50.

Habitats

The investigation predicted the habitat extents likely to result from future scenarios. The analysis omitted actively managed areas from habitat projections, including Blohm, Porter and North Marshes, the Salt Ponds Wetland Complex and Parson's Slough. The analysis did not consider habitat quality, nutrient enrichment or salinity, and determined habitat type only by the duration of inundation. Areas inundated less than 12 percent of the time were assumed to support salt marsh, while areas inundated more frequently were assumed to support mudflat or subtidal habitats.

The marshes of Elkhorn Slough, in the professional opinion of the consultant team, have showed little evidence of accumulating sediment and rising in elevation over time. Based on that observation they assumed that sea level would rise faster than the marsh surface, and that the inundation of the marsh plain would increase over time, leading to continued dieback of the marsh. They projected that during the next 50 years, regardless of the alternative implemented, accelerating sea level rise will convert most of the remaining tidal marsh in Elkhorn Slough to mudflat, unless a supply of marsh building sediment is reestablished. Specific actions to restore the sediment supply were not considered in this investigation, but are now under review by Tidal Wetland Project staff and advisory teams.

The report predicted that shortly following implementation, because of their influence on tidal range, the alternatives that alter the mouth of the estuary would change the distribution of habitats in the slough. Compared to No Action, the Low Sill would result in a 10 percent increase in salt marsh, a 10 percent decrease in mudflat and a 10 percent increase in subtidal habitats. The High Sill would increase salt marsh by 20 percent, decrease mudflat by 35 percent and increase subtidal habitats by 40 percent. The New Ocean Inlet would also increase salt marsh 20 percent, decrease mudflat by 40 percent and increase subtidal areas by 55 percent.

The Parsons Slough project, analyzed in a separate study (Moffat and Nichol et al 2008), could result in a 25 to 35 percent increase in salt marsh and a 15 to 25 percent decrease in mudflats in the slough as a whole, but would not alter the type of habitats outside Parsons Slough. See Table 6.

Under the No Action alternative, current trends were projected to continue: the extent of salt marsh would continue to decline, while the areas of mudflat and subtidal habitats increase (Table 7).

Future predictions showed that the action alternatives would change the habitat distribution compared to the No Action alternative, but that accelerated sea level rise and the lack of a sediment supply would ultimately result in marshes converting back to mudflat, and mudflat to subtidal areas. Compared to No Action, at Year 10 the Low Sill, the High Sill and the New Ocean Inlet would result in more salt marsh, less mudflat and a greater subtidal area (Table 8), but only the High Sill would result in substantially more salt marsh than occurs today Table 9). Compared to No Action, at Year 50 the New Ocean Inlet and High Sill would result in substantially more salt marsh, less mudflat and more subtidal areas, while the Low Sill would result in similar but less pronounced effects Table 10). However, because of sea level rise the action alternatives considered would support 35 to 65 percent less salt marsh and substantially more subtidal areas at Year 50 than occurs in the Slough today (Table 11). Under future scenarios, the Parsons Slough Project would have minor effects on habitat extent outside of Parsons Slough (Tables 10 and 11).

Sediment

The report found that under the No Action, Parsons Slough Project and Low Sill alternatives, that no existing source of sediment to the watershed is sufficient to balance the sediment exported by tidal scour. When accounting for the sediment required to keep pace with accelerated sea level rise, the New Ocean Inlet and the High Sill also result in a deficit of sediment and the continued conversion of salt marsh to mudflat and mudflat to subtidal habitat. The report states that restoration of marsh and mudflat habitats that are sustainable over many decades requires reestablishment of a sediment supply as a primary strategy.

The investigators described the past and present sources of marsh building sediment, and highlighted the diversion of the Salinas River, formerly a major source of marsh-building sediment. They stated that re-routing the river mouth directly to Monterey Bay in the early 1900s fundamentally altered the sediment balance in the estuary, setting the stage for ongoing erosion and habitat conversion. They projected that unless a source of sediment to the estuary is reestablished, the large-scale actions would only temporarily slow or reverse the rate of habitat conversion: rising sea level will submerge the remaining salt marsh, converting it to mudflats, which will likely give way eventually to subtidal habitats. The report also stated that subsided and eroded areas will compete with salt marshes for sediment. It recommended the development of management strategies to add sediment to these areas.

Costs

The report presents conceptual designs and ballpark estimates of costs, which include a 35 percent contingency because of their preliminary nature. The cost estimates were $27 million for the Low Sill, and $94 million for the New Ocean Inlet. A separate effort is currently developing estimates for the Parsons Slough Project, and the costs of the High Sill were not estimated. These costs, while considerable, are comparable to those of wetland restoration projects completed or underway in San Francisco Bay. The final designs of any project could vary substantially from the conceptual designs, including changes to the project location, footprint, materials, and geometry.

Limitations

An array of complex processes govern habitat and geomorphic change in Elkhorn Slough, and the task of rigorously characterizing each of them – and their interactions - would be exceedingly complex even if proven methods were available. The analysis was based on average rates of change and includes numerous simplifying assumptions based on sensitivity analysis, reference sites and professional judgment. These simplifications limit the accuracy of the results. The quantities reported, such as volumes of eroded sediment or areas of habitats, are most useful for comparing between alternatives, and should not be viewed as predictions of exactly what will happen as a result of implementation of alternatives.

Considerations for Implementation

New Ocean Inlet

The investigation included an analysis of inlet stability, which suggested two jetties may be required to ensure the New Inlet remains open under most conditions (see Appendix B of Philip Williams & Associates et al. 2008). The inlet could be prone to closure and additional analysis would be required to determine whether the inlet would be self-maintaining. Two jetties were assumed for conceptual design purposes (see Philip Williams and Associates 2008, Section 7.1).

Alternate locations for a new ocean inlet and connecting channel could be considered. For example, the connecting channel could cut through the Moss Landing Wildlife Area, producing an island to improve breeding success of snowy plovers. The estimated costs of a project could be reduced by design revisions, such as excavating a smaller channel and allowing the channel to undergo limited erosion to reach a stable size.

This alternative would preclude re-establishment of the Old Salinas River channel as a source of sediment to the slough, if that ever became possible. (See Philip Williams and Associates 2008, Section 6.4.1).

