Considerations for Management of the Mouth State of California's Bar-built Estuaries

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Terminology

Sand barrier – a ridge of sand built across the mouth of an estuary or lagoon by waves; the crest of the ridge is typically above high-tide water level in the ocean; elsewhere this ridge of sand forms beaches along the shoreline; during high tides and/or big waves, ocean waters may run up and overtop the sand barrier; this barrier may be composed of sediment that is both coarser and finer than sand; "seepage" refers to a limited flow of water through the sand barrier, which is greater when sediment is coarser.

Breach – a break in the sand barrier that forms through erosion of a channel through the barrier by outflowing water and that can be enlarged through subsequent tidal flows; inflow through wave overtopping is not considered a breach; breaches may occur naturally or through human intervention (see below).

Managed Breach – a breach that is initiated by excavation of sand, irrespective of scale (typically implemented with heavy equipment); this management action is taken intentionally to achieve a desired outcome; human actions can also initiate breaches unintentionally (e.g., digging a channel for fun on a summer day) or for a non-approved management outcome ("rogue breach").

Natural Breach – in the absence of human intervention, the sand barrier will be breached naturally; most common are breaches that occur when the water level in the estuary rises higher than a low point in the crest of the sand barrier, in which case water overflows and erodes a channel in the barrier at that location; natural breaches can be mimicked by managers by water release from a reservoir (this is unusual in California); natural breaches may also occur during large waves, with outflow at a low point in the barrier being driven by widespread wave overtopping and/or through collapse of a fluidized sand barrier (this may only occur in a few places).

Estuary – an estuary is a body of water in which freshwater from a river meets and mingles with seawater; it is typically characterized by salinities between freshwater and seawater levels, but in California and comparable regions the water in the estuary is at times entirely freshwater at times and entirely seawater; in this report and most literature from California, estuaries are broadly interpreted and salinity may even exceed ocean levels due to evaporation (hypersalinity); further, estuaries in California may be temporarily disconnected from the ocean by a sand barrier.

Lagoon – a lagoon is a body of water separated from the ocean by a sand barrier, including times when the sand barrier completely separates the two water bodies and when there is a small break allowing limited tidal exchange between the estuary and the ocean (i.e., a tidal lagoon).

Bar-built Estuary – this term has a similar meaning to "lagoon" but refers to the entire system, not just the impounded water. In addition, it refers specifically to the sand barrier that separates the estuary from the ocean and also recognizes that the body of water is an "estuary", in which freshwater and seawater interact; strictly a "bar" refers to a submerged sand ridge, thus referring to the shoal in the entrance channel of most estuaries in California – even larger estuaries that never fully close and thus "bar-built estuaries".

Open mouth – the mouth of a bar-built estuary when there is a channel that allows significant tidal exchange between the estuary and the ocean; nevertheless, the channel is typically shallow and narrow enough to restrict tidal exchange and the tidal range in most small California estuaries is less than in the ocean; when the mouth severely constricts tidal flows, the estuary is in a “muted tidal” state and tidal range tends towards negligible.

Closed mouth – when the sand barrier fully disconnects the estuary from the ocean, the mouth is closed; there may still be wave overtopping and/or seepage of water through the sand barrier, but there is no continuous surface flow; the estuary water level may be above or below ocean water level.

Perched mouth – when the low point in the sand barrier is above high-tide water levels, but the water level in the estuary is above the low point in the sand barrier, an outflow forms (similar to a weir overflow in a reservoir); if this flow is weak enough that erosion does not occur, this perched state can persist for months; at these times reference is made to a perched lagoon or perched estuary (i.e., estuary water level above highest ocean water level).

Intertidal – refers to levels between the high-tide and low-tide levels in the ocean; this can relate to water levels or to benthic habitat in the estuary.

Supratidal – refers to levels above spring high-tide levels, which are inundated when the mouth of the estuary is closed and water levels are perched.

Spring tide – fortnightly condition (associated with full and new moons) when highest high tides and lowest low tides occur.

Neap tide – fortnightly condition (associated with ¼ and ¾ moons) when lowest high tides and highest low tides occur.

Hypoxia – hypoxic conditions referring to low levels of dissolved oxygen, much less than saturated concentrations and typically when concentration is less than 2 mg/L.

Anoxia – anoxic conditions referring to very low levels of dissolved oxygen, close to zero and typically when concentration is less than ½ mg/L.

Biochemical oxygen demand – a measure of the amount of oxygen that can be removed from the water column through bacterial decomposition of organic matter.

Chemical oxygen demand – a measure of the amount of oxygen that can be removed from the water column through oxidation of reduced compounds like hydrogen sulfide.

Benthic community – ecological community associated with the bottom of the water column (i.e., sediment/rock bed).

Salmon Creek

Acronyms

BBE	Bar-built estuary
LPL	Los Peñasquitos Lagoon
SCE	Scott Creek Estuary
RRE	Russian River Estuary
COD	Chemical Oxygen Demand
BOD	Biochemical Oxygen Demand
CCWG	Central Coast Wetlands Group
NMFS	National Marine Fisheries Service
CDFW	California Department of Fish and Wildlife


San Juan Creek

Executive Summary

Bar-built estuaries are the dominant estuary type in California, and many of these small estuaries are subject to closure with a sand barrier separating a lagoon estuary from the ocean for days, months or even years. In the lagoon impounded behind the sand barrier, water levels may rise or fall depending on net water budget and water quality extremes may develop. These conditions and the obstruction of fish passage motivate managed breaching of the sand barrier in many systems statewide – an intervention that alleviates or pre-empts environmental problems, but which also can result in undesirable secondary impacts due to the acute effect of a single breach or the chronic effect of repeated breaching over years. Management decisions are based on an implicit trade-off between anticipated benefits and costs that depend on the values and priorities of stakeholders.

This report was written to provide an overview of considerations for managed breaching in California. It presents a synthesis of processes and phenomena related to mouth closure and breaching in general and uses this to identify potential impacts of breaching, without intending any judgment of which impacts are more or less desirable. Three specific systems are reviewed in detail: Los Peñasquitos Lagoon in San Diego County, Scott Creek Estuary in San Mateo County and Russian River Estuary in Sonoma County. While there are fundamental similarities in the closure and breaching cycle across all bar-built estuaries statewide, there is also an immense diversity between these systems due to differences in size, in hydrology (wet north to dry south), and in development (rural, urban, agricultural, road/rail). The local community is likely to develop the best management strategy where there is significant effort and experience in local monitoring, science, and stakeholder consultation. However, where there is limited monitoring, science or consultation, the considerations outlined in this report provide preliminary guidance – and comparison with one of the study systems can provide more specific insight to the potential impacts of breaching management decisions.

We synthesize current understanding related to how mouth state influences estuary functions and conditions, which in turn affect ecological services. While both natural and managed breaching affect many processes and phenomena in the estuary, breaching events and managed breaching regimes do not occur in isolation and many other factors affect the estuary functions and conditions, including freshwater inputs, the adjacent landscape, and stressors in the watershed. However, managed breaching is one of very few short-term management options and therefore a valuable adaptive management tool, specifically in systems that are already perturbed or impacted by human encroachment. Although emergency breaches may be required in rare occasions, our recommendation is to develop a breaching strategy for specific systems in which breaching has been used or in which it is likely to be used as a management tool. In this context, we recommend ways in which science can provide improved support for management decisions and identify a few systems in California in which there is already a well-developed, science-based management plan.


Salinas River

1. Introduction

Bar-built estuaries (BBEs) are located at the terminus of creeks and rivers where a wave-built sand barrier restricts connection with the ocean. The formation of this sand barrier is driven by a dynamic set of processes that vary regionally and seasonally depending on watershed and climate, river inflows, river sediment load, tidal flows, nearshore sediment supply, wave exposure, and development (including transportation infrastructure). The constricted mouths of BBEs constrain tidal exchange between the estuary and the ocean and modify estuary hydrology. These mouths close periodically, completely separating the estuary from the ocean and impounding water within a lagoon (a coastal lake), with water surface elevations that may rise above high-tide levels in the ocean (Behrens et al. 2015b). The frequency and duration of inlet closure varies naturally across BBEs and across years (Cooper 2001; Jacobs et al. 2011 Behrens et al. 2013; McSweeney et al. 2017) – and can be altered by mouth management (i.e., breaching). The mouth state is not binary (fully open or fully closed) as these systems transition among multiple mouth states, including non-tidal phases (closed mouth), perched overflow, tidal choking (muted tides relative to ocean), and fully tidal (fully open mouth).

The salinity regime of a bar-built estuary can be highly variable, exhibiting tidal fluctuations when open and different BBEs can be entirely fresh, vertically stratified or entirely hypersaline when closed, dependent on the hydrological balance and the condition of the sand barrier at the mouth of the system. There is a trend toward lower salinities in more northern estuaries where a positive water balance is the result of higher rainfall and river inflow, and higher salinities in southern California estuaries – but conditions also depend on watershed size and yield. Intense, two-layer salinity stratification is common in these systems when the mouth is closed or in transition (perched or muted mouth states).

California's bar-built estuaries afford unique habitats with a wide range of special ecological services. Further, a suite of species listed as threatened or endangered under the federal Endangered Species Act (ESA) depend on these habitats, including the tidewater goby, Belding's savannah sparrow, steelhead trout, and Western snowy plover. In addition, benefits accrue to local human communities such as recreation, flood attenuation, and water filtration. Depending on the local geology and the degree of confinement by adjacent uplands, these systems may support spatially extensive wetland habitats and resources, or they may support only a narrow estuary comprised of an open water channel.

Water impoundment behind the sand barrier can conflict with some site-specific environmental or land-use objectives. Municipalities and resource managers routinely manage mouth state to protect specific environmental conditions or adjacent property. When undesirable water elevation or water quality triggers active management, there are limited options other than implementing a managed breach. Permits are applied for and issued on a case-by-case basis to address a variety of management purposes (*e.g.*, alleviate impacts of flooding, improve estuary water quality, improve conditions for wildlife, improve public access).

The aim of this report is to provide stakeholders and resource managers with science-based considerations when making decisions related to sand barrier management. We review relevant physical and biological processes, effects, and consequences. It is not intended as a prescriptive or restrictive set of rules or regulations regarding sand barrier management. The nature of each estuary is different, in terms of ecological function, legacy issues, and management objectives (Whitfield et al. 2012). The local community is likely to develop the best management strategy where there is significant effort and experience in local monitoring, science, and stakeholder consultation. However, where there is limited monitoring, science or consultation, the considerations outlined in this report provide some guidance – and comparison with study systems should provide further insight to how management decisions may play out for any given system.

Typically, reasons for proposed sand barrier breaching are aimed at addressing one or more of the following management objectives (also see Pratt 2014):

- Alleviate or preclude flooding of agricultural lands, urban infrastructure, special status species habitat and recreational resources.
- Eliminate or reduce undesirable water quality conditions (e.g., hypoxia), including biological impacts resulting from water column stratification.
- Alleviate elevated risk to public health from vector borne illness such as West Nile virus from freshwater mosquito species (e.g., *Culex tarsalis*).
- Allow fish passage for anadromous adults and/or juveniles.

Typical environmental and regulatory concerns regarding managed breaching include one or more of the following:

- Nearshore ocean water quality concerns associated with flushing of estuarine waters that may be high in nutrients or bacteria to the ocean, thereby impacting beach water quality and/or contributing to coastal blooms of toxic algae.
- Flushing or stranding of flora and fauna including tidewater goby and other small fish (also pre-smolt salmonids), plankton, submerged aquatic vegetation (SAV) and invertebrates.
- Undesirable or false environmental signals causing premature migratory cues (adults and juveniles).
- Disturbance of birds and mammals that use beach or dune habitats.
- Biological impacts due to rapid change in water column salinity, temperature, and/or dissolved oxygen; specifically, hypoxia-related fish mortality following a breach.
    - Removal of oxygenated surface layer, forcing fish into hypoxic lower layer
    - Drainage of high oxygen-demand marsh waters into channel
- Loss of channel, floodplain and backwater habitat for juvenile salmonids (and other fish and wildlife).
    - water depths unsuitable and/or unstable
    - loss of channel and off-channel habitat diversity and availability
- Reduced delivery of nutrients and organic matter to adjacent marsh plain.
- Desiccation of marshes and mobilization of metals such as mercury.
- Loss of upstream and fringing freshwater habitat, or connectivity to it.
- Loss of beach sands and impacts to beach-related species.

- Post-breach sedimentation of channels near mouth.

The review of data and published science in this report is intended to inform and provide considerations on common biophysical consequences and illuminate the underlying trade-offs that exist when making decisions regarding mouth management. The benefit or the avoidance of a negative impact that is envisaged by those proposing the breach has to be balanced against the losses and other negative environmental impacts that may occur – both anticipated consequences and the risk of unanticipated negative effects. Ecosystem gains and losses may be realized on different time scales, some effects are immediate (acute impacts) while others are delayed or accrue over multiple breaching events (chronic impacts). Furthermore, each system has individual characteristics and expresses variations on the general biophysical phenomena and conditions we identify and explore. Trade-off decisions are best made at the individual system scale, including all interest groups and permitting agencies and with access to adequate biophysical information to allow assessment of breaching impacts and positive and negative values in addition to long-term sustainability of the system. This report outlines many considerations and highlights typical adverse impacts to ensure that proponents of breaching do not overlook them.

San Mateo Creek

2. Approach

The approach used here to inform management is based on identifying commonalities regarding the effects of breaching bar-built estuaries yet recognizing important differences in how the effects play out in specific systems. The report is structured as follows:

1. Lists of abiotic and biotic factors in BBEs were compiled (Tables 1 and 2 of Section 2).
2. For each parameter (abiotic and biotic), a narrative was drafted that examines how mouth state affects each parameter (Section 3).
3. Three focal systems were reviewed – each with substantial environmental data from long-term monitoring programs – to investigate changes in identified parameters before and after breaching events (Section 4 and Appendices 1, 2 and 3).
4. A set of response predictions was drafted to inform breaching decisions (Section 4). Not all responses are observed in all systems, but they do occur in many; some are more certain and universal, while others are more specific or hypotheses that are not fully tested.
5. These biophysical findings are linked to management decisions (Section 5).
6. Recommendations were developed to improve managed breaching activities, including recommendations to avoid worst scenarios, recommendations to improve biophysical expectations outlined in Section 4, and recommendations for monitoring to develop an empirical base for future decisions in specific systems. (Section 6).

The schematic below (Figure 1) outlines a conceptual model of environmental conditions that change with changes in mouth state (whether closed, open, perched or muted). Mouth condition, combined with the unique characteristics of the surrounding estuary and upland environment are primary drivers of water elevation, water quality and stratification, which in turn affect physical habitat extent, habitat quality and habitat connectivity in the BBE. This suite of conditions and habitats supports, or fails to support, specific species and communities. As we are only addressing interventions associated with breaching, mouth state is highlighted as the focal environmental regulator.

