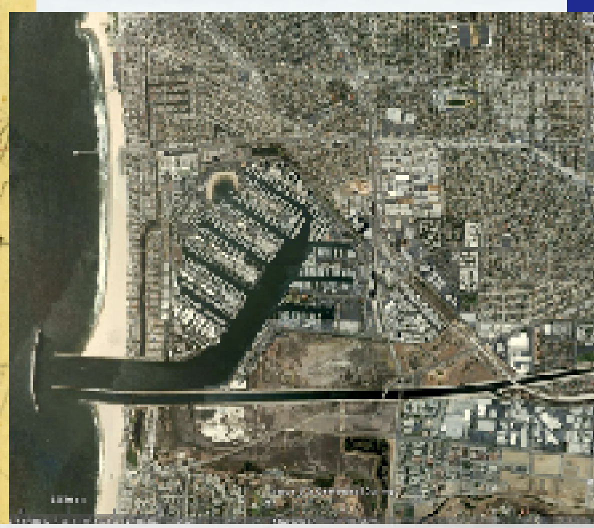
CLASSIFICATION OF CALIFORNIA ESTUARIES BASED ON NATURAL CLOSURE PATTERNS: TEMPLATES FOR RESTORATION AND MANAGEMENT

Revised

David Jacobs

Eric D. Stein

Travis Longcore



Southern California Coastal Water Research Project

Technical Report 619.a - August 2011

Classification of California Estuaries Based on Natural Closure Patterns: Templates for Restoration and Management

David K. Jacobs[1], Eric D. Stein[2], and Travis Longcore[3]

[1]UCLA Department of Ecology and Evolutionary Biology
[2]Southern California Coastal Water Research Project
[3]University of Southern California - Spatial Sciences Institute

August 2010
Revised August 2011

Technical Report 619.a

ABSTRACT

Determining the appropriate design template is critical to coastal wetland restoration. In seasonally wet and semi-arid regions of the world coastal wetlands tend to close off from the sea seasonally or episodically, and decisions regarding estuarine mouth closure have far reaching implications for cost, management, and ultimate success of coastal wetland restoration. In the past restoration planners relied on an incomplete understanding of the factors that influence estuarine mouth closure. Consequently, templates from other climatic/physiographic regions are often inappropriately applied. The first step to addressing this issue is to develop a classification system based on an understanding of the processes that formed the estuaries and thus define their pre-development structure. Here we propose a new classification system for California estuaries based on the geomorphic history and the dominant physical processes that govern the formation of the estuary space or volume. It is distinct from previous estuary closure models, which focused primarily on the relationship between estuary size and tidal prism in constraining closure. This classification system uses geologic origin, exposure to littoral process, watershed size and runoff characteristics as the basis of a conceptual model that predicts likely frequency and duration of closure of the estuary mouth. We then begin to validate the proposed model by investigating historical documentation of three representative estuaries to determine if their pre-development condition was consistent with the structure predicted by the classification. In application of the model, eight closure states, based on elevation of barriers to tidal access, were defined. These states can be determined from historic, maps descriptions and photography. These states are then used to validate models of closure state frequency for different classes of estuaries based on the classification. Application of the classification model suggests that under natural conditions, the vast majority of California estuaries experience some degree of closure, and most spend a preponderance of time completely isolated from the sea or with a limited or muted tidal connection. In this state, stream flow rather than tidal influence is the most critical variable controlling mouth opening. Individual estuaries exist in a variety of closure states over multi-year to multi-decadal time frames. An estuary may exist in a given closure state for periods of time ranging from days to years. The distribution of closure states for an estuary over time can be used to guide management decisions based on dominant closure and hydrodynamics of the system. Success of future estuarine restoration projects could be improved by incorporating consideration of mouth closure dynamics.

Table of Contents

List of Figures

List of Tables

INTRODUCTION

Loss of coastal wetlands is widely recognized as contributing to decreased biodiversity, species declines, and increase in coastal hazards (Zedler and Kercher 2005). In semi-arid regions, such as southern California, the effect of wetland loss is particularly acute because wetlands are oases in a relatively dry landscape (Zedler 1996). Unfortunately, the combination of the small, somewhat isolated nature of coastal wetlands and intense development pressure has resulted in California experiencing some of the highest rate of loss of coastal wetlands in the United States (Zedler 1996). As a result, coastal wetland restoration has been a focus of management activity and public funding over the past two decades. Since 1998, more than $500 million have been spent on acquisition and restoration of coastal wetlands in southern California alone (http://www.scwrp.org/index.htm).

One of the most difficult aspects of coastal wetland restoration is determining the restoration template (Brinson and Rheinhardt 1996). Determining the appropriate physical configuration and habitat mix for restored wetlands is complicated when undisturbed reference sites are no longer present on the landscape (Grayson *et al*. 1999). Consequently, templates from other climatic/physiographic regions are often applied to southern California coastal wetland restoration projects. However, the drowned river mouth estuaries and barrier island systems typically found in more humid, less tectonically active areas, such as the eastern United States are fundamentally different than the small geologically active estuaries found in the semi-arid Mediterranean climate of southern California. Of particular note is the critical importance of streamflow, and the seasonal and episodic variability of that flow, in maintaining estuarine settings. These, in combination with difference in watershed size and littoral process, affect the character of estuarine mouths. The frequency and duration of mouth closure is a far more important phenomenon in west coast than east coast estuaries and can serve as a key factor that determines the groundwater hydrology, habitat types, flora and fauna supported by a specific estuary.

Study of the nature of physical and biological processes in closing estuarine systems has been more systematic in other Mediterranean climates settings, such as Australia (Hodgkin and Hesp 1998; Ranasinghe and Pattiaratchi 1999, 2003; Ranasinghe *et al*. 1999; Roy *et al*. 2001; Shuttleworth *et al*. 2005; Stretch and Parkinson 2006) and South Africa (Cooper 1990, 2001, 2002; Nozais *et al*. 2005; Harrison and Whitfield 2006; Anandraj *et al*. 2007) where systematic studies across suites of seasonally closing estuaries have been conducted. The more limited focus on these systems in California may be, in part, due to the influence of studies of East Coast estuaries, and the presence of a few exemplar open systems, such as San Francisco Bay, and, in southern California, San Diego Bay. Application of physical and biological models and restoration templates from estuaries with fundamentally different geologic origins, climate, scale and geomorphic processes typically found in other regions of the United States appears to create conditions in the name of restoration that, depart from local history are at odds with local processes. Such “restored” systems tend to have high maintenance requirements, and are often inappropriate for the species endemic to estuaries of the California Coast, including endangered taxa. Therefore, development of a set of restoration templates appropriate for medium to small-sized estuaries in Mediterranean climates with variable precipitation and streamflow should be a priority to help inform future restoration and management decisions for southern California coastal wetlands.

A first step in this process is to develop a classification system based on an understanding of the processes that formed (origin) these estuaries and defining their pre-development structure. This report proposes a new classification system for California estuaries based on the geomorphic history and the dominant physical processes that govern the formation of the estuary space or volume within them. The classification system forms the basis of a conceptual model that predicts likely frequency and duration of closure of the estuary mouth. We then begin to validate the proposed model by investigating historical documentation of three representative estuaries to determine if their pre-development condition was consistent with the structure predicted by the classification system. If the historical information about the condition of the estuary is consistent with the predictions based on its landscape position and geomorphological attributes, then our confidence in the predictive ability of this scheme will be enhanced. This initial validation provides the foundation for further testing and application to the numerous restoration plans currently underway. Finally, we explore some of the physical and biotic consequences of changing the closure dynamics of coastal estuaries by transforming them from periodically closing systems into perennially open systems.

METHODS

We propose a classification system based on the geophysical processes that formed and hence govern the behavior of estuaries in southern California. We hypothesize that the typical frequency and duration of mouth closure can be predicted based on an estuarine classification derived from geologic origins, exposure to littoral processes, and watershed size and runoff characteristics (more details are provided below). The classification scheme produces a series of hypotheses about the mouth closure characteristics under natural conditions (i.e., in the absence of major infrastructure that controls estuary opening/closing).

The mouth closure dynamics predicted by the conceptual model were applied to estuaries along the California coast (Figure 1) and investigated in detail using a range of historical data sources for three estuaries of particular management concern. These estuaries, at Ballona Creek, Topanga Creek, and Tijuana River, represent a variety of conditions in terms of size and landscape setting and were selected because they are all currently the subjects of restoration planning efforts. Therefore knowledge of the historical wetland state and mouth dynamics is particularly relevant to assessment of alternative restoration plans and ongoing investments. For these three estuaries, we investigated historical aerial and ground photographs, historical reports and narrative accounts, the California Coastline photograph archive (http://www.californiacoastline.org/), and historical maps from the US Coast and Geodetic Topographic Survey (T-Sheets) to produce a conclusion on the predominant mouth condition. Information was reviewed from the earliest obtainable records (ca. 1870) to the present to represent the study estuaries under a range of natural conditions (e.g., flood, droughts, and different tidal stages) and managed conditions (e.g., levees, excavations). The "observed" condition is then compared to the predicted estuary closure condition developed from the classification system/model as a test of model validity.

In addition to the three estuaries examined in detail, the broader work presented here is supported by personal observation by Jacobs in over 130 small to medium sized coastal lagoons during collection efforts for work on the genetics of coastal fishes (*Atherinops*, *Clevelandia*, *Eucyclogobius*, *Fundulus*, *Gasterosteus Gillichthys*, *Leptocottus*) and invertebrates (*Cerithidia*, *Nebalia*, *Neotrypaea*). These observations were supplemented by the field observations and notes of Camm Swift. Additional observations and communication and collection records from Kevin Lafferty, Ryan Hechanger, Kristina Louie and Todd Haney were considered. Air photos records for all 130 sites (except Vandenberg AFB) were examined using images from the California Coastal Records project. Satellite images for the last two decades were examined using Google Earth. The historic "T-sheet" (Topographic) series for the entire outer coast was examined relative to these sites as were the early hydrographic sheets in some instances (San Pedro, Mission Bay, San Diego Bay, and Mugu). These data were used to inform the conceptual model for each combination of variables, thus predictions are not based on the behavior history of an individual place, but on a generalized summary of similar systems in our combination of variables.

Figure 1. California estuaries discussed in this study.

CONCEPTUAL BASIS FOR ESTUARINE CLASSIFICATION

Formation of California Estuaries

A number of different geologic processes operating though time have influenced the development of California Estuaries. These processes are the basis for the proposed classification system.

Uplift

Much of California's coastal geomorphology results from locally rapid uplift rates compared to other regions of the country. This relative movement has been particularly active over the last 1 to 2 million years, generating many aspects of the coastal topography including the steep topography of the coastal cliffs and islands (Mc Neilan *et al*. 1996, Masters and Aiello 2007). In addition general uplift of the coast has eliminated or reduced in size what were once very extensive embayment systems that penetrated inland in the Los Angeles basin, the Santa Clara, Santa Ynez and Santa Maria Valleys and in the Vicinities of Morro and Monterey Bay/Salinas Valley (Hall 2002, Jacobs *et al*. 2004) into the Late Pliocene or early Pleistocene. These areas still support significant estuarine features, but they are orders of magnitude smaller in their extent than previously existing embayments.

Sea Level Change

Sea level rise, from approximately 140 m below present levels about 20,000 years ago, necessarily exceeding rates of 1 cm/y for several millennia (Slater *et al*. 2002). Rapid glacial melting occurred from about 15,000 to 8,500 years ago, with some degree of hiatus during the cold Younger Dryas 12,800 to 11,500 years ago (Kennett *et al*. 2007). This deglaciation raised global sea level and inundating coastal features. Reduction in the rate of sea-level rise occurred between 8,500 and 6,000 years ago (Fairbanks 1989), and in this time frame the major features of the world's coasts, such as major river deltas, started to develop (Li *et al*. 2002), and the processes that shaped and continue to influence modern west coast estuaries began to operate (Hogarth *et al*. 2007, Masters and Aiello 2007). Records from around the Pacific Basin suggest that sea level rose to a maximal values sometime between 5,000 and 2,000 years ago (e.g., Dickinson 2001). Depending on mechanism envisioned these higher stands (1 to 2 meters) may or may not pertain to the Holocene of the California Coast (Grossman *et al*. 1998). Over the course of the Holocene, uplift may account for several meters of sea-level change in the most active regions of coastal California (Keller and Gurrola 2000; Jacobs *et al*. 2004; Masters and Aiello 2007). Overall, by 2 or 3 thousand years ago a combination of uplift, slight sea level fall, coastal retreat and sedimentary infill had strongly influenced California estuarine systems (Masters and Aiello 2007).

Coastal Retreat-Regressive Shorelines

Much of the California Coast is uplifted and actively eroding under wave attack. When rising sea-level reached heights that roughly approach those of today (within 10 m of modern) approximately 8,500 to 6,000 years ago, waves began to erode a coast that had been uplifted and dissected by stream flow since the last high-stands of the sea (interglacial substages 5a,c,e, at 80,000, 100,000 and 125,000 years ago). This last set of highstands generated the lowest set of terraces along the coast through uplift of these formerly-wave-cut features (Muhs *et al*. 1992, Muhs *et al*. 2002, Niemi *et al*. 2008). These terraces range from near sea level to over 100 meters high (e.g., the seacliff north of Ventura) depending on the local uplift rate (dating of these surfaces provides one of the primary means of measuring uplift). Terraces and other coastal features were then crosscut by stream valleys, as they were uplifted during the last ~100,000 years. Valleys were frequently downcut to levels well below modern sea level due to protracted episodes of significantly low sea-level (e.g., 70,000 to 10,000 years ago). As a consequence of these processes a much more irregular coast was presented to the force of wave action (8,500 - 6,000 years ago) than the coast of today. Wave erosion subsequently smoothed the coast, cutting back headlands especially where they are composed of relatively soft Neogene (Miocene or younger – less then 25 million years old) sediments. Thus many regions of the coast are in active erosional retreat and have been so since the early Holocene. These are the stretches of steep coasts and headlands often with cliffs facing the sea. In some cases offshore erosional remnants indicate retreat of close to a kilometer (e.g., Sonoma County south of the Russia River). These coasts often have stream mouth estuaries in valleys along them; and it has long been recognized that this active coastal retreat eliminates estuarine habitat in these valleys (Hedgepeth 1957). In addition, sediment infill through the Holocene eliminated space for estuaries in these settings (see below). Coastal retreat itself can be a very significant source of sediment to adjacent valley/estuarine settings.

Progradational Shorelines and Estuarine Infill

Although well over half of the California Coast is steep/terraced and retreating as a consequence of Holocene wave erosion on the outer-coast south of San Francisco there are large valley features that were major embayment during the Pliocene. These regions, Salinas, Santa Maria, Santa Ynez, Santa Clara, and the Los Angeles valleys/Basin form stretches of prograding shoreline. Sediments are currently accumulating along these shores and/or have a significant Holocene history of accumulation. Thus there is a history of seaward movement of the shoreline (progradation). These areas associated with relatively high sediment producing watersheds, but also collect sediment moving longshore from adjacent eroding shorelines. Progradation in these systems may ultimately be limited by longshore transport out of the systems. In some instances, longshore transport precludes further seaward progradation of the system, and these regions of shoreline are often bounded by submarine canyons that transport sediment to nearby deepwater basins. Such submarine canyons can limit or define the area of shoreline along which sediment can be transported or accumulate. In some circumstances wind transport and dune accumulation can be similarly seen as an onshore escape for sediments from the shoreline environment.

Processes that Influence Estuary Opening, Closing, and Migration

Closure in California estuaries is a variable phenomenon that is often related to episodes of stream flow. In coastal lagoons opening will frequently occur at much lower stream flows than are required for the efficient export of sediment from the systems, which requires floods. Opening will also often be sustained by stream flow. Thus in larger drainages where stream flow persists for weeks or months at a time estuaries are likely to be maintained open for much of the wet season. Smaller stream mouth systems may open very briefly during short episodes of peak stream flow following rainfall and then close promptly, possibly with the following tidal cycle.

In addition, flood events may on occasion remove sufficient sediment to maintain the system in an open condition beyond the annual cycle, they may then become progressively more closed over a few year period.

Infill of river and stream-mouth estuaries occurs more locally than the larger scale progradational coastal settings discussed above. Sediments in these settings can be derived long-shore from the erosion of adjacent shorelines as well as from downstream transport. Thus estuaries can fill in from the beach side where flood-tidal deltas build into them or when stream mouth deltas prograde into their upstream ends. This sedimentation process is intermittently interrupted by large stream flows that erode sediment to form estuaries. Thus, a quasi equilibrium is achieved, where sediment accumulation, infill of the lagoon/estuary and marsh development is followed by erosive removal of the sediment via large storms followed by subsequent refilling of the estuary until the next large storm occurs. Episodic extreme flood events appear to recur approximately every 200 years based on records from the varved (annually laminates) sediments of the Santa Barbara Basin (Schimmelmann *et al*. 1998, 2003). The most recent such large flooding events likely occurred in 1605 and then between the 1830s to the 1860s. These floods appear to have been particularly effective at creating estuarine space. For example, a good-sized vessel could navigate the San Luis Rey River more than a Mile Upstream shortly after the 1862 Flood (Hayes 1862, in Engstrom 1999). The 1890 topographic surveys show, however, that the San Luis Rey had a raised beach berm crossing its mouth, indicating the evolution of a closing system. The large floods of the 1830s and 1860s also led to rerouting of the Los Angeles River into Ballona Creek as well as the movement of the mouths of the San Gabriel River and shift of the mouth of the Santa Ana to Newport Bay (Reagan 1915, Stein *et al*. 2007). Major precipitation events and floods have been far less frequent since 1890s. The large events in the 20th Century, 1914, 1938 and 1982–83, were subsequent to extensive dewatering, damming of streams, as well as channelization and confinement of estuaries by bridging potentially limiting the extent of scour and reworking typical of earlier flood events. Nevertheless some scouring and channel cutting is evident following these events. Overall, mitigation of flooding through damming and channelization as well as artificial hardening of estuarine mouths into stable, open positions has altered the hydrodynamics and sediment export processes of most California estuaries.

Human alteration of sediment processes is complex and the response of estuarine systems may not be as expected. For example, upstream damming was followed by estuarine infill at Old Creek and Arroyo Grande based on comparison to 19th century mapping. This is presumably due to loss of erosive scour during flood flows. In contrast, channelization of the creeks leading to the large "trapped" system at Mugu Lagoon precludes the distribution of sediments across a broad floodplain. Once altered, sediments are seen to aggrade to higher than the surrounding plain in the diked channels and are consequently delivered to the lagoon. Here, in combination with other anthropogenic manipulations including jettying open of the lagoon mouth, they contribute to the sedimentation of the lagoon.

Tides and Wave Attack

The tidal cycle is semidiurnal in California thus there is one significantly higher tidal cycle in the average day. In addition there is a large Spring/Neap tide difference in the typical fortnightly tidal series. Physically the neap tide series provides a time when estuarine flow and height are low for a number of days at a time. This provides and opportunity for longshore sediment delivery and closure processes to operate unfettered (Behrens et al. 2009). Over a number of neap flood tidal cycles this can establish a large body of sediment at mid-tidal elevation in the mouth that may extend well into the estuary via a flood-tide delta complex and/or wave overwash to form an elevated sand flat. This tidally emergent bar then serves to maintain water at some height impounded in the estuary until opened by flood conditions. This broad sand feature can then be difficult to erode or downcut yielding a semi-closed system. This system then may completely close over time. Lack of efficient channel downcutting during higher spring tide events may in part be due to wave interaction at the mouth, which fills incised channels between tidal cycles. Such semi-closed systems may persist for variable periods prior to full closure others may not attain full closure or do so only intermittently; on the other hand, these systems do not completely drain except during flood events that eliminate the impediments at the mouth.

Wave attack on the California Coast is not constant in wave height or direction. Winter storms in the North Pacific generate waves that approach form the northwest. Southern Ocean and tropical storm waves that approach the coast from the South are more prevalent in the summer. These can produce seasonal cycles of estuary mouth behavior, for example prior to jetty construction the mouth of Elkhorn Slough would turn and elongate longshore to the north in response to summer wave conditions (Woolfolk 2005), and bar formation would restrict tidal action. Similarly, northern and southern seasonal movement of the estuary mouth were reported in the 19th Century in the Bolsa Chica-Anaheim Bay area (Engstrom 2006) (Figure 2).

Longshore Processes

Waves approaching the coast at an angle are generally thought responsible for longshore transport of sediment down the coast. This has a number of implications, sediment delivered to the sea by floods or the ebbing tide at a lagoon/estuary mouth will tend to be returned to the shore downstream away from the direction of approach of the waves (Orme 1985, Schwarz and Orme 2005, Zoulas and Orme 2007). This process can occur on a number of scales. Each wave has a similar asymmetric transport effect with a greater downshore component to onshore wave transport and a more directly offshore retreat. Tidal cycles, both individual and spring/neap, likely result in offshore followed by downstream transport. At the seasonal scale (winter) stream flow events move sediment offshore and summer wave cycles move sediment onshore further down coast. Consequently, when extensive flood event flows or ebb tidal outflow projects sediment offshore from an estuary mouth, those sediments will tend to come onshore primarily on the downcoast side. Conversely there will be net erosion on the upcoast side of the estuary mouth in the direction of wave attack, and the estuary mouth will tend to migrate up-coast (upstream relative to longshore process). Migration of the mouth governed by the above process often proceeds upcoast in the direction of wave attack direction until it meets an impediment, such as a rocky promontory. Such openings can be relatively stable and persistent as the promontory replicates some of the function of a one-sided jetty. This phenomenon likely accounts for the tendency of mouths to stabilize near the upcoast sides of estuaries (e.g., Bodega Harbor, Bolinas Lagoons).

