Physical Evolution of Restored Breached Levee Salt Marshes in the San Francisco Bay Estuary

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Abstract

Since 1972 over 940 ha (2,300 ac) of leveed former salt marsh sites around San Francisco Bay have been restored to tidal action, purposely or through natural processes. The evolution of these sites can inform predictions of rates of marshplain evolution and establishment of tidal channel systems. A review of the history of 15 re-flooded sites ranging in size from 18 to 220 ha (45 to 550 ac) and in age from 2 to 29 years indicates that marshplain vegetation with more than 50% cover was established at nine of the sites within 4 to 20 years. The remaining six sites aged 2 to approximately 20 years continue to be less than 50% vegetated. The evolution of these sites is consistent with the following simple conceptual model of the physical evolution of restored tidal marshes in subsided breached sites. Initially, deposition of estuarine sediment builds up mudflats that allow vegetation establishment once elevations are high enough for vegetation to survive. Sites that are initially lower in the tidal frame take longer to vegetate than those that are initially higher. Three factors appear to retard the time frame for vegetation establishment: limited estuarine suspended sediment supply, erosion of deposited estuarine muds by internally generated wind waves, and restricted tidal exchange. These factors affect evolution more significantly in larger sites. The comparatively short time frame for vegetation colonization and marshplain evolution experienced in earlier, smaller, and/or less subsided breached levee restorations may not necessarily be replicable by simple levee breaching on larger subsided restoration sites now being planned. Our review of the 15 sites also indicates that the formation of tidal channels within the marshes is greatly dependent on whether and how high the site was filled before breaching. Filled sites at high intertidal elevations (above approximately 0.3 m below mean higher high water) can vegetate quickly but after several decades may show little development of tidal channels.

Key words: breach, geomorphic evolution, restoration, salt marsh, San Francisco Bay.

Introduction

Over 90% of the 76,000 ha of historic salt and brackish tidal marsh that once fringed San Francisco Bay has been converted to farmland, salt production ponds, and urban development (Nichols et al. 1986; Goals Project 1999). In 1965 the State of California, responding to environmentalist pressure, prevented further destruction of wetlands in San Francisco Bay by passing the McAteer-Petris Act, among the first "no net loss of wetlands" legislations in the United States. The same environmentalist pressure then led to actions to restore leveed former tidal marshes. Since the first restoration project at the 32-ha Faber Tract near Palo Alto in 1972, more than 10 major breached dike restoration projects have been implemented by a variety of agencies and organizations (San Francisco Estuary Project 1999; Steere & Schaefer 2001). An overview of the history of these efforts is provided by Williams and Faber (2001).

In the first two decades of restoration most of these projects were carried out by different entities with little coordination or even explicit planning of restoration actions. Even fewer projects were monitored after implementation. This fragmentation and lack of rigor in the restoration design process has been a significant impediment to developing an estuary-wide learning curve for restoration practitioners. Nevertheless, long-term monitoring of site evolution was initiated with private funding in 1986 at two restoration sites and since 1996 has been undertaken at three more sites (Table 1). The first restoration project that was a true "second generation" design that used monitoring information from earlier projects to guide its design criteria was the 120-ha Sonoma Baylands project implemented by the U.S. Army Corps of Engineers and the California State Coastal Conservancy in 1996 (Williams & Florsheim 1994).

The 29-year restoration history of a large, heavily modified, and urbanized mesotidal estuary can be in-

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Table 1. Summary of tidal marshes restored though levee breaching in San Francisco Bay, 1978–1998.

Site	*Previous Land Use*[a]	*Salinity Regime*	*Area*[b] *(ha)*	*Date Breached*	*Age*[c] *(yr)*	*Typical Initial Ground Elevation*[d] *(m NGVD)*	*Current Tidal Range*	*Time to 50% Vegetative Cover*[e] *(yr)*	*Tidal Slough System*	*Availability of Long-Term Monitoring*	*Comments/Data Sources*
Bair Island, outer (pond B2)	Salt pond	Saline	73	1979–1983	17–21	+0.30	Full	2–14	Reestablished in remnant channels	—	BIESTF 1977; Josselyn et al. 1991.
Carl's Marsh	Agricultural land	Saline	18	1994	6	−0.91	Full	>6[f]	Developing	1996–present	Siegel 1998; also referred to as Petaluma River Marsh
Cogswell	Salt pond	Saline	40	1980	20	+0.73	Full[g]	13–20	Developing	—	Analysis applies to one area of a larger restoration. TCES 1981; Perez 1981
Faber Tract	Dredged material placement	Saline	32	1972	29	+0.91 (+0.79 to +1.28)	Full	Less than 5–10 (estimate)	No channels in highest areas; extensive channels in lower areas (see text)	—	Small initial breach in 1971; breach widened in 1972. A 1983 aerial photograph shows the site completely vegetated except at the lowest elevations. PWA 1994; P. Williams, personal observation
Greenpoint	Agricultural land[h]	Saline	24	1986	14	0	Full[g]	12	Developing	—	Also referred to as Toy marsh. PWA 1991; PWA unpublished 1989 field surveys.
Muzzi, inner	Dredged material placement	Saline	28	1976	24	+1.34[i]	Full	~5	Channels excavated; no natural channel formation	1986–present	PWA 1994; PWA 2000
Muzzi, outer	Dredged material placement	Saline	20	1976	24	+0.46	Full	~14	Extensive channels	1986–present	PWA 1994; PWA 2000
Nevada-Shaped	Leveed mudflat[h]	Saline	24	1979–1981	19–21	−0.30 to −0.61 (estimate)	Full	>~20[f]	NA (intertidal mudflat)	—	Was originally intended for use as a borrow site and marina (B. Buxton, personal communication, 1999). NOS 1980; PWA 1999
Pond 2A	Salt pond	Brackish to saline	223	1995	5	+0.91[j]	Full	~3	Reestablished in remnant channels	1997–present	MEC et al. 2000; P. Baye, personal communication, 1999. Rate of vegetation from Goals Project (1999).
Pond 3	Dredged material placement	Saline	45	1975	25	+0.91 to +1.52	Full	≤5	Few channels in the highest areas; slightly more channels in the lower areas	—	PWA 1991
Slaughterhouse Point	Agricultural land[h]	Brackish to saline	97	1983	17	0	Full[g]	>17[f]	NA (intertidal mudflat)	—	PWA 1999; J. Zentner, personal communication, 1999; P. Baye, personal communication, 1999
Sonoma Baylands Main Unit	Agriculture with subsequent dredged material placement	Saline	109	1996	4	+0.15	Damped[g]	>4[f]	NA (subtidal mudflat)	1994–present	PWA et al. 1999; PWA 2000; PWA unpublished field surveys
Tolay Creek	Agricultural land	Saline	20	1998	2	NS	Damped[g]	>2[f]	NA (subtidal mudflat)	—	Vincencio 1999
Warm Springs	Deep borrow pit	Brackish	81	1986	14	−4.57	Full	>14[f]	Mudflat channels developing	1986–present	PWA 2000
White Slough	Agricultural land[h]	Brackish to saline	105	1978	22	+0.30	Full	15	Developing	—	Wetlands Research Associates et al. 1995