Low Sill and High Sill

For the purposes of the conceptual design, it was assumed that the sill would be built as a broad ramp armored with rock, but alternate construction approaches, such as a sheet pile coffer dam, were also considered viable. Two sill heights were treated in detail, but a range of sill heights and their effects on tidal prism and tidal range are described in Appendix C of the PWA report.

Both the Low Sill and High Sill were assumed to consist of a single structure for this preliminary assessment, but a variety of configurations are possible that could generate the same effects on tidal scour and habitats in the Slough, with perhaps better results for navigation, fish and wildlife movements, water quality related to stratification, and the dominance of flood or ebb currents. Configurations discussed include a sill notched with a deep section in the middle, a series of lower barriers rather than a single sill, or a long constriction or throat rather than a vertical barrier. For efficiency, a simple geometry was considered here. If the effects of a sill on currents and habitats are considered desirable during the current round of review, these options would be explored further. (See Philip Williams and Associates 2008, Sections 5.3.3, 6.4.2 and 7.2).

This alternative could reduce sediment inputs from the Old Salinas River Channel or littoral transport.

Restoration of Parsons Slough

Planning and development of conceptual designs for the restoration of Parsons Slough is underway and managed by the Elkhorn Slough National Estuarine Research Reserve and the California State Coastal Conservancy. (See Philip Williams and Associates 2008, section 6.4.3.)

Navigation

New Inlet

This New Inlet alternative would prevent boat access to the slough from Moss Landing Harbor, and would substantially increase harbor dredging requirements. Alternate small craft access could be provided, but would require additional infrastructure. Additional analysis would be required to further characterize the effects of the project on the beach and near shore environment. The configuration of this alternative was selected to minimize impacts to the North Harbor. An alternate configuration that would reduce costs (Alternative 2b) was suggested but not recommended for further analysis by the Modeling Advisory Team because of impacts to the harbor. (See Philip Williams and Associates 2008, Sections 5.3.2, 6.4.1 and 7.1)

Low Sill and High Sill

Both sill alternatives would affect navigation, and additional analysis is required to further define those effects. The Low Sill would affect navigation by doubling peak current velocities in the vicinity of the sill and by reducing the available clearance at the lowest water levels to less than 1 m (3.3 ft). The High Sill would essentially prevent navigation across the sill.

Summary tables

Water levels, tidal prism and tidal range

Table 1. Year 0 water levels, tidal prism and tidal range

	peak ebb velocity	peak ebb velocity	tidal prism	tidal prism	Highest water level	Lowest water level	tidal range
Alternative	m/s	% change from No Action	Mm^3/tide	% change from No Action	meters	meters	% change from No Action
No Action	0.75	0%	5.0	0%	1.9	-0.3	0%
New Inlet	0.37	-50%	3.7	-25%	1.7	0.3	-35%
Low Sill	0.59	-20%	4.5	-10%	1.8	-0.1	-15%
High Sill	0.46	-40%	3.8	-25%	1.7	0.2	-30%
Parsons	0.65	-15%	3.7	-25%	1.9	-0.3	0%
1943 conditions	0.28	-65%	1.6	-70%	1.5	0.7	-65%

Table 2. Year 10 water levels, tidal prism and tidal range

	peak ebb velocity	peak ebb velocity	tidal prism	tidal prism	Highest water level	Lowest water level	tidal range
Alternative	m/s	% change from No Action	Mm^3/tide	% change from No Action	meters	meters	% change from No Action
No Action	0.62	0%	Not reported	--	1.9	-0.3	0%
New Inlet	0.28	-55%	--	--	1.7	0.3	-35%
Low Sill	0.53	-15%	--	--	1.8	-0.1	-15%
High Sill	0.46	-25%	--	--	1.7	0.2	-30%
Parsons	0.59	-5%	--	--	1.9	-0.3	0%

Table 3. Year 50 water levels, tidal prism and tidal range [assumes +1.0 ft sea-level rise]

	peak ebb velocity	peak ebb velocity	tidal prism	tidal prism	Highest water level	Lowest water level	tidal range
Alternative	m/s	% change from No Action	Mm^3/tide	% change from No Action	meters	meters	% change from No Action
No Action	0.50	0%	6.3	0%	2.2	0.0	0%
New Inlet	0.28	-45%	4.7	25%	2.0	0.6	-35%
Low Sill	0.50	0%	5.9	5%	2.1	0.0	-5%
High Sill	0.50	0%	4.9	20%	2.0	0.4	-30%
Parsons	0.50	0%	5.0	20%	2.2	0.0	0%

Morphologic change

Table 4. Channel scour during successive time intervals

	Year 0 to Year 10	Year 0 to Year 10	Year 10 to Year 50	Year 10 to Year 50
	m^3/year	% change from No Action	m^3/year	% change from No Action
No Action	98,000	0%	48,000	0%
New Inlet	15,000	-85%	11,000	-75%
Low Sill	43,000	-55%	28,000	-40%
High Sill	11,000	-90%	11,000	-75%
Parsons	61,000	-40%	35,000	-25%

Table 5. Projected channel maximum depth at a station near Hummingbird Island, 4.5 km upstream of the Highway 1 Bridge

	Year 0	Year 10	Year 10	Year 50	Year 50
	meters	meters	% change from No Action, Year 0	meters	% change from No Action, Year 0
No Action	4.0	5.2	30%	8.5	115%
New Inlet	4.0	4.0	0%	4.3	5%
Low Sill	4.0	4.3	5%	6.0	50%
High Sill	4.0	4.0	0%	4.3	10%
Parsons	4.0	5.5	40%	9.5	140%

Habitats

Table 6. Changes to habitats (outside Parsons Slough and other actively managed areas), Year 0

Alternative	deep (>2 m) subtidal	shallow subtidal	Intertidal mudflat	Salt marsh
	% change from No Action, Year 0			
No Action	0%	0%	0%	0%
New Inlet	+55%	+55%	-40%	+20%
Low Sill	+10%	+10%	-10%	+10%
High Sill	+40%	+40%	-35%	+20%
Parsons*	0%	0%	0%	0%

Note: Habitat change in Parsons Slough was not included in these calculations. If the Parsons Slough project resulted in the restoration of the historic extent of salt marsh there, the total extent of habitats in Elkhorn Slough including the Parsons Slough Complex, the Parsons Slough Project decrease total mudflat area by 15 to 25 percent and an increase total salt marsh area by 25 to 35 percent.