Figure 2. Coastal T-sheets (ca. 1876) of Santa Ana-Newport region showing lateral migration of estuarine mouth. Prior to 1862, The Santa Ana River, the largest in Southern California, flowed to the sea somewhere to the northwest (left) of the region in the middle of the map marked "Bitter Lake." After 1862 it took the path shown by the blue arrows flowing behind a beach berm to join with the opening of Newport. Engstrom (2006) also noted oscillation of the mouth on a seasonal basis. The confining aspect of the shallow bar complex at the mouth (see Davidson 1889), as well as the barrier system, more generally contributed to a freshwater to brackish water system (the "Willow Swamp") indicative of broad expanses of freshwater/riparian conditions. These "swamp" conditions were typical across the Los Angeles Basin shoreline at this period (see Swift 2005; Stein *et al*. 2007 for discussion). In comparison, the modern condition separates the Santa Ana River from Newport and directs virtually all flowing fresh water directly to the ocean, as is the case throughout the Los Angeles region. In addition, present day tidal flows are facilitated artificially by dredge channels at Newport.

Conversely, when flood or tidal energy is insufficient to project sediment beyond the swash zone an attached bar will form and build down the beach downcoast away from the direction of wave attack. This bar can form a berm and elongate a drainage channel down the beach. These features are often prominent where wave energy is high relative to the outgoing flow at the mouth. Such spits and channels often form during the closure phase of systems following breaching. Once closed, these channels often form elongate transient extensions of lagoons on the beach top trapped by the beach berm. Beach berms formed by wave action can lead to impoundment or "perching "of water in the lagoon well above sea level where stream flow is sufficient to overcome evaporative loss and percolation through the berm, but is insufficient to overtop and breech the berm (Figure 3).

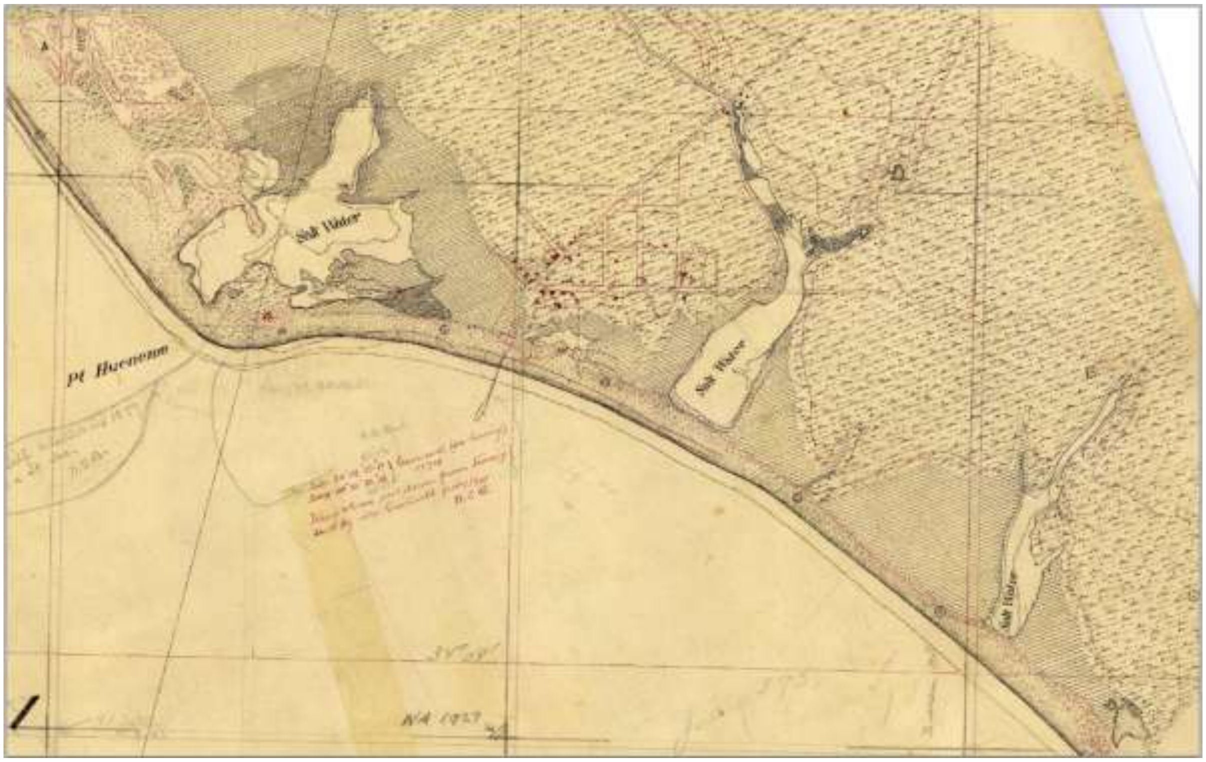


Figure 3. Lagoons south of Point Hueneme as shown on T-sheet 893 (ca. 1857). These lagoons appear to have: 1) formed via downcutting by distributary channels of the Santa Clara River, 2) had the potential to "perch" behind the raised berm and 3) to have had the potential to connect laterally to one another behind the beach berm. Thus when inflow raised water level in one system they may have flowed to adjacent systems.

Larger spits are a product of sediment movement and prograde downshore subparallel to the coast. If water depths are appropriate, spits can extend longshore or offshore at an angle (where they are termed flying spits) entrapping a body of water behind it. This body can then close or nearly close if the spit then approaches the shore. Breaching in these systems is often governed by freshwater flows into them. However, these systems on prograding coasts are not confined to narrow valleys and they are less likely to be directly associated with a stream. Therefore, flooding and associated erosion may not remove sediment with the same efficiency as these systems are less laterally confined than Pleistocene valley stream mouth estuaries. However, in actively prograding systems beach ridges can be formed in series with new spits often forming and prograding downshore, offshore of previously formed spits and estuarine features. Features of this type are found on the progradational shores of Santa Clara Delta, Oxnard plain region where they formed Mugu Lagoon (Figure 4), and such offshore barrier spits and islands characterized the coast from San Pedro to Anaheim. Once formed such barriers were subject to flood related breaching and river channel alteration, as well as to cycles of mouth migration and breaching.

Figure 4. Series of barrier sand spits generating the prograding shoreline and forming much of the space of Mugu Lagoon (ca. 1860). Note the stable sand spits (yellow bars) apparently formed by a succession of longshore "trapping" events. Note also the thin spit (red bar) historically observed to undergo cycles of mouth migration, closure, and breeching as supported by observation, successive mapping, and air photography (see Warme 1971). In addition, the older Holocene inland spit is cross-cut by an outflow channel contributing to the estuary space. This cross cutting feature was apparently associated with flood distributary behavior of the Santa Clara River.

Proposed Classification System for Southern California Estuaries

Southern California estuaries can be classified using four primary attributes that relate to their formation and dominant physical processes, coastal setting, coastal exposure, watershed characteristics, and formation process (Table 1). For simplicity, we propose two to four discrete categories for each attribute. In reality each attribute is a continuum; specific estuaries will often include aspects of multiple states depending on the size and heterogeneity of the system. The dominant condition for each attribute can be used to understand the nature and function of the resultant estuary system including its size and closure pattern of the mouth.

Table 1. Estuary attributes, and associated categories, that describe formation and physical process.

Coastal Setting (S)	*Coastal Exposure (E)*	*Watershed (W)*	*Formation Process (F)*
Prograding (S-P)	High (E-H)	Large, low gradient (W-L)	Inherited space (F-I)
Terraced (S-T)	Low (E-L)	Medium, intermediate gradient (W-M)	Trapped (F-T)
Steep (S-S)		Steep coastal drainage (W-C)	Hydraulic/Flood (F-H)
		Small/ill defined often lowland catchments (W-S)	

Coastal Setting

Prograding (S-P) shorelines where sediment supply to the coast exceeds the removal rate and the shoreline tends to build offshore these are usually low gradient shorelines, although dunes can provide exceptions to this (Figure 5).

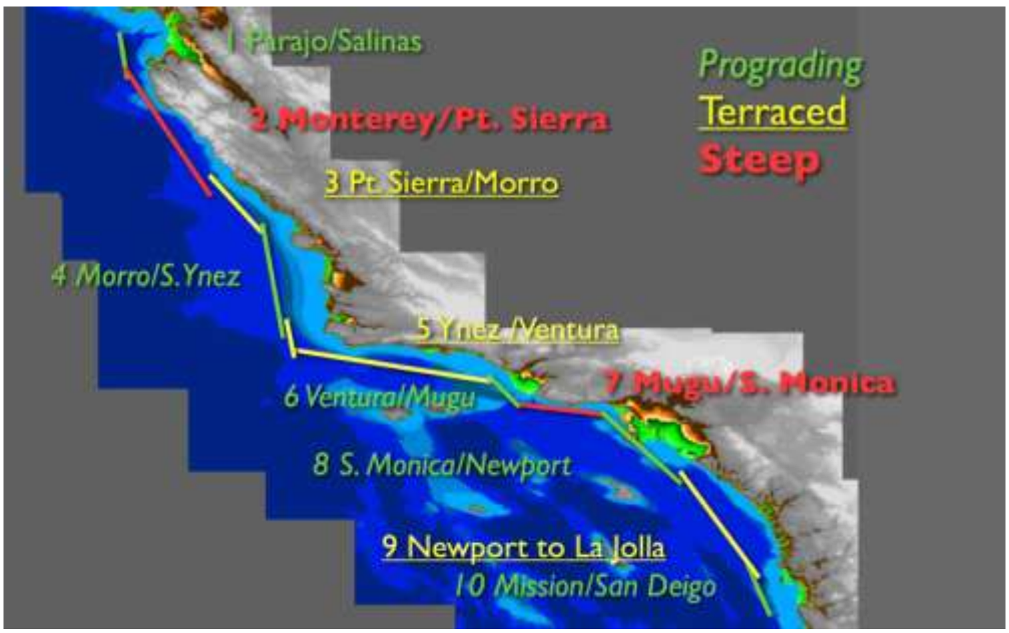


Figure 5. Distribution of coastal settings in southern California. Coastal setting is used here as a regional variable with the coast divided into 10 units with distinctive properties. Each unit is categorized as to whether it is predominantly prograding, terraced, or steep.

Terraced (S-T) shorelines where former wave cut Pleistocene shorelines have been uplifted forming a bench or terrace that has then been subsequently eroded by Holocene wave action such that a cliff faces the ocean (a series of benches may be preserves if the process has been repeated through the Pleistocene).

Steep (S-S) shorelines descend from coastal mountains or raised headlands such that the regional coastline is relatively precipitous. Incised valleys can form confined estuaries in this context.

Coastal Exposure

As discussed above there are a number of factors that influence the exposure of an estuary mouth to wave energy including coastal orientation. This in turn influences longshore process and closure dynamics at the mouths of estuaries. Coastal orientation also has implications for wind direction and dune formation. For sake of simplicity these are summarized in a simple binary variable. Future work may need to consider this variable in greater detail.

High (E-H) - Estuaries on west or northwest facing coasts at higher latitude, and that lack protection from "up-coast" promontories experience greatest wave energy. This energy is also largest from November to May and can be mitigated by coastal promontories. In addition, onshore winds often generate dunes where sediment supply is sufficient. These conditions are most typical of a stretch of coast north of Point Conception and the "Big Sur" coast but other stretches of west facing coast locally qualify.

Low (E-L) - The Santa Cruz, Santa Barbara, and Malibu Coasts, face south, or are protected by promontories (e.g., San Luis Obispo Creek) or offshore islands (some areas of the Bight such that winter wave energy is much reduced. However, some areas (e.g., Malibu) experience enhanced summer wave events often in June and July when southern ocean storms are most active. In addition, many coasts that have a southwesterly orientation likely experience enhance wave energy in El Nino years. Coasts facing directly south tend to have less dune development as winds have less of an onshore component. This exposure variable should be significantly refined in future work.

Watershed Characteristics

Watersheds are here divided into four geomorphic classes based on size and steepness. Watershed attributes may merit treatment as multiple continuous variables in future work.

Large low gradient (W-L) coastal rivers typically drain highlands that are relatively far from the shore. Despite their lower gradient lower reaches, these streams have high sediment load due to their steep upstream reaches. Steep gradients and short intense rainfall patterns in the upstream reaches result in highly variable (flashy) flow conditions. Under natural conditions these larger braided streams occupy relatively wide valleys that are sometimes terraced due to uplift. Often these drainages evolved with and, are oriented along rather than across major structural trends (e.g., Salinas River/ San Andreas; Santa Ynez River/ Santa Ynez Fault).

Medium sized intermediate gradient (W-M) streams typically penetrate and drain beyond the first coastal ridge. They cross rather than parallel significant structural trends and often show evidence of relatively recent stream capture or change in gradient in their upstream reaches. Overall they are relatively high gradient. Clear examples of such streams include Arroyo Grande, Gaviota and Malibu. The Santa Margarita and San Luis Rey Rivers also generally fit this category.

Steep coastal (W-C) drainages that do not penetrate, but often drain the face of the first coastal range. They are often relatively high gradient and are subject to flashy behavior and intermittent flow. Many streams draining the face of the Santa Lucia Range (e.g., Toro Creek), Santa Ynez range behind Santa Barbara, and the Santa Monica Mountains are in this category. Mission Creek and Topanga Canyon are relatively large exemplars of this category.

Small lowland (W-S) catchments have small to minimal often more lowland catchments. Examples would include Parado and Tecolote and Campus Lagoon on the Santa Barbara Coast, and features such as Arroyo Corall and Arroyo Puerto on the Central Coast near San Simeon. Such drainages are numerous in some coastal settings and often historically supported small estuary/lagoonal features at their mouths. The lagoon at Ormond Beach south of Pt. Hueneme is a remnant of a number of systems present in the region historically. These features likely formed as distributary channels of the Santa Clara during flood events, but subsequently operated as small lowland catchments (Figure 3). The catchments of small vernal pool systems would be in the lowest size range of systems in this category.

Formation Process

Inherited space (F-I) estuaries formed through the flooding of preexisting valleys via the substantial ~130 meter rise in sea level associated with the melting of glacial ice that came to an end by about 7kya. This process is most like the formation of East Coast estuaries produced by the "drowning" of river and glacial valleys. However, many of these flooded valley estuaries of California have largely tectonic, rather than erosional origins, such as San Francisco and Tomales Bays.

Trapped (F-T) estuaries formed as a consequence of wave produced sand movement and long-shore migration of spits that confine an embayment. These bear some similarity to the barrier islands of the east coast, but are more modest on the west coast, where they are often associated with or impound areas adjacent to headlands or promontories such as at Morro Bay, Bolinas, Drakes Bay or Bodega Harbor, but can also form in the regions of coast that are prograding and have significant sediment input, such as Mugu Lagoon or the Historic estuaries from Palos Verdes to Newport. In some instances the spit develops dune fields, as at Morro Bay.

Hydraulic Estuaries (F-H) form from the erosion of sediment from the mouths of rivers during larger flood events. These estuaries are typical and common on the California coast and are relatively foreign to the wetter regions of the east that experience significant year-around stream flow. These estuaries are often closed to the sea by a bar across the mouth during low rainfall periods and have some overlap with systems referred to as "bar built" estuaries. In these systems, estuarine space may be episodic rather than stable with larger estuaries established in major flood events then undergoing long periods of infill during decades or centuries with less dramatic flooding as has perhaps been most clearly evident in the San Luis Rey Estuary, which was briefly navigable after historic floods (Engstrom 2006) and subsequently functioned as a closing system.

These three formation process categories are often relatively distinct (Figure 6), but need not operate in exclusion of one another. In addition, over the Holocene time, estuaries that may have initially occupied large flooded valleys ~7kya, have subsequently filled in and become F-H estuaries where recent flood history carves out the estuarine space. Holocene shoreline retreat associated with erosion and generation of wave cut cliffs can also eliminate shoreline features smoothing out smaller headlands and estuarine features along much of the coast, especially where headlands are composed of more easily eroded Neogene sediments.

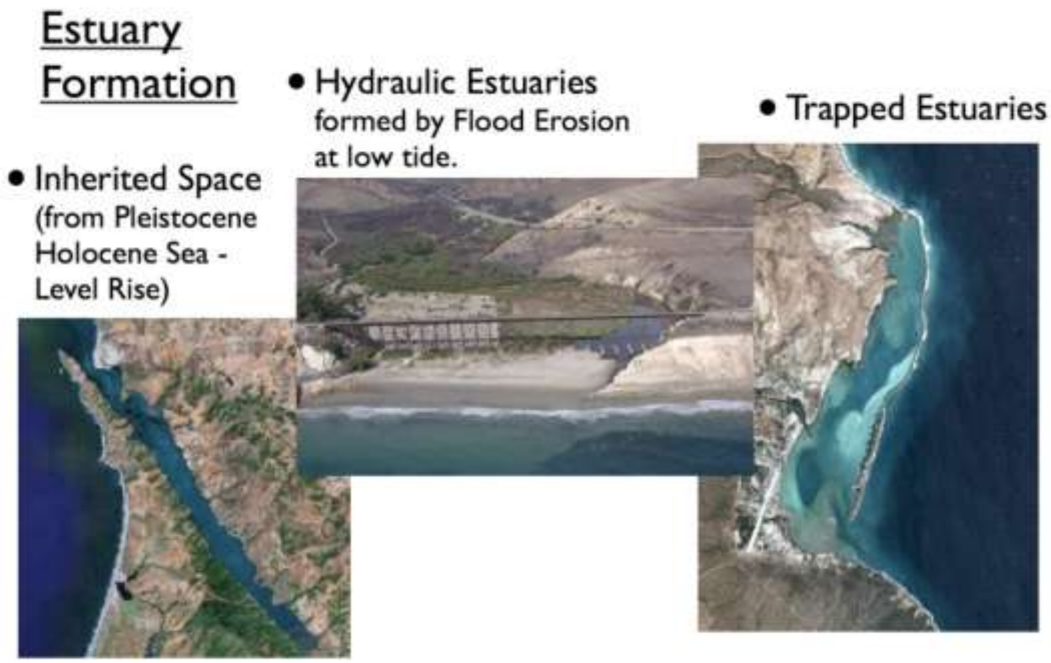


Figure 6. Illustration of three formation processes for southern California estuaries. Oblique photographs courtesy of California Coastal Records Project, www.californiacoastline.org. Copyright © 2002-2009 Kenneth & Gabrielle Adelman.

Closure Pattern

The above classification was generated in part to provide a suite of geomorphic predictive variables for observations of estuarine closure. These can be viewed as input variables in a model. Thus an observable "output" variable for closure itself also needs to be defined. Because closure is a variable phenomenon we define a closure "state" or "condition" as an observation of degree of closure based on a specific observation or record at a given time. We then define closure "pattern" as the summary of closure conditions through time. The goal is to be able to predict the predominant "closure pattern" under natural circumstances (i.e., in the absence of structures or actions that alter natural closure patterns) based on the "classification" of the four variables described above.

Closure is a highly dynamic variable and the degree of closure through time is controlled not only by the relatively static factors discussed above, but by climatic cycles that operate on seasonal, annual, decadal, and multi-decadal times scales. These affect both stream flow and wave action. Here, we propose a set of defined closure "conditions" or "states" that can be compared to time series of observations of the status of mouth closure taken from photographs, maps or description of discrete points in time. Given a sufficient temporally distributed sample closure "pattern" can then be presented as summary graphics or statistics of the closure conditions or states an individual estuary experiences through time.

We describe eight closure states based on the elevation (relative to tide height) at which mouth closure occurs (Figure 7). Because estuaries often display several of these states over their natural hydrologic cycles, we predict the dominant state experienced by an estuary and estimate the proportion of time an estuary exhibits each of its dominant states. These states are identifiable in a range of historic written, cartographic, and photographic data sources, as well as from ongoing aerial and satellite photography and prospectively from time-lapse photography and hydrographic instrumentation. As stated above, systems exist along a continuum and categorization is done as a convenient way to express predominant condition.

Dune-dammed (C-D) systems exist as lakes or ponds that are cut off from the sea by dunes. In a dune-dammed condition "estuaries" often maintain freshwater well above high high-tide. These systems breach at seasonal to decadal or multi-decadal, time scales. They may lack obvious surface connection to the ocean or be connected by intermittent overflow between breaching events. They range in size from interdunal vernal pool features to medium sized closed drainages impounded by dune systems. Features of this sort are present today in northern California, South of Arroyo Grande, and at Oso Flaco in the study region. They were, however, more pervasive historically and are evident from T-sheets and other historical documentation at and around Lake Merced (now an impounded feature on the outer coast south of San Francisco), the Salinas Valley region especially just north of Monterey, between the Santa Clara River and Point Hueneme, on the coast in the region between Ballona and Palos Verdes, and in the region of La Jolla and the northern and southern termini of the outer spit forming San Diego Bay. Coastal vernal systems, a subset of dune-dammed systems are perhaps the most impacted coastal wetland type in the state as they have largely been eliminated (see e.g., Mattoni and Longcore 1997).

