South Bay Salt Pond Restoration Project

SYNTHESES OF SCIENTIFIC KNOWLEDGE

for Maintaining and Improving Functioning of the South Bay Ecosystem and Restoring Tidal Salt Marsh and Associated Habitats over the Next 50 Years at Pond and Pond-Complex Scales

DRAFT FINAL REPORT

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SFEI Report No: **308**

Syntheses of Scientific Knowledge For Key Issues 1 and 3:

(1) Maintaining and Improving Functioning of the South Bay Ecosystem and
(2) Restoring tidal salt marsh and associated habitats over the next 50 years at pond and pond-complex levels

For the Science Team of the South Bay Salt Pond Restoration Project

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This synthesis focuses on the form and function of South Bay landscapes to address the following two issues –

- ***maintaining and improving functioning of the South Bay Ecosystem; and***
- ***restoring tidal salt marsh and associated habitats over the next 50 years at pond and pond-complex levels.***

This synthesis is organized into five parts: (I) Definition of the South Bay Ecosystem; (II) Historical Conditions; (III) Landscape Modifications; (IV) Modern Conditions; and (V) Restoration Tools, Targets, and Related Questions. Specific topics posed by the Science Team Lead are addressed in each part of the synthesis.

What is the importance of these Issues as they relate to the Project Objectives?

The two issues addressed here cut across all six Project Objectives but pertain most directly to Objective One: create, restore, or enhance habitats of sufficient size, function, and appropriate structure to (A) promote restoration of native special-status plants and animals that depend on South San Francisco Bay habitat for all or part of their life cycles; (B) maintain current bird species that utilize existing salt ponds and associated structures such as levees; and (C) support increased abundance and diversity of native species in various South San Francisco Bay aquatic and terrestrial ecosystem components, including plants, invertebrates, fish, birds, reptiles and amphibians.

Furthermore, the recommended approach and emerging design principles for the Project emphasize deference to natural processes of the lands and waters of the South Bay Ecosystem to meet the objectives with minimal infrastructure and management.

Meeting the Project objectives according to the design principles will require understanding of the effects of natural processes and land use on the quantity and quality of all the major habitat types along the gradient from adjacent uplands and creeks through the intertidal zone to the subtidal areas of South San Francisco Bay. This broad view is required because in essence the Project occupies the transition between terrestrial and estuarine systems and thus some portion of the ecological services of the Project depends on adjacent processes, and some of the adjacent processes will be affected by the Project.

What do we know about these issues as they relate to the Project?

This synthesis organizes the pertinent information into a spatial hierarchy starting with what is known about the nature of the major habitat types, and scaling up through typical landscapes to view the South Bay Ecosystem as a whole. Special attention is given to the ecotones between major habitat types because of their influence on overall biological diversity. The history of land use is laid over the knowledge of natural habitats and landscapes to resolve the influence of people on existing conditions. The layering of natural and human history on the spatial hierarchy yields a synthesis of understanding about the ecosystem and its characteristic landscapes (first issue listed above) as well as the habitat types and their physiographic elements (second issue listed above).

I. DEFINITION OF THE SOUTH BAY ECOSYSTEM

The South Bay Ecosystem is the term being applied to the geographic limits of natural processes and land use that more or less directly control the likelihood that the Project will meet its objectives. Since Project success will rely on adequate supplies of water and inorganic sediment from the estuary and from local watersheds (Knebel et al. 1977, McKee et al. 2003), the ecosystem will have a terrestrial-fluvial as well as an estuarine-tidal extent.

There is no existing definition of the South Bay Ecosystem for the Project to adopt. To encompass the geographic processes that are likely to control the performance of the Project, the South Bay Ecosystem should probably be defined as the South Bay and its adjacent watersheds. Recent efforts through the Sate of California (CalWater), the National Hydrologic Database (NHD), the Santa Clara Valley Water District, and the Regional Monitoring Program for Trace Substances (RMP), have produced consistent maps of the outside boundaries of South Bay watersheds that might serve to delimit the terrestrial-fluvial extent of the South Bay Ecosystem (Figure 1).

However, according to the California State and National Boards of Geographic Names, South Bay is not an official place. There is therefore no state or federal map identifying the limits of South Bay. A number of early studies generally referred to the extent of tidal excursion south of the San Francisco Bay Bridge as South Bay (e.g., Conomos 1979, Hollibaugh 1996), whereas other studies commonly identify the San Bruno Shoal as an important hydrodynamic boundary between South Bay and Central Bay (e.g., Powell et al. 1986, Jassby 1996). These bay boundaries are derived from consideration of estuarine processes only, without

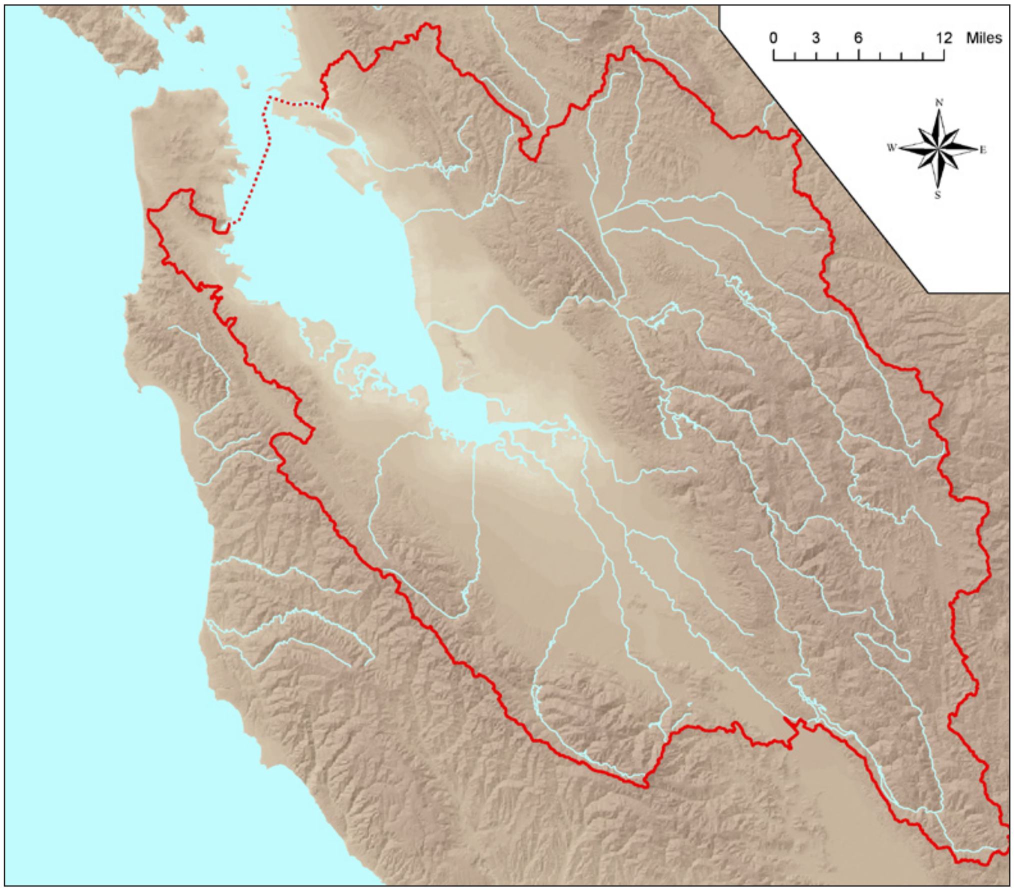


Figure 1: Possible boundary of the South Bay Ecosystem. The outer boundaries of the local watersheds south of San Bruno Shoal comprise the terrestrial boundary of the ecosystem. The estuarine boundary (i.e., where the boundary crosses the estuary) is not as obvious, and may depend on the spatial extent of sediment flux between Central Bay and South Bay. For many ecosystem services, such as waterfowl and fisheries support, the ecosystem extends far beyond the boundaries shown here.

regard to the adjacent terrestrial or fluvial systems. The Baylands Ecosystem Goals Project (Goals Project 1999) refers to the boundaries of local watersheds and the natural morphometry of the Estuary to demarcate South Bay from Central Bay. A line drawn across the Estuary between Coyote Point on the west side and Hayward Landing on the east side approximates the northern limit of South Bay according to the Goals Project. This line is far south of the San Bruno Shoal, however. Considering the fluvial and tidal arguments together suggests that the northern limit of South Bay might extend across the estuary just north of the San Bruno Shoal, and connect to the northern boundaries of the Colma Creek Watershed on the west side, and the southern boundary of the San Leandro Creek Watershed on the east side.

A single, fixed aquatic boundary may not be appropriate for the South Bay ecosystem. The boundary may vary depending upon the ecosystem function of interest. For example, the boundary extends out the Golden Gate and some distance north and south along the coast with regard to salmon and steelhead, and it extends much further along the Pacific Flyway for many species of water birds. With regard to water supply, the boundary extends into the Central Sierra because of water transfers from there to South Bay for human consumption.

Further discussion by the Science Team of the Project is needed to judge the efficacy of alternative spatial boundaries for the South Bay Ecosystem. At this time, the ecosystem is assumed to be South Bay and its attending watersheds as illustrated in Figure 1.

II. HISTORICAL CONDITIONS

This profile of historical conditions is based on a landscape approach to environmental analysis (Forman and Godron 1986, Urban et al. 1987, Noss and Cooperrider 1994, Chapin et al. 2002). The approach is largely founded on the premise that environmental patterns strongly influence ecological processes (Turner 1989). In this approach, every species of plant or animal has a unique effective habitat; multiple species co-exist within habitat types; the types comprise larger habitat mosaics; the mosaics exist in a matrix of ecotones; a mosaic plus its matrix comprise a landscape and the landscapes comprise the region. There is one effective habitat per species. The habitat types are distinguished by how they form, their structure, and the native vegetation they support. Habitat types are apparent in common aerial photography. Tidal flats, tidal marshland, oak savannah, and riparian forests are examples of habitat types. Habitat mosaics are defined by the composition and arrangements of closely associated habitat types. Mosaics, like their component habitat types, are self-evident. Each mosaic has a matrix of ecotones between and around its habitat types. Habitat types, mosaics, and landscapes can interact through the movements of air, water, land, and living resources (Gardner et al. 1992, Johnson et al. 1992). The landscape approach promotes the analysis of these interactions.

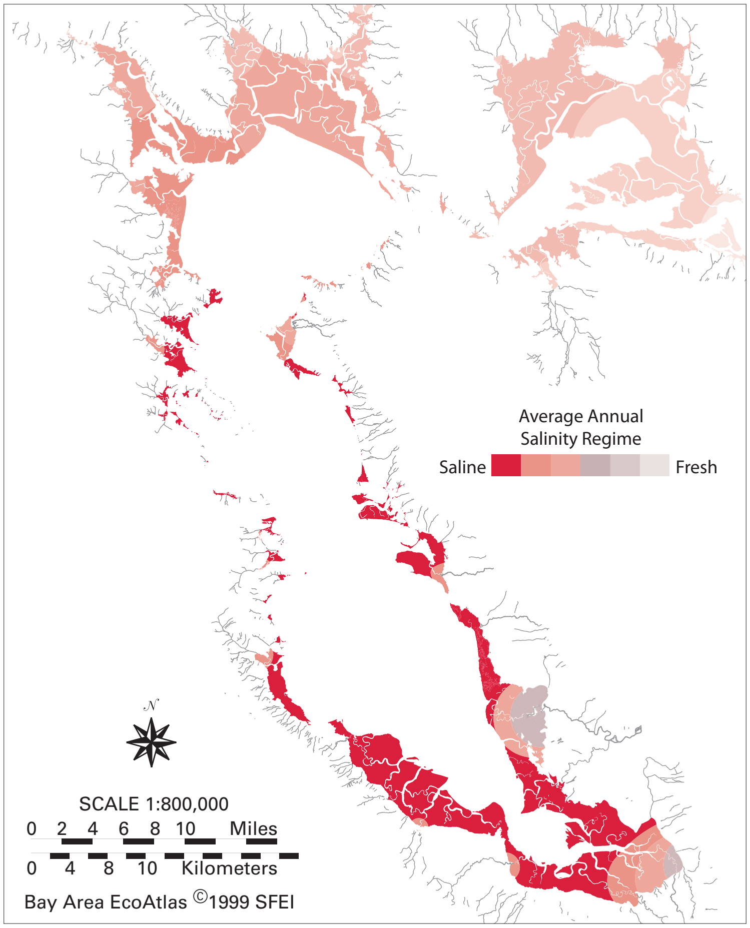


Figure 2: Salinity Gradients within Marshes. Historical distribution of surface water salinity gradients in the San Francisco Estuary. A gradient from non-saline to marine conditions characterized the primary axis of the Estuary from the Delta to the Golden Gate. A gradient from marine to higher salinities characterized the estuarine axis from the Golden Gate to extreme South Bay. Secondary gradients are created by freshwater discharges from local watersheds. These gradients are steepest where local watersheds discharge into very saline conditions. For example, the combined discharges of Coyote Creek and the Guadalupe River created a broad but steep gradient from fresh to very saline condition in extreme South Bay. These gradients have been separated into six classes of salinity based on historical information about tidal marsh plant communities, how tidal waters were used to irrigate crops and pastures, and the plan form geometry of tidal marshland that is sensitive to salinity regimes.

A region can be defined by climate, geology, ecology, and sociology (Thomas 1979, DeBlij and Muller 2003). The sociological aspect of a region gains importance as the number of people who are residents or visitors increases. A highly developed region can be defined by a shared sense of place that reflects a history of how the region is perceived from within and from other regions. The sense of place can have spiritual, commercial, and political aspects (Snyder 1990, DeBlij and Muller 2003, Fellman et al. 2004, Knox and Marston. 2004).

The San Francisco Estuary began to form as sea level rose through the Golden Gate some 10,000 years ago (Atwater 1977, Atwater 1979). The process of sea level rise across the land is called transgression. For thousands of years the rate of transgression was too fast for large areas of tidal marshes to form. But by about 4,000 years ago the rate of transgression had been slow enough for long enough that marshes began to grow. Most of the tidal marshes in the region are fewer than 3,000 years old (Byrne et al 2001, Wells and Gorman 1994, Atwater 1979). At this stage of transgression, there were two primary salinity gradients along the midline of the Estuary. Average salinity increased slightly from the Golden Gate south into far South Bay, and it decreased from the Golden Gate north and east through Central Bay, North Bay, and Suisun. Major creeks, such as Coyote, Alameda, Sonoma, and Napa created obvious secondary salinity gradients (Figure 2). The historical and modern salinity gradients are similar, although the timing of freshwater inputs and the extent and steepness of the gradients can differ locally. In a few places, such as in far South Bay, creeks have been rerouted and the daily discharges from water treatment facilities affect local salinity gradients.

The ecological understanding of historical conditions within the Bay Area has been greatly advanced in recent years due to the advents of Traditional Ecological Knowledge (TEK) and Historical Ecology as lines of scholarly research in the region (http://ip.aaas.org/tekindex.nsf, http://www.switzernetwork.org/dirdetails.taf?id=675). The effort that began ten years ago to reconstruct the historical distribution and abundance of wetlands and related habitat types around the Bay (Goals Project 1999) has led to the creation of a regional program in Historical Ecology at the San Francisco Estuary Institute (http://www.sfei.org/HEP/index.html) that continues to build detail into the original regional maps and Geographic Information System (GIS). In addition to the program at SFEI, The US Geological Survey has been developing and analyzing maps of change in bathymetry of San Francisco Estuary (Foxgrover et al. 2004).

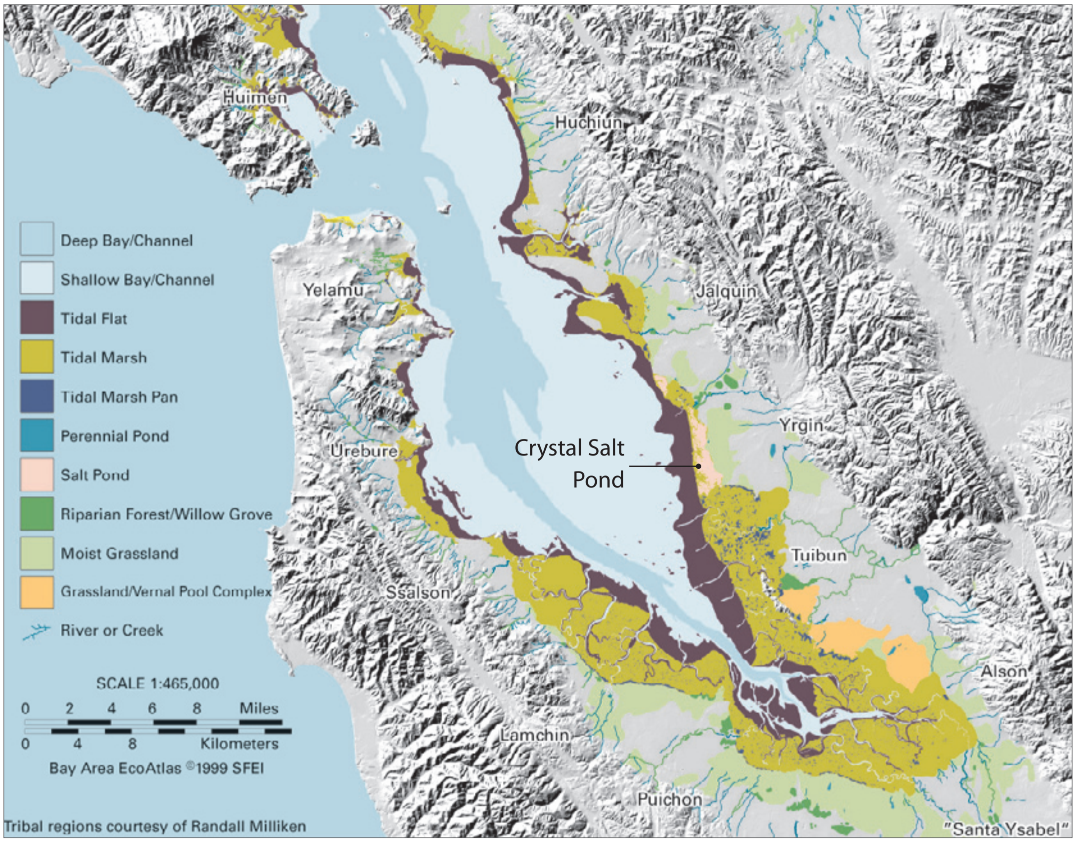


Figure 3: Historical distribution and abundance of tidal marshland and other habitat types of the South Bay Ecosystem (SFEI 1999). This map shows many unique characteristics of South Bay. Close examination reveals which creeks reach the backshore of tidal marshland and which don't; how some tidal channels do not extend across the mudflats and others do; how salinas border the backshore while sausals border the uphill perimeter of moist grassland; how vernal pool complexes are restricted to the margins of large alluvial fans; and how the extent of tidal flat increases with distance south from Central Bay. Special attention is called to the large historical salt pond called Crystal Pond midway along the east shore. Other place names refer to tribal regions of the Ohlone (tribal names courtesy of Randall Milliken).

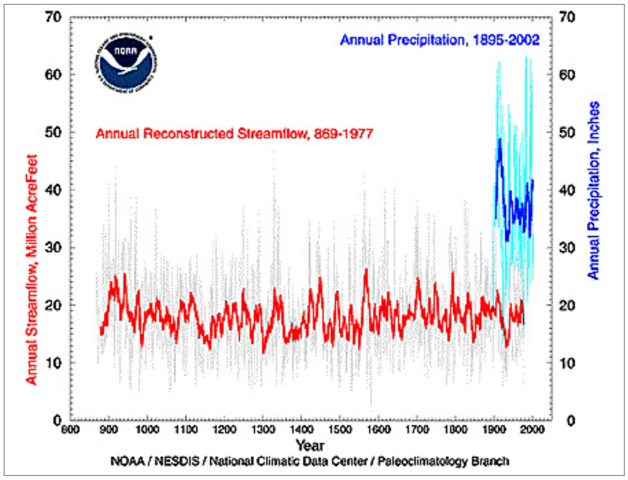


Figure 4: Historical annual stream flow for the Sacramento River basin (Meko et al. 2001). This chart shows patterns of climatic variability on time scales of years, decades, and centuries over the period 800 AD to the present. Analysis of the frequency and duration of droughts indicates that the present climatic regime extends back to about 1400 AD. By then, tidal marshes and other habitat types were well-established in the region.

The existing regional map of historical conditions of the Bay margins (Figure 3) is maintained by SFEI as part of the Bay Area EcoAtlas Information System (http://www.ecoatlas.org/, http://www.sfei.org/ecoatlas/GIS/). The map of historical condition represents the expected average arrangement of wetlands and related habitats at scale 1:10,000 over the 400 years preceding Euro-American contact (i.e., 1400 to 1800 AD). For the greater watershed of the Golden Gate, the timeframe is characterized by moderate climatic variability with multiple droughts and wet periods lasting less than a decade each century. The period prior to 1400 AD is characterized by multi-decadal periods of persistent low and high rainfall and stream flow. (e.g., Figure 4). The map of historical conditions reflects indigenous land use practices, to the extent that they were evident in the local mosaics of habitat types.

RESTORATION IMPLICATIONS

Analyses of historical conditions in this region provide evidence of the combined influence of land use and natural processes for the current climatic regime that began about six hundred years ago. How long the regime will last into the future is unknown.

Local restoration projects should be designed in the context of naturalistic landscapes of habitat types with which the projects will interact through geology, ecology, and sociology.

Landforms and Habitat Types

Islands and Peninsulas

As sea level slowly rose in Central Bay, South Bay, North Bay and Suisun, tidal flats and marshes began to grow around low-lying hills. Some hills became islands in the marshland. Others became hilly peninsulas with narrow connections to the adjacent mainland. Early Spanish and Mexican settlers used some of the peninsulas as potreros, meaning pastures surrounded by marshlands or bay waters that helped corral herds of cattle and sheep. There are many islands and peninsulas surrounded by tidal marshland in the region. For example in Suisun there are the Potrero Hills, Bradmoor Island, and Kirby Island. In North Bay, there are Mare Island, Vallejo Heights, Neils Island, Burdell Island, Long Point and the San Pedro Hills. In Central Bay there are Albany Hill, the Richmond Potrero, Belvedere Island, and Corinthian Island. In South Bay there are Bay Farm Island, Point San Bruno, Coyote Point, and Coyote Hills. The north-facing slopes of some of these islands and peninsulas, especially in western North Bay, supported mixed hardwood forests of madrone and oak, including black oak in some cases, in addition to coastal shrubs and grasslands. Black oaks were favored by the Coast Miwok of the western North Bay (Thalman 1993) as a source of acorns and are closely associated with Miwok town sites (Bibby 1994). This suggests that the spotty distribution of black oaks on islands and peninsulas in western North Bay might reflect indigenous land use.

Creeks and Fans

Most of the larger watersheds supported modest perennial creeks that reached the Bay down broad valleys, such as Ygnacio, Green, Napa, Sonoma, Petaluma, Novato, and Santa Clara. The larger perennial creeks that flowed west from East Bay hills, such as San Pablo, Wildcat, Temescal, San Lorenzo, and Alameda, reached the Bay across broad alluvial fans. Alameda Creek drains the largest watershed in the region. Its terminal alluvial fan extends from the East Bay Hills to the Coyote Hills. For the historical reference period (i.e., 1400-1800), many of the lesser creeks in each major basin did not reach the Bay, but terminated on their fans or in seasonal wetlands at elevations above the bayshore. For every creek that reached the bay, there were a dozen or more that did not. The distance between the bayshore and the termini of creeks tended to be shorter where there was more rainfall.

Alluvial fans are prominent features around the immediate margins of the estuary (Helley et al. 1979) and its attending valleys. The locations of many other habitat types, especially seeps, springs, wetlands, and creeks are determined by the size and shape of alluvial fans. Their roles in sediment storage and groundwater recharge are well studied in some cases (Kunkel and Upson 1960, Figuers 1998, SFBRWQCB 2003). Their role in agriculture is also appreciated (e.g., Boyd undated). But their impact on the distribution and abundance of wetlands and related habitats is understudied.

Sag Ponds

Sag ponds are formed by seismic processes that induce land subsidence along fault traces. Although the immediate Bay Area has many active faults, sag ponds were only prominent along the Green Valley Fault and the central and southern reaches of the Hayward Fault. These ponds were probably perennial, but varied seasonally in depth and size.

Dry Grassland

Except for woodlands on the islands and peninsulas described above, forests and savannas were substantially removed from the Bay edge in canyons along the surrounding hills or at the higher elevations of adjacent alluvial fans. Trees were rare along the bayshore except as the occasional sausals and downstream ends of the narrow riparian forests of a few larger creeks. Vegetation dominated by grasses and sedges was widespread along the shores of the Bay prior to European settlement. Native perennial grassland predominated near the Bay on valley floors and on hillslopes with southwest aspects. These grasslands were composed primarily of perennial bunch grasses and rhizomatous grasses, especially purple needlegrass and creeping wild rye. Example remnants of this community are at Rush Ranch in Suisun and Coyote Hills near Newark.

Moist Grassland

Poorly drained flatlands with clayey soils that lacked direct input from creeks tended to stay moist throughout the wet season due to direct rainfall and overland flooding. Such flatlands supported a flora adapted to saturated conditions and are referred to as moist grasslands. They ranged in size from less than an acre to thousands of acres, and were most extensive along the bottoms of broad valleys with discontinuous channels, such as the upper Petaluma, middle Napa, and lower Santa Clara. Moist grasslands also existed in the lowlands between large alluvial fans, and as a narrow band in the transition zone between the uplands and the tidal marshland, where shallow water tables intercepted the ground surface as seeps and springs. In the Santa Clara and Sonoma Valleys, moist meadows were associated with the artesian belt, where pressured groundwater was sealed by the clay soils. The band of moist grassland surrounding the South Bay marshes was generally a mile or more in width, its continuity only broken by small intrusions of dry grasslands associated with coarse soils on active alluvial fans. Moist grasslands in the South Bay typically extended from the marsh edge to somewhere between the 20- and 50-foot contours, most commonly in the vicinity of the 30-foot contour.

Coastal Prairie

This type of grassland occurred in limited distribution near the Bay in areas that are frequently exposed to moist marine air and which have clay soil. Dominant species include Douglas iris, reedgrass, oatgrass, and hairgrass. Examples occur at Brooks Island.

Vernal Pools

Vernal pools are seasonally flooded depressions on ancient soils that thinly cover an impermeable substrate of hardpan, clay, or bedrock above the tides. The impermeable substrate causes the pools to retain rainwater and local runoff. But the pools are so shallow that they tend to desiccate due to evaporation. Some vernal pools can fill and empty several times during the wet season. They can exist as distinct depressions or as diffuse and interconnected swales along very low-gradient drainages. Large areas with abundant vernal pools or swales are often called vernal pool complexes.

Three significant areas of vernal pools adjoined the Bay. The largest area extended along the backshore of Suisun Marsh from the southern end of the Montezuma Hills to the western end of the Potrero Hills. Some of the vernal pools still existing in this area are more than an acre large. The smaller area adjoining the Sonoma marshlands on the west side of Sonoma Valley and the large area around northern Suisun Marsh mostly consisted of indistinct smaller depressions and swales. Another area of vernal pools existed at the downstream limits of the large alluvial fan associated with Alameda Creek, near present-day Warm Springs. This area mostly consisted of small, distinct depressions among more diffuse swales. These three areas differ in estuarine influences. The areas in northern Suisun and along the Alameda Creek fan are subject to aeolian depositions of salt from the large upwind expanses of salt and brackish marsh. The estuary has been transgressing the lower reaches of these two areas, such that some vernal pools are adjacent to the backshore of the historical tidal marshlands. The area in Sonoma Valley is largely protected from estuarine influences, except in its most downstream reaches.

Sausals

A grove of willows on flat lands away from any creek, at a sink along the creek, or at the downstream end of ephemeral creeks, and sustained by springs, seeps, or a shallow water table was referred to as a sausal by early Spanish explorers. Arroyo willow was the dominant sausal species. Sausals are not strictly riparian or lacustrine in nature. They were strongly associated with the areas of emergent groundwater near the upland boundary of moist meadows on the very low-gradient plains around South Bay, in Ygnacio Valley, and in Livermore Valley. Their restriction from the broad, low-gradient plains of North Bay and Suisun has not been explained. At least some of the sausals in South Bay were managed by indigenous people for medicines and building materials. The largest sausals grew in South Bay, where they ranged in size from less than an acre to over 350 acres (Grossinger 2001). In total, South Bay supported about 1700 acres of sausals. They have become one of the rarest components of any landscape in the region (Collins 1988).

Sausals are represented well in historical accounts of the South Bay. Cooper (1926) describes "dense thickets sometimes 30 feet in height" with blackberry and wild rose. A visitor approaching San Jose in 1850 provides a similar description of a mature sausal:

> "I came, within two or three miles of San Jose, to a large extent of willows, so thickly woven together with wild blackberry vines, wild roses, and other thorny plants, that it appeared as if I could never get through it. But I found a winding trail made by the cattle…the willows were in places 50 feet high and a foot in diameter. The willows where I came from were mere bushes and these astonished me (Manly 1850 in James and McMurry 1933).

Most of these sausals were positioned immediately adjacent to the upland edge of the tidal marsh. Others were located further away from the marsh in sinks along stream courses or at the ends of the many creeks that spread out into seasonal wetlands on the alluvial plain. Almost all of the historical willow groves have been destroyed.

Riparian Forest

Riparian forests border the edges of lakes and creeks. They comprise an ecotone between aquatic systems and their attending watersheds. Natural riparian habitats are characterized by steep and variable gradients of moisture and light, lush vegetation, and very high biological diversity. Of all the habitats in the Bay Area, riparian forests are perhaps the most complex and support the greatest total number of plant and animal species.

The species composition of the riparian forests differed among the subregions. In South Bay, the list of common native riparian trees includes western sycamore and cottonwood. In North Bay, the list includes ash and California bay laurel, and box elder is locally abundant. Some species of willow (red willow, arroyo willow) and oak (coast live oak, valley oak) are common riparian trees. Common understory species were elderberry and wild rose.

For a variety of reasons, the riparian forests in the Bay Area tended to be restricted to the immediate margins of the creeks. In the headward reaches of the fluvial drainages, the restriction was due to a combination of arid conditions and steep topography. At intermediate elevations along valley margins, the arid nature of the alluvial fans helped restrict the distribution of riparian forests. Many of the streams were incised into the upper reaches of the fans, such that the active flood plains were below the valley floors. This also restricted the lateral extent of the riparian forests. The forests expanded somewhat on the valley bottoms, but may have been restricted by the saturated conditions of moist grasslands. Harvesting of riparian forests for fuel or major construction probably did not have much influence on their distribution because the tree species were not suitable for these uses (Grossinger et al. 2004a), and other more suitable trees, such as oaks and conifers, were also available.

Since most creeks did not maintain defined channels across the plains around the bay, little riparian forest existed at the marsh edge. In the saline subregions, such as far South Bay and Central Bay, the upstream excursion of saline tidal water along the few well-defined fluvial channels limited the downstream extent of riparian forest, such that large, mature riparian trees were excluded near the backshore. In fresher areas, such as Suisun and the far northern reaches of North Bay, the riparian forest may have extended further downstream along natural levees into the tidal marshlands. In general, historical documents indicate that the riparian forest extended downstream on the major creeks to approximately the 10-15 foot contour, within several hundred meters of the backshore of the tidal marshlands. Examples of riparian forest still exist along Suisun Creek, San Antonio Creek adjacent to Petaluma Marsh, Sonoma Creek, and Coyote Creek.

Tidal Marsh-Upland Ecotone

The transition between tidal marsh and adjacent terrestrial habitats comprises a zone of varying width depending upon adjacent topography. Since most of the South Bay's tidal marshlands were bordered by nearly flat or gently sloping alluvium, the associated upland ecotones constituted broad, distinctive habitats occupied by both salt-tolerant and upland plant species and flooded by only the highest tides. While these areas were among the earliest and most heavily impacted South Bay habitats, recent historical research by SFEI and botanist Peter Baye has reconstructed some of their characteristics. Summary illustrations of this spatial pattern are presented in Figures 28 and 29, with some details described below.

Historical sources document a common zone of salt grass *(Distichlis)* and native composites occupying the upper edge of tidal inundation. In fact, the habitat was often noted precisely because of its transitional nature, which made it difficult to determine if these lands should be classified as part of the tidal waters of the Bay (and thus subject to public trust). Surveyor Westdahl (1897) did not map this zone as tidal marsh but reported that "The debatable area immediately adjoining the Salt-marsh, which is sometimes covered at high tides, is used for pasture." When botanist Cooper (1926) interviewed longtime local resident GF Beardsley about the Santa Clara Valley in the vicinity of Palo Alto to Mountain View circa 1870, he described the same area above the *Salicornia*-dominated marsh plain and the salinas:

> "The saltmarsh region. First there was the great salt marsh, with all its winding sloughs and creeks, covered with samphire grass [Salicornia] and tufts of Grindelia; next was a line of natural salt pan; next again was a strip of land of varying width, from a few hundred yards to one fourth mile, with a short wiry hard grass [Distichlis] and a plant (composite) growing from six to 15 inches high, densely covered with short leaves…"

Description of a South Bay tidal marsh-vernal pool-alkali ecotone, 1895:

"Plants collected beside the RR track between Newark and the Drawbridges, Alameda Co. This is a level (marshy) country bordering the marshes (with a good deal of alkaline soil about apparently). This stretch of about 8 miles is the richest in flowers of the whole 52 miles from Alameda mole to San Jose and shows how gorgeous the whole plain bordering the marshes probably was before the introduction of foreign weeds and the grazing of cattle and horses . . . [t]he general impression in color is a mass of yellow owing to the abundance of *Lasthenia* and *Blepharipappus* though in places this gives way to masses of green and white of *Trifolium fucatum*. In places the yellow is dotted with the white heads of *Trifolium wormskioldii lehm.* in pools of large size…" (Davy 1895)

Testimony by local farmers in the Berryessa land grant case documents conditions further east, between Coyote Creek and Guadalupe River, several decades earlier. They describe a zone of similarly intermediate characteristics, comprising "marshy land" with "nothing but salt grass," extending all the way to the Milpitas-Alviso Road (approximately present-day Highway 237) and above the road in places (SFEI 1999). In this area, the transitional salt grass zone was 1000 m or more in width.