[a] Planned habitat restoration unless noted.
[b] Includes only the area subject to tidal action; may differ from other published values. Total area = 940 ha.
[c] Age is number of years since breach as of 2000.
[d] At time of breach.
[e] Time to 50% vegetative cover is based on aerial photograph review and site reconnaissance.
[f] Less than 50% cover in 2000.
[g] Tidal range initially and/or currently damped. Cogswell: period of initial tidal restriction unknown; Greenpoint: damped for the first 2–3 years; Slaughterhouse Point: ~70% tidal range in 1994; Sonoma Baylands Main Unit: ~0.27 m diurnal range in 2000; Tolay Creek: existing tidal range not available, but significantly restricted.
[h] Accidental breach or not otherwise a planned habitat restoration. Greenpoint, Slaughterhouse Point, and White Slough: abandoned levee breaches; Nevada-Shaped: planned breach, but not for habitat restoration.
[i] This site subsided to a typical elevation of +1.0 m by 1981.
[j] Initial elevation of +0.9 m based on PWA et al. (1997) elevation transect. Initial elevations may have been closer to +0.6 m NGVD in some areas (P. Baye, personal communication, 1999).
BIESTF, Bair Island Environmental Study Task Force; TCES, Tiburon Center for Environmental Studies; WRA, Wetlands Research Associates; NA, not applicable.

structive for other estuary-wide restoration efforts now being initiated. As of the year 2000 over 940 ha had been returned to tidal action through intentional breaching (690 ha) or accidental breaching (250 ha) (Table 1). Planning is now underway for major restoration projects at Montezuma (720 ha), Cullinan Ranch (600 ha), Middle and Inner Bair Island (650 ha), and Hamilton Airfield (320 ha) (San Francisco Estuary Project 1999) (Fig. 1). There are now proposals and potential funding to restore approximately 14,000 ha of tidal marsh over the next 20 years (Steere & Schaefer 2001).

For many of these larger sites it is the intent to restore wetland functions by simple levee breaching and subsequently allow the site to evolve naturally. The main impetus for these large-scale restoration initiatives has historically been the desire to reestablish significant areas of vegetated marsh and tidal channel habitat, particularly for the recovery of threatened and endangered wildlife species that use the marshplain and tidal channel edge. In recent years there has been a realization of the importance of restoring San Francisco Bay marshes for estuary-wide ecologic functions, including their potential value as salmonid nursery habitat. So far the role of potential restored tidal marshes in sustaining the estuarine food web has not been a prominent objective, even though the scale of potential restoration being contemplated could have significant beneficial effects.

In the planning and design of new large-scale restoration projects it is important to predict how wetland functions will evolve over time. The design approach now favored in San Francisco Bay restoration is to grade a site template that initially creates a wetland in an immature state and encourages natural sedimentation to create the desired mature wetland habitat structure (Williams 2001). This is sometimes loosely defined as a "self-design" approach. We describe what we have learned from our work over the last 20 years planning, designing, and monitoring tidal wetland restoration

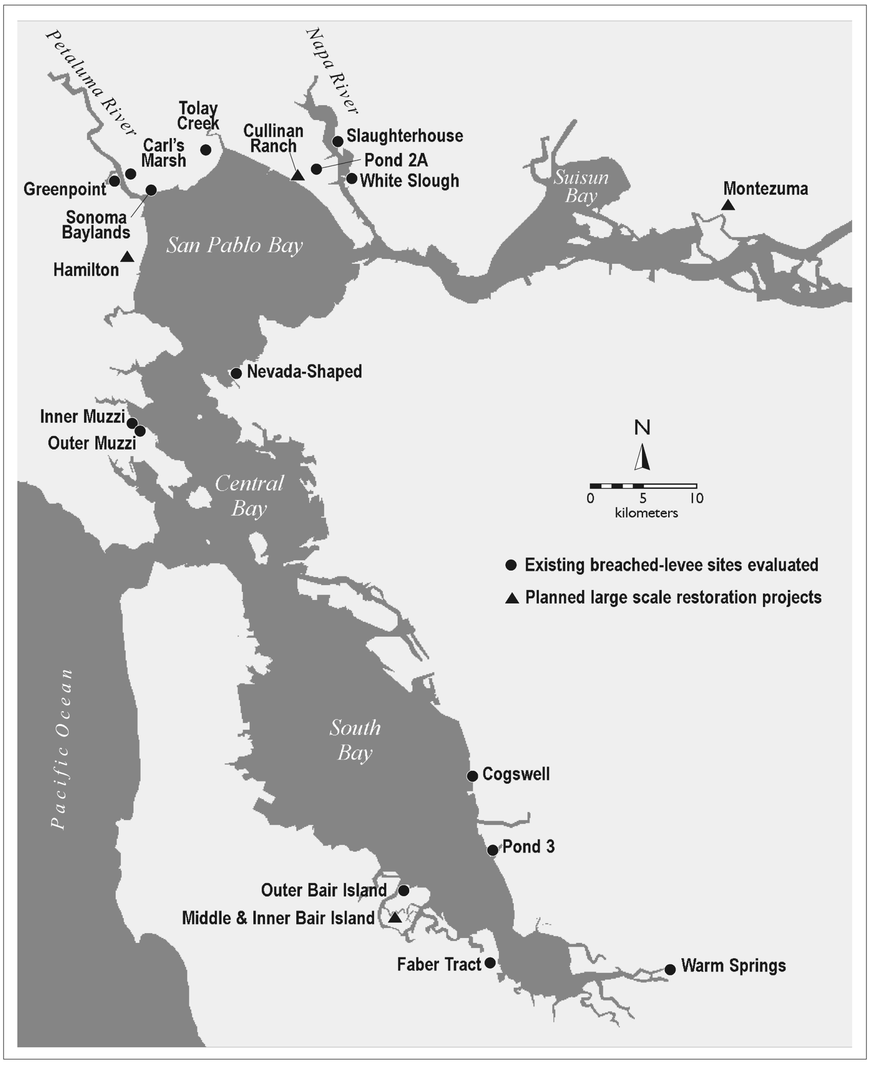


Figure 1. Locations of breached levee restoration sites in San Francisco Bay, including intentionally and accidentally restored sites.

projects. Our focus was to analyze the rates and patterns of evolution of two wetland subhabitats important for fish and wildlife (Goals Project 1999) that are usually included as tidal salt-marsh restoration objectives: vegetated marshplains and tidal channels, referred to as "sloughs" in San Francisco Bay. Because these subhabitats are easily quantifiable they are often selected as indicators of wetland habitat value.

San Francisco Bay Setting

San Francisco Bay (lat 37°50′ N; long 122°20′ W) is the description applied to the salt-water influenced portion of the San Francisco Bay estuary that was formed by the Holocene marine transgression at the mouth of the Sacramento and San Joaquin Rivers. The estuary is characterized by mixed semidiurnal tides whose average diurnal range varies from about 1.5 to 3.0 m within the estuary. Winds are typically strongest in the summer months when an onshore sea breeze blows inland up the estuary to the Central Valley of California. Estuarine sediments in San Francisco Bay are mainly clays with some silt (Buchanan & Ruhl 2000). These sediments are subject to frequent resuspension and recirculation due to the action of wind waves and tidal currents (Schoellhamer 1996).

