Design Guidelines for Tidal Wetland Restoration in San Francisco Bay

Prepared by Philip Williams & Associates, Ltd. and Phyllis M. Faber
Prepared for The Bay Institute
Funding provided by the California State Coastal Conservancy

Low tide in San Pablo Bay National Wildlife Refuge.
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1. INTRODUCTION

Over the last 150 years, approximately 90% of the tidal marshes that fringed San Francisco Bay have been destroyed as a result of progressive diking and filling for agricultural, salt pond, and commercial development. Within the last three decades, however, there has been a dramatic change in public attitudes towards wetlands. They are now valued as uniquely productive natural resources and public policy now seeks not only to protect existing marshes, but also to restore former marshes as functioning wetland ecosystems.

Accordingly, The Bay Institute, with funding from the California State Coastal Conservancy, retained Philip Williams & Associates, Ltd. (PWA) and Phyllis M. Faber (Consultant Team) to evaluate and document actual restoration experience in San Francisco Bay and produce this design guidelines report.

The focus of this work is necessarily limited to:

- San Francisco Bay;
- saline tidal marshes fully connected to the Bay, excluding managed wetlands;
- addressing pragmatic practical design questions often encountered in restoration practice—as opposed to scientific research or regulatory compliance questions;
- advice based upon experience and observation; the guidelines are neither regulation nor specification.

The report's target audience is all individuals who have some degree of responsibility for decisions made on tidal wetland restoration design, including regulatory agency staff, land managers, resource managers and restoration practitioners.

We recognize that restoration practice—as well as restoration science—is continually evolving, with considerable uncertainties and unknowns. The guidance described in this report is based upon observations and experience from monitoring the evolution of restored sites. There are uncertainties related to wetland restoration and there are new approaches, untried as of yet, that need to be explored. We have highlighted these uncertainties and have suggested avenues of research to address them in Section 5. For this reason we see this report as a "living document" and have termed it the 2004 Version.[1] We anticipate that new insights will be provided in future years by continued monitoring data from restored sites and from the results of the CALFED-funded BREACH and IRWM research studies. At some point, we hope there will be an opportunity to update this version.

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[1] We acknowledge the San Francisco Bay Conservation and Development Commission (BCDC) had the foresight to produce an initial design guidelines report at the outset of the restoration era, which could be termed the 1983 Version (see Harvey, H. T. and P. B. Williams (1983). California Coastal Salt Marsh Restoration Design. ASCE Third Symposium on Coastal and Ocean Management, Coastal Zone 83.).

Since the early 1970s, over 45 tidal marsh restoration projects have been constructed around the Bay, restoring tidal action to more than 1,130 hectares (2,800 acres) (WRMP 2003). Over the next 20 years, with current initiatives being implemented, it is likely that thousands more hectares will be restored to tidal action (Steere and Schaefer 2001). Early restoration projects have been implemented by a variety of different entities, with widely different planning approaches and designs. Unfortunately, monitoring of the long-term evolution and performance of these "experimental" or first generation restoration sites was rarely carried out. This has impeded our collective ability to answer key practical design questions (Williams and Faber 2001).

Fortunately, in 1986, with the support of local foundations and citizens groups (Marin Community Foundation, San Francisco Foundation, Fred Gellert Family Foundation, and Marin Audubon Society) Phyllis M. Faber and PWA were able to initiate the first long-term monitoring of two restored sites in San Francisco Bay, at Muzzi Marsh and the Warm Springs Marsh (also referred to as Coyote Creek Lagoon). In later years, long-term monitoring was initiated in more restored sites, notably Sonoma Baylands by PWA for the U.S. Army Corps of Engineers (USACE) in 1994, Carl's Marsh by Stuart Siegel in 1996, Crissy Field Marsh by the National Parks Conservancy in 1999, Martin Luther King Marsh by Wetlands and Water Resources (WWR) for East Bay Regional Parks, and Cooley Landing for U.S. Fish and Wildlife Service (USFWS) in 2000. Table 1 and Figure 1 describe the characteristics and location of these monitoring sites and other restoration sites referenced in this report.

A Scientific Review Committee (see acknowledgements) oversaw the development of the guidelines. The committee met with the Consultant Team twice (February 2003 and June 2004). At the beginning of the project, the contents and methodology were presented and discussed with the committee. The Committee's comments on later drafts were considered and incorporated into the final draft.

The Bay Institute organized and facilitated a workshop (November 2004) to solicit feedback on the final draft from a wider audience. The workshop included restoration scientists from management agencies and non-governmental organizations in addition to the scientific review committee.

We have structured this report to identify and assess key design issues. We do this by:

1. Explaining our conceptual model of how restored marshes evolve and function based on our own observations and other researchers' assessments of restored marshes (Zedler 2000; Zedler and Callaway 1999).

2. Describing the planning context used in restoration practice that creates the framework for design decisions and considering site-specific factors as well as geographic variability in the environmental setting and variation in project objectives.

3. Addressing the major design questions that dictate the grading of the site template prior to reintroduction of tidal action.

Electronic appendices that contain detailed monitoring data from a number of marshes around San Francisco Bay have been provided. These data were used to support the guidance described in this report and include China Camp, Muzzi Marsh, Warm Springs Marsh, and Sonoma Baylands. The full report can be downloaded at the Wetland Regional Monitoring Program website (www.wrmp.org).

Vertical elevations are reported relative to the North American Vertical Datum of 1988 (NAVD) or the appropriate tidal datum. Most of the original elevations were collected in the National Geodetic Vertical Datum of 1929 (NGVD) and have subsequently been converted using Corpscon (USACE 2000). The datum conversions are therefore approximate. Close attention should be taken to the correct specification and use of vertical datums in restoration projects.

Table 1. Examples of Restoration Sites in San Francisco Bay

Site	Previous Land Use	Salinity Regime	Area (ha)	Date Breached	Initial Elevation (m NAVD)	Time to 50% Vegetative Cover (years)	Tidal Slough System	Long-Term Monitoring
Muzzi, Inner	Dredged material placement	Saline	28	1976	2.15	~5	Channels excavated; no natural channel formation	1986 - present
Muzzi, Outer	Diked bayland	Saline	20	1976	1.27	~14	Extensive channels	1986 - present
Warm Springs (Coyote Creek Lagoon)	Deep borrow pit	Brackish	81	1986	-3.74	>14	Mudflat channels developing	1986 - present
Carl's Marsh (Petaluma River Marsh)	Agricultural land	Saline	18	1994	-0.10	>6	Developing	1996 - present
Sonoma Baylands	Diked bayland	Saline	120	1996	1.21	>8	Developing	1994 - present
Faber Tract	Dredged material placement	Saline	32	1972	1.75 (+1.63 to +2.12)	Less than 5 to 10 (estimate)	No channels in highest areas; extensive channels in lower areas	---
Alameda Creek Pond 3	Dredged material placement	Saline	45	1975	+1.73 to +2.34	≤5	Few channels in the highest areas; slightly more channels in the lower areas	---
Crissy Field	Airfield	Saline	7	1999	-0.37	Not vegetated	Lagoon inlet channel closes intermittently	1999 - present
Martinez	Landfill	Saline	5	2002	1.3	>3	Pr-excavated	2002 - present
Cooley Landing	Salt pond	Saline	39	2000	1.52	>5	Evolving	2000 - present
Napa Pond 2A	Salt pond	Brackish to Saline	223	1995	1.73	~3	Re-established in remnant channels	1997 - present
Martin Luther King Jr.	Filled, diked bayland	Saline	35	1998	1.54	4	Developing	1998 - present

2. EVOLUTION OF SAN FRANCISCO BAY WETLANDS

2.1 WHAT IS A TIDAL WETLAND?

Tidal wetlands are the margins of the estuary that are periodically inundated by tides. Therefore, they include all habitats within the "tidal frame" (the elevation range between the lowest and highest tides).

These are:

- intertidal mudflats;
- regularly inundated tidal marsh plain;
- tidal channels within the marsh; and
- infrequently inundated wetland-upland transition zones at the edge of the upland.

The major focus of this report, and of restoration planning, is to develop the conditions that result in the restoration of vegetated tidal marsh habitat within tidal wetlands, incorporating the wetland-upland transition or ecotone within the site boundaries wherever possible. This report does not consider terrestrial ecotones such as hillslopes, alluvial fans, deltas, and beach ridges that lie outside of the site boundaries (which are typically the top of the levees). The design questions in this report address the creation of the form or the physical setting that allows the development of a wetland with all the ensuing functions of an estuarine ecosystem such as nutrient cycling, food production, habitat for estuarine fish, and resting and feeding grounds for shorebirds and waterfowl.

A typical mature tidal salt marsh in San Francisco Bay today has a distinctive vertical profile as shown in Figure 2. This figure shows a transition from intertidal mudflat up a relatively short and steep low marsh zone of Pacific cordgrass (*Spartina foliosa*) to a wide middle marsh zone dominated by perennial pickleweed (*Salicornia virginica*) and a high marsh zone dominated by saltgrass (*Distichlis spicata*). The high marsh transitions into upland in what we are calling a "wetland-upland transition zone". This area, which varies spatially in response to annual rainfall, storm surges, and sea level rise, has been almost entirely eliminated around the Bay by roadways and dike construction. Where fragments remain, it serves as critical habitat and refugia for several species, most notably the salt marsh harvest mouse (*Reithrodontomys raviventris)* and the California black rail (*Laterallus jamaicensis corturniculus*). It also serves as a buffer from landward intrusions of human influences including cats and dogs and predators such as the red fox.

In addition to the most common plants—pickleweed, cordgrass, and saltgrass—a diverse assemblage of tidal marsh salt tolerant plants (halophytes) includes: jaumea (*Jaumea carnosa*), alkali-heath (*Frankenia salina*), fat-hen (*Atriplex triangularis*), sea lavender (Marsh rosemary) (*Limonium californicum*), and gumplant (*Grindelia stricta* var. *angustifolia*). Gumplant grows in the high marsh zone and along channel banks throughout the marsh. A parasitic plant, dodder (*Cuscuta salina*), sometimes establishes in pickleweed marshes, particularly where tidal flushing is depressed. Large patches of alkali-heath and creeping wild rye (*Lolium perenne*) are common in areas of transition to upland vegetation along with introduced rabbitfoot grass (*Polypogon monspeliensis*). Rare plant species of tidal salt marshes include soft bird's-beak (*Cordylanthus mollis* ssp. *mollis*), Point Reyes bird's-beak (*Cordylanthus maritimus* ssp. *palustris*), California sea-blite (*Suaeda californica*), Marin knotweed (*Polygonum marinense)*, and small spikerush (*Eleocharis parvula*).

The distribution of species changes, particularly in the upper marsh, in response to annual rainfall and weather patterns and interspecific plant competition. Physical limitations tend to play a greater role in species distribution in lower elevation zones and interspecific plant competition at higher elevation zones (Russell et al. 1985; Bertness 1991; Pennings and Callaway 1992). Faunal diversity depends on the many functions that vegetation provides, such as food, cover, and resting sites; thus, canopy architecture plays a role in ecosystem function. Species rich marshes exhibit greater layering of the canopy (Keer and Zedler 2002). The Goals Project lists distribution and abundance of selected native vascular plant species occurring in tidal marshes of the San Francisco Bay Estuary (Goals Project 1999, Table 1.3).

The zones are readily observable with patterns of vegetation distribution linked primarily by the depth, duration, and frequency of tidal inundation (the hydroperiod or inundation regime), drainage characteristics, and by the local salinity regime. Vascular plant distribution is strongly influenced by a salinity gradient in the Bay that varies seasonally and by landforms (creeks, open bays, etc.) (Hinde 1954; Atwater and Hedel 1976; Grossinger 1995). Tidal channels influence the distribution and composition of vegetation. Significant increases in species richness occur along channel banks; species richness decreases with distance from channel banks and with decreasing channel size (Sanderson et al. 2000).

Over the long-term, the biota of salt marshes in San Francisco Bay have responded to changes in sea level by increased accretion rates and by shifts in vegetation, from high to low marsh assemblages (Watson 2004). Vegetation itself plays an important role in increased accretion rates through slowing water velocity and contributing organic matter to sediment accumulation. Large plants like cordgrass, bulrush, and cattails produce larger amounts of detritus and organic matter that effect sedimentation dynamics as well as the biologically mediated processes of nutrient and carbon cycling, and food web and habitat support for both plants and animals.

Vegetation patterns in the Bay changed in response to the diversion of fresh water for agricultural use in the 19th and 20th centuries, which resulted in conditions that are more saline for the Bay. Since this use is now regulated and restricted, conditions that are more brackish appear to be developing, particularly in the South Bay. The rare, small spikerush, a plant found in brackish conditions, has established both at Warm Springs in Fremont and at Bahia in the North Bay.

Species inhabiting tidal wetlands must possess special adaptations that enable transpiration of water from a salty environment and special mechanisms to dispose of salt. Below mean high water (MHW), daily tidal flooding maintains saturated anoxic soils and salinities close to those of tidal waters, which creates conditions suitable for cordgrass. In San Francisco Bay, Pacific cordgrass withstands tidal submergence of up to 17 hours per day. Typically, Pacific cordgrass colonizes accreting mud flats and dominates the low marsh.

Where substrate is particularly soft due to rapid accretion or puddled water, the annual form of pickleweed (*Salicornia europaea*) may colonize first. Through evapotranspiration, annual pickleweed solidifies the substrate sufficiently for cordgrass or perennial pickleweed to establish and out-compete the annual form. Above MHW and particularly above mean higher high water (MHHW), less frequent tidal flooding results in wider salinity fluctuations and less moist but more oxygenated soil conditions, which are more suitable for several salt marsh species but primarily perennial pickleweed.

Brackish marshes are transitional between freshwater and salt marshes. While there is a recognizable brackish flora of alkali bulrush (*Scirpus maritime)*, California bulrush (tule) (*Scirpus californicus*)*,* and cattails (*Typha* spp.), their distribution on the marsh depends on fluctuating salinity conditions. In years of heavy rainfall, brackish species extend their range and in years of drought the trend is reversed. Species diversity increases markedly in brackish marshes. The seed bank of a tidal salt marsh in San Pablo Bay is an order of magnitude smaller than in a freshwater marsh (Hopkins and Parker 1984).

The flora found in the Suisun Marsh, where there is significantly less salt because of freshwater flows from the Sierra Nevada, is much more diverse than the marsh flora near the Golden Gate (Newcombe and Mason 1972; Baye et al. 2000). Characteristic dominant plant species in brackish marshes include alkali bulrush, California bulrush*,* and cattails. California bulrush and cattails tolerate deeper flooding in non-tidal wetlands and grow near mean low water (MLW) in the intertidal zone. Common tule (Hardstem bulrush) (*Scirpus acutus*), Baltic rush (*Juncus balticus*), silverweed (*Potentilla anserine* ssp. *pacifica*), jaumea, and saltgrass are all common in brackish conditions (Atwater and Hedel 1976, Atwater et al. 1979). Plant species found in the transitional areas of brackish marshes—once more common but rare today—include Suisun Marsh aster (*Aster lentus*), Suisun thistle (*Cirsium hydrophilum* var. *hydrophilum*), soft bird's-beak, Delta tule pea (*Lathyrus jepsonii* var. *jepsonii*), Mason's lilaeopsis (*Lilaeopsis masonii*) and mudwort (*Limosella subulata*) (Table 3.2, Goals Project 1999).

The extent and location of salt and brackish marshes within San Francisco Bay depends on the tidal and salinity regime. From the Golden Gate, the diurnal range diminishes upstream towards Suisun Bay and increases through the South Bay. The Bay can be disaggregated longitudinally into sequential geographic zones (Figure 3). What is referred to as the Northern Reach of the Bay is a true estuary in which the Delta comprises the freshwater tidal zone, Suisun Bay the brackish zone, San Pablo Bay the seasonally predominant saline zone, and the Central Bay the ocean influenced zone. The South Bay, which is not directly linked to the lowland river system, is characterized as an estuarine influenced lagoon (Nichols et al. 1986).

The local supply of freshwater and sediment from rivers, streams, and outfalls creates secondary gradients that effect estuarine conditions and habitats at smaller scales. These secondary gradients are superimposed upon the primary gradients and lie along channels draining the local watersheds (e.g. Napa River, Alameda Creek).

The primary and secondary gradients affect the ecological variability of the regions and create distinct landscape mosaics. For instance, along the North Bay, Suisun, and the Delta axis, the evolution of marshes is influenced largely by the flow of freshwater and sediment from the Delta and the modification of the tidal wave as it progresses landward.