The salt grass zone integrated into a varied array of seasonal wetlands habitats, including vernal pools and alkali marshes, and moist grasslands. Early botanical descriptions illustrate diverse plant communities only present in small, partial form today, including many locally rare or extirpated species (Baye et al. 2000). Most tidal marsh-upland ecotones have been converted to steep elevational gradients, but there are several remaining areas in the South Bay with some remaining potential for low-gradient tidal-upland transitional zones. These include relatively large areas at Coyote Hills and Warm Springs and smaller areas in the vicinity of the San Jose/Santa Clara Water Pollution Control Plant, the Sunnyvale Water Pollution Control Plant (Figure 5a), and Moffett Field.

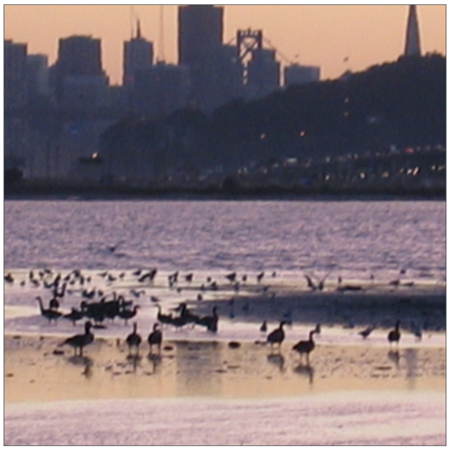
Figure 5a: Residual marsh-upland ecotone in Sunnyvale. This site occupies the historical transitional salt grass-dominated zone at the upper edge of tidal inundation. The high marsh salinas zone was located at the right of the image, where a levee and channel have since been constructed. Prior to diking, this area would have been overflowed with salt water during extreme high tides. Before ditching and draining of the alluvial plain, it would also have been subject to a high groundwater table and seasonal ponding. Residual soil salinity and low-gradient topography still maintain a gradual transition between salt-tolerant and upland plant species.


Salina with water.


Dry salina.


Tidal marsh-upland ecotone with salt grass.zone.


Sandy beach.


Tidal flat.


Marsh panne.


Marsh plain.


Tidal marsh-sausal ecotone.

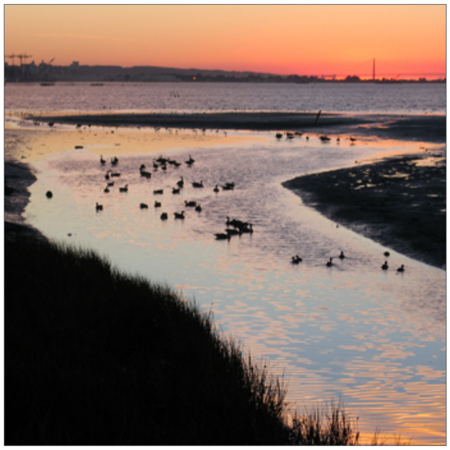

Tidal channel and flat.

Figure 5b: Examples of tidal marsh habitat elements in a recently developed marsh. Tidal channels, an aggrading creek mouth, tidal flats, salinas, marsh pannes, marsh plain, beach, and sausal are all evident at or near the Emeryville Crescent in Central Bay. Although the tidal marsh is too small to sustain a complex channel network indicative of larger areas of marshland, and although the individual patches of other habitat types are also rather small, the site as a whole sustains a complex mosaic that benefits many wildlife species. These habitats all formed within the past 75 years.

Salt Ponds

Salt ponds are large, persistent, saline impoundments of estuarine water that are managed primarily for salt production. The largest historic salt pond, called Crystal Pond on historical maps, extended over 1,000 acres along the eastern shore of South Bay, near present-day Hayward (Figure 3), and was used for salt production by the Yrgin Ohlone. It is possible that other salt ponds existed along the western shore of North Bay near historical Hamilton Air Base, where large ponds are documented by historical maps. These ponds may have been used by the Coast Miwok for waterfowl hunting as well as salt production. These early ponds were probably developed from salinas and marsh pannes by using low berms and weirs to control their hydroperiods. The Spanish and Californios continued salt production in South Bay by modifying natural salinas and pannes (Ver Planck 1958; Brown 1960). The template for salt production during its earlier stage of development after Euro-American contact was largely consistent with the natural distribution of salinas and marsh pannes.

In the mid-1800s, as the commercial and industrial demand for salt rose, there were extensions and improvements of naturalistic salt ponds, plus the additional development of entirely artificial ponds. Artificial salt ponds eventually encompassed their more natural forerunners. Very few examples of the more naturalistic salt ponds remain.

Tidal Flats

Tidal flats represent a dynamic equilibrium between inorganic sediment supply and the erosive energy of waves and tidal currents. They form where these energies and the duration of tidal inundation inhibit most vascular plant growth but promote the deposition of inorganic sediments.

Tidal flats are conventionally defined as the areas of bare clay and silt, sand, or shell hash between local Mean Lower Low Water (MLLW) and either the foreshore of tidal marshland or, if no marsh is present, local Mean Tide Level (MTL). Tidal flats support less than 10 percent cover of vascular vegetation, other than eelgrass. Mudflats of silt and clays comprised the largest type of tidal flats. Most of the flats occurred around the main bays of the estuary, but a significant portion was associated with shallow tidal channels that extended landward from the bays into marshlands and local watersheds.

The distribution of tidal flats within the estuary relates directly to tidal range, salinity regime, and nearshore bathymetry. Since the upper limit of tidal flats is determined by the lower limit of marsh vegetation, anything that affects the lower limit of vegetation also affects the lateral extent of tidal flats. Marsh vegetation grows as low in the intertidal zone as its tolerance to inundation will allow. In this regard, inundation threshold is a proxy term for maximum tolerable wave action, tidal currents, duration of inundation, and frequency of inundation, all of which could be influenced by turbidity, suspended sediment concentrations, and plant species. Tidal range within the estuary increases with distance south from the Golden Gate (Malamud-Roam 2000, Collins 2002), whereas the low tide datums remain relatively constant. This means that the difference in elevation between the MLLW datum and either MTL or the marsh foreshore increases with distance south from the Golden Gate. Therefore, the potential lateral extent of tidal flats also tends to increase with distance into South Bay. Whether or not the potential is realized depends on sediment supply and the other factors that control tidal flat formation and persistence. Northward and eastward from the Golden Gate, tidal range within the estuary tends to decrease, mainly due to increases in the low tidal datums. This decreases the difference in elevation between MLLW and MTL, and thus narrows the potential lateral extent of tidal flats. Furthermore, foreshore vegetation grows lower under fresher conditions (Harvey et al. 1977, Atwater and Hedel 1976, Jones and Stokes et al. 1979, Collins 2002). This reduces the difference in elevation between MLLW and the foreshore, which further restricts the lateral extent of tidal flats. For any tidal range and salinity regime, the extent of tidal flat is constrained by the slope of the intertidal zone. Steeper zones have less tidal flat. These factors help explain the relative abundance of tidal flats around the broad and saline South Bay and North Bay, the paucity of tidal flats in the much fresher Suisun, and the small patches of tidal flat in the steep areas of brackish Carquinez Strait and saline Central Bay.

Seasonal variations around the average conditions have been noted. For example, during the wet season, when suspended sediment supplies to the Bay increase sharply (Schoellhamer, 1996), mudflats can gain elevation and grow some distance into the Bay, depending on their overall slope. During the subsequent summer and fall, the flats can lose elevation (Nichols 1977, Nichols 1979; Thompson 1982), due to re-suspension of sediments by wind-generated waves (Krone 1979; Cloern et al. 1989). The slow rate of change in tidal flat distribution over many years (Foxgrover et al. 2004) suggests that the seasonal gains and losses are roughly compensatory. Little is known about seasonal variations in tidal flats along the sloughs and creeks that innervate tidal marshland. Since these flats are more protected from wave action, they may be more persistent.

Beaches

Beaches are created by waves or tidal currents depositing sand or shell hash across the intertidal zone. On sandy beaches, most of the water coming in on each wave is shed back to the bay as backwash. This serves to flatten the slope of the beach. Shell hash is coarser than sand, more resistant to erosion, and also allows more percolation, all of which reduces the erosive power of the backwash. Beaches of shell hash therefore tend to be steeper than sandy beaches (Bascom 1980). Beaches may erode when wave energies increase, as during major storms, and their maintenance requires an ongoing supply of beach material.

The San Francisco Estuary historically included about 25 miles of beaches. They were most common in the Central Bay, especially along the northern end of the San Francisco Peninsula, where they were nurtured by sand dunes and the littoral drift inside the Golden Gate. They were also common along the present-day Alameda and Oakland shorelines, within reach of the Merrit Sands of the San Antonio Formation, and along the eastern shore opposite the Golden Gate and at the end of the San Pablo Bay fetch, where wave energies are adequate to carry sands from the shallow subtidal zone to the middle intertidal elevations. Sandy beaches existed on both sides of South Bay, in the vicinity of Coyote Point and present-day San Leandro. Beaches of shell hash, mostly derived from native oyster beds, were fairly common on both sides of South Bay north of the Dumbarton narrows.

Lagoons

A lagoon is a perennial impoundment of water that is subject to occasional or episodic connection to full or muted tidal action. The impoundment receives inputs of freshwater through creeks, seeps, or springs. When the tidal connection is closed, a lagoon can become brackish as freshwater accumulates. Large lagoons may become meromictic, with a lower layer of saline water and a fresher upper layer that do not mix. Historical lagoons typically formed behind barrier beaches and therefore had a similar distribution as beaches in the region, except that no lagoons are known to have existed in South Bay. Early maps suggest that overwash berms (Cohn and Kochel 1993) tended to form along the foreshores of marshland perpendicular to long fetches, and that marsh pannes or salinas could form behind such berms (see descriptions of salinas and marsh pannes on page 27). These impoundments were more shallow and temporary than lagoons.

Shallow Bays, Deep Bays, and Subtidal Channels

Shallow bays consist of the benthic sediments and the column of water extending between MLLW (zero tidal elevation) and the minus 18-foot bathymetric contour. The shallow bay sediments are mainly clays, silts, sands, and shell hash, the latter being largely restricted to South Bay (Nichols and Pamatmat 1988). Excluding the intertidal zone, about 65% of the aerial extent of the estuary corresponds to shallow bay. The very large area of shallow bay is a distinguishing characteristic of the San Francisco Estuary and significantly influences its patterns of water circulation (Smith 1987, Cheng et al. 1993, Walters et al. 1985).

Deep bay consists of the benthic sediments and the column of water extending between the minus 18-foot bathymetric contour and the deepest reaches of the estuary. Only about 35% of the aerial extent of the estuary bayward of the intertidal zone corresponds to deep bay. The sediments of deep bay vary from bedrock to coarse sands and very fine clays and silts. In the parts of the Bay where currents are strong, especially in the deeper reaches of San Pablo Bay and Central Bay, the bottom is mostly coarse sand. Prominent sand waves are evident in Raccoon Strait and across Central Bay (http://wrgis.wr.usgs.gov/dds/dds-55/pacmaps/sf_shade.htm). In Suisun Bay and South Bay, however, most of the bottom consists of a muddy mixture of more than 80% silt and clay (Nichols and Thompson 1985).

Shallow bay channels link the larger intertidal sloughs and local creeks to deep bay channels. The channels of the deep bay trace the courses of ancient rivers that drained through the Golden Gate before it was transgressed by the rising sea. The shallow channels were historically maintained in part by the tidal prism of the intertidal zone, including the historical tidal marshlands. The deeper channels are maintained by the larger tidal prism of the bays. Tidal currents are strongest in the deep channels (Cheng and Gartner 1984). The shallow and deep channels together represent critical physical and ecological linkages between local watersheds and deep bay environments.

Tidal Marshland

Tidal marshes are defined as intertidal areas that support at least 10% cover of vascular vegetation adapted to intertidal conditions. The lower marsh edge is called the foreshore, and the high edge against the uplands is called the backshore. Salinas, marsh plains, marsh pannes, and drainage networks are characteristic features or habitat elements of tidal marshland (Figure 5b). These habitat features vary in size, shape, and extent according to marsh age, size, hydraulic gradient, and salinity.

It is generally accepted that tidal marshes in the Bay Area evolve from tidal flats due to colonization by vascular plants (Byrne et al. 2001, Malamud-Roam 2000, Freidrichs and Perry 2001, Williams and Orr 2002). The ancient marshes began developing along the shore of the young estuary about 3,000 years BP, after the rate of sea level rise slowed sufficiently to allow intertidal vegetation to colonize and persist (Atwater et al. 1979). Most of the historical bay-shore adjoined broad areas of shallow bay not subject to great storm surges or very high wave energies, and thus suitable for the formation of retentive environments including tidal flats and marshes (Malamud-Roam 2000). At the time of Euro-American contact, the open bays of the estuary were nearly surrounded by very broad expanses of tidal flats and even broader expanses of tidal marsh (Goals Project 1999). Local watersheds make important contributions of inorganic sediment to the maintenance of tidal flats and formation of marshes (Knebel et al. 1977, Collins 2001, Malamud-Roam 2004, McKee et al. 2003, and see section on increased fluvial-tidal connectivity in Part III on page 53). The relative importance of open bays and local watersheds as sediment sources for intertidal environments probably increases with distance landward along the tidal reaches of local watersheds.

The evolution of tidal marshland from tidal flats may be rapid, as when a diked area of suitable elevation for plant colonization is breached, or more gradual, as when interactions between plants and wave regimes along the bayshore adjust the local sedimentary environment in favor of deposition and retention (USACE 1984, PWA and Faber 2004). Core data from natural marshes indicate that conversion from natural tidal flat to tidal marsh is iterative and generally slow (Byrne et al. 2001), which further indicates that the historical foreshore of marshland was generally in equilibrium with sediment supply, and thus sediment-limited. Eroding foreshores and prograding foreshores are both evident on the historical topographic sheets of the first US Coast Survey of the estuary (1850-66), which predate much land use change. But whether these waxes and wanes of the shoreline were compensatory, or if a net change was occurring has not been determined.

Marsh Channels

Tidal marsh channels are more studied than any other element of tidal marsh habitat. Studies in the Bay Area have focused on the nature of tidal channel formation (Fagherazzi et al. 2004, Kamman Hydrology and Engineering 2004, Siegel 2002), especially with regard to critical sheer stress (Pestrong 1965, Pestrong 1969, Pestrong 1972).

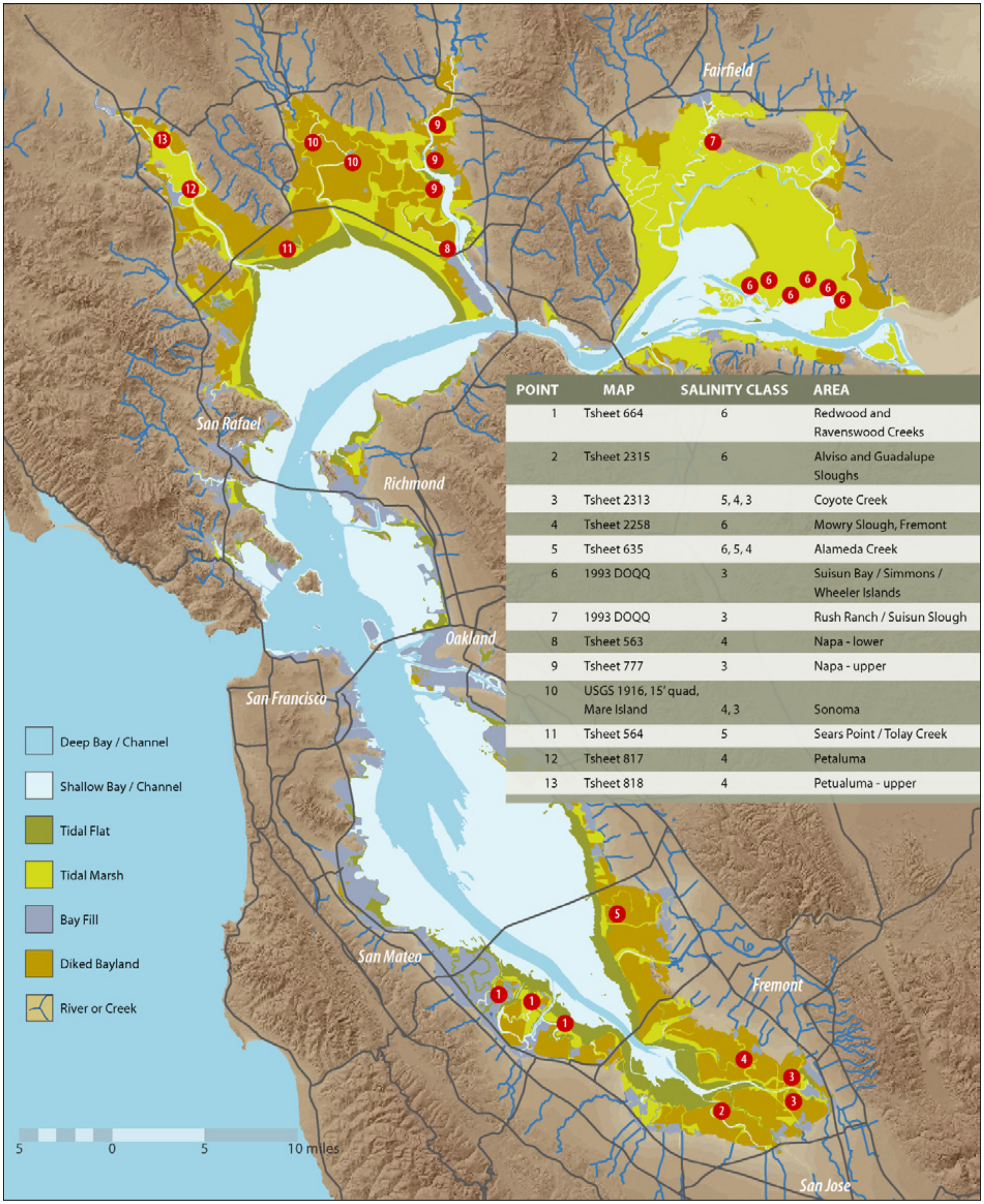
Studies from outside the region suggest that the larger channels on tidal flats become fixed in place as their natural levees or banks become colonized by vascular plants (Beeftink and Rozema 1988). For any salinity regime the density of channels decreases as the marsh plain evolves upward through the tidal range (Ahnert 1960, Steel and Pye 1997). Higher marshes obviously have less water to drain, and channel networks tend to adjust in capacity to changes in tidal prism.

Tidal marsh size can be quantified by drainage order (Leopold et al. 1984, Leopold et al. 1993, Myrick and Leopold 1963; Friedrichs 1995, Meredith 2004) as well as aerial extent. Tidal marsh channels tend to be very sinuous and often comprise complex dendritic networks (Rinaldo et al. 1999a, Fagherazzi and Furbish 2001). Drainage order is determined by the amount of branching of the marsh channel network. An unbranched channel is termed first-order. The confluence of two or more unbranched channels forms the start of a second-order drainage network. The confluence of two or more second-order channels forms the start of a third-order network, and so forth. The largest tidal marsh systems in the region were sixth-order. There were sixth-order systems in all the major subregions except Central Bay, where marsh size is more limited by topography.

Considerable work has been done on the hydraulic geometry of tidal channels, meaning the relationship between tidal prism or drainage area and channel form in cross-section, profile, and plan view, usually in the context of designing channels for restoration projects (e.g., Collins et al. 1987, Collins and Orr 1988, Collins 1991, Coates et al. 1989, PWA 1995, Siegel 1993). The typical log-log plots of hydraulic geometry reveal large variability around trends of increasing cross-section with tidal prism. The variability may be due in part to the pooling of data for restoration projects and remnant natural systems varying in developmental stage or response to hydro-modification. The dataset also under-represents fresh and brackish marshes and the largest (sixth-order) and smallest (first-order) systems in the region.

For the systems studied, the results indicate that channels with base elevations above low tide gain cross-sectional area in the downstream direction due mainly to increases in depth. Further downstream, where base elevations are below low tide, the gains in area are mainly due to increases in channel width. In general, the larger channels (fourth- and fifth-order) are V-shaped in cross-section and seldom dewater during ebb tide, whereas the smaller channels (third-order and smaller) are U-shaped and usually dewater completely (Collins et al 1987). The cross-sectional form of the high-order channels is complicated by slump blocks that occur on the outside of meanders and along both banks of straight reaches (Collins et al. 1987, Fagherazzi et al. 2004). The transition in cross-sectional form and downstream hydraulic geometry between third- and fourth-order channels seems to coincide with the transition from channels that evolved with the marsh plain to antecedent channels that evolved on the predecessor mudflat.

The relationships between plan form geometry and channel order has been examined across salinity regimes ranging from very saline in far South Bay to fresh-brackish at the eastern end of Suisun (Figure 6). Channel width, curvature, wavelength, amplitude, and confluence angle were measured for marsh islands in equilibrium conditions based on topographic sheets (scale 1:10,000) of the first Coast Survey for saline and brackish-saline conditions, digital color IR imagery of 2-m minimum pixel resolution for fresh- brackish conditions (i.e., Rush Ranch and Browns Island), and standard Digital Orthogonal Quarter Quads (DOQQs) for some channel networks captured by historical reclamation projects in eastern Suisun (Pearce and Collins 2004). Channel width, curvature, and wavelength tend to increase progressively from first- to sixth-order channels, although there is much variability for each channel order (Figures 7-9). These parameters do not seem to be affected by salinity regime. For each channel order, however, meander amplitude is greatest under the freshest conditions (Figure 10). Channel density for marsh islands (sensu Novakowski et al.



POINT	MAP	SALINITY CLASS	AREA
1	Tsheet 664	6	Redwood and Ravenswood Creeks
2	Tsheet 2315	6	Alviso and Guadalupe Sloughs
3	Tsheet 2313	5, 4, 3	Coyote Creek
4	Tsheet 2258	6	Mowry Slough, Fremont
5	Tsheet 635	6, 5, 4	Alameda Creek
6	1993 DOQQ	3	Suisun Bay / Simmons / Wheeler Islands
7	1993 DOQQ	3	Rush Ranch / Suisun Slough
8	Tsheet 563	4	Napa - lower
9	Tsheet 777	3	Napa - upper
10	USGS 1916, 15' quad, Mare Island	4, 3	Sonoma
11	Tsheet 564	5	Sears Point / Tolay Creek
12	Tsheet 817	4	Petaluma
13	Tsheet 818	4	Petualuma - upper

Figure 6: Reference materials and locations of reference site for the analyses of the plan form geometry of tidal marshland, as developed for this report. Data development was restricted to intact drainage networks, as evidenced by historical maps and aerial photos, that together represent a broad range of salinity from fresh-brackish to very saline (salinity classes 3-6 based on Figure 2). In Suisun, data were developed from Digital Orthogonal Quarter Quadrangles (DOQQs) that clearly show channel networks as they were historically preserved by diking in the mid 1800s.

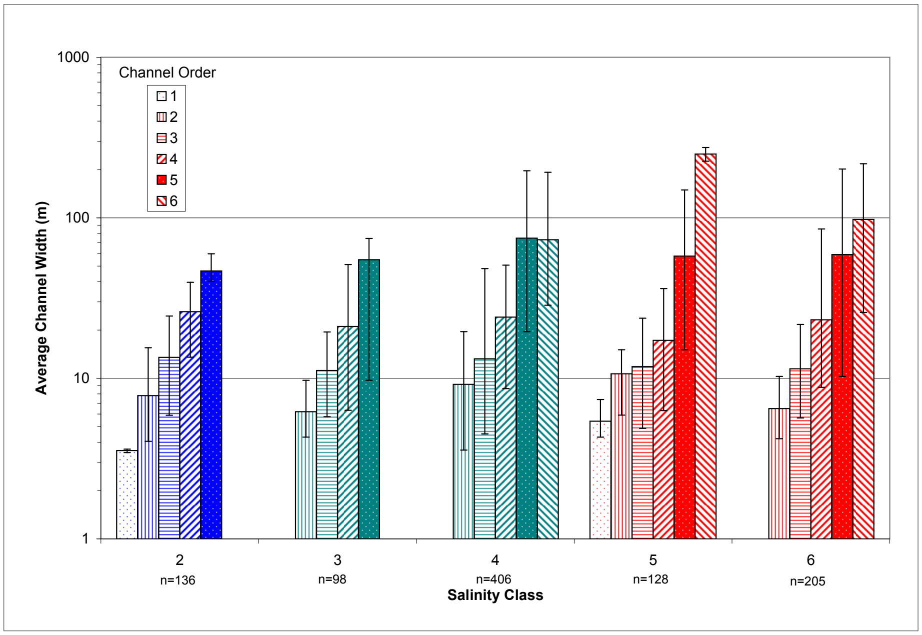


Figure 7: Plot of tidal marsh channel width as a function of aqueous salinity regime for channel orders 1-6, as developed for this report. Width increases with channel order similarly for salinity classes 2-6.

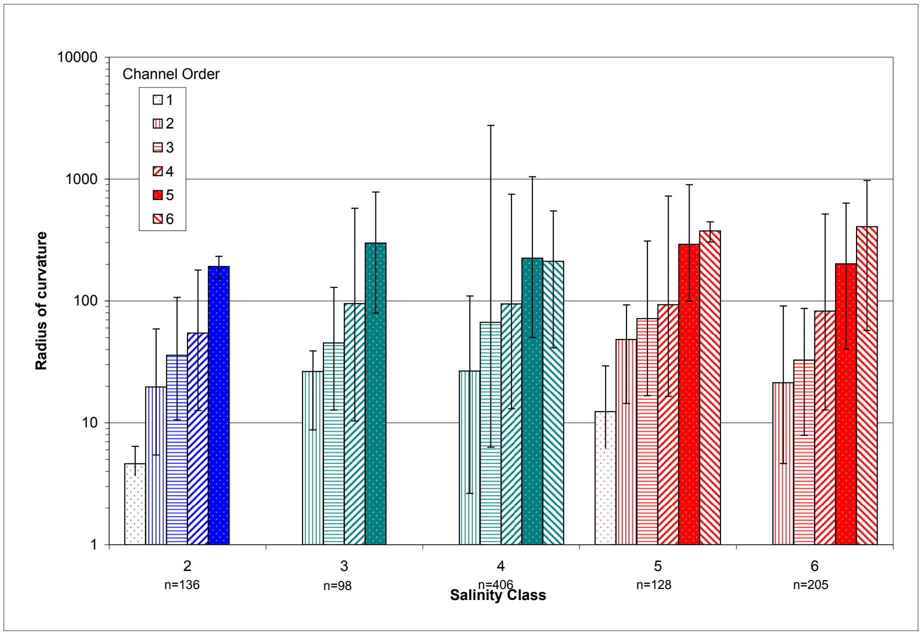


Figure 8: Plot of the radius of curvature of tidal marsh channels as a function of aqueous salinity regime for channel orders 1-6, as developed for this report. Radius of curvature increases with channel order similarly for salinity classes 3-6. First-order channels have less curvature for salinity class 2 than for other salinity classes.

2004) is strongly correlated to island area (Figure 11), and tends to increase from fresh-brackish to saline conditions (Figure 12). Drainage area also tends to be greatest under fresher conditions, especially for the larger channel orders (Figure 13). The angle of confluence between tidal marsh channels is similar for all channel orders and salinity regimes. For about 60% of the 160 confluences examined, tributaries enter within 30 degrees of the point of maximum curvature of a meander on the receiving channels, and essentially all of the tributaries enter within 60 degrees of the point of maximum curvature.

A few studies in this region have focused on tidal flow through marsh channels (Leopold et al 1993, Siegel 1993, Warner et al. in press, Fagherazzi et al. 2004). A central question emerging about tidal marsh channels is whether they are flood- or ebb-dominated. The form of a tidal marsh channel in cross-section, profile, or plan view, and the net direction of sediment transport by channel apparently depend largely on the direction of dominant flow, although sediment grain size, vegetation types, and the bathymetry outside of the channel system are also important (Rinaldo et al. 1999b). It is generally accepted that daily velocity maxima correspond to the channel-forming flows (Rinaldo et al. 1999b). Flood-dominance means maximum flood velocities exceed maximum ebb velocities, and ebb-dominance means ebb velocity maxima are greater (Dyer 1965). The net direction of sediment transport tends to be downstream under ebb-dominance, and upstream or landward under flood-dominance (Dyer 1965). Ebb dominance also causes point bars in the channel to be skewed toward the inner margins of meanders (Barwis 1978). The direction of the dominant flow is also evident as meander asymmetry in plan view. The point of maximum curvature of an ebb-dominated meander is closer to the upstream inflection point, and the maximum curvature is closer to the downstream inflection of a flood-dominated meander (Fagherazzi et al. 2004).

A channel system may consist of both flood-dominated reaches and ebb-dominated reaches. For larger channel networks, there may be a shift from flood-dominance to ebb dominance with distance upstream from the tidal source (Fagherazzi et al. 2004). In large tidal marsh systems, the shift seems to coincide to the transition from fourth- to third-order channels. Looking upstream from this transition, the cross-sectional form of the typical channel changes from V-shaped to U-shaped, and depth decreases faster than width (Collins et al. 1986). There is a shift from channels that don't dewater to ones that do (Collins et al. 1987, Lanzoni and Seminara 1998, Rinaldo et al. 1999b). And ebb-velocities are greater than flood velocities (Leopold et al. 1993). Data for a long natural tidal channel in Petaluma Marsh indicate that the high tide datums are rather flat until the transition from fourth- to third-order, whence they slope downward in the headward direction (Figure 14). Both slopes steepen as they enter small-order channels, although the MHHW datum slopes less than the MHW datum (Figure 14). All of this suggests that the effect of channel friction on flow increases in the headward direction, especially after the transition from fourth- to third-order.

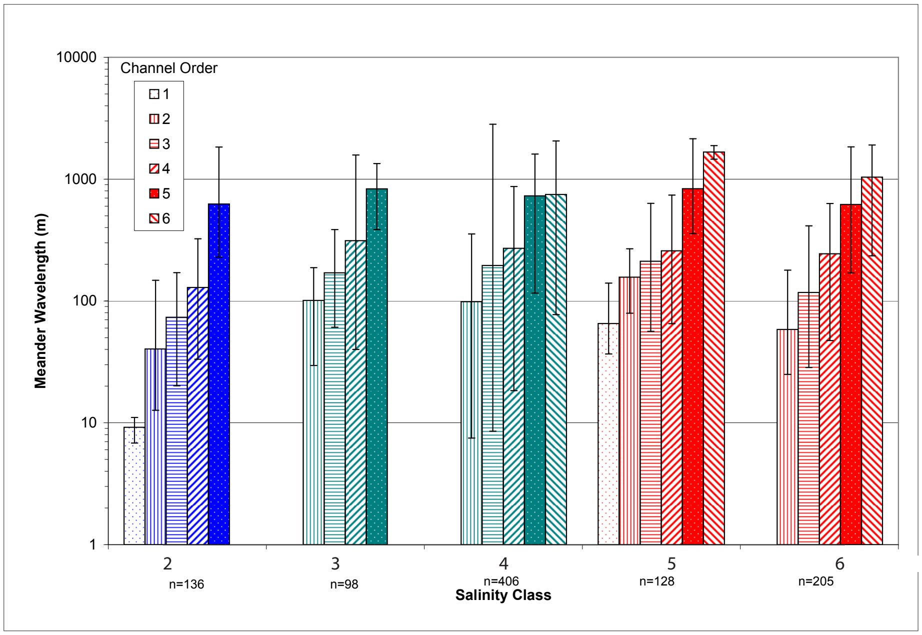


Figure 9: Plot of tidal marsh channel meander wavelength as a function of aqueous salinity regime for channel orders 1-6, as developed for this report. Wavelength increases with channel order similarly for salinity classes 3-6. First-order channels have shorter wavelengths for at salinity class 2 than for other salinity classes.

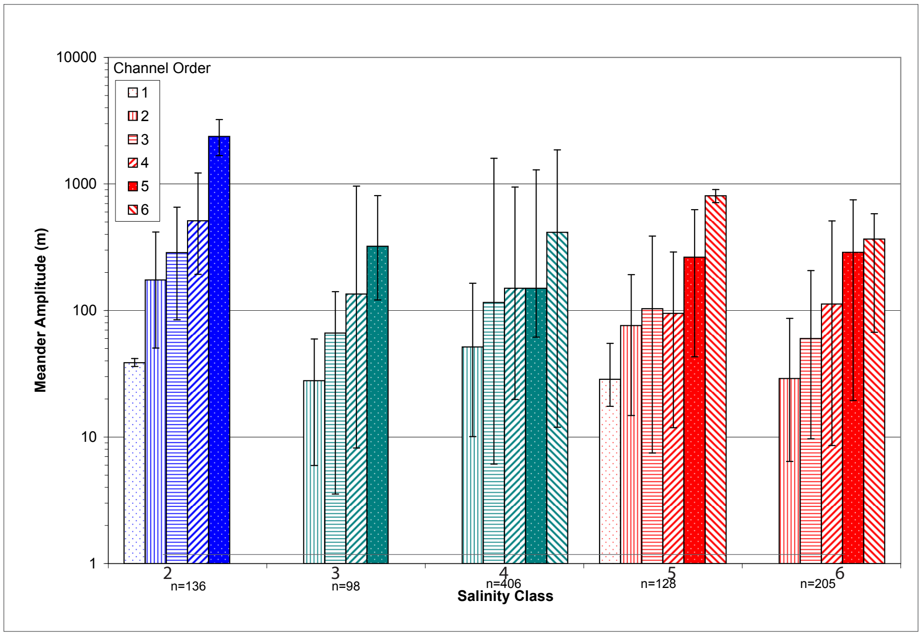


Figure 10: Plot of tidal marsh channel meander amplitude as a function of aqueous salinity regime for channel orders 1-6, as developed for this report. Amplitude increases with channel order similarly for salinity classes 3-6. For all channel orders investigated, amplitude is greater for salinity class 2 than for other salinity classes.

