REPORT OF PESCADERO LAGOON SCIENCE PANEL

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[#] Dr. Bostick participated in a pre-Panel public meeting in February 2013 and initial meetings of the Panel in late 2013. He did not participate in subsequent discussions nor in writing of the report.

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Executive Summary

REPORT OF PESCADERO LAGOON SCIENCE PANEL

The Pescadero Lagoon Science Panel (PLSP) was established in 2013 to provide independent scientific expertise in support of management decisions and possible restoration actions for Pescadero marsh and lagoon. The PLSP focused on physical and biogeochemical processes in the open-water habitats of lagoon, with attention centered on the annual fish mortality events. Concerns for juvenile steelhead were foremost, but this scientific review also gives attention to other listed species (e.g., tidewater goby) and other major concerns (e.g., winter flooding of low-lying lands). The PLSP report is based on best available science, which goes beyond journal publications to offer the panel's best professional judgment, derived also from unpublished work, available data and the insights of other scientists that work on Pescadero Lagoon and comparable systems in California and elsewhere.

Pescadero Lagoon is located in San Mateo County, 60km south of San Francisco Bay and 40km north of Monterey Bay. It is a bar-built estuary, with a mouth that closes when ocean waves deposit sand in the narrow channel that connects estuary and ocean. The lagoon is surrounded by intertidal marshes, an elevated marsh plain and marshes that form part of the river floodplain. The marsh and lagoon provide habitat for many species, including listed species like steelhead trout (*Oncorhynchus mykiss*), tidewater goby (*Eucyclogobius newberryi*), San Francisco garter snake (*Thamnophis sirtalis tetrataenia*), red-legged frog (*Rana draytonii*), Western pond turtle (*Actinemys marmorata*), and Western snowy plover (*Charadrius nivosus*).

Conceptual Models

Extensive knowledge relating to key components of the lagoon system was reduced into conceptual models that capture the essential understanding of how the system functions:

Sedimentation. Lagoon-marsh systems like Pescadero formed in coastal valleys as sea level rose during the Holocene. Over several millenia the lower valley accumulated sediment from both watershed and ocean. In Pescadero, a marsh surface formed 2 to 3m above high tide and the modern lagoon has continued to accumulate sediments. Enhanced fluvial sedimentation occurred in the last century, and it is expected that this will continue as the legacy of earlier human activity in the watershed and due to the loss of floodplain connectivity and sediment storage in the lower watershed. Pescadero Lagoon has changed from an open-water estuary into a shallow-creek delta, with loss of half of its open-water area between 1900 and 1960 – a trend that has continued and the lagoon has shoaled a further 0.4m over the last 25 years. The most significant recent accretion has been observed near the ocean, with growth of the flood-tide shoal. The increased incursion of marine sediments into the lagoon and changes in mouth closure patterns are likely due to changes in sediment supply along the coast and/or changes in sand transport processes in the lagoon near the mouth.

Mouth closure. A sand barrier (or “berm”) is built between the lagoon and the ocean by wave action. Closure usually happens during the dry season and breaching of the berm occurs early in the wet season, when the lagoon fills up and overflows. Following a breach, a new channel is scoured through the berm and tidal action returns, along with the intrusion of seawater. If outflow is too weak to erode a channel and the barrier remains intact, water level in the lagoon remains above ocean high-tide levels and a “perched estuary” forms. Pescadero Lagoon typically closes once a year for a prolonged period during the dry season, and in some dry years a shorter closure may occur also in late winter (February-April). Prolonged seasonal closures appear to follow one of two patterns: spring closures (April-June) and fall closures (September-November), with breach events following rains in November or December. In recent years, closures have occurred in the fall, but there is inadequate data prior to 1990 to assess whether this represents a permanent change in the system.

Hydrology and water levels. The low-lying estuarine area between elevated beach/dunes and uplands fills up with water from the ocean and the two primary creeks (Pescadero Creek; Butano Creek). Water level and inundation of marshes and low-lying human infrastructure is controlled by inflows and outflows to/from the lagoon. High water surface elevations (WSE) in the lagoon and inundation of marshes occur naturally under three scenarios: (i) high sea levels due to tides, storm surge and sea level rise; (ii) damming of the lagoon by the sand berm across the mouth; and (iii) strong river flows that are backed up due to restricted outflow at the mouth. When the mouth is closed, the WSE increases slowly to a maximum (seepage plus evaporation balance inflows), typically about 2.8m above mean low low-water (MLLW), and most marshes are inundated to a depth of 0.2-0.4m. When the mouth is open, WSE maxima are primarily controlled by ocean tides and range from 0.8 to 2.0m above MLLW. During storm surges, high-tide WSE may reach 2.4m, but marshes are seldom inundated. Highest WSE occurs during high creek flows as the berm and bedrock at the mouth slow outflow so that water backs up in the lagoon, e.g., WSE reached 3.53m in a 1955 flood.

Seawater intrusion and salinity structure. When the mouth is open, seawater enters the estuary in the form of a salt wedge – a distinct seawater layer, which intrudes and retreats tidally. The salt wedge typically exhibits near-oceanic salinities and the surface layer is nearly fresh water. When the mouth of the estuary is closed, a layer of high-salinity water is trapped in the deeper parts of the lagoon, overlain by a freshwater layer. Stratification is very strong and persistent, preventing mixing of surface and bottom water masses. During low-energy breaches, the surface layer will flow out without disrupting the lower layer, while high-energy breaches result in mixing across the stratification and flushing of the deep saline waters – typically during strong river flows.

Water quality. Fish mortality events in Pescadero Lagoon are attributed to low levels of dissolved oxygen in the water column following breach events. This low-oxygen water originates in two anoxic environments, which may develop in Pescadero Lagoon: (i) in the lower layer of a highly stratified water column, and (ii) in muddy sediments or beneath matted vegetation in a marsh. When the mouth is open the water column is typically oxygenated, but drainage from marshes can lead to anoxia in the landward margins of the lagoon during dry-season ebb tides (a phenomenon that may be enhanced by shoaling and blocking of water flow in the main Butano Creek channel). When the mouth is closed, an anoxic lower layer develops, in which reduced compounds accumulate that can rapidly strip oxygen out of the water column following breaching. This chemical oxygen demand is exacerbated by drainage from marshes following breaching of the mouth and a drop of the water level below the marsh surface.

Synthesis

Fish and invertebrate mortality events occur in Pescadero Lagoon during low-oxygen events that follow the breaching of the lagoon mouth after an extended closure in late summer or fall. Reasons for an increase in mortality events may be due to any of several interrelated factors: (i) more frequent hypoxic events; (ii) more intense hypoxic events; (iii) more persistent hypoxic events; (iv) occurrence of hypoxic events in a more-sensitive season; (v) more spatially extensive hypoxic events; and (vi) inability of organisms to escape life-threatening conditions by migrating to ocean, up-river or into other parts of the lagoon. Multiple types of hypoxic events may occur, depending on the relative roles of the lower-layer and marsh sources of oxygen demand. Because hypoxia can be alleviated by breaching, it is important to differentiate between breaching that leads to deep scouring and flushing versus breaching that leads to only moderate or shallow scouring and outflow.

Pescadero Lagoon has been subject to a series of changes over the last century and a half. Growing concern with fish mortalities in the last quarter century suggests that the lagoon environment continues to change – in a way that has reduced the ability of the lagoon to support juvenile steelhead and other fishes. The following changes appear to have happened in this system over the last few decades, but causative relations between these changes are not well known and neither is the impact of these changes on fish populations and ecosystem functions: (i) increased tidal prism, (ii) later closure of the mouth, (iii) enlarged flood-tide delta, (iv) shallower mouth channel, (v) changes in artificial breaches, (vi) changes in ocean conditions and rainfall, (vii) changes in bottom depths, (viii) increased sedimentation, (ix) breaks in levee, (x) tule reed growth, (xi) increased flux of chemical oxygen demand from marsh to lagoon, (xii) organic loading of inflow, (xiii) freshwater extraction, (xiv) reconnection of marshes, and (xv) salinity changes in northern reaches.

Fish kills in Pescadero Lagoon have raised stakeholder concerns and a response from management agencies is sought by many. The following management actions have been raised by stakeholders and are briefly reviewed in the report:

- Pre-emptive breaching of the sand barrier.
- Breaching sand barrier during rain events.

- Filling deep backwater sections.
- Installing a bubbler to destratify the water column.
- Manual closure of the mouth in spring.
- Dredging of Butano Creek channel.
- Dredging of the flood-tide delta.
- Reducing the tidal prism.
- Reconfiguring connections to North Pond and North Marsh.
- Developing nutrient management for lagoon inflows.
- Developing water management for lagoon inflows.

A common scientific understanding of the lagoon system has been developed that can serve as a scientific foundation for management decisions going forward. However, the PLSP finds that inadequate data and analyses on key issues related to fish kills preclude the development of specific science-based management recommendations. Further, the concern for annual fish kills needs to be placed in a broader ecological context before the ecological costs and benefits of specific actions can be clarified. To move forward, we need answers to several important scientific questions: How important are fish kills to the affected population? What controls hypoxia and anoxia – whether through seawater trapping in lower layer, or through marsh drainage? What controls the depth of scour during breaching? How has freshwater inflow changed? Does eutrophication occur? What controls the availability of habitat for other sensitive species including tidewater goby, red-legged frog and San Francisco Garter snake?

In spite of ongoing concerns with quasi-annual fish kills in Pescadero Lagoon, and the volumes of spoken and written comment, there is a paucity of critical data, an absence of strategic monitoring, and a general lack of analysis of key issues that need to be validated and articulated prior to management action. Ultimately the community of stakeholders needs to develop a common set of objectives based on a common vision, which will rest on well-founded scientific understanding of how the system works and the availability of actionable scientific information.

Part One: Overview of the Lagoon Environment

1. Introduction

The Pescadero Lagoon Science Panel (PLSP) was established in 2013 to provide independent scientific expertise in support of management decisions and possible restoration actions for Pescadero marsh and lagoon. The PLSP focused on the physical and biogeochemical processes in Pescadero Lagoon, in the context of available aquatic habitat. Our primary aim is to provide a common scientific understanding of the system that can serve as a scientific foundation for management decisions going forward. Although there are multiple objectives for the lagoon/marsh system, which differ between stakeholders, we centered our attention on the annual mortality events that are the nexus of concerns expressed about lagoon management. Response to mortality events vary between those that favor a hands-off approach in the interests of allowing a more balanced ecosystem to develop and those that favor specific actions in the interests of addressing species of concern.

The PLSP focus is on the lagoon – the open water of the marsh/lagoon system – and thus we primarily address the habitats of lagoon inhabitants, most notably steelhead, but remain cognizant of other listed species (e.g., tidewater goby, red-legged frog, San Francisco garter snake, snowy plover) as well as other major concerns (e.g., road/town/farm flooding in winter). Attention was primarily given to the inter-related abiotic processes, such as mouth state, stratification, water levels and oxygen deficiency.

There have been many studies and reports written by different agencies, on different topics, and by different authors with little remedial action or management intervention in the two decades following a major restoration project in the early 1990’s. In the PMWG Forum report (CEMAR, 2010), the recent history of studies, actions and deliberations is reviewed – we use this report as a foundation for our report. Through that, we also base our report on earlier reports, including Curry et al (1985), PWA (1990), Swanson (2001) and ESA (2008), as well as published theses (Sloan, 2006; Smith 2009), the unpublished writings of Professor Jerry Smith, and input received through a series of webinars in late 2013 and early 2014 (Appendix 5).

Coastal estuaries and lagoons are known to be highly productive and they offer a wide diversity of habitats and microhabitats – some more marine, others in the marshes, and some more riverine. Further, conditions may vary dramatically not only seasonally but also from year to year, in response to interannual variability in river flow, mouth closure, and ocean productivity. Nevertheless, no one lagoon can be all things for all species – nor can any lagoon be expected to be the same every year. Populations that have evolved in these systems have an ability to weather the variability, presumably through a rich genetic diversity and/or an ability to respond to changing conditions, using some parts of the lagoon in some years and other parts in other years. This is not a constant environment and management cannot be built on that expectation. While management agencies need to find common objectives and develop a common strategy, they also need a common recognition that the system behavior is not easily predicted and cannot be designed to perform in a given way in every year. Nature has rhythms, but it's not a clock – seasonality in precipitation, waves, upwelling and tides combine in a seasonal habitat cycle that plays out differently each year.

This report is based on a synthesis of best available science (no primary research was conducted). However, it is not limited by what has been published – in developing this synthesis, we go beyond "scientifically established" concepts to offer our best-professional judgment, based on available data and insights on Pescadero Lagoon as well as our knowledge and experience from working in comparable systems in California and elsewhere. We try to be clear about what is based on published science and what is best-professional judgment. In addressing management actions at the end of the report we also address actions to alleviate information constraints, including monitoring and other strategies to strengthen support for key scientific ideas in parallel with on-the-ground action.

Following a description of the site (Section 2), we outline conceptual models (Section 3) for sedimentation, mouth closure, hydrology and water levels, seawater intrusion and salinity structure, and water quality. A synthesis view (Section 4) is written as a stand-alone piece, with specific attention to fish mortality events and recent changes in the lagoon environment. This is a prelude to a discussion of management actions (Section 5) and the conclusion (Section 6).