The vegetated marsh plain is typically drained by a complex dendritic tidal channel system (e.g. Figure 4). Each tidal channel has a tidal "watershed," the marsh area that each channel fills and drains. These localized watersheds are distinguished by very subtle changes in elevation.

In large ancient marshes of San Francisco Bay, permanent ponds in the marsh plain sometimes occurred at the watershed divide. These ponds are usually shallow, well-defined, persistent depressions about 0.3 to 0.6 m (1 to 2 ft) deep that contain about 0.15 m (0.5 ft) of standing water at all stages of the tide. They receive tidal inflow only on the highest tides and can become hypersaline in the summer. In addition, ephemeral ponds can form on the marsh plain because of disturbance from floating debris deposited on the marsh plain. At the inland edge of the transgressing marsh, salt pannes form where tidal drainage is impeded. These features are less well defined and tend to dry out to salt flats in the summer.

Structural diversity and species richness increases landward of the estuarine ecosystem boundary. In the Goals Project, Holstein describes plant communities that historically have formed ecotones with baylands (Goals Project 1999). Today there are few remaining examples of a native vegetational ecotone such as coastal scrub, chaparral, grassland, riparian, or oak woodland communities remaining around the Bay.

Because most restoration sites in San Francisco Bay are surrounded by urbanized land, almost all transitional areas from high marsh to upland vegetation have been eliminated and their function as habitats and refugia is largely missing. In addition, transitional areas historically provided part of the buffer area that served to protect the wetland and its wildlife values; this function is also largely missing.

2.2 EVOLUTION OF NATURAL TIDAL WETLANDS IN SAN FRANCISCO BAY

Guiding our concept of the evolution of San Francisco Bay wetlands is an understanding that the Bay is a dynamic, evolving system and a single, coherent landform. The deep subtidal channels, shallow subtidal bays, tidal mudflats, and salt marshes are all components of the Bay that interact and evolve with each other in response to changes in sediment supply and energy gradients. The distribution and composition of plant species in a salt marsh are influenced by the location and size of tidal channels. Vegetation shows significant increases in species richness in direct proportion to distance from the channel bank and to channel size (Sanderson et al. 2000; Sanderson et al. 2001).

The main physical processes that controls the form of the Bay are the tidal prism (which will determine the size of the main channels); sediment supply (which will determine the ability of the Bay to change its shape); the tidal frame; the wind wave climate; and relative sea level rise rate (which will determine the vertical position of the Bay).

The form of an estuary is altered mainly by the deposition of sediment, either sediment that is reworked from other parts of the estuary or that enters the estuary from the watersheds or ocean. Sediment moves between each of the components within the estuary, allowing the estuary as a whole to continually be adjusting towards some long-term equilibrium form in response to changes in physical or geomorphic processes.

The marshes, mudflats and tidal channel's habitats therefore evolved over thousands of years, sustained by the inflow of sediment eroded from the watersheds of the Central Valley rivers. This material was transported to the Bay during large winter floods on the Sacramento and San Joaquin Rivers. Coarser sediments were deposited upstream on the vast floodplains, leaving the clays and silts to settle out in the shallows of Suisun, San Pablo Bays and occasionally, the South Bay. Typically, later in the year, wind waves would re-suspend these muds, and tidal currents would redistribute them to all parts of the Bay.

The form of the tidal wetland, and the estuary, is therefore the current expression of the interaction and evolution of hydrologic and geomorphic processes within the estuary. This form or "structure" at any given time is a snapshot of an evolutionary landform that is a product of a dynamic equilibrium between key physical processes. At a particular scale and time frame for a particular estuary, these processes dictate a roughly predictable equilibrium form of tidal wetland.

Ten thousand years ago at the end of the last ice age, rapidly rising sea levels flooded the mouth of the Sacramento River through the Golden Gate, dramatically increasing the tidal prism and substantially raising the tidal frame. The initial rapid rise in sea level of 10-20 mm/yr (0.4-0.8 in/yr) only allowed a thin, discontinuous fringe of salt marsh to develop along the expanding shoreline (Atwater et al. 1979).

The extensive ancient marshes fringing San Francisco Bay were 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 1-2 mm/yr (0.04-0.08 in/yr) (Atwater et al. 1979). In this period, marsh plains expanded inland as sea level rose, covering the upland topography—as can be seen at China Camp Marsh (Figure 4). It appears that the landward transgression was usually accompanied by progressive erosion of the bayfront edge from wind wave action. Vegetated marsh plains were able to keep pace with rising sea level at about the elevation of the MHHW through inorganic sediment accretion and organic accumulation.

As marsh plains rose in elevation with sea level, 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). Cordgrass colonized the edges of the larger sinuous tidal channels and estuarine fish were resident within the marsh channels. Ponds and pannes formed on the marsh plain where tidal drainage was least effective, with the ponds forming on the watershed divides and pannes forming at the encroaching landward edge.

Figure 5, created by San Francisco Estuary Institute's EcoAtlas (SFEI 1999) and published by the Goals Project, illustrates the evolving tidal wetlands in the Bay 200 years ago prior to massive human disturbance (Goals Project 1999).

2.3 HUMAN INTERVENTIONS IN THE ESTUARY

European-American colonization over the last 200 years has transformed not only the landscape of the Bay by the diking of 90% of the tidal marshes as shown in Figure 6, but has also changed the processes that sustain wetland habitats of the Bay by altering the sediment budget, hydrodynamics, and salinity distribution.

When marsh plains were diked for agriculture or salt pond production 135 to 35 years ago (Goals Project 1999), they subsided by up to 3 m (10 ft) depending on the duration and effectiveness of land drainage. Typical total subsidence for diked tidal marshes throughout the Bay range between 0.6 and 2 m (2 to 6 ft), which means that unless fill material is used to raise ground elevations prior to breaching, many sites are initially below minimum elevations for vegetation colonization. Regional groundwater withdrawal has caused additional subsidence in the southern part of the South Bay. Isolated from tidal flows, these sites no longer received estuarine sediments or produced peaty organic material. After approximately 100 years of rising sea levels, the land surface is now relatively lower within the tidal frame by approximately 0.15 m (0.5 ft).

Almost all potential restoration sites in San Francisco Bay are located on these diked ancient marshes. Diking required construction of levees—typically constructed by sidecasting Bay mud from a parallel borrow ditch until the levee crest was about 1.2 to 1.5 m (4 or 5 ft) above MHHW, above the highest storm surge water level.

Where land was farmed, fields were ditched, drained and leveled, and the topography of marsh plain channels and ponds was often obliterated. However, in some locations, particularly the North Bay, the subtle topographic expression of former channels and ponds continue to exist as seasonal wetlands within the farmland. Natural transitional marshes were eliminated wherever dikes or roadways were constructed on the marsh perimeter. Today the transitional marsh is usually only a diminished remnant. A brackish interface between a pristine watershed and a tidal salt marsh today only exists in a few preserved areas such as China Camp in Marin County. Here, watershed runoff supports brackish-tolerant plants such as willows, sedges, rushes, and cattails that merge into the salt marsh.

At the same time, substantial human-induced changes have occurred within the Bay. In San Francisco Bay in the 19th century, increased sediment inflows due to hydraulic mining, watershed erosion, and loss of sediment "sinks" provided by the original marsh plain greatly increased suspended sediment concentrations in the Bay, resulting in sediment deposition and newly formed fringing marshes that advanced over the mudflats. These accretionary marshes, referred to as "Centennial" marshes, can be different in character than the ancient transgressive marshes formed by rising sea level. In the 20th century, sediment delivery declined and dams and diversions reduced freshwater inflows, changing the salinity distribution. Other changes may be biogenic, such as the loss of tree trunks deposited on marsh plains, reducing the frequency of disturbance, or the invasion of exotic cordgrass converting mudflats to marsh plain (CSCC and USFWS 2003). In some locations, diked subsided former tidal marshes were accidentally breached and abandoned allowing the reformation of new accretionary restored marshes, such as occurred in the 1930s at Ideal and Whale's Tail Marsh and in the 1980s at White Slough.

2.4 CONCEPTUAL MODEL OF RESTORED TIDAL WETLANDS EVOLUTION

When 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 accretionary sedimentary processes have been described in conceptual models of youthful salt marsh development (Allen 2000). Accretionary processes are different from long-term transgressive processes, which created the extensive ancient marshes of San Francisco Bay and are dominated by sea level rise. In a restoring marsh, floodtides 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 the rate of sedimentation declines.

Once tidal mudflats reach a high enough elevation relative to the tidal frame, pioneer plant colonization occurs. Initial establishment usually occurs by seed or from plant fragments. Colonization becomes progressively more rapid through lateral vegetative expansion from the pioneer plants. Figure 7 illustrates 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 marsh plain. Sites that have relatively high initial elevations will therefore reach colonization elevation more quickly than more deeply subsided sites. For this representation, the influence of episodic events is integrated and sea level rise is excluded.

In San Francisco Bay, Pacific cordgrass, alkali bulrush, or annual pickleweed is typically the first vegetation to colonize an accreting mudflat and dominate the low marsh. Pioneer colonization occurs when seeds or clonal fragments float in on the flood tide. Once established, populations expand vertically by vegetative growth within a species-specific elevation range. Pioneer colonizing cordgrass seedlings require mudflat elevations of approximately 0.2 to 0.4 m (0.7 to 1.3 ft) above mean tide (Siegel 1998; PWA 1999) and sufficiently quiescent conditions for seeds to germinate (Friedrichs and Perry 2001). Once established, cordgrass can expand to lower elevations, as low as 0.0 to 0.3 m (0.0 to 1.0 ft) below mean tide (Atwater and Hedel 1976). Colonization elevations vary around the Bay because of differences in tidal range and salinity. Appendix A.1 contains observations of the elevation ranges for marsh species. For some sites that are not deeply subsided, existing wetland vegetation may persist and expand after breaching, which occurred at Napa Pond 2A and Cooley Landing.

Once mudflat colonization occurs, a vegetated marsh plain forms through lateral expansion of rhizomes from established plants on the mudflat, and from plants along the site perimeter. The presence of vegetation contributes to the slow build-up of the marsh plain through sediment trapping and organic accumulation (Eisma and Dijkema 1997). In addition, vegetation cover stabilizes mudflats by preventing remobilization of sediment deposits during extreme wave events. As the marsh plain rises within the tidal frame, estuarine sediment accretion slows exponentially until a marsh plain forms at an elevation, in the case of San Francisco Bay marshes, within a few tens of centimeters below MHHW (Atwater et al. 1979) (Figure 7). As tidal inundation decreases, maximum soil salinities increase and perennial pickleweed out-competes cordgrass to form the characteristic salt marsh plains of San Francisco Bay.

The presence and distribution of vegetation, in turn, provides feedback that affects physical processes resulting in a deeply complex ecosystem. For instance, once vegetation is established organic material will accumulate within the marsh both above ground as surface litter and below ground, through the decay of roots and rhizomes in the form of peat.

The rate at which the mudflat and marsh plain build up is dependent on the amount of sediment carried into the site by the flood tide, the rate of relative sea level rise, the amount of wind wave action that resuspends deposited sediments, and the rate of organic accretion. The balance between sea level rise and net accretion will determine the ultimate equilibrium marsh plain elevation in an accretionary restored marsh. This may be lower than the marsh plain elevation in a transgressive ancient marsh.

Although suspended sediment concentrations vary widely at any given time, long-term average annual suspended sediment concentrations can vary from less than 50 mg/L to more than 500 mg/L. Concentrations are influenced by the long-term sediment budget of the Bay, as well as 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. Figure 8 shows the potential influence of suspended sediment concentration on the rate of evolution.

Relative sea level rise is due to a combination of global eustatic sea level rise and local long-term subsidence. Eustatic sea level rise is predicted to accelerate due to global warming (IPCC 2001). For average modeling parameters, the Intergovernmental Panel on Climate Change (IPCC) sea level projections for the next 50 years (from 2000 to 2050) for different emissions scenarios range from approximately 2 to 4 mm/yr, which is roughly twice the 20th century rate. The net effect of accelerated rates of relative sea level rise on rates of evolution is shown in Figure 9.

Wind blowing across open expanses of water, such as low restoration sites at high water, can generate waves that are sufficient to inhibit net deposition of suspended sediment from the water column and resuspend already deposited material. This can reduce the net accretion rate, slowing the evolution of the marsh plain and even limit the equilibrium elevation of the site by preventing colonization. In South San Francisco Bay, Shoellhamer found that suspended sediment concentrations were correlated with seasonal variations in wind shear stress (Schoellhamer 1996). 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 (USACE 1984). This means that vulnerability to sediment disturbance and re-working from wave action increases as mudflats build in elevation. Conceptually, this can result in a retarded evolutionary trajectory or, for high wave energy sites, a permanent mudflat too low to be colonized by emergent vegetation. Nicholas and Boon identified the effect of wind waves in maintaining water depths below colonization elevations as a primary determinant of the morphology of coastal lagoons (Nichols and Boon 1994). The net effect of wave exposure on the evolution of the marsh is illustrated in Figure 10.

Where restoration sites are fully tidal, periods of inundation are equivalent to tidal curves for the Bay. Where tides are muted or restricted by culverts or narrow channels, periods of inundation are altered and vegetation establishment can be significantly delayed or restricted. For a number of accidental or intentionally restored sites, 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.

Concurrently with the physical evolution of the marsh plain shown in Figure 7, the tidal drainage system starts to form. As mudflats accrete to intertidal elevations, mudflat tidal channels form and become fixed as vegetation establishes and the marsh plain develops (Beeftink and Rozema 1988). Depending on their contributing tidal watershed, channels may eventually incise into the evolving mudflat (French and Stoddart 1992; French 1993). As vegetation becomes established, these sinuous mudflat channels become imprinted in the marsh plain, eventually forming a dendritic tidal channel system as shown in Figure 11. Within this system, the tidal channel geometry at any given point is mainly dictated by the tidal prism of the area of marsh upstream (Williams 1986). Borrow ditches or drains, if present, will tend to capture and dominate the evolution of the tidal drainage system.

As the marsh evolves from primary colonized mudflat to low marsh and then to high marsh, the density of tidal drainage channels changes. In the young marsh, marsh plain elevations are low, tidal prism is large and drainage density high. As sediments accrete beyond a certain point, tidal prism is reduced and drainage density decreases. The elevation of maximum channel density is estimated to be around the elevation of the neap high tide in semi-diurnal tidal regions but has yet to be defined within the Bay (Steel and Pye 1997). Channel density therefore varies with elevation and hence age of restoration; a low marsh restoration will tend to have more small channels in complex drainage patterns while a higher or older marsh will tend to have a less complex drainage pattern with fewer small channels and eventually marsh plain ponds.

Slough channel edges tend to be better drained and may have subtle variations in topography that results in increased habitat diversity. In the San Francisco Bay, estuarine sediments are almost entirely clays or silts. Only where major creeks discharge into the Bay or wave action creates pocket beaches is there a significant source of coarser sediment. Alluvial sediments from creeks can form transitional alluvial fans and natural levees along channels. Wave action on beaches can create shell and sand chenier ridges. These heterogeneous features provide specialized habitat for plant species.

In restoring tidal wetlands, we are creating a wetland form in an immature state, with the intent that it will evolve as rapidly as possible towards a mature state to provide similar ecologic functions to those in the ancient marsh. However, we have to recognize that the mature restored marsh may differ from, or take a very long time to achieve, the same functions as the ancient marsh.

2.5 HOW RESTORED MARSHES HAVE EVOLVED

The rate at which tidal marshes have evolved has varied at the individual restoration sites listed in Table 1. In general, it appears that monitoring programs of five or ten years have not been long enough to define the complete evolutionary trajectory of key functions like vegetation succession or tidal channel development. Nevertheless, monitoring data from these sites is providing useful information and insight on key design decisions. The following summarizes important features of each site.

Carl's Marsh. Extensive detailed monitoring by Stuart Siegel (Siegel 2002) for the California State Coastal Conservancy and Sonoma Land Trust (WWR 1998; WWR 2003) and by CALFED's BREACH research team, is providing some of the best research data on evolution of an initially subsided restored site. Carl's Marsh was historically part of the Petaluma River's fringing centennial marsh, which was diked for agriculture. The Sonoma Land Trust restored the site in 1994 by breaching the levee at two locations and excavating higher order channels. High sedimentation rates make this one of the fastest evolving sites in the Bay. Initial cordgrass established within two years of the dike breaching at elevations between 0.2 to 0.4 m (0.6 to 1.2 ft) above mean tide level (MTL). Vegetation, which also includes annual pickleweed, perennial pickleweed, and alkali bulrush, has expanded rapidly. Shorebirds forage on the mudflats and Samuel's song sparrows nest on the degraded outboard levee (WWR 2003).