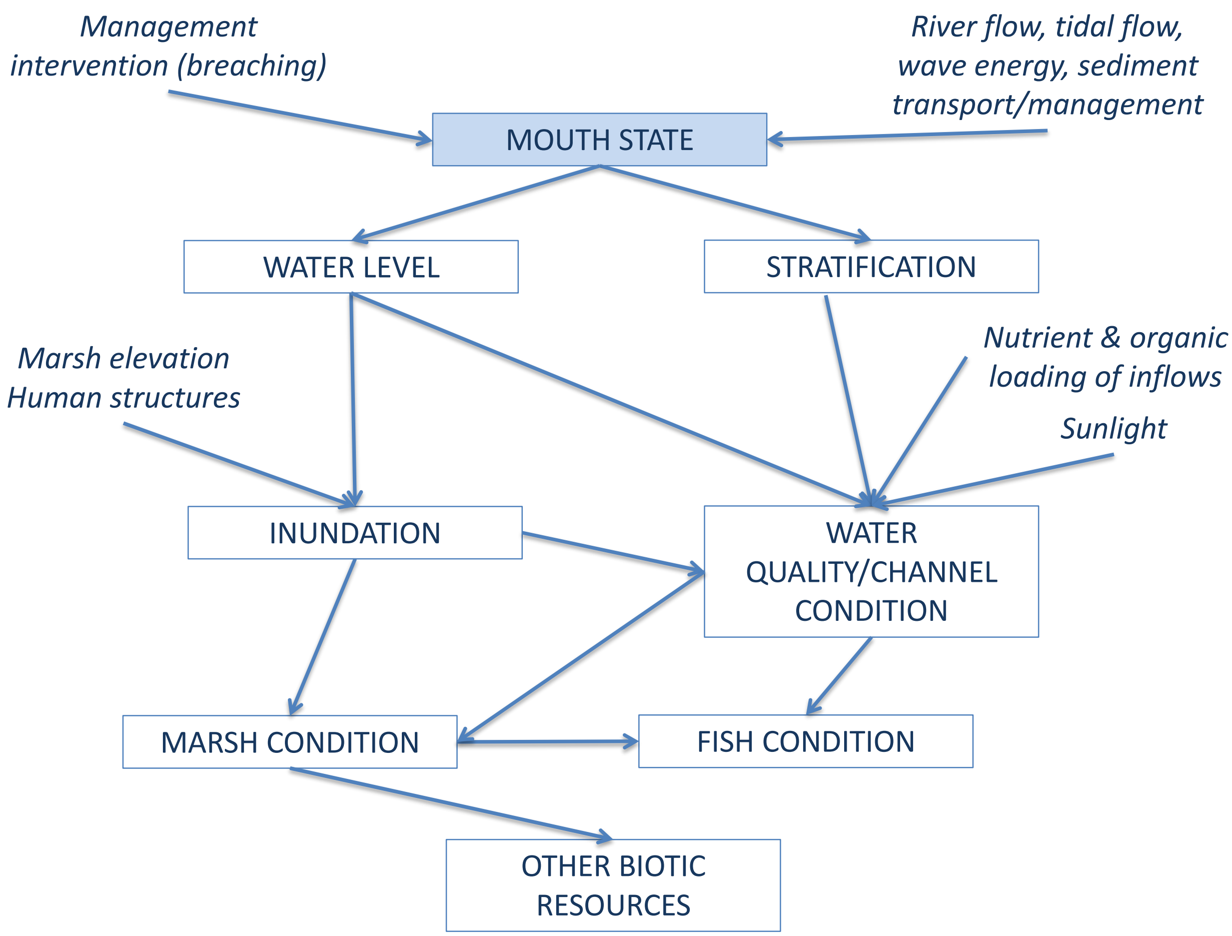


Figure 1. Conceptual model of the effect of mouth state on estuary conditions. Direction of arrow indicates influence.

Using this conceptual model, a list was developed of abiotic and biotic parameters that are potentially affected by BBE mouth breaching (Table 1). Resulting changes to various parameters due to mouth state modifications are discussed below. Data under different mouth states were evaluated within three focus bar-built estuaries: Russian River Estuary, Scott Creek Estuary and Los Peñasquitos Lagoon.

Table 1.Key parameters characterizing the abiotic state of BBEs

State of BBE	
Mouth state	The elevation of the sand barrier determines if the mouth is considered fully open, partially open (muted tides), closed, or perched.
Stratification state	Whether the water body is vertically mixed, weakly stratified, or exhibits intense 2-layer stratification.
Water balance	Positive (filling): more freshwater enters from runoff than leaves by evaporation and seepage through barrier. Negative (draining): less freshwater enters from runoff than leaves by evaporation and seepage through barrier.
Abiotic Conditions in BBE	
Water level	Measure of the daily average and daily range of water level in the estuary.
Stratification	Strength and depth of interface (pycnocline) in the water column.
Light depth	Penetration depth of photosynthetically active radiation (PAR) in water column, often measured as secchi depth.
Temperature	Depth-averaged or upper & lower layer temperatures (daily average; daily range).
Salinity	Depth-averaged or upper & lower layer salinity (daily average; daily range).
Oxygen	Depth-averaged or upper & lower layer dissolved oxygen (daily average; daily range).
Redox state of sediments	Index of oxygen demand at sediment interface
Turbidity	Depth-averaged or upper & lower layer turbidity.
Volume of water	Total volume or layer volumes when stratified.
Area of photic bed	Area of benthic habitat exposed to PAR
Area of inundation	Area of marsh plain inundated by water

Table 2. Key parameters characterizing the biotic state of BBEs.

Biotic Conditions in BBE	
Special Status Species	Surveys of species including fish, turtles, frogs, snakes, birds, etc.
Habitat Condition Score	California Rapid Assessment Method for Wetlands (CRAM)
Marsh plain inundation	Interpretation of extent and duration of wetted marsh based on water level in channel and marsh plain elevation
Soil condition	Salinity and moisture content
Vegetation community	Composition and richness (Environmental Protection Agency's Environmental Mapping and Assessment Program)

Phytoplankton community	Daily average and daily range of primary production and chlorophyll a; species composition and richness
Submerged aquatic vegetation community	Composition, richness, density, distribution, etc.
Invertebrate community	Benthic community composition and richness Water column community composition and richness
Fish Community	Surveys of species including salmonids, goby, flatfish
Marine subsidy	Role and magnitude of marine subsidies (e.g. kelp overwash) in estuary productivity

3. Effect of Mouth State on Estuary Functions and Conditions

Expected relationships between estuary condition and mouth state are outlined in the conceptual model (Figure 1). In this section, a narrative has been drafted that examines how mouth state affects each parameter (abiotic and biotic) described above in Tables 1 and 2.

Overview

The sand barrier between the estuary and the sea is continuously altered by the action of waves, tides, winds, and river outflow effecting sediment erosion, transport and deposition. Bar-built estuaries can be separated from the sea at times when deposition due to the action of waves or wind exceeds the scouring action of flows due to river and tides. Mouth closure is common during the dry season and low-inflow conditions can persist for many months during a drought or in systems with weak river inflow. However, if there is a net water inflow, water level rises until inflows are balanced by a combination of evaporation, seepage through the sand barrier, and limited outflow over the sand barrier. During these perched conditions, water levels often rise enough to inundate marshes, creating high-water conditions in the marsh that differ from tidal systems. Breaches can occur naturally when overflow past the sand barrier is strong enough to erode a new channel – this occurs most commonly in winter. A seasonal cycle of opening and closing occurs naturally and is observed in many regions globally – including California, Australia, New Zealand, South Africa, Portugal, Chile and many other countries (e.g., Ranasinghe & Pattiaratchi 2003; Perissonotto 2010).

Water Elevation

- When the mouth is open, water levels vary tidally. However, tidal fluctuations are typically muted in an estuary with a constricted mouth as the tidal range is limited by the rate at which water can be conveyed through the mouth. Water level minima at low tide are managed by the height of the base of the mouth channel (Behrens et al. 2013).
- During strong river flow, water levels rise in the estuary even when the mouth is open, owing to the constriction of outflow through the mouth.
- When the mouth is closed in wetter regions, during rainy seasons, and/or in urban watersheds with high dry-weather flows, a positive water balance (net inflow) can cause water levels to rise when the mouth is closed. Rising water elevations may inundate marshes and adjacent flood plains (see Sept. 16th through November 7th in Figure 2).
- In arid regions or dry seasons, BBE water level may drop during prolonged closures due to a negative water balance. This results in drying of the marshes and mudflats in late summer. In some BBEs seepage through the sand barrier is significant and this may either accelerate lowering of the water level (if BBE water level is above ocean) or slow it (if BBE water level is below ocean).
- There is often a balance between river inflow and outflow to the ocean due to high BBE water levels that drive barrier overflow and seepage through-flow. This results in water levels that remain relatively steady for months (i.e., perched state). Further, as water level rises, the areal extent of ponded water increases, extending over the marsh plain, thus reducing water level fluctuations and increasing total evaporative water loss.
- Estuary water elevation may increase due to wave overtopping events at high tide (Williams et al. 2014).

- Sand barrier elevation and maximum water levels in the estuary are expected to increase in the future due to sea level rise (Wainwright 2012; Booysen 2017). This prediction assumes sediment is available to build the sand barrier. Sufficient sediment to support marsh accretion is also site-specific and uncertain.

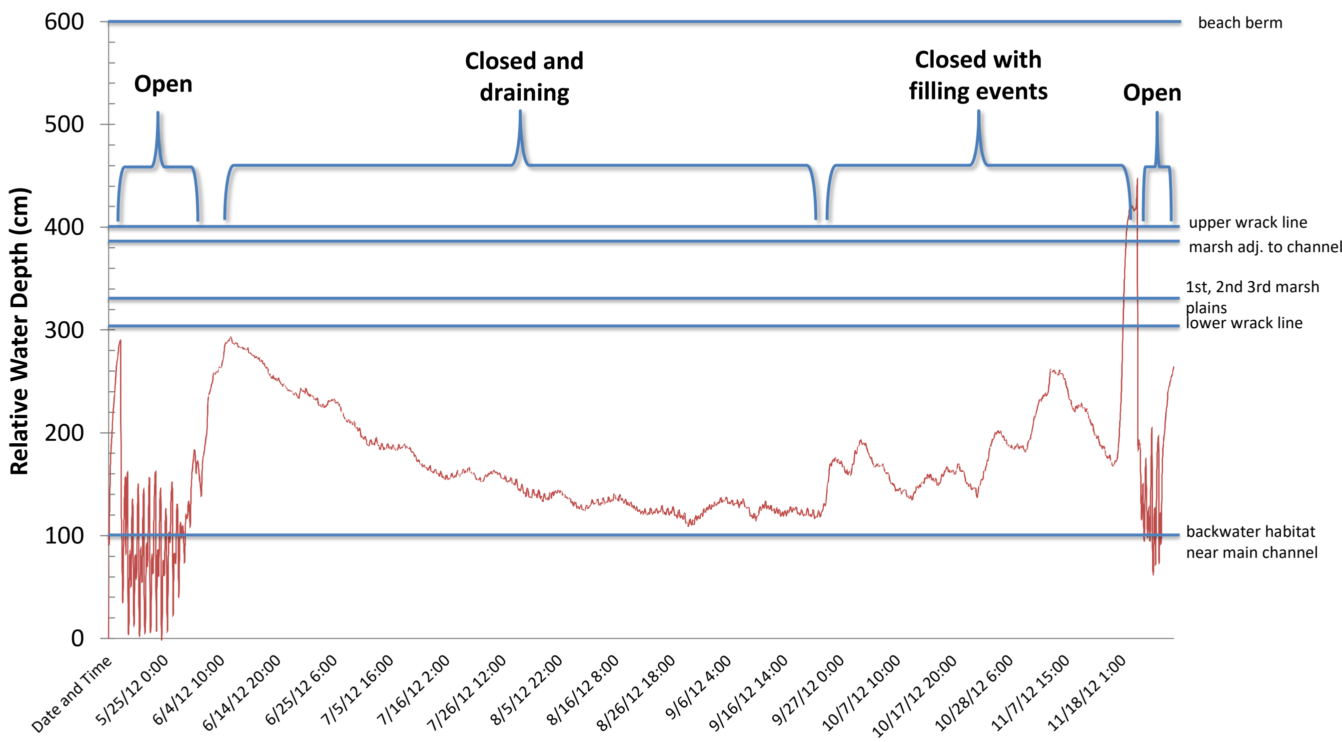


Figure 2. Water elevation (red line) in the main channel of the Gualala River estuary – a BBE in northern CA. This plot shows tidal (open) and non-tidal (closed and draining or filling) states. Blue lines represent the elevations of different features on the marsh plain, while the green band represents the overall marsh plain elevation. Data provided by CCWG.

Stratification

- When the mouth is open, a salt-wedge tidal intrusion of seawater results in tidally varying stratification in some BBEs (Largier & Behrens 2010) while in others the tidal flows can keep the estuary mixed resulting in strong longitudinal gradients in salinity and temperature (Gale et al. 2007).
- When tides are strongly muted, or when BBEs are closed or perched, a layer of seawater can be trapped at depth in the estuary, with low-salinity water near-surface, resulting in water column stratification. Depending on the wind, water depth, and depth/strength of stratification, the water column may mix after a few weeks or months, yielding a homogeneous water column. In BBEs where seepage is important, the dense deep water may be lost through the sand barrier and the water column mixes sooner.

- Stratification in closed BBEs can be enhanced when seawater over-washes the sand barrier during big waves at high tide (Nylen 2015) – and also in some systems by seepage of seawater into the BBE when water levels are lower than in the ocean. Freshwater inflow during closures increases the thickness of the upper layer and thus also increases the vertical stability of the water column.
- When the mouth is perched, with outflow of the surface layer, strong stratification may get stronger as wave/tide overwash is more likely and also because the outflowing surface layer sharpens the stratification.

Water Quality

- When the mouth is open, the outer estuary is characterized by cold, oxygenated ocean waters at high tide and warmer, low-salinity water at low tide (Largier & Behrens 2010). It is unusual to observe extreme water quality levels as the outer basin is readily flushed by tides. However, in the inner basin waters can warm and may be subject to eutrophication effects and/or pollutant accumulation.
- When a closed/perched/muted BBE is stratified, hypoxia (<2 mg/L) can develop in the high-salinity bottom layer due to an accumulation of biological oxygen demand (BOD) and an absence of ventilation through vertical mixing (Hewett 2015; Sutula et al. 2016). At times, this bottom layer can become anoxic when the mouth is closed (Largier et al. 2018).
- Persistent anoxia (<0.5 mg/L) can lead to an accumulation of reduced compounds in the lower layer (Sloan 2006; Richards et al. 2018). When mixed with overlying waters, these compounds drastically reduce oxygen levels throughout the water column.
- Where there is pollutant loading, particle-associated pollutants can accumulate in this trapped bottom layer.
- Seawater intrusion due to wave overwash during a perched/closed state reduces lower-layer hypoxia transiently, but it also enhances stratification and may lead to more severe hypoxia (Largier et al. 2018). Further, wave overwash events may import an abundance of marine algae and kelp that enhances BOD and exacerbates hypoxia.
- Oxygen levels may also decline following the annual die-off of aquatic vegetation (e.g., Potamogeton) or when waters inundate marshes on which there is an accumulation of decomposed plant material (e.g., Pescadero Lagoon, Largier et al. 2018).
- If a closed lagoon remains stratified, the bottom layer may remain cool, whereas if the water column mixes the entire lagoon warms up in summer, reaching temperatures stressful for juvenile salmonids.
- Alternatively, when a closed/perched/muted BBE is stratified, the bottom salty layer's temperature can increase in certain conditions in the absence of tidal cooling. These temperatures are harmful for juvenile steelhead and likely other fish in the lagoon (Smith 1990; Casagrande and Watson 2003; 2nd Nature 2015).