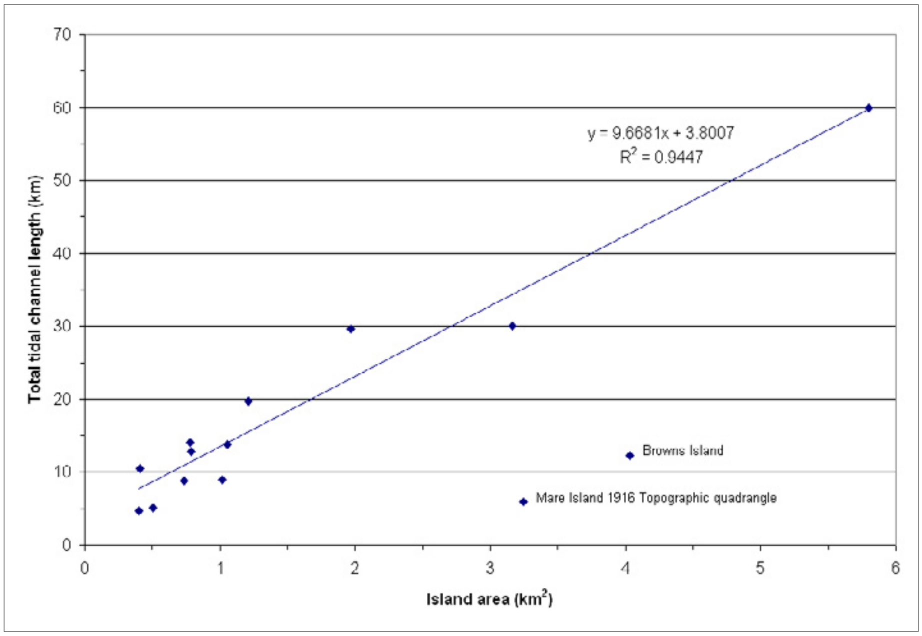


Figure 11: Plot of total tidal marsh channel length as a function of the area of tidal marsh island, regardless of salinity regime, as developed for this report. A marsh island is defined as an intact tidal drainage network surrounded by open water or uplands. A sixth-order tidal channel, as well as tidal flats and bays, is considered to represent open water. A network that shares a high marsh plain with another neighboring network is not considered to be an island. A number of neighboring networks that share some amount of tidal marsh plain as common drainage divides might collectively comprise an island if together they are bordered by upland or open water.

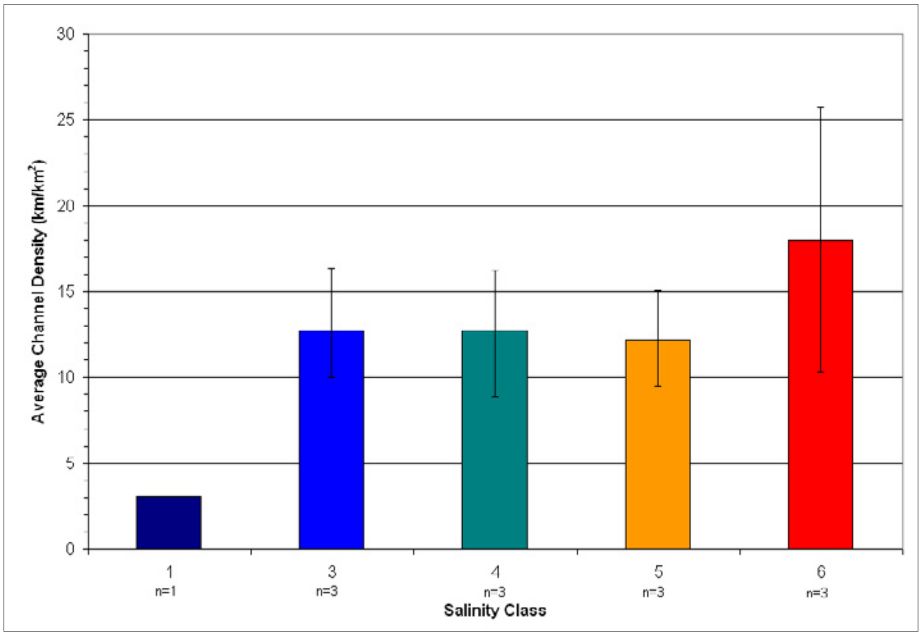


Figure 12: Plot of channel density (total length of channel per unit area of marsh island) as a function of aqueous salinity regime, as developed for this report. See caption for Figure 11 for a definition of marsh island. Channel density is similar across the middle salinity classes (i.e., classes 3-5). It is significantly greater for the most saline conditions (salinity class 6), and significantly less for the freshest condition (salinity class 1).

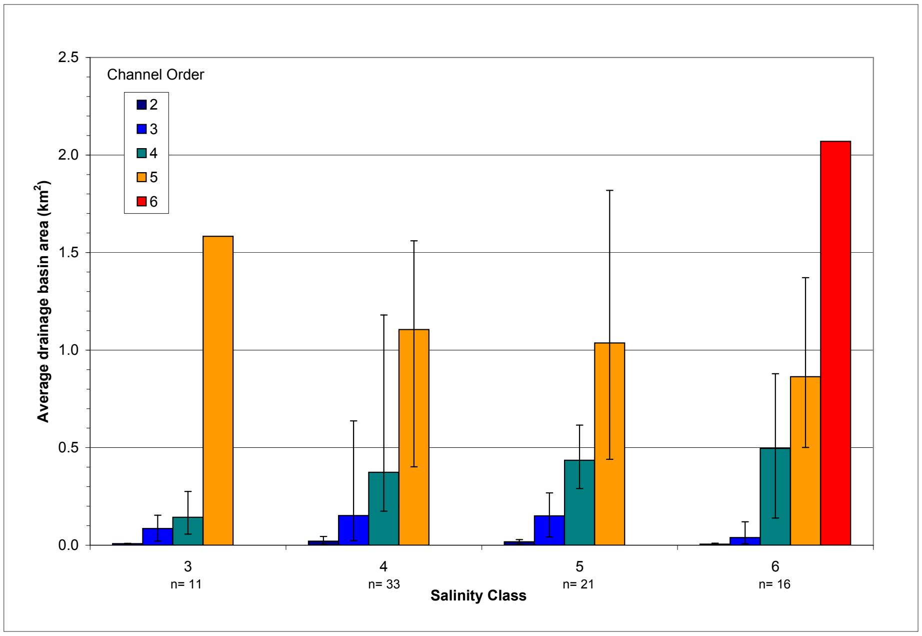


Figure 13: Plot of the drainage area of tidal marsh channels in relation to aqueous salinity regime for South Bay, as developed for this report. Evidence for fresher condition (salinity classes 1 and 2) are not available yet. Data were developed from historical topographic sheets of the First Coast Survey for South Bay (see Figure 6). To focus on a broad range of channel order, drainage areas smaller than any marsh islands (see caption for Figure 11) had to be included. Calculations of drainage area required subjectively drawing drainage divides midway between neighboring channel networks. For the sake of time and expense, the small drainage areas of first-order channels were excluded from the analysis. The relationship between channel order and drainage area is essentially the same for salinity classes 4 –6. Sixth-order systems were only represented for very saline conditions (salinity class 6), but it could be assumed that drainage area would be similar for sixth-order systems in salinity classes 4 and 5. For fourth-order systems, drainage area is apparently much larger for salinity class 3 than for the more saline classes.

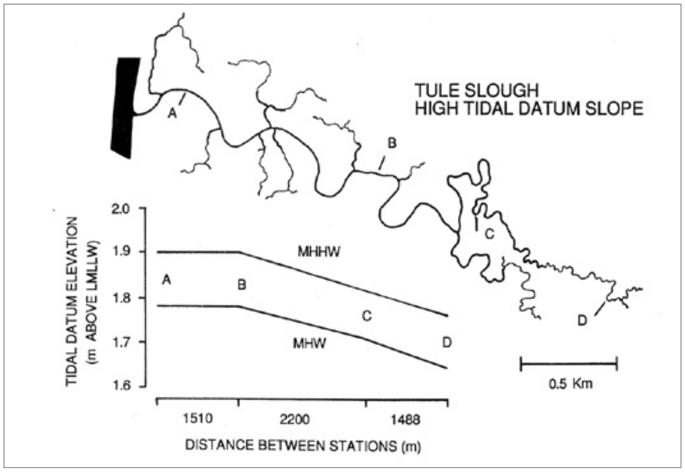


Figure 14: Slope of the high tidal datums along Tule Slough in Petaluma Marsh. Data from Leopold et al. 1993. Tide gauges were maintained for five months at four locations from the mouth to the headward end of the mainstem channel. Mean Higher High Water (MHHW) and Mean High Water (MHW) were reckoned for each station, with reference to the NOAA gauge at Lakeville, across the Petaluma River from the mouth station. Station data were referenced to a common relative datum by the California State Lands Commission with a total closure error of less than 3 mm between any two stations. The downward slopes of the datums increase upstream with each change in channel order, from fourth- to first-order. The higher datum slopes less than the lower datum, presumably because it represents a greater volume of flood flow and hence greater momentum to overcome the friction of the channel.

Whether a channel is flood- or ebb-dominated may depend on the bathymetry outside the channel and the cross-sectional area of the channel mouth, as mediated by vegetation, which relates to tidal range and salinity. Flood-dominant estuaries tend to have small areas of tidal flats; ebb-dominated estuaries tend to have more extensive regions of flats and marshes (Friedrichs and Aubrey 1988, Speer et al. 1991). As an estuary fills, it can therefore shift from flood-dominance to ebb-dominance (Boon and Byrne 1981). In systems in which basin infilling is not advanced or where systematic dredging sustains depth, flood dominance might persist in low-order channels of the tidal marsh network, while ebb-dominance exists in the deeper, high-order channels (Wright et al. 1973). The data from Petaluma Marsh (Figure 14) are consistent with this expectation.

However, some mainstem channels of medium to large–order networks vary little in width over their entire length. How depth varies along these channels is not known, but it might be supposed because of their high order that depth varies little. The headward ends of these channels tend to widen abruptly. In the few cases investigated, the terminal widening appears to be part of the channel, rather than a panne or other topographic low captured by channel migration or headward erosion. Tidal stage has been monitored along one such channel in the fresh-brackish marshland of Browns Island, and the data suggest amplification of the tidal range at the headward end (Siegel 2004). Whether or not the terminal jump in tidal range is a sign of flood-dominance, and how the jump might relate to the abrupt terminal widening are not known.

Amplified tidal ranges have been observed within zones of barotropic convergence, where the flood flow from two sources is combined (Collins et al. 1987, Warner et al. in press). This happens along the middle reaches of a "looped" channel that is open at both ends to tidal inflow. The amplification is due to increases in high tide, rather than decreases in low tide. The convergence happens within an elongated zone rather than a point because of the diurnal inequality of the high tide. If sediment supplies are great enough, the suspended load that is deposited in the convergence zone can lead to division of the channel into two drainage systems with independent tidal sources (Collins et al. 1987).

Few studies have examined the transport of sediment in tidal marsh channels. A single longitudinal profile of depth-integrated suspended sediment in a large (fifth-order) dendritic system during a flood tide that did not exceed the channel banks revealed a decrease in turbulence, an increase in stratified flow, and a decrease in overall suspended sediment concentration in the upstream direction (Figure 15). It also showed that sediment settled from the upper layers of water, and that the network with its "hanging tributary beds" served to decant the sediment, such that little sediment was carried into the most headward reaches of the drainage network or onto the marsh plain (Figure 16). This decanting may be promoted by a headward shift from flood-dominant flow to ebb-dominance at the transition from large- to small-order channels (see discussion above). The decanting process was used to explain the lack of levees in the headward reaches of marsh drainage systems (Collins et al. 1987, Leopold et al. 1993). Studies of sedi-

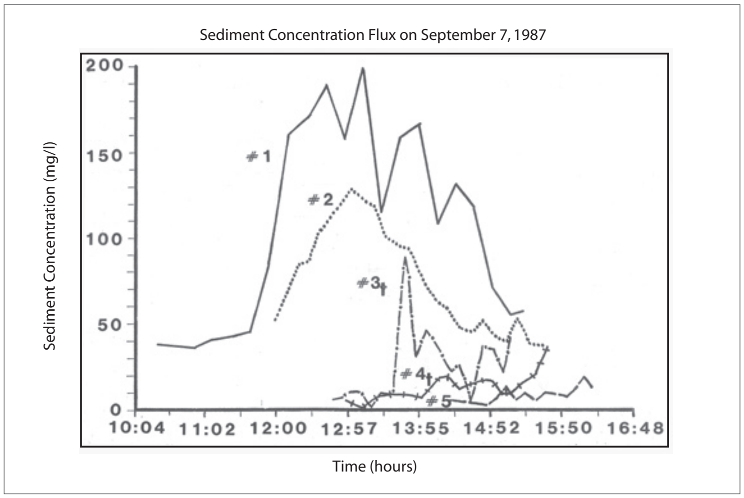


Figure 15: Plot of total suspended sediment concentration during a flood tide below bankfull stage at 5 stations along Tule Slough in Petaluma Marsh. Data provided by Josh Collins, SFEI. All measurements were integrated over depth by continuous manual sampling between the water surface and channel bottom at mid-channel on straight reaches. At the downstream and middle stations (stations 1-3), sediment concentrations increased as the tide rose, peaked during maximum flood velocity, and then decreased until slack high water. At the upstream stations (Stations 4 and 5), sediment concentration was maximized just before slack high water was achieved. It was observed that sediment settled from the upper layers of water as the flow became less turbulent upstream of station 3. Therefore, the upper layers of water that traveled upstream faster carried less sediment. By the time the sediment-laden water rose to the elevation of the hanging beds of the small-order channels, the tide was reversing to ebb flow downstream. Very little sediment every reached the headward end of the mainstem channel, and the sediment that had been deposited along the bed and banks downstream was re-suspended by the ebb flow and carried back out into the Petaluma River. No change in cross-sectional area was observed at any station over a period of years.

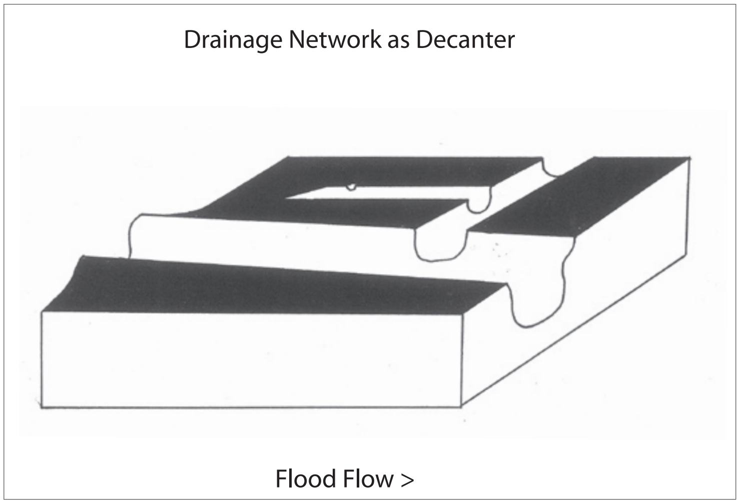


Figure 16: Tidal marsh drainage network as sediment decanter. In saline tidal marshlands, tributaries enter their receiving channels as hanging beds. As flood tides move upstream through the larger channels, flow becomes less turbulent and sediment settles from the upper layers of the water column. The upper layers of water that first enter a tributary carry less sediment than lower layers that enter later. As a result, most of the suspended sediment is retained within the high-order channels. Natural levees are therefore restricted to the downsteam reaches of the largest channels, where turbulence distributes sediment throughout the water column, and allows it to be deposited along the channel banks.

ment transport within a small third-order restored marsh in far North Bay revealed dynamic processes of net inflow and outflow depending on neap-spring differences in tidal amplitude at the channel mouths and the evolutionary stage of the marsh plain. During very early stages, when vegetation was scarce, channels variously formed and filled, until the marsh plain evolved upward to the threshold for plant colonization (Siegel 2002). This suggests that the direction of dominant flow may shift from flood to ebb as low-order marsh evolve from tidal flats.

Marsh Plain

As a tidal marsh matures, it gains elevation, its overall gradient flattens, its tidal prism decreases (Ahnert 1960, Redfield 1972), the total extent and cross-sectional area of its channels therefore eventually decrease (Steel and Pye 1997), the area of poorly drained marsh plain increases, and for saline or brackish marshes soil salinity on the plain probably also increases.

Studies of the physical nature of the tidal marsh plain have focused on sedimentary processes (Krone 1987, Collins et al. 1987, Culberson 2001, Callaway et al. 1996, Williams and Orr 2002, Siegel 2002, Watson 2004), including vertical accretion of tidal marshlands and its inland transgression during Holocene sea level rise (e.g., Byrne et al. 1994, Wells and Gorman 1994). During early stages of marsh formation, the upward development of the marsh plain can outpace sea level rise (Byrne et al. 1994, Byrne et al. 2001, Watson 2004). But as the marsh plain builds upward through the tidal range, the frequency and duration of inundation decrease, and the ability of the channel network to decant suspended sediment increases, such that less and less sediment is delivered to the marsh plain. As the plant cover becomes denser, it functions to filter sediment from the flows of water across the marsh plain, such that the inorganic sediment is trapped near the channel banks (Collins et al 1987, Culberson 2001, Eisma and Dilkema 1997). In advanced stages of tidal marsh development, inorganic sedimentation is largely restricted to areas within a few meters of the channel banks (Figure 17). In the middle reaches of very large drainage divides, organic matter accounts for most of the volume of the sediment pile, indicating very little input of inorganic sediment. Thus, the requirements of marshland for inorganic sediment to keep apace with sea level rise decreases with marsh age and, for well-developed marshland, with distance away from channels mouths and banks. Whether or not the zone of sediment entrapment varies in width with vegetation type is not known. But for well-developed salt marshes, the maximum width of the zone seems to be about 20 meters for larger channels, and 10 meters for smaller channels (Collins et al. 1987). In terms of soil bulk density, organic sediments comprise much of the mature marsh plain. These data can be used to generate a plan view of the approximate distribution of dominant sedimentary processes across the high plain of mature tidal marshland (Figure 18).

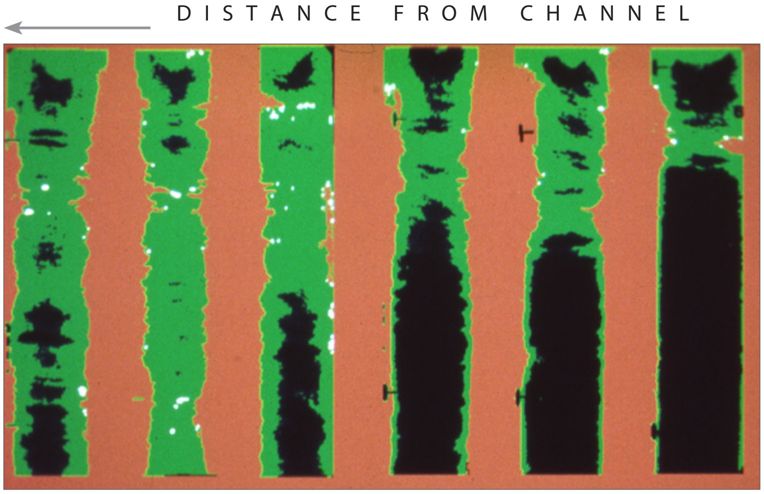


Figure 17: Colored x-ray pictures of shallow sediment cores taken along a transect from the immediate bank (right side of figure) to the nearest drainage divide (left side of figure) in a mature, high-elevation, fifth-order system in Petaluma Marsh. Data provided by Roger Byrne, Department of Geography, University of California at Berkeley. Dark areas in each core indicate abundant inorganic sediments (i.e., silt and clay). Green areas indicate organic sediment produced in-place (i.e., peat.). Cores are 5m apart and about 30cm deep. The amount of inorganic sediment decreases markedly with distance away from the channel bank.

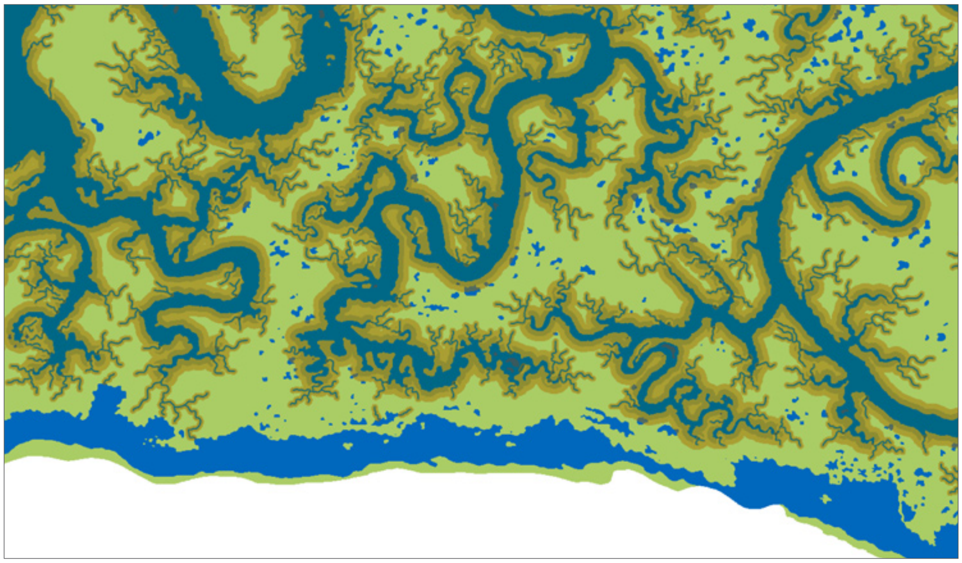


Figure 18: Plan view of the expected distribution of inorganic and organic sedimentary processes across a tidal marsh landscape. Deposition of inorganic sediment is largely confined to a zone within 20 m of large channels (fourth- to sixth-order) and within about 6 meters of smaller channels (third- to first-order). At places further from the channel banks, sedimentation is dominated by biological processes (i.e., the accumulation of plant litter and roots and peat). Marsh pannes and salinas are essentially restricted to the interior marsh plain away from inorganic sedimentation.

In the Bay Area, where most of the marshland seldom if ever receives large pulses of inorganic sediment, tidal marsh vertical accretion tends to achieve and maintain an equilibrium with sea level rise (Byrne et al. 2001). The oldest marshes have continued to

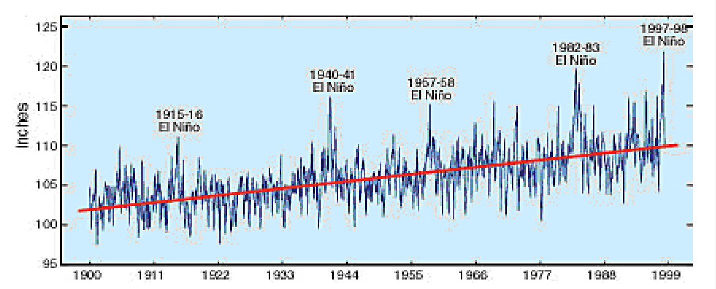


Figure 19: Sea level rise record from the tide gauge at Fort Point on the Golden Gate, showing annual and longer-term variability, punctuated by el nino events. Data from the National Oceanic and Atmospheric Association.

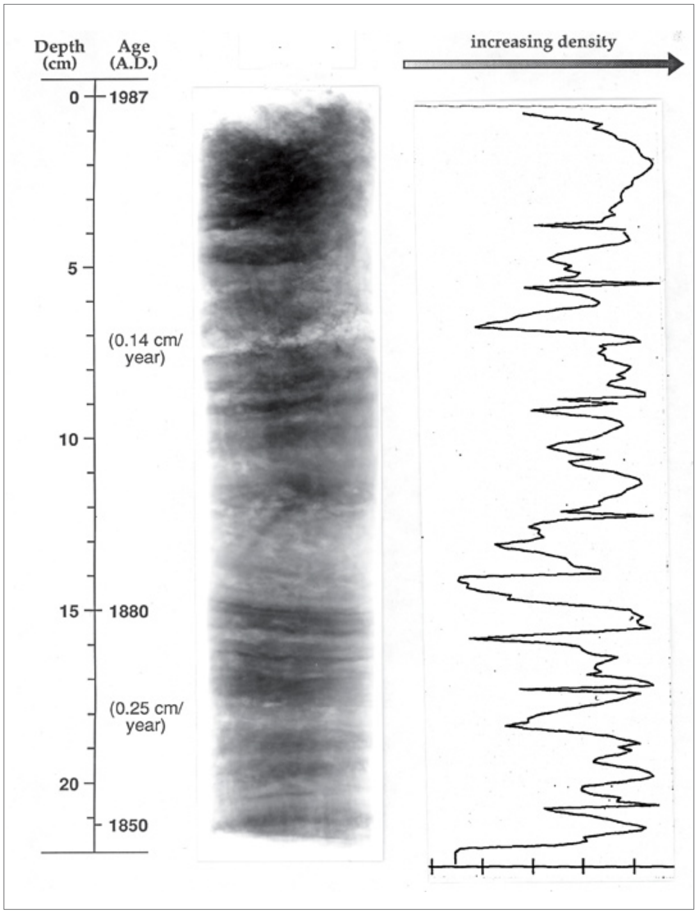


Figure 20: Display of Different Core Depths (1850-1987). Illustration of fine-scale variations in sedimentary processes near the drainage divide of a mature, high-elevation saline tidal marsh. Data provided by Roger Byrne, Department of Geography, University of California at Berkeley. Dark areas in the x-ray negative of the core indicate abundant inorganic sediments (i.e., silt and clay). Light areas indicate organic sediment produced in-place (i.e., peat.). Variations in density (right side of figure) reflects fine-scale layering of inorganic and organic sediments, over periods ranging from one to a few years. Parenthetic values along chronology (left side of figure) indicate sedimentation rates. Scale of chronology reflects sediment compression at depth (i.e., the amount of time represented per unit of core length increases with depth).

build upward at an average rate of about 2 mm per year since their maturity, which matches the average rate of sea level rise for the same period (Atwater et al. 1979, Byrne et al. 1994, Mudie 1975, Wells and Gorman 1994).

The rate of sea level rise and local supplies of sediment are not constant, however (Malamud-Roam et al. 2004). Very large deviations above and below the long-term rate of sea level rise can happen annually, and longer but smaller deviations are also evident (Figure 19), due to atmospheric events such as el ninos and la ninas. The amount of suspended sediment entering the estuary from local watersheds and through the Delta also varies (Gilbert 1917, McKee et al. 2002, McKee et al. 2003). The relative contributions of inorganic and organic sediments for maintaining marsh plains reflect this variability. For example, historical hydraulic mining and marsh reclamation served to greatly increase the supply of suspended sediment while simultaneously removing places for the sediment to go. Marsh cores show that, during the advent of marsh reclamation and as the wave of hydraulic mining sediments entered the estuary, the amount of suspended clays and silts deposited on mature tidal marsh drainage divides greatly increased (Byrne et al. 1994, Byrne et al. 2001, Wells and Gorman 1994). Since then, the cores reveal patterns of seasonal and episodic inorganic sedimentation as alterations between organic material in growth position and thinly bedded clay and silt layers (Niering et al. 1977, and Figure 20). Some layering seems to reflect short-term changes in sea level rise, local dredging operations that increase suspended sediment concentrations, and local flood events. Another example is provided by the tidal marshlands in far South Bay that subsided more than one meter between about 1920 and 1965 due to nearby groundwater extraction (Poland and Ireland 1969). During this period, the amount of inorganic sediment in the marsh soil increased from about 80% to 90% of the total soil weight, and the overall accretion rate increased from about 2 mm per year to 4 cm per year, as needed to sustain the high marsh (Watson 2004). No tidal marshland in South Bay

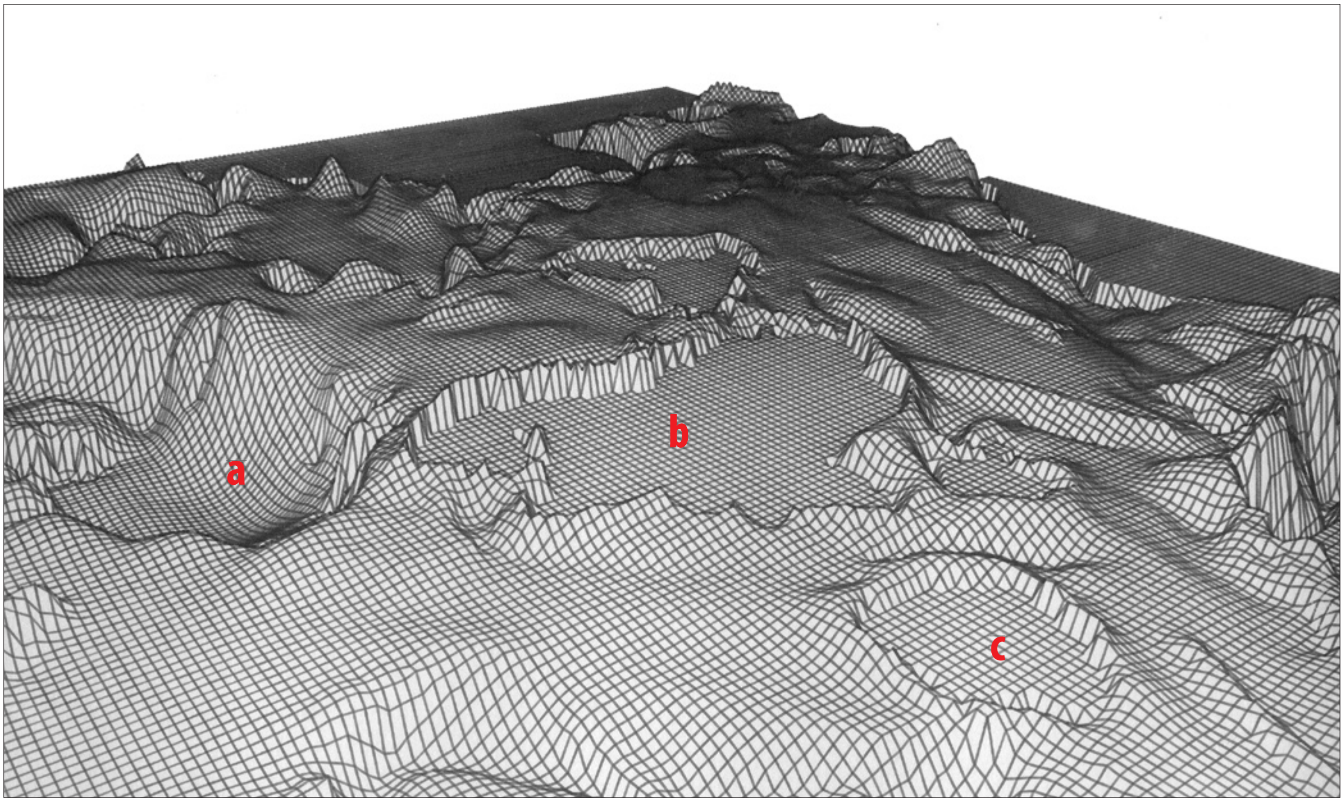


Figure 21a: Topographic map of a drainage divide in Petaluma Marsh, showing (a) a pond captured during last 50 years; (b) 500-year old panne; (c) 800 year-old panne. Horizontal grid of 1-m is vertically exaggerated by 50x.

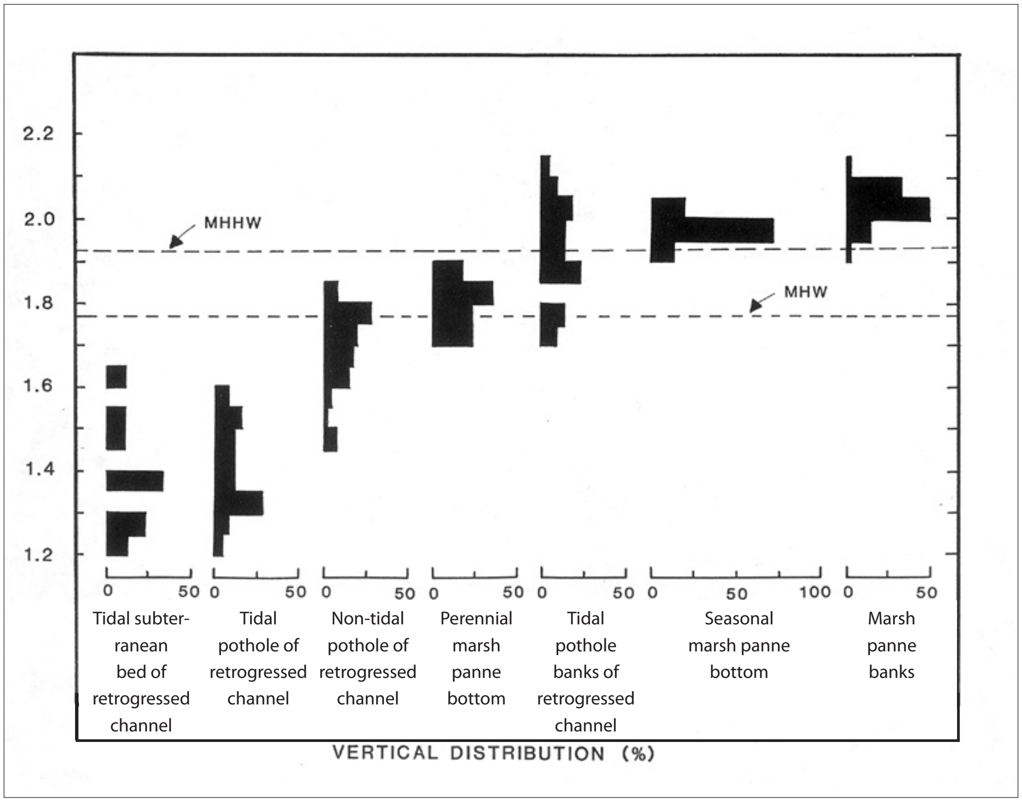


Figure 21b: Vertical distribution of tidal marsh habitat elements associated with high marsh plain of Petaluma Marsh. Tidal water is impounded in pannes at the top of the marsh drainage divides. First order channels advance and retreat (retrogress) around the margins of the divides, creating subterranean channels and potholes with varying tidal connection.

was converted to tidal flats during this period. In fact, new marshland developed where it could, mostly along the foreshores and within the larger tidal channels adjoining reclaimed areas (see Section III on Landscape Modifications). One implication of these findings is that the tidal hydroperiod of high marsh plains may not be optimal for plants, and that some increase in tidal hydroperiod (i.e., more frequent and longer inundation due to subsidence or rapid sea level rise) might increase plant productivity (Morris et al. 2002). Another implication is that existing marshlands would survive greater rates of sea level rise than the maximum predicted for the next century by the Intergovernmental Panel on Climate Change (IPCC 2001).