Cooley Landing. This restoration is a prototype for a shallow subsided salt pond restoration where the original tidal drainage system is still largely intact. At Cooley Landing, the footprint of the historic channel system was preserved; however, the channels had silted in and borrow ditches were constructed around the site perimeter. Mitigation monitoring (PWA et al. 2002a; PWA et al. 2004) is providing an understanding of the effectiveness of design features intended to rapidly rejuvenate the pre-existing tidal drainage system, which include channel guide berms near the two breaches and borrow ditch blocks. Sediment accumulated in the high order historic channels eroded rapidly after restoration by channel head-cutting. The channel guide berms focused tidal flows into the major channels and the ditch blocks have prevented channel formation in these artificial features. First order channels at the back of the site have also been re-occupied. Three years after restoration, approximately 15 percent of the site was covered with vegetation, but stands of non-native smooth cordgrass (*Spartina alterniflora*) have been identified and are being controlled.

Crissy Field. This small restoration project located in the Golden Gate National Recreation Area (GGNRA) is probably the most visited site in the Bay Area. It is an unusual site for San Francisco Bay because it is located near the Bay mouth and is closer in character to the sandy coastal lagoon fringe marshes of the Pacific Coast than the interior marshes of the Bay. The GGNRA is carrying out an extensive long-term monitoring program. Estuarine sedimentation rates at Crissy Field are negligible; however, coarse sand has dynamically formed a flood tide shoal, as is characteristic of coastal lagoons. Vegetation consists of fringing cordgrass and upland species, which were planted as part of the restoration design. The Crissy Field restoration provides valuable opportunities for public access and education.

Faber Tract. The first restoration project in San Francisco Bay was a dredged material disposal site breached in 1972. This was the first site in the Bay where marsh vegetation was observed to restore naturally. Also, this was the first site where cordgrass was planted and established. Faber Tract is now fully covered by pickleweed. Surveys and corings have provided an understanding of how tidal channels form on dredged material (LTMS 1996). Channels did not develop in the marsh plain at the back of the site near dredged material discharge points where fill elevations initially exceeded MHHW. The tidal channel system in the lower portions of the site formed parallel to the slope of the placed dredged material in a pattern that is distinct from sinuous, historic tidal channels. Faber Tract provides important breeding ground for the California clapper rail in the South Bay and is part of the Don Edwards National Wildlife Refuge.

Martinez. Although this site is new and fairly small, it has an extensive mitigation monitoring program in place that is providing valuable information on how filled sites can be graded to allow rapid vegetation colonization (PWA and Sycamore & Associates 2004). The Martinez project site was filled above tidal elevations with construction debris. The restoration design included the excavation of intertidal marsh plain and a sinuous system of dendritic tidal channels. The restoration enhanced flood protection by providing flood storage and flow conveyance along Alhambra Creek.

Muzzi Marsh. This site is divided into two parts with very different characteristics. The high elevation “Inner” Muzzi site was filled with dredged material and the lower elevation “Outer” Muzzi site has filled by natural sedimentation. Pickleweed colonized at higher elevations of the “inner” marsh plain within a year after the dikes were breached (1976) and in the next ten years had spread across most of the “inner” marsh plain. Cordgrass established in several places in the “outer” marsh within three or four years after tidal restoration. Today, the marsh is fully vegetated with extensive stands of cordgrass that are slowly being replaced with pickleweed as the marsh plain matures. Vegetation that established close to breach locations is beginning to erode as the breaches widen. In 2003, the invasive smooth cordgrass colonized in two places near the southern breach.

The distribution of plant species remains dynamic nearly 30 years following dike breaching. The 18-year monitoring of this site has provided a better understanding of both the physical processes and vegetational establishment and succession. There is a population of approximately 15 pairs of clapper rail within the marsh and a small population of harvest mice just outside the marsh. However, no surveys of the salt marsh harvest mice have been conducted within the marsh.

Appendix B.5 has physical and vegetation monitoring data for Muzzi Marsh.

Napa Pond 2A. This project, located in the Napa Salt Pond complex, is the largest restoration in the San Francisco Bay. It has been monitored intermittently. This salt production pond was diked in the 1950s, but was not in operation prior to restoration. The site had experienced little subsidence and the internal tidal drainage system was still intact. In 1995, the California Department of Fish and Game (CDFG) restored Pond 2A by dynamiting a levee breach to South Slough, followed by a second dynamited breach to China Slough in 1997. Vegetation colonization has been rapid since restoration. Within the first growing season, extensive areas of the marsh were vegetated, and today, the marsh plain is covered with pickleweed and alkali bulrush with Pacific cordgrass growing on the edges of channels.

Alameda Creek Pond 3. This was a maintenance dredging disposal site that was planted and restored to tidal action 30 years ago. Unfortunately, the exotic smooth cordgrass was included in the planting and has since propagated in many areas of the Bay. Much of the site was initially too high for tidal action but over time subsided and became vegetated with pickleweed. Tidal channel formation has been limited due to the high elevation of the marsh plain.

Sonoma Baylands. There are two separate parts to this restoration project, the 11-hectare Pilot Unit and the 109-hectare Main Unit. Both sites are being monitored extensively. Dredged material was used to accelerate evolution of the marsh plain, but unfortunately, evolution was retarded by restricted tidal action through pre-existing small tidal channels in the wide outboard marsh that connects the sites to the Bay. This has meant that for much of the time tidal range has been muted and most of the site has been subtidal or intertidal mudflats. The performance of many important design features can be evaluated through the monitoring program, including the gradual erosion of the connector channels and the subsequent increase in tidal prism and sedimentation. Seedling establishment of pickleweed is limited to the higher tidal perimeter of the site and to peninsulas. Cordgrass established first within two years of tidal access in sheltered junctions of the pilot peninsulas and expanded as the tidal range increased. Seedling establishment on the tidal marsh plain suggests that the vegetation is responding to increased ebb drainage times. Full vegetative cover, while initially restricted, may occur within 20 years.

Appendix B.6 has physical and vegetation monitoring data for Sonoma Baylands.

Warm Springs (Coyote Creek Lagoon). This site, located in the furthest reach of the South Bay, was originally a deep borrow pit that was breached to Coyote and Mud Sloughs. Since tidal action was reintroduced, it has silted in rapidly as designed. Continuous monitoring has provided valuable insight on the evolution of a deeply excavated restoration site that has rapidly filled with sediment. Species establishment was effected by variability in the salinity regime of the South Bay and a sudden increase in the Mud Slough connection that altered the hydrologic regime and soil conditions. An early band of pickleweed around the perimeter died back from altered conditions. Native cordgrass established in the second year following breach openings and expanded rapidly as levels were reduced. Cordgrass was entirely replaced by brackish species of bulrush and cattails within ten years. At present, 17 years after the dikes were breached and under current stable brackish conditions, dense stands of bulrush and cattails expand vegetatively 1 to 2 m (3 to 6 ft) a year inward from the perimeter. Mudflats in the center remain mostly bare, though large clumps of bulrush appear to have floated in, established, and have begun to expand. The distribution of plant species at Warm Springs remains dynamic 18 years after the dikes were breached. No surveys for clapper rail or salt marsh harvest mice have been conducted.

Appendix B.3 has physical and vegetation monitoring data for Warm Springs (Coyote Creek Lagoon).

3. PLANNING CONTEXT

3.1 APPROACH

These guidelines are written to assist the process of restoring tidal wetlands as healthy ecosystems. Ecosystem health or integrity is described by ecologists as the:

> *condition in which a system realizes its inherent potential, maintains a stable condition, preserves its capacity for self-repair when perturbed, and needs minimal external support for management* (Karr 1993).

In general, tidal wetland physical processes are the major influence on form and function. The biota evolve more in response to, rather than interactively with, the hydrologic and geomorphic processes that form the physical landscape. Certain important species of plants, fish, and birds have evolved to exploit the physical habitat and the functioning and variability of the physical processes that occur in tidal wetlands. This means that restoring the *physical integrity* of the tidal wetland offers the best opportunity of restoring ecologic integrity.

A more specific definition of a "healthy" functioning tidal marsh that is linked to physical integrity is one that:

> *evolves to a mature state that sustains an intricate slough channel, marsh plain, and tidal pond system; this system is in a state of dynamic equilibrium with sea level and sedimentation, is resilient to natural disturbance such as extreme tides or earthquakes, and needs no management* (Williams 2001b).

A functioning tidal marsh is physically defined, at any given time, as both a landscape structure and a set of physical processes that govern the evolution and sustenance of its morphology. In designing tidal marsh restoration projects, we are restoring physical processes that create and sustain the particular form or structure that supports desired wetland functions. For example, we restore those sedimentary processes that will create a marsh plain and tidal drainage system that will, in turn, support the salt marsh harvest mouse and estuarine fish.

This approach does not attempt to "engineer" a predetermined replicate of a tidal marsh, but provides a setting for the natural evolution of wetland functions and interplay of natural ecologic processes.

In planning tidal marsh restoration, it is important to recognize that tidal marsh is but one component of a geomorphic continuum of landforms. The mudflat, the network of marsh channels, the marsh plain and the transitional zone are all components of the Bay that connect the estuary to the uplands and their evolution is intimately linked. Their inter-relationship must be considered in the site design. This means that the tidal marsh needs to be fully connected to the Bay. The natural equilibrium form of tidal wetlands requires the unimpeded action of the physical processes that create and sustain it. This also means the site design needs to anticipate long-term geomorphic changes in the Bay. This means anticipating future sea level rise, subsidence, sedimentation rates, and channel evolution.

Because most restoration sites are former tidal marshes, the most obvious and straightforward approach to restore a mature marsh is to reverse the original alteration of the marsh landscape by removing levees and let the unconstrained physical processes re-create the marsh over time. This "ideal" approach is rarely possible for three main reasons:

1. **The physical processes that formed the original marsh may be quite different than those operating now**. For example, most mature marshes were formed as transgressive marshes by the gradual rise in sea level over thousands of years. Because most sites have subsided in elevation, restoring marshes will now have to form as accretionary marshes, relying on rapid sedimentation. Under some circumstances, restoring unconstrained natural processes will create permanent subtidal or intertidal mudflat habitat rather than vegetated marsh.

2. **In most restoration sites there are significant human constraints that limit the ability to restore natural processes**. Typically, these constraints are: property boundaries that define and limit how a site evolves, flood protection requirements, and the presence of public access corridors.

3. **The economic investment in restoration is usually directed towards achieving particular restoration goals within a particular timeframe**. For example, resource managers might be directed to quickly recover viable populations of endangered species to protect biodiversity, to achieve wetland functions that support the abundance of desirable fish or birds, and to achieve an aesthetically pleasing landscape where humans can view wildlife. This requires defining restoration success as achieving a particular pre-determined outcome within a certain period. It may also mean trade-offs between created design features that accelerate site evolution and the desire to allow unconstrained "natural" evolution.

Wherever possible in restoration design, we seek to accommodate and take advantage of the natural physical processes that allow the tidal marsh to evolve. This is done by grading the site before the reintroduction of tidal action. We refer to the initial shaping of the site as the "site template." An appropriately designed template will guide the evolution of the wetland towards the desired mature state. This approach means that the initial grading of the site is not done to replicate an "instant" wetland topography, but instead to create the conditions that allow the wetland landscape to evolve through hydrodynamic and sedimentary processes. If the appropriate initial design template is selected, the need for further management interventions is minimized. The initial site template can also be designed to achieve a mix of interim habitat types that provide a mix of valuable wetland functions as the site evolves and to anticipate the evolution of topographical heterogeneity as found on a natural marsh.

Many of the design questions addressed in this report are related to engineering criteria used in designing the site template, as grading costs are often the most expensive part of restoration project implementation.

An example of a representative site template, an interim habitat mix, and an evolutionary end point is shown for the planned Hamilton Airfield restoration in Figure 12.

There are rare examples in which restoration is undertaken as a pure scientific experiment where any outcome is equally acceptable and the resource manager is a passive observer (e.g. Cornu and Sadro 2002). However, restoration projects are now more frequently used as opportunities for "adaptive management" to inform the practice of applied science. The term adaptive management has a range of definitions. It can be thought of as "learning by doing" (and also criticized as tinkering). When applied to reducing uncertainties in restoration design, an adaptive management program can be designed in a rigorous way by incorporating an experiment within the restoration project (CALFED 2000). This is typically intended to assess the effectiveness of different design parameters and then be used to guide the design of other restoration projects. A good example of this is the 8-hectare (20–acre) Model Marsh restoration project in the Tijuana Estuary (Zedler 2000; Zedler and Callaway 2003) that examines the effects resulting from the presence or absence of tidal creek networks.

In contrast to the strategy of grading a site template to allow natural physical processes to restore a marsh, managed or manipulated tidal systems have sometimes been used to create desired wetland conditions quickly (Williams and Faber 2001). These projects typically incorporate artificial manipulation of tide levels through control gates and weirs, maintenance of a perimeter levee, and grading to create sub-tidal and refuge habitat. Subsequent experience has shown that the long-term management and maintenance costs were often underestimated and many sites have not been managed as intended. In addition, the resilience of invertebrate populations and vegetation in these marshes responding to extreme events, such as large floods, and their long-term sustainability has been overestimated. Recent reviews of managed marshes across the U.S. have cast doubt on their long-term effectiveness and ecologic value as compared to restoring natural systems (EPA 1998).

3.2 METHODOLOGY

The design of a tidal wetland restoration is one component in a complete restoration program that starts with the development of restoration goals and objectives, proceeds through planning, design, construction implementation, monitoring and management. We recognize that design decisions are determined by the set of goals and objectives adopted for the project and the planning methodology used.

In early restoration projects, including several evaluated in this report, goals and objectives were not clearly articulated, nor was an explicit methodology articulated or followed. A typical statement of restoration goals has been:

> *To create a succession of tidal wetland habitats from mudflat to mature pickleweed marsh plain as rapidly as possible.*

This statement captures an imperative to achieve the set of wetland functions associated with mature vegetated marsh as quickly as possible. As restoration projects have matured, there is a growing realization that there can be a substantial inverse tradeoff between the extent and cost of site grading and the rate of evolution towards a vegetated marsh. We now appreciate that, even under favorable conditions, it can take multiple decades for a mature vegetated marsh to develop. A number of restoration projects, including Muzzi Marsh and Sonoma Baylands have been prematurely judged “failures” because they have not become a vegetated marsh as quickly as the public, resource managers, or their designers had expected. We now better understand the value of wetland functions provided by the restoring site to the estuary as the site evolves from mudflat to marsh and rapid evolution of a vegetated marsh is not necessarily the primary driver. Based on this experience, a contemporary goal statement might be:

> *To create a succession of biologically rich and diverse tidal wetland habitats, including transitional wetlands and adjacent uplands, as part of a sustainable estuary system that requires minimal long-term intervention.*

A general goal statement like this recognizes the value of interim habitats and the importance of the wetland as part of the entire estuary ecosystem. It is translated into specific operational objectives that are consistent with the conceptual model of tidal wetland evolution of the particular site.

Early tidal wetland restoration projects typically included the following two ecologic objectives:

1. **Achieve rapid evolution to a vegetated marsh plain habitat.**

2. **Provide appropriate habitat to support particular species.**

Now, restoration projects, such as the South Bay Salt Ponds Restoration, are planned as multi-objective projects that fully integrate ecological and social objectives. Typically, restoration projects may include the following seven objectives:

1. **Allow for the evolution of biologically rich and diverse tidal wetland habitats.**

2. **Promote the evolution of a complex tidal drainage system, particularly to support invertebrates, fish and birds.**

3. **Maximize the contribution of the marsh to the estuarine ecosystem, with connections between marshes where possible.**

4. **Create a complete marsh that includes all zones, including a high marsh and transitional wetland-upland habitat along the upland fringe.**

5. **Provide appropriate habitat to support rare, threatened, and endangered species and avoid creating features that will benefit their predators.**

6. **Provide and enhance public access** (this is sometimes treated as a constraint).

7. **Reduce flood hazards** (this is sometimes treated as a constraint).