The ancient marshes fringing San Francisco Bay were mainly formed 2,000 to 6,000 years ago when rates of sea level rise of the Holocene transgression declined by an order of magnitude to their current rates of approximately 1 to 2 mm/yr (Atwater et al. 1979). In this latter period extensive coastal marshplains expanded as sea level rose, covering the upland topography—as can be seen at China Camp marsh (Fig. 2). It appears that the landward transgression was often accompanied by progressive erosion of the bayfront edge from wind wave action. Vegetated marshplains were able to keep pace with rising sea level at about the elevation of the mean higher diurnal tide (mean higher high water [MHHW]) through inorganic sediment accretion and organic accumulation. As marshplains rose in elevation a complex dendritic system of sinuous tidal channels extended inland and kept pace vertically and, except for smaller first- and second-order channels, tended to remain stable in place (Collins et al. 1987). The dominant salt marshplain vegetation was *Salicornia virginica* (pickleweed), with *Spartina foliosa* (California cordgrass) growing along the margins of tidal channels. In San

Figure 2. China Camp Marsh, shown here in 1991, is one of the few extensive areas of ancient marsh remaining in the San Francisco Bay estuary.

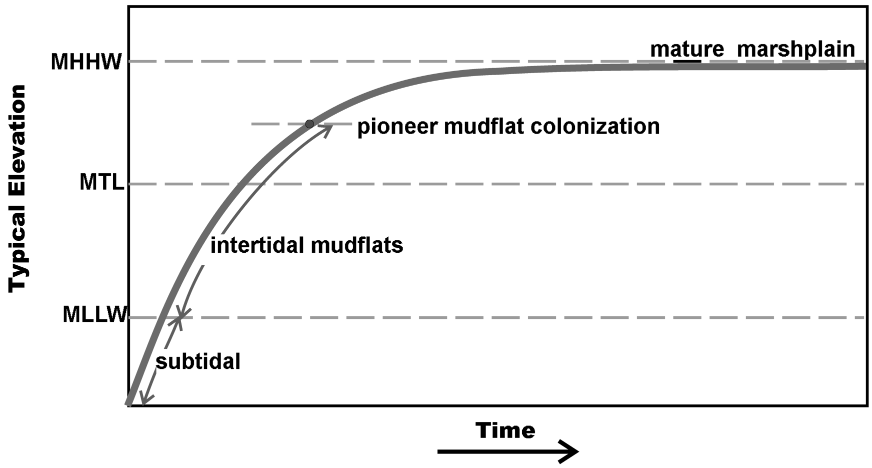


Figure 3. Conceptual model of tidal marshplain evolution with time since breaching. MHHW, mean higher high water; MTL, mean tide level; MLLW, mean lower low water.

Francisco Bay local mean tide level is typically 0.1 to 0.2 m National Geodetic Vertical Datum[1] (NGVD) and local MHHW typically is 0.8 to 1.3 m (Atwater et al. 1979). For a more complete description of the physical characteristics and ecology of San Francisco Bay see Nichols et al. (1986).

Once the original marshplains were diked for agriculture or salt pond production 135 to 35 years ago (Goals Project 1999), they subsided by up to 3 m depending on the duration and effectiveness of land drainage (Woodward Clyde Consultants et al. 1998). Regional groundwater withdrawal has caused additional subsidence in the southern part of the South Bay. Typical subsidence for diked tidal marshes throughout the Bay ranges between 0.6 and 2.0 m, which means that unless fill material is used to raise ground elevations before breaching many sites are initially below minimum elevations for vegetation colonization.

Conceptual Model of the Physical Evolution of Restored Tidal Marshes

Once tidal action is restored to a subsided site through a deliberate or accidental levee breach, physical processes are set in motion that dictate how the site will evolve. These processes for minerogenic marshes such as those fringing San Francisco Bay have been described in conceptual models of youthful salt marsh development. A discussion of these models is provided in Allen (1990) and summarized in simplified form here. Flood tides carry in suspended estuarine sediments that deposit in the slack waters of the flooded site. Ebb tidal currents are insufficient to resuspend deposited muds and silts, except in the locations of nascent tidal channels. As sediment accumulates large areas of intertidal mudflats form. As they rise in elevation the period of inundation decreases and rate of sedimentation declines. Once the mudflats reach a high enough elevation relative to the tidal frame pioneer colonization can occur. Colonization becomes progressively quicker through lateral expansion once initial colonizing plants have established. Figure 3 illustrates in elevation view the conceptual model of how the elevation of a subsided site is anticipated to evolve in response to estuarine sedimentation processes, from subtidal to intertidal mudflat, to initial mudflat colonization by salt-tolerant marsh plants, to ultimately a fully mature vegetated marshplain. For this representation episodic events are smoothed out and sea level rise is excluded. Any long-term sea level rise would result in increased ground elevations over time.

In San Francisco Bay *Spartina foliosa* is typically the first vegetation to colonize a depositing mudflat. Pioneer colonizing *Spartina* seedlings require mudflat elevations of approximately 0.2 to 0.4 m above mean tide (Siegel 1998; authors' unpublished data) and sufficiently quiescent conditions for seeds to germinate (Friedrichs & Perry 2001). These colonization elevations translate to 0.4 to 0.6 m NGVD.

Once mudflat colonization occurs a vegetated marshplain forms through lateral expansion of rhizomes from each established plant on the mudflat and from plants along the site perimeter. Once established *Spartina* can expand to lower elevations, as low as 0.0 to 0.3 m below mean tide (−0.15 to +0.15 m NGVD) (Atwater & Hedel 1976). The presence of vegetation contributes to vertical accretion through sediment trapping and organic accumulation (Eisma & Dijkema 1997). As the marshplain rises within the tidal frame, estuarine sediment accretion slows exponentially until a marshplain forms at an elevation below the highest spring tides (Allen 1990) or in the case of San Francisco Bay marshes within a few decimeters of MHHW (Atwater et al. 1979).

[1]National Geodetic Vertical Datum is a vertical datum fixed at the mean sea level of 1929.

Concurrently with the physical evolution of the marshplain shown in Figure 3, the tidal drainage system starts to form. As mudflats accrete to intertidal elevations tidal channels become defined; they are further imprinted as vegetation establishes and the marshplain develops (Beeftink & Rozema 1988). Depending on their contributing tidal watershed, channels may eventually incise into the evolving mudflat (French & Stoddart 1992; French 1993). As vegetation becomes established these mudflat channels become imprinted in the marshplain. For Pacific Coast mesotidal estuaries such as San Francisco Bay, simple empirical geomorphic models can be developed to predict the hydraulic geometry of tidal channels based on the tidal prism of the area they drain (Williams 1986; Williams et al. 2002, this issue).