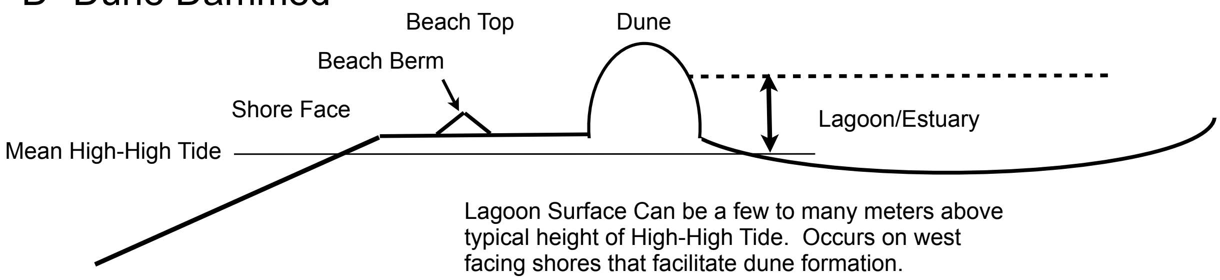
Perched (C-P) conditions form impounded areas behind a beach berm where the water level is substantially above high tide. These tend to be more transitory than dune-dammed systems and generally breach annually or every few years depending on rainfall and storm patterns. More specifically water levels rise a couple of meters above high–high tide in these systems when the right combination of wave built beach berms and stream flow are present. West facing systems tend to have greater wave exposure and higher berms. High wave events that build higher berms may accentuate perching. For higher water level stream flow has to balance or exceed losses via percolation through the berm and evaporation. Perching is known to occur regularly at Lake Earl, at the Russian River Mouth, in the Salinas River and in Aliso Creek, Orange County. All of these locations are actively managed by breaching to prevent flooding of structures, and parking lots. In the Salinas valley very significant areas of farmland would be submerged during the rainy season without artificial breaching at the river mouth. Los Peñasquitos is also managed with breaching and may have a history of perching. Prior to modification by road development, significant perched steelhead habitat typically formed at Pescadero Creek yielding a lagoonal steelhead fishery. A note on the T-sheet for the Santa Clara River (Figure 3) documents that a significant region north of the mapped lagoon is "flooded in winter;" presumably this indicates a perched condition when flow was sufficient to fill the area behind the beach berm, but insufficient to breech and drain. Such behavior was likely typical in a number of additional systems especially in the winter and spring in modest rainfall years. Perching presumably occurred during seasonal rains in Ballona during the late 19th century as is supported by historic documentation of expansive wet season ponding discussed below. Alternating perching and draw down due to partial desiccation in the summer were likely typical of west facing systems with small drainage areas relative to their size such as Buena Vista and Batiquitos Lagoons. French lagoon a small perching system on Camp Pendleton desiccates frequently, and beyond the geographic scope of this analysis, many subtropical systems exhibit seasonal and event dependent cycles of breaching, perching and desiccation in response to rainfall.

Closure near or immediately above high high-tide (C-C) in which a sand or cobble beach or beach berm separates the open sea from a "lagoon." This condition occurs regularly in the majority of California estuaries, and allows for significant departures from marine conditions in the estuary. When completely closed, lagoons are limited in tidal exchange by the permeability of the berm, under most conditions they are effectively not tidal for the duration of closure. Cobble can permit some exchange and intermittently, when there are combinations of high tides and high wave action, waves may overtop the beach/beach berm and introduce marine water to the lagoon. Breaching and closure can occur on a variety of temporal scales: with each significant rainfall event, annually or with multi-year periodicity. Small systems appear to close more rapidly than large systems, in large part due to the greater variation and rapid reduction in stream flow following precipitation in small drainages, but also due the longer times required for longshore or beach processes to close a larger mouth opening a large system.

Closed high in the intertidal (C-H) involves closure below the high high-tide level, but some exchange regularly occurs at higher high tides or high wave events. Such a condition is often evidenced by a region where the beach berm is absent due to recent or frequent wash-over from waves and/or outflow. However, any outflow channels formed are not deeply incised or persistent. Such conditions are likely to persist where excess stream-flow/outflow is modest, a wide beach precludes rapid incision of a channel, and/or where regular wave action limits the continued incision of the same channel between tidal cycles.

Closed in the mid intertidal (C-M) involves significant closure and ponding between the low-high tide and high-low tide levels, but tidal exchange occurs with all, or nearly all, tidal cycles. Such systems often have channel drainages on the beach that persist between tidal cycles. However, these channels generally are turned downs-shore, away from the direction of wave attack, and elongated rendering them of lower gradient in outflow and erosional insufficient to further incise. These elongate features can close and become parts of a closed lagoon as discussed above. A mid-intertidal closure can be roughly diagnosed from aerial photography or mapping that exhibits these turned or shore parallel outflow channels. This condition permits relatively frequent but modest tidal exchange.

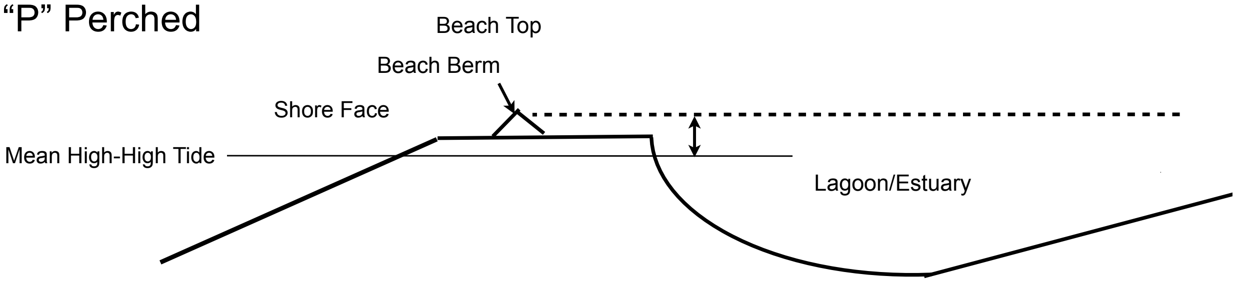
“D” Dune Dammed



Lagoon Surface Can be a few to many meters above typical height of High-High Tide. Occurs on west facing shores that facilitate dune formation.

Oso Flaco, August 30, 1993. Regularly dune dammed system

“P” Perched

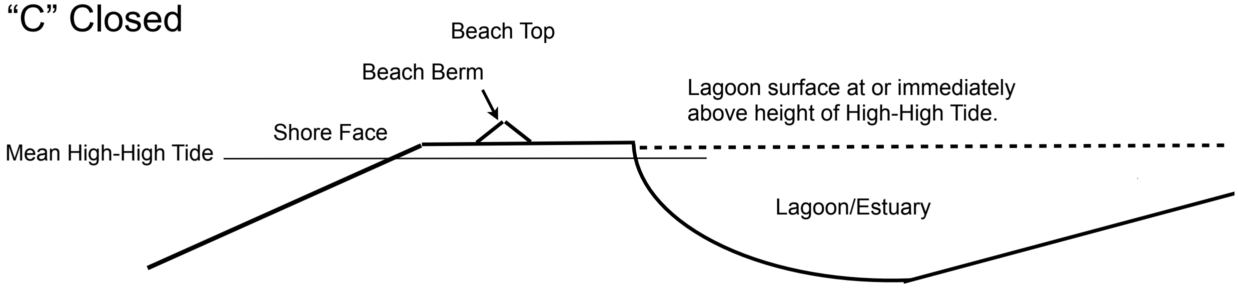


Lagoon surface can be a few meters above typical height of High-High Tide. Beach berm height and perching is accentuated by higher wave energy on exposed west facing shores.

Santa Ynez, January,1989. Perching behind beach ridge yielding high water in lagoon flooding marsh surfaces.

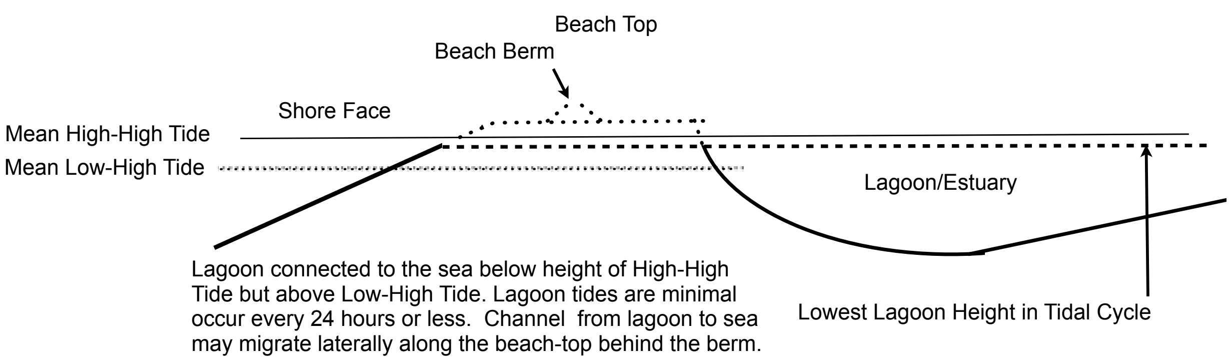
Figure 7. Schematic representations and examples of closure states.

"C" Closed



Malibu Lagoon, September 18, 2008. Closed at or near High-High Tide.

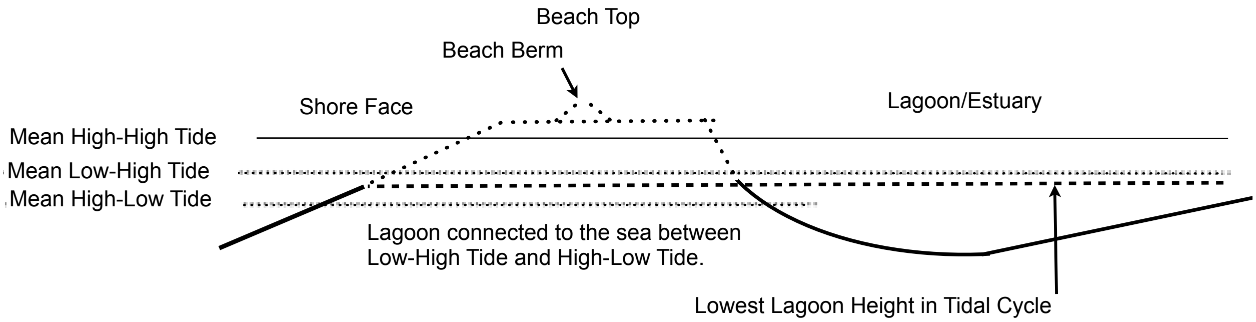
"H" Closure High in the Intertidal



Arroyo Grande Creek, May 4, 1979. Closed high in the intertidal with a lagoon/ channel feature paralleling the shore behind a beach ridge. This often occurs in high intertdal systems and in many systems late in the closure process.

Figure 7. Continued.

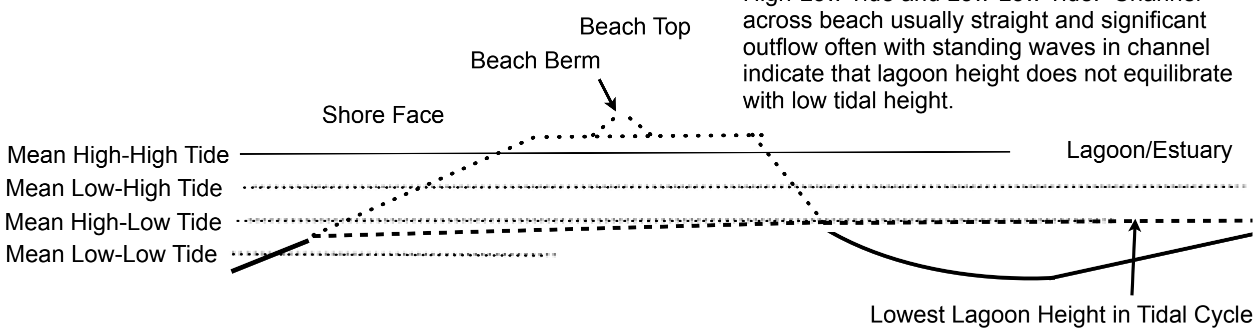
“M” Closure in Mid Tidal range



Aliso Creek (Orange County), Oct 23, 2004. Intertidal Closure. Note the steep North Side of the lagoon caused by a recent high stream flow event. The mouth is likely part way through the closure process.

“L” Closure Near Low Tide

Lagoon connected to the sea between mean High-Low Tide and Low-Low Tide. Channel across beach usually straight and significant outflow often with standing waves in channel indicate that lagoon height does not equilibrate with low tidal height.

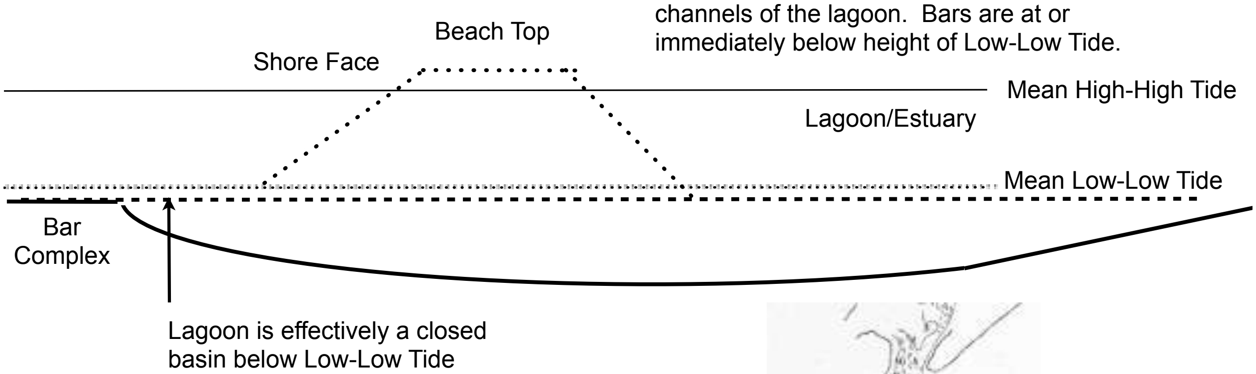


Tijuana River, May 3, 1979. Outflow at intertidal height is often indicated by high gradient flow (standing waves) in the mouth at low water.

Figure 7. Continued.

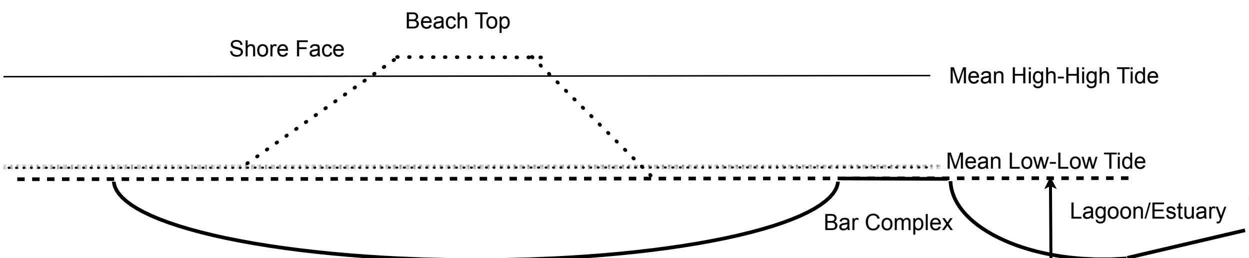
"S" Sub Tidal Closure

Lagoon connected to sea over an outer subtidal bar complex that is shallower than the deeper channels of the lagoon. Bars are at or immediately below height of Low-Low Tide.



Bathymetry on 1855 T-sheet inset of Wilmington Lagoon entrance, San Pedro, showing deep channels within the lagoon extending and terminating in an offshore wave scoured immediately subtidal flat. Similar subtidal barrier often occur immediately inside the entrance of lagoons due to flood tidal delta formation.

"S" Sub Tidal Closure - Flood Tide Delta



Lagoon connected to sea over an inner flood tidal delta-subtidal bar complex. Bars are at or immediately below height of Low-Low Tide. These bars are typical of estuaries on sandy shores that are naturally or artificially open.

Lagoon effectively a closed basin below level of Low-Low Tide

Batiquitos Lagoon, 2008 (from Google Earth). Note rapidly forming flood tide delta complex.

Figure 7. Continued.

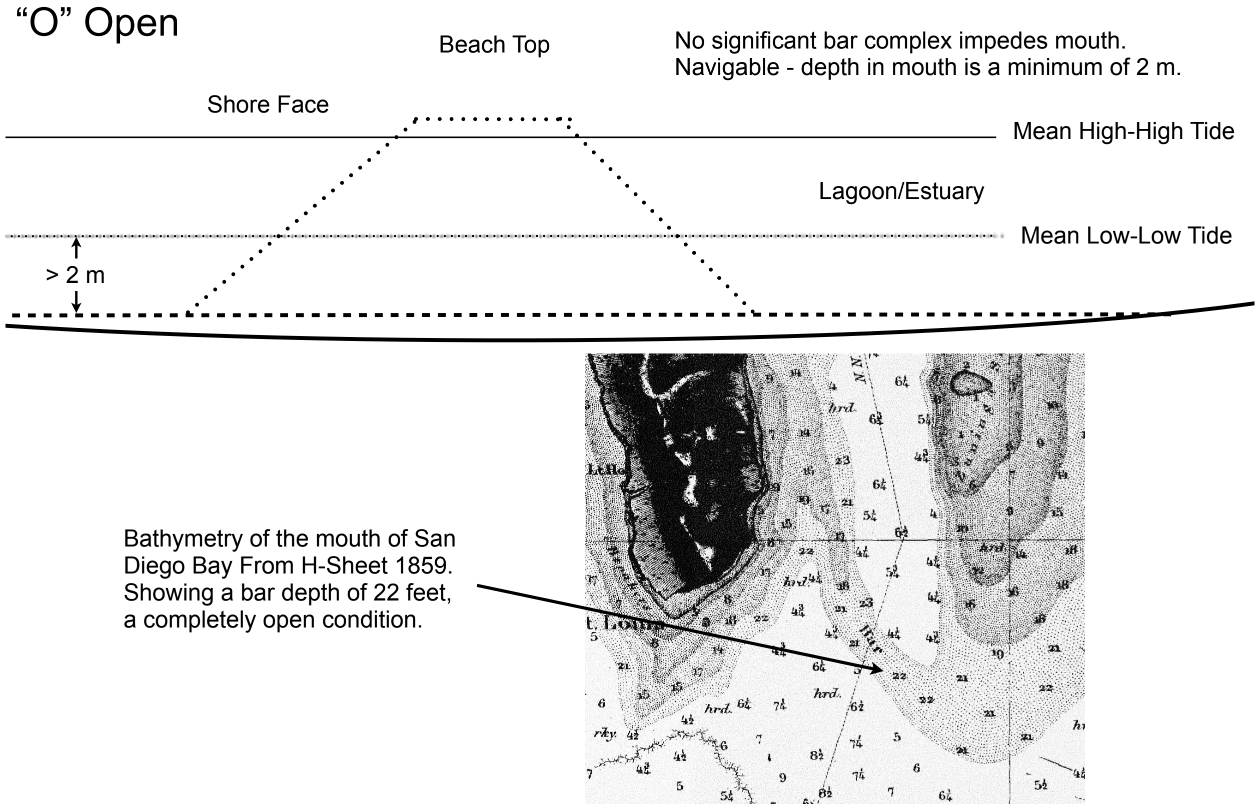


Figure 7. Continued.

Closed in the lower intertidal (C-L) is a frequent estuarine condition. In these systems deeper-water channels in the estuary are ponded at low tide by a barrier above low low-tide and below high low-tide; these channels, presumably relict of high flow events, are often found immediately within the mouth of a broader lagoonal setting. In some systems this lower intertidal closure condition persists, in others it is a stage following erosional (high stream flow) opening in a succession to closure higher in the intertidal (as above). In air photos standing waves in a fairly straight outflow channel at lower tidal heights is fairly diagnostic of this condition, as they document that the water level in the lagoonal system is significantly higher than the sea low in the tidal cycles. Systems in this condition are often viewed as fully tidal, but do not experience full tidal amplitude. Deeper channels often occur within these estuaries and flood-tidal deltas often build into estuaries in this condition.

Closure at or immediately below low low-tide (C-S) is found in lagoons/estuaries with bars near the mouth that are nearly emergent, and/or shallow sand flats and/or flood tide delta complexes that are barely submerged at low water. Bars and flats outside the mouth are produced by wave interaction with longshore and ebb tide derived sediment. These are recognizable in air and satellite photography and also on historic T-sheets and navigational charts (H-sheets) and are generally within a foot or two of low water and subject to regular reorganization. In historic literature such conditions are often indicated by impediments to navigation and regular shifting of navigational instructions. Some systems that tend to maintain this condition at the mouth contain deeper water within lagoonal channels relative to the shallower bar at the mouth. Presumably many of these channels are produced by high flow events and persist due to more limited sediment supply and more erodible substrate relative to the course material reworked by wave action at the mouth. This condition (C-S) was typical of the Wilmington, Alamitos, and Newport lagoons historically (Davidson 1889) and may have occurred intermittently in many other systems (e.g., Mission Bay and Humboldt Bay), as suggested by T-sheets and historic documents. Systems in this condition are connected to the sea but have impediments to tidal exchange. Comparable (C-S) conditions result from the depositional construction of a flood-tide delta on the lagoon side of the mouth. Flood tidal deltas often form when longshore processes do not or are not permitted to act quickly, leading to the sedimentation of the mouths of lagoons after natural or artificial opening of lagoonal systems.

Deep water openings/navigable embayments (C-O) were unusual historically in California. In this condition bars and flood-tide deltas, when present, do not impede navigation or significantly constrain tidal height. For simplicity in historic interpretation, a minimum one fathom or 2 meter depth evident through the inflow channel can be used as a cut off. The historic persistence of such openings is closely correlated with an early year-around history of navigation prior to dredging and jetty construction at harbor mouths. The available evidence suggests that this condition was persistent only at San Diego Bay in southern California. This condition likely occurred intermittently or episodically at Mission Bay and is suggested by the T-sheet for Mugu Lagoon. However, other data document the repeated full closure (C-C) of Mugu (e.g., Warme 1971), demonstrating that open conditions were not persistent. Only in the "open" situation is tidal influx largely unimpeded during spring tides. In a fully open system flood-tidal deltas typically do not develop and build near the surface. In contrast, historic H-sheets of San Diego Bay show an offshore deepwater bar and subtidal natural levees lateral to the main channel in the estuary. These may be comparable to flood tidal deltas because they represent where the energy in the tidal channel dissipated sufficiently to deposit bedload. These features have been removed to further enhance the navigability of San Diego Bay the primary example of a historically continuously navigable open system in southern California.