Salinas

Salinas are natural impoundments of tidal water less than 30 cm deep on the high marsh plain along the transition zone between the marshland and the adjacent upland. They tend to be longer than wide, and to parallel the extreme high tide contour. They are largely restricted to arid conditions away from the immediate influence of creeks, seeps, or springs. Since they exist near the upper limit of the tide, and at places far removed from any tidal source, they are not replenished by every high tide, and they are subject to desiccation during the dry season. Desiccated salinas are white with precipitated salts. They were most extensive in South Bay, where they ranged in size from a few acres to more than 200 acres. Historical descriptions illustrate some of the South Bay salinas.

The French traveler Duflot de Mofras described salinas at the marsh edge in San Mateo County in 1842:

> “at the roadside large dried lake-beds covered with salty crusts that come from a distance, shine in the sun light enormous snow-fields.”

Local surveyor Chester Lyman also described the San Mateo salinas, in 1847:

> “part [of the marsh] is covered with salt, which is gathered for use as we saw little heaps of it in the vicinity of the pools.” (Lyman in Brown 1960)

There was an almost continuous band of salinas at the landward edge of nearly all of the South Bay tidal marshlands. These features occupied a zone ranging from 100 meters to several hundred meters wide. Some salinas were managed as “salt ponds,” first by the Ohlone and later by Euro-americans.

Marsh Pannes

Marsh pannes are topographic depressions on the plains of mature tidal marshlands. In this region, marsh pannes are most common at places most distant from any tidal source, as measured along the pathway of tidal excursion within a marsh. They exist on drainage divides between channel networks, and near the backsides of natural levees. The immediate margins of marsh pannes are usually the highest places in marshes (Figure 21). Pannes range in size from less than an acre to more than a hundred acres, and they range in age from less than 50 years to more than 1500 years, but their depths range narrowly from about 10 cm to 30 cm.

Different formative processes have been identified for marsh pannes in different climates (Yapp et al. 1917, Kesel and Smith 1978, Pethnic 1974, Pethnic 1992, Christie et al. 2002, Ewanchuck and Bertness 2004). In all cases the feature is sustained by the entrapment of salts and persistent saturation of the benthic sediments that inhibits plant growth. The feature must also be isolated from supplies of in-filling suspended sediment.

In this region, where the tidal marshlands are not subject to scouring storm events, gauging ice flows or large deposits of smothering wrack, there are only a few ways that marsh pannes can be formed. They can begin as short lengths of low-order channels that are left during channel retrogression, or they can start as isolated topographic depressions caused by differential rates of vertical marsh accretion. The smaller pannes that begin as remnants of retrogressed channels have been called potholes (Barnby et al. 1985).

The larger pannes form away from any tidal source, where the inputs of inorganic sediment are minimal, and marsh accretion is largely due to organic sedimentation (see Figure 18). Isolated topographic depressions in these areas might result from differential rates of peat production. Once an isolated low area forms, it tends to impound water, causing the vascular vegetation to die. Once the vegetation dies, its contribution to peat production and marsh accretion halts. Therefore, as sea level rises, and the surrounding marsh plain builds upward, panne depth increases. The water table is maintained near the marsh surface by tidal inundation (Figure 22), and thus the water table also rises as the marsh builds upward. Eventually the panne bottom is intercepted by the water table. The discharge of ground water into the panne increases the duration of its hydroperiod, which acts as a negative feedback to vascular plant colonization. Regular tidal inundation prevents the formation of thick salt deposits, although pannes can become hypersaline during autumn, when tidal range is small and rainfall unlikely. The longer hydroperiod also nurtures the abundant growth of aquatic bacteria, diatoms, and macroinvertebrates (Collins et al. 1986, Barnby et al 1985), which comprise a large faction of the sediment that accumulates in the panne. These organic sediments tend to accumulate and build the bottom of the panne upward toward its usual water level, above which the conditions for bacterial and diatom growth decline rapidly. Elevation of the panne bottom is therefore controlled by bacterial and diatom production, which is controlled by the water level is the panne, which is controlled by the surrounding water table, which is controlled by the frequency and duration of tidal inundation of the overlying marsh plain, which is controlled by the frequency and duration of tidal inundation, which is controlled by sea level rise. As sea level rises, so does the marsh plain and its water table, and so does the organic substrate in the panne. Thus, although some pannes might be hundreds of years old, their depth of water remains about the same.

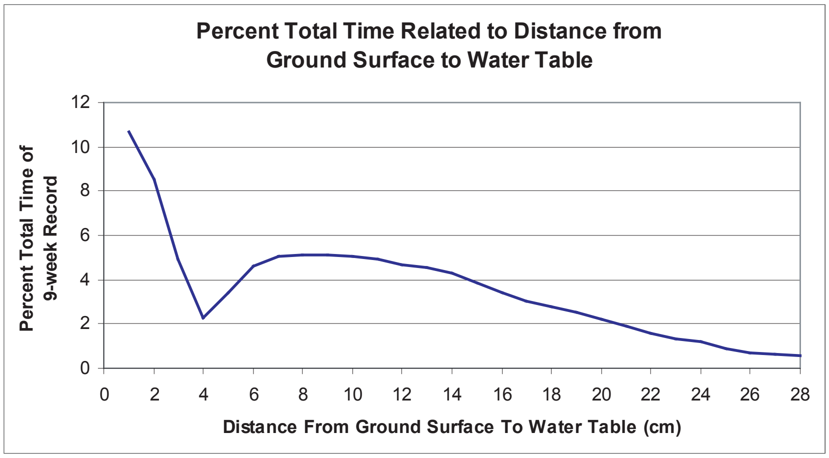


Figure 22: Ground Surface to Water Table. Plot of how much time groundwater spends at different depths below the surface of the vegetated plain on the drainage divide of a mature saline tidal marsh during the dry season. Data provided by Josh Collins, SFEI. Drawdown and recharge through the channel banks are restricted to the nearest 3-4 m of the marsh plain (Howland 1976, Balling and Resh 1983). At distrances further from the channel, recharge and drawdown are due to overbank inundation and evapotranspiration, respectively. The bi-modal distribution is caused by the spring-neap tidal cycle. During the highest tides of a spring tide series, percolation into the peaty soils during their inundation keeps the groundwater high. It spends about 30% of the time within about 4 cm of the marsh surface. When high tides are lower, as during neap tides, and the surface is less frequently inundated, evapotranspiration tends to lower the groundwater. It spends about 40% of the time between 7 and 13 cm below the surface. The depth of the rooting zone across the high marsh plain corresponds to this range in depth of the groundwater surface. The groundwater is seldom more than 30 cm below the marsh surface.

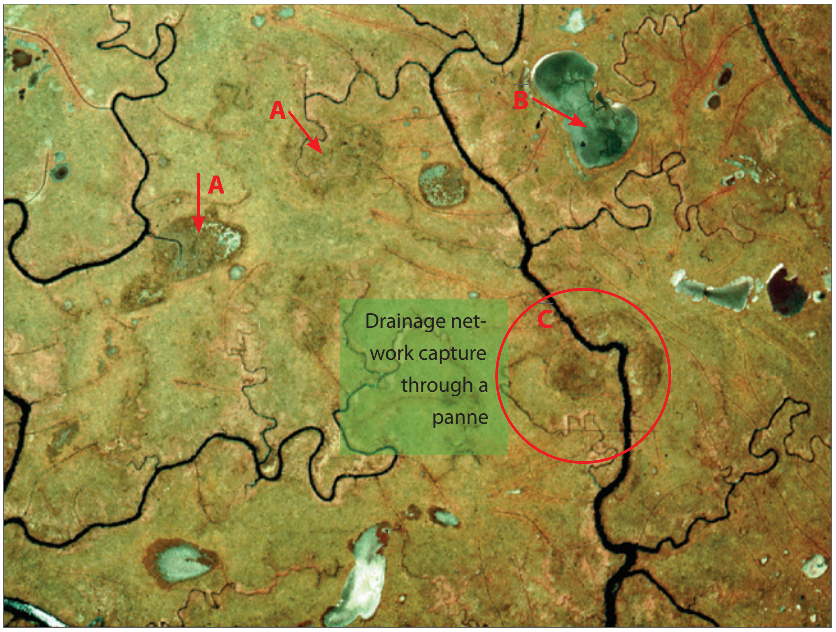


Figure 23: Schematic of Saline Landscape. Color infra-red aerial photo of the detail of tidal marshland, showing marsh pannes in various stages of degradation. Photo provided by Laurel Collins, Watershed Sciences. Dark circular patches (A) are the "ghosts" of pannes that have naturally been captured by channels and have since been colonized by vascular vegetation. In some cases, pannes have reformed after being invaded by channels. Evidence of this can be seen as remnants of extinct channels in extant pannes (B). The capture of one drainage network by another is evident as the extant channel that crosses through an extinct panne that used to occupy a drainage divide (C).

That the geomorphic controls on the formation and natural maintenance of marsh pannes are largely biological is consistent with the spatial distribution or organic and inorganic sedimentary processes across the marsh plain. The high marsh drainage divides and backsides of natural levees where marsh pannes form are the places most distant from inorganic sediment supplies (see Figure 18).

Analysis of time series aerial images plus sediment cores show that pannes in Bay Area marshes disappear if connected to tidal channels (Figure 23). Connection to a tidal channel increases the rate of inorganic sedimentation during flood tides, dewaters the sediments during low tide, and thus promotes plant colonization.

Marsh pannes vary in number and size in relation to tidal salinity regime, with fewer but larger pannes existing under fresher conditions (Grossinger 1995). This pattern is probably influenced by the combined effect of salinity and hydroperiod on the vertical distribution of vascular plants (Collins and Foin 1992). As discussed above with regard to tidal flats, vascular plants of the marsh foreshore grow absolutely lower in the intertidal zone under fresher condition. This prevents channels from extending as high or far into brackish or fresh tidal marsh as they do in salt marsh. The drainage divides of brackish and freshwater marsh plains are therefore broader, and larger pannes can exist without being invaded by channels.

Tidal Marsh Dynamics

Marshes that achieve equilibrium with sea level rise are not static. The larger channels (fourth-order and larger) migrate so slowly (Fagherazzi et al. 2004) that modern aerial images and historical maps of them overlay almost exactly (Grossinger 1995). But there is a dynamic relationship between plant growth and tidal flows that is manifest as changes in the distribution of smaller channels and marsh pannes (Collins et al. 1987). In the headward reaches of the smallest channels, tidal velocities are slight, and vascular vegetation tends to accumulate. A ubiquitous process of channel retrogression is caused by the tendency of vegetation to cover and eventually occlude these very small channels (Yapp et al. 1917, Collins et al. 1987). For very large drainage systems (fourth-order and larger) in saline marshes, channel retrogression at the ends of some channels tends to be compensated by headward erosion in other channels, such that there is no net change in channel capacity for the system as a whole (Figure 24). In general, the retrogression happens in small tributaries, and the headward erosion happens as an extension of the mainstem (Figure 25).

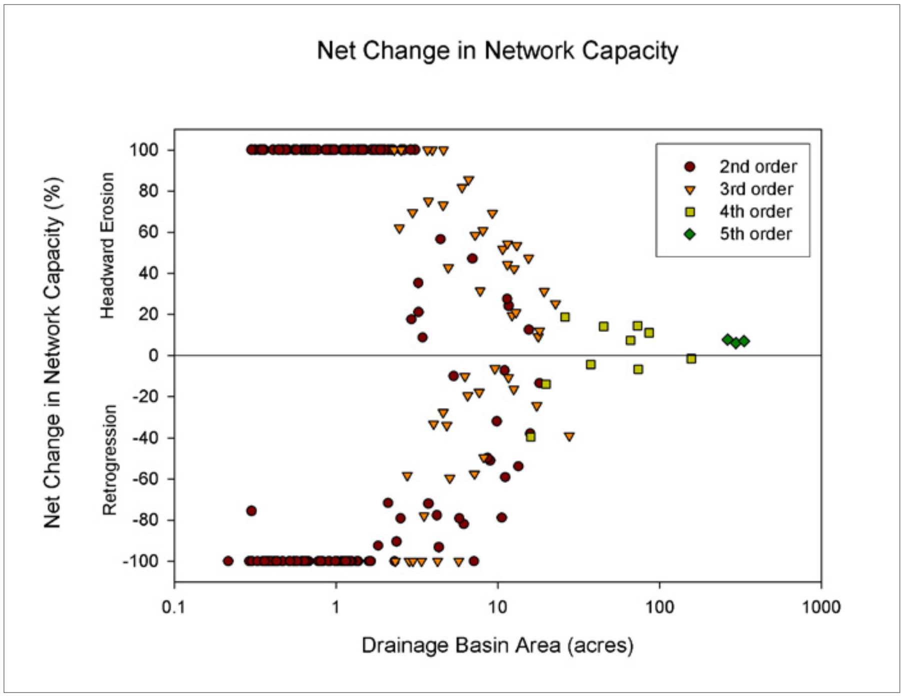


Figure 24: Net Change in Network Capacity. Evidence of compensation between headward erosion and retrogression of first-order channels at the landscape scale, as developed for this report. A study of changes in the arrangement of tidal channel networks in Petaluma Marsh (see Figure 25) revealed that every first-order channel eventually either erodes headward or retrogresses. This figure shows that for the larger drainage systems (fourth-order and larger), the total length of retrogression and the total length of headward erosion tend to be compensatory, such that there is not net change in the total length of first-order channels for the large system as a whole.

The mechanism for this compensation between channel loss and gain is not well understood. In these large systems the ongoing loss of some small channels is evidently insufficient to affect a change in the cross-section of the tidal source; the amount of tidal prism equal to the amount of channel lost is apparently shunted along the hydraulic gradient of the flood flow from the retrogressed tributaries to the end of the mainstem that subsequently erodes headward to accommodate the increase in tidal prism. This requires headward decline in the elevation of the high tide datums (see Figure 14). This model predicts that, once equilibrium between channel capacity and tidal prism has been achieved, any event or process that significantly reduces the tidal prism of the drainage system as a whole will lead to net retrogression, and anything that causes an increase in tidal prism will cause erosion. For example, reducing the size of the marsh or increasing the length of the mainstem channel of a drainage system by moving its mouth will tend to cause retrogression in the headward reaches, and widening an existing mouth will tend to cause channels to erode.

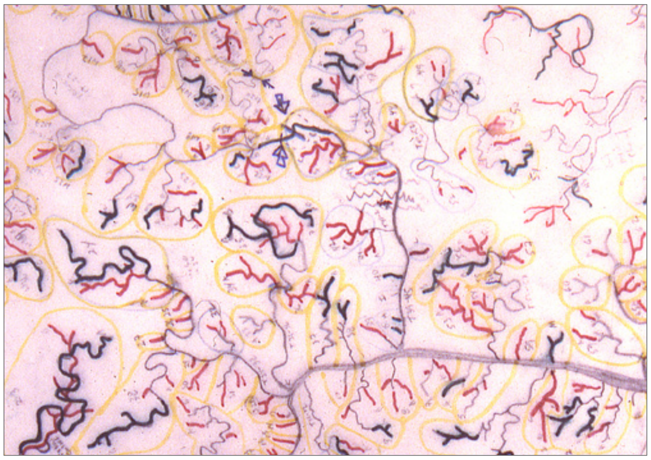


Figure 25: Example of cartographic analysis of change in the number and extent of first-order channels due to their headward erosion (in dark blue) and retrogression (in red), between about 1855 and 1943, as developed for this report. The length of every first order-channel in Petaluma Marsh was measured for two time periods, the 1852-55 (using Coast Survey Topographic Sheets 817 and 818 - scale 1:10000), and 1942-43 (using aerial photography provided by the military archives for the nearby Hamilton Air Force Base – scale 1:12000).

Headward erosion can significantly rearrange drainage systems by causing channels to invade and capturing the tidal prism of marsh pannes or adjacent drainage systems. If there is a time lag in tidal stage between the two systems, then when they come together the tidal prism will move downstream in the direction of the time lag to the convergence zone, where a new drainage divide can form (see Figure 23).

If this process of tidal prism conservation is real, then it follows that naturalistic systems of fourth-order or larger are minimal to sustain all the ecological and hydrological services ascribed to channels large and small. The drainage area of saline marshland encompassing such systems ranges from 0.5 km2 (fourth-order) to 0.75 km2 (fifth-order) (see Figure 13). If the same mechanism of tidal prism conservation exists in brackish marshes, then the minimum size of sustainable marsh drainages might be 0.25 km2 (fourth-order) to 1.5 km2 (fifth-order) (see Figure 13). In any case these values of minimum marsh size would only pertain to large areas of low-gradient marshland. The narrow marshland that fringes some large channels and the bayshore are characterized by parallel drainage systems of first- to third-order with steep hydraulic gradients. The high ebb flow velocities in these steep drainage systems might prevent their overall retrogression.

It would be difficult to overemphasize the effect of tidal channels on the form and function of tidal marsh. All materials exchanged between the marshland and the estuary are conveyed via the channels. If the tidal marsh and flats – the "baylands" - comprise a transitional zone between the uplands and the bays, then the channel banks comprise the immediate boundary. The banks comprise a threshold between aquatic and terrestrial processes. Above and beyond the banks, plants and animals with terrestrial lineage have adapted ways to live near water; below the banks, aquatic species have adapted ways to live near land. Landward of the banks, sedimentary processes are increasingly non-tidal; bayward of the banks, tidal processes control sedimentation. Channel banks are the intersection of air, land, and water. Many functions and services are concentrated within 10m of this intersection (Table 1).

Table 1. Distribution of ecological and geomorphic services along tidal salt marsh channels, showing a concentration of services within 10m of the channel banks, based on (1) Goals Project 2000; (2) Visintainer et al. 2003; (3) Thompson and Lowe 2004; (4) USFWS 1984; (5) Schwarzbach 1991; (6) Evens et al. 1994; (7) Collins and Resh 1985; (8) Marshall 1948; (9) Johnson 1956; (10) Balling and Resh 1982; (11) Shellhammer 1982; (12) Foster 1977; (13) Hobson et al. 1986; (14) Zetterquist 1978; (15) Balling and Resh. 1983; (16) Collins et al. 1986; (17) Duke 2004; (18) Odum 1980; (19) Childers 1994; (20) Agosta1985; (21) Sanderson et al. 2000.

Service	References	**Distance From Channel Bank**				
		In - Channel	**1-5m**	**5-10m**	**10-15m**	**> 15m**
Fisheries Feeding and Breeding	1, 2	🟩				
Aquatic Macrobenthos Diversity	3	🟩				
Clapper Rail Feeding	4	🟩	🟩			
Clapper Rail Breeding	4, 5, 6		🟩			
Song Sparrow Feeding	7, 8		🟩	🟩		
Song Sparrow Breeding	7,8, 9		🟩	🟩		
Salt Marsh Yellowthroat Feeding	12, 13		🟩	🟩		
Macro-invertebrate Diversity	10		🟩	🟩		
Salt Marsh Harvest Mouse Breeding	4, 11		🟩	🟩		
Salt Marsh Harvest Mouse Feeding	4, 14		🟩	🟩	🟩	
Total Plant Productivity	15		🟩	🟩		
Plant Height and Structural Diversity	15, 21		🟩	🟩		
Wildlife Refugia (from high tides)	17		🟩			
Inorganic Sedimentation	16	🟩	🟩			
Nutrient and Sediment Exchange	18, 19, 20	🟩	🟩			

RESTORATION IMPLICATIONS

The formative processes and basic nature of each major habitat type are well enough understood at this time to include them as design features in restoration projects.

The form and function of tidal marshland varies significantly with salinity. To maximize natural biodiversity, and to accommodate the ability of tidal species to track their preferred salinity regimes as sea level rises, or to adapt to new salinity regimes if required, habitats should be restored along the broadest salinity gradients possible.

Marsh channels are extremely important to the overall functions of estuarine landscapes. Except in steep fringing marshes, small channels (first- and second-order) are unable to maintain themselves. In natural fourth-order and larger saline and brackish marshes, there are compensatory losses and gains of low-order channels, with not net loss overall. This suggests that naturalistic marshes of fourth-order or larger are required to sustain channel systems.

Mosaics and Landscapes

A landscape consists of a habitat mosaic plus the matrix of ecotones that exists between and around the component habitat types. Landscapes tend to differ from each other in terms of the number, kinds, and relative sizes of the habitat types that comprise their mosaics. All the habitat types discussed in the previous section of this profile were considered in this description of historical landscapes.

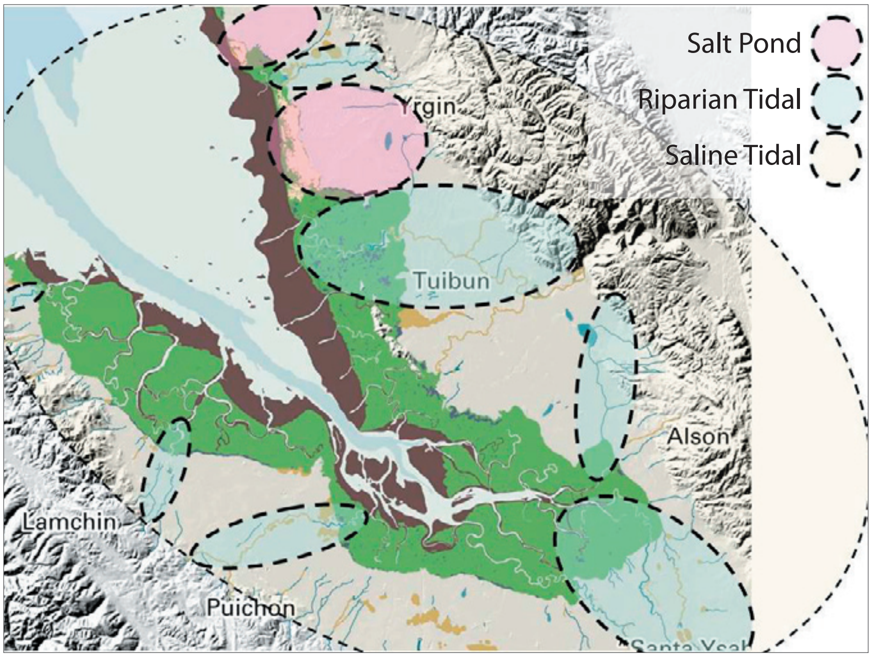


Figure 26: South Bay landscape types. While the Saline Landscape characterized much of the South Bay, the effects of the major creeks and the salt ponds to the north created a heterogeneous landscape pattern. This diagram presents overall pattern at a regional scale; finer patterns could be identified at the local scale.

Three major historical bay landscapes have been identified for the South Bay Ecosystem (Figure 26 and Table 2). Each landscape extends from the shallow subtidal bay environment through the intertidal zone and into the adjacent uplands. The purpose of extending the landscape above and below the intertidal zone is to explicitly acknowledge that the intertidal zone is the boundary between the tidal-estuarine and the fluvial-terrestrial parts of the region. The basic characteristics of the three major landscapes, as evidenced in historical maps and images, are summarized in Table 2. Representative plan form views of the Saline Tidal, Riparian Tidal, and Salt Pond land-

Table 2: Summary of distinguishing qualitative characteristics of the three major types of South Bay landscapes.

	South Bay Saline Tidal Marsh	**Riparian Tidal Marsh**	**Salt Pond**
Thumbnail Description	Saline tidal marshlands with very high channel density among contiguous 5th-order networks; abundant marsh pannes and salinas; moist grasslands along backshore; large sausals and extensive tidal flats	Tidal marshlands along a salinity gradient from fresh to saline or brackish directly influenced by one or more perennial creeks; large range in channel density and marsh panne size; no salinas or sausals; riparian forest near backshore	Tidal marshlands dominated by natural salt ponds; adjacent small salinas and marsh pannes; moist grasslands along backshore; no sausals; extensive tidal flats
Average width of 5th-order channels	~ 450-1200ft	~ 300-600 ft	none
Proportion of tidal flat within major channels	high	moderate	none
Channel density	high	variable	moderate
Marsh panne patterns	many small pannes (2% of marsh plain area;100-200 pannes per 1000 acres)	large size range (5-10% of marsh plain; 100-200 per 1000 acres)	Dominant marsh feature (50-60% of marsh plain area)
Average marsh panne size	0.1 acres	0.5 acres	na
Backshore character	50-60% as salinas in saline zone 300-600 ft wide	Fluvial-tidal interface with riparian forest	narrow marsh plain between salt ponds and grasslands
Width of upland transition zone	900-3000 ft (depending on upland slope)	900-3000 ft (depending on upland slope)	900-3000 ft (depending on upland slope)
Abundance of shellflat or shell beach	Common on west shore	none	uncommon
Abundance of sandy beach, overwash berms	Common on northeast shore	none	Common along northeast shore South Bay
Abundance of Sausals	Abundant	none	none
Large sausal size class	100-350 acres	none	none
Distance range from sausal to backshore	~500-2500 ft	none	none
Abundance of moist grassland above upland transition	Abundant	Abundant outside of riparian corridor	Abundant
Abundance of vernal pool complex	common	none	none
Extent of freshwater influence in tidal marshland	Negligible except as seeps and springs	Pervasive along channel banks	none

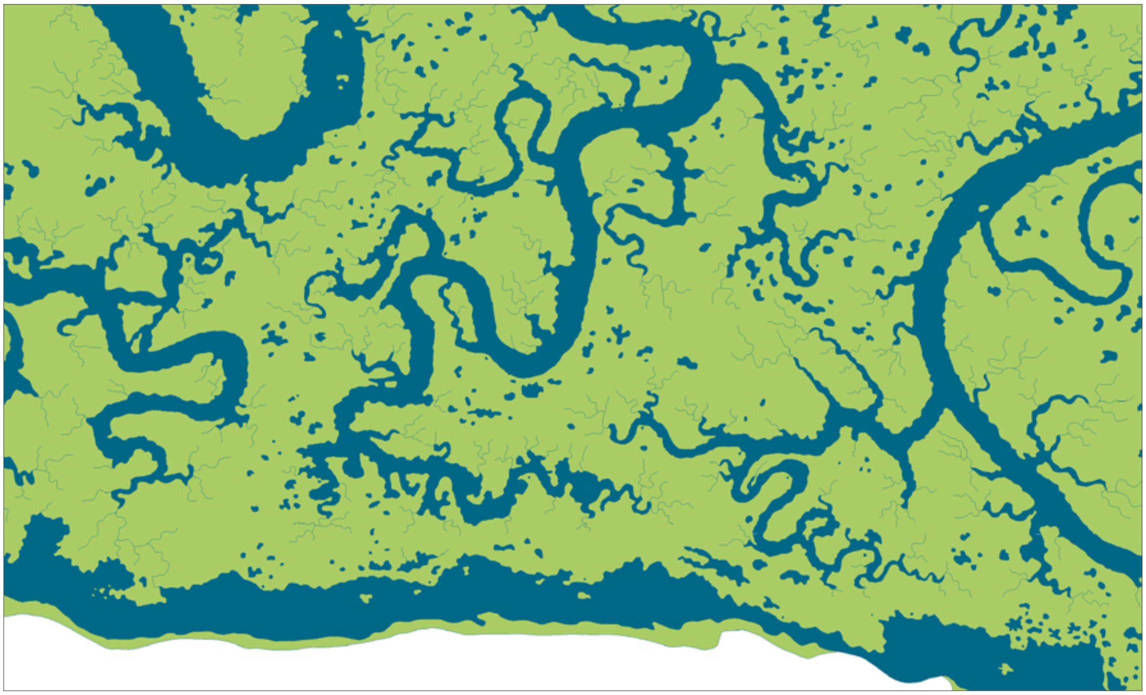


Figure 27a: Representative plan form view of South Bay Saline Tidal Landscape. This map shows the dense, sinuous channel network; broad major sloughs; continuous band of salina (near figure bottom); and many small marsh pannes characteristic to most of the South Bay Ecosystem. This illustration and the ones on the following page were produced by the direct georectification and vectorization of original United States Coast Survey maps, circa 1857. They are each produced at the same scale, covering about 500 acres of marshland, and extending about 1 mile across.

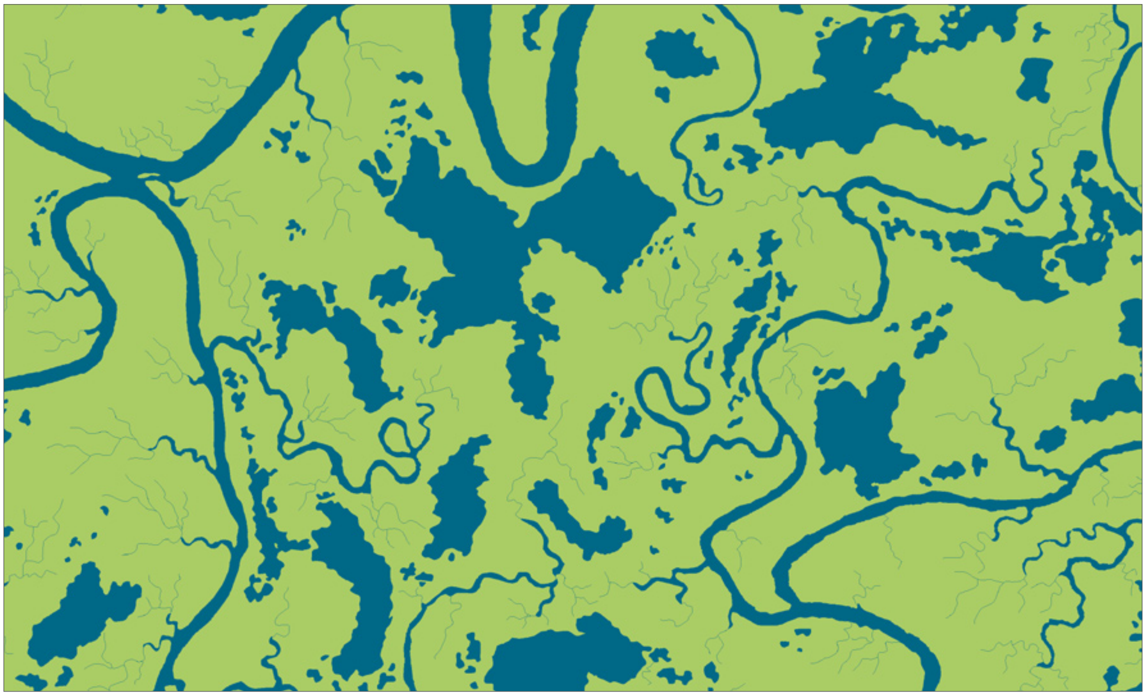
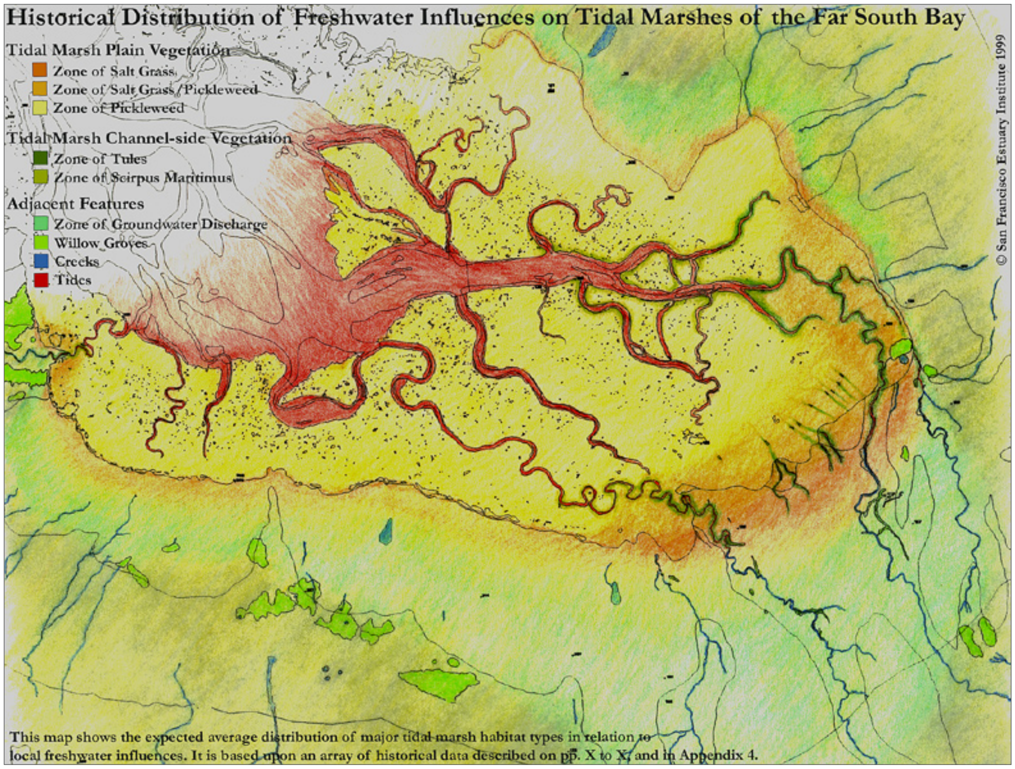


Figure 27b: Representative plan form view of Riparian Tidal Landscape. This map shows the characteristic large marsh pannes and less dense channel networks of tidal marsh plains in the vicinity of major freshwater sources.

Figure 27c: Representative plan form view of Salt Pond Landscape. The salt pond landscape of the native South Bay ecosystem comprised roughly equal areas of tidal marsh and salt pond, with minimal tidal channel networks.



This map shows the expected average distribution of major tidal-marsh habitat types in relation to local freshwater influences. It is based upon an array of historical data described on pp. X to X, and in Appendix 4.

Figure 28: Illustration of the expected historical extent of freshwater influences on tidal marsh plant communities in extreme South Bay, as developed for this report. The freshwater effects were due to groundwater emergence along the backshore of the tidal marshland as well as discharge from Coyote Creek and the Guadalupe River.

scapes, drawn from a recently developed GIS coverage of the historical South Bay marshlands (Grossinger et al. 2004c), are presented in Figure 27.

There are essentially no regional scientific studies of these landscapes or their mosaics. However, parts of some landscapes have been studied with regard to one or more linkages.

Regarding the linkages between subtidal and intertidal habitat types

- The relationship between tidal prism and geometry of tidal marsh channels (e.g., Coates et al. 1989), and the relationship between marsh plain sedimentation and distance from tidal source (e.g., Collins et al. 1986) explicitly relate intertidal form to the supplies of water and sediment coming through shallow bay environments.

- Studies of the movements of waterfowl, shorebirds, or fishes between salt ponds, tidal marshland, and tidal flats or bay waters also demonstrate linkages between these habitat types (Goals Project 2000).