2. Description of Site

Site Overview

Pescadero Lagoon is located in San Mateo County, 60km south of the mouth of San Francisco Bay and 40km north of Monterey Bay. It is a bar-built estuary, with a mouth that closes intermittently when ocean waves deposit sand in the channel that connects estuary and ocean. Pescadero Lagoon includes lower Pescadero Creek and lower Butano Creek (Figure 1). River water mixes with seawater in the lagoon, which backs up during mouth closure periods. The lagoon is surrounded by intertidal marshes, an elevated marsh plain and marshes that form part of the river floodplain. Alluvial fans/deltas of Butano and Pescadero Creeks are building out onto these marsh surfaces.

Historically, most of the marshes were converted to agricultural lands and a part was developed as the town of Pescadero. In recent decades, marshes in the lower floodplain have been restored to natural vegetation. During periods of mouth closure the lagoon water level rises and may inundate surrounding marshes below the Pescadero Road bridge. It appears that during the late 19th and early 20th centuries water levels in the closed lagoon were higher (ESA

2004), due to a higher berm/dune closing the mouth. A more detailed description of the system is provided in Appendix 1.

Figure 1 *– Aerial view of Pescadero Lagoon, showing rivers/channels labeled in blue, road crossings labeled in yellow, and marshes labeled in pale orange (Google Earth)*

Lagoon-marsh systems like Pescadero receive floodwaters and sediment from the watershed. In an undisturbed state most sediment is deposited in the lower watershed and only residual sediment is carried onto marshes, where it is trapped by vegetation and deposited. As floodwaters subside, they drain out through fluvial and tidal channels, scouring the channels as they go. Lagoons also receive organic material from the watershed, accumulating this material and tending towards eutrophic conditions when not subject to rapid flushing. Also, in west-coast lagoons, intrusion of ocean waters is important, supplying nutrients and organic matter to the lagoon. During closure periods or when the mouth is shallow, a deep layer of seawater may be trapped in the estuary, under a low-salinity layer, with important impacts on water column productivity.

Species of concern

Pescadero Lagoon provides habitat for many species, some seasonal or migrant and others year-round residents that depend on the lagoon. Several species that use the lagoon, marsh or beach habitats have been listed under the Endangered Species Act. These include steelhead trout (*Oncorhynchus mykiss*), tidewater goby (*Eucyclogobius newberryi*), San Francisco garter snake (*Thamnophis sirtalis tetrataenia*), red-legged frog (*Rana draytonii*), Western pond turtle (*Actinemys marmorata*), and Western snowy plover (*Charadrius nivosus*). The habitat for each listed species has specific attributes: these are outlined in Appendix 2. However, in addition to species-specific needs, there are whole-system attributes that are also important, including net productivity, water quality, and biodiversity. In this report, our primary focus is on fishes that use the lagoon and the characteristics of their habitats.

Timeline of Environmental Change

Since the onset of ranching in the mid-1800’s, Pescadero Lagoon and Marsh have been impacted by minor and major system-wide perturbations. Present concerns include legacy issues related to watershed erosion over several decades. While logging of the watershed started earlier, intense landscape-disturbing timber harvesting did not develop until after the Second World War – and then it did not last long. Clearly, different generations perceive a different baseline, which has been shifting over the decades since the early 1800s. A broad view of change in the estuary, identifying epochs defined by different activities, change and symptoms is outlined in more detail in Appendix 3 to provide a reference timeline.

3. Conceptual Models

3a. Sedimentation.

Lagoon-marsh systems such as Pescadero formed in erosion-incised coastal valleys following post-glacial sea level rise. Over several millenia the flooded valleys accumulated sediment from both watershed and ocean. In Pescadero, a level marsh surface that extends to the town of Pescadero formed 2 to 3 meters above high tide – likely associated with frequent perched (high water) conditions in the lagoon. Substantial open water was present historically in the lagoon, either resulting from incomplete Holocene sediment filling following sea level rise (primary space) or from scour/removal of sediment by episodic floods, which are critical to the formation/rejuvenation of lagoon space on the California Coast (Jacobs et al, 2011). In the absence of such scour, lagoons fill with sediment and evolve toward marshes and terrestrial landforms. In parallel with infill and scour, creeks deliver and deposit sediment on the marsh plain forming natural levees and alluvial fans.

The modern Pescadero Lagoon/Marsh has experienced rapid accumulation of sediments derived from watershed and ocean. Although, sediment infill is a natural process in lagoons it is not necessarily continuous or unresponsive to human action. Two hundred years ago, prior to human disturbances, Pescadero Lagoon was much deeper, but it has progressively shoaled since then to become a shallow-water lagoon. Something like 5 million metric tons of sediment has been deposited in this marsh/lagoon system over the last one-and-a-half centuries (Frucht 2013), primarily as a result of sediment supply due to disturbances in the watershed and subsequent erosion (CBEC 2014) - and the loss of floodplain storage in the mid/lower watershed (Cluer and Thorne 2013). Three episodes of sedimentation are evident in the last 70 years: (i) in the mid 20th century aggressive logging practices in steep drainages destabilized slopes; (ii) sediment was mobilized in high-flow El Nino years of 1955 and 1982-1983; and (iii) following replacement of Hwy-1 Bridge and restoration that increased tidal prism (plus failure of tide gates), tidal influx of sediment has filled the lagoon near the mouth in what was the deepest part; these sediments have also significantly shoaled North Pond.

The large accumulation of sediment in this fluvial system has greatly altered the hydrologic, geomorphic, and subsequently, the ecologic functioning of the creeks, marshes and lagoon. In spite of the fact that land use activities that advance sediment erosion in the watershed have been reduced, compared with the period from 1850s to 1970s, enhanced fluvial sedimentation has continued in the last quarter century. This suggests that the legacy of earlier human activity in the watershed will continue, with excessive sedimentation and impairment of habitat in the lagoon/marsh system. Reduction in sedimentation following restoration of the watershed will take a long time, and even when sedimentation returns to pre-disturbance days, the sediment mass will remain in the marsh/lagoon system, accelerating a natural tendency for lagoons to evolve into marshes and marshes into floodplain meadows.

Sediment sources

Sources include hill-slope erosion of Tertiary marine sedimentary rocks including sandstone, shale, mudstone, and conglomerates. The majority of these rocks are mechanically weak and highly susceptible to landslides, debris flows, and gully formation. Weathering processes produce soils that are temporarily accumulated as colluvium and subsequently transported downstream via gully formation and episodic landslides, which typically occur during large storm events, which are more intense during El Niño years. Human activities led to an increase in hill-slope erosion and a two-fold increase in the total sediment delivered to stream channels across the watershed. Recent land use changes appear to have reduced this source.

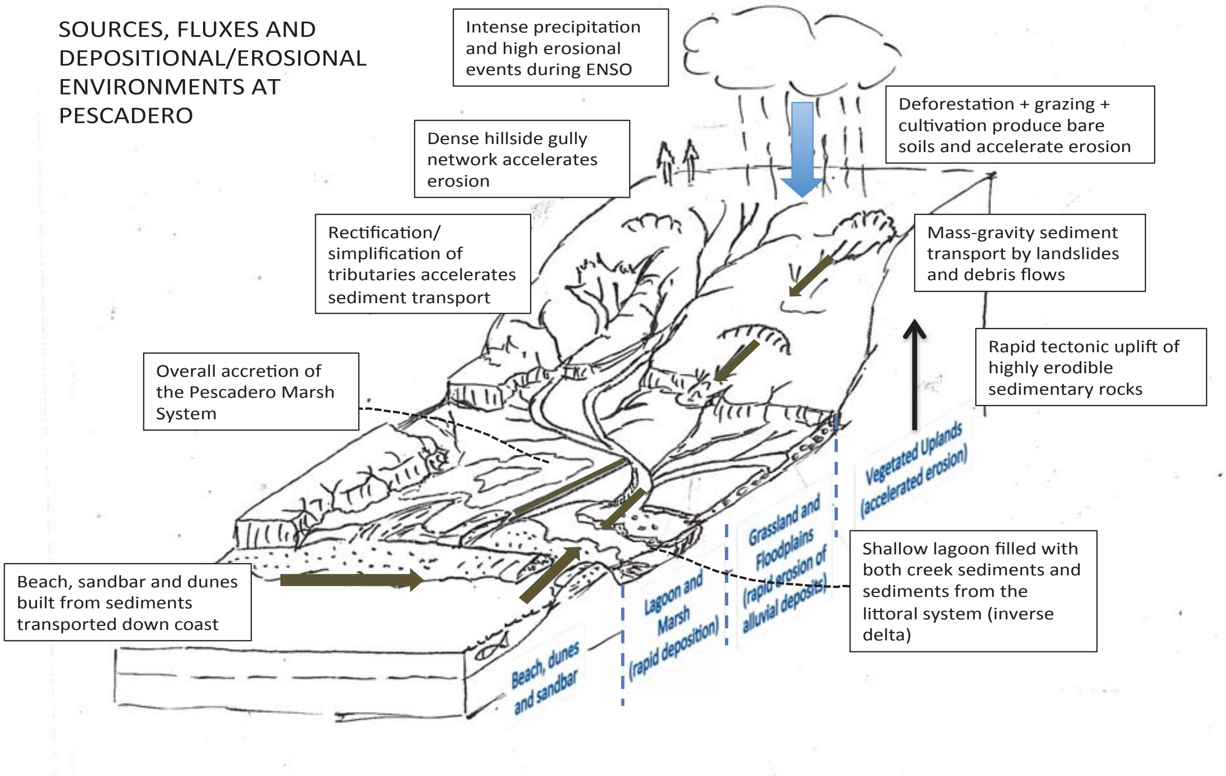

***Figure 2** – Schematic diagram of sediment erosion and deposition in the Pescadero watershed, river, marsh and lagoon.*

Another source of sediment is the channel erosion that is occurring in the lower Pescadero and Butano creeks. Both exposed bedrocks and alluvial sediment are being eroded, some of which was recently deposited. While swampy meadows and floodplains in the lower watershed (near the estuary) typically act as a sediment sink, the channelization of the Pescadero and Butano creeks in the late 1800s and early 1900s has turned previous sediment buffers into sediment sources – with deposition shifting downstream into the lagoon/marsh system. The channel in the lower Pescadero Creek has incised by 15 ft since 1860 (Trso, 2011), but accretion of 0.5 ft has been reported between 1987 and 2011 (Frucht 2013). The channel in the lower Butano Creek has incised by 25 ft since 1920 (Trso, 2011) and bedrock has become exposed recently so that the channel is now widening and eroding laterally into unconsolidated banks, most obviously since 2005. The potential for rapid lateral erosion of sand-size sediment poses a new sedimentation threat to the marsh/lagoon system as sand cannot be flushed from the inner lagoon by tidal action. Sediment yields from the Butano drainage have been much greater than from the Pescadero, and can be expected to continue, due to the erodible nature of the upper reaches and recent incision in the lower reaches (Frucht 2013).

Sedimentation in the Marsh/Lagoon

Pescadero Lagoon has been transformed from an open-water estuary into a shallow creek delta, with a loss of about 50% of its open-water area between 1900 and 1960. This trend has continued with the Pescadero Lagoon shoaling a further 1.3 ft over the last 25 years. The greatest accretion has been observed near the ocean, with 4-6 ft accretion of the flood-tide shoal since 1987. This flood-tide depocenter migrated ~300 ft inland from the Hwy-1 Bridge between 2002 and 2011. The marshes have also accreted. Between topographic surveys in 1987 and 2011, the East Butano Marsh accreted between 0.5 ft and 1.3 ft and the North Pond has accreted ~1ft on average, while no accretion was observed in North Marsh.

This accretion in the lagoon/marsh system is primarily due to upland changes as outlined above, and understood to be a consequence of (i) increased sediment input from the upper watershed, (ii) elimination of sediment storage in alluvial valleys, i.e., swampy meadows and floodplains, (iii) elimination of channel-floodplain connectivity, and (iv) dredging, diking and other man made structures restricting the water flow.

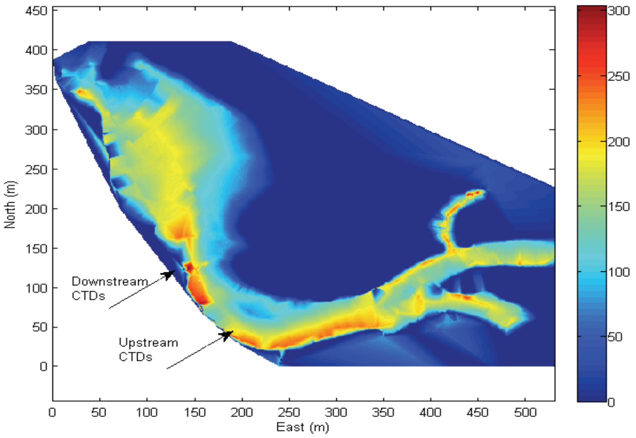

Figure 3 *– Approximate bathymetry starting at Hwy-1 Bridge along upper left boundary and extending to confluence of Pescadero and Butano Creeks (lower right: 400m East and 100m North). Figure from Williams (2014). Depth in centimeters relative to mean sea level. Positions of CTD instruments shown (data plotted in Figures 4 and 9).*

Changes have also occurred at the seaward end of the lagoon, where accretion and landward growth of the flood-tide shoal has been observed and the seasonality of mouth closure may have changed (see Section 3b). Concurrent with the growth of the flood-tide shoal (“inverse delta”, Figure 2) and seasonal delay in closure is a landward movement of the deepest part of the lagoon from close to the Highway-1 Bridge in the 1980s to about 1000 ft southwest of the bridge at present, on the outside of the first major curve in the channel (Figure 3: Downstream CTD). The greater incursion of marine sediments into the lagoon and changes in mouth closure are expected to be due to changes in sediment supply along the coast and/or changes in sand transport processes in the channel connecting the lagoon and the ocean (i.e., the “lagoon mouth”). Much of the seabed offshore of Pescadero is bare rock, so that there is little source material offshore and the supply of marine sediments to Pescadero is likely due to longshore transport from San Francisco Bay and coastal drainages like San Gregorio Creek (Edwards 2002). The Vaqueros Sandstone rocky promontory at the mouth of Pescadero Lagoon plays an important role in trapping this longshore transport of sand, forming a pocket beach and ensuring adequate sand to close the mouth seasonally. However, if San Francisco Bay is the primary source of longshore sediments, this suggests a decrease in sediment supply, as there has been a recent decrease in sediment efflux from San Francisco Bay, at the tail end of the sediment pulse that was exported from the Bay following hydraulic mining (Barnard et al 2013). In parallel, pertinent changes in the lagoon include changes in the volume of the tidal prism due to accretion and also the 1990 restoration, changes in freshwater inflows due to water extraction, and construction of the new Highway-1 Bridge in 1991. Also, sedimentation in the lagoon or on the marshes driven by fluvial processes, as described above, alters tidal processes that in turn can also alter mouth sedimentation. Mouth closure is addressed in more detail below (Section 3b).