APPLICATION OF ESTUARY CLASSIFICATION SYSTEM IN CENTRAL AND SOUTHERN CALIFORNIA

In the following two exercises, we apply our classification to the opening behavior of California estuaries. First we generate a general prediction – a suite of hypotheses, or expectations of closure pattern given the naturally occurring combinations of the four "classification" variables. Thus we use the classification to articulate a model containing an *a priori* prediction of closure pattern. Closure pattern is represented by the frequency of each of the eight states or conditions. This provides a conceptual model for California "closure patterns" in estuaries that is potentially testable. Second, we examine the historical and image data for three estuarine settings where restoration is contemplated. This provides a historical ecological analysis of these systems and a preliminary assessment of the method.

Closure Model

Closure pattern is presented as a frequency for each combination of setting, exposure, watershed character, and formation process that are likely to occur, one or more expected closure states were assigned based on the prior experience of the investigators (Table 2) and presented as graphical output in the general form of frequency histograms. This represents an initial premise of the predicted closure pattern given the geomorphic classification representing know types of estuaries based on the classification variables defined above. Thus the closure frequencies/patterns shown in Table 2, column 5, and illustrated graphically via histogram in Figure 8, represent hypotheses that can be tested by garnering further observation. They also represent our best overall summary view of how we expect these systems behave relative to the suite of geomorphic variable.

Table 2. Predicted closure of California estuaries based on coastal setting, exposure, watershed size, and formation process.[a]

Coastal Setting	Exposure	Watershed Size (These are effectively proxies for stream flow dynamics)	Formation Process	Proportion in Closure State (D, P, C, H, M, L, S, O)	Examples & Notes
Progradational (S1)	"West" High	Large, low gradient (W1)	Inherited space (P1)	S 0.2, O 0.6	San Diego and Mission Bays.
			Trapped estuaries (P2)	C 0.2, L 0.2, S 0.3, O 0.2	Elkhorn historically fell into this category before the Salinas River was diverted.
			Hydraulic estuaries (P3)	P 0.2, C. 0.6, L. 02	Santa Clara River (Ballona Creek considered terraced but is intermediate with this category).
		Medium, intermediate gradient (W2)	Trapped estuaries (P2)	P 0.2, C 0.3, L 0.1, S O.5,	Morro Bay and Mugu Lagoon (at certain cycles through the mid 20th century).
			Hydraulic estuaries (P3)	P 0.2, C 0.4, H 0.1, L 0.1,	Pajaro Creek, Arroyo Grande. San Luis Rey and Tijuana Estuary at some points in time.
		isolated coastal drainages (W3)	Trapped estuaries (P2)	D 0.2, P, 0.2, C 0.4	West facing small systems are prone to dune damming and perching, e.g. Historic Lake Merritt.
			Hydraulic estuaries (P3)	D 0.2, P, 0.2, C 0.4,	Del Rey- Monterey, Morro Creek.
		Small, isolated coastal drainages (W4)	Trapped estuaries (P2)	D 0.3, P 0.2, C 0.3	La Jolla, many small vernal systems associated with dunes.
			Hydraulic estuaries (P3)	D 0.3, P 0.2, C 0.3	El Estero, Del Monte Lakes near Monterey, Ormond.
	"South" Low	Large, low gradient (W1)	Trapped estuaries (P2)	M 0.1, L 0.2, S 0.5, 0.2	Los Angeles, San Gabrial and Santa Anna rivers in their historic conditions.
			Hydraulic estuaries (P3)	C 0.1, M 0.2, L 0.3, S 0.3, 0.2	These have likely existed historically, from time to time in the LA basin, when, Los Angeles, San Gabrial and Santa Ana rivers flowed directly to the sea.
		isolated coastal drainages (W3)	Inherited space (P1)	C 0.7, H 0.2	Devereaux Slough, Andre Clarke (salt pond) , Goleta Slough.
			Trapped estuaries (P2)	C 04, M 0.2, L 0.3, S 0.2,	Carpenteria (Marsh).
			Hydraulic estuaries (P3)	C 0.6, H 0.2, M 0.1	Mission Creek.
		Small, isolated coastal drainages (W4)	Inherited space (P1)	C 0.8,	San Diego Salt Pond/ Andre Clark Marsh (Historic).
			Trapped estuaries (P2)	C 0.7, H.02	Half Moon Bay (historic Lagoon), El Estero Santa Barbara (historic).
			Hydraulic estuaries (P3)	C 0.8	Sycamore Canyon (Santa Barbara).
Terraced shoreline (S2)	"West" High	Large, low gradient (W1)	Hydraulic estuaries (P3)	P 0.1, C 0.6, L 0.2	Santa Ynez and Ballona creeks during some periods.
		Medium, intermediate gradient (W2)	Hydraulic estuaries (P3)	P 0.2, C 0.5, L 0.1	Santa Margarita, San Luis Rey, San Dieguito, Tijuana.
		Isolated coastal drainages (W3)	Inherited space (P1)	P 0.2, C.07	Smaller north San Diego County systems may have some inherted space.
			Hydraulic estuaries (P3)	P0.2, C 0.7, M 02	San Antonio Creek, Aliso Creek, (Orange Co.), several in N. San Diego County.
		Small, isolated coastal drainages (W4)	Hydraulic estuaries (P3)	P 0.1, C 0.8	Portions of N. San Diego County, and a number of small drainages along the coast between Morro Bay and the Big Sur coast.
	"South" Low	Medium, intermediate gradient (W2)	Hydraulic estuaries (P3)	C 0.6, H, 0.1, M 0.1	Gaviota, San Lorenzo.
		isolated coastal drainages (W3)	Hydraulic estuaries (P3)	C 0.7, H 0.2	Aptos, Villa Creek, Rincon Creek.
		Small, isolated coastal drainages (W4)	Hydraulic estuaries (P3)	C 0.9,	Several small drainages in and near Santa Cruz, Hollister Ranch localities on Santa Barbara Coast and several others in and Near Santa Cruz.
Steep shoreline (S3)	"West" High	Medium, intermediate gradient (W2)	Hydraulic estuaries (P3)	P 0.1, C 0.5	Big Sur, Carmel.
		isolated coastal drainages (W3)	Hydraulic estuaries (P3)	P 0.2, C 0.6	Little Sur.
	"South" Low	Medium, intermediate gradient (W2)	Hydraulic estuaries (P3)	C 0.5, H 0.2 M 0.2	Malibu Creek.
		isolated coastal drainages (W3)	Hydraulic estuaries (P3)	C 0.7, H 0.2	Topanga Creek.
		Small, isolated coastal drainages (W4)	Hydraulic estuaries (P3)	C 0.9	Las Flores Creek.

[a]Only the combinations of classes that naturally occur are shown. Closure patterns: D-dune-dammed, P-perched, C-berm closure above high high-tide, H-closed high in intertidal, M-closed in mid intertidal, L-closed in lower intertidal, S-emergent bars at low low-tide, O-deep water openings. Classes are indicated with hypothesized proportion of time in each state. Frequencies do not add up to 1 as brief transition states are not considered.

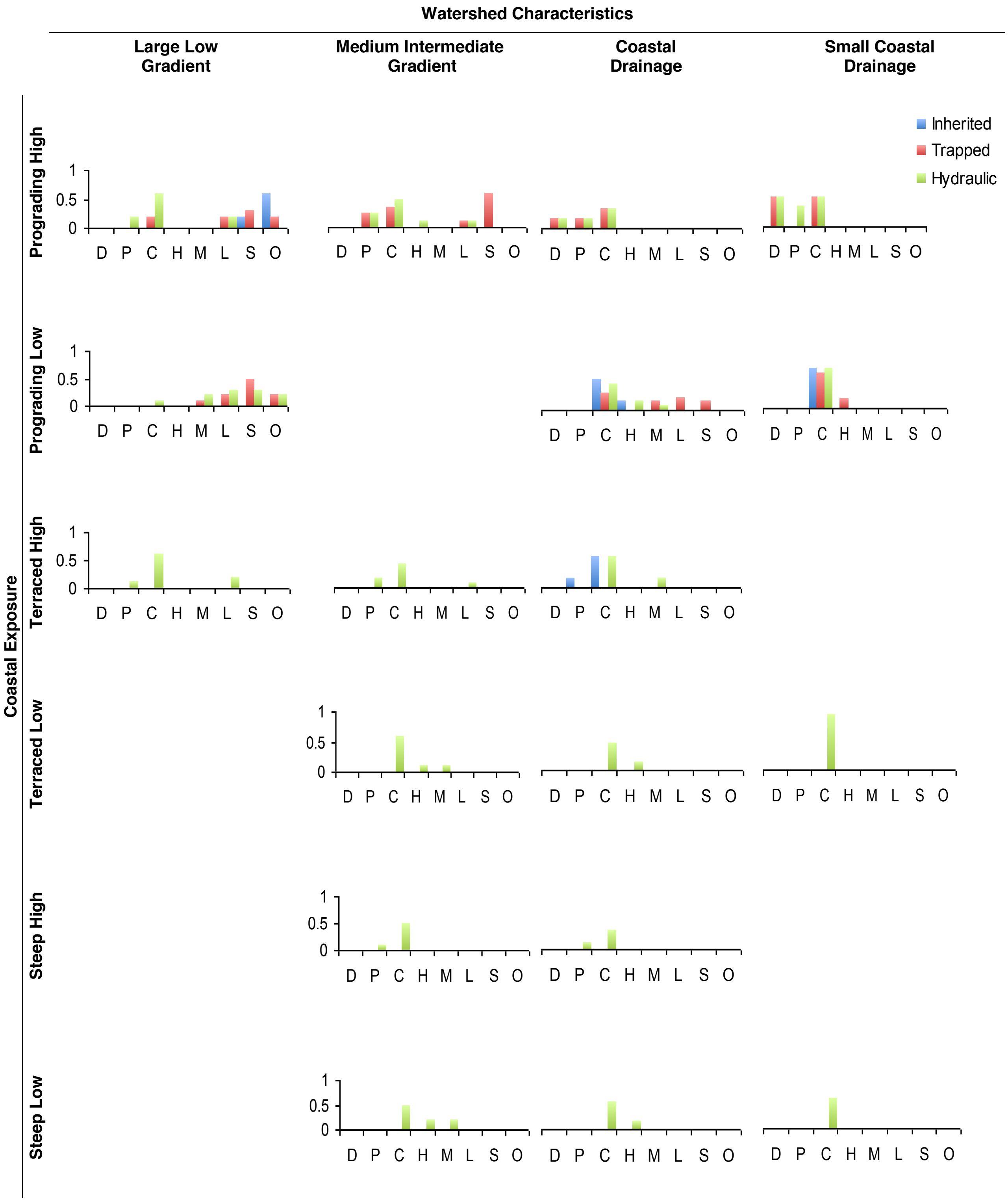


Figure 8. Visualization of closure regime for southern California estuaries, classified by watershed characteristics, coastal exposure, and closure state: D = Dune, P = Perched, C = Closed, H = High Intertidal, M = Mid Tidal Range, L = Low Tidal, S = Sub Tidal, and O = Open. Y-axis is the proportion of time that an estuary exists in each closure regime.

Detailed Assessment of Three Estuaries

The classification scheme that we have presented, based on an understanding of the physical processes that govern estuary dynamics, includes predictions about estuary mouth "closure pattern" that can then be compared with historic conditions. We selected three estuaries for further analysis to assess our approach, as well as to provide historical ecological summaries of systems of interest. Estuary/lagoonal systems at Ballona Creek, Topanga Creek, and the Tijuana River were chosen because they are prospective sites for restoration. For each system a general description of the estuary, its exposure and coastal setting, the watershed characteristics, the estuary formation process, and resulting predicted closure patterns are discussed. We then follow with the historical evidence of closure pattern.

Ballona Creek

General Description

Ballona Creek was, until the great flood of 1825, the outfall of the Los Angeles River (Reagan 1915) when the river changed course and left Ballona Creek with a modest 83,000-ha watershed. The watershed extends westward from the western edge of downtown Los Angeles and along the southern flank of the Santa Monica Mountains. South of downtown Los Angeles, it includes much of south Los Angeles west of the present 110 Freeway and encompassing the Baldwin Hills and the Centinela Creek watershed, which also flows into the Ballona Wetlands at Playa del Rey. The watershed is highly urbanized, with substantial loss of once-extensive wetlands and near-complete channelization of Ballona Creek and its tributaries.

Coastal Setting and Exposure

The coastal setting immediately adjacent to Ballona is terraced (S-T), although this terracing is less apparent due to a complex history of associated dunes. At a larger scale, however, the Ballona system can be seen as connected with prograding sediments from a larger Los Angeles Basin system. This system is constituted from the coalescing alluvium from the Los Angeles, San Gabriel, and Santa Ana rivers. The alluvial fans of these rivers merge on the plain of the Los Angeles basin and this basin wide plain has prograded through a series of gaps in the uplifted terraced high ground along the Newport-Inglewood Fault that forms the southwest side of the Los Angeles Basin. Ballona is at the northern-most of these gaps and Newport Bay the most southerly. This larger context is important to understanding the flood dynamics of the Ballona system over time.

Exposure of the mouth of Ballona Creek is high, as a west-facing beach in the Santa Monica Bay it is subject to greater wave action than south facing beaches along the coast and is designated as high (E-H). However it is somewhat protected by its position within the Southern California Bight and by the Channel Islands. Thus, estuaries to the north and south beyond the limits of the Bight, on northwest facing coasts have substantially more extreme exposure.

Watershed Characteristics

The Ballona Creek watershed is, by our classification, large and low gradient. This classification is, in part, due to its intermittent connection to the Los Angeles River. The highest point within the Ballona drainage proper is only 550 m in elevation. The streams draining the Santa Monica

Mountains are the steepest portions of this watershed. In contrast, drainages of the Los Angeles, San Gabriel and Santa Ana Rivers that drain into the Los Angeles basin extend to elevations in excess of 3,000 m in the San Gabriel and San Bernardino Mountains providing significant runoff following storms as well as through the melting of snow in the winter and spring.

Historically estuarine space in Ballona Lagoon was primarily formed by Hydraulic process (F-H), although this was not the case earlier in the Holocene several millennia ago. Much data on the Holocene history of estuarine settings has been recovered in the context of archeological studies. Interpretation of these data (Altschul & Grenda 2002) suggest that following formation as a flooded embayment during early Holocene sea level rise, the Ballona estuary was trapped by a spit that built across the mouth. First indications of intermittent freshwater conditions 6 kya (Palacios-Fest *et al*. 2006) may suggest the inception of the formation of this barrier. After 4 kya fresh water conditions, presumably associated with closure became more frequent, and open estuary taxa such as oysters and jackknife clams disappear (Palacios-Fest *et al*. 2006). This overall trend became still more pronounced in the last 2,000 years based on ostracod and pollen data (Palacios-Fest *et al*. 2006). By this time we infer that the trapped portion of the embayment had largely filled with sediments from both the Los Angeles River and coastal sediments associated with continued shoreline retreat. Thus, by some time prior to 2,000 years ago, erosion by flooding from the Los Angeles River had become the primary mechanism generating the space in this estuary system. This includes space below low tide and intertidal space; however, intermittent perching appears to have flooded broad expanses of marshland when the appropriate combinations of moderate stream flow and a substantial beach berm were present. The Ballona estuary/lagoon continued to experience closed fresh water and intermittent tidal conditions resulting from breaching during high flows. Infrequent major flooding from the Los Angeles River was likely the major geomorphic agent that removed sediment from the estuary and intermittently maintained space below the height of the beach berm, where water could pond forming the lagoon.

An additional feature of the historic Ballona system is the presence of a double barrier, an inner dune barrier and an outer beach barrier separated by an outer elongate lagoon. The exact mechanism and time formation of this double barrier system is uncertain. However, the outer lagoon, which was over 2 km long paralleling the coast, may be a large example of the kind of feature that forms as flow turns down-coast forming a channel behind an attached spit during the closure process (Figure 9). In this scenario the shoreline may have retreated to the back dune line during one or more major (centennial/millennial) storm events, and /or during major outflow events derived from the Los Angeles River. The beach spit would form following these events trapping the outer lagoon and creating the modern Venice Beach.

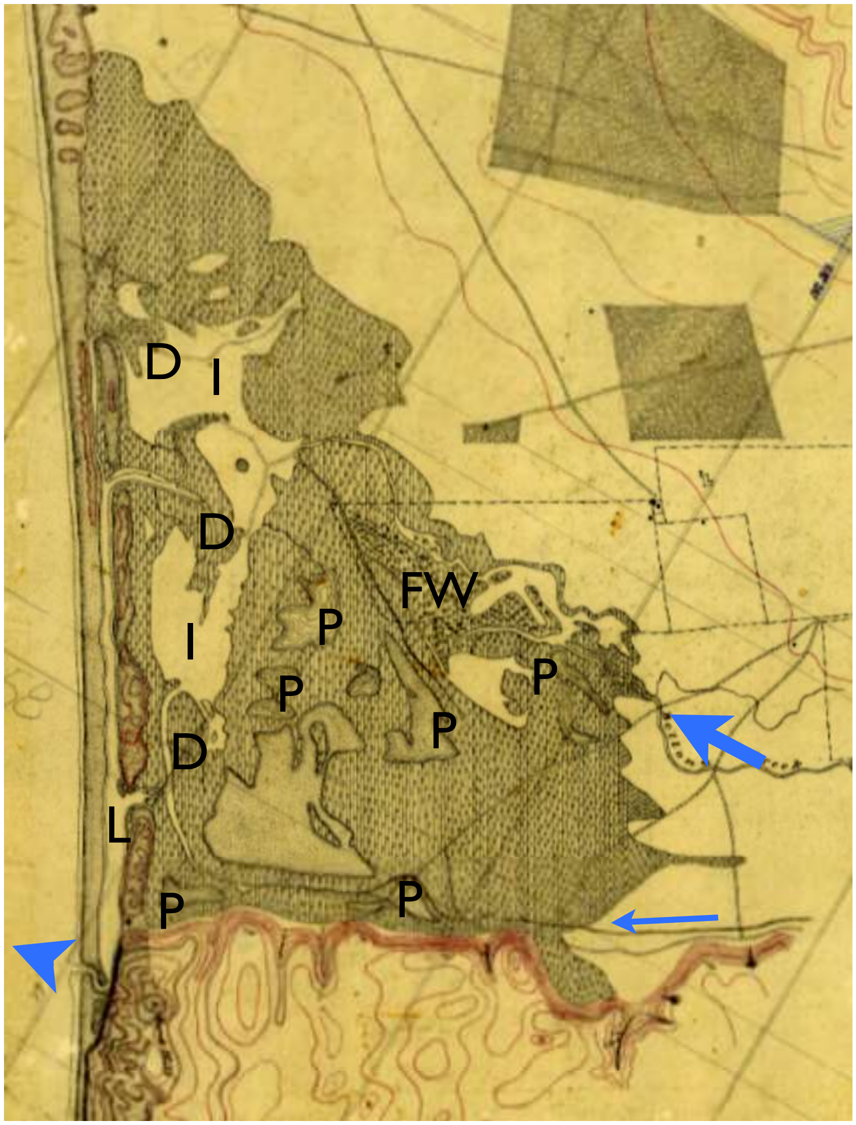


Figure 9. A. Detail of 1876 coast survey map (T-Sheet) of Santa Monica Bay. Mapping for the Coast and Geodetic Survey was primarily conducted in the winter in southern California when systems were most likely to be open. Thus the image likely reflects a more open phase of the system, as discussed in the text. A small opening to the ocean is visible at the southern end of the dune system where it abuts the consolidated terrace (blue arrow). Also note that few tidal marsh channels are evident, suggesting that tidal conditions in the system have not had a pervasive impact on the system, as would be the case in a perennially tidal marsh. The "lake," an elongate outer lagoon feature much used for recreation around the turn of the century, is marked with an "L". "D" marks 3 flood tidal deltas with marsh tops built on them that have formed inside three active openings that cross the inner dunal barrier. "I" marks an internal lagoonal feature – space that is the product of flood-generated downcutting and erosion. "P" marks ponded or permanent water on the marsh surface. "FW" is the region of greatest and most continuous freshwater influence where Ballona Creek enters the system and would have been a site of riparian and emergent vegetation. During winter stream flow the whole surface would at times be flooded with freshwater.

“Lake Ballona” 1902

Figure 9. B. Turn of the century images of the “Lake” feature between the beach and dune line (marked “L” in figure 9A above). Views are to the north up the axis of the “Lake” toward the Santa Monica Mountains. Images courtesy of Los Angeles Public Library.

Ballona 1890

Figure 9. C. Late 19[a] Century photograph of freshwater habitat “Lake” feature between the beach and dune line (marked “L” in figure 9A above). Views are to the north up the axis of the “Lake” toward the Santa Monica Mountains, and show bullrushes and a duck hunting scene, complete with minor efforts to impound water to attract ducks during the winter. An enlargement of the portion of the 1876 map marked “FW” above (Fig 9A) shows similar features. Photograph courtesy of Los Angeles Public Library.

Historic mapping immediately prior to widespread human modification of the watershed (i.e., late 1800s) is consistent with hydraulic (flood) formation of space in the lagoons. Early T-sheet maps document four major passes near sea level across the inner dune line (Figure 9). These would presumably all been active in outflow during major flood events. The middle two of these are mapped as active channels in 1876. In addition the historic outer lagoon extended south of the valley forming a cusp along the bluffs in a region eroded by deflection of outgoing stream flow rather than wave attack. Similar cutting of lateral bluffs by stream flow adjacent to stream mouths in terraced settings is also evident in historic mapping of the mouth of the Santa Clara River mouth and Santa Margarita River mouth, among others. These observations support the argument that stream flow and channel migration during floods are responsible for removing sediments that otherwise accumulate in these estuarine settings, thus defining and maintaining estuary space.

Predicted Closure Pattern

Summary of classification:

- S-T – the coast is terraced locally, but is a portion of a larger complex prograding system building in from the Los Angeles basin.
- E-H – Wave exposure is toward the west and is classified as high in this binary setting, but is likely lower than at Tijuana and substantially lower than northwest facing sites north of Pt. Conception.
- W-L – When the Los Angeles River is considered as a component of this system it is large, and has a low gradient lower reach in any case.
- F-H – Space formation here is hydraulic through the Historic period although that was not likely the case prior to 4,000 years ago early in the Holocene.