Marsh Plain Condition

- When the mouth is open, intertidal marshes are inundated regularly during high tides (e.g. Los Peñasquitos Lagoon). When the mouth closed, intertidal marshes dry out if lagoon water level is low – alternately, they may be persistently inundated when water levels rise.

- Supratidal marsh plains found in BBEs are inundated during mouth closure events or perched conditions after water level has risen sufficiently (e.g., Pescadero Lagoon). These marshes are also inundated during storm events when high river inflow backs up in the estuary due to constricted outflow over the sand barrier (e.g., Russian River). During open mouth conditions, supratidal marsh plains are fully drained and may dry out (e.g. Scott Creek Estuary).
- The marsh plain within a BBE is subject to fluctuations in inundation (depth and duration) and salinity, which support a diversity of stratified plant communities, often residing at different elevations on the marsh plain, and different to those found in perennial estuaries. Thus, these fluctuations support a diversity of aquatic habitats and unique ecological functions, including benefits to terrestrial and estuarine species (feeding, reproduction, etc.). For example, when a marsh plain is flooded, salmonids have access to the flooded marshes, preying on abundant invertebrates, using the side channels for cover, and avoiding high flows and predation in the main channel.
- BBEs that receive dry-weather flows when closed or perched (e.g., urban lagoons in southern California) can experience impacts to sensitive plant species by leaching salt from soils, reduced foraging habitat for listed bird species (Belding's savannah sparrow) as marsh habitat is inundated, and expansion of breeding habitat for vectors known to transmit West Nile virus to human hosts.

Biotic Condition of the Channel

- When the mouth is open, fish can migrate between ocean and estuary, e.g., salmonids and flatfish (Hughes et al. 2014).
- When the mouth is open, imported pelagic nutrients can fuel estuarine primary production (phytoplankton, seagrass, macrophytes) while tidal exchange also serves to export algal blooms, precluding eutrophication effects.
- When the mouth is open, freshwater submerged aquatic vegetation may be constrained by desiccation and/or competition from brackish submerged aquatic vegetation in higher salinity water (DeDecker 1987).
- When the mouth is open, benthic invertebrate communities are dominated by marine taxa (Netto et al. 2012).
- During prolonged closures, the extent and severity of hypoxia and/or high temperatures can severely constrain the quality and quantity of habitat available to fish, specifically juvenile salmonids. Further, when hypoxia prevents fish from using deeper water, they become more exposed to near-surface predation.
- Hypoxic conditions that develop at depth during closed/perched states do not pose a problem for tidewater goby.
- Closed/perched states provide ideal conditions for rearing of juvenile steelhead trout owing to the availability of food in the channel and also on inundated marshes and vegetated banks. Very high growth rates have been observed in Scott Creek (Bond et al. 2008), Russian River (Matsubu et al. 2018) and Pescadero Lagoon (Huber 2018). However, this trophic benefit can be offset by hypoxia, either through removing deep, cool-water habitat (Boughton et al. 2017) or through fish mortality during breach events following closure (Huber et al. 2017; Largier et al. 2015).
- Benthic hypoxia/anoxia during closed state represents a loss of habitat for flatfish in estuaries.

4. Effects of Managed Breaching

The conceptual model (Figure 1), combined with parameters listed in Tables 1 and 2 guided data compilation at the 3 focal sites and development of the causal statements related to breaching in this section.

Overview

California's bar-built estuaries are unique habitats that provide valuable ecological services. These small estuaries have been perturbed by coastal development, hydrological modifications, and pollutant loading – which have altered ecological conditions in the estuary (e.g., water quality and quantity) and also the natural breaching cycle in some systems (Clark and O'Connor 2019). In response to undesirable conditions occurring in closed BBEs, managed breaches have been advocated and implemented (primary reasons given in Section 1). The magnitude of a breaching operation can range from a simple act of people with shovels to a major effort using earth-moving equipment. In the past, the decision to breach was made by local landowners and municipalities, but managed breaches are now regulated by state and federal agencies and require permits (Appendix 5) in recognition of the potential for negative effects that may offset the positive effects that motivate the breach. Nevertheless, BBE mouth management is best implemented through a local collaborative stakeholder process, e.g., Los Peñasquitos Lagoon (Los Peñasquitos Lagoon Foundation 2016) and Russian River Estuary, which are both based on long-term monitoring, science, and dialog that inform management decisions – for comparison, see also Van Niekerk et al. (2017 and 2018) for mouth management plans for Groot Brak and Bot/Kleinmond Estuaries and Wooldridge et al. (2018) for Seekoei Estuary in South Africa.

Decisions at the state or regional scale on permitting breaches are a challenge as no one size fits all. The nature and desirability of breaching varies along with differences in the biophysical pattern and process, differences in management objectives, and differences in competing values and vulnerabilities across BBE systems. Managed breaching may be repeated within a year in some cases (e.g., Lake Earl, San Dieguito Lagoon) and only once in several years in other cases (e.g., Pajaro River, Pescadero Lagoon). Managed breaches are typically implemented through excavation of a channel through the sand barrier, but breaches can also be initiated through water release from an upstream dam (e.g., Groot Brak in South Africa: Slinger et al. 2017) or unintentionally through enhanced river flow (e.g., Mad River). An alternative to repeated breaching is to construct jetties at the mouth to maintain a permanently open system – thus transforming the hydrological nature of the system (e.g. Elkhorn Slough, Bolsa Chica Wetlands, Agua Hedionda Lagoon, and Los Batiquitos Lagoon).

We found few studies of the ecological effects of breaching and no comparative studies that document the relative costs and benefits of different managed breaching techniques in California (i.e. early versus late in the season, breaching when estuary water level is high versus low, or breaching during high river flow or spring tides versus more quiescent conditions). Nevertheless, there is general consensus on the proximal consequences of a breach (whether managed or natural) – a sequence of reactions that initially follow removal of a portion of the sand barrier that retains water in the estuary:

- Water flows out rapidly.
- Channel is eroded deeper into sand barrier.
- Water level drops in estuary.
- Salinity decreases in estuary as shoreward saline water is replaced with low-salinity water from the back-basin.
- Particulate organic material is re-suspended.
- Plankton and weak-swimming biota are flushed from estuary.
- Marginal habitats are disconnected.
- Greater predator access to a smaller area of water habitat

After a tidal cycle or two the estuary transitions to a tidal state, with further consequences:

- Water level reaches an extreme minimum on low tide immediately after scour.
- New seawater intrudes as net outflow recedes.
- Salinity increases in estuary due to seawater inflow.
- Water level varies tidally (often muted).
- Waves enter outer estuary.

In this regard, there are many similarities between breaches in different intermittently closing systems. But, there are differences in the intensity of these consequences, such as the strength of scour (both flow velocity and sediment erosion) and the depth of the water column immediately post-breach (e.g., Scott Creek Estuary has negligible residual volume following a breach event, Nylen 2015). There are also significant differences in the broader context of these breach events, including seasonality of closure, duration of closure, elevation of marsh plains relative to water levels during closure, stability of water column, COD/BOD loading, light penetration relative to depth of stratification, and algal biomass.

Further, in all systems there are both short-term and long-term effects:

- Short-term or acute effects are associated with the breach event itself. They are transient conditions that typically last for less than a week, but impacts may be severe due to intensity (e.g., very strong currents) or rate of change (e.g., sudden change from freshwater to seawater salinity). These effects (listed above) can be tracked directly and are better known.
- Long-term effects are associated with (i) the resultant change in state (open), (ii) the increasing proportion of time that a BBE is open to seawater exchange – and decreasing proportion of time that it is closed, (iii) the decrease in time that water levels are sustained at a high or more variable levels, and/or (iv) additive or chronic effects of multiple breaches, such as sedimentation of the outer estuary. These effects are not as well-known and typically observed through long-lived features like BBE morphology or marsh plain and channel condition.

Given the recognition of short-term and long-term effects of breaching, there are multiple temporal considerations when permitting breach activities. The first consideration is the timing of a specific breach event – a breach may have a negative impact because it is implemented at the wrong time relative to seasonality of hydrology, fish life cycle, or tidal cycles. A second set of considerations relates to the effect of multiple managed breaches over time and the frequency of these breaches relative to each other. The effect of a more permanent change in mouth state condition (open more than it would be naturally) should be evaluated even if each single managed breach event is benign and meets a defined objective (e.g., Van Niekerk et al. 2005).

Study Sites

To evaluate the effects of breaching on California's bar-built estuaries, we compiled environmental information on three sites that experience managed breaches (to varying degrees) and represent a diversity of BBE characteristics (Table 3). More detailed information and data on the three study sites is included in Appendices 1 through 3. Other bar-built estuary systems were considered during our evaluation of breaching effects, including Topanga Creek, Goleta Slough, Carmel River, San Lorenzo River, and Pescadero Lagoon. While data on water levels and water quality before and after breaches are available in these other estuaries, other data on biotic parameters before and after breaching was inadequate to document how abiotic changes lead to ecological change at the community and ecosystem scales. All California sites that have planned or implemented managed breaches through state and federal permits are shown in Figures 3 to 5.

Table 3. Key information on the three focal sites.

Focal Site Name	Region of state	Watershed size (acres)	Annual precipitation	% watershed impervious
Russian River Estuary	North	949,807	45 inches	9.0
Scott Creek Estuary	Central	19,281	35 inches	1.1
Los Peñasquitos Lagoon	South	61,222	10 inches	64.5

- Russian River Estuary (RRE):
  Large/long BBE (426 acres), northern California, river mouth, breached to avoid flooding, long-term monitoring program in place, may be breached several times in a year.
  See Appendix 1 for more detailed information.

  Characteristics of the Russian River Estuary important in comparing with other BBEs in California:
  - Relict jetty at the mouth and buried in sand barrier.
  - Highly regulated river system with releases from two large reservoirs accounting for enhanced summer flow.
  - Positive water balance, so that water level rises when mouth closed.
  - River flows in summer and fall contain agriculture return flows.
  - A deep channel has been scoured by high winter flows so that there is a large residual volume of water even when the mouth is open.
  - Steep-sided valley leaves little area for intertidal or freshwater marshes.

- Valley provides shelter from winds over inner estuary.
- Shoals trap high-salinity lower layer with minimal seepage, resulting in long residence times and the development of hypoxic/anoxic conditions.
- Mouth exposed to both south swell and north swell so that it may close in winter or summer.
- Tidal prism large enough to maintain open mouth channel in absence of larger waves.

The Russian River mouth can close in any season, but winter closures are typically brief and no management action is taken. In summer, closures may persist and water levels rise sufficiently to risk flooding of adjacent and upstream development. The mouth is then breached manually by heavy equipment. After a manual breach, water level drops significantly, but the deep basin within the channel maintains plenty of residual depth even after deep scour of a channel through the sand barrier. During muted and closed mouth states, a high-salinity subsurface layer is retained, and hypoxic conditions develop in about a week, resulting in limited volume of oxygenated water before the low-salinity surface layer thickens. Seawater intrusion following a breach renews most of the near-bottom saline waters. High marshes are rare near the coast in this geologically constrained system, which minimizes the marsh impacts of managing for low water levels in summer. The loss of marsh habitat further upstream that would be maintained by inundation in the absence of breaching the sand barrier has been noted but not been quantified.

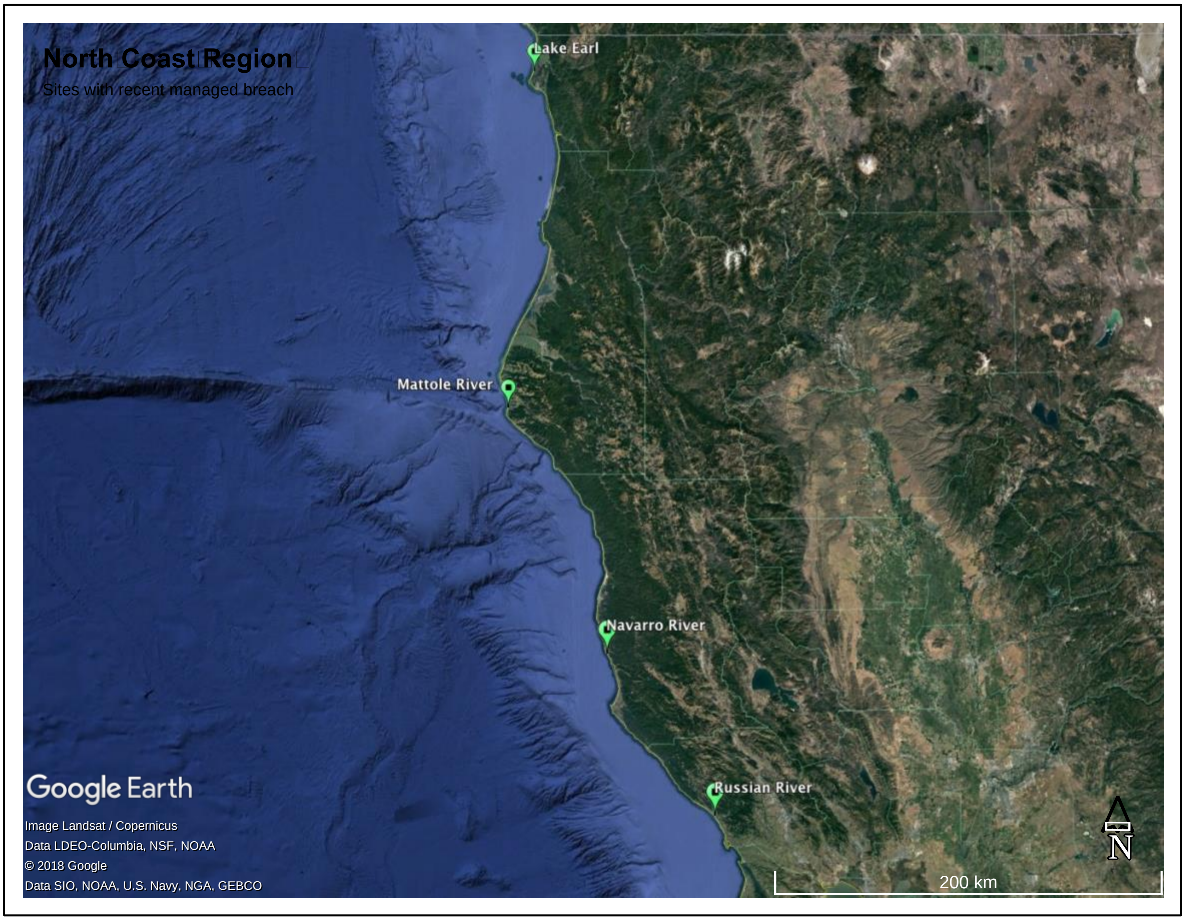


Figure 3. Sites in northern California with recently planned or implemented managed breaches through state and federal permits.

- Scott Creek Estuary (SCE):
  Small BBE (34 acres), central California, creek mouth, permitted to breach to allow fish passage under certain criteria, data collected by many parties, no permitted managed breach has occurred yet. See Appendix 2 for more detailed information.