Table 7. Modeled habitat extents outside Parsons Slough and areas with restricted tidal exchange for the No Action Alternative

No Acton	deep (>2 m) subtidal	shallow subtidal	intertidal mudflat	Salt marsh
	Acres			
Year 0	345	209	1088	695
Year 10	350-400	210-240	1100-1150	620-670
Year 50	450-530	220-260	1220-1440	220-260

Table 8. Projected habitat extents, Year 10, compared to No Action

Alternative	deep (>2 m) subtidal	shallow subtidal	intertidal mudflat	Salt marsh
	% change from No Action at Year 10			
No Action	0%	0%	0%	0%
New Inlet	+50%	+60%	-40%	+15%
Low Sill	+5%	+15%	-5%	+10%
High Sill	+15%	+60%	-30%	+25%
Parsons	-5%	0%	0%	0%

Table 9. Projected habitat extents, Year 10, compared to current conditions

Alternative	deep (>2 m) subtidal	shallow subtidal	intertidal mudflat	salt marsh
	% change from No Action at Year 0			
No Action	+10%	+10%	+5%	-5%
New Inlet	+65%	+70%	-35%	+5%
Low Sill	+10%	+20%	-5%	+0%
High Sill	+30%	+75%	-30%	+20%
Parsons	+5%	+5%	+5%	-5%

Table 10. Projected habitat extents, Year 50, compared to No Action

Alternative	deep (>2 m) subtidal	shallow subtidal	intertidal mudflat	salt marsh
	% change from No Action at Year 50			
No Action	0%	0%	0%	0%
New Inlet	+45%	+80%	-45%	+75%
Low Sill	-15%	+50%	-5%	+30%
High Sill	-25%	+150%	-30%	+85%
Parsons	-5%	-5%	0%	15%

Table 11. Projected habitat extents, Year 50, compared to current conditions

Alternative	deep (>2 m) subtidal	shallow subtidal	intertidal mudflat	salt marsh
	% change from No Action at Year 0			
No Action	+40%	+15%	+20%	-65%
New Inlet	+110%	+110%	-30%	-40%
Low Sill	+20%	+70%	+15%	-55%
High Sill	+5%	+180%	-15%	-35%
Parsons	+40%	+10%	+20%	-60%

Background on then analysis of alternatives

Hydrodynamic Modeling

The cornerstone of the investigation was the development of the hydrodynamic model to predict the effects of management scenarios on current velocity and tidal range. Model output and prior studies of bank erosion and marsh accretion served as the basis for predictions of erosion in the main channel and habitat types. This model, now owned by the Elkhorn Slough Reserve, is available for further analysis of designs and research purposes. It has already been used to develop conceptual designs for the restoration of Parsons Slough.

The PWA team developed the model of the Slough using DELFT3D, a software package that has been demonstrated to accurately represent estuarine conditions, including tidal flows, hydraulic structures and intertidal areas. The model calculates tidal heights and velocity at thousands of points in the slough for a full range of tidal conditions. The model was calibrated to one set of field data by modifying certain model parameters until model results fit the observed data. It was then successfully validated by comparison without modification to a second set of field data (see the PWA report, Appendix A). This implementation of the model is depth averaged (vertical variation in flow and stratification are ignored), but the vertical dimension can be added in the future with the same software.

Morphologic change

The approach predicted geomorphic change by using hydrodynamic model output to calculate the shear stress, or the force exerted by currents on the marshes, mudflats, and bed of the channel. This shear stress was converted to a rate of scour based on data collected by SEA Engineering and the CSUMB Sea Floor Mapping Laboratory, and on simulations of the bathymetry of the Slough in 1943, when no erosion was evident. Once eroded, sediment was assumed to be exported from the system. Sediment deposition was not included in predictions of geomorphic change.

Changes to the morphology (or shape) of the estuary can affect tidal currents by changing the tidal prism, channel dimensions and other landform features. These changes can cause positive feedback loops that increase the rate of erosion over time, or negative feedback loops that reduce the rate of erosion. Investigating the nature of these feedback loops was an objective of the investigation. Many types of morphologic change occur in estuaries, and the investigators conducted sensitivity analysis to compare the influence of channel scour, bank erosion and lowering of the marsh plain on tidal prism and tidal scour. Changes to channel depth exhibited a dominant influence on tidal currents and predicted rates of erosion (see Appendix D of Philip Williams & Associates et al. 2008), and this was the only morphologic change incorporated into Year 10 and Year 50 scenarios. In exploration of the associated feedback loop, the investigation found that as the channel became deeper over time, currents slowed, and the rate of tidal scour decreased. This result yielded the finding that scour is likely to slow over time rather than accelerate.

Habitat projections

Habitat projections were based on output from the hydrodynamic model and projections of geomorphic change. Salt marsh was predicted to occur in wetland areas inundated less than 11 percent of the time. The habitat analysis assumed that sea level would rise by 3 cm in the Year 10 scenario and 30 cm in the Year 50 scenario as a result of climate change. To incorporate the effects of bank erosion and interior marsh loss, the investigators assumed continuation of the trends of recent decades. Main channel bank erosion was assumed to proceed at 20 cm/year. The investigators estimated that the marsh plain could be either losing or gaining elevation, and they bracketed the change in marsh plain elevation with a range of -2.5 to +2.0 mm per year.

Long term trends

The PWA report discussed the broader context for habitat conversion, and identified three major management decisions that led to the imbalance between hydraulic energy and sediment supply in the slough, which is causing the habitat conversion observed now:

- About half of the original salt marshes of Elkhorn Slough were diked and drained, and as salt marsh soils dry out, the ground surface drops in the process of subsidence. These areas, many of which have subsided by a meter or more, are now open to the tides. In addition to the habitat conversion occurring at these sites, these areas likely compete for sediment with other salt marshes and mudflats.
- When the Salinas River was diverted to discharge directly to Monterey Bay early in the 1900s, a major supply of fine, marsh building sediment was lost.
- Construction of the harbor mouth at Moss Landing substantially increased tidal energy, but it also shifted the slough from a flood dominant tidal regime, where flood currents are faster and better able to transport sediment than ebb currents, to an ebb dominant regime. The current conditions provide an efficient mechanism for permanently exporting sediment from the estuary and into the Monterey Bay Submarine Canyon.