We predict that a watershed with these characteristics would be closed to the ocean most of the time. Perching (C-P) above sea level behind a beach berm is expected 20% of the time associated with periods of moderate stream flow. Closure at or about high tide would occur 50% (C-C). During periods when hydraulic discharge is sufficient to open the system, it would develop bars near low low-tide (C-S) and would not typically be navigable (C-O), while intermediate conditions (C-L, C-M, C-H) would likely ensue during the closure process but would not likely persist for a significant fraction of the year.

Actual Closure Pattern

The watershed area of the Ballona Creek mouth was considerably larger before 1825, during a period when the Los Angeles River found its way to the sea along this route. Efforts to maintain a permanently open channel between the outer Lagoon and the Sea began in the late 1880s, although maintaining open conditions proved difficult (see notes on 1887 T-sheet; Figure 10). Our historical investigations have provided narrative descriptions of these events and the conditions between them, and the coastal survey documents the transition from a dynamic estuary mouth to the artificial channel.

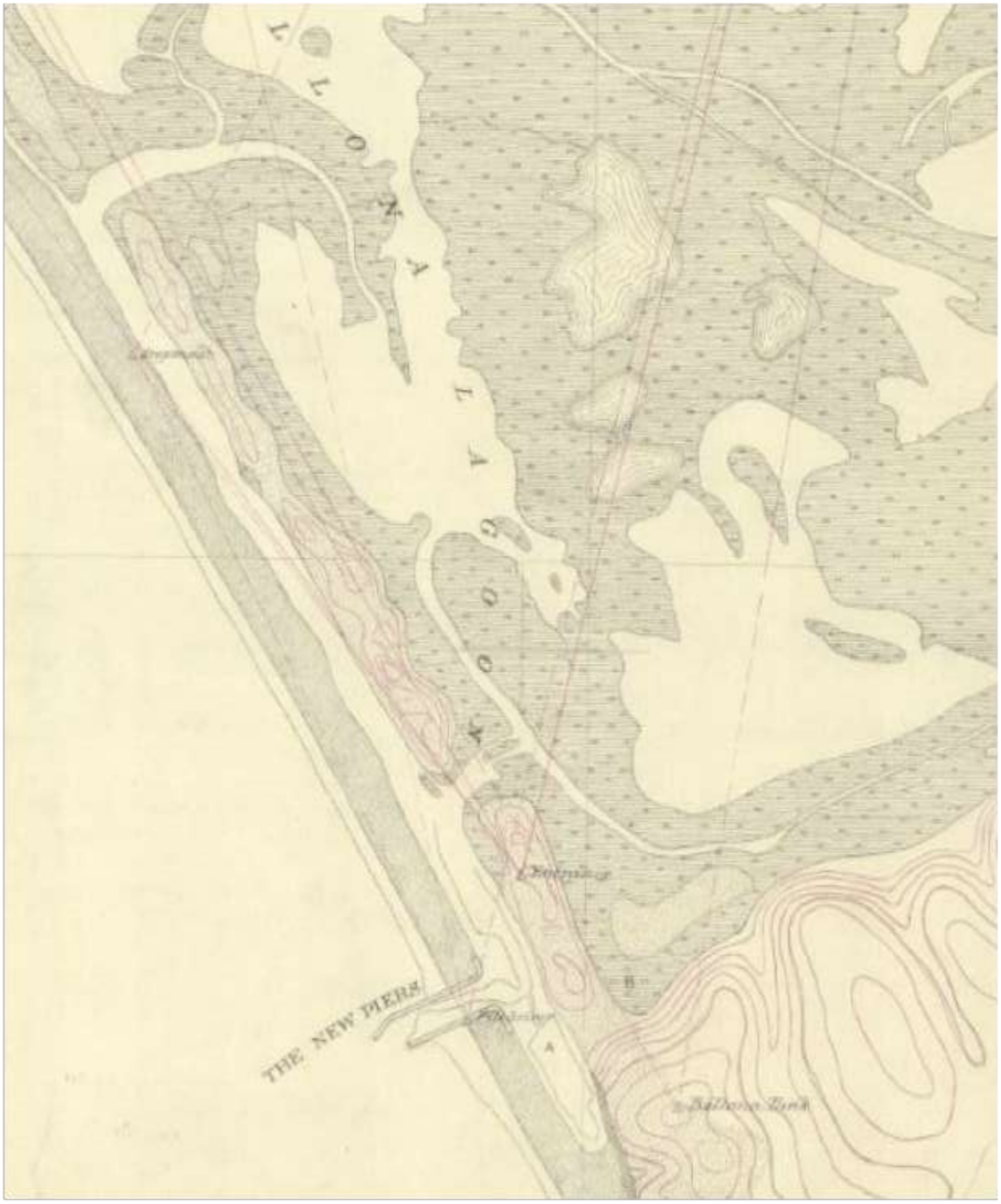


Figure 10. Detail of coastal survey (T-Sheet) from 1887 showing the new piers and entrance to proposed harbor.

The great flood of 1825 caused significant environmental changes throughout the greater Los Angeles/San Gabriel river floodplain. It is described in 1876 as follows:

> In 1825, the rivers of this county were so swollen that their beds, their banks, and the adjoining lands were greatly changed. At the date of the settlement of Los Angeles City, a large portion of the country, from the central part of the city to the tide water of the sea, through and over which the Los Angeles River now finds its way to the ocean, was largely covered with a forest, interspersed with tracts of

> marsh. From that time until 1825, it was seldom, if in any year, that the river discharged, even during the rainy season, its waters into the sea. Instead of having a river-way to the sea, the waters spread over the country, filling the depressions in the surface, and forming lakes, ponds, and marshes. The river water, if any, that reached the ocean, drained of from the land at so many places, and in such small volumes, that no channel existed until the flood of 1825, which, by cutting a river-way to tide water, drained the marsh land and caused the forests to disappear (Anonymous 1876).

It was widely understood that up to this point, the Los Angeles River flowed through Ballona:

> It was commonly understood and talked of in early days by old Mexican people that the Los Angeles river flowed out through the southwest part of the city/ by Ballona and into Santa Monica Bay until the flood of 1825 (William W. Workman, in Reagan 1915).

> It was well understood by the people in the Southwestern part of the city in those days that the Los Angeles River once flowed out through the Cienega and into Ballona Bay (28-29; A.N. Hamilton, in Reagan 1915).

Although the dominant route for the Los Angeles River has not since routed through Ballona after 1825, during larger floods significant floodwaters flowed in this direction:

> The flood of 1884 was probably the greatest in his time. The whole country was flooded. In Los Angeles the water came up to Main St. and he has seen the water three and four feet deep in Alameda St. These flood waters would cross over Main St. and flow to the southwest into Ballona Bay. This was also the case in 1889. This was no doubt the natural channel of the Los Angeles river in earlier times (George A. Wright, in Reagan 1915).

With the decrease in the size of the watershed, the Ballona Creek system began to resemble what the lower Los Angeles River before the great flood of 1825. Without the flow of the larger river to provide a drainage course to the sea, there is evidence that the connection to the ocean became more intermittent. This closure becomes evident in the attempts to create a deepwater port at Ballona in the 1870s.

The newspaper accounts of the attempted development of a deepwater port at Ballona provided a snapshot of the condition of the wetland, estuary mouth, and dune complex at that time. From these accounts, it is evident that by the 1880s, the mouth of Ballona Creek had become more or less permanently closed by a dune created by longshore drift. It was through this 200-foot wide beach that an entrance was excavated in an effort to open up what was described as a “lake” to the sea for use as a protected port.

Before construction of the harbor, the integrity of the lake is well described for the summer and its breaching of the dune described (Los Angeles Times 1887).

> Four miles southwest of Santa Monica, and ten miles southeast of Los Angeles, lying in the shelter of a low range of hills rising from the valley toward the sea, is a small, narrow lake at the point where La Ballona creek debouches into the ocean. It is a true lake, for, although it lies close down upon the sand of the beach, a well-defined earth formation encircles it, and proves conclusively that its water is not drawn by seepage from the sea. As has been said, the lake is exceedingly narrow. Its length along the shore is about two miles, and it varies in width from two hundred to six hundred feet. The water in it varies in depth, in ordinary times, from six inches to twenty feet.
>
> Back of the lake there is a range of drifting sand-hills so common along the seacoast of Southern California; and behind these hills there stretch away for miles the low marsh lands of the Centinella ranch. La Ballona creek comes down through this marsh -- which is, after all; only a wash of sediment from the hills and higher plains toward Los Angeles -- and in the rainy season the creek breaks through the sand-hills, and the waters overflow the lake and find an outlet into the ocean.

A similar description of the construction of the channel was previously reported (Los Angeles Times 1886). Further information about the condition of the wetlands inland from the sand dunes is found in discussion of the proposed sewer and ocean outfall for Ballona in the 1880s.

> That portion of the route passing through the Cienega rancho, a distance of about three miles, is covered with water during the winter, and even in summer the water stands within six inches of the surface. The ground is soft and elastic…
>
> For a long distance the proposed route crosses the Ballona ranch, the surface of which is nearly level and only a few feet above tide-water, and during the winter months is subject to overflow. The soil is soft, and the construction of a brick sewer under such conditions would be very expensive and unsatisfactory in results (Hansen & Jackson 1889).

These narrative accounts are particularly interesting to compare with contemporaneous maps. The 1876 coast survey shows a small entrance to the Ballona Lagoon from Santa Monica Bay at the far southern end of the flat valley near the taller, and older, terraces and associated sand dunes (Figure 9). Then the 1887 coast survey shows the new pier and entrance to the proposed port site (Figure 10). If the historic condition of the mouth of Ballona Creek were to be described from these maps alone, it might be presumed that the Ballona wetlands were always tidal, at least to the extent allowed by a small opening to the sea. The combination of these maps with the narrative accounts lead to a far different conclusion, that the longshore drift of sand rapidly closed the berm connecting Ballona to the sea after major storms and a large freshwater lake was the rule, rather than the exception for the wetlands, even reaching inland up to five miles presumably as a consequence of perching of water behind a berm during modest stream flow episodes. These data are consistent with core data which show intermittent freshwater conditions in Ballona over the last 4,0000 years (Palacios-Fest *et al*. 2006).

The narrative accounts are also useful in that they allow for the description of the 1825 event in which the path of the Los Angeles River shifted from Ballona, as well as the periodic flooding from the Los Angeles River into Ballona Creek that occurred subsequently in the mid-1800s. The generally smaller watershed post-1825, combined with the longshore flow of sediment transformed Ballona into an estuary that was increasingly closed to the ocean, as predicted by our classification scheme.

Narrative accounts documented by the extensive oral histories encompassed in Reagan's report to the County, in 1915, provide some evidence of changing frequency of opening to the ocean. One interviewee indicated that "the tide used to come up nearly to Mesmer Station on the P.E. Ry," and "where Venice now stands was once a sea salt marsh, and the tides came in there all the time." These quotes may refer to the period after the initial dredging maintenance of the opening of the Ballona Channel (Figure 10) and could reflect engineering efforts to keep tides out of the low-lying areas but this deserves further research.

Topanga Creek

General Description

Topanga Creek drains a watershed in the Santa Monica Mountains to the Santa Monica Bay. It is one of three creeks in the mountains to have a population of endangered southern steelhead and endangered tidewater gobies are present in the lagoon. Some areas of the upper watershed have residential development. The lower floodplain and mouth have been highly modified by fill and bridge abutments and is significantly narrowed and laterally confined. Much of the modification of the lagoonal setting was generated in association with widening of the coastal highway in the 1930s where very-high (~10 m) fill pads were constructed primarily on the east and secondarily to the west side of the estuary mouth. These pads effectively occupy much of the lowland area that would have accommodated lateral stream movement, lagoon formation (Figure 11).

Exposure and Coastal Setting

The coastal setting is that of a steep slope (S), as a consequence of a relatively high uplift rate of this the mid portion of the Malibu coast (Niemi *et al*. 2008). This uplift led to the deep incision of Topanga Creek forming Topanga Canyon. Wave exposure at the south-facing mouth of the canyon is low (L) although some long traveled swells can reach this coast from the southern ocean during the northern hemisphere summer months.

Watershed Characteristics

We classify the morphology of the watershed as a steep coastal drainage, (W-C) as it does not penetrate beyond the south face of the Santa Monica Mountains. In the absence of a terrace the Topanga drainage is relatively confined by incision in Topanga canyon. This appears to limit the scale of lagoon formation more so than at terraced or less steep sites.

Figure 11. T-sheet (ca. 1876) detail of Tepango Canyon (currently Topanga Canyon).

Formation Process

The estuary is formed by hydraulic processes (F-H), with sediments removal in floods providing space material that is then closed by berm generated by wave action. Any inherited space from sea level rise has long been filled by sediment so formation and mouth dynamics are now governed by flood, flow, and wave action. The shoreline has slightly prograded as sediments from the canyon have form a local delta extending from the mouth of the stream (Livingston 1949). This provides some of the modest lowland area for lagoon formation.

Predicted Closure Pattern

Based on historical analysis, we would classify Topanga Estuary as follows:

- S-S – Steep coast
- E-L – Wave exposure is low
- W-C – Steep coastal drainage that does not cross the Santa Monica Mountains (the largest coastal drainage on the Malibu Coast)
- F-H – Space formation is exclusively hydraulic (i.e., flood generated)

The estuary characteristics should lend themselves to frequent and complete berm closure at or above the high high-tide line, with winter season breaching by floods and periodic closing at the high tide level. Based on these characteristics, we would hypothesize that the estuary would be closed at or above high-high tide half the time and in the high intertidal 20% of the time. In addition, although the lagoon has been modified, it is not clear how strongly this should effect the closure behavior, although it may have slightly increased opening frequency due to the shortening of the berm length available to accommodate percolation and reduction of the lagoon area due to confinement by fill.

Figure 12. Mouth of Topanga Canyon in USGS topographic map. Left: Draft map from 1925. Right: Final map published in 1928 of 1925 survey.

Figure 13. Mouth of Topanga Creek on October 4, 1926 and December 21, 1929 (Spence Air Photo Collection E-742 and E-3040). Courtesy of UCLA Department of Geography, Benjamin and Gladys Thomas Air Photo Archives, The Spence Collection.

<u>Actual Closure Pattern</u>

The historical record is consistent with a pattern of summer closure and periodic winter opening. The 1876 T-sheet (Figure 11) show a meandering channel in the small Topanga Creek floodplain that turns sharply to the southeast near the beach, showing evidence of closure from longshore wave action typical of high intertidal closure H. The 1925 USGS topographic map (Figure 12), a draft of the map to be published in 1928 shows two channels of Topanga Creek, an active, and a high flow or flood channel joining to form a forked lagoon upstream of the bridge, this is likely continuous with the closed lagoon indicated in the beach on the ocean-side of the bridge. The 1928 final version of the map (Figure 12) the beach extension of the lagoon is no longer indicated. The earliest aerial photographs in 1926 and 1929 are consistent with the 1925 version of the map. The active and flood channels are identifiable and lagoon waters extend below the bridge forming a U that connects these two channels (Spence Air Photo E-742 from October 4, 1926 and E-3040 from December 21, 1921; Figure 13). Both photographs show an extensive width of beach between the lagoon and the ocean. After 1933 the span of the bridge passing over the mouth was reduced, constraining flow to the ocean (Figure 14; Frampton *et al*. 2005). Large 10 m high sediment fill pads are associated with the bridge abutments but are much larger than the road width (Figure 14). These pads fill much of the lowland space, significantly reducing the area where a lagoon could form. This condition continues through the current day. In the 1938 photo, the lagoon spreads out on the beach and is closed (Figure 14). Subsequently, an artificial jetty or berm was placed on the beach on the north side, limiting the spread of the lagoon on the beach to the north and effectively further confining and channelizing it.

Figure 14. Shortened span over Topanga Lagoon. Spence Photo E-9051, November 28, 1938. Courtesy of UCLA Department of Geography, Benjamin and Gladys Thomas Air Photo Archives, The Spence Collection.

Early newspaper accounts about Topanga center around fishing, with occasional reference to flow. For example, in a 1906 article on the trout season, the Los Angeles Times offered the assessment that "The Topanga is too intermittent in its character to account for much" (Anonymous 1906). In his account of southern California geology originally written in 1933, Livingston states that "the sand that accumulates [at the mouth] forms a ridge which, except during time of flood, dams Topanga Canyon, causing a small lake to form" (Livingston 1949).

A series of satellite photographs ranging from 1990 to 2007 (Figure 15) show evidence of a variety of condition the most frequent of which is full closure near high high-tide (C-C) followed by (C-H). These observations are entirely consistent with our prediction. Erosional rejuvenation of estuary space during high rainfall/flow conditions is also evident in the image following the 2004-2005 high rainfall event. Conversely, a low stand or filling the estuary mouth by beach sand is suggested by 1990 imagery following several years of below average precipitation.

We compared the conditions recorded in the recent (1990 - 2007) images with readily available climate data for the Los Angeles Region to explain these conditions and found them consistent with our predictions.

1) September 7, 1990. A minimal lagoon below the bridge is visible. Rainfall was below average from the summer of 1986 through 1990 and 1989 and 1990 were extremely low rainfall years. This is a lowstand in the lagoon or building of the beach into the lagoon due to low stream flow and lack of outflow. Lagoon is closed (C-C) and desiccated.

Figure 15. Aerial photographs of Topanga lagoon from Google Earth, 1990–2007.

2) June 1, 1994. Lagoon full at or above high tide and closed or nearly so with a slight trace of a narrow outflow channel from the south-east corner. Previous rainfall in 1993 was moderate and last significant rainfall event was in February. Streamflow may slightly exceed percolation yielding an outflow. Condition is closed (C-C) with slight overflow.

3) 2003. Large lagoon on beach closed near high tide (C-C).

4) November 13, 2004. Large lagoon on beach closed near high tide (C-C), following significant rainfall of 11.4 cm in the previous month.

5) November 3, 2005. Lagoon appears large on the beach and deep with a sharp southern edge. However, lagoon appears to have a channel to the swash zone and to be closed in the high intertidal (C-H). The previous month of October had had rainfall of 3.5 cm, but the previous winter rainfall was in excess of 89 cm. We conclude that flooding rejuvenated the lagoon by erosion down to or below the low low-tide level as indicated by the extensive deep pool on the beach, and the straight south side.

6) March 16, 2006. Lagoon shows a modest outflow channel stopping at the beach berm and a small outflow channel traversing the beach berm. Lagoon extends onto beach and is not completely full (C-H or possibly C-M). Rainfall was consistent above 5 cm for three months and very high the previous winter. We conclude that stream flow has recently breached the lagoon, but did not cut down below mid-tide. Lagoon has subsequently partially closed.

7) October 23, 2007. Lagoon is fairly large but some encroachment of beach as occurred since the 2005 event. Lagoon closed on beach at beach berm where an old outflow channel is evident. The 2006–2007 water year was lowest on record. We conclude that drought has not caught up with the system and it may take more than two years of drought to desiccate the watershed.

Tijuana Estuary

General Description

Tijuana Estuary, located near the international border with Mexico is the largest un-channelized river mouth south of the Santa Clara River. Although there is significant damming of the drainage, it nevertheless provides an example of a system that retains some natural aspects of hydrologic process. The Tijuana Estuary retains significant coastal marsh habitat, is the stopover point for a large number (370) of migratory bird species and 6 endangered species are present. The history and behavior of the Tijuana River have strong impact on this estuarine setting and is strongly influences by the hydraulic history of this system.

Coastal Setting and Exposure

The general coastal setting of the Mission Bay/San Diego Bay/Tijuana River Estuary region is prograding (S-P). However this estuarine setting occupies an active tectonic basin bounded by a raised fault block to the south at Tijuana, and uplift along splays of the Rose Canyon Fault that have elevated the La Jolla and Point Loma regions. Thus there are steeper coastal segments to the north and south bounding an area of prograding shoreline and significant estuary formation. Even in the Early Holocene following sea level rise the Tijuana River estuary was likely smaller than the massive Mission Bay/ San Diego system to the north.

Tijuana also appears to have been the focus of sediment delivery in the region. Long shore sediment transport from the north is diverted offshore at Scripps Canyon (Inman & Masters 1991), greatly limiting sediment to the Mission Bay system. The rocky substrate offshore of La Jolla Point Loma indicates the sediment-starved nature of these settings (Slater *et al*. 2002), and likely also facilitates bypass of any sediments past the mouths of Mission and San Diego bays. In addition, the somewhat more resistant nature of the Cretaceous rocks that make up La Jolla and Point Loma limit them as a source of sediment along the shoreline. Some fraction of sediments bypassed by Point Loma offshore may be brought onshore by wave action the Tijuana area. Wave climate and transport at the Tijuana River Mouth is likely to vary with seasonal and episodic change in direction of wave attack so long shore sediments from the south may also be accumulating here.

The mouth of the Tijuana River is relatively exposed to the West (E-H). There may be some modest mitigation of swells from the Northwest by San Clemente Island. However, this is clearly the most exposed to Wave action of the system considered here.

Watershed Characteristics

There are four significant watersheds that enter the prograding basin setting of this stretch of coast: the San Diego, Otay, Sweetwater and Tijuana Rivers. These all clearly merit “medium” (W-M) status as these systems extend inland on the order of 50 km to the regional divide with the Salton Sea/Sea of Cortez and are of intermediate gradient. Stream function of these rivers as they enter the lowlands and estuaries is alluvial and distributary with multiple channels that interact in the estuary and become primary components of the estuarine marsh system. This estuary may have some spit trapped space on the North (F2). Much of the rest of the current estuary space appears to be hydraulically/flood generated (F3) space. Channel deepening and open water increase is suggested by satellite images following 1982–1983 el Nino Floods. The mouth closure often occurs at low intertidal elevation trapping water in channels above low low-tide. The mouth-spit interaction is dynamic. First order examination of air and satellite imagery indicate that: 1) mouth position varies dramatically as a function of flood flows, 2) that flood events appear to down cut sediments and form space in the estuary, and 3) that winter wave action occasionally builds berms into the estuary mouth trapping or partially closing the system, and leading to breaching and new mouth formation. A historically closed pond system has been artificially connected to the tidal system (Figure 16).