Characteristics of Scott Creek Estuary important in comparing with other BBEs in California:

- Small basin volume below ocean low-tide level so that basin is mostly drained after a breach that scours a deep channel through the sand barrier.
- Marshes are largely disconnected from open channel and only inundated at highest inundation levels (Beck et al. 2006).
- Significant seepage through closed sand barrier so that high-salinity water exported and stratification does not persist in estuary for more than a few weeks (Nylen 2015).
- Wave overwash imports kelp into the estuary.
- Mouth between two headlands and typically close to northern headland, sheltered from northerly swell in winter – mouth persists in perched state for long periods.
- Main channel exposed to strong winds that enhance vertical mixing even when non-tidal.
- Narrow road underpass constrains channel to one location on beach.

- No rock/cobble sill so that mouth channel can scour deeply.
- Closure occurs typically due to longshore transport and spit developing across mouth.

The mouth of Scott Creek may close at any time of the year, but closures are least common in winter/spring and most common in late summer and fall (Nylen 2015). In the late fall and early winter, freshwater inflow maintains stratification and persistent lower-layer hypoxia is observed, but closures typically do not last long and this lower layer is readily flushed. In summer, closures may last for months. The sand barrier allows seepage loss of the high-salinity subsurface waters and winds can mix the shallow water column, re-oxygenating deep waters after a few weeks. Potential consequences of managed breaching in Scott Creek include the desiccation of some of the high marsh plain and mud flats and significant loss of the small residual water volume within the main channel following a breach (because of engineered changes to the channel pathway, the main channel of the estuary drains when the mouth is fully open). Unpermitted manual breaches have occurred here historically (and reportedly continue in nearby San Gregorio, Gazos, and Waddell Creeks), but because of posted signs, public outreach and diligent local stakeholders, only natural breaches presently occur.

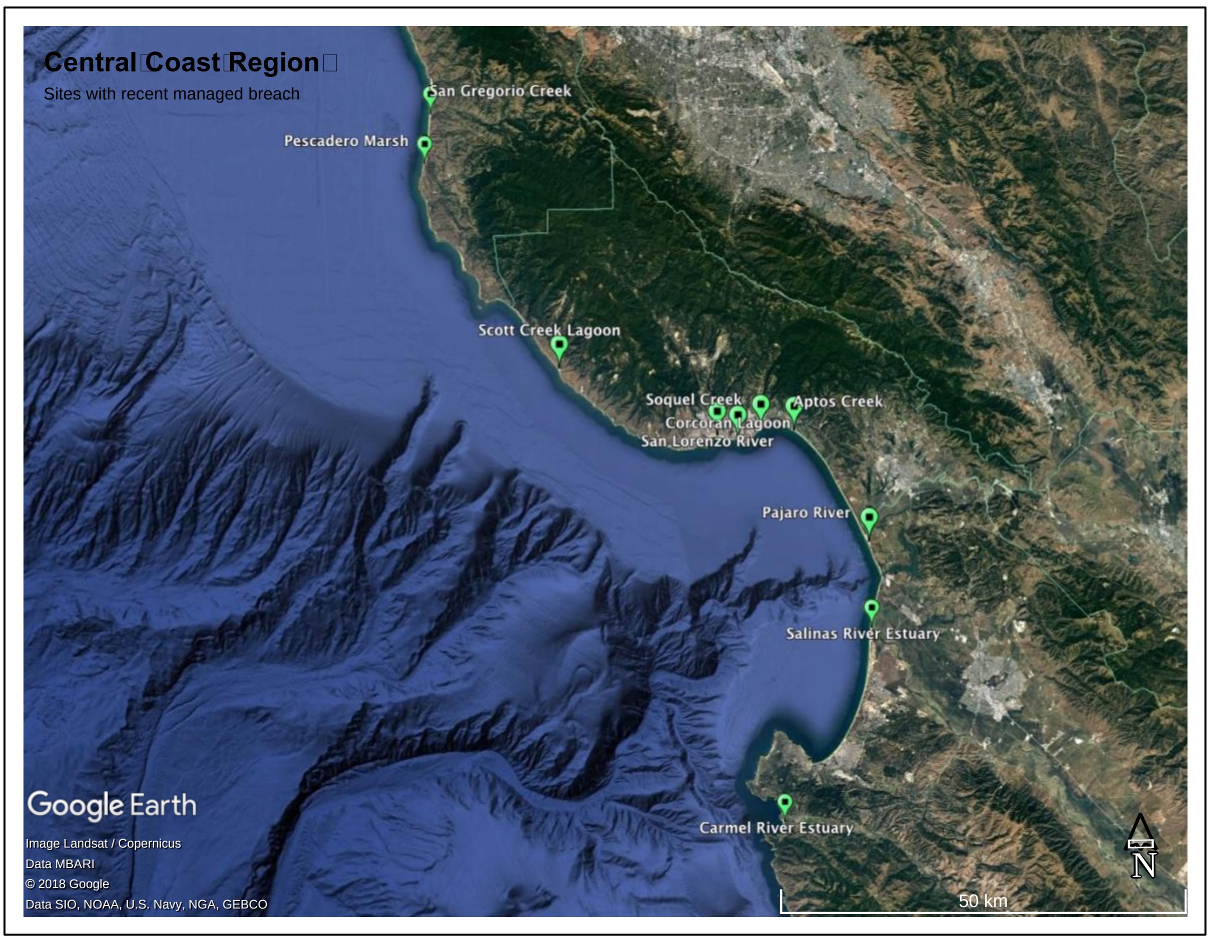


Figure 4. Sites in central California with recently planned or implemented managed breaches through state and federal permits.

- Los Peñasquitos Lagoon (LPL):
  Large BBE (560 acres), southern California, broad marsh, long-term monitoring program in place, breached 1-3 times per year due to water quality, marsh inundation, and disease vector issues. See Appendix 3 for more detailed information.

Characteristics of Los Peñasquitos Lagoon important in comparing with other BBEs in California:

- Large marsh area.
- Marshes are mostly intertidal resulting in large tidal prism that can keep mouth open during spring tides.
- Continuous freshwater inflow of poor quality during dry season from urban runoff ("urban drool").
- Well-defined channel between extensive marshes.
- Weak wind forcing and muted tides allow stratification to persist.
- Broad sand barrier and flood-tide delta that limits seepage outflows.
- Mouth channel cannot scour deeply due to cobble sill – and thus the sand barrier can easily rebuild when wave conditions are suitable.
- Mouth is exposed to south swell in summer and north swell in winter.

Los Peñasquitos Lagoon is breached mechanically to alleviate water quality concerns (specifically low oxygen) and high-water levels in the inner estuary that pose risks to public health through vector-borne brain encephalitis. The estuary mouth closes mostly in winter and spring, due to the action of large waves (in summer tidal flows are sufficient to counter deposition due to weak waves in the elevated mouth channel). Wind-driven mixing is effective at times in this shallow estuary and light can penetrate most of the water column. Therefore photosynthesis and mixing maintain oxygen levels throughout the water column for a few weeks and hypoxia develops slowly. However, increased water column stability and a continuous uptake of oxygen from high BOD leads to hypoxia after a few weeks, triggering a manual breach.

After a breach, the water level drops slightly, while salinity drops significantly as the estuary is flushed by low-saline water from the back-basin. The drop in salinity is usually brief, before seawater intrudes. While some breaches are manually initiated, many breaches occur naturally when water levels crest the low sand barrier (a road bridge maintains a low point in the sand barrier). A long-term management strategy was developed by the LPL Foundation in collaboration with California State Parks (and informed by the Pacific Estuarine Research Laboratory and the Tijuana NERR) and a monitoring program was initiated in 1987. This breaching strategy has been implemented for many years and the marshes are no longer dependent on seasonal closure and/or mouth-driven flooding conditions but rather are supported by tidal inundation.

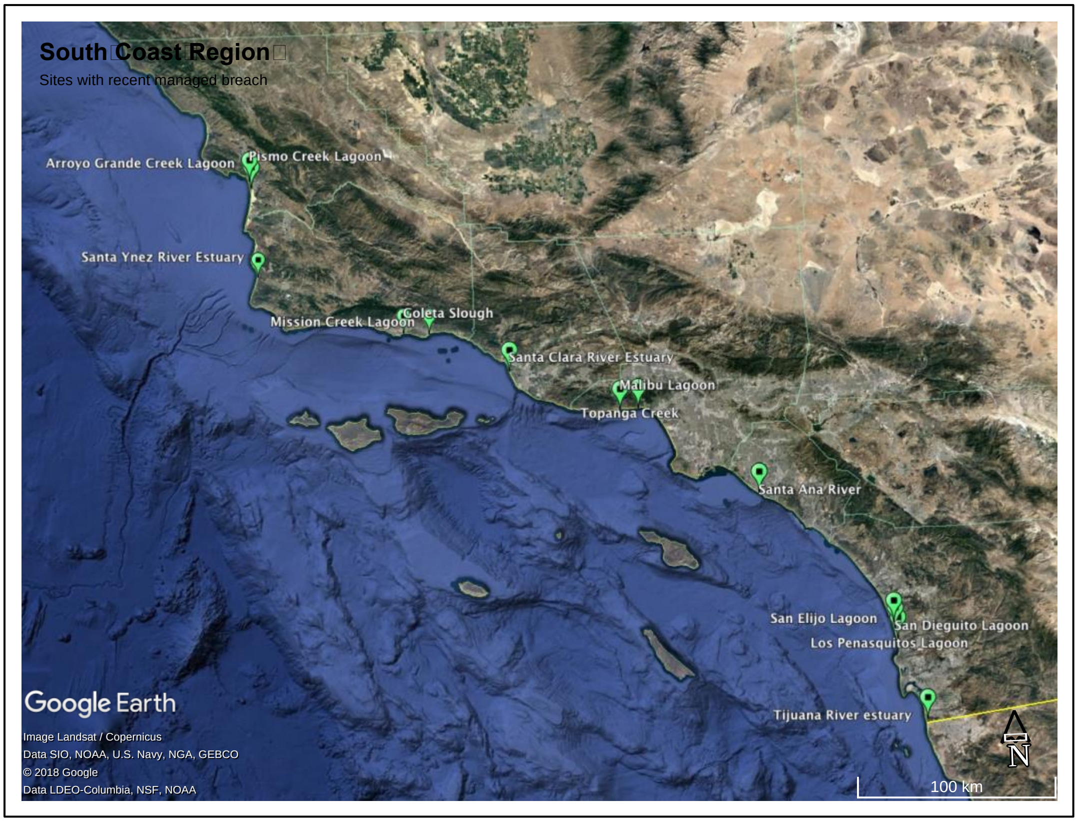


Figure 5. Sites in southern California with recently planned or implemented managed breaches through state and federal permits.

Extant Data and Environmental Observations

Russian River Estuary and Los Peñasquitos Lagoon both have long-term monitoring programs, however there are few biotic data available for either estuary during closed mouth state, precluding comparison of open and closed conditions in these BBEs. There are many studies being conducted by NMFS, CDFW and academics in all three of our focal estuaries, but lack long-term data sets that represent both open and closed conditions. There is a large data set available for Scott Creek Estuary from the Comparative Lagoon Ecological Assessment Project (CLEAP, Beck et al. 2006), which includes both open and closed conditions in 2004-2005. Thus, while the statements below are based on observations and data assembled from the three focal systems, several of the statements are not fully supported by published studies and therefore represent best professional judgment – as such, they represent hypotheses that remain to be tested through future analyses.

Expected Responses to Breaching

We developed a set of statements (below) to explicitly record and describe our expectations of the effects of managed and natural breaching on bar-built estuary environments. In this set of statements, we also note similarities and differences among case studies (and other systems) to represent the diversity of BBEs statewide. Assertions are well supported by monitoring data for effects that are physical and immediate, but less so for biological effects (species population response to proximal physical effects) because of limited data. Even where extensive data are available (e.g., the three focal systems) there is inadequate data to support and thus uncertainty remains regarding some of the statements below. This is addressed in recommendations for improved monitoring. Thus, while most predicted responses to breaching are supported by literature and data, some are assertions based on professional judgment and field experience (and still need to be rigorously tested).

Statement 1. When the sand barrier is breached, the water level drops – then reverts to tidal fluctuations.

When the water level in the BBE crests the lowest point on the wave-built sand barrier (typically found in a wave shadow), a breach may occur. Figures 6 and 8 demonstrate the drop in water level following breaches in Russian River Estuary and Los Peñasquitos Lagoon (also Figure 2). This breaching effect on estuary water elevation is common and certain. Even in BBEs with negative water balances and low water levels in summer, breaches will occur only after winter rain/inflow and/or wave overwash has filled the estuary embayment above ocean water levels. Following outflow and scour of the mouth channel, tidal fluctuations return to the estuary (typically within a day).

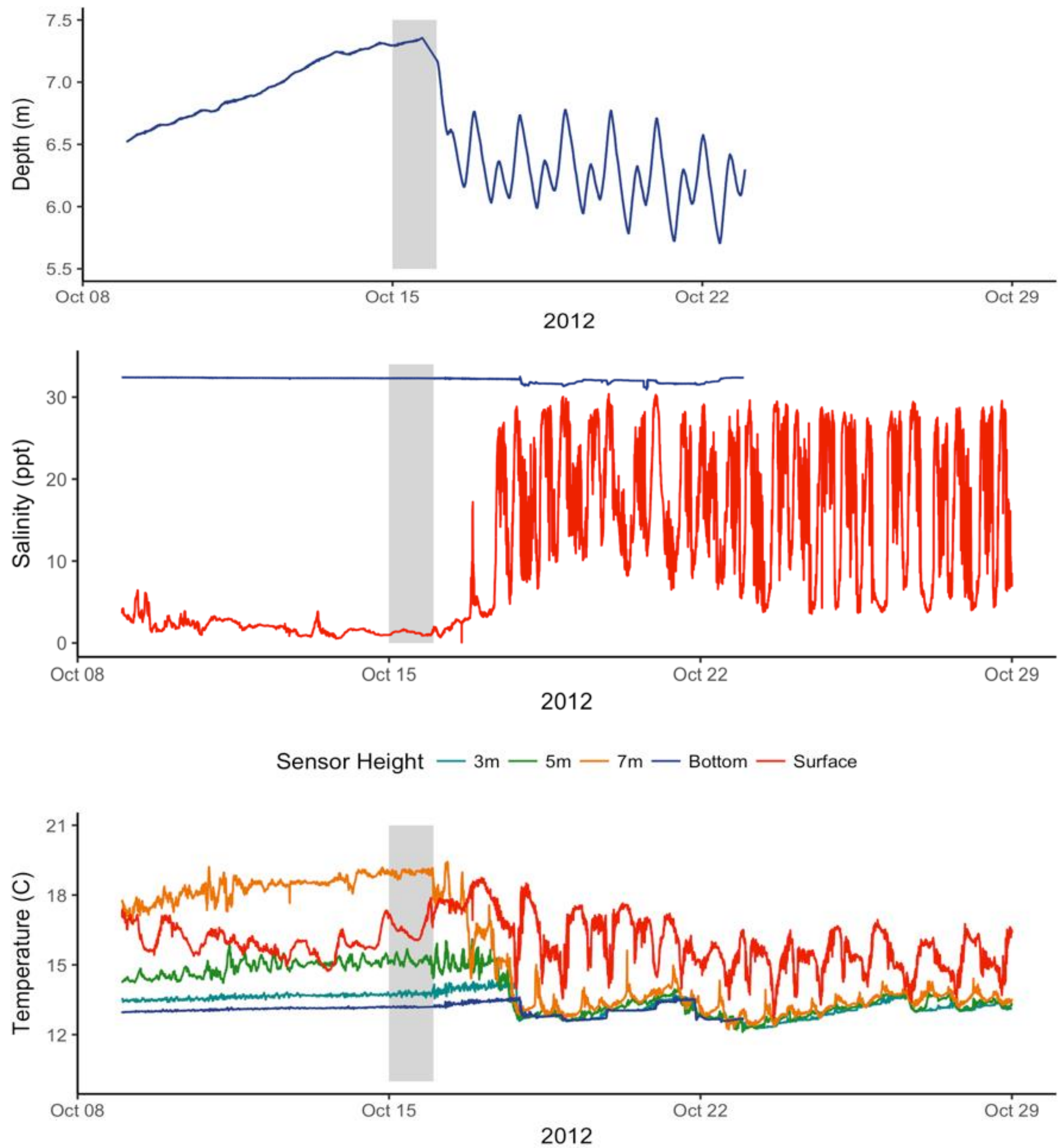


Figure 6. Natural breach (grey bar) in Russian River Estuary, October 2012 (Robart & Largier, 2013). Top panel: water level at Jenner visitors center (~1km from mouth). Middle panel: salinity near-surface and near-bottom at Patty's Rock (~2.5 km from mouth). Bottom panel: temperature at multiple depths at Patty's Rock (~2.5 km from mouth).