Three important physical processes can separately or in combination retard or prevent the physical evolution of a subsided restored site to a vegetated marsh:

(1) *Restricted tidal exchange.* Tidal action can be significantly damped by the hydraulic constriction of a narrow levee breach or small inlet channel. Over time scouring action tends to enlarge these constrictions, eventually restoring full tidal exchange (a full tidal range within the site). Until this occurs the volume of sediment entering the site on the flood tide will be reduced proportionally to the reduction in tidal prism, extending the time of evolution. Poor low tide drainage can also delay vegetation establishment.
(2) *Limited sediment supply.* Long-term average suspended sediment concentrations brought into the site on the flood tide are influenced by the long-term sediment budget of the estuary and by the proximity of the site to the estuarine circulation turbidity maxima or proximity to extensive intertidal mudflats where sediment can be locally resuspended by wave action. Sediment concentrations tend to be lowest for interior marshes, furthest from the estuarine sediment supply.
(3) *Internally generated wind waves.* Propagating waves create turbulence in the water column that prevent deposition, and breaking waves create high bed shear stresses that resuspend deposited estuarine muds, allowing sediment to be exported on the ebb tide. In South San Francisco Bay, Schoellhamer (1996) found that suspended sediment concentrations were well correlated with seasonal variations in wind shear stress. Wave-induced bed shear stresses are a function of wave power, which in turn is a function of fetch length and wind velocity squared and are inversely related to water depth (U.S. Army Corps of Engineers 1984). This means that vulnerability to sediment disturbance and reworking from wave action increases as mudflats build in elevation. Conceptually this results in a retarded evolutionary trajectory or, for high wave energy sites, one whose asymptote will be a permanent mudflat too low to be colonized by emergent vegetation (Fig. 4). The effect of wind waves in maintaining water depths below colonization elevations has been identified by Nichols and Boon (1994) as a primary determinant of the morphology of coastal lagoons. Most U.S. lagoons for which accretionary status has been summarized (Atlantic and Gulf Coast lagoons) are in open water equilibrium with the depth determined primarily by the depth of effective wind wave action (Nichols & Boon 1994).

The conceptual model of tidal wetland evolution in restored sites provides the framework for using observed data to address the following questions:

- What is the time frame for vegetative colonization and how is this explained by the conceptual model?
- What factors affect formation of a dendritic tidal drainage network?
- What are the physical constraints on site evolution

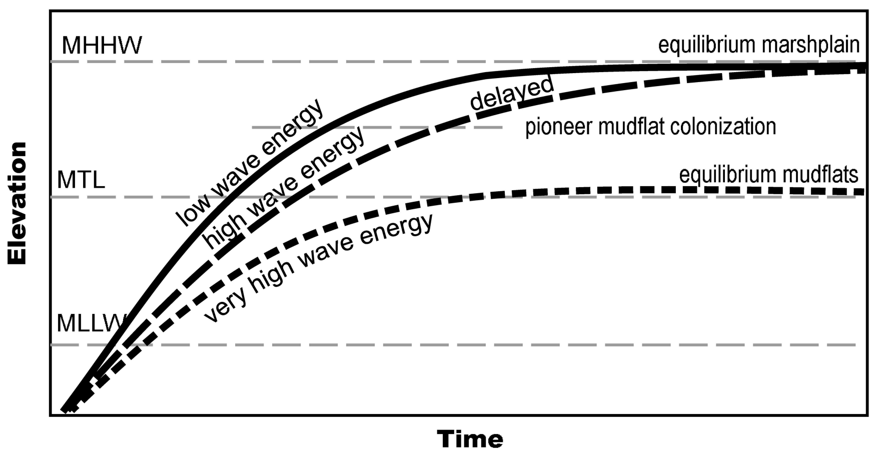


Figure 4. Conceptual effect of wind waves on tidal marshplain evolution.

Table 2. Site wind wave information.

Site	*Primary Fetch Length (m)*	*Average Wind Speed (m/s)*	*Wave Power Index*
Bair Island, outer (pond B2)	1,040	2.8	1.7
Carl's Marsh	400	2.8	0.5
Cogswell	550	3.4	1.2
Faber Tract	610	2.7	0.9
Greenpoint	430	2.5	0.4
Muzzi, inner	370	2.5	0.4
Muzzi, outer	530	2.5	0.6
Nevada-Shaped	370	3.3	0.7
Pond 2A	1,980	3.3	5.5
Pond 3	1,070	3.4	2.8
Slaughterhouse Point	1,100	3.3	2.7
Sonoma Baylands			
Main Unit	300	NS	NS
Tolay Creek	NS	NS	NS
Warm Springs	580	2.7	0.8
White Slough	910	3.3	2.2

NS, not studied.
Sources: Fetch length measured from scaled aerial photographs or maps; wind data from California Department of Water Resources 1978 and J. Dingler (personal communication, 1999).

(e.g., restricted tidal exchange, suspended sediment supply, and internally generated wind waves)?

METHODS

We studied 15 large (>18 ha) breached levee restoration sites in San Francisco Bay, including both intentionally and accidentally restored sites. Study site locations are shown in Figure 1 and site summary information in Tables 1 and 2. The 15 sites include most of the larger restoration sites in San Francisco Bay and all those for which long-term physical processes monitoring data were available.

We identified potential study sites using inventories of completed restoration projects (San Francisco Estuary Project 1996, 1999), regional wetlands mapping (Goals Project 1999), aerial photograph review, and field reconnaissance. There is no comprehensive up-to-date index of breached levee sites around San Francisco Bay that includes unplanned (accidental) breached sites, and inventories of restored sites have not systematically distinguished between tidal and nontidal wetlands or between the types of tidal restoration (breached levee vs. upland excavation or managed tidal marsh).

For each site we identified the following parameters:

- Type of site: planned/unplanned restoration and previous land use;
- Area restored to tidal action;
- Date of breaching;
- Typical initial ground elevation at the time of breaching;
- Extent of tidal range, whether tidal range was initially constricted;
- Approximate length of time until site has more than 50% vegetative cover;
- Existence of developed tidal drainage system;
- Availability of long-term monitoring;
- Typical salinity regime based on location relative to freshwater sources;
- Internal fetch length in the predominant sea breeze wind direction;
- Average annual wind speed from the nearest weather station.

Although San Francisco Bay at the time of writing had a 29-year history of restoration activities, very little data concerning restored marshes has been published in peer-reviewed literature, which largely focuses on natural marsh functions as opposed to restoring marshes. We used available monitoring reports, our own published and unpublished field surveys, local wind station data, site reconnaissance, and other data sources for site characterization. Sources for these data (Table 1) are generally government agency documents. We used time series of aerial photographs to characterize percent vegetative cover and presence of tidal channels. Long-term monitoring of elevation transects available for three of the sites—Warm Springs, Muzzi March, and Carl's Marsh—was used to estimate more detailed evolutionary trajectories.

Formation of the Tidal Drainage System

To evaluate the effect of initial elevation on formation of the drainage system we used elevation surveys and aerial photographs showing channel details. We looked in particular at four sites: inner and outer Muzzi Marsh, which were filled to different elevations; Faber Tract, where dredged material was placed at a slope over the entire site before breaching; and Pond 3, which was filled high in the tidal frame. The elevation of dredged material on the Faber Tract at the time of breaching was estimated based on reported placement volumes, typical depositional slope, and original ground surface. This estimate was generally consistent with coring logs along a surveyed transect (PWA 1994).

Constraints on Site Evolution

Restricted Tidal Exchange. Five of the sites—Cogswell, Greenpoint, Slaughterhouse, Sonoma Baylands, and Tolay Creek—initially experienced restricted tidal exchange due to a hydraulically constricted inlet channel. We used available data to assess the time frame for erosion of the inlet and to assess the effects of restricted exchange on rates of evolution.