Formation Process

The coastal portion of Tijuana River alluvial floodplain likely represents alluvial fill of an earlier Holocene estuarine feature incised into a Pleistocene terrace during low stand. It is possible in the early to mid Holocene the Tijuana estuary was closed by a spit or series of spits built off the proposed Pleistocene terrace promontory to the north. The available evidence suggests, however, that current sub and intertidal space in the estuary is all or nearly all hydraulic space created by floods. This likely includes large early 19th and 17th century events that may have far exceeded floods from the period of rain and stream gauge records (e.g., Schimmelmann *et al*. 2003). Wave erosion during unusual events including following flood opening may also have been important in shaping this space.

Figure 16. Images of the mouth of Tijuana Estuary in May 2002 top and June 2006 bottom showing restriction of the mouth and partial draining of the estuary through the barrier beach as well as ponded areas to the south of the mouth. Images from Google Earth.

Historically the largest fluvial sediment source in the region is the Tijuana River (Inman and Masters 1991). Significant delivery of sediment to the estuary appears to be in the form of flood tide deltas delivering beach/ shore face sediment to the mouth.

Predicted Closure Pattern

Based on historical analysis, we would classify Tijuana Estuary as follows:

- S-P – Prograding coast.
- E-H – Exposure is high.
- W-M – Drainage area extends southeast into Mexico bordered on the south side by up thrown fault block. Overall intermediate gradient.
- F-H – Space formation here is dominantly hydraulic (i.e., flood generated), although some historic role for spit trapping. All inherited space from sea-level rise is gone.

Predications based broadly on coastal systems with this set of attributes suggests that Tijuana should be closed on an annual to multi-year cycle (C-P and C-C), with occasional seasonal opening (C-L). When opening occurs it would be in the low intertidal and subtidal primarily in the winter, as is typical of many systems of substantial size exposed to high wave action. Given that the Tijuana estuary has undergone limited structural modification and is currently an ecological reserve, we would predict that the modern closure pattern remains basically the same as the historical condition, low intertidal closure. Estuarine closure and migration have been affected by several perturbations; however, these are not substantial enough as to cause a change in closure class.

- Dams on upstream tributaries likely have minimized peak flows limiting erosional removal of material.
- There are upstream bridge abutments that confine flow.
- Diked agricultural field and other structures begin on the south side of the valley about 4km from the coast likely preclude sheet flows and lateral channel migration such that the southern part of Tijuana estuary no longer receives as much flood flow and is subject to less channel erosion. Road building on the marsh surface in the south "3" also appears to preclude water flow, and vegetation is much reduced across roads presumably due to loss of flow from side canyons. Flood derived fresh water provides a flux of growth to salt marsh vegetation (Zedler 1983), and may facilitate in the germination of a number of species normally thought of as "salt" marsh taxa *Spartina foliosa* (Zedler 1986). In this area it may be critical to sustaining halophytic vegetation. Changes in ground water may also be important.
- The northern edge of the estuary has been impinged upon by diking and filling for and adjacent to the airport.

Actual Closure Pattern

Multiple relatively low tide images since 1972 indicate seasonal closure in the lowest intertidal range at a somewhat lower frequency that predicted by the conceptual model. Lower tidal images always show outflow with standing waves. These images likely do not record the most open (post flood) or most closed conditions. Detailed correlation with tidal time has not been done, but examination suggests that the estuary is not emptying completely. It appears that the estuary typically does empty to the high low tide level but not to the low low-tide level, yielding significant ponded water in channels and channel cut features in the flood tide delta. These provide “ponded” low tide habitat during more confined/closed non-flood conditions. There is also evidence of perched and ponded features in the southern portion of the estuary. Overall closure may occur at a slightly lower tidal height than for systems used for comparison such as larger west-facing systems north of Conception. Factors that could contribute to this include the artificially continuous nature of the stream flow and wave attenuation due to islands in the bight. Future versions of the model will require more finely categorized wave exposure information.

One of the striking aspects of many of the available images is the building and reworking of tidal (flood tidal) delta complexes that transport sediment from the beach in to the main estuary. These deposits are then crosscut by drainage channels, the most substantial of which appear to be flood induced. Thus the most significant source of sediment to the estuary occurs due to flood tidal opening and tidal delta formation.

The 1852 T-sheet T365 indicates similar features as are present today. Multiple fluvial channels (Ch) enter the active mouth region (2) in similar but not identical in position to the modern channels (Figure 17). Channel-cutting of the flood tide delta complex in the active mouth region falls within the range of behavior exhibited by modern imagery. Differences include a closed ponded area “P” in the north, which has been artificially connected to the tidal circulation. Berms (in yellow) that entrap these ponds could represent a former earlier Holocene spit, with subsequent offshore stepping to form the current beach spit. A more likely explanation is that the spit containing these ponds represents wave reworking after significant opening of the mouth. Similar spits and high points are evident inside the mouth in 1852 (T365), as well as in images from 2003, and are interpreted as a product of wave energy entering the system..

A pond to the south (P?) on T365 presumably represents a channel cut when the active channel(s) of the Tijuana River flowed along the southern edge of the flood plain. This may have occurred during early 19th century flooding (Stein *et al*. 2007), but likely also to represent a time when flow was more active in region “3” of the Tijuana River alluvial system. Flows likely breached the beach berm at this point, but also may have flowed north behind the beach berm scouring space at low tide to an active mouth to the north. Such scouring seems evident in post 1982-1983 El Nino images.

At the Tijuana River Estuary constitutes a seasonal river system where variable flow meets the sea in a series of migratory braided “alluvial fan” type channels. Channel migration typical of these systems likely created features to the north and south of the currently active mouth area. Erosion, at low tide during high stream flow likely removes significant material from the estuarine area and maintains the estuary space. Thus the estuary space is largely formed hydraulically (F-H). The mouth was seen to migrate 500 meters or more then 10% of the north south width of the estuary in less than 10 years following 1994 and at least one-half this distance occurred in a stepwise fashion possibly suggesting closure followed by breaching when winter wave action builds up berms. In addition the 1982-1983 El Nino appears to have generated a mouth 100s of meters wide, and breached an as yet to be determined length of adjacent berm. Thus mouth dynamics and flooding are likely important in the erosive removal of material from the estuary and given changes in the distribution of flood flows and variable wave climate it is likely that mouths migrate over the full length of the berm on century to millennial timescales.

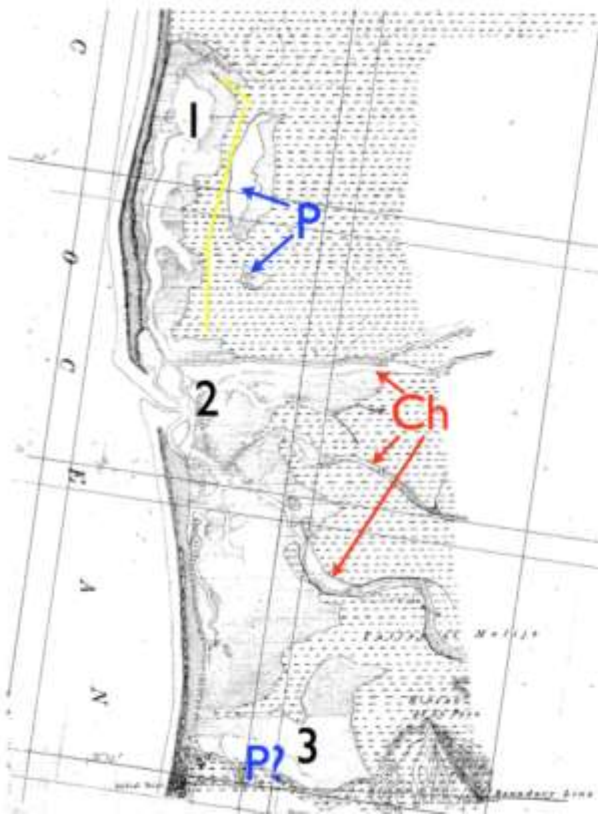


Figure 17. T-sheet of Tijuana Estuary showing ponded areas (P), berms (yellow), location of channels (Ch), and a channel presumed to have been cut by the Tijuana River, in the 19th century (P?).

DISCUSSION

Many of the estuarine wetlands along the central and southern California coast have been filled, encroached upon, or otherwise impacted. In the past two decades substantial effort and resources have been devoted to "restoring" these systems. In many cases "restoration" has involved creating permanently opening systems in places that our historical interpretation indicate were intermittently closing systems. We refer to "restoration" in quotation marks because these projects, which are called restorations, actually involve conversion to a new habitat type. Longcore *et al*. (2000) have argued that such activities are not properly identified as a restoration, which is the "return of an ecosystem to a close approximation of its condition prior to disturbance" (NRC 1992). Because of the importance of closure state to estuarine function and habitat characteristics, we argue that a project that does not maintain historic closure dynamics should not be referred to as restoration, but as creation of a new habitat type to support ecological functions and/or social values identified by project proponents.

Implications of A historic "Restoration" of California Estuaries

In the "restoration" process of central and southern California estuarine systems, many such systems are inferred to have been perennially open with deep-water entrances when they were not *perennially* open at that depth during the last few millennia. As discussed above, it is an oversimplification to consider most estuaries as *open* or *closed*. Most larger and more complex systems experienced closure patterns that were spatially and temporally variable with different portions of estuaries being closed at different depths and for different durations over multi-decadal time scales. Large estuarine systems that are frequently misinterpreted to be perennially completely open (C-O), where there is historic documentation of regular closure at or above high-high tide (C-C), include:

1) Mugu, which is known to have regularly closed (C-C) during the Historic period through World War II (Warme 1971 – see references and aerial photographs therein).
2) Ballona, which also clearly closed (C-C) and impounded freshwater on regular basis during the past 4,000 years (see discussion above).
3) Elkhorn Slough, which appears to have closed seasonally (see Woolfolk 2005).
4) The lagoons in North San Diego County, which all closed (C-C) for long periods of time as indicated by historic records such as T-sheets, USGS maps, interpretation of geomorphic evolution in the Holocene (Masters & Aiello 2007) and historic documentation (Engstrom 1999).

In addition to the conversion of systems that closed at or above high tide to open systems, discussed above, a number of systems been opened that historically closed at lower tidal heights According to our estuary classification, developed above, the San Pedro to Newport complex is a prograding coast (S-P), with low wave exposure [(E-L) because it is south facing and protected by the Palos Verdes Peninsula and San Clemente Island, where several large, low-gradient drainages (W-L) converge, and where space is largely formed by trapping (F-T) via longshore spits. In this context, multiple large trapped systems formed in associating with migrating river mouths (see Stein *et al*. 2007, 2010) and limited wave energy. That these systems close low in the intertidal or immediately in the subtidal along a single stretch of coast is consistent with the trapping process and the limited wave energy. Subtidal closure was evident in all systems from Wilmington (San Pedro) to Newport in the 19th century as described in the Coast Pilot (Davidson 1889). None of these Los Angeles Basin systems were navigable or deep water (C-O) at their entrances as further supported by historic analyses (Engstrom 2006). The sole exception appears to have been Bolsa Chica which was presumably typically closed in the mid-intertidal or higher as indicated by the presence of breakers at all tides (Davidson 1889). Subtidally or low intertidally closing systems were not reported to break at high tide and such systems could be accessed by appropriate craft at highest tide (Davidson 1889). All systems (Anaheim, Alamitos, Wilmington, and Newport) were dredged to increase depth and mouth opening during the late 19th and early 20th centuries to facilitate navigation and recreation. In addition these systems were subsequently fitted with flood control channels to pass freshwater from the Los Angeles, San Gabriel and Santa Ana systems to the sea. The sole exception that retained a closing dynamic through the 20th century was Bolsa Chica. It was dredged open and fitted with jetties and surrounded by cement and riprap berms in 2006 to "restore" it and "mitigate" for harbor construction elsewhere.

Despite the historic partial openness of these systems to tidal influence, it appears that the further dramatic opening of these systems, combined with the channelization of the three major river systems on this coast, has had profound effects on regional hydrology, on coastal sediment processes and on the biota. Prior to channelization rivers spread out on the flood-plain channels migrated leaving a variety of fresh water bodies evident on early maps and riparian vegetation (e.g., Stein *et al*. 2007, 2010). They then entered the sea through estuarine systems that were partially impounded by low intertidal closure such that relatively fresh conditions in lagoons were maintained by river and groundwater discharge. Loss of freshwater and anadromous fishes of the LA Basin such as the currently endangered steelhead and unarmored three-spined stickleback occurred in the mid 20th century (Swift *et al*. 1993), closely following the channelization of rivers and the opening of lagoonal systems. Channelization, combined with the loss of the impounding effect of the coastal lagoonal systems, appears to have reduced the potential for coastal recharge and the maintenance of freshwater aquifer conditions (see Reagan 1915: Swift 2005; Engstrom 2006). During flood years, fresh water lagoons were continuous across the Los Angeles basin (Engstrom 2006) and freshwater covered much of the lowland landscape in part because of the limits to drainage provided by long shore lagoonal barrier systems. Thus lagoon dynamics appear to have contributed to the maintenance of groundwater and extensive riparian conditions noted in historic reconstructions (Stein *et al*. 2007, 2010).

In general, lowered water tables in the LA basin and salt-water intrusion are considered a product of freshwater extraction exclusively, ignoring any contribution of modification of coastal systems or stormwater export. Currently fresh water is injected in wells along the coast to prevent saltwater intrusion (e.g., Foreman 2003). This groundwater recharge appears similar to the historic function of estuaries suggested here. In a recent report focused on Alamitos Bay, however, Swift (2005) made a strong argument that the loss of freshwater delivery to coastal lagoonal settings through bypass of rivers and loss of groundwater has had dramatic impacts on the coastal fauna of California and the Los Angeles Basin region in particular. He documents the absence of a suite of brackish-water dependent estuarine fishes, which were historically present in the area and likely depended extensively on the brackish conditions in the lagoons along the San Pedro to Newport coast. These fishes are now either rare in the region or, in the case of the Gulf Sierra (*Scomberomorus concolor*), have been extirpated.

The recent "restoration" of Bolsa Chica illustrates many of the points discussed above. One troubling aspect of this "restoration" is that it appears to mimic the historic harbor and marina construction in the region with deepening and opening of the mouth comparable to the historic impacts on surrounding systems on this coast intended for navigation, recreation and flood control. Thus the "restoration" design took habitat in the same direction as the trend of historic anthropogenic impacts in the region. In addition, there is significant doubt as to whether the habitat being replaced in this mitigation existed historically (Grossinger *et al*. in review). Opening of this system resulted in desiccation or freshwater brackish marsh habitat and further eliminated riparian vegetation that had been largely eliminated throughout the region (Stein et al, 2007) (see Figure 19). An additional impact of such systems is their deepwater openings immediately start to fill in due to flood tidal delta formation and are difficult to maintain. This process has proceeded rapidly at Bolsa Chica since its construction in 2006.

The changes from fully closing systems (C-D, P, C) to deepwater, perennially open (C-O) systems have profound, and often unanticipated, biologic and geomorphic consequences. There is a broad literature on the proposed benefits of open systems, most of which comes from research in other parts of the world. In this work we enumerate the impacts of converting historically closing systems to perennially open systems in terms of a range of apparently adverse consequences. There may indeed be significant societal benefits associated with perennial opening of these systems, particularly in light of urban encroachment and changes in delivery of water, sediment, and material (e.g., organic matter, pollutants) from the watersheds. *Balancing the presumed benefits of opening estuaries against the adverse ecological impacts of such actions is beyond the scope of this report, but will have to be considered on a case by case basis in California coastal estuaries.*

The adverse consequences of type converting an estuary that historically closed intermittently to a permanently open, deepwater habitat are further enumerated below:

1) *Increased sedimentation of the lagoon from the coast.* One of the primary sources of sediment in estuaries is from along the shore rather than conveyed from the land through streamflow. This is generally not well recognized in estuary restoration, although it is evident in the maintenance of harbors. Batiquitos (see images above) is an example of a "restoration" project impacted in this fashion. Thus "restoration," when out of equilibrium with historical processes in the landscape, has impacts that include depriving beaches of sediment, and can generate significant ongoing "need" to remove sediment from the mouth through frequent dredging to maintain the disequilibrium aspects of the "restoration." Thus negative impacts to beaches and unanticipated high maintenance costs are often associated with artificial opening of naturally closing systems.

2) *Export of pollutants to the beach during the high summer use period.* Closure of estuaries during low-flow limits delivery of pollutants from streams and lagoons to the beach and nearshore ocean. Slow flow or percolation through a berm allows for the elimination of bacteria, pollutants and nutrients before they are delivered to the coastal ocean. Permanent opening of the lagoon curtails or eliminates this ecosystem function (He and He 2008, Jeong *et al*. 2008).

3) *Introduction of anomalous substrates*. Modified open systems often include anomalous substrates such as riprap that introduce novel suites of organisms into estuaries and lagoons, including rocky shore taxa such as crabs and octopus. More subtly, dredging creates situations where grain size is out of equilibrium with the typical flow conditions, thus deeper dredged settings are often still water that accumulate flocs and may accumulate nutrients. One concern is that such atypical habitats may not be conducive to the persistence of native species and may invite the establishment of unwanted exotics. That this is likely to be the case is suggested be the appearance of the toxic invasive green alga *Caulerpa* in the artificially open Agua Hedionda system. The issue of association of invasion with anomalous unnatural substrates associated with estuary "restoration" needs further investigation.

4) *Loss of freshwater, including groundwater, from wetlands systems*. In some ways closing systems can be thought of as valves; when rainfall and stream-flow are high they open to the sea exporting excess water and sediment. As stream-flow diminishes water tends to be impounded within and sediments are kept out. This dynamic maintains a freshwater lens near high tide on the coast. Under natural circumstances this maintains the height of the aquifer and limits saltwater intrusion during dryer periods, which is a valuable ecosystem service. It is noteworthy that saltwater intrusion became a significant aquifer problem in the Los Angeles basin in association with the channelization of the major river systems to the sea in the 1930s and 1940s. The estuaries were drained and no longer received significant fresh water input which rather than infiltrating and keeping the aquifer filled and preventing saltwater intrusion, was bypassed directly to the sea. More recently, following the opening of Bolsa Chica, the local water table dropped, extensive freshwater habitat desiccated and riparian vegetation perished (see Figure 18). Retention of fresh water, including groundwater, permits the maintenance of riparian vegetation and freshwater dependent fauna. These include stream fishes that often take refuge in lagoons including stickleback and other native freshwater taxa such as the endangered Santa Anna Sucker. Lowering of water tables with lagoon opening also has profound implications for amphibians and freshwater dependent reptiles such as garter snakes and turtles multiple several of which are endangered (e.g., red-legged frog) or threatened. Furthermore, perennial openings reduce the extent of wet and intermittently wet habitats that historically were extensively used by ducks, geese, and other migratory birds and waterfowl (see description of historic bird use of Ballona Swamp in Chambers 1936).

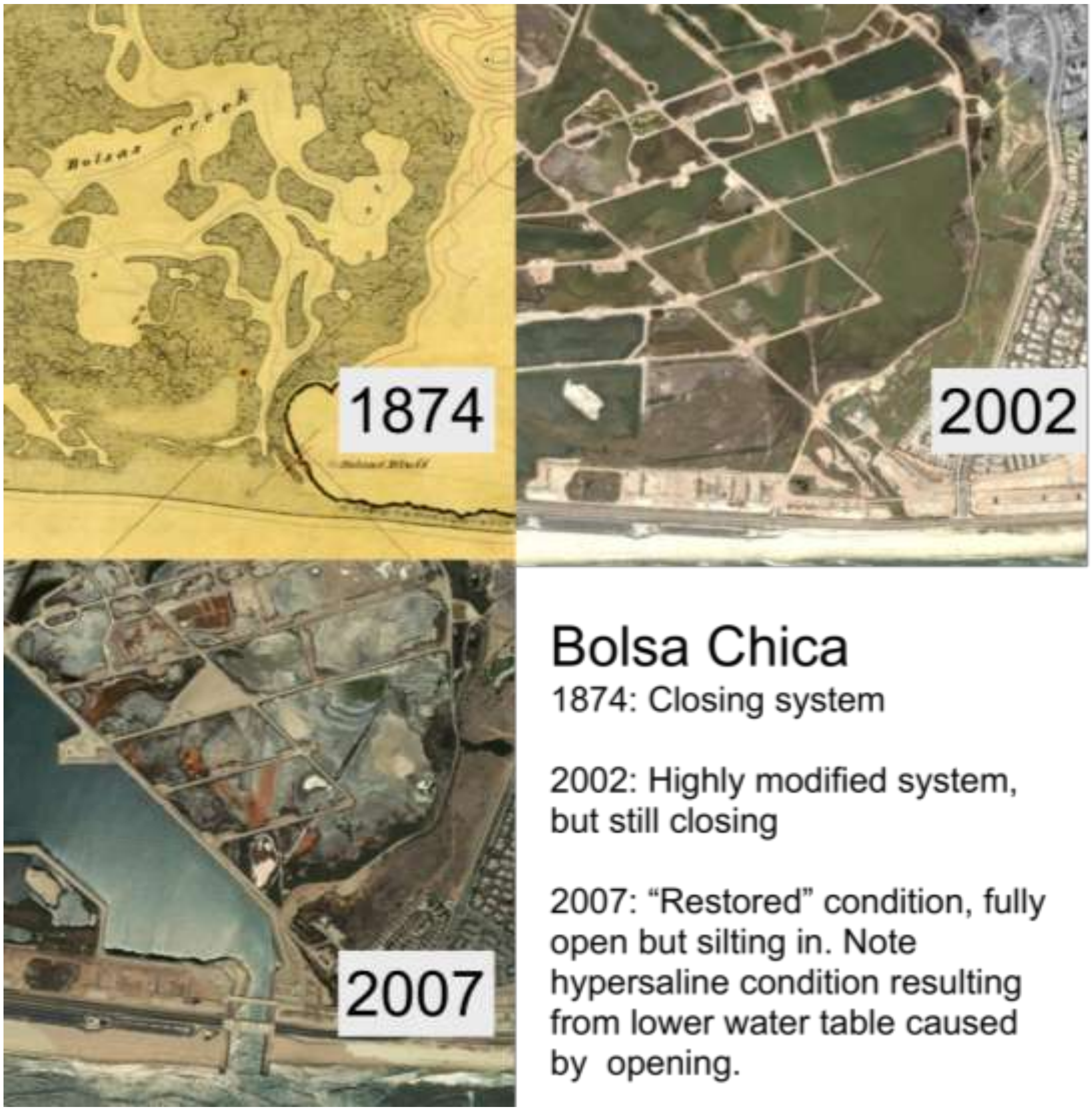


Figure 18. Creation of ahistoric conditions at Bolsa Chica through jettying a perennial deepwater channel. This "restoration" will require frequent and expensive dredging because existing physical processes do not support the fully open condition that was constructed. The areas surrounding constructed wetland appear to be drier and saltier because the water table will have dropped following complete opening.