3b. Mouth closure.

As in most other California estuaries, a barrier of sand is built between Pescadero Lagoon and the ocean by wave action (known as a “berm”). In smaller estuaries like Pescadero, the berm may build across the mouth and close the estuary off from the sea. This usually happens during the dry season and breaching of the berm usually happens during the wet season when the lagoon fills up and overflows, leading to scour of a new channel between lagoon and ocean and the return of tidal action and seawater intrusions to the estuary. The natural timing of closure and breaching depends on changes in wave forcing (builds sand berm), river flow (fills lagoon with water; erodes channel through berm), and tidal currents that depend on the tidal prism volume (maintain channel through berm by erosion). While a seasonal cycle of summer closure and winter breaching is typical, some estuaries may experience several cycles in a year (e.g., Russian River estuary – Behrens et al 2009, 2013) and other estuaries may remain in open or closed state for longer than a year before transitioning to the alternate phase (e.g., Estero Americano, unpublished data).

Pescadero Lagoon is formed by a beach and dune system that dams the Pescadero and Butano Creeks and results in accumulation of water in a broad valley. During the dry summer and fall, if the mouth closes, inflow is inadequate to overfill the lagoon and the mouth is likely to remain closed. During wetter seasons, inflows will fill the closed basin and overflow at the lowest point in the berm. At times the lagoon water rushes out with enough speed to scour a deep channel such that the bed is below high-tide water levels – resulting in tidal inflow during the next high tide and the return of tidally reversing flows through the mouth (e.g., November 2011: Figure 4). The deeper the inlet channel, the stronger the tidal flows to/from the lagoon, the greater the scour of the mouth channel, and the greater the tidal signal in water level in the lagoon. In its present configuration, this low point in the berm always occurs at the south end of the beach (in line with Hwy-1 Bridge), where the sandstone outcrop shelters the beach from wave-driven sand deposition.

At other times, overflow from the lagoon may be weaker, unable to erode a deep channel through the sand barrier, and a shallow overflow channel develops. The barrier remains intact and the water level in the lagoon is maintained above high-tide levels so that no tidal signal is seen in the lagoon (known as a “perched estuary”). This overflow channel typically develops adjacent to the rock outcrop, protected from wave action, and it may persist for extended periods. Eventually a perched state may give way to an open tidal state if the channel outflow strengthens and erodes a deeper channel – or it may transition to a fully closed state following a wave event that deposits sand in the mouth and builds the height of the berm adjacent to the rock outcrop. A perched estuary may also close following reduction in river inflow so that the estuary water level drops below the channel bed elevation. The mouth of Pescadero Lagoon can also be opened by humans digging a channel (“manual breaching”) – this may lead to fully open conditions or the mouth may close again after a few days, depending on the wave/tide/river conditions at the time of breaching.

The interplay of wave, tide and river influences have been explored in many studies, most recently reviewed and advanced by Behrens et al (2013) for closure events at the mouth of the Russian River estuary and by Rich (2013) for natural breach events at the mouth of the Carmel River estuary. Where watersheds are small, strong winter flows are likely to drop off quickly in spring, before wave energy decreases. In such systems, if the tidal area and associated tidal prism in the estuary is also small, then flow through the inlet will be too weak to remove sediment deposited by wave action and the mouth is likely to close in spring (Goodwin 1996). In most cases, these small estuaries will remain closed all summer; only breaching again with the arrival of winter rains at the end of the year (“spring closure estuaries”; e.g., Salmon Creek, Prunuske Chatham 2006). However, in estuaries with a small estuarine floodplain area there is insufficient storage volume and even weak inflow from the watershed may overfill the basin and the mouth may breach soon after closure. This scenario occurs also where a rocky outcrop shelters a portion of the beach from wave action, resulting in a low berm at the mouth that is easily overtopped. In these smaller systems, one may see a repetitive cycle of closure and breaching (e.g., Scott Creek, Nylen 2014), at times exacerbated by manual breaching to prevent flooding of low-lying structures (e.g., Russian River during fall). Alternatively, where watersheds are larger, strong flows may continue into early summer, by which time wave action has decreased and even weak tidal action and/or weak freshwater inflow may keep the mouth open, so that closures occur only in late fall when wave energy increases again (“fall closure estuaries”, e.g., Russian River, Behrens et al 2013). In some lagoons the mouth never closes as the tidal prism is large enough and/or the mouth is sheltered from waves (e.g., Bolinas Lagoon).

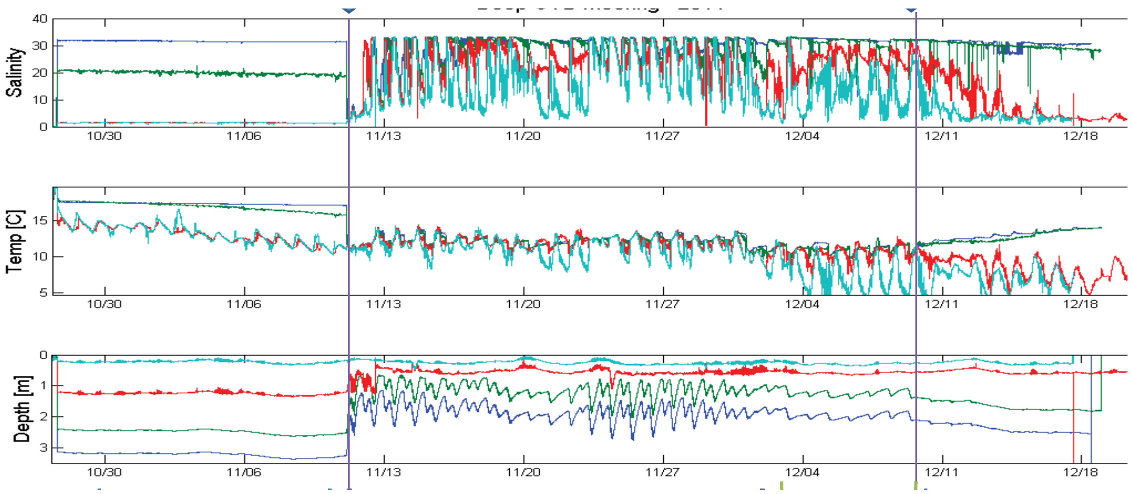

Figure 4 *– Salinity, temperature and depth in Pescadero Lagoon from 28 October to 20 December 2011, at site 100m SE of Hwy-1 Bridge ("Downstream CTD" in Figure 3). The deepest sensor (blue line) is fixed near-bottom and uppermost sensor (cyan line) is floating near-surface; the deeper mid-depth sensor (green line) is attached to the anchor whereas the shallower mid-depth sensor (red line) is attached to the surface buoy. Top panel shows salinity data, middle panel shows temperature data, and bottom panel shows depth of the sensor. The deepest sensor gives total water depth: a 1.5m drop in water level is observed following breaching of the sandbar on 11 November. Tidal conditions in late November transitioned to perched/closed conditions in mid-December, with increasing water level. Data provided by M. Williams and M. Stacey, UC Berkeley.*

Pescadero Lagoon typically closes once a year for a prolonged period during the dry season (Figure 5); and in some dry years a brief closure also occurs in late winter (February-April). Prolonged seasonal closures appear to alternate between spring closures (mouth closes in April-June) and fall closures (mouth closes in September-November), with seasonal breach events typically occurring with the onset of rains in November or December. While it has been suggested that a change to fall closures happened in the 1990s, there is inadequate data prior to 1990 to assess this change or the drivers of change (e.g., spring closures were usual during the 1987-1992 drought). The recent 11-year series of fall closures 2002-2012 (interrupted only by the 2013 drought) may be due to greater freshwater inflow, weaker wave action in spring, a larger tidal prism, or limited availability of beach sands – all factors that can preclude spring closures. Multi-year droughts also influence mouth dynamics, as in 2013, 2014 and 2015 when the mouth closed early. In 2013 the mouth closed in May and it did not breach until February 2014. In 2014, it closed in March and breached in December. In 2015, it closed in July and again breached in December. In all years there were brief closures in late winter (April 2013, February 2014, March 2014, April 2015).

When the sand barrier at the mouth is breached, lagoon waters rapidly drain to the ocean. Different types of breach event can occur, based on the strength of outflow and scouring of the sand barrier, which depend on the river inflow rate and the water-level difference between lagoon and ocean at the time of breaching. With weak outflow, the barrier will be only partially breached, and a perched state will ensue without allowing tidal inflow. With moderate outflow, the barrier will be scoured more deeply, allowing limited tidal intrusions of seawater. The most energetic outflow events will result in deep scour of the mouth, full flushing of the lagoon and strong tidal exchange.

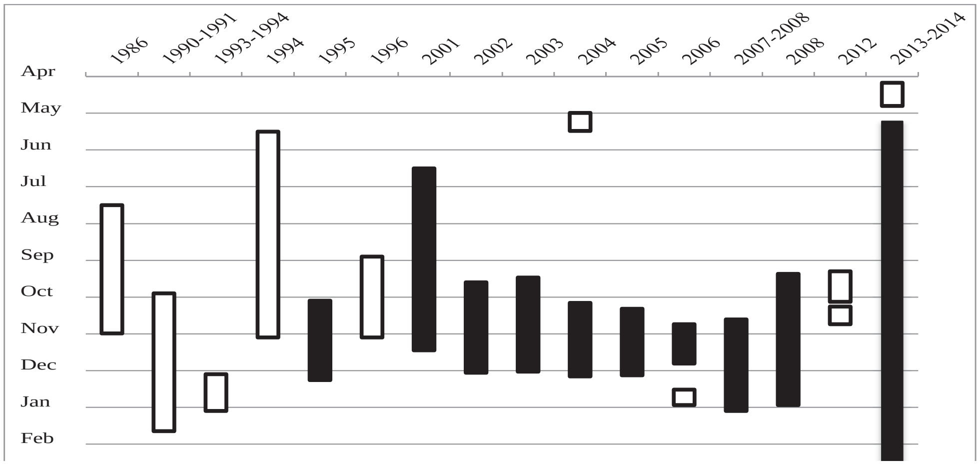

Figure 5 *– Record of closed mouth periods from 1986 to 2013 – bars represent times when there is no surface-water connection between lagoon and ocean. Filled bars indicate closures that resulted in fish kills, and open bars indicate closures for which there are no reported kills. Data from Smith (2009), plotted by Volpi (2014).*

Changes in mouth morphology and closures

Changes in the Pescadero lagoon/marsh system over recent decades include the 1993-97 restoration, replacement of the Highway-1 Bridge in 1991, and ongoing fluvial sedimentation. Changes due to water extraction (reduced freshwater inflow) and climate change (freshwater inflow, waves, winds) are not well documented and difficult to evaluate in terms of mouth closure, as well as their influence on water levels and water quality in the lagoon (see Sections 3c and 3e). The most likely explanation for a shift to fall closures is an increased tidal prism following the restoration actions that improved hydrological connectivity to North Pond and North Marsh – and further enhanced in the last decade as the tide gates no longer close. ESA/PWA (2011) estimates that the tidal prism increased from 55 acre-feet in 1990 to 60 acre-feet in 2011, which may have been larger immediately post-restoration and before accretion over the last two decades. While this may be sufficient to tip the balance so that tidal currents can keep the mouth open during spring in most years, there are no analyses to support or counter this idea. However, the growth of the flood-tide shoal suggests an increase in the strength of tidal inflows, or at least of the influx of sediments due to tide and wave forcing (an increased tidal prism would enhance flow speeds and flood-dominant landward sediment transport in shallow tidal areas). The shoal expansion may also be associated with the change in bridge design in 1991, so that the bridge no longer blocks sand transport from the beach into the lagoon and thus promotes the formation of overwash/flood-tide deposits that are evident in aerial images on the north side of the channel (Figure 6). Due to development of this flood/overwash bank on the north side, the ebb-tide channel follows the south bank closely, where it enters the ocean alongside the sandstone outcrop. This rock outcrop thus protects the mouth from the full force of waves, reducing the tendency for closure – specifically, the mouth is protected from south swell, which is the probable direction of beach-building waves in summer. Further, the growth of the flood-shoal results in a broader sand barrier between lagoon and ocean, which is an impediment to breaching: lagoon overflows form a longer channel to the ocean, which results in greater frictional loss and lesser channel slope that together greatly reduce the likelihood of vertical scour. Transition to an open mouth with significant tidal action (that in turn can keep the mouth open) is now less likely. Downcutting of the mouth channel may also be restricted by the presence of a shallow rock sill at the South end of the beach, which acts as a grade control and serves to create a broad shallow channel with slower flow speeds.