In many systems, the highest water levels are observed immediately prior to breaching and lowest water levels occur soon after breaching due to deep scour of the mouth channel. If not breached, water level in the estuary embayment will rise further until triggering a natural breach. The mechanisms that control the water level response in a BBE following a managed breach are the same as those following a natural breach, but the nature of the breach differs owing to the context – specifically the height of water level prior to the breach (hydraulic head) and the strength of stream/river inflow to the BBE (which sustains outflow through the breached sand barrier) are typically less for managed breaches owing to the time of the year that the breach occurs.

Of particular interest is the occurrence of an annual minimum in water level following breach events, when the mouth channel is scoured more deeply through the sand barrier than at other times of the year. This annual minimum in water level is notable in Scott Creek Estuary, where the channel bed is above ocean low-tide level (similar to Salmon Creek in Sonoma County) – also see November 18th in Gualala River Estuary (Figure 2). During these low-water-level time periods, there is negligible pelagic habitat and persistently inundated mudflats are exposed to direct sunlight and desiccation. Although a transient stress, these evacuation events are natural – typically occurring in winter for smaller BBEs, following rainstorms and river flow events. Managed breaches that result in evacuation during summer months may not mimic natural evacuation events as desiccation and related impacts are much larger following summer breaches due to weather and the absence of river inflow.

Statement 2. When the sand barrier is breached, high velocities occur as water flows out rapidly.

There is an absence of data on the velocity of discharge flow within the mouth channel, but estimates can be made from water mass balance calculations, direct observations, and modeling (Parkinson & Stretch 2006; Wainwright 2012). Speeds can be much greater than 1m/s, which is more typical of open-mouth tidal inflow/outflow velocities. Discharge velocities during breaching thus account for the highest velocities in many systems, and scour of sand along with flushing of algae, plankton and other biota. However, in systems with large river inflow, peak winter outflow through the mouth are comparable with breaching velocities through the sand barrier.

Statement 3. When the sand barrier is breached, a deep channel is cut by the scouring action of outflow.

As addressed in Statements 1 and 2, relating to water levels and velocities, a breach leads to high-velocity outflow that erodes the sand barrier to create a narrow deep channel at the estuary mouth (Stretch & Parkinson 2006; Rick & Keller 2013). While this breaching effect always occurs, the degree of scour depends on the sediment erodibility (and any presence of bed rock, coble or gravel), as well as river discharge velocities and duration of high outflows through the sand barrier. As compared with a natural breach, managed breaches are often implemented when a BBE exhibits a lower hydraulic head and weaker river inflow to the estuary, resulting in slower and briefer outflow through the barrier that is not as effective in channel scour (Beck & Basson 2008; Young 2018). Breaching at spring tide can mitigate this effect as there is a large water-level head at spring low tide – but the timing of the breach becomes critical (and a serious challenge to management) as waves may deposit sediment in the channel on the subsequent spring high tide and also the open-mouth condition may be brief as neap tides follow a few days later. Post-breach mouth state depends on site-specific stream discharge and wave conditions, as well as tidal flows. In some circumstances, a manager may choose a partial-breach option to avoid deep scour and preclude super-low water levels and evacuation of the estuary in summer. This can have negative secondary effects, such as export of the upper water column layer only (see Statement 4) and net accretion when the sand imported through open mouth post-breach conditions exceeds the sand eroded and exported during the breach event (over several breaches, this accretion can develop as a serious additive effect). There are insufficient field data to infer a scouring efficacy for past breach events, which makes it difficult to quantify scouring potential.

High velocities during a breach event can also resuspend sediment in the estuary basin, releasing pollutants that have accumulated in the sediment or deep water column as well as high-COD particles.

Statement 4. When the sand barrier is breached, estuary salinity drops and later increases with new tidal inflows.

With the outflow of water from the BBE, the salinity at specific sites decreases due to seaward movement of lower salinity water previously in the inner estuary and over the marshes. This is most evident in the shallow Los Peñasquitos Lagoon where the salinity dropped from 20 to 10 ppt following the April 2014 breach (Figure 7, grey bar). This drop in salinity is often short-lived and salinity rises again as new seawater intrudes once the estuary water level has dropped to within the tidal range (Figure 7). The salinity minimum is typically less than a day but may persist longer if the breach is accompanied by strong river inflow. For example, the salinity minimum persisted for up to a week in Scott Creek Estuary (Figure 8). During weaker breach outflows, dense salty water near-bottom that is trapped by shoals may not flow out (e.g., Slinger et al. 2017) and it is only flushed if there is a significant intrusion of seawater after the breach. With draining of high oxygen-demand waters from marshes post-breach, a partial breach may exacerbate deep-water hypoxia by a particle flux into the trapped lower layer.

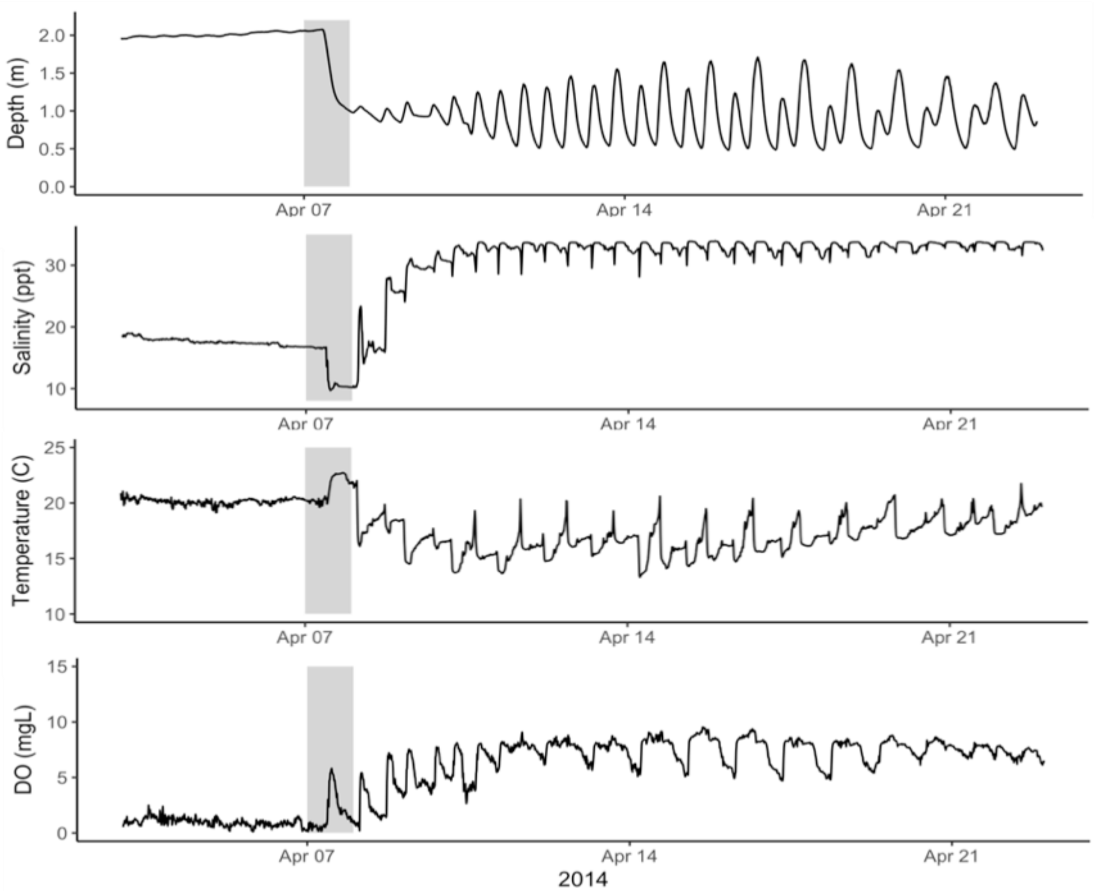


Figure 7. Managed breach event (grey bar) in Los Peñasquitos Lagoon, April 2014 (Los Peñasquitos Lagoon Foundation (2016). Top panel: water level. Second panel: salinity near-bottom. Third panel: temperature near-bottom. Bottom panel: dissolved oxygen near-bottom.

Statement 5. When the sand barrier is breached, estuary temperature changes.

Temperature in the estuary may either increase or decrease following a breach, depending on relative temperatures in ocean, estuary, river and marshes. In summer and fall, the freshwater input and marsh waters are typically warmest and the ocean coolest, so that a breach results in a brief warming followed by cooling, as in Los Peñasquitos Lagoon (Figure 7). However, in winter the ocean may be warmer.

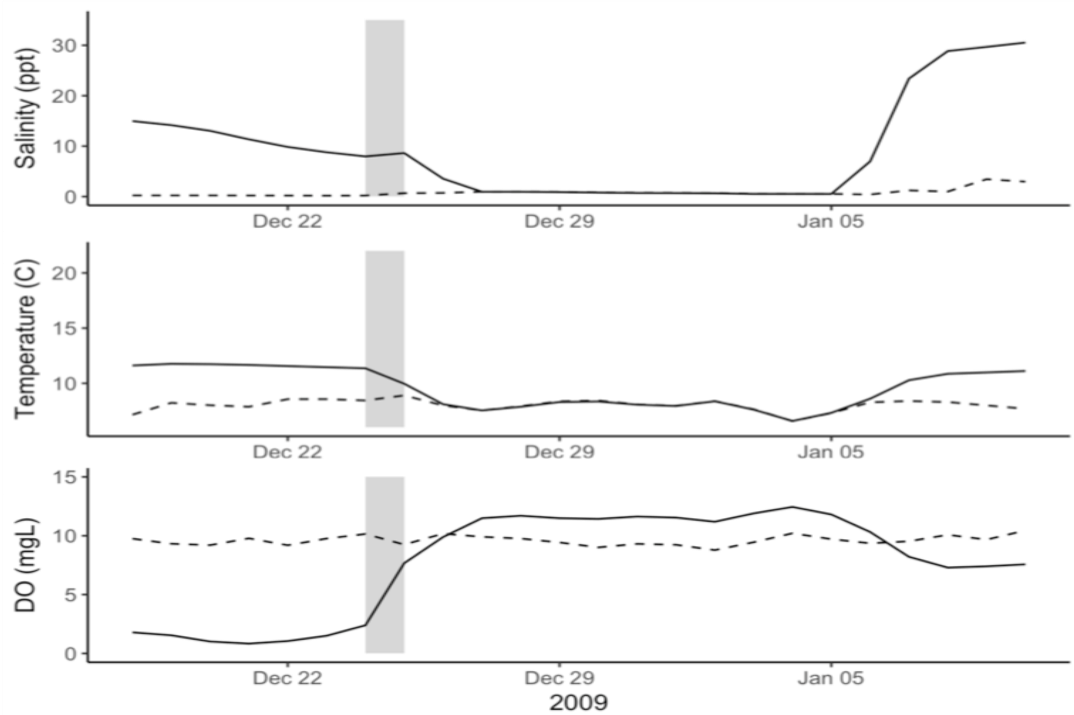


Figure 8. Natural breach event (grey bar) in Scott Creek Estuary, December 2009 (Nylen 2015). Top panel: daily average salinity near-surface (dashed line) and near-bottom (solid line). Middle panel: daily average temperature near-surface (dashed line) and near-bottom (solid line). Bottom panel: daily average dissolved oxygen near-surface (dashed line) and near-bottom (solid line).

Statement 6. When the sand barrier is breached, stratification is broken down – and subsequently restored with new seawater intrusion.

When a BBE is stratified during closure, the dense near-bottom water can be flushed either during the breach (e.g., Los Peñasquitos Lagoon, Figure 7) or by new seawater intrusions within a few days of breaching (e.g., Russian River Estuary, Figure 6) – also see Largier et al. (1992) and Slinger et al. (2017). Either way, the top-bottom salinity difference is reduced and often salinity and other water properties become uniform due to tide- or wind-driven mixing (e.g., Scott Creek Estuary, Figure 8). During the subsequent tidal phase, stratification varies with tidal intrusions of a salt wedge – and over time there is a tendency towards stronger or more persistent stratification returning as the mouth shoals. While this is common, there are important exceptions when only the upper layer flows out and the mouth does not scour deep enough to allow the water level to drop low enough to restore tidal inflows (or the tidal prism is smaller than river inflow over tidal period). In these cases, more typical of managed breaches, the lower layer with higher salinity remains trapped (Human et al. 2015). Meanwhile, the upper layer salinity drops so that stratification increases, and the outflowing surface layer may sharpen the halocline, establishing intense stratification that precludes any vertical mixing (Behrens et al. 2015a). Nevertheless, this highly stratified water column is shallower post-breach with a thin surface layer that may be mixed by strong winds that would be incapable of mixing a more stable deeper water column.

Statement 7. When the sand barrier is breached, oxygen is restored to the hypoxic lower layer.

When an estuary is stratified during closure, the high-salinity lower layer typically becomes hypoxic. Following Statement #6, this lower layer is renewed either by direct flushing or by seawater intrusions – both replenishing oxygen near-bottom. Both processes may occur, as in Los Peñasquitos Lagoon (Figure 7), where initial oxygen increase occurs concurrently with salinity decrease at the sensor (within gray bar) and subsequent oxygen increase occurs concurrently with salinity increase (after gray bar). In Scott Creek Estuary oxygen increases with the salinity decrease (Figure 8, just after grey bar), representing a flushing out of near-bottom water as the persistent stream outflow erodes the shallow halocline and removes the entire bottom layer over a few days. As in Statement #6, there are important exceptions when the lower layer is not flushed and hypoxic water is retained in the estuary. In the worst case, there is only hypoxic, saline water remaining in the estuary after it has been emptied, which significantly reduces suitable fish habitat and may result in mortality (e.g., Becker et al. 2009; Largier et al. 2015). Another special case occurs when accumulated oxygen demand (specifically COD) is released from the anoxic lower layer and/or drains off marshes, stripping oxygen out of oxygenated surface waters and resulting in a rapid and severe decrease in oxygen concentrations post-breach that can persist for a few days. While uncommon in most BBEs, this scenario has occurred repeatedly in Pescadero Lagoon, resulting in fish mortalities (Largier et al. 2015; Largier et al. 2018).