Regarding the linkages between watersheds and the intertidal zone

- A few studies have begun looking at the influence of suspended sediment load and bed load from local watersheds on tidal marsh shoaling (Collins 1998), natural maintenance of marshland (Malamud-Roam 2004), and on the influence of tidal marsh restoration on fluvial flooding (Kamman Hydrology and Engineering 2004).

- There is evidence from historical maps and surveys that the larger perennial creeks were able to move their bed loads through the natural tidal marshlands without the chronic shoaling and narrowing so characteristic of these channels once their adjacent marshlands are reclaimed (see description of Riparian Tidal Landscape on page 38).

- Previous studies of the historical influences of fresh water on the form of tidal marshlands have focused on marsh channels and pannes (Grossinger 1995) and the overall distribution of vegetation communities sensitive to water salinity (Figure 28).

- Studies of anadromous salmon in other northwest coast regions have demonstrated the importance of tidal marshland as rearing and feeding habitat, and salmon have been captured in Bay Area marshlands, but the importance of tidal marshland for anadromous fishes in this region has not been quantified (see Fishes Science Synthesis).

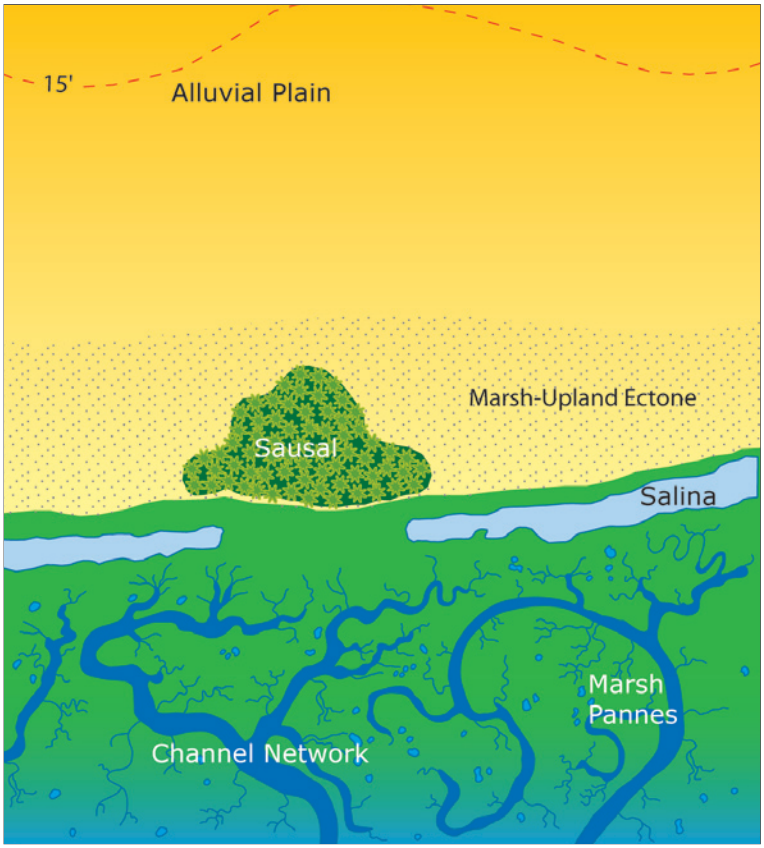


Figure 29: Schematic of Saline Tidal Landscape. This conceptual diagram illustrates both the tidal habitats and the adjacent upland habitats characteristic of much of the historical South Bay ecosystem. Sausals were associated with springs and seeps, but freshwater influence was limited. The width of the zones of salinas, sausals, and the tidal marsh-upland ecotone varied substantially according to the steepness of local topography (see Table 2).

Regarding the linkages between local watersheds and deep or shallow bay

- A recent compilation of data for sediment yield from local watersheds highlights their importance to the overall sediment budget for the estuary (McKee et al. 2003), but the fate of these sediments within either the subtidal or intertidal environment is not known.

- The influence of local discharge on the quality of bay water and sediment continues to be studied through the Sources Pathways and Loading Group of the Regional Monitoring Program for Trace Substances (see Contaminants Science Synthesis).

- The influence of fluvial discharge through the Delta on estuarine salinity along the main gradient of the estuary has been the subject of many studies, but the influences of local watersheds on secondary salinity gradients have not been well described. A simple conceptual model of expected salinity patterns has been developed based on existing botanical surveys and geomorphic patterns (see Figure 2).

Saline Tidal Landscape

This landscape is characteristic of saline regions of South Bay lacking local fluvial influences (Figure 29). The tidal marshland has the greatest channel density, largest number of pannes, smallest average panne size, largest salinas, and largest sausals of any bay landscape. There may be adjacent wet grasslands and vernal pool complexes. Beaches of sand or shell hash are uncommon components of the habitat mosaic. Tidal flats tend to be very extensive. The marshlands consist of contiguous fifth-order drainage systems. The mainstem channels typically extend into but not through the tidal flats.

This landscape differs between the west and east side of South Bay in a number of regards. The landscape on the west side lacks vernal pools and has larger sausals that are further inland from the backshore. This can be attributed to the west side having a narrower plain composed of less extensive but more numerous alluvial fans. The largest channels (fifth-order) are much wider on the west side, and there are more large marsh islands. The reason for this is unknown, but tectonics may be involved. The area of especially wide channels belongs to the San Francisco Block that is lower than other South Bay terranes and may be down-warping (Figure 30). The shallow subtidal environment of this terrane has been serving as a sediment sink, aggrading while other subtidal areas of South Bay have been degrading (Figure 31).

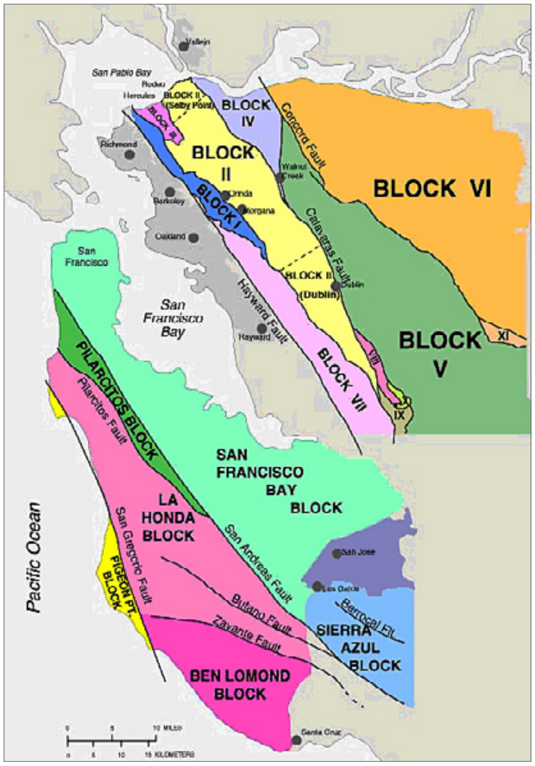


Figure 30: Map of subterranes and blocks bordering South Bay. The San Francisco Block is a topographic low relative to the uplifting blocks to the south and west. Source is the US Geological Survey at http://wrgis.wr.usgs.gov/wgmt/sfbay/blocks.html .

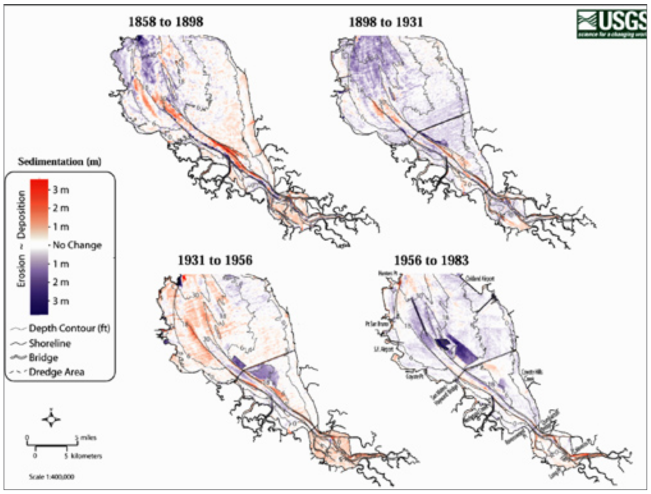


Figure 31: Maps of subtidal sedimentation in South Bay showing a greater tendency for deposition to happen on the west side, as if it is functioning as a sediment sink. Large (4th- and 5th-order) tidal marsh channels are especially wide on the west side, indicatjng that the marshes tend to be lower there. The two conditions may indicate tectonic downwarping. Figure is provided by Bruce Jaffe of the US Geological Survey.

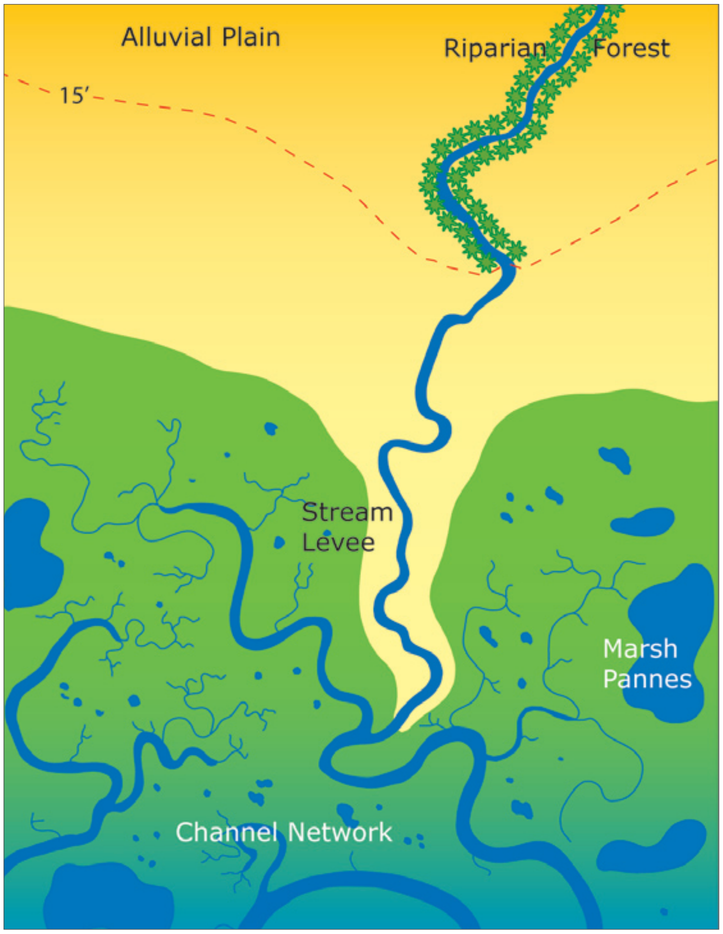


Figure 32: Schematic of Riparian Tidal Landscape. This conceptual diagram, produced to the same scale as Figure 29, shows the habitat mosaic associated with major creeks entering the South Bay marshlands. Marsh pannes are larger, but salinas are uncommon. Riparian forest follows a well-defined channel confluent with a tidal slough, but is excluded from the marsh edge by saline influence. In the immediate vicinity of the active alluvial fan, relatively steep and coarse alluvium precludes sausals.

Riparian Tidal Landscape

This landscape is characterized by one or more perennial creeks that intersect the intertidal zone (Figure 32). The fluvial discharge from the creek strongly influences the geomorphology and ecology of the attending marshlands. Channel density and the number of pannes increases with distance downstream along the tidal reach of the creek, and with distance away from the creek banks. Ponds tend to be larger, with sizes of five to twenty-five acres common. There are no salinas or sausals. There is a riparian forest extending downstream along the creek banks at least to the head of tide. There may be adjacent moist grasslands but no vernal pool complexes. Tidal flats are extensive, unless the brackish conditions extend beyond the foreshore. The mainstem channels of the creeks tend to extend through the tidal flat to the shallow bay environment. The largest creeks, such as Sonoma, Napa, Guadalupe, and Alameda, had channels that extended into deep bay. The marshlands consist of contiguous fourth- and fifth-order drainage systems, depending on topographic constraints. The riparian tidal landscape produces brackish marsh at the interface with the saline landscape.

The geomorphic nature of the interface between the fluvial and tidal environments varies with creek discharge and sediment load. Historical records relating to navigation indicate that prior to reclamation of adjacent marshlands, channel depth was naturally maintained, regardless of the sediment load (SFEI 2001, Collins and Leising 2004). How these channels maintained themselves is not known. Channels with large bedloads that reached the backshore tended to build levees that penetrated the tidal marshland. Such levees might have confined the flows far enough bayward to move the bedload into shallow bay channels, where tidal ebb flows could then move the load further out of the intertidal zone (Kamman

Hydrology and Engineering 2004, Collins and Leising 2004). These ideas have not been tested through either models or empirical observations of bedload transport.

Salt Pond Landscape

This landscape is dominated by unnaturally large impoundments of saline estuarine water that are managed for salt production and/or waterfowl hunting. The salt ponds are surrounded or fringed by saline tidal marsh with low-order drainage systems and small marsh pannes. There may be natural salinas and marsh pannes adjacent to the salt ponds. There are no sausals or riparian forest. There may be adjacent wet grasslands and vernal pool complexes. There is at least a moderate expanse of tidal flat, but without channels.

RESTORATION IMPLICATIONS

The South Bay Ecosystem consists of three major landscapes with distinctive mosaics of habitat types centered on tidal marshland as the transition between fluvial-terrestrial and tidal-estuarine processes. Restoration of the ecosystem should involve all the landscapes and their habitat types. The composition of the restored mosaics may be more important than habitat patch size, assuming that minimum patch sizes can be accommodated.

Restoration of Riparian Tidal Landscapes may provide the most diverse array of ecological services over the longest term because they involve broad gradients in salinity and elevation that transcend the boundary between fluvial-terrestrial and tidal-estuarine environments with the greatest range in plant architecture and off-channel habitat elements.

III. LANDSCAPE MODIFICATIONS

If restoration is the link between the contemporary South Bay Ecosystem and the enhanced ecosystem of the future, history is the bridge between the present-day system and the exemplary patterns and processes of the native, historical landscape. This history has literally shaped the historical landscape into the contemporary landscape, establishing many of the opportunities and constraints for present-day management. The land use history of the South Bay involves numerous social, cultural, and physical changes. This section focuses on the major, and in some cases largely undocumented, land use impacts and their implications for restoration.

Only disturbed remnants of most habitat types exist, and knowledge about their nature depends on interpretations of diverse kinds of evidence of historical conditions (Atwater 1979, Goals Project 1999). Although the science of Historical Ecology is gaining recognition (Striplen and DeWeerdt 2002, Egan and Howell 2001, Balze 2003, Swetnam et al. 1999), and the number of such studies of Bay Area environments is increasing (e.g., Grossinger et al. 2004a,b, Goals Project 1999), few historical ecology studies have advanced into the primary literature.

Bay Filling

Significant portions of the South Bay marshlands have been mechanically filled, generally by pumping dredge materials, beginning as early as the 1920s. This process created dry land in Foster City, areas around Redwood Creek and Bair Island, and many parts of the backshore ecotone. There is also evidence that the landward edge of the South Bay marshes was filled by terrestrial sediments through alluvial processes, some of them purposeful. However, overall only about 16% of the historical intertidal area has been filled above the potential range of the tides. And with land subsidence and sea level rise, some low-lying but historically upland areas now lie within the tidal range.

Diking

The South Bay Ecosystem has been greatly reshaped by the historical and modern use of diking technology, including successive generations of construction, modification, and maintenance . While dikes, or levees, were constructed in most other parts of the estuary primarily to prevent water from entering marshland for the purposes of agriculture, South Bay levees serve to capture and enclose saline Bay waters.

The diking history of South Bay also differs from that of the other large marshlands in the estuary with regard to its timing, which is relatively heterogeneous and late. Figure 33 shows the substantial regional variation in the sequential development of the current salt pond landscape. While the northeast portion of South Bay was diked for salt ponds almost immediately following American statehood, many pond complexes were not created until nearly a century later, during the middle decades of the 20th century. Throughout the 19th-century, most of the South Bay tidal marshlands remained. In fact, substantial areas of tidal marshland lasted longer in South Bay than in any other part of the estuary (Atwater et al. 1979).

Some of the latest areas to be diked happen to be those located at the mouth of Guadalupe River, a major source of mercury-contaminated sediment from the New Almaden

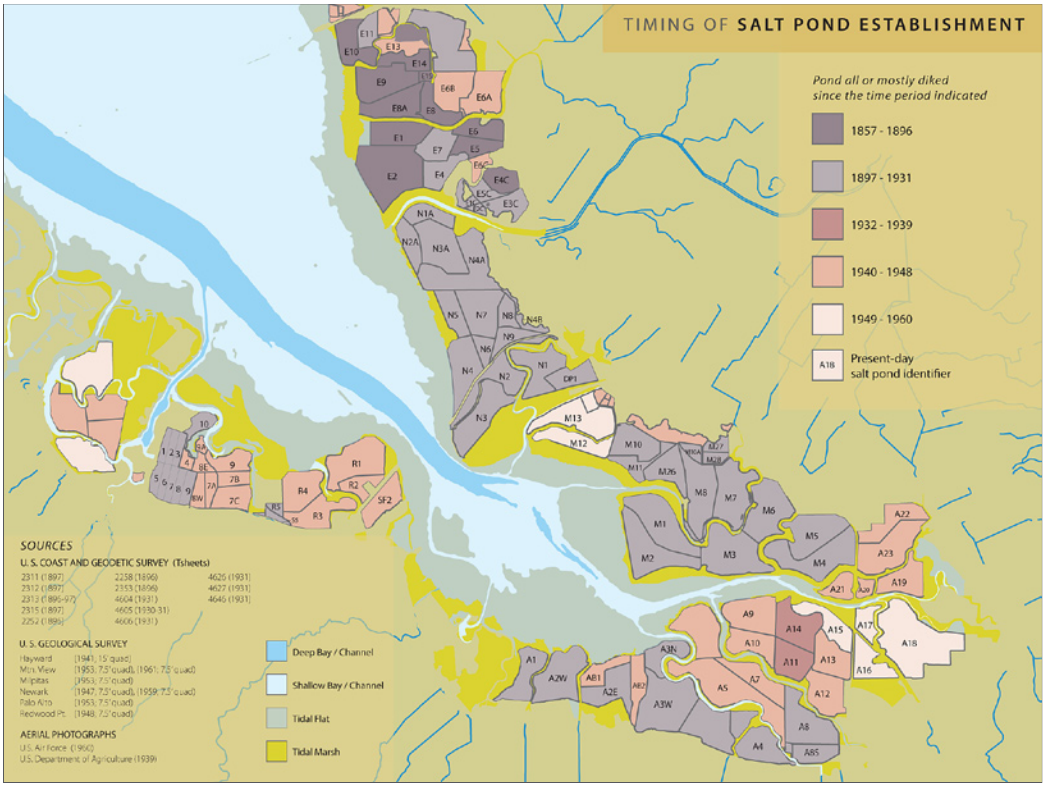


Figure 33: Timing of Salt Pond Establishment. The present-day salt pond landscape was created in phases over the past 150 years. While some marshlands persisted into the second half of the 20th century, other areas have been diked for the near duration of the region's American history. Of particular interest to understanding historical mercury deposition is the location of Guadalupe and Alviso Sloughs, the two historical outlets of Guadalupe River. The sediment core taken by Conaway et al. (2004) to examine mercury contamination from the New Almaden Mine was taken from Triangle Marsh, east of pond A17.

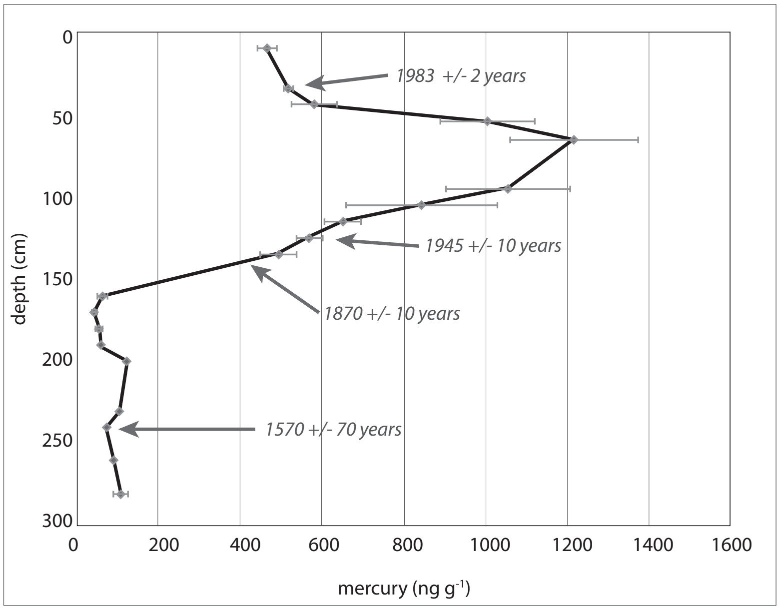


Figure 34: Mercury concentration versus depth at Triangle Marsh. While this sediment core data from Conaway et al. (2004) represents only a single core some distance from the mouth of Guadalupe River, it provides evidence for the rapid increase in mercury deposition in the marshes of the extreme South Bay during the late 19th and 20th centuries.

mining area. Intensive mercury production at New Almaden took place for over a century, after American settlers discovered the long-standing cinnabar mine used by local tribes (Salcedo 1999, Bailey and Everhart 1964). While about 95% of the mine's mercury output took place by 1905, the one deep sediment core analyzed for mercury contamination in the South Bay shows elevated concentrations after about 1870, with highest values reached during the middle decades of the 20th century (Figure 34; Conaway et al. 2004).

As a result, all of the marshes in far South Bay were exposed to historical mercury contamination in their undiked state. Marshes along the tidal outlet of Guadalupe River likely received highest exposure. Complicating this history is the fact that while Guadalupe River historically flowed into Guadalupe Slough, it was redirected into Alviso Slough in the first decades of the 20th century. We would expect that ponds along both sloughs,

Figure 35: Tidal marshes along Alviso Slough in 1939. While areas at the lower and upper right are already diked by this time, most of the marshes shown here along the modern tidal outlet of Guadalupe River were fully tidal and continued to maintain their tidal elevations despite rapid land subsidence since 1920.

such as A5, A7, and A9-13, were thus exposed to regionally high mercury contamination. The ponds immediately adjacent to Alviso Slough would have received the most direct exposure to the mid-20th-century contaminant pulse at the same time that they were presumably undergoing rapid sediment deposition and vertical accretion in response to local land subsidence (Figure 35).

Particularly with much of the surrounding marshes already diked off, the marshes in the Guadalupe-Coyote area were significant sediment sinks during the first half of the 20th century. In contrast, the adjacent salt ponds limited their intake of Bay waters to a few high tides during summer months when suspended sediment concentrations were presumably relatively low. Additionally, ponds A15-18, the most recently diked marshes of far South Bay, surround the Triangle Marsh sampling point and experienced an even longer duration of exposure.

RESTORATION IMPLICATIONS

The relatively late diking of the extreme South Bay allowed marshlands to continue accumulating sediment during the period of greatest land surface subsidence associated with groundwater withdrawals, thus minimizing current elevation problems for restoration.

The differential timing of tidal marsh reclamation means that some areas experienced substantially longer exposure to local sediment supply, increasing exposure to sediment-associated contaminants such as mercury.

The persistence of large areas of undiked marshland throughout the 19th century and the first decades of the 20th century allowed continued use of tidal marshlands for waterfowl sport hunting, a history which is documented in local newspapers and other accounts (see Avian Use section below).

Salt pond management history

One of the results of the relatively slow development of South Bay salt ponds for present-day restoration planning is that there is a long recorded history of human interaction with tidal marshland, including substantial documentation of waterfowl hunting, and examples of different characteristics of salt pond/tidal marsh management and associated landscape patterns.

The history of salt pond management can be divided into three general eras with distinct spatial and functional characteristics (Table 3). In the Indigenous Era, salt ponds in South Bay were developed and managed by the Ohlone as simple modifications of natural salinas and tidal marsh pannes. It is likely that these ponds were operated by the Ohlone for centuries before Euro-American conquest around 1800. The Ohlone operations appear to have continued largely unchanged under Spanish control, as the Spanish made Ohlone salt workers continue producing salt for the missions (Kurlansky 2002). The scale of individual salt pond complexes grew during the Traditional American Era (from about 1850 through roughly the 1920s). By the end of this era, levees and wind-driven pumps were being used to enlarge the salt ponds, but only in the context of fourth-order tidal marsh drainage systems. Levees did not cross fourth-order or larger channels, and each complex basically consisted of equal areas of tidal marshland and salt ponds. The Modern Era began during the late 1920s with consolidation of local salt works. The scale of salt pond operations expanded to cross major channels. Most of the saline tidal marshlands, brackish tidal marshlands, and riparian tidal landscapes of South Bay were converted to highly managed salt pond landscapes.

Table 3: Eras of salt pond management. The history of South Bay salt pond management can be divided into three general eras, with associated spatial and functional characteristics.

	Era	Scale	Ownership	Product Distribution/Use	Water Control	Percent salt ponds (per landscape unit)
First-generation: Ohlone/Spanish	Prehistory to 1850s	Tens of acres to 1000 acres	Indigenous families/tribes; Mission San Jose; Mexican land grantees	Local and regional	High tides, potentially tide gates	~50-60% (Crystal-Edens Landing area)
Second-generation: Traditional American	1850s to 1920s	Tens to several thousand acres	10-20 American businesses	Local and regional?	High tides, levees, tide gates, windmills	~40-60% (1896 Crystal-Edens Landing area)
Third-generation: Industrial	1930s to 2003	Several thousand to tens of thousands of acres	Single American business	National and international	High tides, tide gates, windmills, electrical pumps	~100%
Fourth-generation	?	?	?	?	?	?

At the close of the 19th-century, the Mount Eden area presented an interesting combination of tidal and diked habitats (Figure 36). Salt pond complexes at this time did not cross most of the fourth-order or larger tidal channels. While even the modern-day salt pond complexes have maintained the largest, sixth order channels sloughs in most places, salt pond complexes of the Traditional American era illustrated here are contained within selected fourth-order drainage systems. Many of these systems were selected because they had large natural marsh pannes (Figure 37). Each salt pond complex includes ponds of different salinities interspersed with large areas of saline tidal marshland. The Traditional American Era provides a potentially useful model of a salt pond landscape that equally favors the ecological services of salt ponds and tidal marsh.

Commercial salt production in South Bay has always relied on the particular combination of three critical environmental conditions: saline tidal water, consistent winds, and long dry summers. During the Ohlone and Traditional American eras, salt production relied on winter rains to wash impurities from the evaporated salt. From the perspective of "terroir" (the unique attributes of a particular geography), Bay salt may be considered an illustrative expression of the region's distinctive physical character. During the Traditional American era, levees and windmills were constructed to further control water movement among the salt ponds, es-

Figure 36: Mt. Eden-Baumberg area at the end of the 19th century. Salt ponds, many of them built from natural salt ponds are located primarily along the bayshore and tidal sloughs with large intervening areas of tidal marsh.

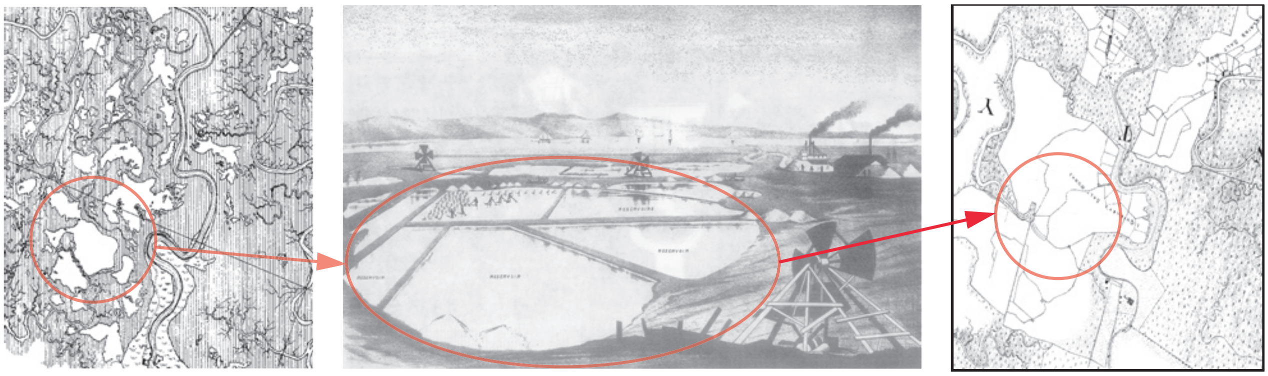


Figure 37: Development of modern salt ponds from natural marsh. Historical marsh features were the origin of many early Euro-American salt pond complexes. Management for salt production most likely converted these features from seasonally variable salinities to more consistently saline environments.

tablishing a range of pond salinities within a relatively small area (Figure 38). The use of larger pumps and pipes in the Modern Era allowed tens of thousands of acres to be operated as single complexes, with a few large evaporator complexes and trans-Bay piping. The replacement of windmills with electric pumps decreased dependence on less predictable winds and increased reliability, but at considerable increases in operating costs. Depending on the scale of future water management, smaller ponds and historical technologies might be effective.

RESTORATION IMPLICATIONS

The salt works of the Traditional American Era of the South Bay salt industry from about 1850 to the 1920s provides a model for the re-integration of salt ponds within the tidal marsh landscape.

Techniques from the Traditional American era of salt pond management may provide viable ideas for future salt pond engineering while also serving to educate the public about historical land uses

Efforts at Agricultural Reclamation and Soil Salinity Reduction

The general lack of 19th-century development of South Bay tidal marshlands, demonstrated in Figure 33, was not due to lack of effort. While between 1850 and 1900, while salt production was limited almost exclusively to the marshlands north of Coyote Hills, other endeavors were explored on the marshes further south and on the west side. For example, as early as the 1870s, there was substantial interest in reclamation for agriculture. Given their high level of organic matter and obvious proximity to navigable waters, the marshlands appeared to some agricultural interests to have great potential.

One author stated that land reclaimed from the Bay's salt marshes:

> "will certainly be much more valuable than the adjoining uplands, for it will be greatly more productive" because "[f]or grazing and dairy purposes, they will be extremely valuable (Browne 1873: 305)."

Another author describing the Santa Clara Valley observed:

> "many thousand acres of salt marsh…will be reclaimed, and among the most productive and valuable in the county (Belden 1887: 565)."

Despite the obvious challenges of high salinity, the notion of tidal marsh reclamation as a boon to agriculture was being extrapolated from the Delta to South Bay. Designs for reclamation involved using nearby local streams and artesian wells for freshwater to reduce soil salinity.

It was observed that :

> "Immediately upon the exclusion of the salt water by suitable embankments, freshwater streams can be turned in upon them; and, in some instances, the leaching process can be hastened by means of flowing artesian wells (Browne 1873: 305)."

Landowners recognized that local sources of freshwater could be used to convert saline marsh to arable land, and particularly looked for ways to expand the spatial and temporal influences of the Guadalupe River and Coyote Creek.

There was apparently some short-term success in the use of levees, artesian wells, and local streams to convert salt marsh to moist grassland suitable for agriculture.

Exemplary reclamation efforts at Dumbarton Point by Beard, a prominent Alameda County agriculturalist, were noted in 1873:

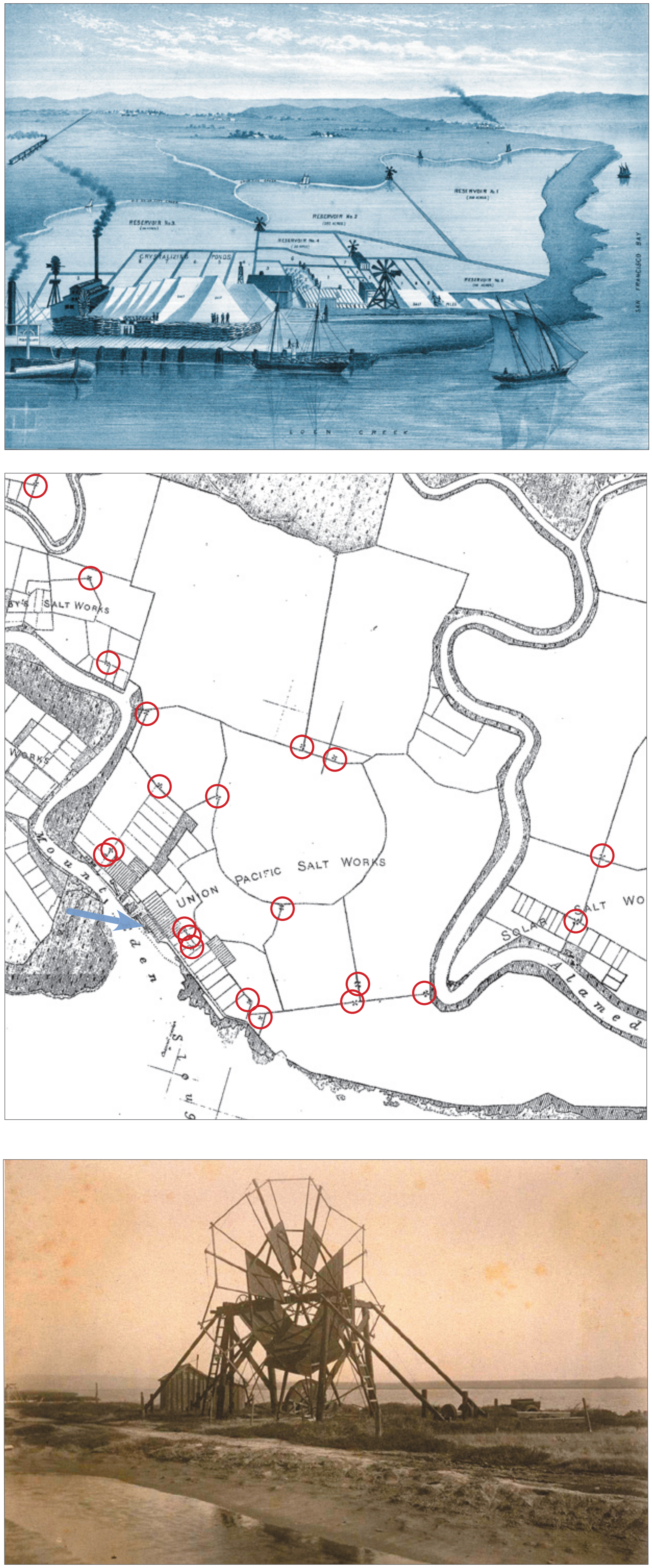
> "Already, in a single season, that portion of land which he has completely inclosed [sic] and submerged in fresh water shows a fine growth of flags, grass, and willows, and will be excellent meadow-land in another season, even without cultivation. (Browne 1873)."