Limited Sediment Supply. One significant data gap is the lack of long-term suspended sediment concentration measurements close to the breached site inlet. Regional suspended sediment concentrations are measured by the U.S. Geological Survey only in the deepwater channels of San Francisco Bay (Buchanan & Ruhl 2000). Suspended sediments in the water column above the shallow mudflats of the Bay, more representative of inflow to the sites, have been monitored only over short periods of time in a few locations. Because of this lack of information we were unable to systematically distinguish between those sites subject to higher or lower average estuarine sediment supply.

In the absence of site-specific suspended sediment data we used sensitivity analysis modeling to provide a general assessment of the effects of suspended sediment supply on rates of long-term sedimentation. The model, a one-dimensional mass-balance model, is based on the methods of Krone (1987) for calculating coastal marsh sedimentation. It calculates the depth of sediment deposited during each period of tidal inundation and sums that amount over many tide cycles. Inputs to the model are initial ground elevation, ambient suspended sediment concentration (constant) in flood tide waters, tide levels (time series), particle fall velocity, sea level rise, and dry density of sediments in the deposit. We modeled a range of suspended sediment concentrations from 100 to 400 mg/L. This range, representing the estimated range of long-term average near-bottom concentrations, is from regional suspended sediment monitoring (Buchanan & Ruhl 2000) and from unpublished model runs calibrated to observed local sedimentation rates at selected locations.

Internally Generated Wind Waves. For each site we calculated an average wave power index as an indicator of water velocity at the bed and the potential for wind wave inhibition of sedimentation. The wave power index is proportional to the product of wave height squared and wave period. Wave height and period calculations were based on linear wave theory, using shallow water wave forecasting equations, and follow standard methods described in the U.S. Army Corps of Engineer's Shore Protection Manual (1984; equations 3-39 to 3-40). They were calculated for each site using the simplifying assumptions that wind speed is equal to the average hourly wind speed and fetch equal to fetch in the predominant wind direction. To facilitate comparison between differently aged and evolved sites, wave indices used a constant depth of 1.5 m and vegetative condition was identified or estimated (in the case of younger sites) for a constant time of 15 years after breaching.

Results and Discussion

Time Frame for Vegetative Colonization

The time frame for vegetative colonization is determined by occurrence of extensive spontaneous colonization of emerging mudflats by *Spartina* or *Salicornia.* For sites where initial ground elevations were higher than the typical colonization elevation more than 50% vegetative cover was achieved quickly. For more deeply subsided sites colonization is slower and relies on the

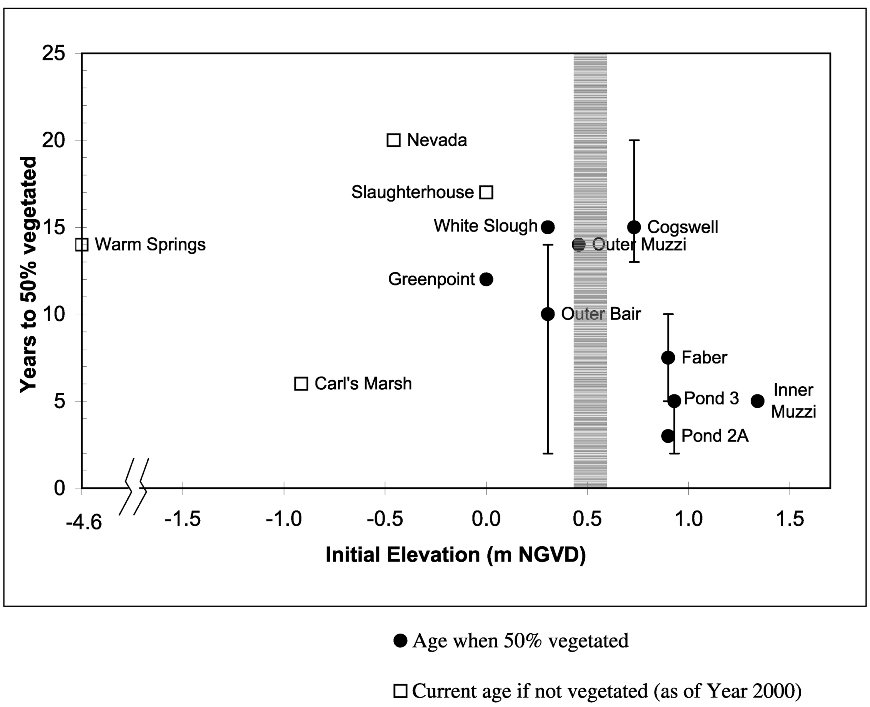


Figure 5. Number of years for marshplain vegetation to establish versus initial elevation. Shaded bar identifies the approximate *Spartina* colonization elevation. Error bars represent the range of uncertainty based on the data available to bracket the time frame. Damped tidal sites excluded.

Figure 6. Carl's Marsh 5 years after breaching (fall 1999). Isolated patches of *Spartina foliosa* and *Scirpus maritimus* (alkali bulrush) have colonized the newly deposited interior mudflats.

rate of sedimentary processes building up mudflats to suitable colonization elevations.

For two of the sites examined there are indications that net sedimentation rates are extremely slow, possibly indicating that a permanent mudflat may be an evolutionary end point. Figure 5 shows the time frame for colonization for all the sites that currently have a full tidal range (13 sites). The four highest sites, initially at or above approximately 0.9 m NGVD, were vegetated with *Salicornia* within 4 to 10 years. The four sites between 0.3 and 0.9 m NGVD, generally near the mudflat colonization elevation for *Spartina*, colonized in approximately 10 to 20 years. For the five lower elevation sites the rates of evolution varied. The first initial mudflat colonization occurred within 3 years at Carl's Marsh (Siegel 1998), the smallest of the sites. Figure 6 illustrates colonization on emerging mudflats at Carl's Marsh after 5 years of evolution, although after 7 years (at the time of publication) vegetative cover is still less than 50%. Three deeper and larger (Nevada, Slaughterhouse, Warm Springs) sites had no significant mudflat colonization after 14 to approximately 20 years. For most sites where mudflats had not yet been colonized slow lateral expansion of perimeter vegetation by rhizomes was occurring. Typical lateral expansion of marsh vegetation at the Warm Springs site is shown in Figure 7. Average vegetative expansion rates from the perimeter of Carl's Marsh were approximately 1.5 to 1.8 m per year over the first 2 years (Siegel 1998). At this rate of expansion it would take more than 50 years to vegetate even a small site like Carl's Marsh if this were the only vegetative process occurring. Very little perimeter edge colonization is occurring at the approximately 20-year-old Nevada site (Fig. 8), which is intertidal, or the 17-year-old Slaughterhouse site.