A rigorous planning methodology requires that these objectives be made “operational” by defining measurable indicators of their performance. Examples of these indicators are presented in Table 3 (p. 59). These indicators provide the metrics for comparing the merits of alternative restoration plans, the outcome of the selected restoration design, as well as the basis for a monitoring and adaptive management program. They also provide the ability to compare expected with actual performance, improving experience in restoration design and giving the opportunity to produce an updated version of these Design Guidelines sometime in the future. In many early restoration projects, performance indicators were either ill defined, or specified as unrealistic regulatory compliance criteria, such as percent vegetation cover of a particular plant species.

In the planning process, alternatives can be developed that provide for a mix of evolving habitats: transitional marsh, marsh plain, mudflats and subtidal open water that change over time. Projections can be made of the performance of the set of indicators for these different alternatives—including the no-action alternative—at different times into the future. Typically, these projections will examine and compare the evolution of desired wetland functions from different site templates at Year 0, to a mature state, taking into account future changes in physical and ecologic processes. These projections need to be based on an explicit conceptual model of how wetland functions are expected to evolve, assisted by various analytic tools available to predict physical evolution, as well as empirical data of the type included in this report. Expected performance is based on a projection of how, and when, wetland functions will evolve within the planning period.

The human as well as the ecologic landscape has to be considered in restoration. This means that non-ecologic constraints often have a major influence on site design and usually preclude returning a site to its pre-disturbance condition, even where physical processes have not changed significantly.

Each particular site will have design questions dictated by its own set of constraints. Typically, the most significant constraints result from local man-made topography, such as levees, landfills, or property boundaries that are unrelated to the natural landscape, and man-made infrastructures such as sewer lines or roadways. These constraints usually define the site template “footprint” that limits the aerial extent and shape of the wetland and its relation to the upland watershed that would naturally adjoin it.

The following five constraints are often encountered in restoration design:

1. **Potential impact on offsite flood hazards and drainage** (Nowadays often included as an objective)**;**

2. **Presence of public access or utility corridors** (Nowadays often included as an objective)**;**

3. **Prevention of colonization or intrusion by invasive species;**

4. **Requirements for mosquito control; and**

5. **Impacts resulting from the conversion of existing wildlife habitats (e.g. salt pond, seasonal wetland, or diked salt marsh) to tidal wetland.**

Therefore, the restoration design is usually directed by the integration of two sets of planning issues: those intended to achieve the ecologic objectives of the project and those required to address constraints on the restoration plan.

3.3 FRAMEWORK FOR DESIGN DECISIONS

Each of the restoration objectives and constraints pose key design questions that can be asked of most restoration projects (see summary in Table 2). This report is intended to address each of these questions based on current restoration experience. As can be seen, the same questions listed below may address several different objectives or constraints. The questions are:

1. Should the site be filled?
2. Should fill be removed?
3. Should a levee breach and outboard channel be excavated?
4. Should wave breaks be constructed?
5. Should the bayfront levee be lowered?
6. Should new tidal channels be excavated?
7. Should the pre-existing drainage system be modified?
8. Should the site be graded to encourage panne formation?
9. How should the wetland-upland transition be designed?
10. Should soil be treated?
11. Should plants be planted?
12. How do we provide habitat features for target species?
13. How should public access be provided?
14. How should we integrate flood management issues?

3.3.1 Objective 1: Allow for the evolution of biologically rich and diverse tidal wetland habitats

The evolution of tidal wetland habitat will depend upon the achievement of an appropriate elevation with respect to the tide, suitability of the substrate, and the availability of a seed source.

Elevation

If the site is subsided below the colonization elevation, the site may be filled high enough for colonization to occur, hence ***Question 1: Should the site be filled?*** If the site has been filled to above the typical marsh plain elevation, the site must be excavated, hence ***Question 2: Should fill be removed?*** For many subsided sites, it is too costly or impractical to import fill material and instead we rely on natural estuarine sedimentation to raise mudflat elevations into the colonization range. The question may be *how can we accelerate natural sedimentation rates*?

Maximizing the amount of sediment brought in on the flood tide and minimizing the amount leaving on the ebb tide accelerates natural sedimentation rates. The amount of sediment brought in on the flood tide is dependant on the volume of the tidal prism, and thus, on the tidal range within the site and the suspended sediment concentration in the water column. These are influenced by the levee breach geometry and location, hence ***Question 3: Should a levee breach and outboard channel be excavated?***

A significant factor influencing how much sediment leaves the site on the ebb tide is the wave energy within the site. Wave action slows deposition rates and induces resuspension of deposited mud. The amount of wave energy affecting a site is dependant on the wind climate, which cannot be controlled, and the fetch length, which can. Internally generated waves can be limited by suitable grading of the site template, hence ***Question 4: Should wave breaks be constructed?*** Remnant bayfront levees can be used as wave breaks, hence ***Question 5: Should the bayfront levee be lowered?***

Substrate

Colonization requires a suitable substrate in the rooting zone in terms of its soil chemistry, grain size and bulk properties. Wetland plants are adapted to take advantage of and thrive in naturally deposited estuarine sediments. Filled sites may have unsuitable substrates, perhaps due to high acidity, low nutrients or excessive compaction. There are two strategies for dealing with this problem: removing enough fill so that a sufficient depth of estuarine sediment will accumulate, hence ***Question 2: Should fill be removed?***, or modifying the soil substrate, hence ***Question 10: Should soil be treated?***

Seed source

Normally it would be assumed that restoration sites have a substrate of bay mud and would be relatively close to other vegetated marshes to receive naturally transported seed for most native salt and brackish marsh plants. In cases where the site is isolated from other tidal marshes or where a rapid diversification of species is desired, there are circumstances where planting is necessary, which raises ***Question 11: Should plants be planted?***

3.3.2 Objective 2: Promote the evolution of a complex tidal drainage system, particularly to support invertebrates, fish and birds

Coincident with the evolution of the vegetated marsh plain, we need to ensure the development of a complex tidal drainage system that fully connects the marsh to the tidal estuary. This channel system acts as a pathway for estuarine processes and migrating organisms and as a distinct habitat corridor that sustains certain species. The channel complexity—an amalgam of the size, shape, sinuosity, and density of the drainage system—provides a variety of microhabitats that support many marsh-dependent species.

How quickly a drainage system will develop in an evolving marsh depends on how easy it is for channels to form. Its complexity will depend on how we design the restoration site template. There are three ways to address this question:

1. Encourage tidal channels to develop on emerging mudflats.

As intertidal mudflats develop due to natural sedimentation in a restored site, a channel system forms in the newly deposited mud. Plants tend to preferentially colonize the mudflat channel edge stabilizing and defining the nascent tidal drainage system. Over time, as the site becomes vegetated, the channel system develops and extends further into the marsh plain (Figure 11). The rate at which this process develops is dependent on the rate of sedimentation that can be encouraged by implementing the design criteria aimed at accelerating the rate of sedimentation as described above: ***Question 3: Should a levee breach and outboard channel be excavated?***, ***Question 4: Should wave breaks be constructed?***, and ***Question 5: Should the bayfront levee be lowered?***

2. Encourage formation of channels in the pre-existing marsh plain.

There are two ways of encouraging channel formation. The first is by pre-filling the marsh plain to an elevation that permits development of tidal channels in the freshly deposited estuarine mud. As these channels become defined and vegetated, they will scour into the placed fill. This design criterion is described in ***Question 1: Should the site be filled?*** The second is by excavating channels in the marsh plain fill. This is addressed in ***Question 6: Should new tidal channels be excavated?***

*3. Rejuvenate pre-existing tidal drainage system***.**

Most restoration sites are former tidal salt marshes that have been diked and have subsided, but have not been filled. On some of these sites—particularly salt ponds—the original dendritic tidal drainage system, although silted in or filled, is still imprinted in the land surface. With suitable design elements, tidal flows can be redirected into this system allowing it to reform. This is addressed in ***Question 3: Should a levee breach and outboard channel be excavated?*** and in ***Question 7: Should the pre-existing drainage system be modified?***

Complexity within the tidal drainage system can be achieved by designing the size and shape of the site template to encourage the formation of large high order channels within a dendritic tidal drainage system. This is done by grading, fill placement, location of levee breaches, ***Questions 1: Should the site be filled?, Question 2: Should fill be removed?, Question 3: Should a levee breach and outboard channel be excavated?, Question 6: Should new tidal channels be excavated?***, and by minimizing the influence of artificial ditch systems, ***Question 7: Should the pre-existing drainage system be modified?***

3.3.3 Objective 3: Maximize the contribution of the marsh to the estuarine ecosystem

Marshes do not function in isolation of the estuary—their carbon storage potential and dynamic carbon cycling can make marshes an integral part of the estuary's ecological system. There are two pathways for tidal interaction between the marsh and the estuarine ecosystem: through a fully developed well-connected tidal drainage system and across the bayfront marsh edge. Design criteria for the tidal drainage system are described above. The main barrier for tidal flooding across the bayfront edge is the remnant bayfront levee. This issue is addressed in ***Question 5: Should the bayfront levee be lowered?***

3.3.4 Objective 4: Creation of transitional wetland-upland habitat along the upland fringe

The high marsh vegetation in a tidal salt or brackish marsh, typically intergrades with upland plant species in a transitional wetland-upland ecotone. The boundaries shift according to seasonal wind and rainfall patterns and heights of extreme high tides. The high marsh portion of this transitional habitat may be a topographic feature on the marsh plain such as a channel bank levee or a wave-deposited mound or ridge. This transitional wetland-upland habitat was once significantly larger spatially and supported a larger flora. With the 90% loss of tidal wetlands in San Francisco Bay, the most severe losses are the transitional areas where roads and dikes have been constructed. Several plant species have either been extirpated from the Bay or are extinct today. Today, four plant species that were once more common are rare because of the loss of transitional marsh habitat by agricultural, industrial, and residential conversion of tidal marshes: Point Reyes bird's-beak, soft bird's-beak, Suisun thistle, and the Delta tule pea (Goals Project 1999).

The upland transition of a marsh is important in terms of providing habitat and refugia for numerous wildlife species. In addition to this valuable habitat function, high marsh and transitional areas provide buffer space from disturbances emanating from adjacent land uses and from landward transgressions into the marsh. Today, in most areas around the Bay, transitional high marsh areas have been eliminated and transitional wetland-upland habitat is limited by the presence of steep levees, vegetated primarily by weedy non-native species, or roadways. Transitional wetland-upland habitat is important to many marsh wildlife species as it provides refugia and cover during extreme high tides and provides habitat for feeding, roosting, and breeding birds. In addition, transitional wetland-upland habitat can play in important role in mitigating flood hazards by dissipating and reducing wave action and providing an erosional buffer zone.

For many species, the adjacent uplands—not just the wetland-upland transition—are important habitats in their own right. For example, the salt marsh harvest mouse (and other marsh species) often forage in adjacent uplands. Also, adjacent uplands serve as refuges for mice and rails during extreme high tide events. Thus, tidal marshes that lack a substantial area of adjacent uplands have a lower habitat value for many tidal species.

Functional, sustainable transitional wetland-upland habitat requires a sufficient width, opportunities for disturbance through the deposition of wrack at very high tides, and availability of nearby seed sources for appropriate transitional vegetation. The first consideration is addressed in ***Question 9, How should the wetland-upland transition zones be designed?*** Facilitating the deposition of wrack is addressed in ***Question 5: Should the bayfront levee be lowered?*** Establishing vegetation is addressed in ***Question 11: Should plants be planted?***

3.3.5 Objective 5: Provide appropriate habitat to support endangered species

All the design criteria described above are intended to provide the mix of vegetated marsh habitats needed to support target species as discussed in ***Question 12: How do we provide habitat features for target***

species*?** Specific requirements for salt marsh harvest mouse refugia and suitable conditions for Soft bird's-beak are addressed in ***Question 9: How should the wetland-upland transition zones be designed?

3.3.6 Objective 6: Provide and enhance public access

Question 13: How should public access be provided? considers how public access can be incorporated in the design template. These decisions can also influence ***Question 5: Should the bayfront levee be lowered?*** While maintenance access for utility corridors are not specifically addressed in this document, their issues are similar to those of public access.

3.3.7 Objective 7: Reduce flood hazards

This issue is considered in those design criteria that address coastal and fluvial flood hazards and are addressed in ***Question 14: How should we integrate flood management issues?*** In addition, design features that reduce or accommodate wave run-up and erosion of levees can play a significant role in reducing flood hazards. These are addressed in ***Questions 4: Should wave breaks be constructed?, Question 5: Should the bayfront levee be lowered?, and Question 9: How should the wetland-upland transition zones be designed?***

3.3.8 Constraint 1: Potential impact on offsite flood hazards and drainage

This is often treated as an opportunity and is discussed above in Objective 7: Reduce flood hazards.

3.3.9 Constraint 2: Presence of public access and utility corridors

This is often treated as an opportunity and is discussed above in Objective 6: Provide and enhance public access.

3.3.10 Constraint 3: Prevention of colonization and intrusion by invasive species

The two main plant species of concern are smooth cordgrass, which is invading mudflats in the Central and South Bay areas and hybridizing with the Pacific cordgrass, and Pepper grass (*Lepidium latifolium*), which grows aggressively in wetland-upland transition areas, particularly in brackish marshes and adjacent upland areas. The transitional area is particularly vulnerable to colonization by invasive exotics because of frequent disturbance. These invasive species are impossible to control without intensive weeding and constant maintenance.

No specific design criteria are presented in this report for invasive cordgrass control; however, close consultation with the California State Coastal Conservancy's Invasive *Spartina* Control Project (CSCC and USFWS 2003) is advised for all restoration projects in the South and Central Bay areas.

Limiting access for exotic predators such as red fox are discussed in ***Question 4: Should wave breaks be constructed?*** and ***Question 13: How should public access be provided?***

3.3.11 Constraint 4: Requirements for mosquito control

Mosquitoes occur in Bay ecosystems where certain species can be vectors for viral diseases such as forms of encephalitis and more recently West Nile Virus. Understanding the life cycles and habitat requirements of the species that can be disease vectors is important in their control. Mosquitoes rarely occur in significant numbers in fully tidal marshes, and tidal marshes do not provide good habitat for the two most troublesome mosquito species. However, problems can occur in seasonally ponded wetlands, in densely vegetated tidal areas that pond water between tides, or where tidal drainage has been interrupted. Tidal wetland restoration can reduce mosquito populations as tidal fluctuations keep water moving so that mosquitoes do not have standing water in which to breed. Design elements should be done in consultation with local Mosquito Abatement Districts. Wide buffers between wetlands and residential areas are desirable; access points for mosquito surveillance and control are important (Collins 1991; Goals Project 1999).

Providing unimpeded tidal drainage minimizes mosquito habitat. This is a consideration in the design of the tidal drainage system addressed in ***Questions 2: Should fill be removed?, Question 6: Should new tidal channels be excavated?,*** and ***Question 7: Should the pre-existing drainage system be modified?***

3.3.12 Constraint 5: Mitigation for conversion of seasonal wetland habitat to tidal wetlands

Most restoration sites are subsided former salt marshes that now provide seasonal wetland habitat of varying quality depending on the water management regime of the site. The main value of this type of habitat is for shorebirds and migratory waterfowl. Compensating for the loss of this habitat has been a major constraint in the planning of several projects and has often led to a desire to incorporate seasonal wetland features in the restoration design. The most appropriate natural analog to artificially created seasonal wetlands appears to be seasonal pannes and marsh ponds. Pannes and marsh plain ponds are typical features of extensive, well-developed tidal marshes and vary considerably in size, sustainability, and salinity according to drainage and inundation regimes.