By 1896-97 the second detailed federal survey of South Bay, the United States Coast and Geodetic Resurvey , documented extensive levee networks enclosing large areas of marshland off Alviso and Mud Sloughs, and Dumbarton Point (Figure 39). Numerous artesian wells were associated with these areas, indicating efforts at agricultural reclamation. A small area was also diked for shrimp farming, part of the region's shrimp fishery that was largely managed by Chinese immigrants.

However, despite the construction of miles of levees surrounding thousands of acres, these efforts to reclaim saline marsh for agriculture ultimately failed. The turn-of-the-century levee network mapped by the Coast Survey was described as "ineffective and decaying" by the surveyors in the accompanying Descriptive Report (Rodgers 1897), noting that:

> "For several years good crops of barley and hay were raised on a piece of diked marsh near Alviso Slough… but through neglect the salt water broke in and ruined it."

Abandoned artesian wells in the marshes continued to flow, contributing to decreasing hydraulic head in wells in the adjacent Santa Clara Valley and necessitating capping legislation by the 1880s (Foote 1888: 190). A quarter of a century after the experiments described in 1873, Beard's diked area remained less than 200 acres in size and was still mapped as salt marsh, with tidal channels and ponds. By the 1930s, the area had been developed into salt ponds.



The agricultural efforts in the South Bay marshes were unsuccessful even prior to competition from the expansion of the salt industry and the decline of groundwater tables, probably because of the extreme soil salinity which distinguished them from more successful agricultural operations in the Delta. Only the historical brackish or riparian tidal landscape between Mud Slough and Coyote Creek (Figure 40; now the Newby Island landfill) was successfully converted to agriculture for any appreciable period.

Overall, the South Bay levee network built for agricultural reclamation was remarkably short-lived. Even areas that were farmed appear to have rapidly returned to marshland. Those areas that were not converted to salt ponds by the 1930s can be examined using 1939 aerial photography, showing natural marshland with little evidence of the former levee network.

Because agricultural reclamation was rapidly exchanged for large-scale salt ponds in South Bay, the great majority of the diked areas have not experienced desiccation and the related subsidence that is a chronic problem for other diked areas in the region.

Figure 38: Oblique and plan views of a late 19th century salt pond complex on Mount Eden Slough. These illustrations show the Rock Island Salt Works of the Union Pacific Salt Company. Bay water is taken into the intake pond along the Bay shore during high summer tides and moved through a sequence of reservoirs before arriving at the Crystallizing Ponds adjacent to the landing and warehouses. The drawing above (Thompson and West 1878), while likely demonstrating some of the stylization and simplification typical of historical atlases, generally illustrates the pattern mapped more precisely by the United States Coast and Geodetic Survey (1896) two decades later. Windmills in the map are circled in red. The vantage point of the oblique view is shown with a blue arrow on the plan view. The bottom image shows a 19th century salt works windmill.

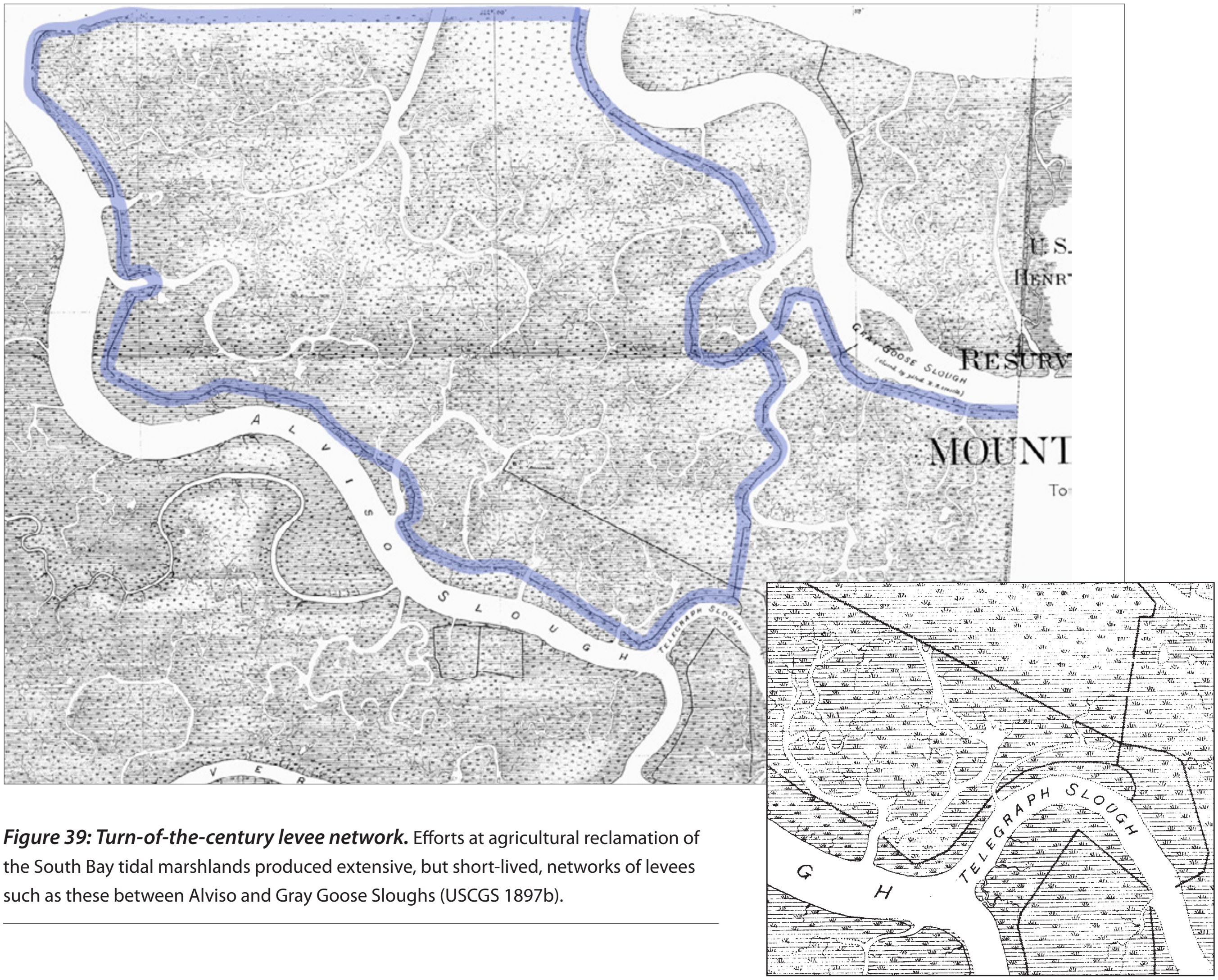


Figure 39: Turn-of-the-century levee network. Efforts at agricultural reclamation of the South Bay tidal marshlands produced extensive, but short-lived, networks of levees such as these between Alviso and Gray Goose Sloughs (USCGS 1897b).

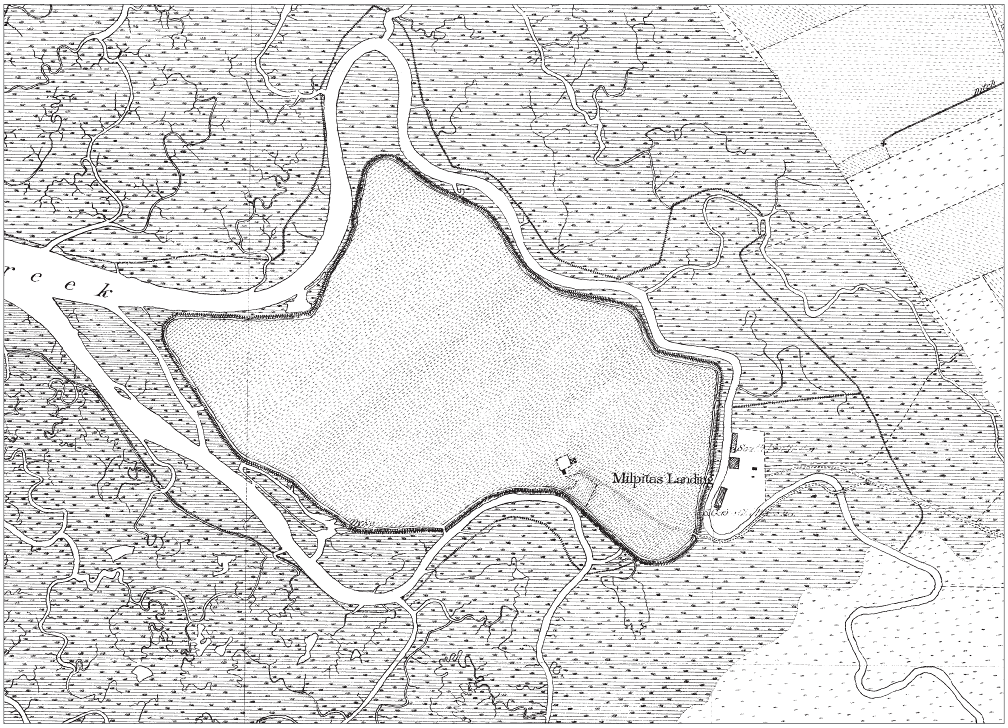


Figure 40: Newby Island 1897. Now the Newby Island Sanitary Landfill, this marsh island was previously one of the few persistent agricultural reclamations of the South Bay. Located just downstream of Coyote Creek, the site probably benefited from lower soil salinity, available freshwater, and higher natural channel-side levees, all associated with fluvial influence (USCGS 1897a).

RESTORATION IMPLICATIONS

Natural tidal processes tend to attack conventional salt pond levees. Ongoing maintenance is required to prevent levee failure. Large pannes form and persist on high tidal marsh plains without any structures resembling levees. To reduce maintenance costs, and to utilize natural processes of the landscapes as mush as possible, restoration designs should incorporate pannes, based on the natural tidal landscapes.

Previous "Restorations" of Salt Ponds

The rapid demise of the 19th-century network of agricultural levees illustrates the ability of tidal processes to quickly remove levees of dubious design and construction. But there were also diked areas that persisted for decades before reverting to tidal marsh. The landward half of Greco Island, now considered to be mature tidal marshland, is an example of early "restoration" (Figure 41). Almost half of the island was developed by Greco into salt works during the early 1900s and managed as the Greco Salt Company for at least two or three decades (Ver Planck 1958). Some of the earliest aerial photographs of the South Bay marshlands, taken of the Ideal Cement factory in the 1920s, show a fully developed salt works with active ponds, landings, and occupied buildings. However, maps and images dating from the mid 1940s show a breach in the perimeter levee and that all but the northwestern portion of the complex had reverted to tidal marshland. By 1959 the entire area of the historical salt works has reverted to marsh. Local experts of the time described the "restored" marsh as largely unchanged over the past three years (Counts personal communication). Presently the reversion back to salt marsh is so complete that few people know of the prior salt works. While rates of restoration will likely vary in the future and in different parts of South Bay, the Greco Island example and the agricultural reclamation examples illustrate the fairly rapid erasure of levees by natural processes.

RESTORATION IMPLICATIONS

Whole complexes of salt ponds have completely reverted to tidal marsh in the past due to levee failure.

The rate of tidal marsh development from salt ponds in relation to elevation, salinity, and expected sediment supply could be evaluated using sequential sets of historical aerial photographs and maps of reverted sites.

Smattering of historical avian use information

As a result of the relatively slow rate of tidal marsh reclamation in the South Bay, the use of tidal marshlands for sport and market prior to diking hunting is particularly well-documented. Skinner (1962), in his historical review of Bay area wildlife resources, provided few details about South Bay waterfowl hunting but some noteworthy overall statements.

He describes South Bay as part of the "prime waterfowl habitat" in the region (Skinner 1962), stating that:

> "… areas most heavily used were the vast marshlands on the east and south shores of San Francisco Bay and on the north shores of San Pablo and Suisun Bays."

Figure 41: Changes at Greco Island. In the top, oblique aerial photograph, the Ideal Cement Company can be seen at lower center and Bair Island is at the upper left, across Redwood City Creek. The Greco Salt Works (right center of image, partially obscured by smoke) occupied much of the island for several decades. With the consolidation of the industry, the salt works were apparently abandoned. By 1946 no associated buildings are shown and the levees have begun to fail. Few indications of this history remain as the ponds have revegetated. (George Russell photograph circa 1920s, courtesy California State Lands Commission; USGS 1948; 2001 aerial photograph courtesy the Center for Land Use Interpretation).

Skinner identifies "the vicinity of Alvarado" as the best historical hunting area in the Bay Area, just ahead of the Suisun and Napa marshes. This perspective, and the accounts sampled below, suggest that the historical tidal marsh landscapes of South Bay provided waterfowl habitat on a par with, and in places even exceeding, that of the more well recognized waterfowl hunting areas in the region. Skinner's summary describes broad and general use of tidal marshlands by waterfowl and also suggests that the areas of highest value were salt marshes with some freshwater influence, such as Suisun, marshes downstream from Napa River (one of the three largest local streams), and the marshes at the mouth of Alameda Creek (the largest Bay area stream). These areas comprise "brackish" and "riparian tidal landscapes" as described in Part II of this profile.

However, no comprehensive effort has been made to compile the wealth of evidence about the historical use of the South Bay habitats by water birds. The limited sample of accounts presented here suggests that substantial data are available about historical avian use of undiked marshlands, in early journals and accounts, newspaper articles, and hunting records. Historical accounts appear to provide information on seasonal patterns of use and movement between the foreshore or tidal flats, tidal marshes, and the adjacent uplands. Information appears to be available to link some species to specific habitat types. Given that tidal marsh landscapes may in the future be expected to provide some of the avian support functions of the existing salt pond landscapes, it may be useful to understand the support functions of the historical tidal marshlands. It should be noted that this selection of historical accounts does not represent an organized research effort for this profile, but materials collected fortuitously as part of other projects. For example, it makes use of just a few of the many local newspapers that reported on hunting. As expected, more evidence is available for waterfowl popular with hunters than for other water birds, such as rails or shorebirds.

Describing marsh pannes in the "salt-marsh region" from "the village of San Leandro" to "Harrisburg" [now the Warm Springs District of Fremont]:

> " . . . it is a dreary waste of green, with here and there a pool of muddy and unpoetic water, covered with flocks of ducks of various colors, and with flocks of wild geese of both the white and gray varieties. In summer, the same dreary waste of green — to thought and eyesight alike repulsive — the same offensive pools of water; but, instead of the ducks and geese, it is inhabited by snipes of two varieties . . ." (Farley 1871)

Describing marshes in the lower South Bay, north of Alviso (from the perspective of San Jose) in an article titled *Duck Hunters Eagerly Await Dawn of October 1:*

> "At the end of the next seventeen days the thousands of sprigs, mallard and teal ducks, which have been feeding and breeding in perfect security since March in that vast marshy country to the northward of Alviso, will again be forced to depend upon their speed for safety . . . Shore birds, such as curlew and plover, are commencing to arrive here already, but the law will protect them and the rail from the sportsmen until after the duck season has been open fifteen days." (San Jose Mercury 1907a)

Describing duck hunting in the Alviso sloughs in an article titled *Quail Hunters Succeed In Bagging The Limit::*

> "Canvasbacks and bluebills are being harvested in goodly number at the local marshes. James de Fremery and two sons . . . went out for a two days' shoot in the Alviso sloughs. They brought in seventy-five birds. Of this number thirty-six were 'cans." *(San Jose Mercury* 1907b)

Describing the Redwood City-Ravenswood marshes in an article titled *Menlo Park Occurrences:*

> "This week large numbers of duck have lined the bay shore and are gradually coming into the marshes. Hunters are preparing for their fowling pieces for an assault." (Redwood City *Times-Gazette* 1899)

> "The law prohibiting the killing of wild ducks has been in force since February 15, yet hunters are shooting this game on the marshes back of the Flood place these moonlight nights. It is well known that the mallard hatches out its young and raises its brood in the fens along the marshes and at this season of the year are easy prey for the hunters. Such flagrant violation of the game laws should be severely punished." (Redwood City *Times-Gazette* 1896)

> "The Sequoia Hunting and Preserve Company, a local association composed of sportsmen, has recently been launched and steps have been taken to establish a hunting preserve on the marsh west of the salt works…Harry Lovie has contracted to bore an artesian well from which it is expected a sufficient flow of water will be secured to flood number of ponds which are to be located at various points throughout the preserve. (Redwood City *Times-Gazette* 1901)

Describing market hunting in marshes at the mouth of San Leandro Creek (quantity sent to San Francisco in the month of February 1852):

> "125 wild geese, 52 canvas-back ducks, 69 teal, 63 broad-bill ducks, 192 curlews, 207 plovers, 48 dowitches, 156 'peeks,' 48 snipe, and one rabbit." (Sandoval 1988: 43)

RESTORATION IMPLICATIONS

Restoration of South Bay tidal marshlands may support greater increases in waterfowl and shorebirds than has been previously recognized.

Abundant use of tidal marsh landscapes by water birds may be scale-dependent. For example, it may require the existence of shallow bay channels, tidal flat, moist grassland or other upland habitat types, and especially large marsh pannes that only form and persist on drainage divides between fourth-and fifth-order tidal marsh system, and that are larger in brackish tidal marsh landscapes and riparian tidal landscapes than in saline tidal marsh.

Development of Duck Ponds

Surveys by the US Coast and Geodetic Survey in 1931 show the exact locations of a number of duck clubs in South Bay. On the east side, in the areas of Edens Landing and Coyote Hill, where tidal marshland had already been developed into salt ponds, "duck ponds" several hundred acres in size were noted at the historical backshore ecotone, especially in association with seasonal wetlands and vernal pools. In far South Bay, the location of clubs is associated with railroad access, but actual ponds are not shown. The Drawbridge Station was the noted hunting town in the middle of South Bay tidal marsh along the South Pacific Coast Railroad.

On the west side, duck ponds were found closer to the foreshore of tidal marsh. The ponds in the vicinity of Ravenswood appear to have been developed from smaller marsh pannes on drainage divides as semi-artificial, 50-100 acre duck ponds surrounded by tidal marshland (Figure 42). Like the 19th-century Mount Eden salt pond landscape, the "tidal marsh with drainage divide duck pond" example provides a potential model for the integration of tidal and diked habitats into a productive ecological and cultural landscape.

Figure 42: Duck ponds in the Ravenswood marshes. In the South Bay, ponds managed for waterfowl are found both towards the Bayward edge of broad saline marshes and at the landward edge, sometimes associated with vernal pools (as at Fremont). USCGS 1931, USDA 1939

RESTORATION IMPLICATIONS

Small duck ponds created in place of tidal marsh pannes on drainage divides provide a historical model for enhancing waterfowl habitat and for focusing hunting activities.

Increased Fluvial-Tidal Connectivity

There has been a substantial increase in hydrological connectivity between local watersheds and the intertidal zone in South Bay. This has significantly changed the distribution of water and sediment within and between fluvial-terrestrial and tidal-estuarine landscapes. The increase in hydrological connectivity mostly happened before the 20th century and has since become part of the baseline understanding of landscape form and function. Its impact on natural processes has been largely forgotten.

As described in Part II, most fluvial channels from local watersheds did not reach the intertidal zone. Most creeks dissipated through their alluvial fans or onto the alluvial plain landward of the backshore. Most tidal channels also did not reach the backshore. There were few connections between local creeks and tidal channels. In South Bay, the transitional zone from tidal marsh to upland commonly included a high marsh plain with salinas and most grassland in a matrix of drier conditions. The few streams that connected to tidal channels could create substantial local effects, but the vast majority of the tidal marshland was isolated from direct freshwater effects.

Most of the increase in hydrological connectivity was intentional. During the 19th-century, farmers created ditches to reduce flooding on the lower alluvial plains (Figure 43). By 1900, creeks such as Calabazas, Stevens, Agua Caliente, Scott, and Penitencia were extended across their lower alluvial plains and connected to tidal marsh channels. Alluvial fans were ditched to either prevent or direct the spread of sediment, depending on the location (Williams 1912). Existing sinuous channels that coursed down the native valleys were replaced by straight ditches along valley margins to maximize pastures and the convenience of farming or ranching. Entirely new channel networks were created to drain wetlands, sag ponds, sausals, and shallow lakes (e.g. Williams 1912). A substantial portion of the existing drainage infrastructure consists of artificial channels constructed not just to carry upland flow down valleys, through fans, and across the alluvial plains, but to remove groundwater when it emerged on the valley bottoms and along the backshore. Many of the larger artificial channels have since been given names, including Sunnyvale East Channel, Sunnyvale West Channel, and Estudillo Canal. The lower reaches of some well-known creeks, such as Stevens Creek, are entirely unnatural and have no historical precedent. To these named features can be added many hundreds of anonymous drainage ditches and storm drain systems.

The creation of salt ponds tended to complicate the effort to drain the lowlands. Interior and exterior levees ran perpendicular to both the original and new upland drainage channels.. In several places the interior levees of new salt ponds effectively blocked the flow from creeks that had been recently extended to the intertidal zone, leaving no viable outlet for the flow (Figure 43). Modifications were made later to enable drainage between salt pond complexes (Micko et al. 1992). As a result, not all of the existing large tidal channels are remnants of natural, historical channel systems. In fact, a significant portion of the tidal channel infrastructure has been created solely to provide drainage for the adjacent valleys and alluvial plains. Many of the shapes and features of the existing salt pond landscape are derived from efforts to improve upland drainage. For example, Moffett Channel, lower Stevens Creek, Flood Slough, and the Alameda Creek Flood Control Channel are unnatural waterways that bound salt ponds. Furthermore, even the existing historical tidal channels have effectively been re-engineered to serve as extensions of fluvial drainage systems, rather than as the highest-order component of intertidal channel networks. Most of the historical sixth-order channels have been modified to function as the lower reaches of fluvial systems or discharge canals for treated effluent or non-point source runoff. Although the levees along these large channels generally demarcate their historical plan form, their cross-sections have been altered not only by the reduction in tidal prism but also by the increase in fluvial flow. In some cases, these channels have been dredged repeatedly to maintain their flow capacities.

These intended changes to drainage patterns along the valleys, plains, and through the intertidal zone had unanticipated consequences. The straightening of existing mainstem channels and their increased connection through wetlands and across fans to tributary channels caused chronic incision and headward erosion. More water and sediment was delivered to the valleys and plains by more extensive and confined drainage systems. The lower reaches of the modified systems began to aggrade. As the streambed was elevated, the risk of flooding increased. To prevent the loss of bridges and other engineered stream crossings, and to reduce flood hazards, the lower reaches of these systems are commonly dredged. Another

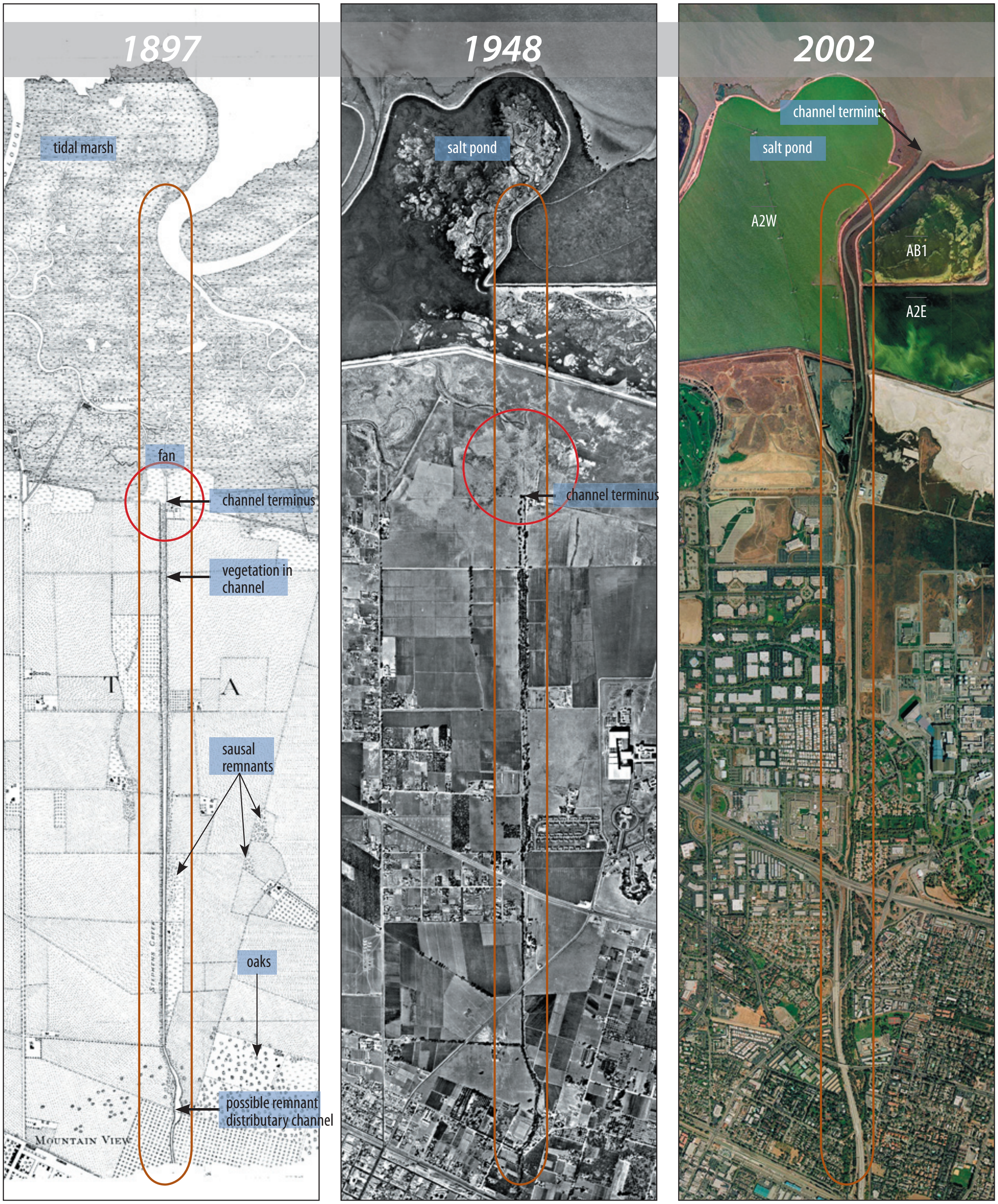


Figure 43: Lower Stevens Creek: 1897, 1948, 2002. This sequence shows the relationship between the lower reach of Stevens Creek and the changing tidal marsh/salt pond landscape. Stevens Creek is one of many South Bay streams that spread out on the alluvial plain prior to 19th-century channel extension. Since the major changes in the alignment of Stevens Creek occurred during the 1870s, the channel position is largely similar across the eras shown here. In the 1897 view, a likely remnant of the former distributary system at the historical downstream end of Stevens Creek can be seen. Residual patches of the roblar (oak grove) and sausals (willow groves) are also visible. The area circled in red in 1897 and 1948 shows the apparent extension of a fan of sediment that the creek mouth into undiked and diked tidal marsh, respectively. By 2002, a completely new tidal channel has been constructed through the salt pond complex to the South Bay open waters (Grossinger and Askevold 2004).

consequence of channel aggradation is that the tidal reach is shortened. Even as sea level rises, the estuary is receding in the lower reaches of local creeks. In these tidal reaches, the sediment pile along the channel bed may consist in large part of material from far upstream in the local watersheds, in addition to material carried into the channel by the tides (Collins 1998, McKee et al. 2003, Malamud-Roam 2004).

There is evidence that sediment supplies from local watersheds have been significant for marsh development during historical times. Some of this information comes from the history of pragmatic efforts by local farmers to use the sediment supply contained in local stream flows to reclaim marshlands. As early as the 1850s, local farmers reported extending their farmland into the former marshlands in the vicinity of Coyote Creek. They described farming on sediment recently deposited by winter stream flows over the salt marsh.

Parker (1863), testifying in the Rincon de los Esteros land grant case, describes former "marshy land" that has been made suitable for farming: "wherever the flood has washed soil onto it from above, and from the tide backing up, it has improved [the soil]."

Another local farmer, Bloomfield (1863), reported that on the high marsh plain dominated by salt grass near Milpiltas,"the freshet in the spring of 1853 deposited from 18 to 20 inches." Bloomfield goes on to say that there had been two additional overflows in the decade since.

The initiation of intensive grazing and plowing of the alluvial plains adjacent to the tidal marsh mobilized sediment, affecting both the upland marsh edge and the expansion of low elevation marshland. This effect is noted repeatedly by the late 19th century USCGS Resurvey parties. In the vicinity of Palo Alto, Westdahl (1897) notes that: "the leveling rod was held on the marsh outside of where it was affected by wash from the solid land or tramping of cattle."

On the Alameda County side of the Bay, Rodgers (1895), speaking with a nearly half-century perspective (having led many of the 1850s era surveys) reports "Freshet Debris: heavy winter rains scouring new plowed fields, has changed the interior margin of the Salt-marsh lands." He ascribes the aggradation of marshland at the mouth of San Leandro Creek (Arrowhead Marsh), despite overall shoreline erosion, to these localized "freshet debris" flows:

> "The shore-line within the limits of present sheet has receded from 30 to 90 meters & marked & wasting erosion is only stopped by bulkheading to prevent further loss of acreage."

Techniques were developed to directly capture these seasonal sediment flows from some of the local creeks that did not naturally have the ability to move their sediment through the intertidal zone. As ditches were dug across the alluvial plain to connect streams that dissipated above the backshore, these became sources of sediment for marshland reclamation.

Clark (1924: 19) summarized the practice as follows:

> "Advantage is taken of this rapid sedimentation both here [San Francisquito Creek] and on Alameda Creek for reclaiming the saltmarsh. The reclamation work is accomplished by building a levee around a certain portion and allowing the flood waters to spread over it and thus drop the sediment at the desired place."

An example is described below:

> "Faber eight years ago purchased 800 acres of land adjoining Runnymede. More than 300 acres of the tract was untillable at that time because of the spreading outlet of the creek on its way to the sea. The water from the stream, released at the mouth, spread over the Faber land, the Seal tract, the lower end of Embarcadero road and over the site of the municipal waterworks. By digging a new channel for the creek, erecting levees on both sides and another against the bay sloughs, a reservoir covering 150 acres was formed. A spillway enabled the emptying of the reservoir into the bay, and the retention of the sediments built new land over the once salty marsh, making possible the cultivation of alfalfa and other crops where only mud once was encountered. Having successfully reclaimed 150 acres of waste land by that experiment, Faber now is preparing to take 110 acres more from old Neptune's holdings by digging the creek channel to the opposite side of the present course of flow." (Redwood City *Times-Gazette* 1921)

Through these practices, farmers ditched and moved local creeks as "sediment hoses" to increase alluvial deposition at the marsh edge. The technique was applied at the mouth of Stevens Creek several miles to the East as well, where sequential images show the development of a fan in diked former marshland (Figure 43). This and other similar areas were referred to as Farm Reclamation Areas (Hermann 1929).

RESTORATION IMPLICATIONS

There is historical precedent for the anthropogenic use of the sediment loads of local creeks to raise ground elevations on tidal marsh plains. Local creeks could serve as sources of sediment for tidal marsh restoration. Large creeks may provide suspended sediment that can be carried by the tides into restoration sites. Smaller creeks and artificial drains could be directed onto the restored backshore to provide sediment for high marsh plains and upland transitions. All dredging operations for tidal channels, upland creeks, and reservoirs should be considered as potential sediment sources.

Alteration of Major Creeks and Aquifers

The creeks that historically flowed through the intertidal zone still do, but they have been altered in a variety of ways.

Alameda Creek has historically moved from one side of its large alluvial fan to the other, leaving reaches of abandoned channels as the fan grew higher and wider. Discharge from the Alameda Creek watershed is presently conveyed through salt pond complexes at the south end of the Eden Landing tract via the Alameda Creek Flood Control Channel (ACFCC). The ACFCC alignment is about equidistant from the historical (19th century) creek alignment to the north, and an older channel to the south. Both natural routes historically supported riparian forests. Moist grasslands and vernal pool complexes existed along the fan margins. The ACFCC approximates the route of an even older channel now called Crandall Creek. The channel scars of Crandall Creek historically supported one of the largest sausals in the region, remnants of which still exist. Ohlone shellmounds are associated with the sausal. Flooding of Alameda Creek was historically encouraged by local farmers to provide fresh soil across the alluvial fan (Williams 1912). Since the ACFCC was constructed, flooding is rare, and the fan is not being maintained. The historical recharge function of the fan has been restricted to an area of constructed recharge basins near the fan apex. Recharge plus runoff from recent development on the fan, in addition to a cessation of agricultural extraction of groundwater are contributing to renewed groundwater emergence and wetland formation along the base of the fan (SF Bay WRP 2003). In some places the groundwater is converting diked saline marshland and seasonally moist grasslands to perennial wetlands. The historical sausal is being nurtured by the emerging groundwater. These various conditions are noted to illustrate the complex mosaic of habitats that results from layers of land uses interacting with natural processes of active alluvial fans.

The Guadalupe River historically flowed into the large tidal channel named Guadalupe Slough. Sometime during the second half of the 19th-century, the river was also connected to Alviso Slough, another large tidal channel with no natural fluvial connection (and a less sinuous route to the Bay). Guadalupe River flowed into both sloughs until at least 1900 and was disconnected from Guadalupe Slough with the construction of the A8 salt pond complex prior to 1929. As a result, both sloughs were exposed to elevated mercury levels associated with New Almaden mine, and Alviso Slough presumably received the higher exposure. Coyote Creek is the only major creek in South Bay that has generally retained its historical alignment into the intertidal and shallow subtidal areas.

The effect of historical groundwater extraction in Santa Clara Valley on artesian water supplies, springs, surface runoff, and land subsidence is well documented (Robie 1975, Ikehara et al. 1998). The water table has returned nearly to the land surface during the last decade (Figure 44) for a variety of reasons, including decreased pumping from wells in the shallow aquifer (less than 100 feet deep), decreased pumping from wells in the deep aquifer (below a depth of 200 feet), enhanced recharge of the deep aquifer with surplus surface water, the continued existence of abandoned deep-aquifer wells that "leak" water between the deep and shallow aquifers, and the cessation of land subsidence (Ingebritsen and Jones 1999). As the water table rises, springs and seeps will tend to form along the valley bottom and historical backshore, where alluvium meets the less permeable estuarine clays.