The observed evolutionary trajectories of the three monitored sites are shown in Figure 9. Inner Muzzi began at relatively high elevations and was vegetated with *Salicornia* within approximately 3 years. For Carl's Marsh *Spartina* initial colonization occurred as soon as mudflats reached appropriate elevations. For the deeply excavated Warm Springs marsh, sedimentation has been rapid (Fig. 9). Although some mudflats are now higher than the fringing vegetative marsh that has spread lat-

1986 (Pre-breach grading)

1997 (11 years of tidal evolution)

Figure 7. At Warm Springs intertidal benches graded before breaching are colonized with salt and brackish marsh vegetation 11 years after reintroduction of tidal action.

erally from the perimeter levees, they remain below the initial colonization elevation and widespread spontaneous vegetative colonization has not yet occurred (Williams et al. 2002, this issue). The time required for *Spartina* to be replaced by *Salicornia* can be long. At two sites, outer Muzzi and the lowest part of Faber Tract (below the typical elevation plotted in Fig. 5), the marshplain vegetation is still predominantly *Spartina* more than 20 years after its initial colonization.

Formation of Tidal Channel System

Generally, for subsided sites that were not filled (e.g., Carl's Marsh, Cogswell, Greenpoint, outer Muzzi, and White Slough), dendritic tidal channel systems developed as intertidal mudflats deposited. For shallowly subsided salt ponds, such as Outer Bair and Pond 2A (Fig. 10), where the topographic imprint of the original tidal channel system remained intact, the channels appear from aerial photographs and available field surveys to have scoured and reestablished after the sites were breached. For the four sites that were filled with dredged materials (inner and outer Muzzi, Pond 3, and part of Faber) the tidal drainage system has not developed in the areas filled close to the equilibrium marshplain elevation (MHHW) after 24 to 29 years of tidal action. The marshplains in these higher areas were rapidly vegetated with S*alicornia.* The negative effect of

Figure 8. The Nevada-Shaped site currently remains below the *Spartina* colonization elevation, approximately 20 years after breaching. This 1995 photograph is representative of existing (2000) site conditions.

high fill elevations on channel development is apparent in the difference in tidal channel development between inner and outer Muzzi, filled to different elevations before breaching (Fig. 11).

The Faber Tract and Muzzi data indicate an approximate threshold fill elevation at the time of breaching below which extensive channels form (PWA 1994; Williams & Florsheim 1994). This threshold initial elevation is best demonstrated in the 29-year-old Faber Tract, which was filled with hydraulically placed material that sloped from an elevation of approximately 1.3 to 0.8 m NGVD. Below an initial elevation of about 1.16 m NGVD (0.15 m below MHHW) some tidal channels have formed; below about 1.01 m NGVD (0.3 m below MHHW) numerous channels have formed (PWA 1994) (Fig. 12).

Constraints on Site Evolution

Restricted Tidal Action. The inlet channels at three sites that initially experienced damped tides—Cogswell, Greenpoint, and Slaughterhouse—have now eroded sufficiently to provide full tidal ranges within the sites. At Greenpoint this erosion took less than 4 years. Tides at two of the younger sites with long inlet channels—Tolay and Sonoma Baylands—remain damped. At Sonoma Bay-

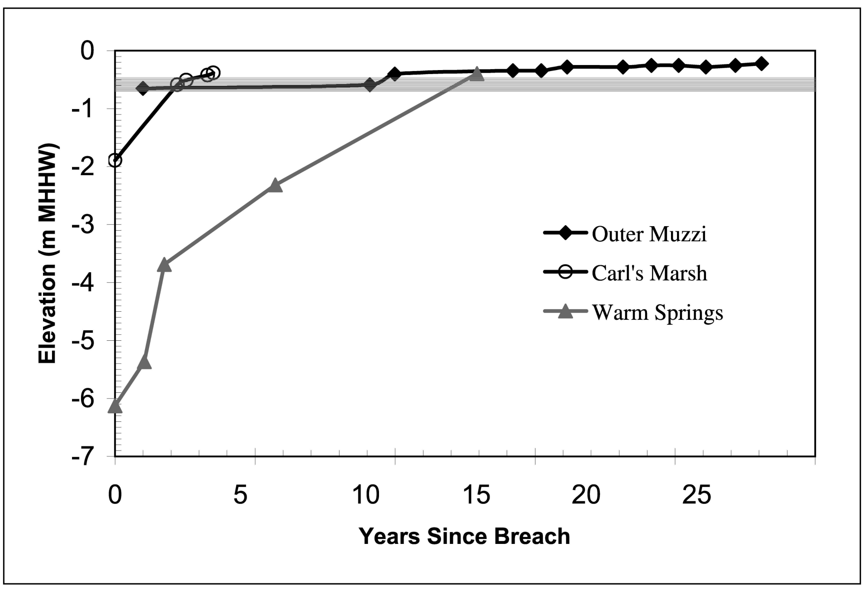


Figure 9. Evolutionary trajectories of three sites and approximate *Spartina* colonization elevation (represented by the shaded bar). Elevations are presented relative to MHHW, the approximate predicted marshplain elevation. At Carl's Marsh the 1997–1998 El Niño winter, 3.5 years after breaching, assisted rapid sediment accretion. Sources: Siegel 1998; PWA 2000.

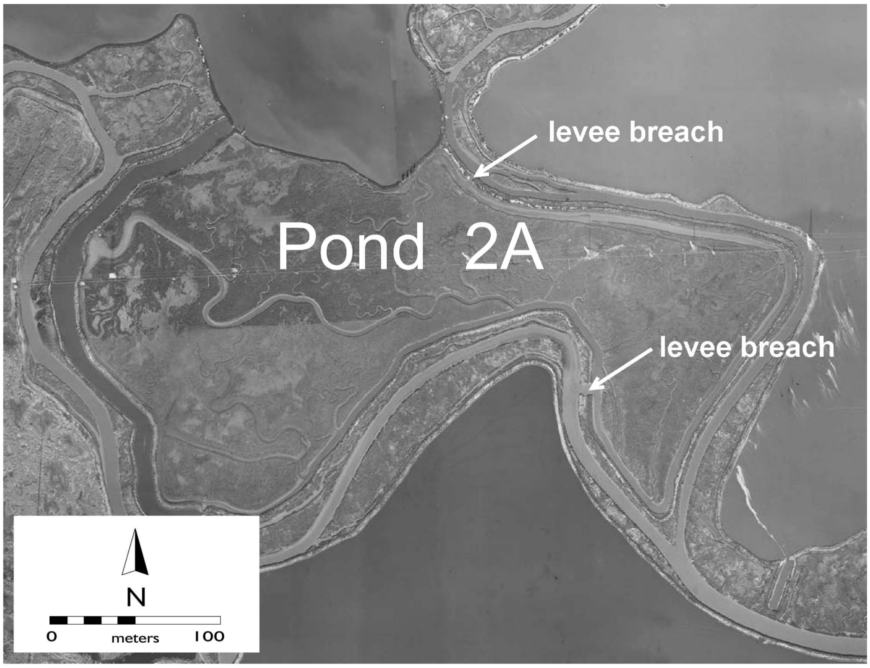


Figure 10. Reintroduction of tidal action to Pond 2A allowed remnant slough channels in this former salt production pond to reestablish and resulted in more than 80% brackish tidal marsh vegetative cover within three years (Goals Project 1999). December 1998 photograph.

lands, where physical processes monitoring is available, the channel is eroding but after 5 years still significantly reduces the tidal range (PWA et al. 1999; Williams et al. 2002, this issue). Damped tides not only reduce the volume of sediment brought into the site in a tidal cycle, but can also aggravate wind wave action and inhibit vegetation colonization by increasing the inundation period at low elevations as have been observed at Tolay.