Major Considerations

Costs

The PWA report presented conceptual designs and cost estimates. These estimates include a 35 percent contingency because of their very preliminary nature. The Low Sill alternative had a cost estimate of $27 M, including $1.5 M for mobilization, $3.5 M for the sill, $15 M for sediment placement in the main channel, and a $7 M contingency. The New Ocean Inlet had a cost estimate of $94 M, including $4 M for mobilization, $ 45 M for earth moving, $12 M for jetties and a tidal barrier at the Highway 1 Bridge, and $8.7 M for a new highway bridge, with a $24.4 M contingency. If recommended, these designs would likely undergo substantial revision prior to implementation.

Opportunity Costs

The sustainability of estuarine wetlands depends on a supply of sediment. As sea level rises, accelerated by climate change, this requirement increases as well. The report recommends replacing sediment lost to subsidence and scour at considerable cost. At $10 per cubic meter, the current annual rate of channel scour (98,000 cubic meters per year) has a replacement cost of about $1 M. The Parsons Slough Project, by reducing the rate of channel scour by 40 percent, would reduce the cost of such future sediment additions by $400,000 per year.

The report lists the approximate costs of ten existing and planned large scale wetland restoration projects in San Francisco Bay. The per acre cost of these projects ranged between $1,700 and $75,000, with a mean of $24,000. Extrapolated over the 430 acres in Parsons Slough and over 2700 acres in Elkhorn Slough this figure yields amounts of $10 M and $65 M respectively.

Feasibility

Sections 6.4, 7.1 and 7.2 (Philip Williams and Associates 2008) discuss feasibility considerations with respect to construction of the major alternatives. Topics include bridge construction, inlet stability, disturbance to managed ponds, water quality in Elkhorn Slough, recreational navigation, dredging in Moss Landing Harbor, fluvial sediment delivery and access for marine mammals and fish. The degree to which adverse effects could be minimized or mitigated would depend on further refinements to project designs.

Phasing implementation with adaptive management

The PWA report recommends an adaptive management framework where large-scale actions could be implemented in a sequence of projects with increasing effects on the ecosystem. Each step could be conducted only as necessary and guided by pilot projects and monitoring studies. The sequence would begin with the Parsons Slough project, followed with a low sill under Highway 1. That sill could later be raised to the height of the high sill, which could ultimately be converted into a complete barrier as part of the project to build a new inlet for the estuary. This approach would contain costs, impacts to users and existing habitats and reduce risk to the ecosystem.

Inlet stability

The work included was an analysis of the stability of a new ocean inlet with respect to seasonal closure. That work indicated that seasonal closure of the New Inlet could not be ruled out as a possibility, and that further analysis would be required to make a definitive statement about the stability of a new ocean inlet.

Sediment supply

The PWA report discusses sediment supplies from a variety of sources, including the Salinas, Pajaro and Carneros Creek watershed. Increasing organic sediment accretion by the introduction of native *Spartina foliosa* is discussed and not recommended without careful consideration. The report recommends sediment additions and/or the restoration of a sediment supply.

The report presented estimates of the sediment required to sustain tidal marshes in the slough along with past and present sources of sediment. The amount of sediment required to support the tidal marshes is comparable to approximations of the sediment delivered to the slough from the local watershed under current conditions. Channel scour is about 10 times greater than this amount, and the accumulated sediment deficit from the past subsidence of marshes is greater by a factor of 40 (see Philip Williams and Associates 2008, Section 3.5).

Flood and Ebb dominance

Estuaries often exhibit differences in peak velocity between the flood and ebb tides. Flood dominant estuaries have higher peak current velocity estuaries on the flood tide and tend to import and retain bed sediment while ebb dominant estuaries tend to export this sediment over time. At Elkhorn Slough, sediment exported from the estuary is lost to the Monterey Submarine Canyon.

Analysis by the PWA team indicated that Elkhorn Slough was likely flood dominant under 1943 conditions, before the harbor mouth was opened. After the harbor mouth was opened, the estuary likely shifted to an ebb dominant condition, which persists today. A flood dominant tidal regime could help retain sediment and sustain estuarine wetlands. Of the alternatives considered, only the New Inlet alternative recreates a flood dominant condition. However, there may be options to configure the Low Sill alternative such that the ebb dominant conditions it maintains could be reduced and perhaps reversed.

1943 Model Implementation

Conditions observed in 1943 were simulated as an example of highly depositional conditions in contrast to the erosional environment observed today. In the geomorphic analysis, the peak velocity of the 1943 conditions was used to define thresholds for erosion. One result of this choice is that channel scour is predicted to occur until the energy regime approaches 1943 conditions.

Rather than a restoration reference condition, 1943 serves as a snapshot low tidal energy conditions (Van Dyke and Wasson 2005). Large areas of salt marsh and entire branches of the slough had been diked off from the tides, reducing the tidal prism of the estuary and leading to extensive shoaling and the periodic closure of the mouth. This environment was highly depositional and shallow compared to records from the late 1800s.

The results of the 1943 simulation indicate the tidal range at that time was much narrower. As the channel eroded, high water levels likely increased during the years following the opening of the harbor mouth. This suggests excess inundation (marsh drowning) as a cause of marsh dieback. The lowering of low water levels since 1943 helps explain the incision and widening of tidal creeks.

Assumptions and uncertainties

Numerous simplifying assumptions were made to enable this analysis. These are discussed in sections 5.4.2 Habitat Projection Considerations, 5.4.3 Tidal Habitat Composition Projections, and Section 6.5 Project Assumptions and Uncertainties (see Philip Williams and Associates 2008).

Limitations

Consideration of several important factors was beyond the scope of the effort.

Marsh accretion rates

The habitat projections made by this work are strongly dependent on assumptions about the rate at which the salt marsh accretes material and gains elevations over time. If the marshes gain elevation faster than sea level rises, then they can outpace sea level rise, but if not, in the long run they will drown. Local data on marsh accretion is limited, making these projections highly uncertain. Existing data indicate that the marsh is not keeping pace with current rates of sea level rise (see Philip Williams and Associates 2008, Section 5.4.2.2). Increased input or retention of sediment would be required for higher rates of accretion.

Mudflat sustainability

The habitat projections show most of the salt marsh converting to mudflat when inundated for more than 11 percent of the time. The mudflats were assumed to be stable and not eroding. The text indicates that this assumption may overstate longevity and future extent of mudflats. Particularly in a sediment starved, ebb-dominant estuary the export of sediment will gradually convert mudflats to subtidal habitats. Mudflats are dynamic environments where surface sediment is regularly mobilized by wind waves and redeposited during quiescent periods. Because vegetation dampens wave energy, marsh sediments are less dynamic and more likely to be retained (Steve Crooks, personal communication).