At this stage in restoration practice we do not know how to design for restoring marsh plain ponds. However, the site template can be designed to create sustainable seasonal pannes at the marsh perimeter. This is described in ***Question 8: Should the site be graded to encourage panne formation?***

Table 2. Summary of Key Design Questions

Objectives	**Indicators**	**Design Questions**
1. Allow for evolution of biologically rich and diverse tidal wetland habitats.	Rate of species establishment and the diversity of species, Area of vegetation	How will a restored site become vegetated marsh? Q1-5, 10, 11
2. Promote the evolution of a complex tidal drainage system, particularly to support invertebrates, fish and birds.	Drainage density, Length and number of high order channels, Sinuosity	How do we achieve a complex tidal drainage system? Q1-7
3. Maximize the contribution of the marsh to the estuarine ecosystem.	The extent of tidal exchange, Connectivity with estuary and uplands	How do we connect the restored marsh to the estuarine ecosystem? Q5
4. Create transitional wetland-upland habitat along the upland fringe.	Lineal extent, Composition and structure	How much transitional wetland-upland habitat do we create? Q5, 9, 11
5. Provide appropriate habitat to support endangered species.	Stable populations of target species	What habitat supports target species? Q9, 12
6. Provide and enhance public access.	Extent of public access corridors, Accessibility of utility corridors	Q5, 13
7. Reduce flood hazards.	Flood damage potential, Water levels, Reliability of levees	Q4, 5, 9, 14
Constraints		
1. Potential impact on offsite flood hazards and drainage.	See above	See above
2. Presence of public access or utility corridors.	See above	See above
3. Prevention of colonization or intrusion by invasive species.	Presence of invasive species in the site and the vicinity	See EIR/EIS Guidance (CSCC and USFWS 2003) Q4, 13
4. Requirements for mosquito control.	Extent of poorly drained wetland with emergent vegetation	Q2, 6, 7
5. Mitigation for conversion of existing seasonal wetland habitat to tidal wetland.	Area of suitable shorebird habitat	Q8

4. DESIGN QUESTIONS

4.1 QUESTION 1: SHOULD THE SITE BE FILLED?

THE PROBLEM

Most restoration sites are located on diked former tidal marshes that have subsided due to soil compaction and organic material oxidation. In many instances, these areas have subsided below the colonization elevation of emergent vegetation (Appendix A1). If the restoration objective is to re-create a vegetated marsh rather than an intertidal mudflat, there are two different strategies that can be applied. The first and most economical strategy is to take advantage of natural estuarine sedimentation to build up mudflats to elevations where plants can colonize. The second is to fill the site with imported sediments to raise elevations.

Accretion of estuarine sediments depends on the amount of sediment carried into the site and deposited on flood tides, the amount of sediment eroded and carried out of the site on ebb tides, and the consolidation of deposited sediments. The amount of sediment carried into the site depends on the suspended sediment concentration at the source of sediment supply, the distance of the site from the sediment source, and the degree to which tidal exchange to the site is restricted. The expected rate of natural estuarine sedimentation at a restored site should be estimated from an analysis of measured suspended sediment concentrations, observed rates of sedimentation at similar restoration sites or nearby dredged marinas, and simple models of tidal sedimentation calibrated to measurements and observations (Krone 1987).

Sources of suspended sediment include the resuspension of estuarine sediments from intertidal mudflats, silt and clay eroded by watershed runoff that drains to the Bay, and zones of high turbidity caused by estuarine circulation. Suspended sediment concentrations vary greatly in response to spring-neap tide cycles, seasonal changes in wind and rainfall patterns, and severe or El Niño storm events. Suspended sediment concentrations are higher in San Pablo Bay due to the presence of extensive mudflats and, to a lesser degree, sediment supply from the Petaluma, Napa, and Sonoma Creek watersheds. Subsided sites located near large sources of sediment have a greater opportunity to be restored through the processes of natural estuarine sedimentation.

The rate of sedimentation in a restored site due to flood tide deposition will decrease with the period of tidal inundation as the mudflats build in elevation (Figure 7). Estimates of sedimentation rates should also account for the relative decrease in mudflat elevation due to the consolidation of deposited sediments over time. As the mudflats increase in elevation within the tidal frame, consolidation occurs due to the self-weight of the material and increased dewatering at low tides. Unfortunately, there are no data on consolidation rates of mudflats and this effects the predictions of net sedimentation in the upper part of the tidal frame.

The amount of material that is carried out of the site on the ebb tide depends mainly on the degree of wind-wave agitation of deposited sediment from the mudflat. Waves cause high water velocities at the bed that can inhibit cohesive sediment deposition and, if sufficiently high, scour previously deposited sediments. The potential for high bed velocities and inhibition of deposition decreases with depth and increases with wind speed and fetch length. For a given site, deposition tends to continue until a critical bed velocity is reached. Once the site reaches this critical threshold, no further deposition will occur. If the critical threshold is reached while mudflat elevations are still low, vegetation will not establish, and the site will remain bare.

Sedimentation rates will also depend on the tidal connection between the restored site and the sediment supply. Restored sites located in the interior of a larger marsh complex are connected to the estuary and sediment source by long and narrow slough channels. Tidal floodwaters that carry sediment to the site will not be recharged with sediment if the tidal excursion of water draining from the site down the connector slough on the ebb tide is insufficient to reach the sediment source. For this reason, sites that are removed from the sediment source will experience lower rates of estuarine sedimentation than sites with a direct connection to the sediment source. Also, tidal exchange and sediment supply to a restored site will be limited if the levee breaches or outboard slough channels are undersized compared to the large initial tidal prism of a subsided site. As the breaches or slough channels erode in response to the large tidal prism, tidal exchange and sediment supply will increase.

Large deeply-subsided sites have the potential to act as major sediment sinks and alter the local sediment budget. As the site fills in with sediment, source concentrations and the rate of sedimentation at the site may be reduced. The long-term sustainability of sediment sources is uncertain given the declining trend in sediment supply from the Central Valley and the projected sediment demand from future restoration projects (Williams 2001a). Estimates of sedimentation rates should include an assessment of the impact of the restoration on the local sediment budget.

For sites that are subsided by more than several feet below MTL, it may take a decade or more for the site to reach vegetation colonization elevations through natural estuarine sedimentation. Wind-wave conditions may delay sedimentation and vegetation colonization, potentially causing the site to remain as intertidal mudflat in the long-term. If the above factors are considered and the estimated rate of natural estuarine sedimentation is found to be too low to achieve target habitat conditions and restoration within the desired timeframe, the alternative strategy is to fill the site with imported material to raise site elevations and shorten the time required for site evolution.

To raise the elevation requires filling with large volumes of easily transportable material. Dredged estuarine mud is the only effective and cheap source of large quantities of material. The cheapest way to handle large volumes of dredged material is through hydraulically pumping the material onto the site and allowing it to settle out before breaching the levee to the Bay. Placement of fill in this way results in a gradually sloping (at about 1,000:1) uniform plain. For large sites, this means there will be a significant variation in elevation throughout the site depending on where the discharge pipes are located. In placing the fill, there is little control over how the material is deposited, except by relocating discharge locations. After placement, it is difficult and expensive to rework deposited sediments.

If the site is filled to the colonization elevation, marsh vegetation can propagate rapidly and wave action is significantly reduced. However, the higher the site is filled, the smaller the volume of the diurnal tides flooding the site. This means that the higher the fill, the weaker the tidal scouring, and the longer it takes for tidal channels to form. With a lower filled site, natural sedimentation will eventually build up the marsh plain and allow for the unimpeded development of first and second order tidal channels. Therefore, there is a compromise between filling the site high for vegetation establishment and keeping it low enough for a tidal channel system to form. As described above, wetlands created with fill material placed too low in the tidal frame, coupled with high wave activity, may run the risk of delayed evolution. Also, filling the site with dredged material above the root zone of pioneer vegetation (approximately 0.3 m (1 ft) below the surface of the mudflat) may result in substrate that is of lesser quality for successful colonization. Sediments that are naturally deposited may provide a better substrate than dredged material.

Finally, in calculating the final elevation of the created surface, consideration should be given to assessing the amount of elevation loss that will take place with time as the fill material consolidates. Dredged material is commonly placed as liquefied slurry at densities lower than found on natural marshes. After placement, the slurry dewaters and consolidates resulting in a fall in surface elevation. The amount of subsidence depends upon the depth of fill and its water content as well as the bearing capacity of the underlying material. Because of their lower density and lesser bearing capacity, intertidal mudflats will consolidate to a greater degree than compacted bayland soils under the same depth of fill material. The rate of subsidence declines with time as both the fill and supporting sediments adjust. Full consolidation may take several years.

The amount of subsurface adjustment to loading will vary around the Bay, increasing with the organic content of the soils as well as any changes in sediment texture (whether the deposit is sand grain or clay matrix-supported). In Suisun Bay and the Delta region, where mineral sedimentation rates are low and alluvium in much of the region consists primarily of organic material, considerable elevation change can take place under loading (Orr et al. 2003).

EXPERIENCE FROM RESTORATION SITES

Restoration sites in the San Francisco Bay have experienced a range of natural estuarine sedimentation rates due primarily to differing initial site elevations and proximity to sources of sediment supply. The highest rate of estuarine sedimentation has occurred at Carl’s Marsh, located at the mouth of the Petaluma River. A large mass of suspended sediment moves between the mouth of the Petaluma River and San Pablo Bay on the ebb and flood tides. This “cloud” of suspended sediment is maintained by successive erosion and deposition of sediments from San Pablo Bay mudflats and the bed of the Petaluma River (Schoellhamer et al. 2003). The initial rate of sedimentation at Carl’s Marsh was up to 0.6 m/yr (2 ft/yr) due to high suspended sediment concentrations during the wet El Niño year of 1997/1998 (WWR 2003). Sedimentation rates were observed to decrease after approximately three years as the site elevation increased and suspended sediment concentrations decreased after the El Niño event (WWR 2003). Average site elevations decreased between the fourth and fifth years after restoration due to the consolidation of initial layer of deposited material. Following this period, net accretion rates leveled off to 0.04 m/yr (0.14 ft/yr).

Across the Petaluma River at Green Point Marsh, sedimentation rates have been three times less than at Carl's Marsh. Although Green Point was restored eight years prior to Carl's Marsh and started at an elevation approximately 0.6 m (2 ft) higher, today the elevation of Green Point is less than 0.15 m (0.5 ft) higher than Carl's Marsh. Sediment supply to Green Point was initially limited by the narrow outboard slough channel, which eroded over five to ten years. Much of Green Point Marsh is vegetated—however, mudflat areas remain at the back of the site where the delivery of suspended sediment is limited. The sedimentation rates at Green Point and Carl's Marsh are likely to converge as sedimentation rates at Carl's Marsh level off.

At Crissy Field, estuarine sedimentation is minimal because of a lack of sediment supply at the mouth of the Bay. Very little suspended sediment that is re-worked in other parts of the Bay or from Bay watersheds reaches the mouth.

Early examples of the use of dredged material in marsh restoration were the Faber Tract (1972), Pond 3 along the Alameda Creek Flood Control Channel (1974) and Muzzi Marsh (1975). Monitoring data of how vegetation and tidal channels had developed in these first generation projects were used in developing design guidelines for the "second generation" Sonoma Baylands project implemented in 1996 (Williams and Florsheim 1994). In restoration sites where the material was placed close to the equilibrium marsh plain elevation (MHHW), these sites have not developed slough drainage systems, despite colonization by pickleweed and after 25 to 30 years of tidal action. This has been observed at "Inner" and "Outer" Muzzi Marsh, Faber Tract, Alameda Creek Pond 3, and other early dredged placement sites such as Bothin Marsh in Richardson Bay.

Muzzi Marsh initially contained two distinct elevation zones separated by a training dike (Figure 13). The upper portion of Muzzi Marsh was originally filled to 2.1 m (7.1 ft) NAVD, an elevation higher than MHHW. In contrast, the lower unfilled portion of Muzzi Marsh ranged between 1.1 to 1.4 m (3.7 to 4.7 ft) NAVD (between MTL and MHW). Only one small slough channel system developed naturally in the upper portion of Muzzi Marsh, the remainder contains few channels including those constructed as mosquito ditches. A dense network of sinuous slough channels exist on the mudflat and marsh plain in the lower portion of Muzzi Marsh, indicating that the lower elevation allowed for the successful evolution of the slough channel system and simultaneous development of the marsh plain.

A similar situation exists at the Faber Tract where the upper portion of the site was filled to an elevation of about 2.1 m (7.0 ft) NAVD (between MHW and MHHW) and the lower portion of Faber Tract was filled to an elevation of 1.6 m (5.4 ft) NAVD (between MTL and MHW). While slough channels developed on the lower portion of Faber Tract, the lack of slough channels in the upper portion of the site indicates that it was filled too high. Figure 14 shows a schematic diagram of the relationship between slough channel development and marsh plain elevation in the Faber Tract. In this figure (Figure 14), the Faber Tract is divided into three zones: no channels with an estimated elevation after fill between about 2.1 and 2.0 m (7.0 and 6.6 ft) NAVD; intermittent channels between 2.0 and 1.8 m (6.6 and 6.1 ft) NAVD; and abundant channels between 1.8 and 1.6 m (6.1 and 5.4 ft) NAVD.

The slope of the marsh plain generally determines the orientation of the slough channel drainage system. This can be seen at the Faber Tract, where the channels are generally oriented away from the location where dredged material was discharged. The dredged material discharge sites were high points that extend radially from the south edge of the marsh. This high portion of the marsh supports upland vegetation, but lacks slough channels. The gradient of the marsh is from south to north and the majority of the slough channels are oriented in the same direction—toward one large slough channel. This channel formed at the low point of the site and now serves as the major drainage for the diked marsh. The effect of the gradient on the orientation of slough channel development is also evident at Warm Springs where small slough channels have formed (similar to rill formation) in a direction toward the former major slough channel.

Assessment of the evolution of the earlier sites (PWA 1991) led to a design recommendation for Sonoma Baylands of fill placement to 0.5 m (1.5 ft) below the marsh plain elevation of MHHW. However, in the 11-hectare (27–acre) pilot unit fill material was only placed to an elevation of 1.0 m (3.1 ft) NAVD. In the main unit, the site was typically filled to 1.3 m (4.1 ft) NAVD and it has since subsided by about 0.15 m (0.5 ft) due to compaction as shown in Figure 15.

Another consideration in placing fill is its effect on limiting wind wave action. Sites without fill, but with relatively high initial elevations above the colonization elevation, experienced rapid colonization by cordgrass and appear unaffected by wave activity. Pond 2A and Bair Island provide good examples of rapid vegetative colonization. Once cordgrass becomes established, it traps sediment and reduces wave energy. In contrast, in sites where the initial elevation is below the colonization elevation, it appears that internal wind waves can reduce rates of colonization. This can be seen at Slaughterhouse Point and the Nevada-shaped parcel. Only where wave power is low and suspended sediment concentrations are high, such as at Carl's Marsh, does the colonization rate appear to be unimpeded.

Figure 16 shows available data on the time required for appreciable vegetation colonization versus the initial elevation at the time of restoration.

DESIGN RECOMMENDATIONS

1. Estimate the expected rate of natural estuarine sedimentation in the site, accounting for proximity to sediment supply, consolidation of deposited material, compaction, and wind-wave re-suspension of deposits.

2. Determine the mature marsh plain elevation based on local tidal characteristics and adjacent reference marshes.

3. Design fill placement to be about 0.3 m (1 ft) below the marsh plain elevation at the time of breaching to give sufficient tidal prism for channel development and to allow for the deposition of a substrate suitable for plant colonization.

4. For dredged fill sites, allow for compaction between time of placement and breaching.

5. For hydraulically placed fill, identify a disposal location so that fill slopes will drain towards the main drainage network.

6. Design the fill placement so that there are significant areas above the colonization elevation that will vegetate quickly and reduce wave impacts.

7. In specifying particular elevations for grading, in general it should be noted that grading tolerances of +/-0.15 m (0.5 ft) can be expected on most sites. The placing of dredged material is particularly problematical and the slope of the dredge spoil should be anticipated as well as hydraulic sorting of the sediment.

8. Close attention should be taken to the correct specification and use of vertical datums.

4.2 QUESTION 2: SHOULD FILL BE REMOVED?

THE PROBLEM

A number of restoration sites are located on former tidal marshes that have been filled close to or above the normal elevation of a mature marsh plain. In these instances, a decision needs to be made whether fill should be removed, and if so, how much should be removed. This decision is a tradeoff between the cost of fill removal and disposal and the achievement of desired wetland functions within a given period. Most fill placement is recent and is often still gradually subsiding. It is possible that over long periods with gradually rising sea level a filled site may become intertidal.

Removal and disposal of fill is costly. Thus, the goal would be to minimize the amount of fill removed from the site while ensuring that wetland functions are not impaired. The temptation has been to grade the site down to a typical marsh plain elevation of MHHW and restore tidal action.