Limited Sediment Supply. Model results indicate that the time required for a 1.5-m subsided site to reach mudflat colonization levels ranges from 10 to more than 30 years over the likely range in suspended sediment supply (Fig. 13). These rates are for sites sheltered from wind wave activity and reflect long-term average trends. They do not represent short-term fluctuations in sedimentation due to seasonal and interannual variations.

Internally Generated Wind Waves. Figure 14 shows the vegetative state of the fully tidal sites as a function of wave index and initial elevation. The data are consistent with the known phenomenon of wind wave suspension and

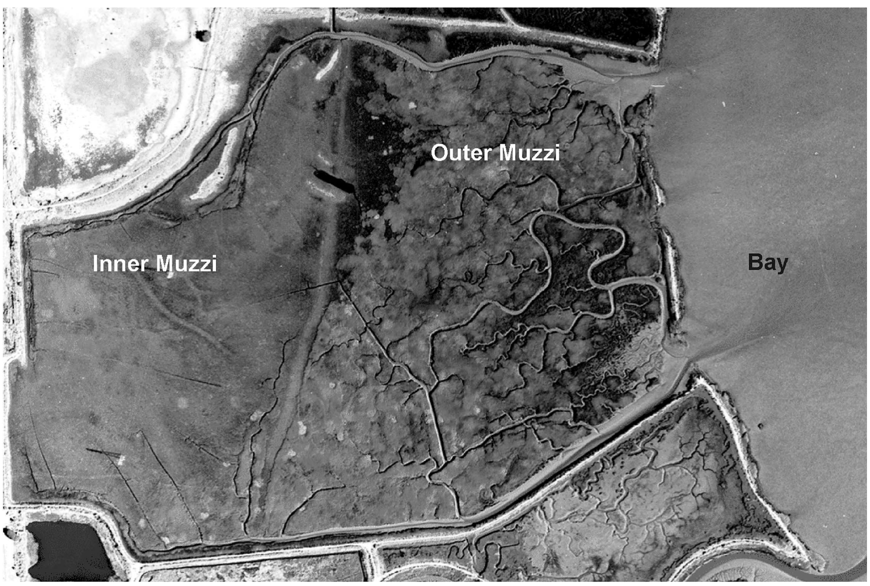
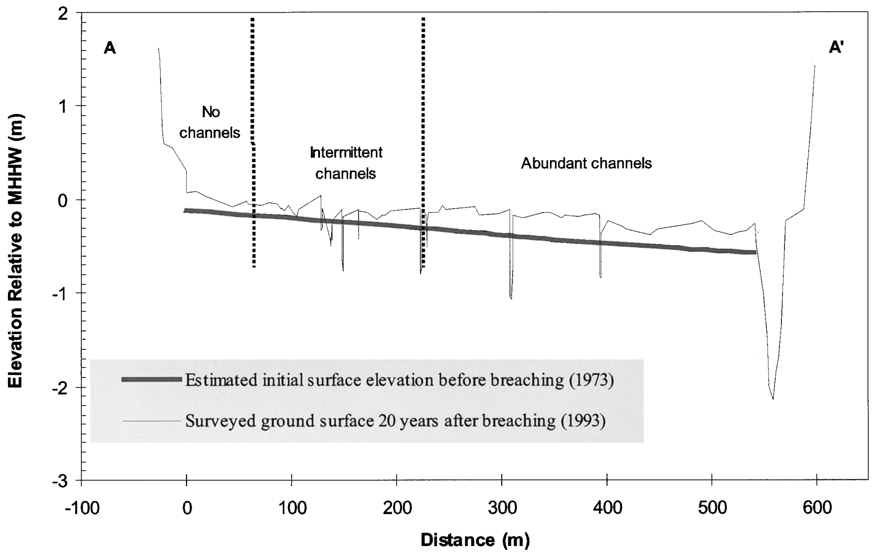


Figure 11. Relative channel abundance at inner and outer Muzzi Marsh 22 years after breaching (1998). At the time of breaching inner Muzzi Marsh was filled to 0.4 m above MHHW and outer Muzzi to 0.5 m below MHHW. Ten years after breaching inner Muzzi had subsided to 0.1 m above MHHW.



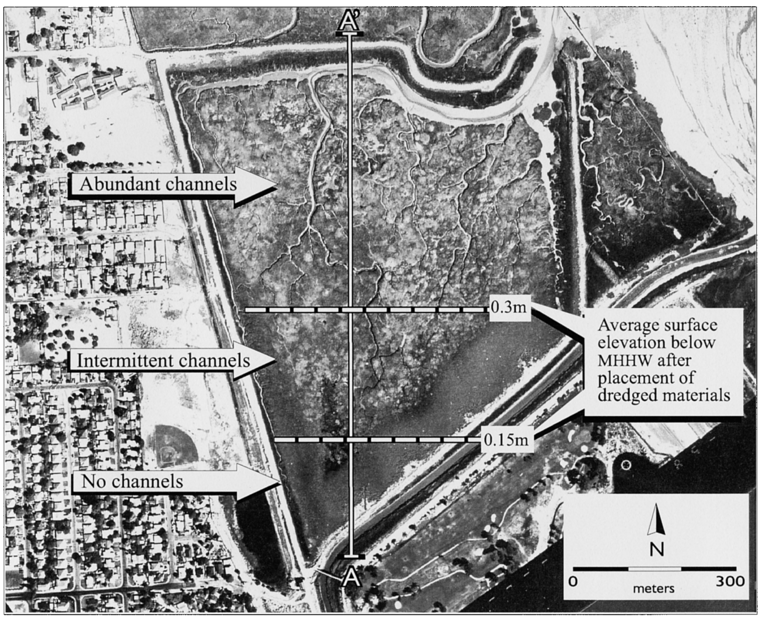


Figure 12. Pre-breach ground surface elevation and slough channel abundance at Faber Tract. Elevation profile at top shows estimated initial ground elevations before breaching (1973) and zones of channel abundance corresponding to the zones indicated at bottom in the 1995 aerial photograph. MHHW, mean higher high water. Source: PWA 1994.

transport but do not provide a conclusive illustration of this phenomenon. Sedimentation rates at two of the higher energy sites—Nevada and Slaughterhouse—have been very limited, and after 15 years mudflat elevations are still too low for colonization, even though these sites were not originally deeply subsided. In comparison with Carl's Marsh the physical evolution of these sites appears to have been retarded. The data may reflect a wind wave sheltering effect at Carl's Marsh. However, other factors complicate the relationship. At Slaughterhouse an initially damped tidal range and probable lower suspended sediment supply because of its location further from the Bay mudflats are expected to have retarded rates of development. At Carl's Marsh probable higher suspended sediment supply because of its location near the Bay mudflats is expected to have accelerated rates of development. The 7-year-old Carl's Marsh (at time of publication) is now vegetating rapidly and is expected to have a significantly vegetated marshplain by year 15. So far no deeply subsided site in high wave energy conditions has a vegetated marshplain after approximately 17 to 20 years.