Limits to Channel Scour

The geomorphic approach incorporated the assumption that the channel would not scour below 10 m (33 feet), which is about the dredged depth of the Harbor. This assumption was based on the reasoning that scour was unlikely to extend below the depth of the harbor, and that the harbor would continue to be maintained at that depth. The projected channel scour reached this limit in portions of the Slough for the No Action, Parsons Slough Restoration, and Low Sill alternatives. The geomorphic projections used downward channel scour as the only process for the adjustment of the channel cross section to excess energy and shear stress. In natural settings, channel widening also occurs in the process of adjustment.

Together, these assumptions may result in an underestimation of the long-term potential for channel scour and widening.

Sediment deposition

The geomorphic approach focused on long-term average rates of tidal scour. It did not consider redeposit of sediment or inputs from episodic events.

Alternate explanations for salt marsh dieback

The report lists several factors that may contribute to the observed changes in marsh cover but were not investigated as part of this work, such as plant physiology, herbivory and microbial processes (Philip Williams and Associates 2008, Section 5.4.1).

Water quality

The purpose of this document is to present the results of an analysis of the tradeoff between reducing tidal exchange and increasing the risk of dissolved oxygen problems in the slough.

Water quality overview

Water quality affects a wide range of services provided by Elkhorn Slough, from supporting biodiversity, to providing a safe place to paddle, to the production of food for flatfish, sharks and rays, shorebirds and sea otters. The slough receives water highly enriched in nitrogen from various sources, from the head of Carneros Creek to the city of Salinas. The primary source is the watershed of Gabilan Creek, the Reclamation Ditch and Tembladero Slough, which drains through the Old Salinas River Channel to the southern end of Moss Landing harbor. A large fraction of this water is swept into Elkhorn Slough on the rising tide.

Just as nitrogen fertilizer accelerates plant growth in farm fields, is does the same in estuaries, particularly with respect to algae and tiny plants in the water column (phytoplankton). This increase in primary production is termed eutrophication. Produced by these plants during the day, oxygen is used continuously by both plants and the organisms that consume them. In highly enriched sites the production and consumption of oxygen can cause concentrations to fluctuate widely, which can impact a variety of organisms. Other changes to the estuary may result from nutrient enrichment, ranging from changes in the competitive advantage to certain species to changes in water chemistry.

While some fluctuations in dissolved oxygen are considered natural, low concentrations (hypoxia) or the complete depletion of oxygen (anoxia) can alter ecologic functions such as compromising the fish production (Diaz and Rosenberg 1995), such as occurs in the Gulf of Mexico ‘dead zone’ off the Mississippi Delta and in many other parts of the world, including parts of Elkhorn Slough (Diaz and Rosenberg 2008).

Long-term monitoring programs coordinated by the Elkhorn Slough Foundation and Elkhorn Slough National Estuarine Research Reserve during past two decades have revealed strong diurnal fluctuations at all sites in the estuary, symptomatic of nutrient enrichment. In particular, some shallow sites and locations with water control structures such as culverts that restrict tidal exchange experience widely fluctuating dissolved oxygen concentrations. One study (Beck and Bruland, 2000) described North Azevedo Pond in Elkhorn Slough as ‘hyperventilating’ because of the dramatic swings in dissolved oxygen observed there.

Understanding the system

Since 1989, the Elkhorn Slough National Estuarine Research Reserve, in partnership with the Monterey County Water Resources Agency, Moss Landing Marine Laboratories and the Elkhorn Slough Foundation, has monitored water quality monthly in a volunteer sampling program at 24 stations. Beginning in 1995, the Reserve has participated in the National Estuarine Research Reserve’s system-wide monitoring program. This program uses water quality sondes deployed at 4 stations on the Reserve, which collect data every 15 minutes around the clock, and maintains a weather station. Some of the data are sent via satellite to a server where they become available almost immediately, while all the older data can be downloaded by any user via the web.

During the past ten years Ken Johnson and a team of scientists at the Monterey Bay Aquarium Research Institute developed an innovative approach to understanding water quality in estuaries, which is based on a sensor network they developed. The network consists of buoys moored at representative locations and capable of measuring several key parameters, including dissolved oxygen, salinity, depth and nitrate using an innovative optical sensor they invented. A similar ammonium sensor is in development. Data at the network, the Land/Ocean Biogeochemical Observatory (LOBO), is collected every 60 minutes and relayed to shore by wireless communications, making it available essentially in real time.

Some estuaries are less sensitive to nutrients than others and despite high inputs, do not experience dissolved oxygen ‘crashes’, fish kills or other easily observed outcomes of eutrophication. This is related to physical and biological characteristics of the estuary, such as tidal exchange, which mixes the water column and brings in higher quality water from the ocean (Cloern 2001). The main channel of Elkhorn Slough presently falls into this type of estuary. Observations by the LOBO array and the sensors operated by the Research Reserve have shown wide daily swings in dissolved oxygen concentration, but there are not records of widespread fish kills. Water quality impairment is clearly affecting some areas: in parts of the estuary where tidal exchange is restricted by culverts, dissolved oxygen frequently drops to levels stressful for fish and invertebrates, and biodiversity is substantially reduced compared to full tidal exchange areas (Ritter et al. 2008).

Assessment of alternatives

The proposed large scale actions are intended to reduce tidal scour and salt marsh loss by reducing tidal velocity and tidal range. When these alternatives were originally developed, is was widely acknowledged that one of the greatest risks in implementing them would be an increased risk of hypoxia and the formation of a ‘dead zone’ in Elkhorn Slough. Dr. Johnson and his team from MBARI took on the challenge of describing this risk.

During the past year, they analyzed the extensive LOBO dataset to understand whether large scale actions might trigger water quality problems. To do this Dr. Johnson developed a numerical model of dissolved oxygen for the Slough. The model incorporates the flow and mixing of water, the exchange of oxygen with the atmosphere, and oxygen consumption and production by various groups of organisms, including plankton in the water column, algae on the mudflats, and the benthic community of invertebrates and microbes living in the mud at the bottom of the channel.