Figure 6 *– Aerial images of Pescadero mouth on 19 May 2007. Note the lobe of sand extending landward under the Hwy-1 Bridge as a subsurface flood-shoal. Photos courtesy of Rusty Holleman.*

Clearly the dynamics of mouth closure are complex and involve many factors and feedbacks, making behavior difficult to predict. Indeed, tidal inlets are known for non-linear dynamics and "free behavior" in which the shape of the mouth may change dramatically even in the absence of specific forcing/disturbance but rather from complex feedback interactions (Clarke et al 2014). Here is a good example of "shifting baselines": there is a tendency to see the state of the mouth in recent decades as a true baseline when in fact it may have been very different to how it was several decades or a century ago. Our earliest views of the mouth are from 1855 T-sheets and anecdotal records. From a review of these, plus later photographs and aerial imagery, it is apparent that seasonal closures were common, but also more open conditions during high streamflow and muted tidal conditions at other times. Multi-year closures have occurred during low streamflow, as in the 1897-98 drought (ESA 2004), when streamflow was insufficient to breach the beach/dune dam and high water levels developed in the lagoon, inundating agricultural fields and threatening the town. It is also evident from the T-sheet that North Pond is a scour feature associated with an alternative northern mouth – an observation corroborated by recent sediment coring (Clarke et al 2014; Aiello unpublished data). This northern mouth is now precluded by the presence of the Highway-1 roadbed.

3c. Hydrology and water levels.

The low-lying estuarine areas between the beach and uplands fill up with water from the ocean and the rivers. Inflows and outflows to/from the lagoon control the water level and inundation of marshes and low-lying human infrastructure, as well as the strength of currents and the transport to/from the lagoon.

Ocean waters flow in and out with the tides, controlled by tidally fluctuating sea level and the width/depth of the channel through the sand barrier that constrains the mouth of the lagoon.

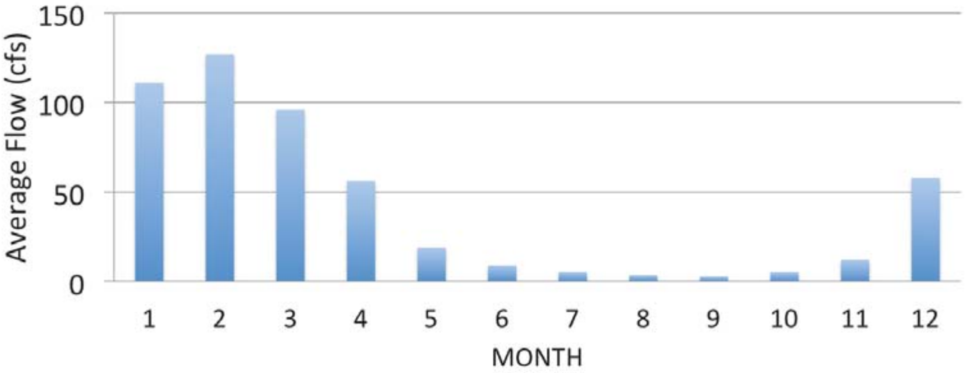

***Figure 7** – Mean monthly flow in Pescadero Creek recorded at USGS gage over 52-year period from 1951 to 2013. Data from website: waterdata.usgs.gov/nwis/ uv?cb_00060=on&cb_00065=on&format=gif_default&period=31&site_no=11162500*

Freshwater Inflows

Pescadero Lagoon receives freshwater inflow from Pescadero Creek and Butano Creek. Discharge from these relatively small watersheds is highly variable, following precipitation that varies from day to day through the wet season, as well as seasonally and between years. The Pescadero watershed (45.9 mi^2) is about twice the size of the Butano watershed (21.2 mi^2), and produces 59% of the streamflow (Curry et al 1985). Annual runoff at the USGS Pescadero gauge, which is above the confluence with the Butano, varied by two orders of magnitude over 50 years (1952-2011), from 1.5 to 147 million m^3 (1250 to 119,000 AF). Mean annual runoff from this watershed is 35.8 million m^3 (29,000 AF), which corresponds to a mean annual runoff to Pescadero Lagoon of 61.6 million m^3 (51,000 AF) or mean inflow rate of 69cfs. Peak flows occur in winter, with strongest flows expected in January-March (Figure 7). Maximum daily flow in Pescadero Creek exceeds 1000cfs in most years (and exceeded 10,000cfs in 1998). September monthly mean flow is less than 3cfs (Figure 7), but in dry years the monthly mean flow can drop below 1cfs in June-October. The amount of water extracted in the watershed is unknown, and inflows to the lagoon during dry periods may be significantly lower than at the USGS gage, which is well upstream of agricultural activity in the vicinity of the town (*waterdata.usgs.gov/nwis/*).

Hydrologic balance when mouth closed (dry season)

When the mouth of the lagoon is closed, freshwater flows into the lagoon from Pescadero and Butano Creeks and seawater may also flow in at times due to wave overwash at high tide. Water leaves the system slowly by evaporation and by seepage through the sand berm. Seepage is driven by a pressure gradient between the lagoon and the ocean, due to higher water levels in the lagoon. This pressure gradient pushes water through the sand at a rate that increases as lagoon water level rises. Preliminary work has been done by Volpi (2014), but the rate of seepage flow has not been quantified – it is thought to be low in the case of Pescadero due to the bedrock sill across the mouth, and it has likely decreased over the last couple of decades with landward growth of the flood-tide shoals (Sections 3.1 and 3.2). When the mouth is closed, water surface elevation (WSE) in the lagoon changes slowly (Figure 4). However, even during weak freshwater inflow during the dry season, the water balance is usually positive and WSE gradually increases to a quasi-steady maximum, when seepage plus evaporation balance inflows. If freshwater inflows increase for a short period, the lagoon may overflow the sand berm without breaching it. When the mouth is closed, maximum WSE is typically about 2.8m above MLLW (Figure 8), although it reached 3.42m MLLW during a very long closure event in the 1977 drought – and may have been higher during 19th century events (ESA 2004). When the water level is 2.8m MLLW, most of the marshes are inundated to a depth of 0.2-0.4m. If the water balance is negative during closures, the WSE will decrease. While this is less common in Pescadero Lagoon, it was observed in late 2013 as the dry season extended into winter months due to the absence of seasonal rains. WSE decreased also in 2014 (summer) and marginally in 2015.

Hydrologic balance when the mouth open (wet season)

During typical open conditions (low/moderate streamflow), fresh water flows into the lagoon from Pescadero and Butano Creeks, and seawater flows into the lagoon from the ocean with the flooding tide. Mixed waters flow out of the lagoon during ebb tides. Williams (2014) found that inflow to Pescadero may be enhanced by pulses of infra-gravity waves (period ~2min) that are created by the interaction of ocean swell with nearshore topography adjacent to the lagoon mouth. The importance of ocean swell, wave setup and infra-gravity waves is due to the shallowness of the lagoon mouth, which limits tidal forcing even in the open state. While WSE maxima are primarily controlled by ocean tides when open, WSE minima are primarily controlled by the elevation of the bed of the mouth channel. Typically WSE ranges from 0.8 to 2 m MLLW in the lagoon, but

WSE also responds to storm surges when high tide elevations may be up to 0.4m higher than normal due to wind and/or wave effects. Average WSE is 1.1 to 1.4m MLLW – much less than during closure periods (Figure 8). When the mouth is open, marshes are inundated only during extreme high tides enhanced by storm surges.

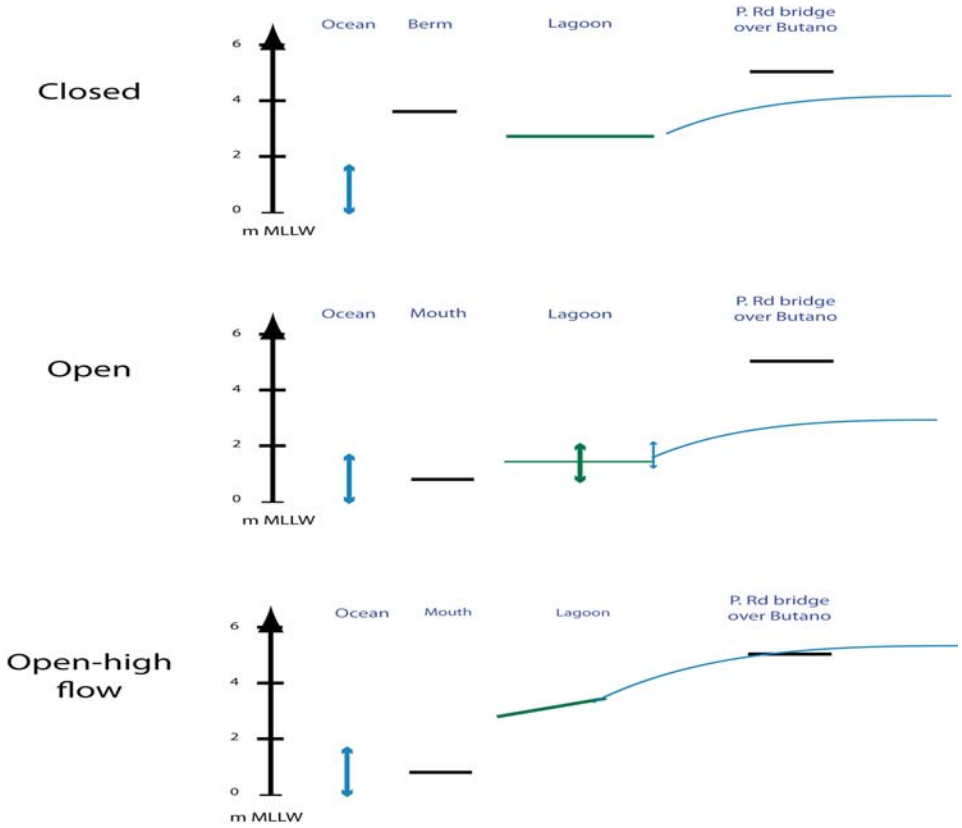

Figure 8 *– Schematic of water surface elevation (WSE) in the lagoon and berm height for the three hydrological states discussed in the text (closed, open, and open with high river flow). Also shown is the height of the Pescadero Road Bridge over Butano Creek.*

During high streamflow events, the rate of outflow is limited not only by the berm but also by bedrock at the base of the lagoon’s outlet channel, which appears to form a hydraulic control, backing up water in the lagoon. As a result, WSE is elevated during extreme stream flow, regardless of tidal stage. In effect, the entire lagoon functions as part of the lower river/floodplain (Figure 8). For example, US Army Corps of Engineers backwater modeling predicts water levels of 5.85m MLLW in a 100-yr flood, which is 1.3m above the elevation of the bridge over Butano Creek (elevation 4.55m MLLW). In the 1955 flood (20-yr return interval), WSE in the lagoon was 3.53m MLLW, which is higher than the maximum WSE observed during mouth closures.

In summary, high WSE in Pescadero Lagoon and associated inundation of marshes may occur naturally under three scenarios: (i) high sea levels due to tides, storm surge and sea level rise; (ii) damming of the lagoon by a sand berm across the mouth, and possibly by wind-built dunes in earlier times; and (iii) strong river flows that are backed up due to restricted flow out through the mouth. The third scenario has also caused flooding of Pescadero Road and the town of Pescadero on numerous occasions, but this flooding has not occurred as a result of the first two scenarios (although sea level rise may change that in the future).

3d. Seawater intrusion and salinity structure

Both fresh water from the land and saline water from the sea are retained in Pescadero Lagoon, at times mixing and at other times forming two distinct layers. The salinity structure in Pescadero Lagoon is strongly tied to mouth state and oceanic forcing, as well as to freshwater inflow. Here we consider separately times when the mouth is open, closed or transitional (breaching). Although there is a continuum of states between “open” and “closed”, we discuss the end members here to provide a conceptual framework with which the intermediate states can be interpreted.

Open Mouth State

When the mouth of the estuary is open, transport of salt from the ocean to the estuary is driven by tides, storm surge, ocean swell, and infra-gravity waves (Williams 2014). Wave-driven inflow contributes significantly to the transport of salt into the estuary, such that more seawater is expected to be transported into the lagoon during times of larger waves (swell or infra-gravity) as well as during wind-driven storm surges. Seawater typically enters the estuary in the form of a salt wedge, often exhibiting a plunge line as it drops below freshwater landward of the shallow mouth and flood shoal (Largier 1992). A sharp salinity gradient (or front) is advected landward on the flood tide and then back seaward during the ebb, with a high-salinity layer beneath a sharp halocline (interface between high-salinity bottom layer and low-salinity surface layer). The salt wedge typically exhibits near-oceanic salinities (~33 psu) and the surface layer is nearly fresh water (~0 psu), with the halocline much less than 1m thick. As the salt wedge intrudes and retreats tidally, many estuary habitats experience a full range of salinities in each tidal cycle.