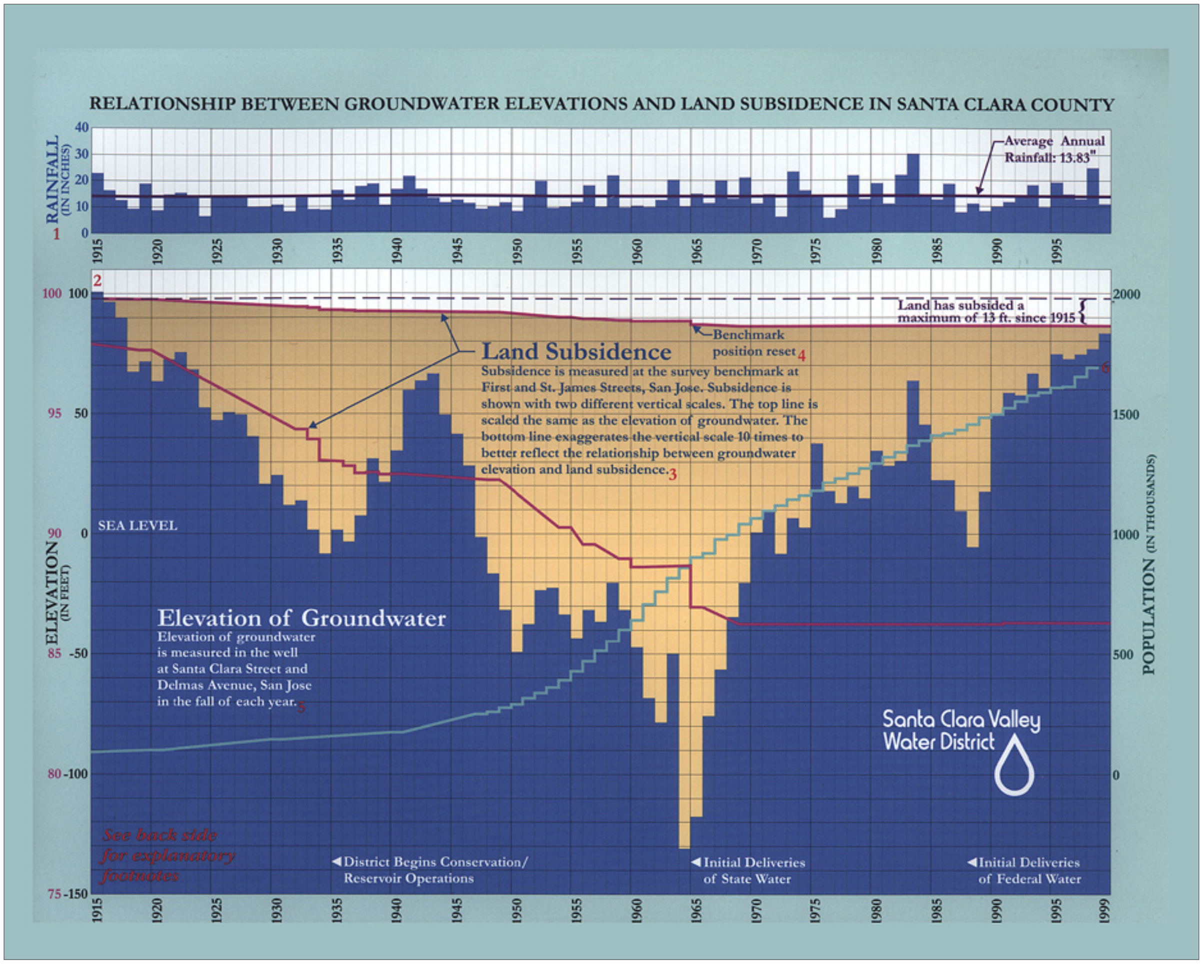


Figure 44: Chronology of changes in Santa Clara Valley groundwater height relative to various environmental and land use factors. Figure courtesy of the Santa Clara Valley Water District (2000). During a period when average annual rainfall has not changed, consumptive use by agriculture caused the water table to drop far below the land surface, which in turn caused the land to subside. Importation of water from outside the valley plus groundwater recharge has caused the water table to almost return to the subsided land surface. This suggests that groundwater may become a local resource for wetland restoration.

RESTORATION IMPLICATIONS

There is historical precedence for re-aligning creeks to meet management objectives for the alluvial plains and the historical backshore of tidal marshlands.

The cessation of agricultural extraction of groundwater in combination with recharge practices and land subsidence may increase the local availability of groundwater for restoration purposes, especially along the banks of fluvial channels and the backshore of tidal marshland.

Flood Control Levees

Some of the historical riparian tidal landscapes had natural fluvial levees that penetrated the tidal marshland, but never all the way to the foreshore. The arrangement of natural fluvial levees in the intertidal zone might have helped move the bedload from upstream through the marshlands to shallow and deep bays, and thus maintained channel depth (see description of Riparian Tidal Landscape in Part II on page 38). Although the same creeks have since been channelized and/or leveed all the way to the foreshore, they lack the capability to maintain themselves. They tend to aggrade at the fluvial-tidal interface, or just above it, such that dredging is required to maintain channel capacity. In some cases, enough of the bedload is moved downstream to build deltas outward from the foreshore. For example, there is a prominent delta at the mouth of the Alameda Creek Flood Control Channel.

One consequence of the extensive system of flood control levees is that the freshwater flows are unable to dissipate across the marsh plains. The confinement of the flows causes them to penetrate further into the estuary, resulting in local brackish conditions along the foreshore. This has probably contributed to local increases in brackish marsh vegetation and the colonization of channel flats lower in the intertidal zone (e.g., Duke et al. 2001).

RESTORATION IMPLICATIONS

Interpretations of the natural riparian tidal landscape suggest that fluvial levees need not extend to the foreshore if there is sufficiently large areas of tidal marsh beyond the ends of the levees and below the flood stage of the creek for the flood waters to disperse over the marsh at high tide, and for the ebb tidal prism of the marshlands to help transport fluvial sediment loads into the subtidal areas of the bay.

Effect of diking on tidal reaches of creeks

Diking of the intertidal zone has major effects on the remaining intertidal channels. Since the channels are adjusted in cross-section and profile to accommodate the tidal prism they convey (e.g., Dedrick 1979, Coates et al. 1989), any substantial change in prism will cause a change in channel form. Large-scale tidal marsh reclamation causes a major decrease in tidal prism for the tidal channels that remain among the reclaimed marshlands. A comprehensive study of how the depth and width of such channels in the San Francisco Estuary changed following reclamation was developed by the California State Lands Commission (Dedrick and Chu 1993). The study clearly shows that channels tend to narrow and shoal (Figure 45 and Table 4). The response to reclamation begins with a loss of depth, and then the channel starts to narrow. In South Bay, most of the channels that still convey the tides among the salt pond complexes are less than half as wide and deep as they were historically (Figure 46). A number of these larger tidal sloughs served as im-

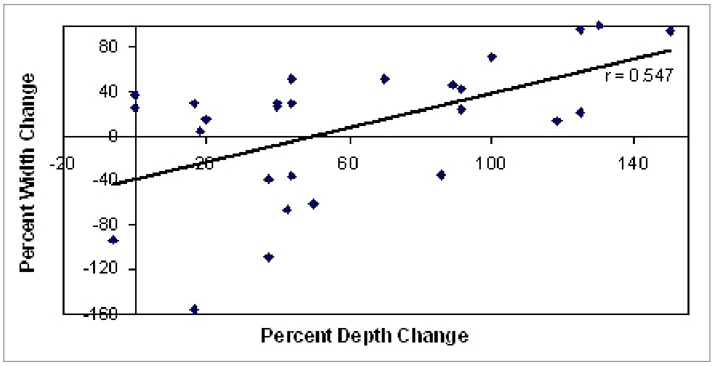


Figure 45a: Plot of the correlation between historical changes in width and depth of large tidal channels in South Bay, due to reclamation of neighboring tidal marshlands, between the mid 1800s and mid 1980s (Dedrick and Chu 1993). A loss in tidal prism causes a reduction in channel cross-sectional area. Depth begins to change before width, but eventually both change together. For channels in advanced stages of adjustment to changes in tidal prism, width and depth are strongly correlated. Channels below the regression line have not yet experienced much change in width. These tend to be very large channels for which reductions in cross-sectional area proceeds more slowly. Dredged channel were excluded from this analysis.

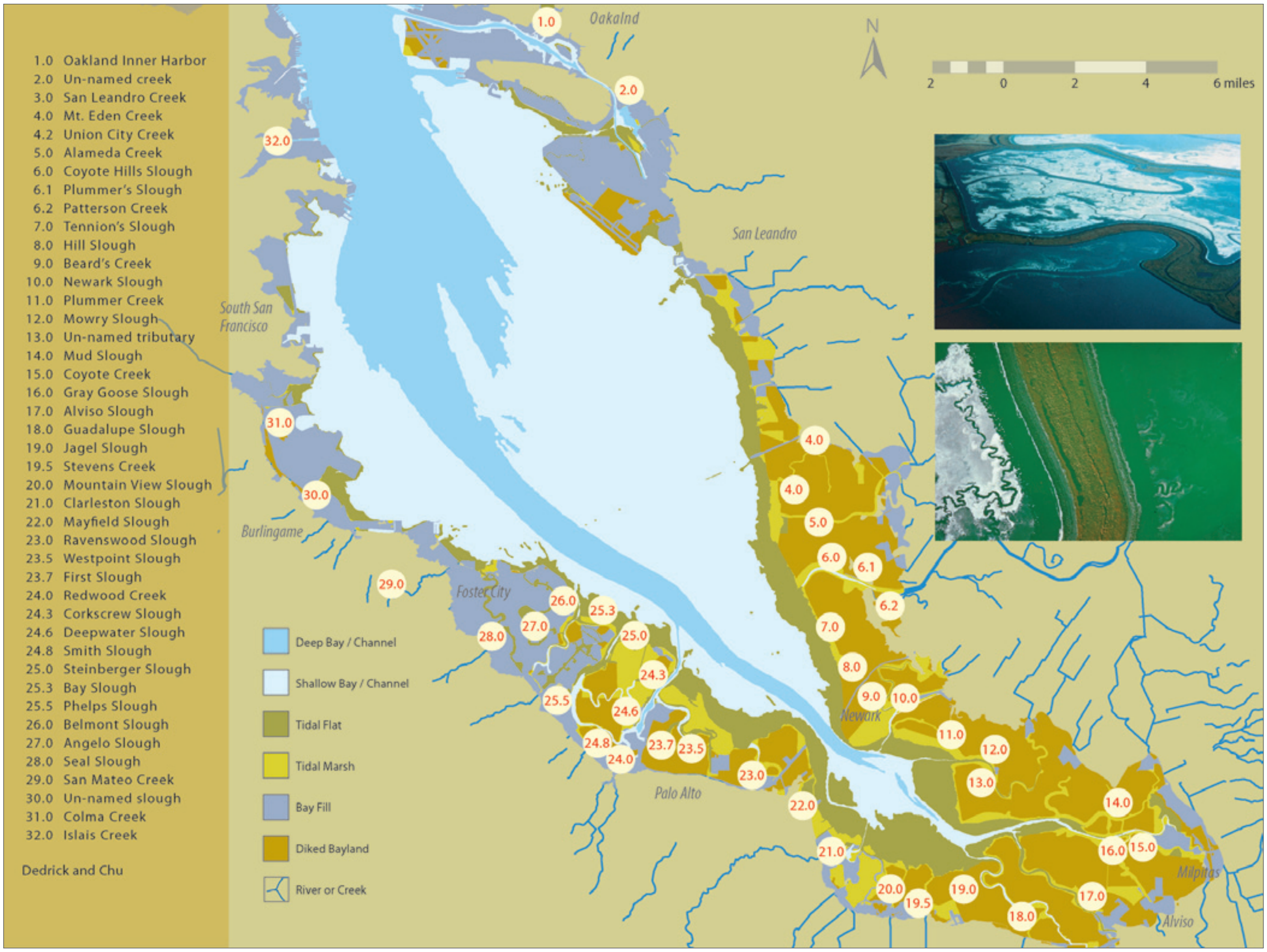


Figure 45b: South Bay sites for the State Lands Commission Study (Dedrick and Chu 1993) of historical channels in the depth and width of large tidal channels.

portant transportation corridors for indigenous and Euro-American residents, providing access between the uplands and the open Bay waters (Grossinger and Brewster 2003). The loss of tidal prism within these channels has thus also resulted in the loss of many of the navigable channels of the estuary.

RESTORATION IMPLICATIONS

If it can be assumed that a large increase in the tidal prism of a channel will cause it to erode (widen and/or deeper), then the restoration of tidal marsh will cause large-scale erosion of existing marshlands that have developed in the historical fifth- and sixth-order channels since reclamation of the attending tidal marshlands. The channel erosion is likely to be the closest source of sediment for flood tides to pick up and deliver to the nascent marsh plain behind nearby levee breaches. The uncertainty about relying on tidal processes to erode the sediment from major channels and deposit it in restoration sites could be avoided by dredging the channels and placing the sediment where it is needed, based on project designs.

Historic Widths and Depths from NOS/NOAA and USGS Topographic and Hydrographic Surveys										
No.	Name of Waterway	Starting Date	Ending Date	Starting Width at 100′ (in feet)	Ending Width at 100′ (in feet)	Percent Width Change	Starting Depth (in feet)	Ending Depth (in feet)	Percent Depth Change	Comments
1.0	Oakland Inner Harbor	1852	1959	2250	800	64.4	na	na	na	
2.0	Un-Named Cr., San Leandro Bay	1855	1959	450	0	100.0	na	na	na	
3.0	San Leandro Creek	1855	1959	270	0	100.0	na	na	na	
4.0	Mt. Eden Creek aka Union City Cr.	1857/1858	1952/1931	720	30	95.8	-4	1	125	
4.1	Mt. Eden Creek (N. fork of 4.0)	1857/1858	1952/1931	130	0	100.0	-5	1.5	130	
4.2	Union City Creek (S. fork of 4.0)	1857	1896	170	0	100.0	na	na	na	
5.0	Alameda Creek	1857	1952	300	70	76.7	na	na	na	
6.0	Coyote Hills Slough (mouth)	1857/1858	1952/1956	460	130	71.7	-4	0	100	
6.1	Plummer's Slough (N. fork of 6.0)	1857	1952	150	50	66.7	na	na	na	
6.2	Patterson Slough (S. fork of 6.0)	1857	1952	220	70	68.2	na	na	na	
7.0	Tennion's Slough	1857	1931	120	0	100.0	na	na	na	
8.0	Hill Slough (N. of Beard's Cr.)	1857	1931	200	0	100.0	na	na	na	
9.0	Beard's Creek (aka China Slough)	1857	1952	480	0	100.0	na	na	na	
10.0	Newark Slough (aka The Gap)	1857/1897	1952/1957	230	320	-39.1	-32	-20	37.5	Width measured at 500′.
11.0	Plummer Creek (near Newark Sl)	1857	1952	360	270	25.0	na	na	na	
12.0	Mowry Slough	1857	1952/1957	680	480	29.4	-10	-6	40	
13.0	Un-named trib. of Mowry's Creek	1857	1931	160	0	100.0	na	na	na	
14.0	Mud Slough	1857	1957	940	460	51.1	-10	-3	70	
15.0	Coyote Creek	1857	1956	940	590	37.2	-7	-7	0	
16.0	Gray Goose Slough	1857	1931	500	480	4.0	-11	-9	18	
17.0	Alviso Slough	1857	1952/1956	770	1040	-35.1	-32	-4.5	86	Slough was dredged.
18.0	Guadalupe Slough	1857	1952/1898	460	1180	-156.5	-6	-5	17	Slough was dredged.
19.0	Jagel Slough (aka Indigo Slough)	1857	1952/1957	520	390	25.0	-2	-2	0	
19.5	Whisman Slough	1857	1952/1957	1090	50	95.4	-6	3	150	
20.0	Mountain View Slough	1857	1952	400	540	-35.0	na	na	na	
21.0	Charleston Slough	1857	1952/1957	300	210	30.0	-6	-5	17	
22.0	Mayfield Slough	1857	1897/1957	260	190	26.9	-5	-3	40	
23.0	Ravenswood Slough	1857	1968	760	800	-5.3	na	na	na	
23.5	Westpoint Slough (east end)	1857/1858	1956	200	170	15.0	-5	-4	20	
23.6	Westpoint Slough (west end)	1857/1858	1952/1956	450	870	-93.3	-16	-17	-6.25	Slough was dredged.

Table 4: Summary table of net changes in width and depth for large tidal channels in South Bay, based on the State Lands Commission study of the response of navigable channels to tidal marsh reclamation (Dedrick and Chu 1993). There have been significant reduction is channel size, including the complete closure of some channels, due to reclamation of adjacent marshlands (continued on next page).

Historic Widths and Depths from NOS/NOAA and USGS Topographic and Hydrographic Surveys

No.	Name of Waterway	Starting Date	Ending Date	Starting Width at 100′ (in feet)	Ending Width at 100′ (in feet)	Percent Width Change	Starting Depth (in feet)	Ending Depth (in feet)	Percent Depth Change	Comments
23.7	First Slough	1857/1858	na/1956	350	na	na	-6	1	117	Slough cut-off by levees.
24.0	Redwood Creek	1857	1952	1190	1300	-9.2	na	na	na	Slough was dredged.
24.3	Corkscrew Slough (east end)	1857/1858	1952/1956	310	500	-61.3	-8	-4	50	
24.3	Corkscrew Slough (west end)	1857/1858	1952/1956	510	440	13.7	-11	2	118	
24.6	Deepwater Slough (north end)	1857/1858	1952/1956	320	170	46.9	-9	-1	89	
24.7	Deepwater Slough (south end)	1857/1858	1952/1956	400	230	42.5	-12	-1	92	
24.8	Smith Slough (east end)	1857/1858	1931	440	310	29.5	-8	-4.5	44	
24.9	Smith Slough (west end)	1857/1858	1952/1956	460	350	23.9	-6	-0.5	92	
25.0	Steinberger Slough	1857/1858	1952/1956	560	760	-35.7	-16	-9	44	
25.3	Bay Slough (east end)	1857/1858	1952/1956	620	300	51.6	-4	-2.25	44	
25.4	Bay Slough (west end)	1857/1858	1952/1956	440	730	-65.9	-7	-4	43	
25.5	Phelps Slough	1857	1952	370	120	67.6	na	na	na	
26.0	Belmont Slough	1853/1858	1956	950	740	22.1	-2	0.5	125	
27.0	Angelo Slough	1853	1952	420	0	100.0	na	na	na	
28.0	Seal Slough aka Marina Lagoon	1853/1858	1952/1931	230	480	-108.7	-8	-5	37.5	
29.0	San Mateo Creek	1853	1931	60	0	100.0	na	na	na	
30.0	Un-named Slough in Millbrae	1854	1895	190	90	52.6	na	na	na	
31.0	Colma Creek	1854	1930	700	700	0.0	na	na	na	
32.0	Islais Creek aka Du Vree's Cr.	1852	1899	290	290	0.0	na	na	na	

Width measurements taken from topographic survey by NOS/NOAA (National Ocean Service/National Oceanic and Atmospheric Administration) and U.S. Geological Survey Quadrangle Map.

Depth measurements taken from hydrographic survey by NOS/NOAA.

Table 4: Summary table of net changes in width and depth for large tidal channels in South Bay, based on the State Lands Commission study of the response of navigable channels to tidal marsh reclamation (Dedrick and Chu 1993). There have been significant reduction is channel size, including the complete closure of some channels, due to reclamation of adjacent marshlands (table begins on previous page).

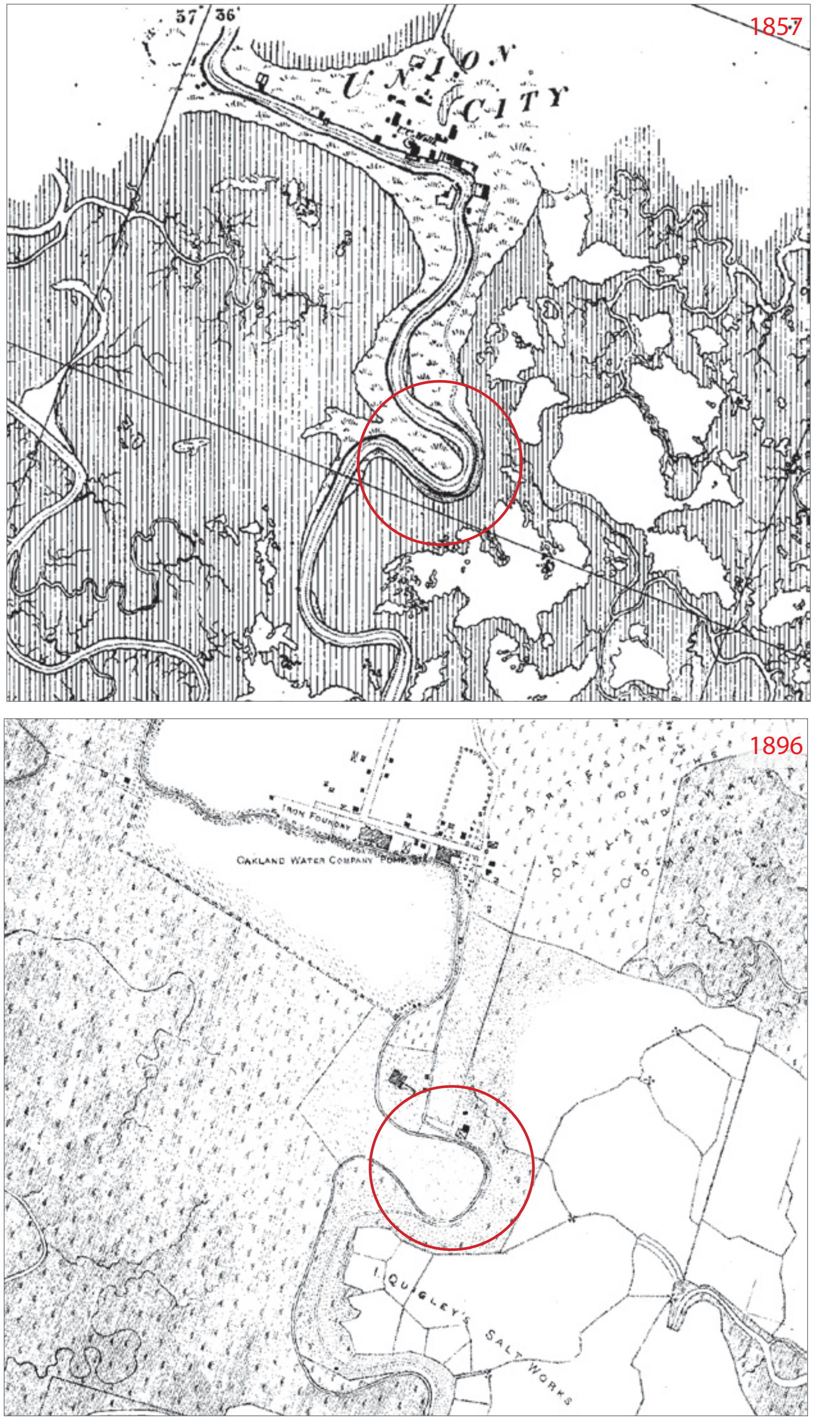


Figure 46: Changes in the fluvial-tidal interface at Alameda Creek. This comparison shows the reduction in active channel size on Alameda Creek between 1857 and 1896 as a result of the development of the local salt industry. At the creek-marsh interface in 1857, the natural stream extended several thousand feet into the marsh while tidal influence extended upstream, as indicated by the dotted low tide line and lack of trees due to salt water influence (that the absence of riparian forest in this survey is meaningful is confirmed by the presence of willow trees in other places on the map). In 1896, the former low waterline is now the extent of active channel and the former intertidal area has been colonized by riparian vegetation, presumably willow trees. Roughly half of the tidal marshland served by the drainage has been diked at this time; channel width in the natural levee section has decreased from ~40 m to less than 10 m. The red circle shows a corresponding channel meander.

IV. MODERN LANDSCAPE CONDITIONS

Regional Patterns of Landscape Response to Past and Present Land Use

The first three parts of this profile focus on native conditions and the effects of historical land use change, with an emphasis on major habitat types. In this final part, the effects of land use are viewed from the landscape perspective, with an emphasis on tidal marshland and its function as wildlife habitat.

Much has been written in recent years on the historical changes in the distribution and abundance of tidal and diked habitat types. This information is summarized elsewhere (Goals Project 1999, Foxgrover et al. 2004). The essential fact is that the estuary as whole shrank from the outside in, with an inward displacement of most major habitat types, and, with the exception of salt ponds and deep bay, a decline in their total area almost everywhere (Table 5). The losses started on the arable alluvial plains and fans adjacent to the backshore, and proceeded bayward. The riparian forests, grasslands, and vernal pool complexes were the first habitat types to be affected by modern land use. They were almost completely eliminated, first by agriculture and later by urbanization. Most of tidal marshland reclamation happened during the agricultural phase. In some areas, sequential sets of parallel levees were constructed, one bayward of the other, to capture new marshland and tidal flats as they developed. Some abandoned areas of diked marshland converted to ruderal grassland and saline seasonal wetlands, providing some of the ecological services of the historical uplands and backshore. In a general sense, the alluvial plains and valleys became farms and cities; the tidal marshlands became salt ponds and seasonal wetlands; some tidal flats became tidal marsh; and some of the shallow bay became tidal flats. But the total area of each of these habitat types declined.

The examination of the ecological effects of these landscape changes has only recently begun. Ecological studies of existing habitat types have focused as much on the values of diked area as tidal marshland (e.g., Anderson 1970, Madrone Associates et al. 1983, BCDC 1982, USFWS 1987, The Bay Institute 1987, LSA 1989). The emphasis on tidal marshland increased after the listing of tidal marsh wildlife as endangered (USFWS 1984, Josselyn 1983, Josselyn and Bucholz 1984, Harvey et al. 1992, Dedrick 1989). The first detailed regional comparison of historical and modern wildlife habitats was conducted a decade later (Goals Project 1999, Goals Project 2000).

Habitat Fragmentation

It is commonly stated that modern land use has fragmented the intertidal habitats (USFWS 1984, Harvey et al. 1992). Fragmentation involves a reduction in size and increase in separation between patches of like habitat, often with changes in patch shape (Temple and Wilcox 1986, Hargis et al. 1997, Trani 2001, McGarigal 2002). It involves both habitat loss and the breaking apart of habitat (Fahig 2003), and the isolation of some habitat patches (Dorp and Opdam 1987, Fahig and Paloheimo 1988). In this context, habitat is species-specific. The theoretical effect of habitat fragmentation is an increased risk of local extinction (Wilcox and Murphy 1985, Quinn and Hastings 1987) due to various factors, including simplified food webs (McArthur and Wilson 1967), reduced genetic variability (Freckleton and Watkinson

Habitat	**% Remaining**	**Shift in Tidal Proportion**	**Source**
Deep Bay	97%	6% —>9%	Goals Project 1999
Shallow bay	110%	31% —> 57%	Goals Project 1999
Tidal flat	71%	17% —> 20%	Goals Project 1999
Tidal marsh	17%	45% —>13%	Goals Project 1999
Marsh channels	?	--	--
Marsh pannes	4%	--	SFEI 1998
Salinas	< 2%	--	SFEI 1998
Salt pond	1975%	--	Goals Project 1999
Tidal marsh-Upland ecotone	<1%	--	Estimate
Moist grassland	2%	--	Goals Project 1999
Grassland/vernal pool complex	41%	--	Goals Project 1999
Sausals	<3%	--	SFEI 1998

Table 5 . Habitat Change in the South Bay Ecosystem. Different habitats comprising the habitat mosaics of the South Bay ecosystem have experienced dramatically different fates since European contact. While tidal marsh has experienced the largest decline of the historically dominant habitat types, a number of less-recognized habitats are even more poorly represented today. The shift from mature, large marshes to young, small marshes is reflected in the discrepancy between the decline in tidal marsh in the decline in marsh pannes and salinas, features associated with larger, intact systems. With diking and filling, the tidal area of the South Bay has decreased by 40%, but there has also been a redistribution in the relative proportions of subtidal, lower intertidal, and upper intertidal habitats.

2002), and more disease, competition, predation, and invasion (Ambuel and Temple 1983, Quinn and Hastings 1987). Fragmentation can result in metapopulations (sensu Hanski and Gilpin 1987) for some wildlife species. The survival of a local metapopulation depends on the ability of its individuals to move among neighboring patches to overcome the factors that favor extinction at any one patch. Patch boundaries can vary in their function as barriers to movements, depending on their structure, distance to nearest patch, and species behavior (Tischendorf et al. 2003). The movement occurs along corridors of conditions that favor inter-patch movements, and the condition of the corridor can also affect the function of a patch boundary as a barrier (Rosenberg et al. 1997).

Measures of fragmentation would ideally be based on quantitative, empirical information about the dispersal behavior of the subject species. Such information does not exist for any wildlife species in the region. A substitute approach consists of a few logically simple steps (Keitt 1997):

1. Select subject species that are important to manages of bay landscapes;
2. Assemble regional experts most familiar with the natural history and field population studies of the selected species;
3. Develop a rule set for each species that defines habitat patch composition and boundaries;
4. Develop maps of habitat patches for each selected species,
5. Develop protocols for calculating basic fragmentation metrics, including patch size, distance between patches, patch shape, and patch isolation;
6. Apply the protocols for metric calculations to the patch maps.

Four species or species groups were selected: (1) resident intertidal rails, especially the California clapper rail (this rule set also defines marsh patches that are separate contributors to the tidal prism of a large channel or the bay); (2) resident intertidal passerine birds (especially intertidal song sparrows); (3) resident intertidal small mammals (especially the salt marsh harvest mouse), intertidal amphibians and reptiles; and (4) migratory waterfowl and shorebirds.

The rules sets for defining patches are basic (Table 6). They are based on the best available data about the habitat affinities and usual dispersal distances of the selected species for this region. Variations in boundary or corridor quality and the effects of species behavior, including the role of individuals with relatively strong dispersal tendencies, are disregarded. As knowledge about dispersal patterns and habitat affinities improves, the habitat maps and rule sets for assessing fragmentation can be updated.

Examination of Table 6 reveals that the rule sets change from one species or group of species to another by removing dispersal barriers. The initial rule set for resident tidal marsh rails is the most restrictive, and the final rule set for water birds is least restrictive. The barriers that are removed for each successive species group, beginning with resident rails, are mostly unnatural features, such as levees and roads. For the historical landscape, the southern salt marsh song sparrow, southern salt marsh harvest mouse, and the California clapper rail had similar patch arrays, since they were all restricted to tidal marshland and had similar dispersal barriers. This may help to explain their high degree of endemism. Only the rails are restricted to tidal marsh in the modern landscape. For them, historical and modern fragmentation patterns can be compared, based on the arrays of tidal marsh patches for the rail rule set.

Table 6: Rule sets for habitat fragmentation analysis. Habitat boundaries are based on environmental conditions that inhibit natural movements of selected wildlife. Boundary definitions vary among wildlife species. For example, large areas of open water or uplands may be willingly crossed by some species and not others. A set of boundary definitions were developed for important wildlife species that inhabit tidal marshland in South Bay. The rule set starts with the species most restricted to tidal marshland and least willing to move through other habitat types. The rule set is then broadened to include other species that are les restricted to tidal marshland. For each species or group of species, a separate map of the habitat patches is generated.

Patch Types	Patch Boundary Definitions
Intertidal Rails	Patch boundaries are any or all of the following: (A) the foreshore, (B) any non-tidal area at least 200 ft wide, (C) any area of open water at least 200 ft wide at low tide, (D) any man-made levee as shown on 1:24k scale USGS topographic quadrangles, (E) any roads 4 lane or larger, (F) any "large channel" (i.e., tidal marsh channel or tidal reach of river or stream that is at least 200 ft wide in cross-section from bank-top to bank-top at most points along the channel length or that receives perennial freshwater discharge). Having considered all rules above, two patches that come together at a point are considered two separate patches because the point of intersection creates a place of such high risk of predation that two patches are ecologically separate.
Intertidal Song Sparrows	Same as Rail Patch except disregard any man-made levees from rule D that partition or separate tidal marsh or muted tidal marsh.
Salt Marsh Harvest Mouse	Same as Sparrow Patch except also disregard any man-made levees from rule D that partition or separate abandoned salt ponds (except where flooded), ruderal baylands, and diked managed marsh.
Waterfowl and Shorebirds	Same as Mouse Patch except include low-salinity and medium-salinity salt ponds, include treatment ponds and tidal flats, include upland fill less than 60 meters wide, disregard rule E (any roads 4 lane or larger), disregard rule F and disregard all tidal channels regardless of their widths.

The South Bay patch arrays for resident rails, intertidal song sparrows, salt marsh harvest mouse, and water birds are displayed as Figures 47-51. In each figure the separate patches of habitat are uniquely colored. Figures 52-55 present the results of fragmentation analyses for the California Clapper Rail. The results for rails indicate the following.

- There were historically 107 patches of clapper rail habitat in South Bay. Now there are 124 patches.
- Small patches (< 25 acres) have always accounted for a large proportion (58% to 68%) of the total number of patches in South Bay. The number of patches less than 500 acres in size has increased, and the number of patches larger than 500 acres has decreased. There are no longer any patches over about 1,500 acres.
- The minimum distance was measure between nearest neighbor patches. Historically, about 58% of the patches were less than 50 m apart. Modern land use has generally increased the distance between patches
- Patch isolation was assessed as the distance between nearest neighbor patches divided by their combined size. Larger values mean greater isolation. Rail patches have become more isolated.

- The complexity of patch shape was calculated as the ratio between the perimeter length of a patch and its total area. Patch shape for rail habitat has increased in complexity due to diking and levees. The historically broad expanses of contiguous fourth- and fifth-order tidal marsh systems have been replaced by sinuous patches that fringe the historical sixth-order tidal channels.