What was revolutionary about this approach is that rather than assign rates to the biological sources and sinks of oxygen, Dr. Johnson’s model calculated the rates directly by testing a range of possible values and determining which best fit the dataset. This tuned the model to Elkhorn Slough and allowed for variation in the parameters over time to reflect how rates change with the tides and with seasonal changes in productivity. Dissolved oxygen data for 2006 were used to calibrate these parameters, and then the model was validated by successfully predicting oxygen based on physical inputs for the 2007 dataset. This calibration indicated extremely high rates of oxygen consumption by the benthic community in the upper slough, and the MBARI team conducted field work that confirmed rates among the highest published in the literature. Flow was calibrated to field observations and to a detailed hydrodynamic model of Elkhorn Slough developed by Nick Nidzieko of Stanford University.

With the model up and running, the team turned to the question of the large scale actions by changing the flow conditions in the model to match the conditions predicted for each alternative by the hydrodynamic model of the slough developed by Philip Williams and Associates. They then focused on July conditions in the Upper Slough near Kirby Park, as that is the critical period and location for dissolved oxygen concentrations. The Upper Slough has high abundance of phytoplankton (N. Welshmeyer, personal communication), benthic invertebrates (J. Oliver, personal communication) and macroalgal cover, all of which contribute to oxygen consumption. Oxygenated water from Monterey Bay takes a long time to reach this area, and during summer conditions, the water in this area could have an age of two to seven weeks compared to less than a day near the mouth of the slough (N. Nidzieko, personal communication, Largier *et al* 1997).

Because of uncertainty about how biological productivity and water circulation patterns might change, Dr. Johnson declined to model future scenarios with respect to dissolved oxygen concentrations because the high degree of uncertainty involved. Since biology plays such a large role in dissolved oxygen cycling, such predictions would need to be based on the future populations of phytoplankton, algae and benthic organisms. These populations are affected by water circulation and bathymetry but those relationships are complex. Philip Williams and Associates and H.T. Harvey and Associates projected rates of tidal scour, sea level rise and the future habitat composition of the slough, but did not develop predictions of future bathymetry or perform three dimensional circulation modeling. The Modeling Advisory Team discussed these issues and found that insufficient information was available at this time to make predictions of how these attributes and processes would change under future scenarios. Further complicating predictions of water quality, many other factors in addition to physical drivers contribute to population changes and effects on water quality of these populations.

Rather than make specific predictions about the future, Dr. Johnson emphasized that substantial risks exist with respect to dissolved oxygen, discussed below.

Findings: a delicately poised estuary

Dr. Johnson’s team found that the role of biology was far greater than the role of physics in determining oxygen concentrations in the slough. The rates of oxygen production and consumption in the Slough are extremely high, exceeding most of the values published for other estuaries. Oxygen is produced and consumed faster than the exchange of water with the bay can affect concentrations. Among physical processes and properties, water depth, wind and sunlight turned out to be more important than tidal exchange. In fact, under present conditions two weeks of light wind and fog during the summer could result in severe oxygen depletion problems in the main channel of Elkhorn Slough. In shallow areas and tidally restricted areas, oxygen depletion already occurs regularly.

While two to four weeks are required for tidal exchange to mix highly oxygenated water between Monterey Bay and the Upper Slough, respiration particularly by the benthic community can consume much of the available oxygen in just 12 hours. More important than tidal exchange are the processes that add oxygen to the water column on a daily basis. The investigation isolated four factors that influence these processes: sunlight, which drives photosynthesis, and wind and current speed, which affect the exchange of oxygen between the air and water, and the depth of water, which affects the reservoir of oxygen available.

Dr. Johnson described dissolved oxygen in Elkhorn Slough as ‘delicately poised’ under existing conditions. A period of several foggy and windless summer days could produce hypoxic or anoxic conditions in the Upper Slough and Parsons Slough. Such conditions could kill some fish and invertebrates or drive others from the estuary. Such conditions occur occasionally in parts of the slough. Leopard sharks leave Parsons during the late summer, with timing coincident to low dissolved oxygen concentrations at the ESNERR monitoring stations (Carlisle 2007).

Benthic oxygen demand is very high and the deeper the water column the more oxygen is available to satisfy that demand. This conclusion is strongly supported by the observations of the Volunteer Monitoring Program (with monthly sampling) and the ESNERR Long Term Monitoring Program (sampling every 30 minutes), which show frequent oxygen depletion in shallow areas with muted tidal range (Brent Hughes, John Haskins and Kerstin Wasson, personal communication). See Figure 3.

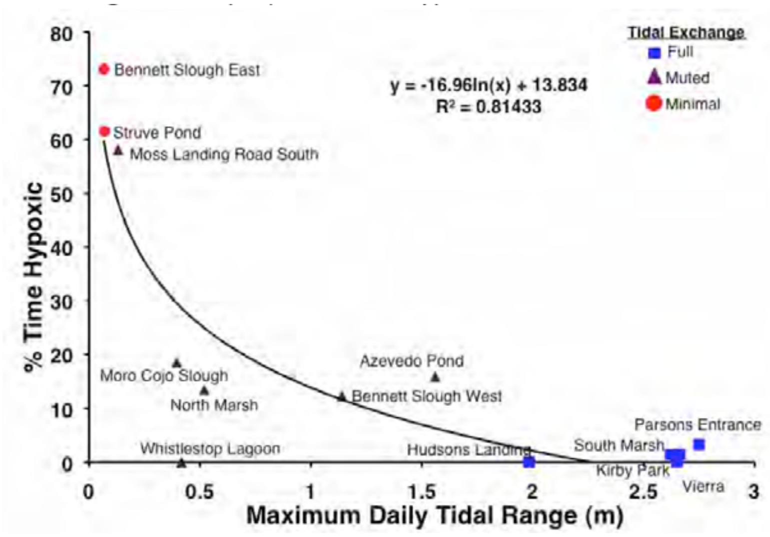


Figure 3. Dissolved oxygen, tidal range and water depth.

Water quality data from the Elkhorn Slough Volunteer Monitoring Program and the ESNERR Long Term Monitoring Program indicate a strong relationship between tidal range and frequency of low dissolved oxygen concentrations. Hypoxia in this analysis was defined as dissolved oxygen concentrations less than 2.3 mg/L.

Deep portions of the Upper Slough show a night time drop in dissolved oxygen, but in shallow areas dissolved oxygen is removed entirely (Beck and Bruland 2000). The role of water depth helps explains why tidally restricted areas, most of which are shallow, have such low night time oxygen levels. While current velocity affects the exchange of oxygen between the atmosphere and the water column, currents would need to be slowed to nearly a standstill for that effect to be meaningful in comparison to other sources and sinks.