5) *Impacts on fish habitat at intertidal height.* As opposed to estuaries on the East Coast, where the two tides in the semi-diurnal cycle are nearly equal, the two diurnal tides on the West Coast are unequal. In addition the degree of difference between the spring (highest) and neap (lowest) tides in the fortnightly tidal cycle is also greater on the west coast. Consequently, the upper reaches of the intertidal are less frequently wetted in California than they are on the east coast. This in combination with the seasonally arid climate exposes the intertidal to more frequent desiccation. Consequently, the intertidal portions of California tidal estuaries have relatively low fish diversity (Desmond *et al*. 2000). One effect of closure high in the intertidal is that it generates flooded conditions

that support a specialized fresh and brackish water fish fauna (Swift 2005). Moreover, California estuaries are often "restored" at considerable expense via extensive excavation to generate enough area *below* low tide to support biomass and diversity of marine fishes. However, such diversity is often distinct from native diversity even of large estuarine systems (Swift 2005), and these sites then become sediment sinks and require dredging to maintain the "restored" condition.

6) *Decreased marsh productivity and carbon storage*. Salt marshes are more productive and fix more carbon when intermittently flooded with freshwater (Zedler 1983). Thus opening estuaries has potentially negative implications for greenhouse gas sequestration. In addition to little studied impacts on the local community. The maintenance of soil carbon (e.g., peat) is also significantly enhanced by the maintenance of higher water tables.

7) *Loss or adverse impacts to endangered, closed-estuary, specialist taxa.* The federally endangered tidewater goby is a closed estuary specialist taxon whose habitat is directly eliminated by the opening of lagoons. This goby is the most locally differentiated coastal vertebrate on the Pacific coast. Suites of estuaries contain multiple locally differentiated stocks (Dawson *et al*. 2003; Earl *et al*. 2010). The genetic subdivision, the isolated and ephemeral nature of the habits, the separation of seasons of reproduction and migration, combined with control of dispersal by known hydrologic processes, make this goby a critically important system for the scientific study of metapopulation dynamics and the conservation genetics of subdivided populations. In the San Diego area, southern tidewater gobies have been documented to be distinct at the species level with an estimated divergence time over 1 million years ago. At a minimum, recovery of this genetically distinct unit will be much more difficult, and extinction risk significantly increased by, ongoing and planned "restoration" through opening of estuaries in northern San Diego County (e.g., Earl *et al*. 2010).

8) *Adverse impacts to other sensitive and endangered taxa use closing (C-C) estuaries*.
    a. In Central California, steelhead depend on resources in closing lagoons for successful maturation and return (Bond 2006; Bond *et al.* 2008; Hayes *et al*. 2008; Hayes et al. *in press*). Southern steelhead appear to have been significantly impacted by loss of such closing lagoonal habitat. Presence of closing lagoon systems should be considered in plans to recover populations of steelhead in central and southern California because the return rate of juveniles that feed in lagoons is far greater than those that are not able to feed in closed lagoons before going to sea (Bond 2006; Hayes *et al.* 2008).
    b. Nesting and foraging of the endangered least tern and snowy plover appear correlated with historically closing lagoonal habitats (see MacDonald *et al*. 2010). Least terns in particular likely fed on the small fishes typically found in these closing systems (Carreker 1985; Cooper 2005; a subject that needs further investigation).
    c. In management of the endangered clapper rail in California, *Spartina*, which is typical of the more open systems, is presumed to be critical. In southern California, however, *Spartina* is shorter and grows lower in the intertidal than

elsewhere, which renders it of little use in nesting. Moreover historical documents indicate that clapper rail in California takes advantage of other classes of vegetation typical of high marsh surfaces in both open and closing systems (Dawson *et al*. 1923; DeGroot 1927) and such vegetation is observed to be taller and denser in marshes with some freshwater influence, presumably due to higher growth rates (Zedler *et al*. 1983). Even *Spartina foliosa* may require pulses of freshwater, typical of intermittent closure, for germination (Zedler 1986). Thus clapper rails may well have preferred intermittently closing systems when they were available (a subject that needs further investigation).

d. The endangered red-legged frog similarly was endemic to coastal southern California lagoonal systems prior to the elimination of their freshwater, riparian aspect (Jennings and Hayes 1994). This habitat loss appears to have been a critical component to the extirpation of the genetically distinct southern red-legged frog, which now only persists in Baja California.

9) Because of the historic loss and inadequate study of the biota of closing systems knowledge of their biotic diversity and ecologic function is not complete and may be lost. This issue is brought to the fore by the recent description of a new species of sea slug, *Alderia modesta* (Ellingson and Krug 2006, Krug *et al*. 2007). This taxon is exclusive to coastal California lagoons, and the life cycle appears adapted to the estuarine closure cycle; dispersive larvae are produced in the winter when esturies are open, and non-dispersive crawl-away larvae are produced in the summer when estuaries typically close. The recency of this dramatic observation suggests the limited information in hand about the biologic evolution and function of lagoons; as does the recent recognition of steelhead use of lagoons discussed above. The lack of study of the south-coast garter snake, a species of special concern endemic to the coastal wetlands of the LA Basin is another example. This snake occurred historically in Ballona Marsh and across the coastal LA Basin. It is now extirpated from these habitats and may persist immediately to the north and south in Ventura and Orange Counties (Jennings and Hayes 1994) but very little research has been done on this taxon since 1994. Despite its apparent taxonomic distinction no genetic work has been done and no surveys performed.

10) Riparian habitats found at the upstream end and margins of closing systems depend for their existence on the closing nature of the systems that maintain the water table. This has significant impacts on the specific endangered and understudied taxa discussed above. Such negative impacts to riparian systems undoubtedly have negative implications for a broader suite of taxa and for regional biodiversity.

Recommendations for Management

This report cannot effectively address all the issues confronted by management in each estuary or balance all the societal needs for flood control and other demands relative to the apparent benefits of maintaining natural function. Nevertheless we do attempt to provide some proscriptions for management that consider the historic nature of estuaries in central and southern California.

1) *Management for loss of flood function.* Flooding or peak flows establish estuary space by eroding sediment from the systems. Rivers and streams that are dammed upstream of esturies experience more uniform flows and do not erode and rejuvinate terminal estuaries. On the contrary, the estuaries of dammed systems tend to aggrade as sediments fill in the lagoonal space over time. Often these sediments are derived from the beach or ocean-side of the system, and the lagoon will often fill to close to the typical height of closure. These systems could be managed for more efficient erosion of the lagoon through timed release of flows from upstream dams that would provide pulses of flow coordinated with a series of very low tides at the lagoon. This has the potential to remove sediments from the lagoon in those years when excess stored water is available and to improve sediment delivery to the adjacent beaches. Nearly all major systems in southern and central California are affected by dams; therefore, lagoonal function in a great many of these might be enhanced by a timed release program. Systems with upsteam dams where the effect on lagoons is very obvious include Arroyo Grande and Old Creeks on the central coast San Luis Obispo County. Currently management for the lagoon at Arroyo Grande is focussed exclusively on maintaining a minimum flow thorughout the year to sustain steelhead and tidewater goby. Habitat for these taxa would likely be greatly enhanced by a release program of the sort described above. Other systems that could benefit from timed release programs include the Santa Ynez and Ventura Rivers, Malibu Creek, San Luis Rey River, and the Tijuana River. Even smaller systems such as Los Flores/Los Pulgas on Camp Pendleton might benefit from such a program. Such efforts could be focussed in the winters of high rainfall years when there was sufficent water available, and would be presuamably be far more cost effective than dredging.

2) *Use of currently channelized fresh water* Channelized systems tranfer huge volumes of fresh water to the sea. These waters tend not to be integrated into the design of estuary "restoration" in a way that would enhance riparian vegetation and lagoon – like function. Low upstream weirs could be used to direct these waters to side channels where they could flow through sets of lagoons and marshes to imitate riparian and impounded portions of estuarine systems. This would help recover intermitently fresh or brackish habitats that have been eliminated from these systems. Designs that trap low flows and bypass or pulse high flows such that they eliminate sediments from the systems, should be possible while maintaining or enhancing provisions for flood control. Use of high flow for scouring precludes the need for expensive dredging. Use of low flow employes fresh water resources that are now going to waste and may limit the hazard of delivery of bacteria to beaches. Systems where such an approach could be directly applied include planned "restoration" at Ballona, ongoing "restoration" at Bolsa Chica, restoration of the mouth of the Santa Ana River and the mouth of the San Diego River. Other benefits of this approach could include:

    a. Passage of water through marshes would allow for an ecological filtering function such that water released to the sea and adjacent beaches would have reduced contaminants.

b. Increased recharge and raised ground water have broad benefits for riparian fauna. Recharge provides other ecosystem benefits in terms of reducing the amount of water needed to be injected to protect aquifers, and ultimately constributing to ground water cosumption for human use.
c. Increased riparian vegetation providing suites of habitat similar to those historically present, such as willow swamps, scirpus and catail marshes, channels ponded water, vernal wetlands, and lagoons. It is also noteworthy that intermittent freshwater flux benefits salt marshes. Thus "*Salicornia"* flats or salt pans may be enhanced by intermitent flooding with freshwater.
d. Endangered and sensitive taxa that depend on seasonally closing fresh or brackish systems could be established (see discussion above). Establisment of tidewater goby in Ballona would greatly enhance the (metapopulation) stability of the LA/Ventura management unit and would dramatically enhance the probability of persistence of this taxon.
e. Further use of freshwater resources to enhance riparian and seasonal freshwater habitat would also enhance a broader range and diveristy of breeding and migrating water and riparian birds, including ducks and geese that were historically present in large numbers in these systems but are now less diverse and confined to far more limited habitat.

3) *Restoration of lagoons habitats in association with available state resources and transportation structures*. The historic habitat configuration of many estuaries and lagoons is not superficialy obvious. This is particularly true for small lagoons that can provide a suite of ecosystem functions. Small lagoons can serve as tidewater goby habitat, provide habitat for stickleback and stream-dependent sculpins such as *Cottus asper* (see Swift et al. 2005), can facilitate the functionality of steelhead streams, can serve as breeding pools for amphibian reproduction, and can provide wetland and riparian habitat for breeding and migrating birds. In many cases area around lagoons are in public ownership (e.g., State Parks). In fact a considerible number (on the order of 20) of these systems are occupied in whole or in part by state park parking lots and campgrounds. In addition, many have been impacted by transportation structures. Redesign and upgrading of these structures provides opportunites for restoration of estuarine area and function. Perhaps the largest area of opportunity where detailed "restoration" is not well advanced is a former lagoonal region between Pismo Creek and Arroyo Grande Creek, which were conjoined historically behind a beach berm. This area now contains a complex of state park structures which could be modified or removed to increase lagoonal habitat and function.

4) *Management of and for variabiliy.* Stream flow is less predictable than are the tides. This is especially so in central and southern California where rainfall can vary over an order of magnitude from year to year and systems are often subjected to multi-year wet or dry periods. For each system or even component of a system some understanding of the likely annual and seasonal/precipitation response needs to be incorporated into restoration planning. Many systems are adapted to and benefit from fairly large interannual changes in runoff and vernal or seasonal freshwater conditions, which sustain a range of habitats and ecosystem services. Thus mandates for particular flow conditions may not always be

appropriate, and management planning needs to embrace the variation, and use it appropriately to flush systems of sediment when excess water is available and deliver it to systems, where even "salt marshes" may benefit from periods of fresh water immersion.

5) *Monitoring and adaptive management.* Given the variability inherent in central and southern California estuaries, monitoring needs to be long term. Most systems will require monitoring over decades. Only with this sort of approach will adaptive management be feasible because annual variation in fresh water input and sediment accumulation, among other variables, are likely to influence a wide range of geomorphic and biotic processes over time.

6) *Estalishing an accurate historical context.* We do not advocate that history be the only or primary source of inference for management. But we do advocate that language about historical conditions, or that implies a knowledge of historical conditions be employed as accuarately as possible and with appropriate references to historial sources. Many "restoration" plans assert the nature of historic conditions without documentation. In a surprising number of instances these are inaccurate, misleading or contraindicated by 19th century mapping and/or historic documents. It is often not explicitly stated what time period, and what historic evidence was used to infer previous conditions. It is often not stated what historic conditions are appropriate or of interest and in those cases where historic data are mentioned, data ranging in age from 10 to 10,0000 years ago are combined. Proposed management objectives that are based on "restoration" must be clearly related to a specific time period in order to be objectively evaluated. In many cases such as Mugu Lagoon there is excellent documentation of closure, but open conditions have been maintained artificially for many decades, and naturalists and scientists are often unaware of the ongoing management to maintain the open system. In many cases history is invoked to justify actions that are undertaken for other reasons, such as the elimination of eutrophic conditions, that are partially consequences of human activities. Again such management decisions may be justified, but should stand on there merits relative to their costs, rather than as restoration of natural conditions. Finally, establishing an accurate context and time point for historical comparison will help guard against "shifting baselines" whereby more contemporary altered systems are percieved or promoted as "natural" or "historic."

CONCLUSIONS

The classification model we propose suggests that geology, watershed characteristics, and coastal processes are the main factors that govern the general structure of coastal wetlands in the absence of anthropogenic influences. One of the key controlling factors of coastal wetland structure is the nature and frequency of mouth closure, which in turn strongly influences hydrology, water chemistry, and ultimately habitat distribution (Edgar *et al*. 2000, Ritter *et al*. 2008). Initial testing of the conceptual model proposed by the classification systems suggests that these factors can be successfully used to infer the unaltered nature of estuarine mouth closure.

Application of the classification model, combined with review of hundreds of first hand and air photo observations of estuaries indicates that the numerically predominant condition for southern California estuaries is closing either seasonally or for one or more years at a time. This is in part because most systems occupy small to medium sized drainages. Thus the most common natural condition for a large majority of California estuaries would be seasonally tidal or non-tidal. Open, perennially tidal systems are relatively uncommon, and only occur under specific circumstances, typically in prograding systems with large watersheds and in systems with significant inherited or trapped space. Even relatively large systems have a propensity to close at some height relative to the tide for at least a portion of the annual/hydrologic cycle. Fully open estuarine conditions have only persisted in exceptionally large trapped or inherited spaces.

The proposed model suggests that California estuaries have a far greater propensity to close than estuaries on the East Coast. In historical terms, very few estuaries permitted deep or even modest draft navigation through the course of the tidal cycle prior to navigational improvements; small vessels had to be secured to enter harbors (Van Dyke and Wasson 2005, Engstrom 2006). Using a criterion of navigability throughout the year San Diego Bay is the primary example of an open system in southern California. Thus such completely perennially open systems are anomalous on the southern California Coast. However, other systems may be open to tidal influence for much of the year and closure up into the intertidal in these systems may be rare (e.g., Wilmington). Some systems that have been presumed to be perennially open to tides were not historically (e.g., Mugu, which is well documented to close regularly prior to human intervention). The low amount of subtidally dominated habitat in Southern California relative to San Francisco Bay was also noted by Grossinger *et al*. (2011) who analyzed historical distribution of coastal wetland habitat based on ca. 1870 T-sheets and concluded that approximately one-third of historical habitat was subtidal. Grossinger *et al*. (2011) estimated that approximately 75% of the subtidal habitat was associated with two systems, San Diego Bay and Mission Bay, which were the only predominantly open embayments in southern California in their analysis.

Morphometric assessment of coastal lagoons along the east coast of Australia in similar settings as those that occur along the California coast found a bimodal distribution with 70% of systems being closed for more than 60% of the time and 25% being mostly open (i.e., closed for less than 20% of the time). As in California, the degree of closure in these systems is strongly influenced by catchment characteristics, rainfall and coastal geomorphology (Haines *et al*. 2006).

Few studies have considered the role of stream flow in the closure dynamics of California estuaries (Webb *et al*. 1991, Elwany *et al*, 1998). Furthermore, no broad syntheses across estuaries that consider this dynamic are available for California as they are for South Africa (e.g., Cooper 2001, 2002) or Australia (e.g., Roy *et al*. 2001, Haines *et al* 2006). Consequently most restoration planning relies on estuarine models developed from older port construction and navigational literature (O'Brien 1931, Bruun 1986). These exclusively emphasize the interplay between the tidal prism in maintaining opening juxtaposed with wave energy that is presumed to close it. Most southern California restoration projects have relied on guidance provided by Johnson (1973) who regressed wave energy and tidal prism relative to closure state and produced a simple binary variable for large west coast estuaries. In these assessments, wave energy is presumed to facilitate shore-face transport of sediment and closure, and the area of the estuary is used to calculate tidal prism or volume and flow. These calculations have some value as a rule of thumb relative to one set of processes. However, they lack consideration of a number of important variables/processes and tend to single-out the tide, rather than seasonal or intermittent stream flow, and geologic setting as important variables in these systems. When applied to estuary restoration they tend to limit the discussion of the full set of critical physical processes considered in California estuaries by excluding consideration of stream dynamics and freshwater input as important factors to consider in closure dynamics and their influence on restoration design.

There is also a tendency to discuss estuaries as either open or completely closed. In reality, estuaries exist along several continua relating to relative duration of open vs. closed conditions, frequency of opening events, and the degree of closure. In our classification we simplify this temporal complexity as the proportion of time that a specific estuary exists in each of the eight closure states (relative to tidal height) as shown in Figure 8. The oversimplified characterization of estuaries as either "open" or "closed" can lead to an underestimation of the period of estuarine closure, especially in situations where closure is irregular or partial. Additional variables not systematically considered in their effect on closure include: the angle of wave attack, the presence of promontories adjacent to estuaries, the seasonality of movement of sediment on and offshore and their effect on beach width, the evolution of outflow channel orientation and length, and impediments to flow within the lagoonal systems. All these factors likely contribute to or modify the potential for at least seasonal or intermittent closure. Finally, consideration of episodic opening of predominantly closed systems is also often neglected, which can have important ecological consequences in terms of species dispersal and recolonization (Lafferty *et al*. 1999, Earl *et al*. 2010).

The misimpression of California systems as predominantly open has influenced past restoration activities, which have tended to focus on creating "open" estuaries by converting historically lagoon systems with seasonal or intermittent tidal access to perennially full tidal systems. Because inherent physical processes favor recurring mouth closure, estuarine mouths are often kept open by artificial means, such as groins, levees, and regular dredging. As we have elaborated above, creating "artificial" open systems has several ecological implications. Opening of systems lowers the coastal water table and further increase the efficiency of regional engineering modifications that export fresh water to the sea. A secondary effect of increased water delivery to the sea is decreased contact time with estuarine surfaces (sediment and plants) that can function to filter out pollutants. This increased "flushing" may result in increased pollutant delivery to the sea, potentially impacting beaches and near coastal areas.

Conversion of lagoons to open systems has broad biological impacts. A number of California species are especially adapted to closing estuaries or take particular advantage of them in their life history. These species are directly threatened by the artificial opening of closing estuarine habitat. Such species include the federally endangered tidewater goby (*Eucyclogobius newberryi*; Swift *et al*. 1989, Lafferty *et al*. 1999, Lafferty 2005, Earl *et al*. 2010), southern steelhead (*Oncorhynchus mykiss*) (Bond 2006; Bond et al. 2008), as well as the sea slug *Alderia* (Ellingson and Krug 2006, Krug *et al*. 2007). As discussed above clapper rails likely benefit from the increased vegetation height and heterogeneity afforded to "salt" marshes exposed to intermittent freshwater events facilitated by closure; and, impacted riparian taxa including endangered reptiles and amphibians appear to benefit by the maintenance of high water tables and fresh water through the summer in closing systems. The importance of closure for these biotic functions has not been given much attention in the context of estuary "restoration". In contrast much emphasis has been placed on the presumed benefits of fully open systems for fisheries, especially California Halibut. However, the relative importance of estuaries as nurseries has only recently begun to be addressed (Fodrie and Levin 2008), and it is unclear whether or not partial closure might be beneficial even to California Halibut production. Overall closed systems typically contain more water and are more productive in terms of marsh plant growth (Zedler 1983). Due to this persistent wetted condition the intertidal heights of closed or partially closed systems may well be more productive in terms of fish biomass than the intertidal of open systems, and these intertidal settings are known to be low in diversity (Desmond *et al.* 2000). In the future, more comprehensive and balanced assessment of biotic impacts of estuary modification in the name of "restoration" should be considered.