Implications for Restoration Design

(1) Realistic predictions of the time frame of evolution need to be incorporated in tidal wetland restoration planning. These predictions are used as the basis for determining performance criteria for different habitats within the marsh. The successful restoration of

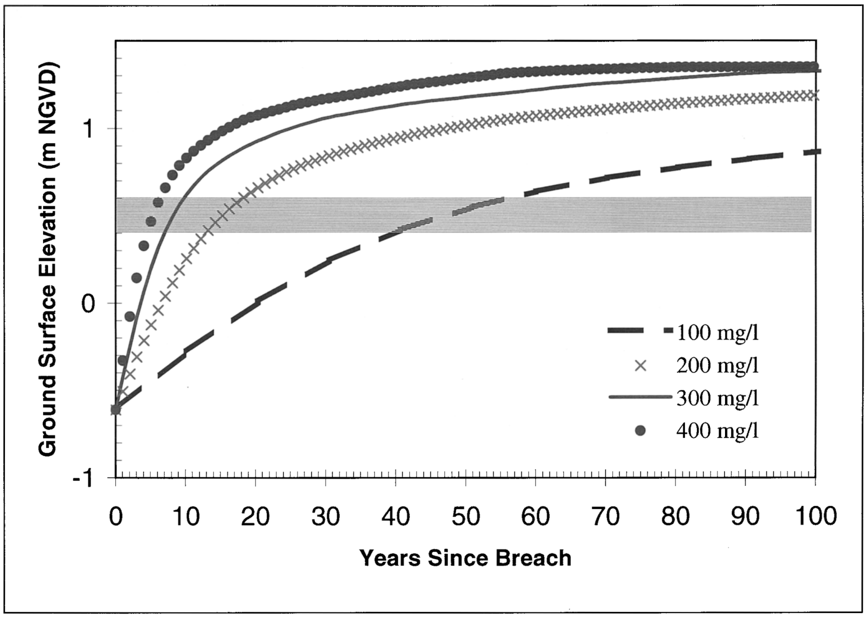


Figure 13. Effect of suspended sediment concentration on marshplain evolution over time for a site sheltered from wind wave action. Shaded bar identifies the approximate *Spartina* colonization elevation. Prediction is based on tides at the Presidio, no sea level rise and 550 kg/m^3 dry density of inorganics typical for San Francisco Bay. NGVD, National Geodetic Vertical Datum, a vertical datum fixed at the mean sea level of 1929.

tidal wetland functions in sites like Faber Tract, Muzzi, Carl's Marsh, and Pond 2A has helped generate substantial public support for new large scale restoration around San Francisco Bay. However, it should be appreciated that many of the sites proposed for restoration present additional constraints on site evolution. Many of the large areas of diked former marshes suitable for restoration are deeply subsided and located along interior channels that typically have lower suspended sediment concentrations than channels close to the Bay margin. The large size of these restoration projects makes them subject to higher internally generated wind wave energy. These factors in combination make it likely that evolution rates to achieve vegetated marshes will be slower than observed in the smaller, more sediment rich, and less subsided sites that have been restored to date.

(2) It is possible that levee breaching could result in the creation of extensive areas of long-term or even permanent intertidal mudflats instead of vegetated marshplains. This is a theoretical possibility that cannot be rejected based on the observations of site development to date. No deeply subsided breached

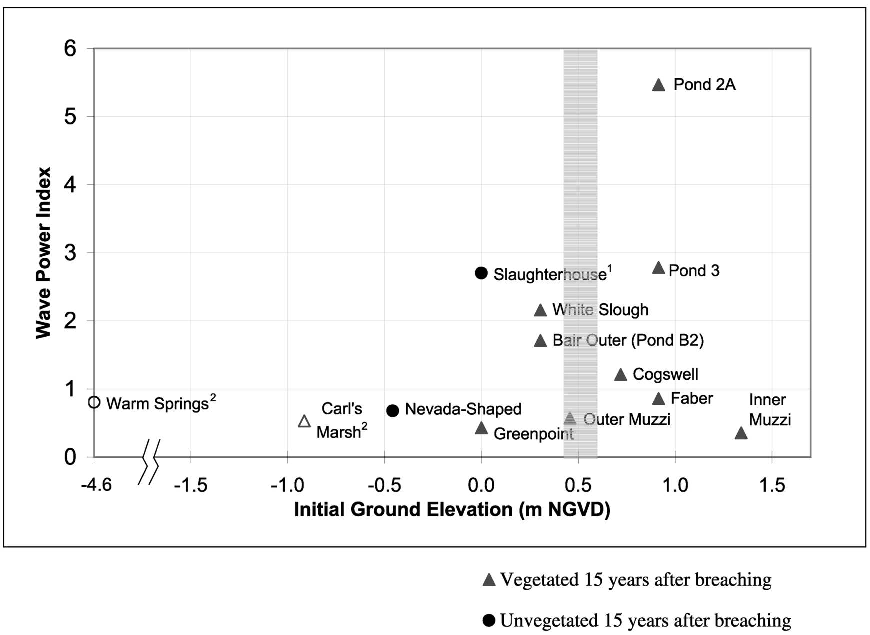


Figure 14. Initial ground elevation, wave power index, and vegetation status of study sites. Vegetative status refers to at least 50% cover. Most vegetated sites are either near or above the *Spartina* colonization elevation (represented by the shaded bar) or are low energy sites. The few unvegetated sites are higher energy and/or initially low elevation. [1]Slaughterhouse site evolution has been slowed due to initially restricted tidal exchange. [2]Open symbols at Warm Springs and Carl's Marsh refer to expected vegetative condition at year 15 (both sites are younger than 15 years old).

site with high wave energy and a low to moderate sediment supply has been observed to develop into vegetated marsh in San Francisco Bay. (The Warm Springs site had high suspended sediment concentrations.)

(3) It is possible to develop design criteria for the initial site grading template that will maximize rates of evolution of desired habitat characteristics in large subsided restoration sites. This can typically be accomplished by measures such as raising ground elevations, sheltering the site from high energy wind waves, ensuring that the full tidal range is not dampened by channel constrictions, and, wherever possible, locating levee breaches close to sources of high suspended sediment.
(4) Tidal wetland restoration can rely on natural physical and vegetative processes to restore wetland functions once physical constraints on evolution have been adequately addressed by the design.
(5) Restorations that include the placement of fill to accelerate marshplain establishment should avoid overfilling, which impedes tidal channel formation.
(6) Pre- and post-project monitoring of key physical characteristics, such as mudflat elevation and tidal range, are recommended to assess rates of evolution and whether or not performance criteria have been achieved. There is an unmet need for archiving, dissemination, and quality control of long-term monitoring data required by practitioners to effectively learn from prior restoration experience.

Conclusions

A review of the state of 15 restored marshes in San Francisco Bay ranging in age from 2 to 29 years indicates that the evolution to a vegetated marshplain with a well-developed tidal drainage system can occur within a period of less than 5 years to more than 20 years depending on initial site conditions. For sites subsided below elevations suitable for mudflat colonization, more than 7 years (the age of Carl's Marsh at time of publication) is required to allow the evolution of a substantially vegetated marsh. For the larger restoration projects now being considered in San Francisco Bay, the evolutionary trajectory can be retarded by initially restricted tides, limited sediment supply, and internally generated wind waves. Our review of the 15 sites also indicates that filled sites at high intertidal elevations can vegetate quickly but after several decades may show little development of tidal channels.

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