Statement 8. When the sand barrier is breached prematurely and repeatedly, sand accumulates in the flood-tide shoal.

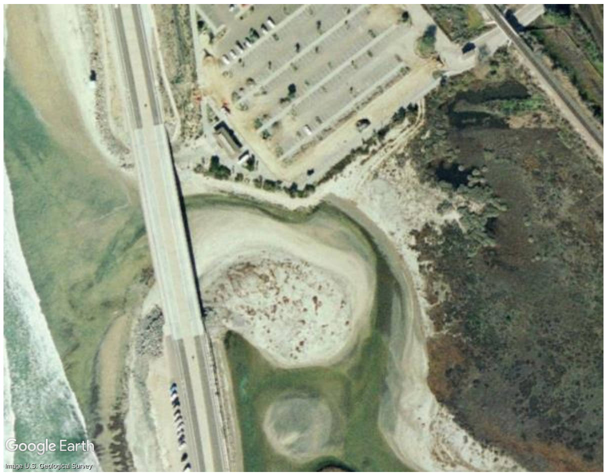
Although a single sub-optimal breach event may result in limited accretion, repeated breaches with insufficient scour result in accumulation of sand in the flood-tide shoal so that it becomes shallower (reducing tidal prism) and broader (decreasing the probability of deep-scour breaches, Figure 9). Partial breaches can still allow inflow, but often this will be in the form of shallow swash (infra-gravity waves, e.g., Williams 2014), which transports sand into the estuary. To persist in a quasi-equilibrium state, the volume of sand scoured from the mouth region during breach events and/or winter flow events must balance the volume of sand deposited by wave overwash and shallow tidal inflows with wave action.

While flood tide shoals characterize more intertidal systems like Los Peñasquitos Lagoon and Pescadero Lagoon, this is less important in supratidal systems where tidal inflow is weak or absent (e.g., Scott Creek and Salmon Creek). In these systems, aeolian deposits (migrating sand dunes and wind-blown sand, e.g., Santa Maria River, Salinas River) and wave-driven overwash fans may be more important in producing shoals at the mouth.

In BBEs with weak river inflow, the annual breach event is critical for scour and low-energy managed breaches may lead to additive long-term sediment accretion and a change in breaching seasonality and effects. This is specifically a concern when the mouth is breached during high waves that can readily transport sediment into the estuary.

Further, breaching allows wave action to enter the estuary, which can result in shoreline erosion in the outer estuary (e.g., Russian River Estuary). When the mouth is open more often in the low-flow season, shoreline erosion in the outer estuary may impact developments like roads and buildings.

2008



2012

2015

2016

Figure 9. Shoaling at the mouth of Los Peñasquitos Lagoon, just east of Pacific Coast Highway. (© 2002-2015 Kenneth & Gabrielle Adelman, California Coastal Records Project, www.californiacoastline.org).

Statement 9: When the sand barrier is breached, water drains off the marsh plain and the marsh dries out.

While some marshes are inundated during high tides (e.g., Los Peñasquitos Lagoon), many BBE marsh plains are only inundated during perched water levels (e.g., Scott Creek Estuary, Pescadero Lagoon). In these systems, a breach event terminates high-water-level conditions and the marsh drains – resulting in scour of marsh channels and tidal creeks, counteracting sediment accumulation during winter flooding and summer perched conditions. Marsh soils and vegetation then slowly dry out over weeks following the breach – with higher desiccation rates during long and dry summer days. If a breaching regime is enacted to reduce flooding of adjacent properties, the duration and depth of marsh plain flooding is reduced significantly. Figure 10 depicts changes in the duration that various portions of the marsh plain are flooded due to small changes in water elevation (Scott Creek Estuary). The left panel shows the percent of time that portions of the plain were flooded under natural conditions and the right panel shows the reduction in time flood waters would cover most of the marsh plain if breaching were implemented before water elevations reached the natural perched height (i.e. implementing a management program to restrict water elevations to below 1.45m above mean sea level (MSL)).

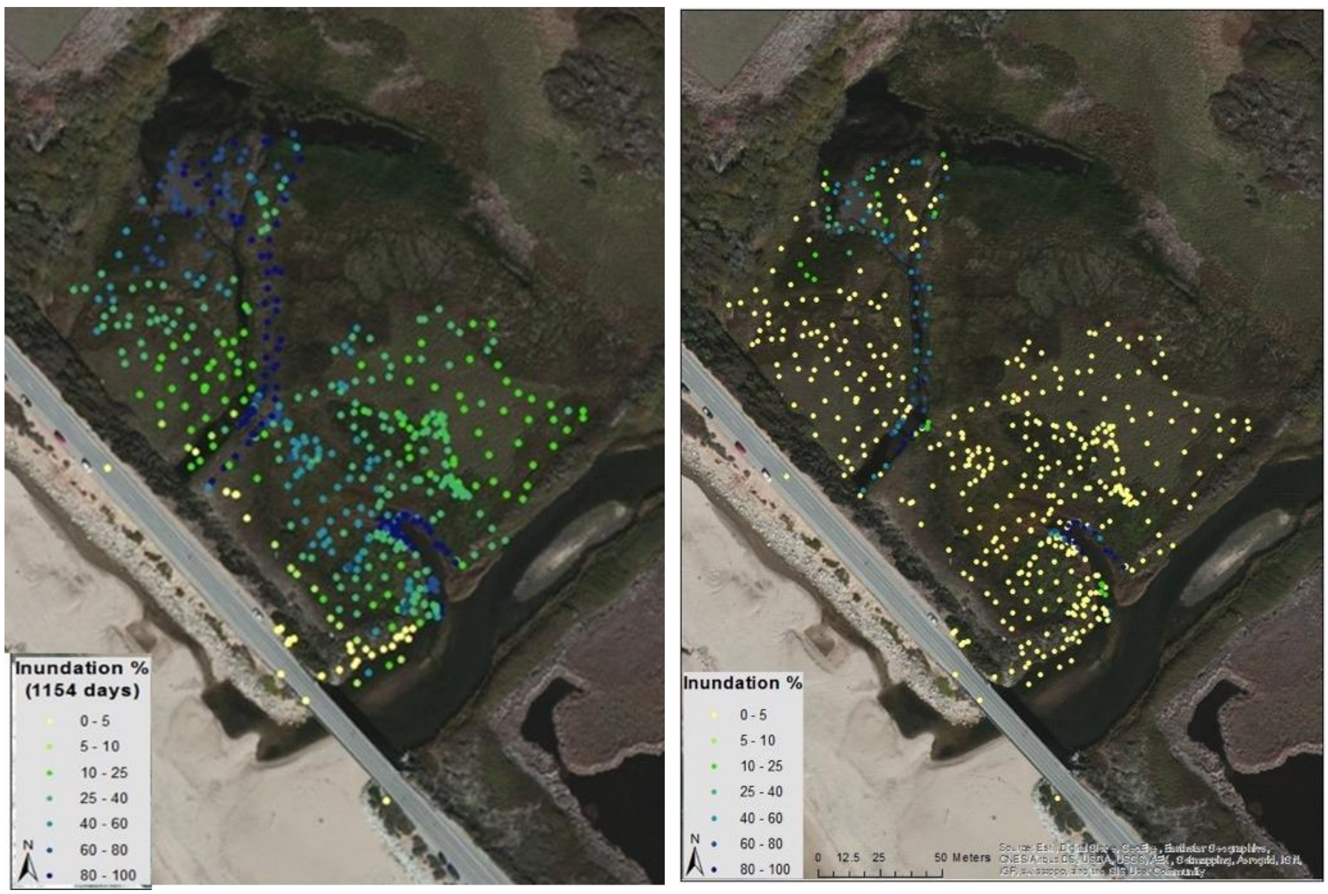


Figure 10. Left panel: percent of time that points on the marsh plain and side channel locations are inundated in Scott Creek Estuary from 2013 to 2016, over a period of 1164 days. Right panel: Percent of time same points on the marsh plain would be inundated if a hypothetical managed breaching regime limited water level to 1.45 MSL.

Breaching also leads to less variability in "wetness" of marsh habitats, separating habitats into primarily submerged (flooded 80-100% of time) and exposed upland conditions (flooded less than 20% of the time) – Figure 11. These hydrologic changes impact soil chemistry, lead to significant changes in vegetation communities and aquatic food webs, eliminate many unique habitat areas within the marsh plain, and reduce off-channel refugia for species such as tidewater gobies and other fish.

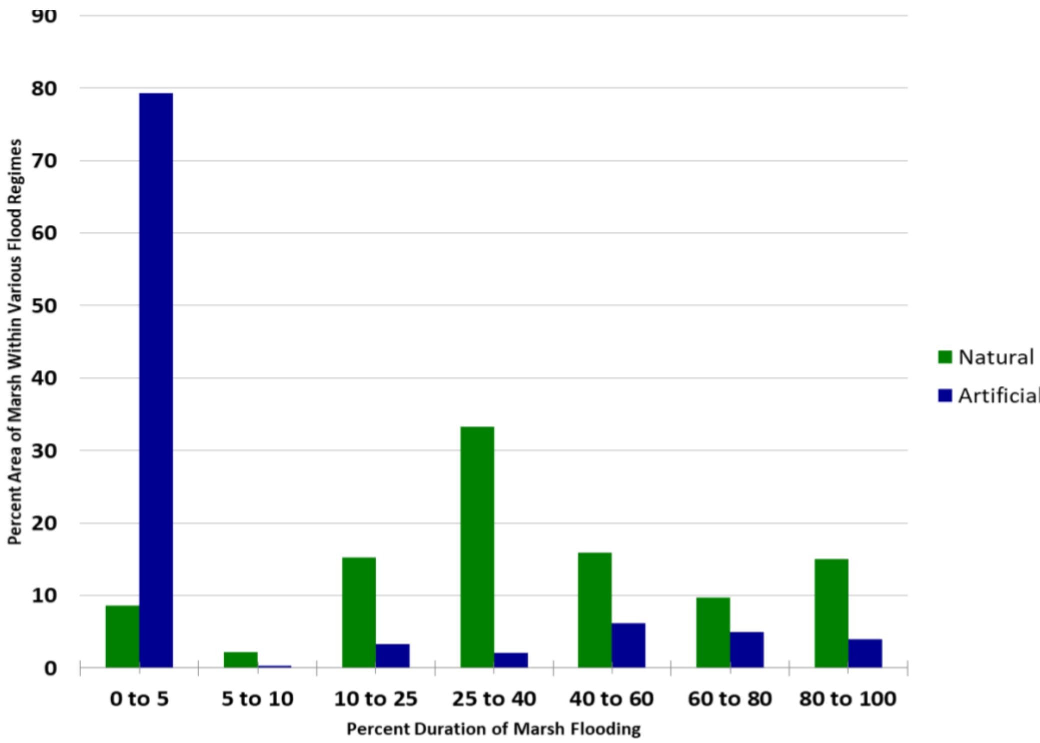


Figure 11. Percent of the marsh plain flooded under natural conditions (green bars) and under a hypothetical 1.45 m maximum water elevation breaching strategy (blue bars)

Statement 10: When the sand barrier is breached repeatedly, marsh condition and plant diversity are altered.

Managed breaches are premature by definition (they occur before a breach would happen if it occurred naturally), and thus they represent shorter periods of marsh inundation (see Statement 9). The ecological effects of repeated managed breaches are only likely to appear after a few years. At given elevations on the marsh, plant species will experience reduced inundation and be replaced by plant species adapted to dryer conditions (Figure 12). The California Rapid Assessment Method (CRAM) has been used at over 100 BBEs to assess wetland condition and impacts from human alterations (CCWG 2013, Heady 2015) (see Appendix 4). A comparison of estuaries showed a decrease in several CRAM metrics for BBEs with altered "hydro-period", i.e., marsh inundation time (Figure 13). Lower CRAM scores denote more degraded habitat conditions. Although CRAM scores are not available for the same system under both managed and natural breaching scenarios (which may reveal benefits to marshes from breaching in perturbed systems), in general the following trends are associated with systems in which managed breaching is more common:

- The CRAM hydro-period metric score decreases (alterations to the typical period of marsh inundation).
- The CRAM structural patch richness metric score decreases – if breaching prevents inundation, then some physical patch types will not form on the marsh plain (e.g., large woody debris, pannes or pools, wrack line or organic debris in channel/floodplain/depressional wetland plain,

secondary channels on floodplains or along shorelines, and swales on floodplain or along shoreline).

- The CRAM topographic complexity metric score decreases, due to reduced formation of channels and pools on the floodplain.
- There is a desiccation of plants and a shift in community composition to more upland plant species (Figure 12), which can lead to a change in the number of different plant layers, the number of co-dominant species, and the number of invasive species.

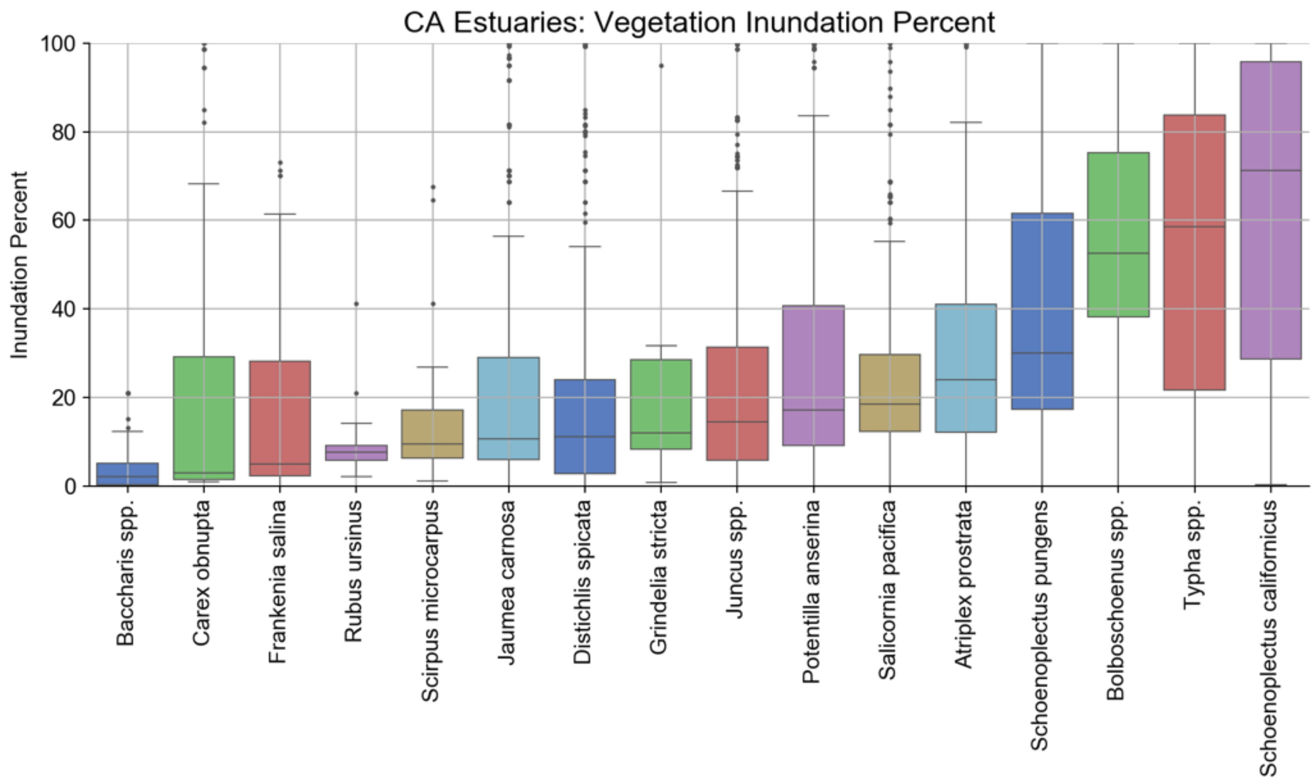


Figure 12. Plant species commonly found in bar-built estuaries organized by the amount of time they were inundated at 30 estuaries along the California coastline. The box represents the quartiles of the data. The mid-line of each box is the median, lower end of the box is the mid-value between the lowest value and the median. The higher end of the box is the mid-value between the highest value and the median. The whiskers show the extremes (max & min) values, while the dots are outliers. (data provided by CCWG).