The structure of the salt wedge changes from flood to ebb tide, with a sharper and more vertical structure on the flood (Figure 9d) that diffuses longitudinally and becomes more horizontal on the ebb. The diffusion of the salt front within the estuary is driven by a combination of tidal trapping in the upper estuary (some high-salinity waters are trapped in upper estuary) and vertical shear dispersion. Thus the longitudinal gradient of salt is strongest and highly localized during the flood tide as the salt wedge intrudes landward, it is weakened during early ebb as the wedge moves back downstream, and then it is further weakened late in the ebb when saline water retained through tidal trapping in the upper estuary moves back down into the body of the estuary.

In the open state, the salt content of the estuary responds to changes in oceanic forcing, primarily spring-neap variation in tides but also changes in ocean swell and the associated forcing of the infra-gravity waves. During neap tides, transport out of the estuary is reduced, particularly in the lower layer where saline waters are retained through the ebb and bottom salinity can remain persistently high for a week during the neap-tide period. During spring tides, the estuary returns to the oscillatory salt wedge described above.

Closed Mouth State

When the mouth of the estuary is closed, tidal inflows are blocked by the sand barrier and the only way for seawater to enter the lagoon is via wave overwash, which can occur when large ocean swells/infra-gravity waves coincide with spring high tides and/or storm surge. At the same time, there is very limited salt flux out of Pescadero Lagoon, which may occur as seepage through the sand barrier in other California coastal lagoons but appears to be blocked here by shallow bedrock and a broad sand barrier. Thus a layer of high-salinity water collects at depth in Pescadero Lagoon, primarily in the deepest part between the Highway-1 Bridge and the Pescadero-Butano confluence.

The closed period is characterized by extremely strong vertical stratification, and freshwater inflow to the lagoon remains on top of the high-salinity lower layer, thickening the low-salinity surface layer. Mixing of surface and bottom water masses is limited owing to the strong vertical stratification – and the stability of this two-layer structure increases as the surface layer thickens. During the closed period, mixing can only be driven by winds acting on the surface. While strong afternoon winds may tilt the surface and interface (halocline) sufficiently to upwell dense and salty bottom water (as in a salt-stratified lake), the salinity structure relaxes back to a stratified state as soon as the wind subsides. The observed net mixing is limited (5-10% of the stratification may be eroded by a large event) and any decrease in stability is more than compensated by new inflows of fresh water from the watershed and seawater inflows during wave overwash events. As the dry season progresses, the winds weaken and the surface layer thickens, increasing the two-layer stability. Thus, the strong salinity stratification in Pescadero Lagoon typically persists through the entire closed state.

Transition from Closed to Open State

When the sand barrier at the mouth is breached, lagoon waters rapidly drain to the ocean (Section 3b). The effect of the breach on salinity structure depends on the depth of scour of the mouth channel relative to the halocline depth, as well as the strength of outflow currents in the lagoon. The weakest breach will allow the surface layer to flow out without disrupting the lower layer, and without allowing for tidal action (i.e., mouth in perched state; e.g., February 2014). While a moderate breach may still leave the lower layer intact, subsequent tidal inflows and seawater intrusions can flush out high-salinity waters at depth (Slinger et al 1995). The most energetic breaches mix across the stratification and flush out the deep saline waters with the near-surface low-salinity waters – typically during strong river flows (e.g., 21 January 2012, Figure 9).

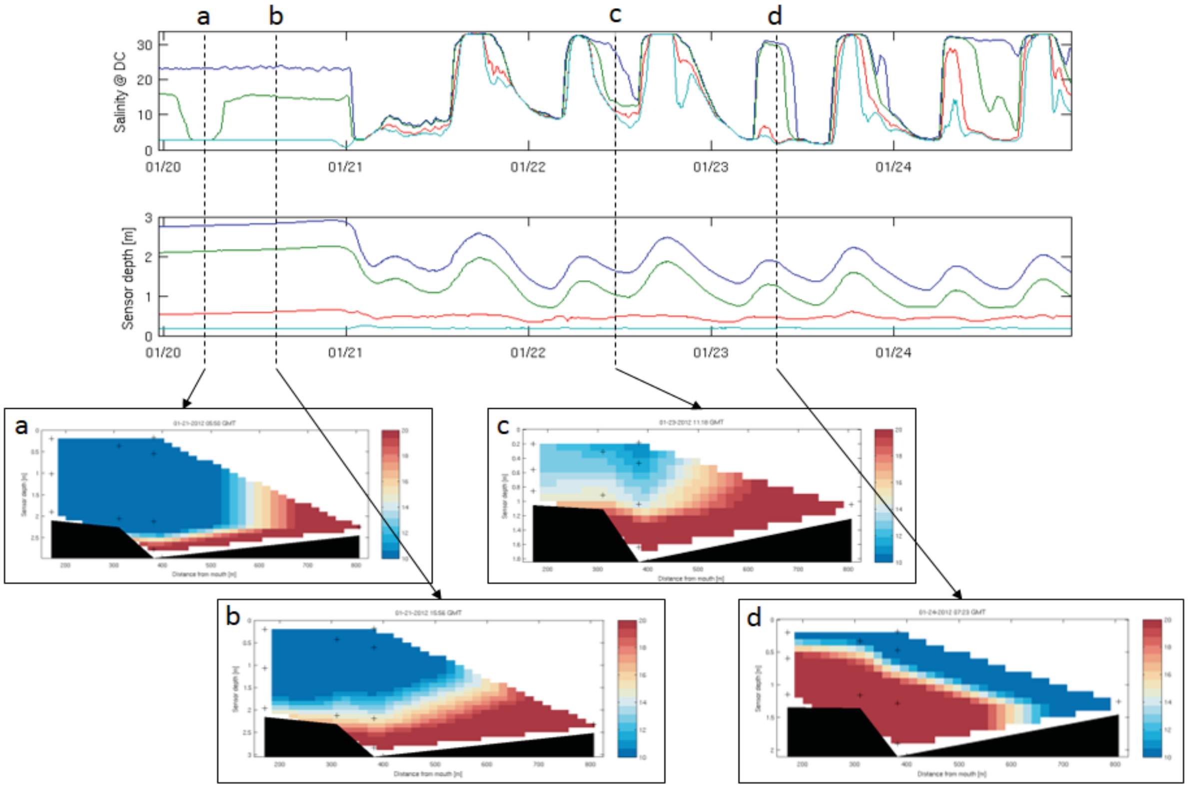

Figure 9 *– Upper panels: Salinity and depth in Pescadero Lagoon from 20 to 24 January 2012 at site 100m SE of Highway-1 Bridge ("Downstream CTD", Figure 3). The deepest sensor (blue line) was on the bed and uppermost sensor (cyan line) was floating near-surface; the deeper mid-depth sensor (green line) was attached to the anchor whereas the shallower mid-depth sensor (red line) was attached to the surface buoy. Breaching of the sandbar is seen as a 1m decrease in water depth on 21 January (blue and green lines), followed by tidal intrusions of high-salinity waters. Lower panels: Longitudinal salinity structure between mouth (on left) and confluence (on right) – salinity ranges from 10 (blue) to 20 (red). (a) Closed state with wind-induced upwelling/downwelling. (b) Closed state at rest. (c) Open state during ebb tide. (d) Open state during flood tide. Data provided by M. Williams and M. Stacey, UC Berkeley.*

The dynamics of breaching have not been adequately quantified to date, but ongoing studies of hydrodynamics in Pescadero Lagoon (Williams 2014) are providing new insight to how breaching events play out, and which factors are most important in determining flushing of the lower layer and whether it occurs suddenly or slowly over a few tidal cycles. In addition to the dynamics, the fate of the flushed lower layer is important – key differences in water quality will depend on whether the lower layer is exported immediately to the ocean or whether it is flushed during an incoming tide and advected landward or flushed late on the ebb tide and retained in the lagoon over the subsequent tidal cycle. At this stage, this information is not available, but retention of water in the lagoon likely plays an important role in the persistent hypoxia observed following breach events (see Section 3e).

3e. Water quality

Recent fish mortality events in Pescadero Lagoon immediately following breach events are attributed to poor water quality – specifically conditions associated with low levels of dissolved oxygen in the water. Given the paucity of information on contaminants in the lagoon, we cannot assess their role, although they are a possible contributing factor in mortality events. Attention is given to the following variables that reflect the major chemical and biological reactions associated with hypoxia/anoxia in Pescadero Lagoon:

- Salinity, described above
- Dissolved oxygen (O_2) as DO
- pH of water, marsh soil and estuarine sediment
- Redox potential
- Sulfur (S), including sulfate (SO_4^{2-}), a soluble and non-toxic form, and sulfide (H_2S or HS^-), which is typically insoluble and toxic, and that can form precipitates with Fe; H_2S dominates at pH<7, HS^- dominates at pH>7
- Iron (Fe), including ferric iron Fe(III), an insoluble form, and ferrous iron Fe(II), a soluble form that can form precipitates with sulfides.

Typically the water column in coastal lagoons is oxygenated, such that oxidized compounds are found in the water column and in most cases levels of dissolved oxygen are high enough to support healthy fish populations (DO > 5mg/l). In some highly stratified systems, however, if sufficient biological oxygen demand (BOD) is found in the lower layer due to oxidizable organic matter, dissolved oxygen can be lowered to hypoxic (DO < 2mg/l) or even anoxic levels (DO < 0.5mg/l). Low-oxygen events typically occur in bar-built estuaries during closed or perched conditions, and these events may be exacerbated by changes in organic loading (oxidizable organic matter), or by changes in lagoon hydrology (inflows) and morphology (mouth closure; channel depth) that affect stratification and retention, or by changes in light penetration that affect sub-surface photosynthesis (which produces DO). Although hypoxia/anoxia occurs naturally in bar-built estuaries (e.g., Russian River estuary: Largier & Behrens 2010; Hewett 2015), there are global reports of expanding “dead zones” in estuaries and ocean where eutrophic river outflow leads to concurrent stratification and BOD loading in estuarine and coastal waters (Diaz & Rosenberg 2008). This raises questions whether human activity in the watershed has led to worsening of lower-layer anoxia/hypoxia in bar-built estuaries.

In contrast to the water column, conditions in muddy sediments are typically anoxic due to the inability of atmospheric or water-borne oxygen to be transported into the sediment beyond the depth of burrowing fauna. Here reduced compounds are found. If these reduced compounds are released into the water column, they represent a chemical oxygen demand (COD) that acts much more rapidly than BOD: seconds to hours instead of hours to days (Smith 2009). COD may enter the water column either through resuspension of bottom sediments due to energetic flows (or slowly via diffusive sediment-water fluxes), or through drainage of interstitial waters from marsh sediments into lagoon channels during low WSE (typically marked by the black color of FeS, turning to orange as it is oxidized to ferric iron).

Thus two anoxic environments may develop in estuaries where oxygen transport is inadequate to meet oxygen demand due to chemical and biological processes: (i) in the lower layer in a highly stratified water column, and (ii) in muddy sediments below the depth of burrowing. In bar-built estuaries, the two may combine where a dense saline layer fills a deep section of the estuary. In addition to BOD imported with seawater, this lower layer can be dark (precluding oxygen generation through photosynthesis) and it can slowly accumulate additional BOD through organic particles, dying phytoplankton and flocs settling out of the over-flowing surface layer. If BOD is sufficient, this lower-layer sump becomes anoxic and the reduced conditions typical of sediment anoxia may expand upward to fill the water column below the halocline. In contrast to cohesive muddy sediments that are difficult to resuspend, this lower layer and accumulated epi-benthic monosulfidic ooze represents a large source of high-COD that is released quickly when stratification breaks down and turbulence contacts the bed (cf., Johnston et al 2003) – typically following a breach event.

Open Mouth State

Inflow to and outflow from the lagoon occurs readily during the open-mouth state, without retention of oxygen-demanding organic matter in the water column and also ensuring a ready flux of oxygen from the atmosphere to all depths in the water column. Stratification associated with salt-wedge intrusions is transient and resident bottom layers are observed only briefly, if at all. The water column remains oxygenated. Thus, oxidation mechanisms predominate, including sulfur oxidation and iron oxidation, replenishing the pools of ferric iron and sulfate. However, marsh drainage leads to high COD and sulfide oxidation, so that conditions can still be strongly reducing and anoxia can occur in the landward parts of the lagoon during ebb tides when marshes drain into lagoon channels.

Closed Mouth State

When the lower layer is trapped by a closed mouth and strong stratification (Section 3d), BOD due to heterotrophic bacteria breaking down organic matter results in consumption of dissolved oxygen, which is not replenished owing to an absence of vertical mixing. DO decreases steadily over time, and anoxia may develop in the lower layer (hypolimnion) – and it can persist until the sand barrier is breached. As a consequence, chemical reactions such as ferric iron reduction, sulfate reduction and precipitation of iron sulfide minerals prevail in the lower water column as well as in the sediment. Not only is DO absent, but toxic hydrogen sulfide can accumulate, with observations of H_2S concentrations that exceed the US EPA acute toxicity concentrations more than 2,000 times. The degree of water quality degradation varies, with most extreme values being observed in the Butano Channel, and higher values of H_2S being observed the longer the system is closed (Richards 2016). On the marsh plain, if the water level is high enough to cover the marsh, DO levels fluctuate day and night, with low values at night being replenished by the effects of photosynthesis during the day (Beck & Bruland 2000). Although water over the marsh may be oxygenated, interstitial waters and waters trapped beneath mats of vegetation are anoxic. If the lagoon water level is below the marsh plain, then these anoxic waters slowly drain from the edges of the marsh. This drainage is expected to be more persistent as a result of accretion in the main Butano Creek channel together with removal of dikes that now allow creek inflow to inundate the Butano Marshes (Figure 1), which are at lower elevations than the creek bed (CBEC 2014). It is expected that this inflow will maintain a higher water table and hydraulic gradient in the marsh so that a greater flux of high-COD waters moves from marsh to lagoon – specifically entering the Butano Channel (Figure 1).