However, problems remain with this grading approach: it is difficult to precisely control grading—especially in wet bay mud. Grading tolerances are typically plus or minus 0.15 m (0.5 ft). This means that large parts of the site might be graded too high for typical marsh plain vegetation, and uneven grading can create depressions impeding drainage. In addition, fill material is often compacted, may contain construction debris, or be nutrient poor, and may not consist of cohesive estuarine sediments, the soils most suitable for salt marsh plant species. Under these conditions, while vegetation may colonize these sites, the substrate is likely to impede the vigor of vegetation growth. In addition the small tidal prism means that erosion and deposition within any artificially graded channels is slow, and it may take a considerable time for them to adjust to a more natural form (see Section 4.6, Question 6: Should new tidal channels be excavated?).

A different approach is to excavate fill to the level of the bottom of the root zone, which is typically about 0.3 m (1 ft) deep, and allow natural sedimentation to accumulate in order to provide a better substrate to support colonizing wetland plants, and to build the marsh plain back up to its equilibrium elevation (see Section 4.1 Question 1: Should the site be filled?). This means that eventually, over several decades, the marsh plain plants can grow in deposited estuarine muds deposited on top of the artificial fill.

EXPERIENCE FROM RESTORED MARSHES

A number of small, earlier restoration projects, such as Creekside Park in Corte Madera, Third Avenue Marsh in Foster City and the Palo Alto Yacht Harbor, have required removal of fill material. However, no monitoring data are available for these projects. More recent projects include Crissy Field, where fill was excavated to create a 7-hectare (17–acre) lagoon that is anticipated to evolve into a vegetated marsh, and Martin Luther King Jr. Regional Shoreline Wetlands Project in Oakland, where excavating fill material created 13 hectares (33 acres) of tidal marsh.

We can obtain useful insight of the evolution of two dredged material filled sites that have been monitored, "Inner" Muzzi, and Pond 3 along Alameda Creek. Although neither of these sites had their marsh plains graded, within a few years of dredged material placement, large areas of these restoration sites had subsided to approximately the same elevation as the mature marsh plain. However, for many years pickleweed cover was sparse and stressed (Figure 17). After 25 years, the tidal drainage system has not evolved on these marsh plains beyond the initial artificial ditches (Figure 18).

The more recent 4-hectare (10–acre) Martinez Marsh (Figure 19 and Figure 20) is a good example of how a graded fill restoration site evolves. Here, a sloping marsh plain was excavated to at least 0.3 m (1 ft) below MHHW, the elevation of nearby reference marshes, in order to eliminate pepper grass. After two years, approximately 0.15 m (0.5 ft) of estuarine sediment had deposited and vegetation had started to establish (Figure 21) and no pepper grass was colonizing the lower elevations.

DESIGN RECOMMENDATIONS

1. If most of the site is filled higher than 0.3 m (1 ft) below equilibrium, marsh plain elevations fill removal should be considered.

2. Where the site to be graded is upland or compacted fill, excavate to 0.3 m (1 ft) below the anticipated equilibrium marsh plain elevations to permit natural sedimentation and unimpeded root growth.

3. Assume that specified grading tolerances will be +/-0.15 m (0.5 ft).

4. Remove any large pieces of construction debris.

5. Design marsh plain grading to provide slight slope towards nearest tidal channels.

6. Close attention should be paid to the correct specification and use of vertical datums.

4.3 QUESTION 3: SHOULD A LEVEE BREACH AND OUTBOARD CHANNEL BE EXCAVATED?

THE PROBLEM

In general, once a breach is made in a levee, natural scouring will eventually erode the breach and a channel across any outboard fringing marsh to reconnect the site to full tidal influence. The new connecting channel that forms eventually reaches equilibrium with the evolving tidal prism within the restored site. However, reaching this equilibrium may take decades, depending on the erodibility of the levee, the extent of outboard marsh, the size of the initial levee breach, and sedimentation rates within the site. During this period tidal amplitude and circulation will be limited, sedimentation rates low, and wave erosion of perimeter levees high. If the objective of the restoration is to maximize the rate of marsh evolution and marsh functions, it is desirable to restore full tidal action to the site as quickly as possible. Full tidal action establishes the appropriate hydroperiod to which marsh plants are adapted and also maximizes input of estuarine sediments carried in on the flood tide. Full tidal action can be achieved by excavating the levee breach (as well as lowering the remaining part of the levee—see Section 4.5 Question 5: Should the bayfront levee be lowered?) and outboard channel to the Bay large enough so they do not constrict the hydraulics of tidal flows to the site.

In practice, many restoration sites are separated from the tidal source of the Bay by marsh plains outboard of the levees, or by silted up tidal channels, both of which can provide valuable wetland habitat in their own right. Excavating a full-sized tidal channel through the levee and outboard marsh may result in large costs for removal and disposal of Bay mud. To reduce these costs and disruption of existing habitat, it is possible to excavate a smaller channel, or to take advantage of a small pre-existing channel, and then let the tidal flows scour these channels to their ultimate dimensions in equilibrium with the tidal prism of the restoring site. The design decision then becomes a tradeoff: on the one side, between high cost and habitat disturbance, and on the other, by a time delay before the site achieves a full tidal range and vegetated marsh functions.

To predict the time delay we need to recognize that as the restoration site evolves, the tidal prism and equilibrium channel dimensions will change. At first, the tidal prism may be reduced by the hydraulic constriction of the entrance channel and breach. As the channel scours and deepens, the tidal prism will increase and then decrease again due to intertidal siltation in the restoration site. This means an undersized channel or breach first scours and increases in size and then might eventually silt in and diminish in size. This rate of change is further complicated by differential rates of erosion of marsh sediments and compacted levee materials.

The location of the levee breach and outboard channel has been mainly determined by the need to minimize excavation requirements. This is done by selecting a breach location with only a short distance across an existing marsh to a major slough channel, locating the breach to rejuvenate a pre-existing internal drainage system, or locating the breach to adjoin and take advantage of an existing marsh tidal channel. In addition, breach and channel locations can influence salinity and sedimentation rates in the restored sites. Typically, levee breaches upstream on a fresh water-influenced tidal slough will encourage a lower salinity regime in the restoration site; breaches closer to tidal waters with high turbidity, such as wave-exposed shallows, will encourage higher rates of sedimentation.

There are a few locations in San Francisco Bay where strong wave action forms ebb tide sand shoals across the mouth of tidal channels (e.g. Oro Loma, Crissy Field). These shoals can naturally limit low tide drainage and must be taken into account in the restoration design.

EXPERIENCE FROM RESTORED MARSHES

Over the last 20 years, numerous surveys of the morphology of tidal channels in San Francisco Bay marshes have enabled us to develop empirical hydraulic geometry relationships that correlate the equilibrium channel depth, top width, and cross-sectional area with tidal prism. These relationships are described in Williams et al. 2002 (Appendix A.2), and provide a useful tool for designing tidal channel and levee breach dimensions.

Long-term monitoring of the Warm Springs and Sonoma Baylands projects provide valuable insights on how quickly and the manner in which undersized outboard channels and levee breaches erode towards their equilibrium geometry.

The 81-hectare (200-acre) Warm Springs project was breached in 1986 at the south end directly to Coyote Slough and at the north end to Mud Slough (Figure 22). For the first four years, the tidal connection to Mud Slough was largely ineffective because the levee breach was separated from the slough by about 120 m (400 ft) of outboard marsh plain that was densely colonized with alkali bulrush. This meant that almost all the tidal flows were conveyed through the South Breach to Coyote Slough. The South Breach was excavated as a 15 m (50 ft)-wide notch (Figure 23). Sixteen months later, the breach to Coyote Slough had widened to more than 30 m (100 ft) and deepened a further 1.5 m (5 ft), thus increasing its effective flow area about 10 times. Over the next seven years, the breach doubled in area again and stabilized close to its equilibrium geometry. Six months later, tide monitoring in the site (Figure 24) showed a muted tide about 60% of the full diurnal range; 18 months later as the breach eroded the tide was about 90% of the full range (Figure 25); five years later, the tides inside and outside the site were essentially the same (Figure 26).

Reintroduction of tidal action through the South Breach significantly increased the tidal prism in Coyote Slough, resulting in rapid deepening and then widening. In the first year the Coyote Slough channel had deepened about 1.5 m (5 ft), from 3 to 4.5 m (10 to 15 ft) below MHHW (Figure 27). After nine years the channel depth had reached equilibrium at about 5.8 m (19 ft) deep. This increase in depth undercut the banks resulting in large slump blocks that slowly slid into the channel and were eroded away, resulting in progressive widening. Only after 16 years did the channel reach equilibrium at about twice the original cross sectional area and with channel bank slopes of approximately 4:1. Much of the channel widening and increase in cross section occurred after the tidal prism upstream was diminishing due to the rapid sedimentation in the restored site. Over time, Coyote Slough is expected to now reduce in size in response to this reduction in tidal prism. The evolutionary trajectory of the Coyote Creek channel is shown in Figure 28.

The Mud Slough channel eroded in a similar way after the North Breach channel eroded through the fringing marsh plain four years after initial breaching. Over the following five years, it deepened from about 2.1 to 3.9 m (7 to 13 ft). Then over the next four years, it widened significantly as banks slumped into the channel (Figure 29).

Because Coyote Slough is now much larger than Mud Slough it has permanently captured most of the tidal circulation of the site. The tidal “null” point between the sloughs is close to the north breach and an emerging mudflat has separated the two tidal drainage systems.

The design of the Sonoma Baylands project in the early 1990s was informed by the monitoring experience of other marshes including observations of the first eight years of evolution at Warm Springs. In the original plan for Sonoma Baylands, the levee breaches and excavated channels through the fringing marsh from the Pilot and Main units to the Bay were to be sized to the expected equilibrium dimension appropriate for the tidal prism expected in the mature marsh, instead of “notching” as was done at Warm Springs’ South Breach. It was anticipated that immediately after breaching, the initial tidal prism would be large and result in erosion, which would then be followed by sedimentation.

However, although the levee breaches were excavated to the equilibrium dimension to remove compacted levee material, a decision was made to not excavate the connecting channel across the fringing marsh because of its cost and adverse ecologic impacts. This meant that after breaching, tidal flows could only enter the site through two small pre-existing channels: a 420 m (1,400 ft)-long channel to the pilot unit and an approximately 300 m (1,000 ft)-long channel to the main unit. Tidal flows were further restricted by the unusually high elevation of the centennial fringing marsh on the north shore of San Pablo Bay—about 0.15 m (0.5 ft) above MHHW—that prevented most spring tides flowing across the marsh plain into the restoration sites.

The hydraulic constriction of the tidal channel and the large potential tidal prism of the site meant that tides were initially severely muted at Sonoma Baylands, thus limiting the actual tidal prism moving in and out of the two restoration areas. Over the last eight years, the channels have eroded and expanded the tidal range in the two areas, thus increasing the actual tidal prism. This, in turn, tends to increase the rate of erosion of the channels. As tidal range increased, sedimentation rates increased. The increased sedimentation rates will now begin to reduce the tidal prism and will eventually bring the channel dimensions into equilibrium. Detailed monitoring of the site (Appendix B.6) provides valuable information on the rate of evolution and erosion of the breach and outboard channels.

The excavated levee breaches first silted in and then started eroding again as tidal prism increased (Figure 30). The freshly deposited material in the levee breach appeared to be more erodible than the marsh plain sediments, thus allowing the levee breach to enlarge more quickly than the outboard channel (Figure 31). Once the channel had started incising into unexcavated material in the breach, the difference in erosion rates disappeared. The evolutionary trajectory of the Sonoma Baylands channels is shown in Figure 28.

In both the pilot and main unit channel, the same pattern of erosion was observed as in Coyote Slough. First, channel deepening occurs that induces bank slumping and widening as shown in Figure 32. In the Pilot unit, channel deepening was impeded for the first three years by construction debris that had been dumped in the channel. After removal, the depth has increased from about 1.2 m (4 ft) below MHHW to about 2.7 m (9 ft) in eight years and the cross section area has increased close to the equilibrium value as shown in Figure 28. However, because channel banks have been destabilized, it is possible for the channel to widen beyond the equilibrium area. With the erosion of the channel the diurnal tidal range within the pilot unit is approximately 60% of the full range. Over the first six years, the main unit channel eroded gradually and then rapidly accelerated as the diurnal tidal prism started increasing. After eight years, the channel has increased in depth from approximately 0.9 to 3.7 m (3 to 12 ft) below MHHW and has increased in cross sectional area by an order of magnitude (Figure 28). Large bank slumping cracks are observed on the marsh plain within the 4:1 slope intersection zone (Figure 33).

The main unit channel discharged onto a 300 m (1,000 ft)-wide mudflat. After approximately three years, the tidal prism had increased enough to scour a deep channel across this mudflat. The mudflat channel has increased in size in parallel with erosion of the marsh connector channel. Similarly, at Cooley Landing, the original channels dissipated on an extensive mudflat. Within the first six months after restoration, a channel had formed across these mudflats (Figure 34). It does not appear that the scouring of channels on mudflats is a constraint on site evolution.

The location of the breaches at Warm Springs was determined by several factors. In order to take advantage of anticipated scouring of the channel to improve flood conveyance, the South Breach was located where fringing marsh was at a minimum and as far south on Coyote Slough as possible. In addition, this location maximized the length of large subtidal channel habitat within the restoring marsh. The North Breach was originally located immediately adjacent to Mud Slough where there was a minimum of fringing marsh, but was later relocated by the civil engineers responsible for final design.

Similarly, but on a smaller scale, flow from Martinez Marsh in Suisun Bay was directed through Alhambra Creek to create environmentally beneficial flood protection measures for the City of Martinez. Tidal flows were directed through the lower reaches of the river, which not only enhanced and widened the riparian corridor, but also assisted in sustaining a channel form to support floodwater conveyance during winter months.

At Sonoma Baylands, the breaches were located where it was originally anticipated the outboard channels would be excavated. For the 110-hectare (270–acre) main unit, a single breach was selected deliberately to concentrate tidal flows to ensure the development of a single high order tidal drainage system within the site. At Cooley Landing, the bayward perimeter levee was breached in two locations to reactivate the remnant complex tidal drainage system that still existed in the old salt pond.

At Crissy Field the breach is located down drift of a beach groin because a strong littoral drift significantly effects the entrance channel hydraulics leading to closure during periods of high swells and neap tides (PWA 2004). This is due to the location of the site at the mouth of the Bay, close to the Golden Gate, and not typical of the majority of restorations in San Francisco Bay.

In all restoration sites with multiple breaches, slough channels may be initially connected, but sediment deposition creates watershed divides that isolate drainage systems for each breach. This can be seen in Carl's Marsh (Figure 35) and Warm Springs (Figure 22).

DESIGN RECOMMENDATIONS

1. The decision whether a breach and outboard channel needs to be excavated depends on the tradeoff between the cost of excavation and the rate of evolution and achievement of desired wetland functions.

2. Sizing levee breaches and channel dimensions requires estimating both initial post-restoration and long-term equilibrium channel dimensions using empirical hydraulic geometry relationships (Appendix A.2). It should be noted that there can be a significant error band in these predictions and, wherever possible, they should be calibrated with data on similar marshes in the vicinity of the restoration site. The consequences of overestimating or underestimating equilibrium or transient channel dimensions need to be considered in the design. Post-restoration or short-term channel dimensions are calculated using the tidal prism of flooded site upon breaching. Long-term equilibrium channel dimensions can be inferred from estimations of the predicted marsh drainage area; assuming that a mature vegetated marsh will eventually evolve.

3. Constructing levee breaches and connecting channels to the predicted larger sizes for the initial post breach tidal prism is generally not necessary if the channel and breach is free to erode.

4. A levee breach should be excavated to at least the smaller long-term equilibrium dimensions to remove compacted material. This size breach will usually allow for a large enough tidal prism to quickly erode the breach to a larger size, but this should be checked by hydrodynamic analysis or modeling. The rate of breach erosion is site specific and determined by the volume of the body of water available to scour through the breach.

5. In general, it is also preferable to construct connecting channels to reflect long-term equilibrium dimensions to minimize excavation costs and to allow them to naturally evolve towards equilibrium dimensions, which are likely to be smaller than the estimated short-term dimensions.

6. It is more important to excavate channels and breaches to their anticipated depth, and then allow for bank slumping to the angle of repose, than to replicate a specific cross section.

7. In designing connector channels it should be anticipated that they may scour to the maximum size appropriate for the initial tidal prism and may widen beyond predicted equilibrium geometry due to bank slumping.