The study also identified surprising interactions between biological and physical factors. For example, the higher of the two daily high tides during spring tide series occurs during the night in the summer. During these periods, mudflat algae consume oxygen when submerged at night, depressing dissolved oxygen levels. Low tide occurs during the day, when these algal mats produce oxygen. But that oxygen is released to the atmosphere, rather than replenishing the oxygen removed from the water column. More extensive mudflats would increase this effect, resulting in lower dissolved oxygen conditions in the summer.

For the different alternatives, the investigators predicted the percentage of the time for hypoxia, which could have sub-lethal negative effects on fish or invertebrates. Hypoxia was defined as 75 micromoles per liter, or 2.3 mg/L, which corresponds roughly to 30 percent saturation. They found that most of the alternatives would not increase hypoxia substantially under normal conditions. They also considered a worst case condition of a month without wind, and looked at conditions in the Upper Slough and in Parsons Slough, as two large areas most vulnerable to hypoxia.

The study found that under normal conditions the New Ocean inlet would result in small lowering of dissolved oxygen concentrations (Table 1). The Low Sill would have little effect on dissolved oxygen. Restoration of Parsons Slough would have little effect on dissolved oxygen in the main channel, but could have adverse effects in Parsons Slough, depending on how the restoration is conducted. These effects are accentuated when considering four weeks of no wind or no wind and prolonged fog (Table 2).

Table 1. Dissolved oxygen under typical weather conditions

Scenario	Percent of the time hypoxia occurs[1]		Minimum dissolved oxygen concentration, uM (mg/L)	
	Upper Slough	Parsons Slough	Upper Slough	Parsons Slough
Present conditions	0	2	98 (3.0)	68 (2.1)
New Ocean Inlet	0	4	89 (2.8)	63 (2.0)
Low Sill	0	2	98 (3.0)	66 (2.1)
Parsons Slough	0	10	87 (2.8)	19 (0.6)
Low Sill and Parsons Combination	0	not reported	98 (3.0)	n/r
No flow (hypothetical case)	0	2	93 (2.9)	67 (2.1)

[1] during the simulation period (July 2007), with hypoxia defined as dissolved oxygen below 2.3 mg/L (75 uM)

[2] simulated by making Parsons Slough 50 percent shallower

Table 2. Dissolved oxygen under windless conditions

Scenario, assuming a series of windless days	Percent of the time hypoxia occurs[1]		Minimum dissolved oxygen concentration, uM (mg/L)	
	Upper Slough	Parsons Slough	Upper Slough	Parsons Slough
Existing conditions	2	17	47 (1.5)	9 (0.6)
New Ocean Inlet	10	30	29 (0.9)	4 (0.1)
Low Sill	2	21	47 (1.5)	9 (0.3)
Parsons Slough	2	n/r	47 (1.5)	n/r
Low Sill and Parsons Combination	3	n/r	47 (1.5)	n/r
No flow (hypothetical case)	14	39	12 (0.4)	3 (0.1)
No wind and foggy (existing conditions otherwise)	25	37	30 (0.9)	5 (0.2)

Guidance on evaluating alternatives

Dr. Johnson's team found that dissolved oxygen concentrations fluctuate widely under present conditions related to extremely high rates of primary productivity related to external inputs of nitrogen. This analysis indicated that large portions of the slough are at risk of disruptive events where dissolved oxygen drops to levels that could kill invertebrates or cause avoidance behavior in fish. They found that tidal exchange, which would be reduced by the large scale actions, does not play a major direct role in dissolved oxygen cycling in the slough.

This study does not give a green light for projects like the Low Sill or New Ocean Inlet, but clearly calls for caution. Dr. Johnson called the ecosystem ‘delicately poised’ and ‘at risk’ with respect to dissolved oxygen. Also, the study was limited in its scope. It did not predict how the biological processes that drive the system might themselves change after a project. For example, less exchange with the ocean might allow the abundance of phytoplankton or algae in the slough to increase, heightening the risk of dissolved oxygen problems.

In considering large scale alternatives, the researchers found that details of the project apart from tidal exchange could dominate the effect on dissolved oxygen. For example, restoration of Parsons Slough in a way that made the entire area shallower would likely have an adverse impact on dissolved oxygen. The study recommended restoration approaches that retain deep channels and subtidal areas. In areas where fill is placed, the elevation should be raised to that of salt marsh or high mudflats, rather than low intertidal mudflat or shallow subtidal habitats.

Large scale actions that induce stratification of the water column would be strongly detrimental. Each of the alternatives could increase the likelihood of stratification by reducing current velocity or by the geometry of the structure. Determining whether that increased likelihood is a concern may require further investigation with a three dimensional hydrodynamic model.

Stratification, where warm or fresh water near the surface does not mix much with cool or saline water near the bottom, can isolate the plankton and algae that produce oxygen from the benthic organisms that consume most of it. In many eutrophic estuaries, this leads to anoxic conditions near the bottom, which can adversely affect the invertebrate community and the food web.

Nonlinear interactions occur between biological and physical factors, such that this analysis entails a high degree of uncertainty. Plankton, algal and benthic communities might change over time or in response to large scale actions. Such changes could alter the rates of oxygen production and consumption. The analysis used rates determined under existing conditions, and different rates would yield different results. For example, alterations to the tidal prism may affect the residence time of water in the upper slough. We do not presently know what that effect may be, or how those changes in residence time would influence biological processes such as phytoplankton abundance, which would in turn affect water quality. As another example of these relationships, subembayments with restricted tidal exchange exhibit different biogeochemical conditions than the main channel. Moro Cojo Slough, an area of minimal tidal exchange, develops large mats of macroalgae on the surface. Similar accumulations of algal mats in the main channel of Elkhorn Slough do not occur because the high tidal energy rapidly dissipates them. The threshold of tidal energy required to break up these mats is not known and was not incorporated into the analysis.

Worst case scenarios

The risk to the system of a severe anoxic event is unknown. Coastal waters subjected to anoxia show different patterns afterwards with some ecosystems failing to recover (Diaz 2008). Deployments of benthic chambers in Elkhorn Slough by Dr. Johnson’s team demonstrate a strong flux of hydrogen sulfide from the sediments. Under present conditions, this sulfide does not accumulate because tidal currents mix sufficient oxygen into the benthic boundary layer to convert it to less toxic forms. Reduced mixing rates may allow it to accumulate to toxic concentrations, damaging the ecosystem in such a way that impairs the process of recovery.