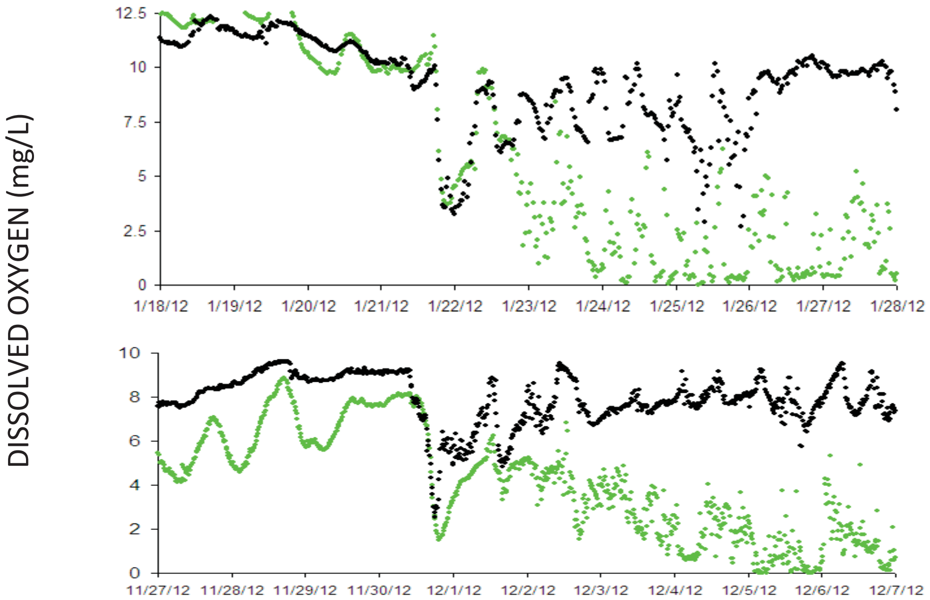

Figure 10 *– Dissolved oxygen levels (mg/L) following breach events on 21 January 2012 and 30 November 2012. Data are near-surface at Butano Channel Bridge (green line) and at Pescadero-Butano confluence (black line). Data and plots from Huber (2016); similar data are plotted in Sloan (2006).*

Transition from Closed to Open State

When the sand barrier at the mouth is breached, lagoon waters rapidly drain (Sections 3b, 3c and 3d) and hypoxic/anoxic conditions can be observed throughout the water column (Figure 10). As outlined above, during mild breach events the surface layer may be skimmed off such that near-surface sensors will be lowered into the anoxic lower layer. During more energetic breaches, the COD-rich lower layer is mixed with the surface layer in such a way to remove all oxygen from the mixed water column. The extent of hypoxia is too large to be explained simply by mixing anoxic bottom water with oxygenated surface water (Smith 2009), indicating the critical role of oxygen demand stored in the lower layer. Further, anoxia/hypoxia is observed throughout the water column immediately after the breach (Figure 10), requiring the rapid action of COD rather than slower acting BOD. The COD due to hydrogen sulfide, ferrous iron and iron sulfide minerals is mixed into the water column with anoxic water, ooze and sediments during breach events. The resultant DO depletion results in the production of H^+, and a rapid drop in water pH (values as low as 6.7), but an equally rapid decrease in hydrogen sulfide toxicity. Field data show a strong positive correlation between DO and pH following breach events, supporting the idea that COD is the direct cause of oxygen depletion upon bar breach. Oxygen depletion is more severe in shallow locations, where the effect of COD from sediment resuspension will be less diluted. It also appears that oxygen depletion is more extreme during breach events after the lagoon has been closed for a longer period of time and/or water levels are high, flooding over the marshes.

Not only does DO drop rapidly during breach events, but hypoxia/anoxia in the water column may persist for days – specifically in Butano Channel (Figure 10). This is not explained by the high COD load released during mixing, which is expected to react quickly. The persistence of low DO in spite of an oxygen flux from atmosphere to water implies an ongoing oxygen demand that may be explained two ways: (i) the slower reaction of BOD released during the breach event; or (ii) an ongoing release of COD from the marshes adjacent to lagoon channels. This second phenomenon requires further investigation: Is the COD flux from marsh edges sufficient to maintain low DO in channels that are flushed more slowly, e.g., Butano Channel? To what extent does the flow of Butano Creek waters over the marsh enhance this flux? Very long flushing times are expected in short, dead-end channels due to minimal tidal exchange, and this may be a contributing factor for the persistent low-DO conditions.

Part Two: Synthesis of Understanding

4. Synthesis View

4a. The lagoon habitat.

The water column habitat in Pescadero Lagoon is a product of processes in the lagoon and processes that govern the interaction of lagoon waters with adjacent marshes, upstream watershed, beach morphology, and nearshore ocean waters (Figure 11). Through the mid-Holocene, the Pescadero basin filled with sediments derived from watershed and ocean, yielding a lagoon comprised of channels and extensive high-tide marshes. River inflow combined with tidal exchange is enough to maintain an open mouth during the wet winter season – but not a fully open mouth: tides in the lagoon are muted and water level seldom falls to the level of low tides in the ocean. The lagoon mouth is partially sheltered from wave action by a rocky outcrop, which promotes open-mouth conditions. Closures during winter are uncommon and short-lived. During the dry season, tidal flows or perched-lagoon overflow can maintain an open mouth in the absence of any significant wave forcing, but tidal scour is inadequate to maintain the mouth during wave events that move sand into the mouth. The mouth closes in most summers, either in early summer associated with a late winter swell event or in fall associated with an early winter swell event. In summer the mouth is sheltered from south swell. While closure may happen in spring in some years, this closure tends to be short-lived as river inflow is high and overflows the mouth within a couple of weeks, breaching the sand barrier and scouring open a new channel so that tidal flows are re-established.

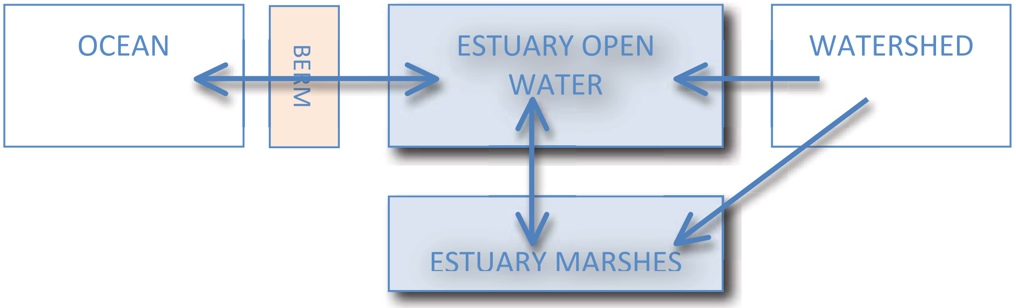

***Figure 11** – Schematic illustrating interactions between open-water habitats in the lagoon with adjacent habitats: marsh, watershed, berm and ocean.*

During closures (and perched or neap-tide conditions), a lower layer of dense seawater is trapped in the deeper portions of the lagoon. Neither wind-driven vertical mixing nor seepage through the sand barrier that separates the lagoon from the ocean appear to be capable of flushing/removing this lower layer and it generally persists until the mouth is breached, which may be weeks to months later. Biological oxygen demand (BOD) from decomposition of allochthonous and autochthonous organic matter reduces levels of dissolved oxygen, which is not replenished in deeper saline waters owing to an absence of vertical mixing with the oxygenated surface layer. Hypoxia develops in this lower layer and over time anoxic conditions may develop if the surface layer is deep/turbid enough that light does not penetrate the halocline and photosynthesis is absent at depth. Once anoxic, this lower layer can accumulate chemical oxygen demand (COD) by reduction of sulfur and iron compounds – a condition that is typically only found in muddy sediments. On breaching of the mouth, these anoxic waters and a layer of benthic ooze can be mixed into the whole water column, with the COD rapidly removing oxygen from the water – resulting in anoxia or severe hypoxia extending throughout the water column, and leaving fish with little or no oxygenated water. Specifically in Butano Channel (and also at times in Butano Creek), an anoxic/hypoxic water column may persist for days following the breach owing to a lack of flushing of these dead-end channels, the additional effect of BOD released during breaching, and/or ongoing release of COD from marshes and sediments. At other times, when breaching of the mouth results in limited scour, the oxygenated surface layer may flow out to sea without disrupting the lower anoxic layer, again leaving fish and other organisms in a water column that is anoxic or severely hypoxic from top to bottom. These are the two primary scenarios for major fish mortality events observed in Pescadero Lagoon.

Recurrent mortality events have led to growing concern for the health of the Pescadero Lagoon ecosystem and specifically for the steelhead population, which is a listed species. On the other hand, tidewater goby is also a listed species and no mortality of this hypoxia-tolerant fish has been observed. Available information and oral records indicate that annual mortality events are a new phenomenon, but data do not exist to vigorously verify this – nevertheless, the implication is that the system is out of balance and no longer functioning naturally. A baseline for natural function is not available, as the lagoon, marsh and watershed have been significantly altered by a series of human activities over the last century and a half. It is difficult to determine how the system functioned prior to this disruption. Indeed, different analyses are referenced to different baselines, and the idea of "shifting baselines" is clearly a challenge (Jackson et al 2001). Irrespective of the original state of the lagoon, it is generally believed that conditions in the lagoon have deteriorated in the last quarter century, since the early 1990's. In the following sections we summarize (i) what appears to be responsible for the annual fish kills, and (ii) what has changed in the system since 1990, with a view to providing context for the fish kills.

Insights to Pescadero Lagoon functioning can be gained from comparable systems in California and elsewhere: systems that are subject to seasonal hydrology, steep/small watersheds with brief strong flow events, intermittent connection to the ocean, and intrusion of ocean waters enriched by upwelling. In particular, during the dry season, conditions can develop naturally that may be perceived as unnatural and undesirable in estuaries in other areas – this includes hypoxia/anoxia, algal blooms, odors from decomposition of organic matter, and fish mortality events. While data in Pescadero Lagoon are lacking prior to human disturbance, it is probable that all of these phenomena occurred at various points in the undisturbed past. These dramatic seasonal changes in habitat conditions in west-coast estuaries account for enhanced habitat diversity that may enrich the ecosystem through species diversity and/or the occurrence of endemic species, as well as enriching the genetic and phenotypic diversity of populations (Hayes et al 2011).

Organisms found in the lagoon likely derive a net population benefit from use of this habitat. In spite of mortality events, the system can still have a net positive effect on a population: for example, for steelhead, if a higher percentage of estuary-using juveniles survive to reproduce (greater juvenile mortality, but higher ocean survival) than non-estuary juveniles (lower juvenile mortality, but lower ocean survival), then the estuary provides a net benefit to the population. These ideas have been explored by Bond et al (2008) and Satterthwaite et al (2012). If the steelhead rearing capacity of the lagoon has decreased, then wise lagoon management has the potential to reduce juvenile mortality and help to restore a population that is also impacted by human development/disturbance in the watershed. But such species-oriented “restoration” design runs the risk of damaging other species that use the system, and may even yield a decline in ecosystem-level attributes and functioning. For example, enhanced breaching of the mouth may have negative effects on the tidewater goby population through flushing of fish from their obligate habitat (Swenson 1999), and also on the listed red-legged frog and San Francisco garter snake that require freshwater pond habitat.

4b. Fish mortality events.

Fish and invertebrate mortality events occur in Pescadero Lagoon during anoxic-hypoxic events following the breaching of the lagoon mouth after an extended closure in late summer or fall. The proximal cause of death is unknown, but it is related to the lack of oxygen – and it is thought to be directly due to the lack of oxygen. Further, it is generally thought that mortality events have increased over the last few decades, although this is not based on long-term scientific data.

Reasons for an increase in mortality events may be due to any of several interrelated factors: (i) more frequent hypoxic events; (ii) more intense hypoxic events, i.e., lower minimum values; (iii) more persistent hypoxic events; (iv) occurrence of hypoxic events in a more-sensitive season; (v) more spatially extensive hypoxic events; and (vi) inability of organisms to escape life-threatening conditions by migrating to ocean, up-river or into other parts of the lagoon – either because passage is blocked or because hypoxia/toxin disrupts escape behavior.