8. In determining breach location, the following factors should be considered:

- Minimizing the length of connecting channel required across existing fringing marshes;
- Maximize opportunities for creating single large complex tidal drainage systems within the marsh rather than multiple smaller systems. Multiple breaches will ultimately create multiple separate tidal drainage systems within the site. Ideally, marsh watershed areas should be large enough to sustain high order, subtidal channel habitat within the marsh;
- Maximize opportunities of deepening existing tidal channels for navigation and flood level reduction;
- Allow for rejuvenation of remnant tidal drainage features on the restored site. Where possible, the breach should be sited to take full advantage of any opportunities to reestablish a connection between an existing remnant channel network within the restoration site and the truncated higher order channel on the natural marsh. In this respect, the location of the breaches, the location of any internal watersheds and the internal channel network should be seen as an integrated design;
- Compatibility with public and maintenance access;
- Proximity to high suspended sediment source—for example, adjacent mud flats where wind waves resuspend fine sediments back into the water column or in areas close to estuary entrapments zones; and
- Minimize risk of remobilizing contaminated sediments. For example, consider locating the breach away from outboard slough channels with known sources of contaminated, erodible sediments.

4.4 QUESTION 4: SHOULD WAVE BREAKS BE CONSTRUCTED?

THE PROBLEM

Subsided sites evolve into vegetated marsh plains by progressively accumulating cohesive sediment until the mudflats reach an elevation at which vegetation can establish. In large wind-exposed sites, wind wave action can slow or stop this sedimentary process by inhibiting deposition, or, if wave action is sufficiently high, previously deposited sediments are scoured and then are transported out of the site on the ebb tide.

For given site conditions, the potential for wind-induced inhibition of net deposition rates generally increases as mudflat elevations increase and water depths decrease, causing even small waves to break. This means that vulnerability to sediment disturbance and re-working from wave action increases as site (or rather fetch) size increase, as mudflats build in elevation, and water depths decrease. For a location within a site for a particular wave climate, net deposition rates will tend to progressively decrease and approach zero at a particular elevation, as illustrated in Figure 10. If this elevation is above the typical colonization elevation, vegetation will eventually become established, as it appears that the pioneer colonizers, Pacific cordgrass or alkali bulrush, can withstand the wave action typically experienced in the Bay. The presence of vegetation then promotes further marsh plain elevation building through increased sedimentation, protection from scour, and accumulation of organic material. Once an extensive vegetated marsh plain develops, it will dissipate wave energy and prevent the scouring of accumulated sediment on the marsh plain (French and Stoddart 1992).

However, if a given wind wave climate dictates an equilibrium mudflat elevation below the colonization elevation, the site will remain bare mudflats. If this is an unacceptable outcome, wind wave effects will need to be reduced. This can be done in two ways: by filling the site to above the colonization elevation or constructing wind wave breaks within the site.

Wind wave breaks can be graded as high elevation areas, berms, or peninsulas. These can be designed to define tidal watersheds, guide wind driven circulation, focus sedimentation in preferred locations, and guide the shape and location of the evolving tidal channel network. High elevation areas or berms that are planted with or colonized by marsh vegetation can provide an alternate means of reducing wind wave action. Wave break design will be a trade-off between height, width, slope, vegetation, cost, and design objectives. For example, vegetated wave breaks that are lower within the tidal frame would need to be broader and have gentler slopes than a higher wave break.

In the 1970s, the USACE conducted extensive experiments in the planting of smooth cordgrass in East coast estuaries for wave energy dissipation. This technique has been applied extensively in the Chesapeake Bay area. Similar experiments using the Pacific cordgrass in San Francisco Bay were also successful in stabilizing shorelines, except for severe wind wave conditions (Newcombe 1979 p.108). Generally, it appears that the effectiveness of marsh plants is dependent upon stem height and density and the depth to which plants grow in the tidal frame as well as the wave energy. The use of limited areas of Pacific cordgrass as internal wave breaks for substrate stabilization within a subsided site has not been tested and is not expected to be effective. However, berms with slopes colonized by Pacific cordgrass are desirable for berm stabilization and habitat. It is possible that bands of bulrush could be encouraged to grow in appropriate locations to reduce wave energy (see Section 4.11 Question 11: Should plants be planted?). If bulrush is planted too low within the tidal frame, it will not survive after tidal action is restored. Vegetation detritus on the marsh surface may encourage sedimentation within a site by providing additional bed roughness. However, this method has not been tested and its effectiveness is uncertain.

For all restoration sites, the effect of wind wave action has to be considered in restoration design. The most extreme wave conditions would be experienced if bayfront levees were removed and subsided sites were fully exposed to storm waves generated at high tide across the Bay. This is a major constraint and is addressed in Section 4.5 Question 5: Should the bayfront levee be lowered? More typically, restoration sites are protected from large waves generated in the Bay and it is wave action generated within the site that needs to be considered.

EXPERIENCE FROM RESTORED MARSHES

The interaction of waves on intertidal cohesive mudflats is a complex and poorly defined process. Analytic methods, such as those incorporated in numerical models, can be used to develop insight into how a site may evolve, but need to be calibrated with local conditions. More typically, empirical methods are used to make decisions on whether filling or wave breaks are needed.

Williams and Orr have collated the available limited information on the delay in site evolution of breached subsided sites due to wind wave effects (Williams and Orr 2002). As an indicator of the rate of evolution of the site, they used the time from initial flooding of a mudflat to pioneer colonization on emerging mudflats. The effect of wind waves was characterized by a wave power index proportional to the product of wave energy and period, which, in turn, is dependent upon the fetch length, strength, and duration of winds. Figure 36 shows the vegetative state of the fully tidal sites as a function of wave power index and initial elevation.

Sites with initial elevations close to the colonization elevation (above approximately +0.3 m [+1 ft] above MTL) experienced rapid colonization by cordgrass. Pond 2A and Bair Island are good examples of locations where rapid colonization has occurred. Although high wave power may inhibit sedimentation in such sites, this was not observed in these sites. Once cordgrass becomes established, it traps sediment and reduces wave energy. In contrast, for sites below colonization elevation, it appears that internal wind waves can reduce rates of sedimentation. No large, deeply subsided site in high wave energy conditions has yet achieved a vegetated marsh plain after approximately 20 years.

Sedimentation rates at two of the higher energy sites—Nevada-Shaped Parcel and Slaughterhouse Point—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 (Figure 37 and Figure 38). However, the retardation may not be solely due to wind wave activity. At Slaughterhouse, an initially damped tidal range and probable lower suspended sediment supply could also have delayed rates of development. At the Nevada site, lower suspended sediment concentrations may be a factor. In contrast, Carl’s Marsh, although deeply subsided, has small wind fetches and high sedimentation rates and has not been affected by wind wave action.

Wave break peninsulas were included in Sonoma Baylands. These were designed to minimize wave energy effects on sedimentation and site evolution by reducing fetch lengths to approximately 300 m (1,000 ft). Without these peninsulas, fetch lengths would have been approximately 600 – 1,200 m (2,000 – 4,000 ft). These peninsulas were graded as continuous berms high enough to dissipate wave energy at high tide levels (at about 0.6 m (2 ft) above MHHW) during the period before extensive vegetation had become established. It was intended that these peninsulas would eventually erode, subside and disappear in the evolving marsh plain over the next 50 years. The spacing of the peninsulas was determined by a reconnaissance of other sites to determine minimum fetch lengths that were clearly effecting sedimentation (PWA 1991). Subsequent experience, such as at Tolay Creek, where fetch lengths are approximately 250 m (800 ft), indicates this minimum spacing may be too optimistic.

The layout of the peninsulas at Sonoma Baylands was also intended to define channel development and sedimentation patterns within the site.

It has taken six to eight years for a significant tidal range to develop on the site because of the time required to erode the constricted connecting channel to the Bay. During this period, the site was permanently flooded and wave action eroded a number of the more exposed peninsulas (Figure 39) instead of the flood control levee. Now that full tidal action is occurring, the peninsulas are functioning as intended. This can be seen from the differential sedimentation rates of the sheltered versus less sheltered portions of the site (Figure 40).

Wave break peninsulas can have additional functions, such as providing edge ecotones and refugia. At Sonoma Baylands, a band of pickleweed formed around the site perimeter and along the peninsula edges within the first two years and expanded outward as increased tidal exchanges exposed more mudflat area. Initially, cordgrass colonized the sheltered angles of a peninsula in the pilot unit and gradually has established along the perimeter below the pickleweed band. However, in common with other areas within the transition zone (see Section 4.9 Question 9: How should the wetland-upland transition zones be designed?), exotic plant species have established on the upper parts of the peninsulas.

Portions of the peninsulas have become very desirable bird roosting and nesting areas. However, because tidal action was limited, other portions have provided habitat for rodent burrows. Now that the tidal range is increasing, it is likely these habitats will be flooded. Concerns have also been raised that the peninsulas provide access corridors for predators, such as red fox, which are present in the area. For this reason the peninsulas were disconnected from the levee (Figure 41).

DESIGN RECOMMENDATIONS

1. For each site, wind wave action needs to be evaluated to determine whether it needs to be considered in the design. In general, if fetch lengths are smaller than about 300 m (1,000 ft) and elevations are above the colonization elevation, wave effects are usually minor. If fetch lengths are greater than about 300 m (1,000 ft) and the site is above the colonization elevation potential, wave erosion of perimeter levees needs to be considered during the period until the marsh plain is fully vegetated. If fetch lengths are greater than about 300 m (1,000 ft) and the site is more deeply subsided, filling or grading to create wave breaks needs to be considered.

2. There are two different strategies for designing wave breaks:

    - The strategy adopted at Sonoma Baylands is intended to minimize the effects of wave action on net sedimentation and therefore maximize rate of evolution to a vegetated marsh.
    - An alternative strategy is to limit wave action to ensure only that net sedimentation is positive and that the site will eventually evolve to a vegetated marsh. This allows for larger spacing of wave breaks than the former strategy and the possibly of a longer period when the site supports emerging intertidal mudflats.

3. Wave breaks should be designed to dissipate most of the wave energy during the period until the site becomes fully vegetated. This can be done by grading a berm to the appropriate dimensions (i.e. high enough and/or wide enough). In general, it is more cost effective to grade a higher

narrow berm than a broad shallow one. Encouraging the establishment of marsh vegetation on berm slopes will provide additional wave dissipation. A minimum width of vegetated marsh of 10 m (30 ft) on berm slopes of 1:15 will provide adequate wave dissipation (Knutson 1990 p.95).

4. The wave break crest should be constructed as low as possible within the tidal frame but high enough to trip and break waves passing over during extreme tides. If the wave break is too high, upland exotic vegetation may establish itself and predators may use the peninsula for access.

5. Because locally generated waves have a short period and wavelength is small, wave energy dissipation due to refraction is negligible. Therefore, wave breaks need to be either continuous features, or if discontinuous "islands" they need to completely block waves from the dominant fetch directions because there would be minimal dissipation of wave energy due to refraction through the gaps.

6. Because the dominant fetch directions are not usually well defined, it is preferable to configure wave breaks as curved features that offer protection from a variety of wave directions.

7. Allowance must be made for the initial subsidence of the wave break peninsula.

8. Allowance does not need to be made for rising sea levels since the role of the peninsulas diminishes as the site elevations evolve.

9. The design of the spacing of wave breaks depends upon the wind climate of the site.

10. Wave breaks are essentially sacrificial structures; they are only needed until vegetation is established along the edges of wave breaks and marsh plain elevations have accreted. There is no need to armor the slope unless the wave breaks perform some other function, such as guiding where channels are forming.

4.5 QUESTION 5: SHOULD THE BAYFRONT LEVEE BE LOWERED?

THE PROBLEM

Most restoration projects are subsided sites separated from the Bay or a major slough by levees. These levees are usually constructed of sidecast, dried, and compacted Bay mud. The bayfront levee not only acts to block tidal flows across the marsh, for which it was originally designed, but also acts as a barrier for a number of other processes. The levee blocks the movement of water, sediment, organic plant material, and detritus that would otherwise move between the outboard mudflat and the marsh on spring tides or during storm surges. Therefore, the persistence of a levee limits the ecological connectivity of the marsh with the estuary.

At the same time, the remnant bayfront levee may provide protection to the evolving site from the erosive effects of externally generated waves. The effects of this wave action can be severe, as discussed above in

Section 4.4 Question 4: Should wave breaks be constructed? For deeply subsided restored sites, remnant levees therefore perform a valuable function of reducing incident wind wave energy and allowing sedimentation to occur within the site until marsh vegetation can colonize. In addition, the outboard levee may reduce wave energy that might otherwise erode the inboard levee. The need for the outboard levee diminishes as the surface of the evolving marsh gains elevation relative to the tidal frame. Once high marsh is established, shallow water depths, high canopy wave baffling, root binding, and high sediment shear strengths ensure greater resistance of the marsh to wave erosion. Once the site is fully colonized, the outboard levee becomes a redundant feature. Over time the relic levee will erode and subside into the marsh plain.

Remnant or relic bayfront levees can provide other opportunities and constraints. Levees may be maintained in place to provide for trails and public access. They can provide transitional marsh habitat (see Section 4.9 Question 9: How should the wetland-upland transition zones be designed) as well as a colonization corridor for exotic plants. Remnant levees can also provide refugia for birds and wildlife. They may also provide corridors for access to the marsh interior and den-sites for predators (e.g. red fox and feral cats).

Therefore, there is a tradeoff between leaving the levee in place to provide sufficient protection from waves—allowing sedimentation to occur during the initial evolution of the site—and reconnecting the geomorphic unit and ecological processes in the long-term so that the marsh is sustainable.

EXPERIENCE FROM RESTORED MARSHES

At Muzzi Marsh, the levee was left in place (Figure 42). In Corte Madera Bay, there are long fetches to the east and wave energy can be high. This has caused continual retreat of the shoreline and erosion of the levee over the last 25 years. During this period, protection provided by the levee has allowed sedimentation to occur and vegetation to establish. Large sections of the levee have now disintegrated and the newly created marsh plain is starting to erode (Figure 43 to Figure 45). However, more than approximately 600 m (2,000 ft) of new marsh plain has formed in front of and now protects the new flood control levee to the west. If the remnant levee had been removed at the time of restoration, it is probable that large areas of this site would have remained mudflat. A portion of remnant levee is now utilized as a seal haul-out area because of its isolation.

The Sonoma Baylands project is also located on the bay margin where fetch lengths and winter storms can create intense wave action. However, in the century since the original levee was constructed, a 300 m (1,000 ft)-wide fringing marsh has formed that dissipates wave energy. In this project the bayfront levee was lowered to approximately the elevation of the outboard marsh. However, because of compacted soils, uneven topography, and limited tidal range, the vegetation that has colonized includes many upland species.

At Cooley Landing sections of the bayfront levee have been lowered to 0.15 m (0.5 ft) above MHHW to provide a source of fill for construction and to restore high marsh habitat (Figure 46). The levee design elevation 2.3 m (7.5 ft) NAVD was selected to provide as much wave-breaking function as possible, while still being low enough for high marsh vegetation to establish upon it. The previously existing levee crest was between approximately 2.6 m and 3.5 m (9 and 12 ft) NAVD and supported primarily exotic upland vegetation. Lowering of portions of the bayfront levee has allowed marsh front exchange of sediment-laden waters during spring and storm surge tides.

DESIGN RECOMMENDATIONS

1. If incident wave energy propagating into the site is likely to be high enough to retard sedimentation, then the levee should be left in place but its crest elevation may be lowered. The levee has only to reduce wave energy and not act as a complete barrier.

2. A wide outboard marsh and mudflat will dissipate significant proportions of incident wind wave energy propagating from the Bay. In this case, protection of the site by a levee may not be necessary. Findings from the U.K. (e.g. Moeller et al. 1996) suggest that at sites fronted by extensive marsh (greater than 100 m [300 ft] in width), the requirements for a bayfront levee are considerably less.

3. If the levee is removed and the desire is to achieve a seamless vegetated marsh plain, it may be necessary to over-excavate the compacted levee material by up to 0.3 m (1 ft) and allow natural sedimentation to restore suitable elevations and substrate.

4. If portions of the levee are retained, they can be graded in a way that creates a wetland-upland transitional habitat (see Section 4.9 Question 9: How should the wetland-upland transition zones be designed?).

4.6 QUESTION 6: SHOULD NEW TIDAL CHANNELS BE EXCAVATED?

THE PROBLEM

Where restoration sites have been filled, or where surface sediments have been compacted, tidal channels may need to be excavated. A higher elevation of fill material within the tidal frame will lead to a smaller tidal prism and decreased tidal scouring once tidal action is reintroduced. If tidal scouring is limited, it may take many decades for tidal channels to form naturally on the fill material. If the restoration site is a diked former tidal marsh that has been farmed, the surface soils may have become compacted and more erosion resistant, thus retarding the formation of a tidal drainage system by natural scouring.