Although managed breaches result in an alteration of the natural hydro-period (shift to more tidal conditions), in heavily urbanized systems with enhanced dry-weather inflows (urban drool) or systems with modified hydrology or persistent pollutant loading, breaching may be necessary to maintain native habitats and special status species. In general, managed breaches alter the number of unique habitat niches, topographic complexity and structural patches due to less flooding of the marsh plain – and desiccation of plant communities that leads to a shift to more upland species. Changes may also include a reduction in the availability of secondary channels and off-channel habitats that provide refuge, breeding and rearing areas for animal species, including cold-water refugia for salmonids (mouth closure backs up water not only over marshes but also into floodplain environments that provide cool, high-oxygen respite from warming lagoons in late summer). These habitat changes may also represent a reduction in the habitat available for special status species that rely on the marsh plain ecosystem (i.e., fish, turtles, frogs, snakes and birds), as well as habitat patch size, separation distance and connectivity. In this way, these changes can translate into a reduction in conservation value for habitat that supports the life-history needs of the species (Federal Register Vol. 81, No. 28, February 11, 2016).

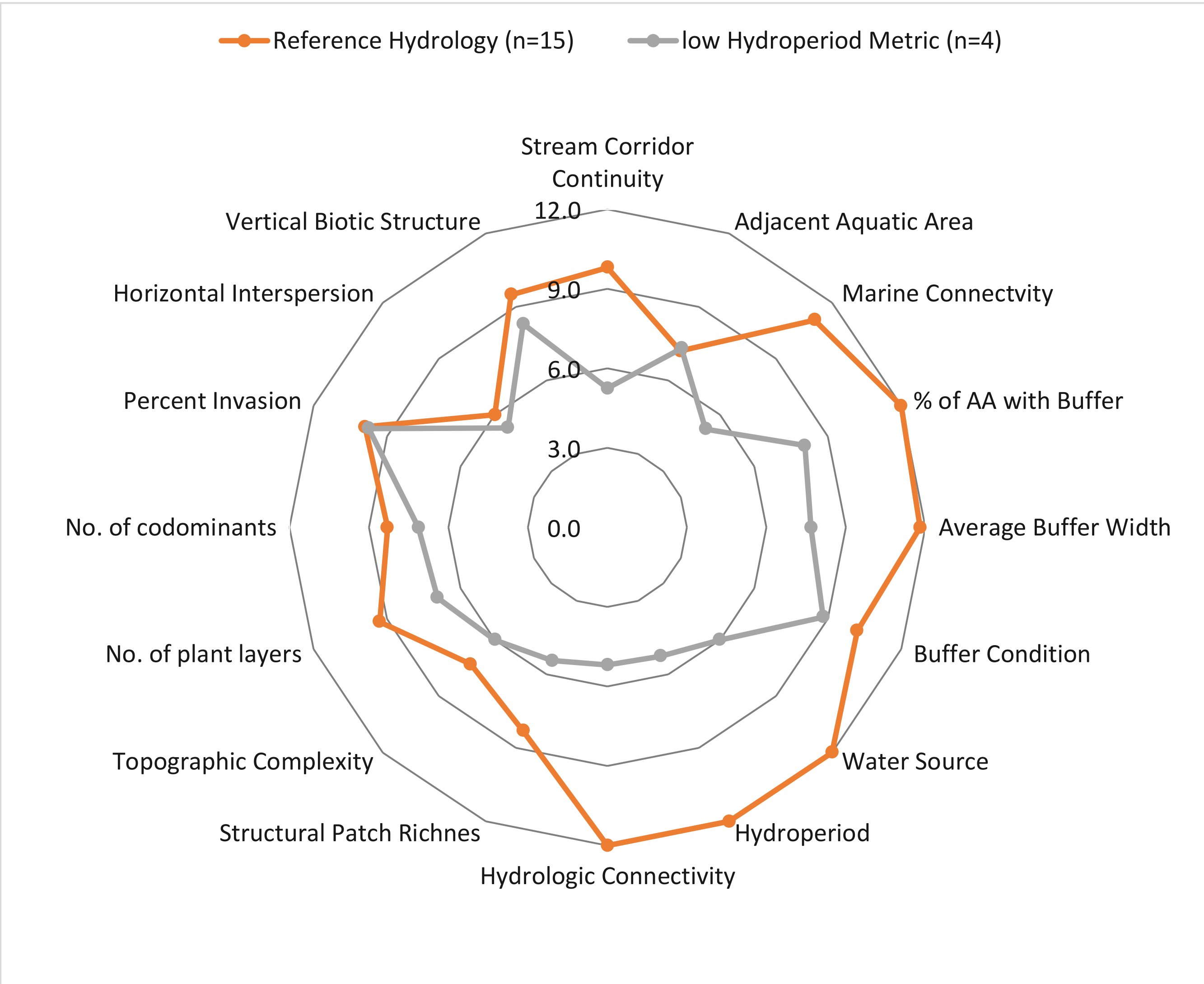


Figure 13. CRAM metric scores at BBEs with reference hydrology conditions (orange line) and at BBEs with breaching and impediments to natural mouth migration that lead to reduced marsh inundation (grey line). Points further from the center denote higher quality habitat conditions (unpublished data by CCWG available from EcoAtlas.org)

Statement 11. When the sand barrier is breached, small fish and invertebrates are flushed from the estuary or stranded on the exposed mudflats.

Breaching of the sand barrier leads to a rapid outflow from the estuary (Statement 2) and the high-velocity flows may flush many small fish from the estuary, including young salmonids, gobies and flatfish, or leave them stranded on exposed mud flats (Swift et al. 2018). While breaches allow salmonids to transit through the estuary, either during upstream migration for spawning or out-migration to the ocean, early breaches can force juvenile salmonids (most notably steelhead) to enter the ocean before they are physiologically ready, removing them from food-rich BBE habitats, and exposing them to ocean predation. For tidewater goby, breaching may reduce the available habitat (e.g., side channels) and flush gobies out of their preferred BBE habitat. Flatfish (e.g., starry flounder) may also benefit from open-mouth conditions through the ability to migrate in to or out of estuaries, either for spawning or feeding, but again breaches may force fish to enter the ocean before they are physiologically ready and remove them from high-food and refuge areas. In contrast, a lack of breaching can trap these marine fishes in a non-marine environment, which may eventually limit habitat space or food.

Breaching may also flush invertebrates and icthyoplankton (i.e., fish eggs and larvae) in high-velocity outflow and result in subsequent import of marine meroplankton (i.e., larval planktonic life stage), thus altering the composition of zooplankton (Froneman 2004) and subsequent recruitment to the benthic community. Also, the transition to tidal conditions influences stratification and pelagic habitat for zooplankton, favoring more marine-reliant species. Further, breaching may directly impact benthic invertebrates through resuspension and flushing from the estuary – as well as population crashes due to a sudden change in salinity (e.g., Netto et al. 2012). Using data from Scott Creek Estuary, a marked difference in the counts of each category of invertebrate was observed between periods with an open mouth versus closed mouth (Table 4).

Table 4. Average count of individuals of benthic invertebrate groups during open and closed mouth conditions from 2003-2005, showing large differences in counts for each category and in overall abundance (data from Beck et al. 2006). See Appendix 2 for more information.

Benthic Invertebrate Group	Mouth closed	Mouth open
Amphipod	23.7	19.3
Annelids	20.7	5.6
Aquatic Insect	13.5	18.0
Arachnid	1.0	1.0
Copepod	1.5	4.0
Insect Larvae	1.9	2.9
Isopod	34.0	11.7
Mysid	2.0	44.5
Ostracod	4.3	0
Total Average	**19.8**	**12.2**

Statement 12. When the sand barrier is breached, spawning fish may return to estuary and river habitats.

Natural breaching of the sand barrier allows anadromous fish to migrate back into the estuary and up-river. Prior to these natural breaches that typically occur in early winter, spawning adults can be observed off shore waiting for the bar to open and allow for their inward migration. Early-winter breaches can be delayed by hydrological modifications in the watersheds, such as water extraction and dams, which limit early-winter river flows that help to initiate natural breaching. While managed breaches may allow migration into the estuary, in the absence of sufficient river flows, fish cannot migrate upstream to spawn – possibly negating the intended benefit.

Statement 13. When the sand barrier is breached, phytoplankton and macro-algae are flushed from the estuary.

The loss of water from the estuary during a breach leads to an export of phytoplankton and other suspended particulate material from the estuary, including loosely attached macro-algae. This can preclude or mitigate late-summer eutrophic conditions, but it can also represent a loss of food available to various fish species and invertebrate consumers within the estuary. However, the subsequent intrusion of high-nutrient ocean waters and phytoplankton/kelp can lead to an increase in food availability during open conditions. Data from Scott Creek Estuary show a greater phytoplankton concentration during open-mouth periods (Table 5; Figure 14) whereas studies in Navarro River, Salmon Creek, Laguna and Waddell Creek show an accumulation of macro-algae in BBEs through summer closures that is removed when river flows increase and the mouth breaches in early winter (Sutula et al. 2016).

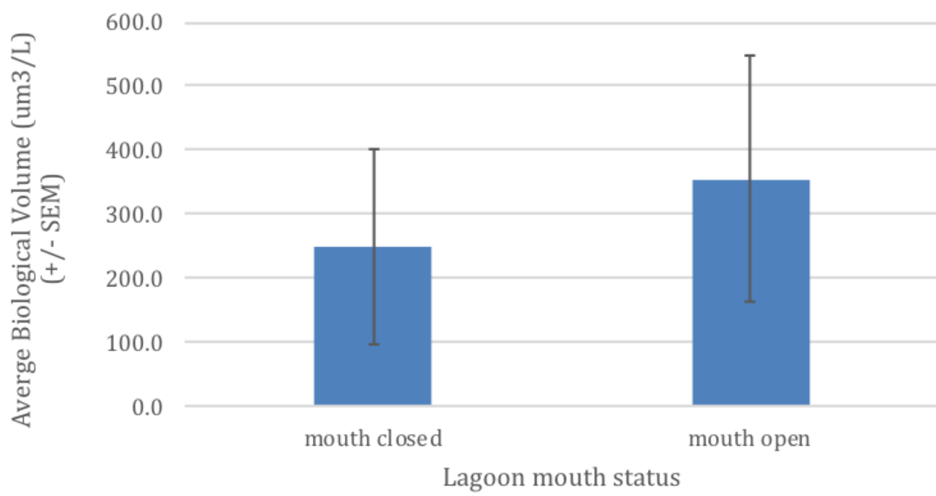


Figure 14. Average biological volume of phytoplankton (+/- Standard Error of the Mean) at Scott Creek Estuary when the mouth is open and closed from 2003-2005 (data from Beck et al. 2006). See Appendix 2 for more information.

Similarly, a decreased area of submerged-aquatic-vegetation (SAV) habitat is available after water levels drop following a breach. For example, an analysis of data from Scott Creek Estuary shows a higher percentage cover of the macro-algae Ulva and SAV Potamogeton when the mouth is closed (Table 5).

Table 5. Average percent cover of benthic macro-algae, two species of submerged aquatic vegetation, and Ulva at Scott Creek Estuary from 2003-2005 (data from Beck et al. 2006). See Appendix 2 for more information.

Type	**Mouth closed**	**Mouth open**
Benthic macro-algae	0.0	5.0
Potamogeton	10.7	2.3
Rupia	0.0	0.7
Ulva	25.0	10.0
Total Average	**13.4**	**4.7**

Statement 14. When the sand barrier is breached, poor water quality can occur nearshore.

A pulse of accumulated pollutants and poor water quality (e.g., hypoxic waters) can be rapidly flushed from the estuary during a breach, resulting in the degradation of nearshore water quality. Accumulated fecal indicator bacteria, pathogens, and agriculture runoff (Anderson et al. 2010, Miller et al. 2010) in BBEs during summer closures represent a public health risk concern. It is often recommended to avoid swimming near estuary mouths following breach events and local municipalities typically post signs on beaches to notify the public of the potential health risk of the outflowing water.


Waddell Creek

5. Management Decisions on Estuary Breaching

Science-based management decisions regarding whether to breach a river mouth rely on the best-available science to discern the expected proximal, deferred, indirect, and additive effects of managed breaching. Decision makers often note both positive and negative effects of breaching when deciding management policy, with proponents of breaching typically outlining the benefits (positive effects) and the permitting agencies noting the likely of perceived costs (negative effects) of mouth management.

In Section 4 above, we identified the typical consequences or proximal effects of breaching (including both natural and managed breaches). All these effects and consequences should be considered when reviewing an application to breach the sand barrier, evaluating the likelihood, severity and associated secondary effects of each of these proximal effects (Statements 1 to 14) on a specific BBE.

This includes an assessment of biological populations and communities in the estuary and how they are expected to respond to these disturbances. As most native/endemic populations are resilient to natural breaching, care should be taken to mimic natural breaches and avoid changes that lead to significant shifts in the nature of these proximal effects. However, in cases where inflows/development have perturbed the functioning of BBEs, a more aggressive breaching management policy may be wise as it can yield a more desirable system. For example, in Los Peñasquitos Lagoon managed breaches are used to preserve endemic flora and fauna by offsetting the effects of surrounding development. However, such management policies require significant investment in data and scientific analysis to support design of the management strategy, as has happened in both Los Peñasquitos Lagoon and the Russian River Estuary.

Under natural conditions, closed BBEs may breach over a relatively wide range of water levels. An occasional managed breach within this range is not likely to have a significant environmental impact since it falls within the expected natural distribution. However, over the longer term, numerous managed breaches, especially at low water levels, are likely to have a significant environmental impact since it alters the natural distribution of types of breach events, in terms of both frequency and closure duration. Typically, managed breaching results in more breaches and breaches that occur at lower water levels (and often lower river flow), with reduced scouring/flushing efficacy – thus in turn changing the distribution of habitat conditions and connectivity in the BBE as well as the degree and timing of exchange with nearshore ocean waters and migration of fish species. These changes may overwhelm the resiliency of some populations and communities, so that the system changes – increasingly dominated by a few remaining resilient populations and communities. In the presence of repeated managed breaching, succession in these estuary ecosystems may follow a different trajectory than they would have with only natural breaching. Further, these changes may develop slowly and the altered ecosystem trajectory may not be documented until years later.