Nutrient loading and Management

The investigation quantified the discharge of nitrate from the Old Salinas River Channel, and the transport of nitrate into and out of Elkhorn Slough. Approximately 1600 kilograms of nitrate nitrogen discharges daily form the Old Salinas River Channel. On the outgoing tide this water fills Moss Landing Harbor and creates a freshwater plume into Monterey Bay. When the tide comes in, water in the harbor and plume, along with about 50 percent of the nitrate from the Old Salinas River Channel is drawn into the slough.

Nearly all of the nitrate appears to be transformed in the slough. One year of observations with ammonium sensors shows that approximately 80% of the nitrate that enters the Slough is converted to ammonium, perhaps by dissimilatory nitrate reduction to ammonium in the Slough sediments. The remainder is either assimilated into plankton or algal biomass or lost through denitrification.

Dr. Johnson’s analysis attributes the high rates of primary productivity to these high nutrient inputs, but the analysis did not quantify the relationships between nutrient loading, primary productivity and dissolved oxygen cycling. Those relationships remain important. Management scenarios that reduce inputs would reduce the growth rates of algal and phytoplankton communities, which could reduce the likelihood of hypoxia. The New Ocean Inlet, for example, would distance the Elkhorn Slough inlet from the nitrate inputs from the Old Salinas River Channel. While this benefit may be substantial in the long run, it may not have immediate effects. The work of Dr. Johnson's team on nitrogen in the slough found that primary productivity in the slough relies on two major sources, one from the Old Salinas River Channel and one from within the slough itself. This second source appears as the export of ammonia from enriched bottom sediments that have accumulated over many years. This internal source of biostimulation could sustain elevated productivity for an unknown period of time, potentially many years, following management actions that reduce external nitrogen inputs.

The Reclamation Ditch Watershed, which contributes essentially all of the fresh water to the Old Salinas River Channel, includes urban areas, industrial land uses and supports 39,000 acres of irrigated cropland (Casagrande and Watson 2005). Typical applications of nitrogen on lower Salinas Valley lettuce crops is 200 to 300 lbs per acre, with less nitrogen applied in the second and third crops (Tourte and Smith 2001, R. Smith personal communication). Nitrogen applications are not tracked, making estimations imprecise, and nitrogen loading from other sources has not been quantified. The amount of nitrogen measured in the stream is probably in the range of 5 to 20 percent of the total amount applied as fertilizer.

Reducing the delivery of nitrogen to Elkhorn Slough could be accomplished through a variety of ways. These include the diversion of flow from the Old Salinas River Channel away from Elkhorn Slough to another receiving water body such as the Salinas River Lagoon or directly to Monterey Bay, changed nutrient or irrigation management practices in the watershed, or the removal of nitrogen from the water column using treatment wetlands in the Old Salinas River Channel watershed.

Monterey Bay productivity

In comparison to upwelling processes in the Bay, the amount of nitrate contributed by the Old Salinas River is relatively minor. But for an enclosed estuary such as Elkhorn Slough, the input of nitrogen is substantial. The upwelling of deep ocean waters rich with nitrate drives seasonal high productivity along the Central California Coast. Using published data on upwelling rates and nitrate concentrations, Dr. Johnson and Dr. Erika McPhee-Shaw of Moss Landing Marine Labs estimated the mass flux of nitrate to Monterey Bay surface waters. This analysis suggests that the Old Salinas River load of 1600 kilograms/day of nitrate nitrogen is a small contributor to the total nitrogen budget of the bay. A similar quantity of nitrate is delivered by wind-driven coastal upwelling along just 40 to 100 meters of coastline. Internal tidal transport of deep water from the upper Monterey Bay Submarine Canyon also supplies significant nitrate to the inner shelf almost daily. Nitrate from the Old Salinas River channel could theoretically be important when upwelling is not occurring, but unusual circulation and stratification patterns that prevent the dilution of the nitrate plume would also be required for this effect to be significant.

One unique aspect, which has potential impacts in Monterey Bay, is the outflow from Elkhorn Slough of relatively high ammonium concentrations that appear to produced in Slough sediments during nitrate reduction. Although the total amount of nitrogen appears small, compared to natural nitrate sources, it will exert some selective pressure that might allow blooms of otherwise rare phytoplankton to be initiated. Dr. McPhee-Shaw and student Tanya Novak are continuing to investigate the role of nitrogen exports from the Slough.

Summary

In summary, the investigations led by PWA and Dr. Johnson generated several important findings:

1. A shallower slough, with more low intertidal and shallow subtidal areas, would be more prone to hypoxia, as these are the types of habitats where the depletion of oxygen is most likely to occur. Restoration activities that increase the extent of these areas may increase the frequency of hypoxia.
2. As marsh dies back, the more extensive mudflats will also likely result in lower minimal dissolved oxygen concentrations.
3. Slightly reduced current speeds such as those likely to result from the large scale actions do not pose a major problem for dissolved oxygen under present circulation conditions (without stratification). However the combined effects of lower current speed and an extended period of low wind speed resulting from anomalous weather conditions may substantially increase the frequency of hypoxia.
4. Actions that induce stratification of the water column could be strongly detrimental. Large scale actions should be evaluated and managed in an adaptive framework to minimize the likelihood of that possibility.
5. Reducing the inputs of nutrients to the estuary is essential to restore a more stable ecosystem.
6. Gas exchange with the atmosphere is critical. Low wind, floating algal mats and other factors that reduce gas exchange may exacerbate hypoxia.
7. A worst case scenario could result in the release of substantial quantities of hydrogen sulfide from the bottom sediments, which could impair the ability of the estuary to recover from such an event.

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Glossary

anoxia – the condition where dissolved oxygen is absent

bed shear stress – the force exerted over an area of the bed of a slough, river or other water body, which is related to the likelihood of scour

hypoxia – the condition where dissolved oxygen concentrations are low, typically defined as 75 uM or 2.3 mg/L

MHHW – Mean higher high water, the average elevation of the higher of the two daily high tides

MLLW – Mean lower low water, the average elevation of the lower of the two daily low tides

thalweg – the deepest part of the channel

tidal prism – the volume of water exchanged in a tidal cycle

tidal scour – the erosion of the bed of the channel by tidal currents