Based on the conceptual models and synthesis outlined above, multiple types of hypoxic/anoxic events may occur, and each poses different threats to oxygen-dependent lagoon fauna. There are two primary sources of oxygen demand:

- Lower layer of seawater – Stratification isolates the deep waters from atmospheric oxygen and a lack of light penetration precludes oxygen production via photosynthesis, so that BOD associated with decomposing organic matter (plus respiration of benthic consumers) can lead to anoxia after a week or two. Once anoxic, a concentration of reduced S and Fe compounds (COD) can develop in this saline layer (Section 3e). At the same time, additional organic particles fall out of the low-salinity surface layer and accumulate further BOD in this sump. Anthropogenic nutrient loading and surface layer eutrophication may amplify this additional BOD loading. While the lower seawater layer may be pushed out to the ocean through the sand barrier in other smaller systems, this does not appear to occur in Pescadero Lagoon (Section 3c). Neither is wind forcing effective in mixing the surface and bottom layers. From a preliminary review of mortality events over the last two decades, it appears that after a month of closure the buildup of COD in this lower layer is sufficient to result in anoxia during breach events. If this were the primary source of low-oxygen waters post-breach, one would expect lowest oxygen values associated with higher salinity waters; and high turbidity in these waters would indicate significant resuspension of benthic BOD flocs and particles.
- Marsh pore waters – Oxygen is absent in muddy sediments below the depth at which burrowing organisms allow a flux of oxygenated waters to/from surficial sediment. Where vegetation mats cover the sediment, anoxia may reach the surface and extend into the matted vegetation. When the water level in the lagoon is below the marsh surface, these anoxic COD-rich pore waters drain from the edges of the marsh into lagoon waters due to a pressure gradient (hydraulic head). This flux is strongest following lagoon breaching, when the marsh water table is at/above the marsh surface. While flow rates and COD loading are unknown, rough estimates suggest that this persistent flux of COD may be an important factor in maintaining low DO in channels that are flushed slowly by the tide (e.g., Butano Channel). Further, the routing of Butano Creek flow over the marsh and into Butano Channel may result in a higher marsh water table and a larger/more persistent flux into lagoon waters whenever the lagoon water level is below the marsh plain (Section 3e).

Types of breaching and hypoxic events

To date, mortality events have been observed only in association with hypoxia following breaching events. Breach events differ, depending on pre-breach conditions, river flow, tidal phase and waves at the time of breaching. In terms of hypoxic outcomes, we contrast four types of event. The spatio-temporal pattern of oxygen depletion is different for these four types, with different challenges for organisms in escaping hypoxia and requiring different management actions to preclude/mitigate mortality events.

#1. Deep scour with strong river flow: When the mouth breaches during high river flow, the hydraulic head between lagoon and ocean creates a strong and persistent outflow that can scour a deep channel at the mouth (Section 3c).

Strong river flow also can overcome the density difference between the layers and completely mix and rapidly export the anoxic lower layer with its COD and BOD loading (Section 3d). Many (perhaps most) fish will be flushed from the lagoon during these events, likely escaping all but a brief exposure to hypoxia (but any dead fish would also be flushed and mortality is unlikely to be observed). This breach type would be most desirable for juvenile steelhead, but least desirable for tidewater gobies and other estuary-resident fish.

#2. Moderate scour with moderate river flow: When outflow is less energetic, the channel will not be scoured as deeply, and the seawater layer may be retained in the lagoon without mixing (Section 3d). Fish can remain in the outflowing surface waters, migrate out to sea or possibly migrate upstream. Hypoxia-tolerant gobies may remain in the lower layer and escape flushing from the estuary.

#3. Moderate scour with low river flow: While the lagoon-ocean water level difference alone may breach the mouth and scour a new channel, the absence of river inflow has significant consequences. Firstly, on breaching the surface layer may flow out without being replaced by river inflow, so that only the lower anoxic seawater layer remains and unless fish migrate to the ocean with the initial outflow they will be forced into anoxic waters (e.g., Becker et al 2009). The low water level will preclude fish passage up Butano Creek as it is blocked by tule marsh. Secondly, because the water level in the lagoon remains below the marsh plain, a persistent influx of high-COD water from the marshes is expected. Thirdly, as the tide rises, with insufficient river inflow to fill the lagoon, seawater may enter the lagoon and mix with or displace the anoxic layer, breaking down any residual stratification and mixing low-DO, high-COD water throughout the water column and lagoon (cf., Slinger et al 1995). Also, in the short Pescadero Lagoon this release of anoxic, high-COD water will occur on an incoming tide, which will enhance retention of these waters in the inner estuary – particularly in dead-end channels where tidal flushing is weak, e.g., Butano Channel, Butano Creek. These low-inflow breaches are typical of artificial breaches, but low-inflow breaches can also occur naturally (e.g., during drought in February 2014).

#4. Shallow scour with low river flow: When the lagoon water level overflows the sand barrier, whether due to weak river inflow or wave overwash, a shallow outflow channel may develop (Section 3c). In the resulting perched lagoon state, much of the surface layer will flow out and residual low-salinity waters may subsequently be mixed with the lower layer due to wind forcing, extending hypoxia throughout the water column. Also, if the lagoon drains below marsh levels, marsh pore waters may yield a significant COD flux to the lagoon surface waters, further exacerbating hypoxic conditions.

Fish escape routes

Recent observations of rapid growth of juvenile steelhead in coastal lagoons (e.g., Scott Creek, Pescadero Lagoon, Russian River) show that much can be gained from rearing in these habitats. Further, Bond et al (2008) have shown that lagoon-fattened steelhead later dominate the spawning population. But, at times the water quality in coastal lagoons is poor enough to stress these and other fish, as well as benthic invertebrates (e.g., Dungeness crab). While invertebrates and small fish (e.g., sculpin, stickleback) cannot move away quickly, larger fish like juvenile steelhead are expected to migrate away – out to the ocean, upstream to river habitats or into other parts of the lagoon. Hayes et al (2011) have shown that juvenile steelhead in Scott Creek return to the upper watershed when estuary conditions deteriorated. Similarly, Shapovalov and Taft (1954) documented the upstream migration of juvenile steelhead in nearby Waddell Creek in late fall. In contrast to steelhead, no tidewater goby deaths have been recorded – they adopt a strategy of remaining in the lagoon, hunkering down on benthic surfaces during breach events, and exhibit a tolerance of low-oxygen concentrations (supporting the idea that hypoxia was a common occurrence during their evolution in these coastal lagoons).

The upstream movement of fish in Butano Creek is severely limited by shoaling of the river channel as it enters the lagoon and invasion of tule reed in this region. Further, low water levels where the river enters the lagoon, due to water extraction in dry months, may further limit the prospects of upstream migration. With no escape routes from Butano Creek and Butano Channel, juvenile steelhead may have significantly diminished chances of escaping hypoxia in the lagoon. While seaward migration may be common during high/moderate inflow (types #1 or #2), this is less common during low inflow (type #3) – when marsh refuges are also not available, and at the same time as hypoxic conditions are the worst. If indeed juvenile steelhead have evolved an upstream escape strategy, then it is possibly cued on salinity, which raises the prospect that Butano Channel represents the road to nowhere, drawing fish in towards freshwater that flows out over the marsh but without offering any hope of finding a migratory route to the river.

Mortality of small fish may also occur through stranding on the marsh plain during a rapid drop in water level following a breach event. In Pescadero Creek, for example, only stickleback and sculpin were found in the kills, presumably because these small-bodied fish (weak swimmers) were stranded as water dropped. In contrast, in Butano Creek, steelhead were also found in the kills, presumably due to oxygen effects (these fish should be able to avoid mortality due to stranding because they are larger and stronger swimmers).

4c. Changes in the lagoon environment.

Pescadero Lagoon has been subject to a series of changes over the last century and a half. And concern with fish mortalities in the last quarter century suggests that the lagoon environment continues to change – and in a way that has reduced the ability of the lagoon to support juvenile steelhead and other fish. We note here the changes that have happened in this system over the last few decades – including changes that may have occurred, but for which there are no data. The causative relations between these changes are not fully known (e.g., one causing, exacerbating or ameliorating another), and neither is the impact of these changes on fish populations and ecosystem functions.

- Increased tidal prism. Through restoration actions implemented in the early 1990's, the tidal prism in Pescadero Lagoon increased about 10% (Section 3c). Since the failure of the gates on the channel linking the lagoon to North Marsh and North Pond, this increase may be larger.
- Later closure of mouth. The mouth has closed in late summer or fall in most years in the last two decades (with exception of recent drought), whereas during the 1980s it is reported to have closed more typically in spring (Section 3b). Existing records and analysis of mouth closure are inadequate to confirm a systemic delay in closure, or to assess large-scale forcing (i.e., decadal fluctuations in waves and river flow). However, it is quite possible that this has happened, due to the increase in tidal prism (which serves to keep the mouth open longer) or due to fluctuations in wave and river forcing.
- Enlarged flood-tide delta. There has been a landward expansion of the shoals built by deposition of sand during inflow to the lagoon over the beach (Figure 1). This effect can result directly from enhanced flood-tide currents and sediment transport associated with an increased tidal prism. Tidal changes may be amplified by the action of infra-gravity waves that are active in this mouth channel (Section 3b) and account for peak flow velocities. Sediment transport through wave overwash may also have increased following replacement of the old bridge, which included supports that impeded wave action.
- Shallower mouth channel. With the broadening of the flood shoals and thus the sand barrier, the mouth presents more of a frictional drag on outflow and it may be that the channel does not scour as deeply as previously (making full breaches less common). Further, a long shallow mouth channel provides an environment in which infra-gravity waves can be of increased importance, propagating as bores with enhanced flow velocities and landward sediment transport (thus further growing the flood-tide delta).
- Changes in artificial breaches. While there are no data on unofficial manual breach events, any change in this intervention may be important for three reasons: (i) artificial breaches are typically of type #3 or #4, with high likelihood of hypoxic conditions and fish mortality, (ii) without the support of river flow, artificial breaches are less likely to scour out the mouth, with the possibility of long-term accumulation of sand in the mouth, and (iii) unofficial breaches are often done at night or early morning to avoid detection, which is when oxygen levels are lowest because surface-water oxygen declines through the night as respiration exceeds photosynthesis.
- Changes in ocean conditions and rainfall. Decadal fluctuations in ocean conditions and rainfall occur along the west coast and there is a possibility of this leading to decadal changes in the timing of mouth closure, stratification, or water quality in the lagoon. In spite of interannual variability (e.g., Figure 12), to-date there are no analyses that explore the relation between interannual variability and observed changes in Pescadero Lagoon (cf., Behrens et al 2013).

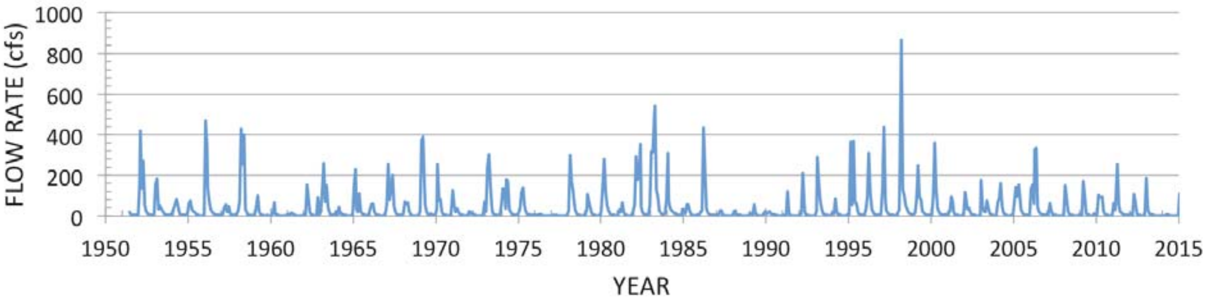

Figure 12 *– Mean monthly flow in Pescadero Creek from 1951 to 2013. Data from website: waterdata.usgs.gov/nwis/uv?cb_00060=on&cb_00065=on&format=gif_default&period=31&site_no=11162500*

- Changes in bottom depths. There have been two important changes in the location of deep water in the Lagoon, where dense seawater can be trapped and anoxia develops. The first is the landward shift of the deep section as the flood-tide delta has grown (Section 3a). Now well back from the Highway-1 Bridge, there is little chance that this deep seawater layer can be purged through the sandbar at the mouth (Section 3d). Secondly, during the 1990's restoration, a deep section was created in the low-energy Butano Channel, where seawater can be trapped with little chance of mixing; organic particles and flocs are also trapped, thus creating an environment in which anoxia develops readily. In natural systems, deep sections are created by episodic river-flow maxima, which scour out accumulations of fine organic sediment.
- Increased sedimentation. While sedimentation of Pescadero Lagoon has been anthropogenically enhanced for many decades, over the last quarter century Butano Creek has continued to accrete so that the channel bed is now above the marsh plain (CBEC 2014).
- Breaks in levee. During the restoration in the early 1990's, portions of the levee on the west side of Butano Creek were removed to allow water to spread out over the marsh. With accretion of the creek channel, waters flow over the marsh from the river not only during periods of high flow but also during low flow (i.e., preferring to flow over the marsh than down the aggraded creek channel).
- Tule reed growth. Over the last couple of decades, tule reeds have grown to choke what remains of the Butano Creek channel. This further deflects water from river to marshes and also blocks fish passage, except during high water levels. Tule reeds may also be important in water loss through evapo-transpiration, resulting in lower water inflow to the Lagoon in summer.
- Increased COD flux from marsh to lagoon channels. With continuous flow of Butano Creek waters onto East and South Butano Marshes, the water table remains high on those marshes and a continuous drainage of pore waters to

the Lagoon is expected to continue through the dry season (Section 3e).

- Organic loading of river inflow. While no data are available, it is likely that nutrient and organic matter (BOD) loading of creek inflows to the lagoon has increased over recent decades. This would advance eutrophication and the flux of BOD particles into the sump formed by the resident seawater layer (Section 3e).
- Freshwater extraction. Along with watershed erosion driving sedimentation and nutrient/organic loading driving eutrophication, most coastal systems are subject to reduced river inflow owing to extraction of water in the watershed. No data are available on water extraction and changes in the inflow hydrograph, e.g., diversion to storage facilities in the Bean Hollow watershed. Anthropogenic reduction of flow during the dry season may influence mouth dynamics, sedimentation, stratification, and water quality.
- Reconnection of marshes. During the 1990's restoration, marshes were partially reconnected to the lagoon in order to enhance habitat in the Pescadero Lagoon/Marsh system. The importance of this as a source of BOD and COD to the lagoon is unknown – nor whether there is a multi-year flushing of accumulated organic material off the marsh plain.
- Salinity changes in North Pond and North Marsh. Also due to the 1990's restoration, increased connectivity between the outer lagoon and northern parts led to increased salinity in North Pond and North Marsh and a possible loss of freshwater habitats. Few salinity data are available to assess this.