While every estuary has its own special characteristics (Whitfield et al. 2012; Hughes et al. 2014), there are many similarities between bar-built estuaries –and most BBEs exhibit similarities with at least one of the three focal BBE systems. For more detailed information and data on the three focal systems, see Appendices 1 through 3. With even minimal data on water levels, salinity and basin shape (e.g. marsh plain, depth of channels, etc.), these similarities can be identified. Features of interest include seasonality of closure, duration of closure in different seasons, strength of scour and flushing (both flow velocity and sediment erosion), depth of water column post-breach, elevation of marshes relative to water levels during closure, stability of water column, BOD loading and light penetration that control lower-layer hypoxia in stratified systems, and algal biomass that determines net respiration. Ecological responses depend on these abiotic and lower trophic level effects combined with the unique characteristics of the surrounding environment at each BBE, and ecological responses develop over a longer time with multiple feedback mechanisms. This, in addition to the wide range of seasonal hydrologic and sand barrier conditions create the real site-specific complexities that need to be understood for effective management of each system.

The challenge for managers is more than simply a challenge to understand the biophysical system, because the decision to breach depends on judgments related to "costs" and "benefits" of the breach. Decisions to breach manually involve a tradeoff, in which benefits (or avoidance of costs of external human activity) are considered to outweigh costs incurred (negative effects). This is not entirely a science-based decision and thus one cannot develop a simple deterministic decision tree. These decisions involve dialog with other stakeholders and a collaborative evaluation of costs and benefits. However, when some of the expected costs and benefits are not well quantified, this dialog is curtailed and consensus decisions become more difficult. Better quantifying expected environmental costs and benefits is where scientific analysis[1] and monitoring can improve future decision-making. Scientific study is also important in identifying unanticipated costs and benefits, and the probability of these impacts occurring. Thirdly, science can better articulate and quantify the trade-off that we now make intuitively (i.e., environmental economics).

And, finally, while analysis may lead to identification of an optimum scenario, BBEs are characterized by variability (over time in one BBE and between BBEs) so that any long-term effective management strategy must result in a diversity of conditions from year to year, yielding habitat diversity and ultimately the biodiversity that characterizes these systems and accounts for their observed resilience.

San Lorenzo River

[1] "Scientific analysis" includes analysis of existing data, design and analysis of monitoring data, modeling BBE systems, and both long-term and short-term field experiments.

6. Recommendations for Improved Management

Immediate Actions

In lieu of an understanding of the probable and possible effects of breaching (both desired and undesired) for individual systems, we recommend at least avoiding the specific scenarios described below to ensure physical and biological features of these systems maintain their conservation value for special status species:

- Avoid partial managed breaches that evacuate the top freshwater layer if the system is stratified pre-breach. This forces fish to enter the hypoxic near-bottom waters, resulting in mortality (e.g., Becker et al. 2009).
- Avoid breaches that lead to an extreme evacuation of the estuary embayment and/or extreme high-velocity flows that flush fish and other key biota from the estuary at the wrong time of the year.
- Avoid a managed breach early in juvenile steelhead rearing season to prevent fish from being exported from the estuary prior to being fully developed.
- Avoid shock events that result in massive die-off of SAV, which leads to severe eutrophication and hypoxia.
- Avoid large-scale mobilization of organic sediments without concurrent rapid and persistent flushing from high river flow as this may release high loads of oxygen demand (chemical and biological), pollutants and nutrients.
- Avoid always conducting a managed breach before the marsh plain is inundated because periodic flooding of the marsh supports a diversity of habitats and ecological functions in marsh channels and on the marsh plain.

Nevertheless, estuarine habitats are notoriously variable and this variability should be retained, including severe events, as this benefits the diversity and thus resilience of the communities and populations in these estuaries. The specific scenarios describe above do occur naturally, but care should be taken that these scenarios don't become common through managed breaching.

Scientific Contributions Needed to Improve Management

Ultimately, we seek a full understanding of the probable and possible effects of breaching, to support informed and collaborative decisions regarding when to breach a specific system (or not). The following are examples of critical questions that need attention to allow science-based decisions on managed breaching for specific systems:

1. What perched water level is required in a BBE prior to a breach for a breach to be effective, including deep scour or partial scour scenarios? See Stretch and Parkinson (2006).
2. What are the conditions that lead to the development and persistence of hypoxia and temperature effects within bottom waters, and how are these conditions impacted by natural or artificial breaches? See Largier et al. (2018). How does this change with seasons and other controls on light

levels at depth? Once hypoxia is established in a given system, will it become more severe or will it dissipate if the mouth is or is not breached?

3. What is the relationship between lagoon hydrology and morphology? See Cooper (2001). What is the distribution of inundation conditions (depth, duration, seasonal timing) under which present marshes developed? What is the feedback of managed breaching on the frequency/timing of natural breach events?
4. How has closure probability changed with water extraction, local land development, shifts in water runoff associated with climate change, ocean conditions, sea level rise, and channel modification? See Van Niekerk et al. (2005). How is closure probability expected to change with sea level rise and alterations in sediment supply associated with climate change and watershed management?
5. What types of breach events will lead to significant flushing of estuary fish and/or plankton populations? How does this alter prey availability or predation pressure on critical populations?
6. How will a proposed breaching regime alter the seasonal cycle of marsh inundation and desiccation? How will this alter the marsh community and potential for accretion under sea level rise?

These scientific analyses can inform improved management. In addition to modeling and field studies, much can be learned from strategic monitoring of estuaries before, after and during breaching. Permit conditions can ensure that we learn from each managed breaching event, whether the system responds after a breach event as anticipated or not. This is the basis for the recommendations in the next section.

Learning through Monitoring

A better understanding of the effects of managed breaching (direct and indirect; anticipated and unanticipated) can be advanced by requiring monitoring as a condition of a breach permit – so that the effects of breaching will be better known, providing an empirical basis for minimizing adverse impacts to both special status species and their habitat features. Monitoring requirements can be included within a biological opinion's incidental take permit under the Endangered Species Act, when incidental take is expected due to a managed breach. An example of a long-term collaborative monitoring program that informs sand barrier management is at Los Peñasquitos Lagoon. The Los Peñasquitos Lagoon Foundation and California State Parks have worked directly with staff at the Pacific Estuarine Research Lab to adaptively manage the inlet using continuous data sets from a monitoring program initiated in 1987 to achieved desired management outcomes.

There are a number of cost-effective data collection protocols that will improve breaching decisions. Ideally, both managed and natural breaches will be monitored to improve our understanding of BBE responses and the function of BBEs under different management approaches. Dependent on the management objectives and potential effects of breaching, a subset of these monitoring efforts could be used. These monitoring recommendations assume that ancillary data on external forcing are available, such as river flow, tides, and offshore wave conditions. If these data are not available, then they should be included in a monitoring program.

- *Water Level and Photographic Records:*
  Mouth state and closure duration are key considerations for management of BBEs. Mouth state can be determined from water level and photo documentation. Documenting water elevation in relation to channel depth, marsh plain elevation and off-channel water depth is important for understanding the effect of mouth state on diverse estuarine habitats. Placement of low-cost pressure sensors within BBEs should be a standard practice in all managed systems. In addition, automated cameras can be placed at the mouth of key BBEs to track mouth migration, mouth state, wave overtopping and breach events.

- *Morphology Surveys:*
  The height of the sand barrier can be monitored through simple horizon-sighting techniques during a closure episode, so that the natural-breach water level is known. Further, through pre- and post-breach morphological surveys of the sand barrier (and channel depth), scouring efficacy can be related to pre-breach water-level head and post-breach accretion in the mouth channel (and also reveal seasonal changes). While estimates of channel depth and width can be obtained from water-level records and photographs, morphological surveys provide a more complete view of sand barrier modification through breaching. Morphology surveys should include the upper extents of marshes and floodplains that can be inundated by the highest water levels as well as sand dunes adjacent to the estuary mouth, which can play a key role in closures and water level maxima.

- *Stratification and Water Quality Records:*
  Salinity, temperature and dissolved oxygen can be monitored through deployment of time-series sensors at representative sites that capture temporal variability. Periodic water chemistry transects (profiles at a set of stations), and water nutrient and toxicity samples will help document spatial patterns in water chemistry, including identification of refugia for species escaping poor water quality. These data can also be used to track changes in stratification, which is a primary determinant of water quality in the lower layer. Data during closure events and before/after breach events allow assessment of the spatial extent and temporal duration of water quality effects of breaching.

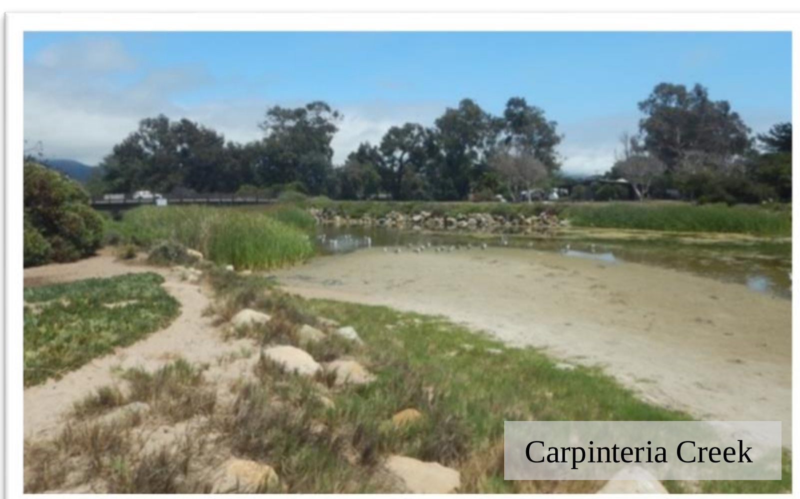
- *Marsh plain and Submerged Aquatic Vegetation (SAV) Condition Surveys:*
  Marsh plants and channel SAV species distribution, abundance, diversity and elevation can be surveyed and related to water elevation data within the estuary. Long-term surveys are more important than pre- and post-breach surveys because marsh plant and SAV communities will likely not be affected by a single manual breaching effort. It is also important to note that in the absence of site-specific monitoring data on water depth and water quality, vegetation can provide insights about lagoon hydrology (depth/duration/frequency of inundation, salinity), especially over the long-term. Long-term surveys of plant composition are critical for assessing breaching protocols (e.g., routine breaching that maintains water level below natural peaks) – including the potential for secondary impacts to the marsh communities or subtidal communities (De Decker 1987). Site-specific information on species distribution relative to marsh plain elevation can help minimize impacts to marsh communities by determining the minimum water elevation needed to flood specific plant communities (and the maximum water elevation to avoid flooding of other land uses).

- *Fish and other faunal surveys:*
  Monitoring of fish and other fauna during open/closed states and immediately post-breach is needed to assess impacts of breaching. Surveys can document both immediate effects of breaching on various species as well as longer term effects on resident populations. Population studies should be conducted to assess the additive effects of multiple managed breaches on species like steelhead and tidewater goby as well as species of concern (e.g., frogs, turtles, birds). Emerging monitoring techniques involving the use of sampling for DNA markers (eDNA) in the water column may increase the efficiency of monitoring for fauna in BBEs.

Processed-Based Approach to Management

The material in this report underscores the need for BBE management that seeks to identify and characterize the spatial and temporal variability in the drivers that govern responses in lagoon hydrology, morphology, and ecology. Anything less risks unintended consequences that can jeopardize ecological services. To support process-based management, we suggest resource managers:

1. Identify ecological costs and benefits of different estuary states and of different breaching protocols to allow for informed decisions on tradeoffs when management actions are taken.
2. Adopt a regional approach to maintaining habitat diversity by ensuring a diverse combination of BBEs systems thrive (i.e., the regional portfolio approach).
3. Prioritize habitat enhancement and restoration activities within BBEs to reestablish functions and services that have been regionally lost.
4. Understand the dynamic processes that control observed conditions in BBEs (based on field data).
5. Develop quantitative conceptual models that capture the processes and environmental variability of BBEs across seasons – and use these models to inform management decisions.
6. Identify ecosystem functions and services provided by a specific BBE and determine how they are changed by mouth management practices. Further, anticipate future changes in the processes that underpin ecological functions and services – including changes due to watershed management, coastal management and climate change.
7. Develop monitoring programs and data/indicators to inform management decisions.


Carpinteria Creek

7. Conclusion

A breach may benefit one ecosystem element and impair another, or it may even benefit one species at one stage of its life cycle but impair habitat for another stage of its life cycle. This conflict between ecosystem components is often exacerbated by a regulatory permit system that is focused on individual "species of concern" and specific environmental characteristics. Our knowledge of the relationships between breaching, biota and community resilience are imperfect and these relationships are undoubtedly non-linear and probably not fully predictable. BBEs are notoriously variable, even in their natural state, with some estuaries remaining closed for longer than a year and then remaining open for longer than a year – or opening for just a day or closing for one tidal cycle. This intense habitat diversity is a hallmark that gives rise to high genetic diversity facilitating the persistence of unique species endemic to California and also supports a diverse assemblage of species. This advocates for a management strategy that maintains environmental variability and associated habitat diversity (including extreme events) that can maintain the immense biodiversity of these systems. At the very least, managed breaches should not be executed in exactly the same way every time – but the challenge is to quantify the variability under which these systems evolved and conduct occasional managed breaches in a way that sustains this variability over the years.

Best-available biophysical understanding suggests that occasional managed breaches may be implemented with little long-term impact, if certain conditions are avoided (see Section 6). In spite of imperfect knowledge, this review provides a summary of how water level, salinity, temperature, and oxygen may fluctuate before, during and after breaching (see "statements" in Section 4). Management agencies can use best-available knowledge of how this will play out in the system of concern and relate this to the priority resources in that system with the aim of averting extreme conditions after any one breach and also averting a slow decline in system health over years of breaching interventions. Both of these aims require strategic monitoring (see recommendations in Section 6). While managed breaching may be a suitable emergency response, long-term management strategies should combine management of mouth state with management of freshwater inflow/loading and management of development that constrains water levels or mouth morphological dynamics. Examples of organizations taking this approach and showing success include the Los Peñasquitos Lagoon Foundation, the San Elijo Lagoon Conservancy and the Sonoma County Water Agency – each with a long record of adaptively managing their inlets.

Regional and statewide management and monitoring strategies should be developed to ensure that bar-built estuaries remain healthy ecosystems able to provide a unique set of services along the entire California coastline. In addition to improved breaching strategies and enhanced standardized monitoring programs in general, regulatory agencies should work together to identify priority estuaries where restoration may address the underlying reasons for executing a managed breach. For example, raising or removal of development within the estuarine floodplain can promote the ecological functioning of BBEs and mitigate the consequences of sea level rise. Alternatively, better watershed management of hydrographs and pollutant loading can reduce the need for managed breaching to address urban runoff, water quality and fish migration challenges.

This report provided a background on the biophysical understanding of lagoon systems, guidance on specific scenarios to avoid, critical questions that can be applied to any system, and elements to shape a robust monitoring program for breaching events or for a long-term breaching program. Ultimately the decision to breach rests on a tradeoff between projected beneficial and deleterious effects following a breach compared with projected beneficial and deleterious effects if the mouth is not breached. This tradeoff decision varies from system to system, but this decision-making is improved by an improved assessment of these effects in BBEs, for which additional quantitative scientific insight is needed. Finally, although emergency breaches may be required in rare occasions, we recommend that managed breaches are implemented as part of a clear breaching strategy that is developed for specific systems in which breaching has been used, or in which it is likely to be used as a management tool.

Santa Maria River

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