Success and long-term sustainability of restored coastal wetlands can be improved if the design is consistent with underlying landscape controls of wetland processes (Mitch and Wilson 1996, Zedler 2000). Undisturbed reference sites are often used to provide insight to these controls and the appropriate form for given landscape positions. Unfortunately, like many developed coastal regions, undisturbed reference sites are difficult to find along the California Coast, particularly in southern California. In the absence of reference sites, models based on a range of historical information can be used to provide insight into the relationship between landscape setting, physical process, and resultant wetland form and function. The conceptual model presented in this document provides a tool to aid in consideration of appropriate design for coastal wetland restoration in California. Knowledge of the "native" form should be coupled with consideration of existing landscape constraints and practical and logistical considerations when determining preferred restoration designs. Designs that more closely match controlling landscape processes, require less ongoing maintenance, and should have fewer unintended consequences for the native flora and fauna. Regardless of the ultimate decisions made regarding restoration and management of central and southern California estuaries, a more full and open consideration of historical conditions would result in restoration projects more closely aligned with historic processes and conditions.

ACKNOWLEDGMENTS

This publication has been produced with support from the National Sea Grant College Program, National Oceanic and Atmospheric Administration, U.S. Department of Commerce, under grant number NA 06OAR4170012. The views expressed herein do not necessarily reflect the views of NOAA or any of its sub-agencies. The U.S. Government is authorized to reproduce and distribute copies for governmental purposes. We thank Camm Swift for insightful discussions on California estuaries. Christine Lam and Nicolas Hall provided valuable research assistance. Beau MacDonald and Henry Thomassen provided significant mapping assistance. We thank Bryant Chesney, Andrea Wolfolk, and Beth Watson for constructive comments on the first revision of this report. Robin Grossinger provided assistance in obtaining and interpreting T-sheets and useful comments on the manuscript. The UCLA Department of Geography, Benjamin and Gladys Thomas Air Photo Archives facilitated access to valuable collections. Modern aerial photographs are Copyright © 2002–2009 Kenneth & Gabrielle Adelman, California Coastal Records Project, www.californiacoastline.org. Previous versions of this paper were presented at the 2009 meeting of the California Estuarine Research Society and the Headwaters to Ocean (H20) conferences.

LITERATURE CITED

Altschul, J.H. and D.R. Grenda, (eds). 2002. Islanders and Mainlanders: Prehistoric Context for the Southern California Bight. SRI Press. Tucson, AZ.

Anandraj, A., R. Perissinotto and C. Nozais. 2007. A comparative study of microalgal production in a marine versus a river-dominated temporarily open/closed estuary, South Africa. *Estuarine Coastal and Shelf Science* 73:768–780.

Anonymous. 1876. An Historical Sketch of Los Angeles County, California, From the Spanish Occupancy, by the Founding of the Mission San Gabriel Archangel, September 8, 1771 to July 4, 1876. Louis Lewin & Co. Los Angeles, CA.

Anonymous. 1906. Snowy water now clearing. *Los Angeles Times*, July 15. Los Angeles, CA.

Behrens, D. K., F. A. Bombardelli, J. L. Largier, and E. Twohy (2009), Characterization of time and spatial scales of a migrating rivermouth, *Geophys. Res. Lett.*, *36*, L09402, doi:10.1029/2008GL037025.

Bond, M.H. 2006. Importance of estuarine rearing to central California steelhead (*Oncorhynchus mykiss*) growth and marine survival. Master of Arts thesis: University of California, Department of Ecology and Evolutionary Biology. Santa Cruz, CA.

Bond, M.H., Hayes, S.A., Hanson, C.V., & MacFarlane, R.B. 2008 Marine survival of steelhead (*Oncorhynchus mykiss)* enhanced by a seasonally closed estuary. Canadian Journal of Fisheries and Aquatic Sciences 65:2242-2252

Brinson, M. and R. Rheinhardt. 1996. The role of reference wetlands in functional assessment and mitigation. *Ecological Applications* 6:69–76.

Bruun, P. 1986. Morphological and navigational aspects of tidal inlets on littoral drift shores. *Journal of Coastal Research* 2:123–145.

Carreker, R. G. 1985. Habitat suitability index models: least tern. U.S. Fish and Wildlife Service Biological Report 82(10.103). 29 pp.

Chambers, W.L. 1936. The hunter in southern California versus wild animal life. *Condor* 38:199–202.

Cooper, J.A.G. 1990. Ephemeral stream-mouth bars at flood-breach river mouths on a wave-dominated coast: comparison with ebb-tidal deltas at barrier inlets. *Marine Geology* 95:57–70.

Cooper, J.A.G. 2001. Geomorphological variability among microtidal estuaries from the wave-dominated South African coast. *Geomorphology* 40:99–122.

Cooper, J.A.G. 2002. The role of extreme floods in estuary-coastal behaviour: contrasts between river-and tide-dominated microtidal estuaries. *Sedimentary Geology* 150:123–137.

Cooper, D.S. 2005. Special-status bird species of the Ballona wetlands. Report prepared for Cooper Ecological Monitoring Inc. www.cooperecological.com/**special_status_species**web.htm

Davidson, G. 1889. Coast pilot, Pacific Coast. United States Coast and Geodetic Survey, Washington, D.C.

Dawson, M. N.J. Staton and D. K. Jacobs. 2001. Phylogeography of the Tidewater Goby, *Eucyclogobius newberryi* (Teleostei, Gobiidae), in Coastal California. *Evolution* 55:1167–1179.

Dawson, W.L. 1923. The birds of California: a complete, scientific and popular account of the 580 species and subspecies of birds found in the state. Moulton & Co.

De Groot, D.S. 1926. The California Clapper Rail: its nesting habits, enemies and habitat. *Condor* 29:259–270.

Desmond, J., J. Zedler and G. Williams. 2000. Fish use of tidal creek habitats in two southern California salt marshes. *Ecological Engineering* 14:233–252.

Dickinson, W.R. 2001. Paleoshoreline record of relative Holocene sea levels on Pacific islands. *Earth-Science Reviews* 55:191–234.

Earl, D.A., K.D. Louie, C. Bardeleben, C.C. Swift and D.K. Jacobs. 2010. Rangewide microsatellite phylogeography of the endangered tidewater goby, *Eucyclogobius newberryi* (Teleostei: Gobiidae), a genetically subdivided coastal fish with limited marine dispersal. *Conservation Genetics* 11:103–114.

Edgar, G.J., N.S. Barrett, D.J. Graddon and P.R. Last. 2000. The conservation significance of estuaries: a classification of Tasmanian estuaries using ecological, physical and demographic attributes as a case study. *Biological Conservation* 92:383–397.

Ellingson, R.A. and P.J. Krug. 2006. Evolution of poecilogony from planktotrophy: Cryptic speciation, phylogeography, and larval development in the gastropod genus Alderia. *Evolution* 60:2293–2310.

Elwany, M.H.S., R.E. Flick and S. Aijaz. 1998. Opening and closure of a marginal southern California lagoon inlet. *Estuaries* 21:246–254.

Engstrom, W.N. 1999. The nineteenth century physical geography of the Camp Pendleton coastline. *Pacific Coast Archaeological Society Quarterly* 35:65–78.

Engstrom, W.N. 2006. Nineteenth century coastal geomorphology of southern California. *Journal of Coastal Research* 22:847–861.

Fairbanks, R.G. 1989. A 17000-year glacio-eustatic sea level record: influence of glacial melting rates on the Younger Dryas event and deep-ocean circulation. *Nature* 342:637–642.

Fodrie, F.J and L.A. Levin. 2008. Linking juvenile habitat utilization to population dynamics of California halibut. *Limnology and Oceanography* 53:799–812.

Foreman, T.L. 2003. Management of seawater intrusion in the Los Angeles coastal basin, California: an evolution of practice. pp. 137–148 *in*: J.A. Lopez-Geta, J.A. de la Orden, J. de Dios Gomez, G. Ramos and L. Rodriguez (eds.), Coastal Aquifers Intrusion Technology: Mediterranean Countries. Instituto Geologico y Minero de espana, Madrid.

Frampton, C., C.K. Webb, W. Jin and R. Dagit. 2005. Topanga Creek and Lagoon restoration feasibility study: a watersed-scale approach. Proceedings: California and the World Ocean '02. American Society of Civil Engineers. Santa Barbara, CA.

Grayson, J.E., M.G. Chapman and A.J. Underwood. 1999. The assessment of restoration of habitat in urban wetlands. *Landscape and Urban Planning* 43:227–236.

Grossinger, R. E.D. Stein, K. Cayce, R. Askevold, S. Dark, and A. Whipple. 2011. Historical Wetlands of the Southern California Coast: An Atlas of US Coast Survey T-sheets, 1851-1889. Southern California Coastal Water Research Project Technical Report #589, SFEI Contribution #586.

Grossman, E.E., C.H. Fletcher III and B.M. Richmond. 1998. The Holocene sea-level highstand in the equatorial Pacific: analysis of the insular paleosea-level database. *Coral Reefs* 17:309–327.

Haines, P.E., R.B. Tomlinson and B.G. Thom. 2006. Morphometric assessment of intermittently open/closed coastal lagoons in New South Wales, Australia. *Estuarine, Coastal and Shelf Science* 67:321–332.

Hayes S.A., M.H. Bond, C.V. Hanson, E.V. Freund, J.J. Smith, E.C. Anderson, A.J. Amman, and R.B. MacFarlane. 2008. Steelhead growth in a small California watershed: upstream and estuarine rearing patterns. *Transactions of the American Fisheries Society* 137:114–128.

Hall, C.A. 2002. Nearshore marine paleoclimate regions, increasing zoogeographic provinciality, molluscan extinctions, and paleoshorelines, California: Late Oligocene (27Ma) to Late Pliocene (2.5Ma). *Geological Society of America. Special Paper* 357:1–489.

Hansen, G. and J.E. Jackson. 1889. Opinions: Of the Ballona Outfall and Storm Drains. *Los Angeles Times*, August 24. Los Angeles, CA.

Harrison, T.D. and A.K. Whitfield. 2006. Estuarine typology and the structuring of fish communities in South Africa. *Environmental Biology of Fishes* 75:269–293.

Hayes, S.A., Bond, M.H**.,** Wells, B.K., Hanson, C.V., Jones, A.W., MacFarlane, R.B. In press. Using archival tags to infer habitat use of Central California steelhead and coho salmon. American Fisheries Society Symposium, "Advances in Fish Tagging and Marking Technology."

He, L.-M. (Lee), and Z.-L. He. 2008. Water quality predication of marine recreational beaches receiving watershed baseflow and stormwater run-off in southern California, USA. *Water Research* 43:2563–2573.

Hedgepeth, J.W. 1957. Classification of marine environments. *Geological Society of America Memoirs* 67:17–28.

Hodgkin, E.P. and P. Hesp. 1998. Estuaries to salt lakes: Holocene transformation of the estuarine ecosystems of south-western Australia. *Marine and Freshwater Research* 49:183–201.

Hogarth, L.J., J. Babcock, N.W. Driscoll, N. Le Dantec, J.K. Haas, D.L. Inman and P.M. Masters. 2007. Long-term tectonic control on Holocene shelf sedimentation offshore La Jolla, California. *Geology* 35:275–278.

Inman, D.L. and P.M. Masters. 1991. Budget of sediment and prediction of the future state of the coast. pp. 9-1 to 9-105 *in*: US Army Engineer District (ed.), Coast of California Storm and Tidal Waves Study, State of the Coast Report, San Diego Region. US Army Corps of Engineers. Los Angeles, CA.

Jacobs, D.J., T.A. Haney and K.D. Louie. 2004. Genes, diversity, and geological process on the Pacific Coast. *Annual Review of Earth and Planetary Sciences* 32:601–652.

Jeong, Y., B.F. Sanders, K. McLaughlin and S.B. Grant. 2008. Treatment of dry weather urban runoff in tidal saltwater marshes: A longitudinal study of the Talbert marsh in southern California. *Environmental Science & Technology* 42:3609–3614.

Johnson, J.W. 1973. Characteristics and behavior of Pacific Coast tidal inlets. *Journal of Waterways, Port, Coastal and Ocean Engineering* 99:325–339.

Keller, E.A., and L.D. Gurrola. 2000. Earthquake hazard of the Santa Barbara fold belt, California. Final report, July, 2000. University of California, Institute for Crustal Studies. Santa Barbara, CA.

Kennett, D.J., J.P. Kennett, J.M. Erlandson and K.G. Cannariato. 2007. Human responses to middle Holocene climate change on California's Channel Islands. *Quaternary Science Reviews* 26:351–367.

Krug, P.J., R.A. Ellingson, R. Burton and A. Valdés. 2007. A new poecilogonous species of sea slug (Opisthobranchia: Sacoglossa) from California: Comparison with the planktotrophic congener *Alderia modesta* (Lovén, 1844). *Journal of Molluscan Studies* 73:29–38.

Lafferty, K.D. 2005. Assessing estuarine biota in southern California. pp. 1–15 *in*: B.E. Kus and J.L. Beyers (eds.), Planning for biodiversity: bringing research and management together. Gen. Tech. Rep. PSW-GTR-195. Department of Agriculture Forest Service, Pacific Southwest Research Station. Albany, CA.

Lafferty, K.D., C.C. Swift and R.F. Ambrose. 1999. Extirpation and recolonization in a metapopulation of an endangered fish, the tidewater goby. *Conservation Biology* 13:1447–1453.

Li, C.X., P. Wang, H.P. Sun, J.Q. Zhang, D.D. Fan and B. Deng. 2002. Late Quaternary incised-valley fill of the Yangtze delta (China): Its stratigraphic framework and evolution. *Sedimentary Geology* 152:133–158.

Livingston, A. 1949. Geological journeys in southern California. William. C. Brown Co. Dubuque, IA.

Longcore, T.R., R. Mattoni, G.F. Pratt, and C. Rich. 2000. On the perils of ecological restoration: lessons from the El Segundo blue butterfly. pp. 281–286 *in*: J.E. Keeley, M. Baer-Keeley, and C.J. Fotheringham (eds.). 2nd Interface Between Ecology and Land Development in California. U.S. Geological Survey Open File Report 00-62, Sacramento.

Los Angeles Times. 1886. Port Ballona. A chat with the cheif engineer about it. *Los Angeles Times*, February 14. Los Angeles, CA.

Los Angeles Times. 1887. Ballona harbor: the new port canvassed by a Los Angeles scribe. *Los Angeles Times*, May 1. Los Angeles, CA.

MacDonald, B., T. Longcore, and S. Dark. 2010. Habitat suitability modeling for western snowy plover in central California. The Urban Wildlands Group, Los Angeles. 129 pp.

Masters, P.M. and I.W. Aiello. 2007. Postglacial evolution of coastal environments. pp. 35–51 *in*: T.L. Jones and K. Klar (eds.), California Prehistory: Colonization, Culture, and Complexity. Altamira Press. Lanham, MD.

Mattoni, R., and T.R. Longcore. 1997. The Los Angeles coastal prairie, a vanished community. *Crossosoma* 23:71–102.

McNeilan, T.W., T.K. Rockwell and G.S. Resnick. 1996. Style and rate of Holocene slip, Palos Verdes fault, southern California. *Journal of Geophysical Research* 101:8317–8334.

Mitsch W.J. and R.F. Wilson. 1996. Improving the success of wetland creation and restoration with know-how, time, and self-design. *Ecological Applications* 6:77–83.

Muhs, D.R., T.K. Rockwell and G.L. Kennedy. 1992. Late Quarternary uplift rates of marine terraces on the Pacific Coast of North America, Southern Oregon to Baja California Sur. *Quaternary International* 15/16:121–133.

Muhs, D.R., K.R. Simmons, G.L. Kennedy and T.K. Rockwell. 2002. The last interglacial period on the Pacific Coast of North America: timing and paleoclimate. *Geological Society of America. Bulletin* 114:569–592.

[NRC] National Research Council. 1992. Restoration of aquatic ecosystems: science, technology, and public policy. Washington. D.C.

Niemi, N.A., M. Oskin and T.K. Rockwell. 2008. Southern California Earthquake Center Geologic Vertical Motion Database. *Geochemistry Geophysics Geosystems* 9:Q07010.

Nozais, C., R. Perissinotto and G. Tita. 2005. Seasonal dynamics of meiofauna in a South African temporarily open/closed estuary (Mdloti Estuary, Indian Ocean). *Estuarine Coastal and Shelf* 62:325–338.

O'Brien, M.P. 1969. Equilibrium flow areas of inlets on sandy coasts. *Journal Waterways, Harbors and Coastal Engineering Division ASCE* 95(WW1):43–52.

Orme, A.R. 1985. The behavior and migration of longshore bars. *Physical Geography* 6:142–164.

Palacios-Fest, M.R., J.A. Homburg, E.C. Brevik, A.R. Orme, O.K. Davis and S.D. Shelley. 2006. Late Quaternary palaeoecology of Ballona Lagoon in southern California. *Ciencias Marinas* 32:485–405.

Ranasinghe, R. and C. Pattiaratchi. 1999. The seasonal closure of tidal inlets: Wilson Inlet - A case study. *Coastal Engineering* 37:37-56.

Ranasinghe, R. and C. Pattiaratchi. 2003. The seasonal closure of tidal inlets: Causes and effects. *Coastal Engineering Journal* 45:601–627.

Ranasinghe, R., C. Pattiaratchi and G. Masselink. 1999. A morphodynamic model to simulate the seasonal closure of tidal inlets. *Coastal Engineering* 37:1–36.

Reagan, J.W. 1915. USACE Los Angeles County Flood Control Research, 1914–1915. 2 vols. Huntington Library Manuscript Call # HM66796.

Ritter, A.F., K. Wasson, S.I. Lonhart, R.K. Preisler, A. Woolfolk, K.A. Griffith, S. Connors and K.W. Heiman. 2008. Ecological signatures of anthropogenically altered tital exchange in estuarine ecosystems. *Estuaries and Coasts* 31:554–571.

Roy, P.S., R.J. Williams, A.R. Jones, I. Yassini, P.J. Gibbs, B. Coates, R.J. West, P.R. Scanes, J.P. Hudson and S. Nichol. 2001. Structure and function of south-east Australian estuaries. *Estuarine Coastal and Shelf Science* 53:351–384.

Schimmelmann, A., C.B. Lange and B.J. Meggers. 2003. Palaeoclimatic and archaeological evidence for a similar to 200-yr recurrence of floods and droughts linking California, Mesoamerica and South America over the past 2000 years. *Holocene* 13:763–778.

Schimmelmann, A., M. Zhao, C.C. Harvey and C.B. Lange. 1998. A large California flood and correlative global climatic events 400 years ago. *Quaternary Research* 49:51–61.

Schwarz, K.M. and A.R. Orme. 2005. Opening and closure of a seasonal river mouth: The Malibu estuary-barrier-lagoon system, California. *Zeitschrift für Geomorphologie, Supplement* 141:91–109.

Shuttleworth, B., A. Woidt, T. Paparella, S. Herbig and D. Walker. 2005. The dynamic behaviour of a river-dominated tidal inlet, River Murray, Australia. *Estuarine Coastal and Shelf Science* 64:645-657.

Slater, R., D. Gorsline, R. Kolpack and G. Shiller. 2002. Post-glacial sediments of the Californian shelf from Cape San Martin to the US–Mexico border. *Quaternary International* 92:45–61.

Stein, E.D., S. Dark, T. Longcore, N. Hall, M. Beland, R. Grossinger, J. Casanova and M. Sutula. 2007. Historical ecology and landscape change of the San Gabriel River and floodplain. Technical Report 499. Southern California Coastal Water Research Project. Costa Mesa, CA.

Stein, E.D., S. Dark, T. Longcore, R. Grossinger, N. Hall, M. Beland. 2010. Historical ecology as a tool in assessing landscape change and informing restoration priorities. *Wetlands* 30:589–601.

Stretch, D. and M. Parkinson. 2006. The breaching of sand barriers at perched, temporary open/closed estuaries - A model study. *Coastal Engineering Journal* 48:13–30.

Swift, C.C. 2005. Draft report on historical changes and ecological requirements of fishes in Alamitos Bay, Orange County, California, by Camm Swift, April, 2005.

Swift, C.C., J.L. Nelson, C. Maslow and T. Stein. 1989. Biology and distribution of the tidewater goby, *Eucyclogobius newberryi* (Pisces: Gobiidae) of California. *Natural History Museum Los Angeles County Contributions to Science* 404:1–19.

Swift CC, T.R. Haglund, M. Ruiz, and R.N. Fisher. 1993. The status and distribution of the freshwater fishes of southern California. *Bulletin of the Southern California Academy of Sciences* 92:101–167

Van Dyke, E. and K. Wasson. 2005. Historical ecology of a central California estuary: 150 years of habitat change. *Estuaries and Coasts* 28:173–189.

Warme, J.E. 1971. Paleoecological aspects of a modern coastal lagoon. University of California Publications in Geological Sciences Volume 87.

Webb, C.K., D.A. Stow and H.H. Chang. 1991. Morphodynamics of southern California inlets. *Journal of Coastal Research* 7:167–187

Woolfolk, A. 2005. Evolution of Elkhorn Slough and Associated Wetlands: 20,000 Years Before Present (ybp) to 1880 A.D. Elkhorn Slough National Estuarine Research Reserve. Watsonville, CA.

Zedler, J.B. 1983. Fresh-water impacts in normally hypersaline marshes. *Estuaries* 6:346–355.

Zedler, J.B. 1986. Catastrophic flooding and distributional patterns of Pacific cordgrass (*Spartina foliosa Trin.)* of the Southern California Academy of Sciences, 1986.

Zedler, J.B. 1996. Coastal mitigation in southern California: The need for a regional restoration strategy. *Ecological Applications* 6:84–93.

Zedler, J.B. 2000. Progress in wetland restoration ecology. *Trends in Ecology and Evolution* 15:402–407.

Zedler, J.B. and S. Kercher. 2005. Wetland resources: Status, trends, ecosystem services, and restorability. *Annual Review of Environment and Resources* 30:39–74.

Zoulas, J.G. and A.R. Orme. 2007. Multidecadal-scale beach changes in the Zuma littoral cell, California. *Physical Geography* 28:277–300.