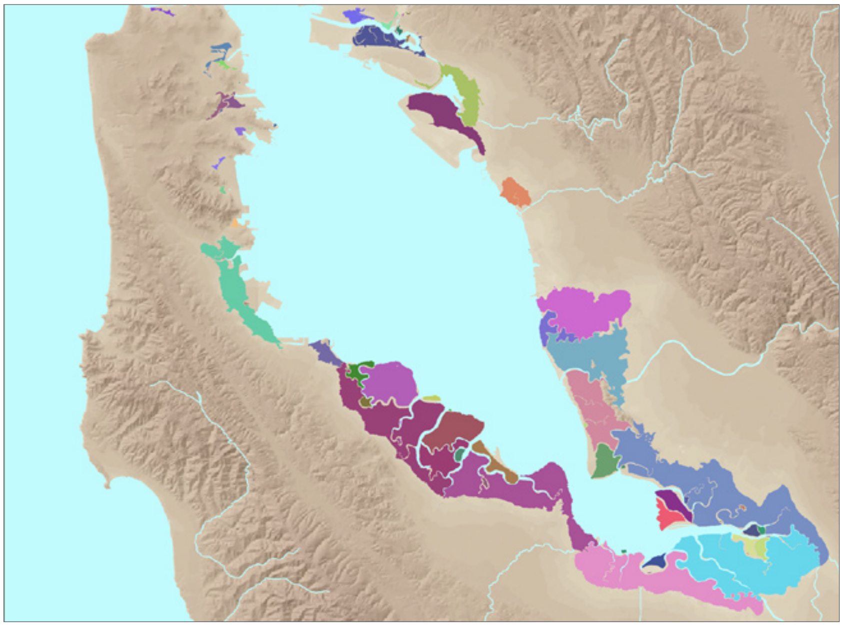


Figure 47: Example habitat patch arrays for historical intertidal rail habitat

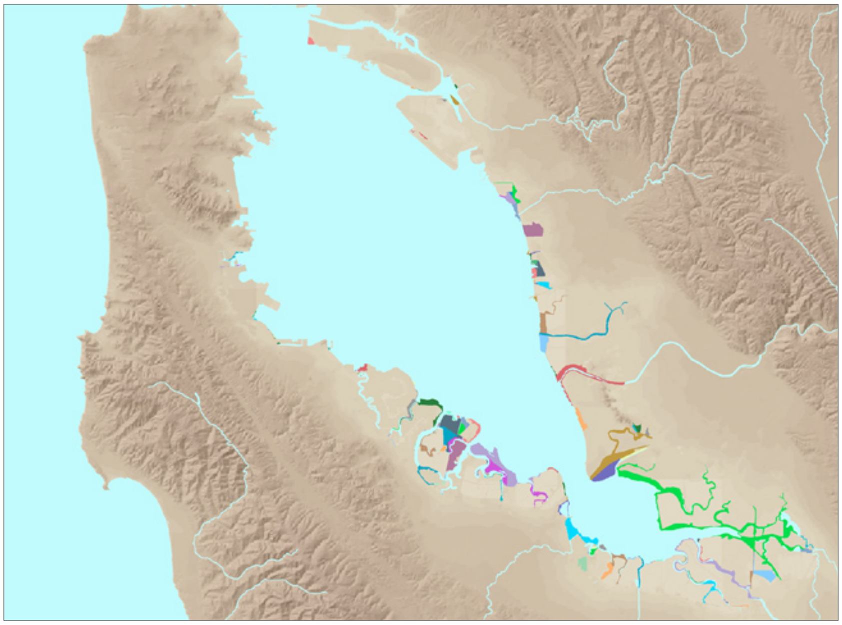


Figure 48: Example habitat patch arrays for existing rail habitat

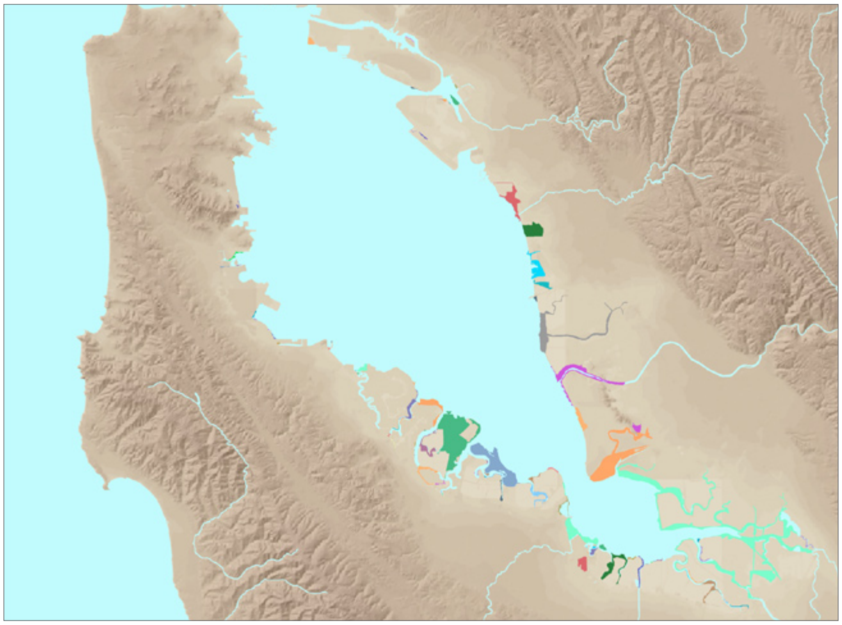


Figure 49: Example habitat patch arrays for existing intertidal song sparrow habitat

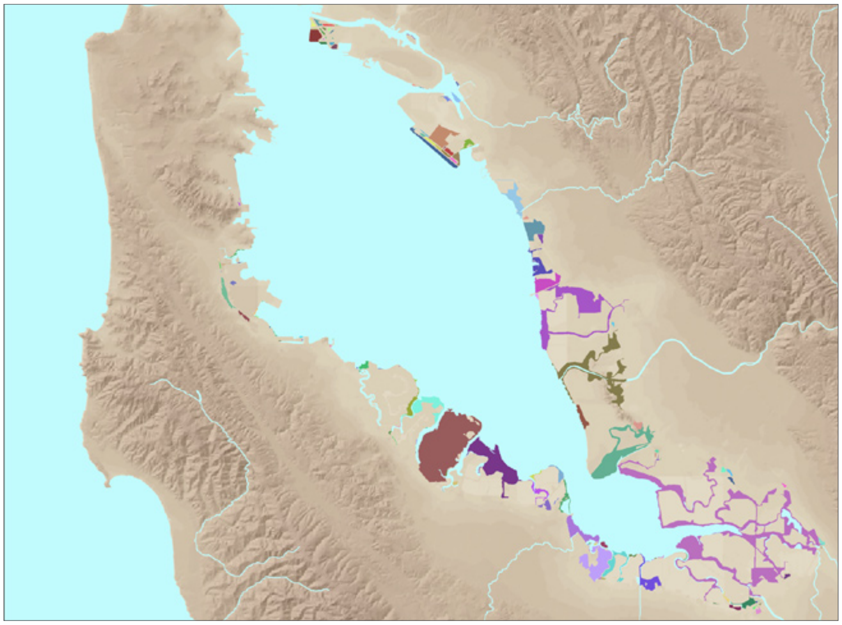


Figure 50: Example habitat patch arrays for existing salt marsh harvest mouse habitat;

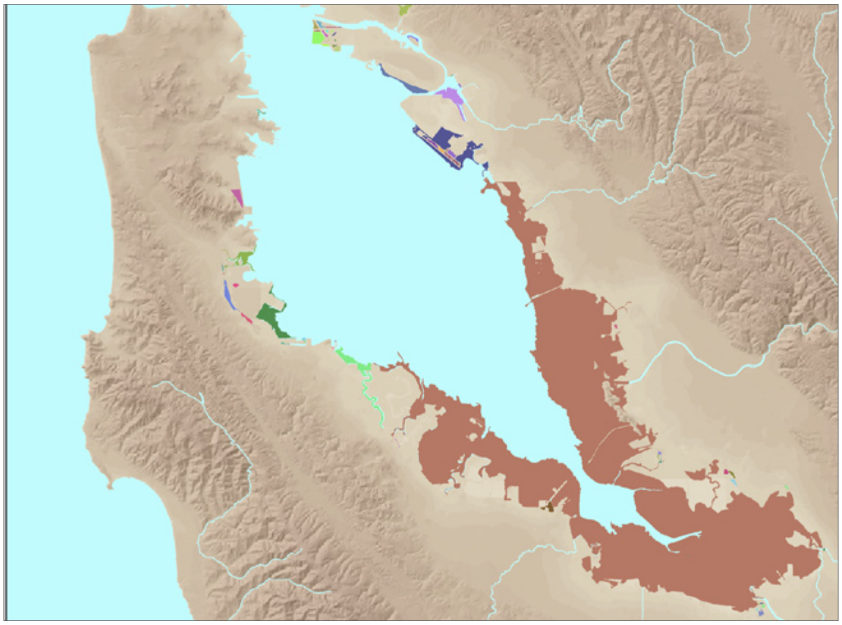


Figure 51: Example habitat patch arrays for existing waterfowl and shorebird habitat, based on the patch rules in Table 6.

Whether any of the changes in fragmentation metrics for rails cross threshold of ecological significance in not known. It is expected, however, that the reduction in patch size and shape has increased predation pressure, especially since the changes are caused by levees that serve as corridors for predators, even if the increases in inter-patch distance and isolation are not ecologically significant.

The overall loss of tidal marshland and the straightening of shorelines with levees and riprap have reduced the total length of the foreshore. Most of the historical foreshore consisted of the banks of sinuous tidal marsh channels. For the larger tidal marsh systems, the first-order channels comprised almost half of the foreshore. Analysis of aerial imaging shows that the historical reduction in tidal marsh patch size has caused chronic retrogression of first order

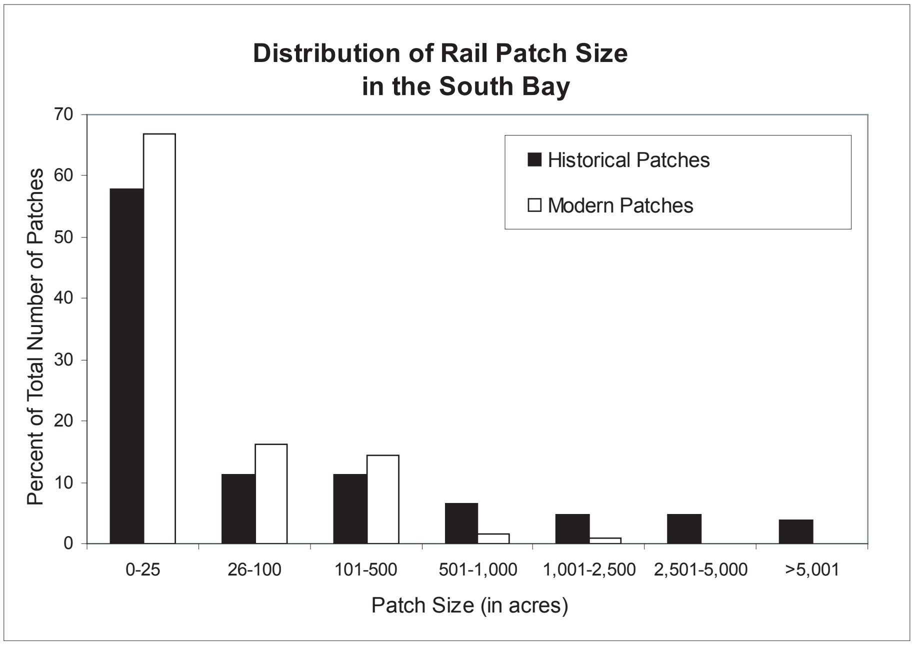


Figure 52: Distribution of historical and existing habitat patch size for the California clapper rail in South Bay. The historical and modern arrays contain some of the same patches. Small patches have been abundant throughout the historical period. However, the number of small patches (i.e., < 100 acres) has increased, and the number of large patches (i.e., > 500 acres) has decreased. Most of the historical small patches have been entirely destroyed. The existing small patches are remnants of patches that used to be larger. There are no longer any very large patches (i.e., > 2,500 acres).

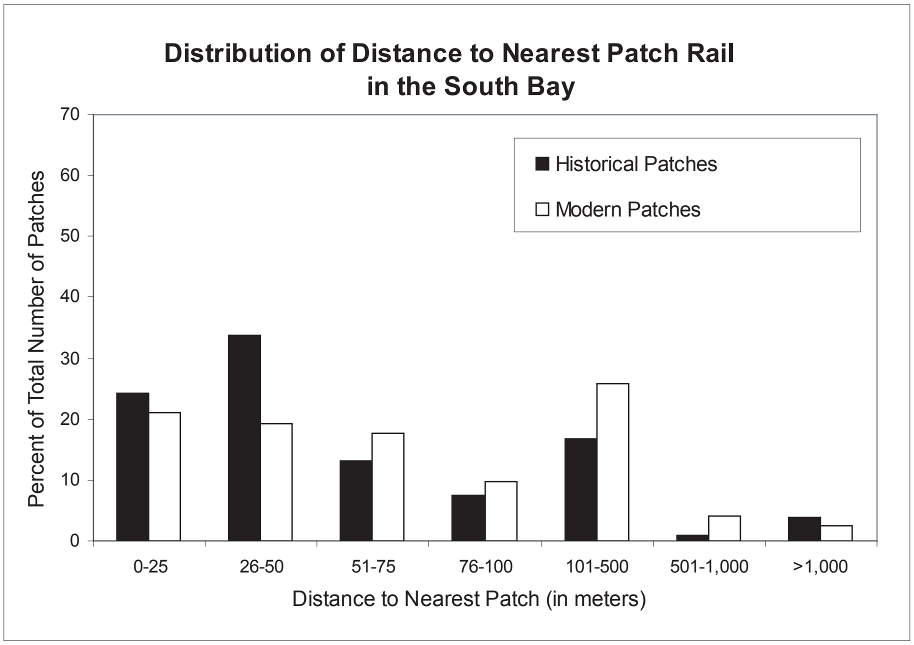


Figure 53: Distribution of distance to nearest patch type 1. Historically, 58% of the patches were within 50 meters of another Type 1 patch. Modern land use has altered the landscape by increasing the distance between patches and fragmenting the habitat for wildlife. The total number of historical and modern Type 1 patches in the South Bay is 107 and 124, respectively.

channels within remnant patches, as predicted from the model of tidal marsh dynamics (see section on dynamics in Part II on page 28). Tidal marsh reclamation and channel retrogression together have reduced the total length of the foreshore in South Bay by about 80%, from almost 11,000 km to less than 2,000 km. This represents a major loss in the boundary between tidal waters and the vegetated shore. It might be surmised that losing 80% of the foreshore has greatly reduced the ability of the intertidal zone to provide important services such as sedi-

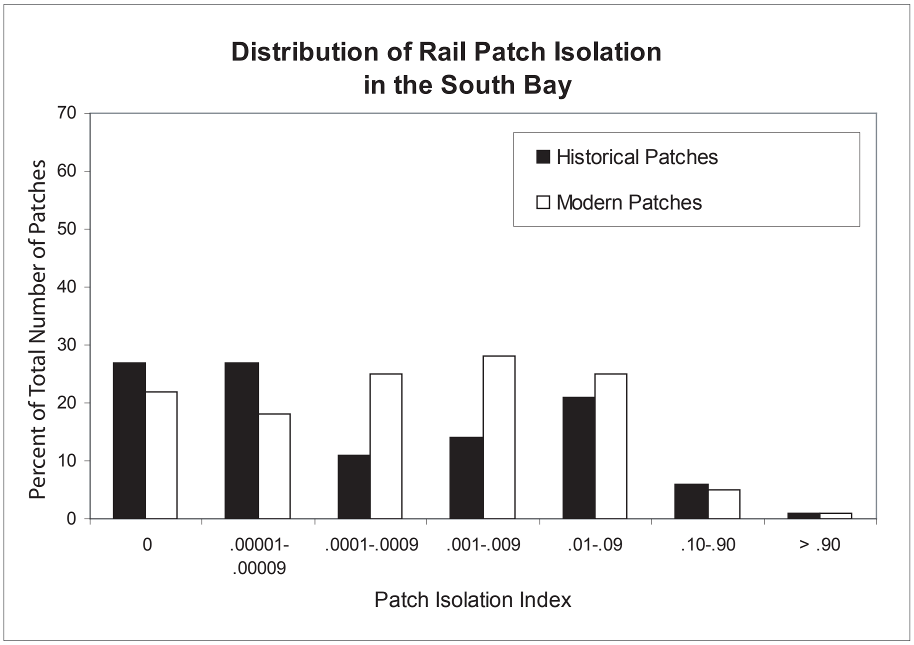


Figure 54: Distribution of patch isolation values for historical and existing patch arrays for the California clapper rail in South Bay. Isolation is calculated as the shortest distance between neighboring patches divided by their combined area. The highest values would therefore be for small patches that are far apart. There are fewer patches of rail habitat that are minimally isolated (isolation index <.00001), and many more patches that are more isolated (isolation index > .0001).

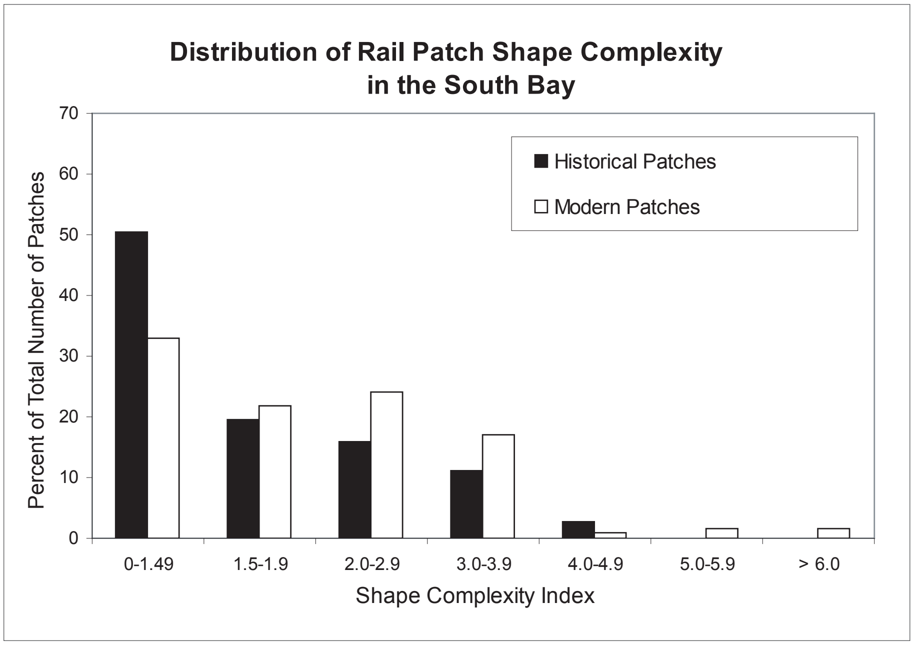


Figure 55: Distribution of shape complexity values for historical and existing patch arrays for the California clapper rail in South Bay. For any give patch, shape complexity compares the ratio of patch perimeter to patch area to the same ratio for a perfect circle have the same area as the patch. The minimum value is therefore 1.0, which would indicate that the patch shape is a perfect circle. The shapes of rail patches have become much more complex (see also Figures 47 and 48). There are much fewer round patches (i.e., shapes index <1.5). Some very long and sinuous patches have formed as fringing marshland along tidal channels that have narrowed due to losses in tidal prism (see Figure 48). Such patches may be more subject to invasion and other disturbances

ment entrapment, nutrient exchange, and support of edge species of wildlife, including the endangered salt marsh harvest mouse and California clapper rail (see Table 1).

RESTORATION IMPLICATIONS

Whether a patch of habitat is large or small depends on the species of interest. For example, a large patch for the Salt Marsh Harvest Mouse may be small for the California clapper rail. Restoration designs should reflect the habitat requirements of a group of species selected to represent a range of expected minimum requirements for habitat patch size.

Not all tidal marsh restoration projects have to be large for any species. Small patches of tidal marsh can serve as refugia for plants and wildlife, and as "stepping stones" that enable species to move between larger habitat patches.

In general, tidal marsh patches should be more round than elongate, and should not be bordered by uplands that serve as corridors for terrestrial predators, including feral pets, that tend to invade tidal marshland.

Restoration should maximize the length of the foreshore by achieving a naturalistic density of tidal marsh channels in systems that are fourth-order or larger.

V. RESTORATION TOOLS, TARGETS, AND RELATED QUESTIONS

What is the level of certainty of our knowledge?

Interactions between natural processes and land use account for existing landscape conditions. The effects of land use are difficult to assess because there are no unaffected places to show what would happen if nature worked alone. Baseline conditions reflect an unknown amount of indigenous land use. Studies of historical change typically lack evidence of interim conditions between the distant and very recent past. The work by USGS on bathymetric change is an important exception. However, land uses have become so extensive and intense that their general effects are obvious.

What's been done is clear. How much should be undone in not clear. The critical gaps in understanding pertain to thresholds of ecological response to natural change, land use change, or management actions. For example, while the elevation threshold for intertidal plant colonization is fairly well understood, the threshold of plant cover that corresponds to significant decreases in inorganic sediment demand is not known. It is difficult therefore to scale tidal marsh restoration to match the availability of suspended sediment. The threshold of marsh patch size for sustaining tidal channel networks might be known, but the influence of freshwater inputs or various edaphic factors such as grain size on channel formation is not known. The habitat affinities and food preferences are well known for key wildlife species, but their minimum viable habitat patch sizes and optimal spatial array of patches are not known. The ability of tidal marsh vegetation to respond to changes in hydroperiod is well known, but the limits of response are not known. It is also unknown, therefore, how restored marshland will survive increased rates of sea level rise. Long-term success of the Project may depend on a sustained supply of sediment from local watersheds. Sediment yield from local watersheds can be measured, but the threshold response of the watershed to sediment management is not known. Furthermore, the Project is likely to be phased, and one phase may affect another. For example, early phases may alter sediment supplies for later phases, and these effects may vary depending on the relative positions and sizes of the phased efforts. Simply stated, the ecological services of the landscapes and habitat types are well enough understood to draft broad restoration guidelines, but scaling and phasing of the restoration effort probably cannot be prescribed at this time.

What predictive tools exist for gaining an understanding of these issues and what tools are needed to reduce uncertainty to an acceptable level?

The Project is relying on hydro-geomorphic models to forecast rates of habitat development, and models of wildlife movement and survival to predict ecological endpoints, such as species composition and population density. The uncertainty of the Project grows as the forecasts extend further into the future because climatic, geologic, and land use changes that affect habitat conditions cannot be exactly known. Even with the best possible models, conditions at the 50-yr Project horizon probably cannot be known well enough to map. There are no sources of data to calibrate models for the response of habitats to climatic changes and land uses that are unprecedented in the record of habitat evolution.

The corollary is that near-term geomorphic outcomes are relatively certain. The Project may want to invest in workshops to explore ways to maximize the chances of early success despite long-term uncertainties. For example, there may be ways to prepare salt ponds for restoration by discing the substrate and farming the diked areas for marsh vegetation before breaching.

Such workshops could fit into a program of phased implementation of broad restoration guidelines. Each phase might be designed to answer questions about formative processes and ecological responses that reduce the uncertainty of subsequent phases. This adaptive approach is likely to extend the life of the Project to accommodate research and adjust the guidelines.

One advantage to this adaptive approach is that it eliminates the need for a fixed Project horizon. The 50-yr horizon that has been adopted by the Project bears no relation to any known periodicity or rate of natural processes or known administrative cycles (Table 6) except the planning period for projects funded through the federal Water Resources Development Act (WRDA). Another advantage is that it affords the Project time to adjust to unforeseeable changes in habitat controls, restoration constraints, or opportunities. A related advantage is that the phased adaptive approach could enable better integration of the Project with local watershed management initiatives, such that the Project has a greater chance to influence the upland supplies of water and sediment, and to improve the overall health of the South Bay Ecosystem.

Table 6: The duration or frequency of things that pertain to large scale tidal marsh restoration in South Bay. The purpose of this table is to identify natural or anthropogenic processes or events that are expected to occur within the planned 50-year horizon of the Project. The 50-year timeframe represents a number of generation intervals for some key wildlife species, but otherwise does not correspond to any particular cycle of nature or periodicity in the actions of people. It does, however, conform to the planning horizon of projects funded through the Water Resources Development Act (WRDA) of 1990.

QUESTION	ANSWER	SOURCE
Wildlife Ecology		
Life Span Information		
Avg. Lifespan of a Coast Live Oak (Quercus agrifolia)	250+ years	16
Avg. Lifespan of a Valley Oak (Quercus lobata Nee)	400-600 years	16
Avg. lifespan of a sycamore	400-600 years	4
Avg. lifespan of a willow		
Avg. lifespans of White Catfish/Age of maturity	3-4 yrs. to maturity	25
Avg. lifespans of Common Carp/Age of maturity	12-15 yr. lifespan in the wild	25
Avg. lifespans of coho salmon/Age of maturity	3 yr. Lifespan, 16-18 mo. to maturity	25
Avg. lifespan of chinook salmon/Age of maturity	3-5 yrs. to maturity	25
Avg. lifespan of Largemouth bass/Age of maturity	2-3 yrs. to maturity	25
Avg. lifespan of striped bass/Age of maturity	<10 years lifespan, 4-6 yrs.(Females), 2-3 (males) to maturity	25
Avg. lifespan of rainbow trout/Age of maturity	5 yr. Lifespan, 1-5 yrs. to maturity	25
Avg. lifespan of brown trout/Age of maturity	<9yrs. Lifespan, 2-3 yrs. to maturity	25
Avg. lifespan of steelhead trout/Age of maturity		25
Avg. lifespan of sturgeon/Age of maturity	~30 yr. Lifespan, 15-20 yrs. to maturity	25
Avg. lifespan of sacramento split tail/Age of maturity	5-8 yr. Lifespan, 2 yrs. to maturity	25
Avg. Life span of the salt marsh song sparrow	4 years	14
Avg. Life span of the salt marsh harvest mouse (Reithrodontomys raviventris)	8-12 months	33
Avg. Life span of the Clapper Rail	~20 years	11

continued

Table 6: (continued)

QUESTION	ANSWER	SOURCE
Wildlife Ecology		
Life Span Information		
Avg. Life Span of the Harbor Seal	20-25 years	6
Avg. Life Span of the Red Tailed Hawk	5-10 years in the wild and up to 29 years in captivity	39
Hydrology		
How long does it take to deliver 100,000 tons of sediment to the Bay?	9.3 years (based on WY 2003)	20
How long does it take to deliver 1000kg of Hg?	~ 8 - 10 years	22
Geology		
How many years does it take for the mountains to be uplifted by one meter?	350-1000 years	24
Wetlands		
Rate at which small channels come and go in tidal marshes	~ every 7 years	8
How long before suitable intertidal habitat is densely colonized by vegetation?	5 yrs.	8
Climate		
What is the interval of El Ninos?	Since 1970 El Ninos have been occurring every 2.2 years, up from every 3.4 around 1870, every 4.5 years around 1750, and every six years in the late 1600's. The data were obtained from coral growth rings from the Galapagos Islands, where the coral are particularly sensitive to water temperature from El Nino.	32, 34
What is the interval of major droughts in the Bay Area?	In the past 150 years, notable droughts (defined as less than the 30th percentile) have been during the periods of 1929-1934, 1946-1950, 1960-1966, 1975-1977, and 1987-1992.	20
What is the typical duration of droughts in the Bay Area?	4.4 years average	20
How long will it take for sea level to rise by 3 meters at historical rates?	3,000-6,500 years	16
Land Development		
How long does it take to lose 100,000 acres of wildlife habitat due to urbanization?	~ 10 years	31
How long will it take to double the area of urban land?	~60 years	31
Land Management		
How long does a typical restoration project take from planning to changes on the ground?	~10-30 years. Examples: 1. Crissy Field: 1997-1999 from actual start of restoration to end. Planning began nearly a decade before that in 1987.	17, 29
What is the average age that a person begins working on environmental projects?	~30 years old (Post Graduate School)	17
How long do people who are making major environmental policy decisions maintain the same job title and job responsibilities?	15 years	16
What is the average age that a person retires?	~64 years old	12
Are there environmental protection/restoration laws concerning specific time periods?	Water Resources Defense Act (WRDA) mandates that the project define "authorized periodic nourishment period" as "the authorized Federal participation in the periodic nourishment of the Project for a period of 50 years"	http://www.netlobby.com/WRDA_LegalAnalysis_LF.htm

What are the potential restoration targets and performance standards for evaluating the progress of the restoration project?

A variety of ideas about restoration design have been presented in the preceding Part III and Part IV of this synthesis. The core elements of those ideas are reiterated here.

The historical South Bay landscapes, habitat mosaics, and their component habitat types can serve as a flexible template for the Project. The mosaics reflect basic hydrological gradients and topography that either still exist in South Bay or can be recreated. The existing salt pond complexes at Eden Landing, Ravenswood, and Guadalupe River have the basic physiographic structure of the historical Salt Pond, West Side Saline Tidal Marsh, and Riparian Tidal Landscapes. It should be noted that there is no a-priori minimum patch size for salinas, marsh pannes, salt ponds, or sausals. Mosaics of small patches of these habitat types might be restored in smaller landscapes than existed historically. But the existing salt pond complexes are large enough to accommodate large marsh pannes in the context of replicate fourth- and fifth-order tidal marsh drainage systems, with their full complement of channels large and small.

The early salt works of South Bay might serve as a model for salt pond restoration. The salt works of the late 1800s featured salt ponds that were essentially elaborations of natural salinas and marsh pannes. The salt ponds were therefore naturalistic in shape, and were surrounded by high marshland that protected them from erosion and sediment input. Levees were low and easily repaired. Windmills were used to move water to and from ponds. The moderate size of the salt ponds afforded easy control of water levels and salinity with minimum energy expenditures.

Systematic measures of the quantity of restored habitat types should comprise the foundation of the monitoring program. These measures should focus on the shape and size of habitat patches. Strict habitat definitions, routine aerial imaging, and standard protocols for image analysis will be needed to assess changes in the distribution and abundance of habitat types within the target mosaics and landscapes. Additional measures of selected habitat elements, such as channel density, pannes, and tidal prism will also be needed to track landscape evolution.

Net accretion and erosion across the intertidal landscapes and subtidal areas should be routinely assessed. This will include measuring change in channel density and capacity, topographic change across the intertidal zone, and bathymetric change in response to tidal landscape restoration. The assessments of vertical change are essential to calibrate models of sedimentation. Workshops will be needed to consider a broad range of monitoring methods and schedules. With regard to topographic change, image analysis rather than point measures should be considered, so that the need for extrapolation is minimized. The assessments of intertidal topographic change should be augmented with measures of the organic and inorganic factions of the sediment pile, based on a spatial sampling plan that accounts for the effects of elevation and distance from tidal source. These data will help calibrate models of sediment demand.

Simple measures of the total length of the foreshore and backshore might be the most robust indicators of tidal landscape change. Any tidal marsh restoration would increase the lengths of both shorelines, but the creation of dendritic channel networks would lengthen the shoreline most. Erosion or submergence of tidal flat or marsh would shorten the shoreline. A similar measure could be used to track changes in salt ponds and pannes. In these cases, the edge of the ponded area would be measured. Ponds with naturalistic shapes would provide more edge than unnatural ponds. It is expected than many ecological objectives of the Project, including support of shorebirds, special status species, and fisheries relate to the amount of tidal edge created by the Project.

What key questions essential to the success of the restoration need to be addressed through further studies, monitoring, or research?

Project success may depend on phasing restoration to match sediment demand to available sediment supplies. During the planning for every new breach, the questions will arise: is there enough sediment and where will it come from? To help answer these questions, a South Bay Ecosystem suspended sediment budget is needed, resolved to the spatial and temporal scales of project phases.

The budget should entail assessments of fluvial/terrestrial as well as tidal/estuarine sources. The potential availability of sediment from the erosion of tidal flats and tidal channels within and adjacent to breached ponds should be considered. The yield from hillslope processes, creek incision and bank failure, and sediment piles stored behind engineered creek crossings should also be considered. These assessments need not be exhaustive, but they should describe expected differences in sediment supply between local watersheds and salt pond complexes.

Measures of demand should reflect what is known about changes in sedimentary processes, including especially the decrease in inorganic sediment demand as tidal marshland develops upward through the tidal curve. This could be ascertained by coring through well-developed marshes at varying distances from channels and tidal sources within the selected marshland, developing chronologies for the cores, and subsequently quantifying the changes in amount of inorganic sediment through time. The result would be a three-dimensional map of inorganic sediment demand per tidal marsh drainage system.

These basic terms of supply and demand can serve to scale each restoration phase. But they are unlikely to generate accurate predictions of the rate of habitat evolution, since this depends on knowing how fast sediments will be delivered to restoration sites, what the rate of sediment entrapment will be, and how these rates are affected by climatic variability and changes in topography or bathymetry outside of the restoration phase. The rates can only be known for sure by monitoring topographic and bathymetric change. As the empirical record of change grows, it can be used to improve the predictive capabilities of simulation models. Models of sediment dynamics might be tested according to their ability to reproduce the known patterns and rates of shoaling and marsh development in the remaining fifth- and sixth-order channels among the existing salt ponds (see Table 4).

There are lingering questions about the efficacy of restoring natural tidal impoundments, such as salinas and marsh panes. Whether or not these features provided the same kinds of ecological services as the modern salt ponds can probably be determined by thorough review of historical environmental accounts for South Bay. There is a wealth of written records of the character of these features that could be recovered through local and regional archives.

A separate question pertains to the sustainability of salt ponds as compared to more natural features, such as salinas and marsh pannes. Salt ponds exist because peripheral levees prevent tidal incursion and inputs of suspended sediment. But the levees have to be maintained, and the hydroperiod of salt ponds must be artificially regulated. The efficacy of converting some salt ponds into large pannes surrounded by high marshland lacking channels should be investigated. The analysis of historical marsh form and function suggests that a broad high marsh plain would dissipate wave energy, filter sediments, and naturally regulate the panne hydroperiod. In the context of broad, high marsh plains, large pannes might be created that sustain themselves without levees, and seasonal and spatial variations in panne salinity could be naturally achieved. In general, the ability to scale natural processes to meet the Project objectives with minimum operational costs should at least be tested through experimental designs for early phases of restoration.

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