5. Management Actions

Fish kills in Pescadero Lagoon have raised stakeholder concerns that seek a response from management agencies. However, actions aimed at reducing the severity and frequency of fish kills during breaching events must be placed in the context of broader ecological aims, including steelhead conservation, conservation of other listed species, and overall health of the lagoon/marsh ecosystem. Further, any actions will need to be consistent with actions taken to reduce flooding risk for agricultural and residential areas, addressed by CBEC (2014). Fish kills occur during hypoxia/anoxia events that occur following breaching of the lagoon – as addressed in Sections 3 and 4. Below we outline several management actions that have been raised during our consultation with the community and scientists. In many cases, information is lacking and we base our comments on best-professional judgment, endeavoring to provide an assessment of costs, benefits, and risks associated with these actions. There is inadequate data or analysis of data to provide a science-based recommendation for specific actions. In the next section we recommend how to move forward in developing a scientific basis for management of the Pescadero Lagoon.

Short-term management actions that may mitigate a mortality event.

1. Pre-emptively breach sand barrier.
As BOD and COD build up slowly during extended closure events, one may preclude the worst occurrence of hypoxia and associated fish mortality in the lagoon by breaching the mouth a few weeks after closure. As managed breaches often occur during low river flow, which is the least desirable time for breaching (Section 4b: type #3), this pre-emptive breaching will need to be done early enough that COD has not yet accumulated significantly in the seawater layer. In turn, this may lead to repeated and frequent breaching. Analysis of existing DO data would provide improved insight to what controls the development of anoxic conditions, but ultimately management decisions will need to be based on real-time observations of stratification and buildup of BOD and COD in the system (i.e., a monitoring protocol to guide decisions). These early and possibly repeated breaches are likely to diminish the lagoon growing habitat for steelhead, reducing size at ocean entry and survival through the ocean phase, thus potentially having a net negative impact on the population in spite of decreasing estuarine mortality. A population analysis is needed to assess the net population benefit. Equally important is that breaching has negative impacts on tidewater goby, which need to be assessed. Also, the impacts of breaching on freshwater habitats for red-legged frog and San Francisco garter snake need to be assessed – breaching lowers the water table and is likely to eliminate ponded habitat. Finally, repeated breaching may promote sedimentation in the lagoon, expanding the flood-tide shoal, and hastening the further loss of open-water habitat. In summary, a clear data-based protocol for breaching decisions needs to be developed, ensuring that breaches are well-planned, implemented seldom and with specific net benefits identified.

2. Breach sand barrier during rain events.
While more natural in approach, this action entails the risk that a breach happens prior to rain or during an initial weak river-inflow event (as in February 2014), resulting in significant hypoxia and fish mortality. The decision whether to breach pre-emptively (as above) or to await rains in early winter should be based on field data, including data on berm height, stratification, dissolved oxygen, and BOD/COD levels – quantifying habitat volume in the closed lagoon. Further, management action is needed to ensure that no unofficial manual breaching occurs prior to rain and increased river flow in early winter.

Medium-term management actions that may diminish the likelihood of a severe mortality event developing.

3. Fill deep backwater sections.
Where deeper sections are not due to scouring by strong river flows, they could be filled to obtain a monotonically deepening thalweg in lagoon channels and

reduce the likelihood and extent of seawater trapping and anoxia. This refers specifically to the deep section created in the Butano Channel. Naturally scoured deeper sections do not need to be filled (may be important habitat for steelhead), such as those on the bend in the lagoon between the confluence and Hwy-1 Bridge, and in Pescadero Creek above the confluence. To assess this action prior to implementation, field data should be collected/analyzed on stratification and development of anoxia plus accumulation of benthic ooze and COD in targeted deep sections. The expectation is that the highest COD loading develops in non-scoured deep sections, which also occur in dead-end channels where tidal flushing is weak (e.g., Butano Channel).

4. Install bubbler.
The volume of seawater trapped in lower layers in deep sections of the lagoon is not large – so that artificial destratification is an option. By pumping air into the lower layer, one slowly mixes the water column precluding development of anoxia, and also one injects oxygen at depth. While stratification during closure is typical in these systems, it can be mixed naturally by winds and there is no obvious habitat loss associated with the absence of stratification. While such a system needs to be large enough to be effective, the visual/noise impact may be minor – however it is likely to alter the "sense of place" for some visitors. Field monitoring will be needed to assess how well this device works and to assess wildlife disturbance.

5. Close mouth in spring.
If indeed the mouth used to close at the beginning of summer when inflow is higher, and this is a primary factor in precluding mortality events, then the mouth could be manually closed in spring or early summer (with timing based on seasonal forecasts for river flow and wave events). While this action needs more in-depth assessment, better articulating the link from early closure to reduced hypoxic impacts, it could be implemented as an experimental action with monitoring of conditions through the summer until breaching in the fall. An early closure is expected to allow a thick, low-salinity surface layer to develop (in a normal or wet year), providing steelhead habitat through the summer. Also, an early closure may result in a smaller volume of trapped seawater, which may be mixed by the wind and represents reduced capacity to accumulate COD. Finally, the buildup/persistence of the low-salinity surface layer is expected to benefit freshwater marshes and habitat for the red-legged frog.

Long-term management actions that may create a system in which mortality events are rare and minor.

6. Open Butano Creek channel.
The removal of tule reeds and dredging of the thalweg of Butano Creek will allow fish passage as well as enhance flushing of organic-rich sediment from the system during strong winter flows. Further, by lowering the bed of the channel (Figure 8), inflows will follow the creek channel during low flow and only spread out over the marsh during high flows (as would have occurred pre-disturbance).

Also, this action will increase tidal flushing in this part of the lagoon. Opening of the Butano Creek channel between Pescadero Road and the lagoon has been identified by CBEC (2014) as a way to alleviate flooding of the road, farmland and town. But, while dredging will open the channel, the lagoon will continue to receive excess sediment and the channel will accrete again, unless there is a reduction in the sediment source. Dredging without floodplain restoration and sediment supply reduction is a likely to be a temporary fix and repeated dredging is costly and incurs repeated disturbance impacts on the system. Sedimentation is a key factor in flooding analyses and is being addressed following the report by CBEC (2014).

7. Dredge the flood-tide delta.
Remove sand from the flood-tide shoal to re-establish a narrower sand barrier. While benefits may include more effective breaching/flushing and export of deep seawater via seepage through the sand barrier, it is not clear that this is a necessary or desirable action – and the underlying causes of growth of the flood-tide delta would need to be identified and addressed to prevent it from growing again. If this proved to be an important action, a groin beneath the bridge could be considered as a way to prevent overwash and sediment influx.

8. Reduce the tidal prism.
While an increase in tidal prism appears to have been a factor in maintaining an open mouth through summer, which has been linked to hypoxic events during subsequent breaching, the arguments for this understanding need to be supported by data analysis. Further, the pre-disturbance lagoon appears to have had a much larger tidal prism. The strategy to reduce the tidal prism involves a reduction in tidal area, which also represents a loss of intertidal habitat. This is unlikely to be a desirable action and probably not necessary (although disconnecting North Pond and North Marsh is an option).

9. Reconfigure connections to North Pond and North Marsh.
While the hydrology of connections from the lagoon to these northern parts of the lagoon/marsh system does not seem to mimic natural systems, without an improved understanding of how this northern region could function hydrologically there does not appear to be a strong argument for new earth movement. It is unclear whether the occurrence of red-legged frog habitat in North Marsh was a transient outcome of earlier human activity, or a long-standing habitat that survived human alterations to the system. Nevertheless, the persistence of low-salinity habitat in this region is most likely dependent on freshwater inflows assisted by early mouth closure, which would allow a higher water level and thicker low-salinity layer to develop throughout the lagoon.

10. Develop nutrient management for lagoon inflows.
There is no information suggesting that Pescadero Lagoon inflows carry an excessive load of nutrients that result in cultural eutrophication and enhanced oxygen demand in the lagoon, but there is well-founded concern that this may be the case. Prior to considering action on this front, the extent and impact of any nutrient loading needs to be assessed.

11. Develop water management for lagoon inflows.
As for nutrient loading, there is no evidence that reduced freshwater inflow to Pescadero Lagoon is a primary factor, but there is well-founded concern given that a significant portion of the hydrograph is removed from the system. The season of concern is summer, when irrigation withdrawals reduce freshwater inflow and may preclude development of a surface layer thick enough to provide expanded fish habitat. Freshwater inflow at the time of breaching is also a factor in deeper scouring of the mouth.

6. Conclusion

The PLSP has developed a common scientific understanding of the lagoon system (Sections 3 and 4) that can serve as a scientific foundation for management decisions going forward. However, the lack of appropriate data and analyses on key issues related to fish kills precludes specific science-based management recommendations. Further, the need to place the concern about annual fish kills in a broader ecological context raises additional questions that preclude clarity on ecological costs and benefits of specific actions.

In Section 5, a variety of management actions are reviewed, identifying pros and cons as well as specific information needs. In short, there is an absence of rigorous analysis of key issues. Science-based management of Pescadero Lagoon is likely to be comprised of short, medium, and long-term approaches, that are based on rigorous scientific analyses, development of clear decision criteria, and implementation of a strategic monitoring/assessment plan. To expand on the need for rigorous scientific analysis, we outline several key issues to be addressed prior to forging ahead with specific management action:

(i) *How important are fish kills?* Data on estuarine mortality need to be placed in the context of total mortality across all life stages to understand the true impact of the fish kills at the population level. Is 10% of the population affected by the kill event, or 90%? How is mortality in the lagoon counter-balanced by enhanced ocean survival of fish that benefitted from rapid growth in the lagoon? Answering these questions requires long-term monitoring across life stages. Further, estimates of the number of dead fish need to be compared with estimates of the number of live fish in the lagoon – we do not know whether any lagoon steelhead survive the event. Recognizing that fish kills may occur naturally during breach events, attention should be directed at the conditions that yield the largest fish kills. To identify the most severe kills and to understand the population-level effect, more rigorous fish mortality and fish monitoring data are needed.

(ii) *What controls hypoxia and anoxia?* Analysis of existing data and strategic collection of new data is needed to identify when and where seawater trapping or marsh drainage is the primary cause – as well as how anoxia and COD loading develops and is released from both sources. Lower layer anoxia depends on organic loading, stratification, wind mixing, lagoon water level, light penetration, and breaching. The impact of marsh anoxia depends on lagoon water level, water flow paths (and link to sedimentation), organic loading, and the form of breaching. Management actions to reduce the occurrence or impact of anoxia will be based on this information, and operational decisions will benefit from clear decision criteria combined with field data. Information is needed specifically before, during and immediately following breach events.

(iii) *What controls the depth of scour during breaching?* To determine if, when, where, and how managed breaching should happen, better information is needed on scouring outcomes following breaching – specifically, how the depth of scour depends on river flow and the initial lagoon-ocean water level difference under different wave and tidal conditions, as well as on berm/sand characteristics.

(iv) *How has freshwater inflow changed?* While the seasonality of freshwater flow has received attention, data on changing freshwater inflow during closure periods is not readily available. Extraction of water in the lower watershed as well as water loss through evapotranspiration may significantly alter low summer flows, allowing additional seawater intrusion as well as precluding buildup of a low-salinity layer in the lagoon, which is important in providing habitat for a number of key species.

(v) *Does eutrophication occur?* A primary source of BOD in estuarine systems is algal blooms, which produce labile organic matter that is easily oxidized during decomposition. An enhanced influx of labile organic matter or nutrients that support algal blooms will enhance BOD and advance the development of anoxia and COD in the lagoon. Data on nutrient loading and lagoon eutrophication are not readily available, precluding any assessment or management response.

(vi) *What controls availability of habitat for tidewater goby, red-legged frog, and San Francisco garter snake?* In order to properly account for impact of management actions on gobies, frogs and snakes, information on spatial distributions, habitat determinants and habitat controls is needed.

In response to suggestions that a science panel is simply suggesting “another study”, our response is that science-based management is based on scientific understanding. In spite of the ongoing concern with quasi-annual fish kills in Pescadero Lagoon, and the volumes of spoken and written comment, there is a paucity of data, an absence of strategic monitoring, and a general lack of analysis of key issues that need to be validated and articulated prior to management action. These issues and information needs are outlined above.

Management will benefit from a common scientific understanding of the system that can serve as a foundation for developing a stakeholder consensus. It will also benefit from science-based criteria for operational decisions (e.g., when to do an emergency breach), and a strategic monitoring plan that allows ongoing assessment and adaptive management approaches. However, all of these benefits rely on adequate data and analysis of the problem. By combining existing data with new data and rigorous analyses, a preliminary scientific foundation can be developed readily quickly.

Many people care deeply about Pescadero Lagoon and Marsh. In spite of differences in foci across stakeholders, a common set of objectives can be developed, based on a common vision for the lagoon/marsh. Ultimately, this vision rests on a well-founded scientific understanding of how the system works, and effective achievement of objectives rests on the availability of science-based information to support management actions (and science-based metrics of success). This report outlines the science needed to get there.

The Estuary Mouth – where the Lagoon connects to the Ocean

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