The decision to excavate channels is a trade off between the cost of excavating fill material low enough to allow appreciable natural scouring, versus the cost of excavating channels and the longer evolution of the tidal drainage system. Highly compacted filled sites may take hundreds of years for sea level rise and marsh accretion to create an appropriate tidal drainage system.

Earthwork is usually the largest part of construction costs for a restoration project and channel excavation can add disproportionately to the costs for fill removal and disposal. If the fill or underlying material is

Bay mud, the limited bearing capacity makes using heavy equipment difficult and may require placement of temporary load bearing pads or mattresses for construction equipment to work from. In addition, slumping of the banks of cut channels is difficult to predict or control. It is particularly difficult to excavate small first and second order channels within a reasonable tolerance using standard construction equipment, and sinuous or curved channels can be difficult to survey and stake out for construction crews.

RESTORATION EXPERIENCE

During the 1970s, several sites that were filled with dredged material were restored to tidal action (e.g. Muzzi Marsh, Alameda Creek Pond 3, and Faber Tract). In all of these sites, the evolution of the natural drainage system was impeded. At "Inner" Muzzi and Alameda Creek Pond 3, dredged material had been placed to high elevations, at or above MHHW, and large areas remained poorly drained and barren for many years. In both these projects, large channels were later excavated in the dredged material to improve tidal circulation. However, 30 years later, even though the marsh plains have now been colonized extensively by pickleweed and are close to the elevations of mature marshes nearby, their tidal drainage system is not well developed. At Muzzi Marsh, the channel excavation was done "in the wet," but proved extremely difficult to execute and was abandoned when partially complete. Subsequently, most of these large channels have silted in to varying degrees. In addition to these large excavated channels at Muzzi Marsh, small mosquito ditch channels were dug and excavated material sidecast to drain ponded areas on the marsh plain (Figure 44 and Figure 45).

At Faber Tract, hydraulically pumped dredged material was deposited in a series of coalesced depositional cones that sloped from supratidal to low intertidal elevations. A complex tidal channel system developed on the lower portions of the site, first on freshly deposited mud and then incised into the underlying dredged material. However, fill material at high elevation clearly limited channel formation and surveys showed that wherever the original fill material was higher than about 0.3 m (1 ft) below MHHW, no tidal channels formed.

This information was used in specifying target dredged material fill elevations for the Sonoma Baylands Project. Although the constricted outboard tidal channel retarded evolution, a dendritic channel system is now forming on the emerging mudflats on the site and is incising into the placed dredged material. However, in some locations the deepening bed of the channel has eroded down to the original compacted field soils and this may further retard the rate of deepening (Figure 47).

Some restoration sites have been filled with upland fill or construction debris (e.g. Martinez and Martin Luther King). At the small Martinez Marsh, because the fill material was not estuarine sediment and could be erosion resistant, a complete dendritic tidal drainage system was excavated in the fill material to replicate typical natural tidal drainage density and sinuosity (Figure 19). Hydraulic geometry correlations with mature marshes provided minimum channel dimensions. Because of limitations on construction equipment the first and second order channels in this system were over-excavated and, since breaching, are rapidly silting in.

DESIGN RECOMMENDATIONS

1. Channel excavation on filled sites should be considered if typical fill elevations are higher than 0.3 m (1 ft) below MHHW.

2. Excavated channel dimensions should be based on hydraulic geometry relationships derived from mature reference marshes (Williams et al. 2002).

3. Channel density and sinuosity should be determined from nearby reference marshes.

4. Cost savings can be achieved by specifying depth and bottom width of channels and allowing channel banks to stabilize as they are cut, rather than requiring a design side slope.

5. Adjacent marsh plains should be gently sloped to the channel edge to encourage drainage and ensure channels do not evolve in undesired locations.

6. Any erosion resistant material, such as compacted sediments or concrete rubble, should be removed to 0.3 m (1 ft) below the bottom of the channel.

7. Wherever possible excavation should be done in the dry—before reintroduction of tidal action.

4.7 QUESTION 7: SHOULD THE PRE-EXISTING DRAINAGE SYSTEM BE MODIFIED?

THE PROBLEM

When tidal action is reintroduced to a subsided site, tidal flows will tend to concentrate in existing ditches or depressions that then fix the location and morphometry of the tidal drainage system. Once formed, tidal channels change very slowly and it is likely that once the pre-existing drainage system captures the tidal flows, its pattern is likely to persist for hundreds of years. As sedimentation occurs, mudflats build up and evolve into marshes in which the imprint of the pre-existing drainage system can persist and dominate the nature of the tidal channel system in the new marsh. Often the pre-existing drainage systems consist of straight field drains or borrow ditches on the backside of levees and, in some cases, newly formed tidal channels might be poorly located or could erode adjacent infrastructure. With suitable grading prior to reintroduction of tidal action, a different channel system template can be created.

There appears to be a consensus that a dendritic sinuous tidal channel system provides a more complex habitat and supports a wider range of wetland functions than linear channels. For example, a sinuous channel will sustain both steep overhanging vegetation and shallow areas that allow cordgrass colonization within the channel system.

On some subsided diked former salt marshes, and particularly in salt ponds, the original dendritic sinuous tidal channel system is still expressed in the topography, even if the channels have been mainly filled over time or interrupted by interior levees. Concentrating tidal flows into the old channels to scour out the loosely deposited sediments and rejuvenate the entire tidal drainage system can restore these channels. This can be done by suitable selection of breach locations, removal of obstructions, and blocking of borrow ditch channels.

The decision whether to modify the pre-existing drainage system is based on a trade off between the costs of grading to modify the system versus the potential benefits of, or adverse impacts avoided by, a modified system.

RESTORATION EXPERIENCE

Before it was breached in 1986, the Green Point Marsh was drained by a series of straight artificial field ditches and perimeter levee borrow ditches, and its topography modified by low road embankments (Figure 48a). By the time the site had fully vegetated, the artificial drainage system and effect of the road embankments had become permanently imprinted in the marsh plain (Figure 48b).

In Napa Pond 2A, the original tidal marsh drainage system was largely undisturbed in the decommissioned salt pond. However, when tidal action was reintroduced by a single levee breach in 1994, most of the tidal flow was conveyed in the deep levee borrow ditches around the site perimeter. In some locations, this has helped rejuvenate the old tidal channel system; in others, the borrow ditch has captured flows that could have been directed into old channels on the marsh plain. As a result of the modifications to the channel system, there are many “looped” channels that ultimately will separate due to siltation at drainage divides, forming new tidal watersheds (Figure 49).

The Cooley Landing restoration was also a former salt pond where the imprint of the old marsh channel system remained. Typically, these old channels had silted in. The restoration design was intended to rejuvenate this original natural channel system. The design therefore sited the levee breaches opposite where the major slough channels had flowed to the Bay, and blocked the interior levee borrow ditch to force tidal flows into the old drainage system (Figure 50a). After three years, significant portions of the old tidal channels were rejuvenating by head-cutting into the deposited sediments (Figure 50b).

At Carl’s Marsh, a shallow channel was excavated and material sidecast prior to breaching. This channel, and small ridges left after the removal of the pre-existing field drainage system, have dominated the formation of the tidal drainage system. These influences persist as the site continues to accrete—even though the original features are now buried under recently deposited sediment (Figure 35).

DESIGN RECOMMENDATIONS

1. Existing site topography should be analyzed to identify how the tidal channel system is likely to evolve with no action. If the evolving channel system is likely to form in undesirable locations, the following measures can be taken to guide the location and layout of the tidal drainage system:

    - Pre-existing field ditches and drains can be filled and artificial obstructions to tidal flows removed.

    - Pilot channels can be graded in the desired location as was done at Carl's Marsh.

    - The site can be graded or filled with dredged material to create low points where tidal flows will be concentrated.

    - Wave break peninsulas can also be used to define tidal watersheds and the location and size of evolving tidal channels.

2. Where the remnant tidal channel remains intact, the site template can be graded to encourage tidal flows to reoccupy the original tidal system. This is done by choosing a suitable breach location, removing interior fill that might have divided the tidal system, and installing channel blocks in the interior borrow ditches. These interior borrow ditch blocks can be placed to completely isolate the borrow ditch as was done at Cooley Landing, or placed between levee breaches at the anticipated location of the drainage divide between two slough systems.

4.8 QUESTION 8: SHOULD THE SITE BE GRADED TO ENCOURAGE PANNE FORMATION?

THE PROBLEM

Pannes and ponds were typical, but not ubiquitous, features of historic salt marshes that were important for bird use. In this report we distinguish between "pannes", that are seasonally ephemeral playa-like features typically found at the poorly drained inland margin of the marsh or where tidal drainage is interrupted, and "ponds", that tend to be well-defined, persistent, shallow, sometimes hypersaline features that persist on watershed divides within the marsh plain. It appears that marsh plain ponds can only evolve on fully mature marsh plains. At this time, we have not identified any feasible way to accelerate their evolution or design their analogs—except to allow unobstructed access to the marsh from the bayfront edge to allow wrack and debris to create depressions or disturbance to the tidal drainage system. This is done by lowering the bayfront levee (see Section 4.5 Question 5: Should the bayfront levee be lowered?).

It is possible to grade the margins of restored sites to replicate the functioning of seasonal pannes. Allowing isolated shallow depressions to fill during the highest spring tides, which typically occur during the winter, can do this. This water then evaporates, creating a salt panne with high soil salinities in the summer that prevent vegetation colonization. The bare, shallow panne seasonally ponds water and provides feeding opportunities for shorebirds. If these depressions are located in the path of a freshwater flow or groundwater seep, they will quickly become vegetated.

The decision to deliberately create pannes in a tidal marsh design is influenced by the relative importance attributed to this kind of habitat compared to tidal marsh or transitional zone and the relative cost of grading. For filled sites it may be comparatively easy to grade depressions at appropriate elevations at the upper end of the tidal frame. Over the long-term, tidal pannes will gradually convert to vegetated marsh with anticipated sea level rise. Another factor in the decision to deliberately create poorly drained areas, such as pannes, is whether seasonal ponding of this type creates mosquito habitat.

RESTORATION EXPERIENCE

A portion of the dredged material disposal site adjacent to Muzzi Marsh (Figure 45) has inadvertently provided a good model of how sustainable panne habitat can be created and managed. Portions of the fill site have subsided into a depression connected to the Bay through culverts. The shallow depression collects rainwater, but receives tidal water a few times a year, sufficient to replenish the salts that prevent vegetation encroachment. This area has functioned as a seasonal panne for more than 20 years (PWA et al. 2002b).

Elsewhere on dredged material disposal sites (e.g. River Park in Vallejo), pannes have initially formed in topographic depressions but ultimately, within a decade, rainwater washes out the salts, thus allowing vegetation to establish.

At Wildcat Marsh in Richmond, sedimentation at the mouth of Wildcat Creek had obliterated a large area of ancient marsh plain and interrupted tidal drainage forming pannes (Figure 51). As mitigation for a flood control project, tidal channels were excavated in the alluvial sediment (PWA 1988). To preserve the functioning of two large pannes, low flashboard weirs were constructed to retain salt water on spring tides. However, within a few years the rejuvenated tidal drainage had bypassed the weirs, effectively draining the depressions and converting them to tidal marsh.

At Sonoma Baylands, wave break peninsulas were used to guide the formation of a tidal drainage system emphasizing a series of long, narrow tidal watersheds. It was anticipated that the upper end of these watersheds would receive less sediment and become poorly drained, thereby encouraging the formation of tidal pannes (Figure 52). At this time, it is too early to determine if this approach is successful.

DESIGN RECOMMENDATIONS

1. To create pannes, shallow depressions can be graded at the marsh margin. The sill of these depressions should be broad enough to preclude erosion and at an elevation in the tidal frame that allows for inundation several times a year on spring tides.

2. These pannes should be isolated from freshwater flows and seeps.

3. To retain water and salts, the panne soils should be comprised of low permeability Bay muds.

4.9 QUESTION 9: HOW SHOULD THE WETLAND-UPLAND TRANSITION ZONES BE DESIGNED?

THE PROBLEM

In a tidal wetland, the high marsh lies between the typical marsh plain elevation of MHHW and the extreme high tides. The high marsh is subject to wide variability in soil salinity, wave action during storm surges, and disturbance from floating driftwood and debris (wrack) (Maser and Sedell 1994). As a result, the landward boundary of the high marsh shifts from year to year and is best described as a zone of transition, or a wetland-upland transition zone (Figure 2). The marsh plain is vegetated almost entirely by a small number of native halophytes, but a larger number of species—some native, some non-native, and all adapted to harsh conditions—grow at the upper landward portion of this zone. This area provides critical feeding, resting, and refugia habitat to a number of animals and plants. The transition zone can also serve as part of a buffer to protect the marsh plain from disturbance and predators.

In a transgressive estuary like San Francisco Bay, the area of the wetland-upland transition zone was always small, but has been greatly decreased by the placement of fill for development, levees, and roadways along the marsh margin. Currently, the wetland-upland transition zone is very limited in extent and, if present, may consist of a band less than three meters (10 ft)- wide on a levee bank. These narrow zones provide inadequate high tide refuges for animals and insufficient room for plants to establish a sustainable community.

The transition zone and adjacent uplands are particularly important as they serve as refugia during extreme high tides for animals such as the clapper rail, black rail, and the salt marsh harvest mouse. In the past, adjacent grasslands served as feeding grounds for animals such as the salt marsh harvest mouse and as habitat for the burrowing owl. With the loss of adjacent grasslands, the burrowing owl population has declined precipitously and retreated to small areas of wetland-upland transition zone. The subsequent loss of this transitional habitat has further reduced the number of burrowing owls.

In addition to a wetland-upland transition zone, buffer areas that extend beyond the transition zone are important for various wetland functions, such as sediment filtration or retention, pollution retention, habitat and food web support, and flood protection. The character of a buffer is important to consider—whether it is mowed grassland or wild, open space with paths or dikes. Buffer widths are better determined by the buffer's required functions rather than by a preset value.

EXPERIENCE

The opportunity to re-create a functional wetland-upland transition zone has not been realized in past restoration projects. In most sites, the surrounding levees were graded at maximum stable slopes to minimize costs, or sites were graded to maximize marsh plain area, resulting in steeply sloping banks and narrow transitional marshes. The wetland-upland transition zone that has been created was incidental to the design. For example, at the Faber Tract, the transitional zone is wide as a result of allowing hydraulically placed dredged material to form gently sloping deposition cones to high elevations.

At Muzzi Marsh, dikes surround the site and the highest tides reach approximately 0.3 m (1 ft) onto the dike edge. Native salt marsh species cannot tolerate the harsh conditions along the dike edge, which is commonly vegetated with non-native New Zealand spinach (*Tetragonia tetragonioides*), Australian saltbush (*Atriplex semibaccata*), wild radish (*Raphanus* spp.), and sweet fennel (*Foeniculum vulgare*). Of these four plants, only the Australian saltbush provides cover for the salt marsh harvest mouse.

At Warm Springs Marsh, a graded bench was created at the toe of the levee for erosion protection and to accelerate colonization of wetland plants. However, while the bench was successful in erosion protection, it only extended to slightly above MHHW and did not provide adequate wetland-upland transitional habitat.

At Crissy Field, because of sandy substrate and limited seed sources, extensive planting of native species was undertaken in the wetland-upland transition zone. Over several years, the species distribution has changed, but the cover remains abundant.

DESIGN RECOMMENDATIONS

1. To allow re-creation of wetland upland transition habitat, the perimeter levee of the restored marsh should be graded to create a gently shelving bench between current MHHW and future extreme high water (EHW) (allowing for sea level rise). Typically, this shelving bench will have a maximum slope of 1:10.

2. The wetland-upland transition zone should have a minimum width of 30 m (100 ft) to provide quality habitat.

3. Where possible, any adjacent protected upland habitat that provides wildlife values to tidal marsh species should be incorporated into the planning effort.

4. Wherever possible (see Section 5, Question 5: Should the bayfront levee be lowered?), lower the bayfront levee to allow for unimpeded deposition of wrack and debris.

4.10 QUESTION 10: SHOULD SOIL BE TREATED?

THE PROBLEM

Almost all the sediment entering San Francisco Bay comes from soil erosion. Clay and silt minerals and relatively small amounts of fine sand are carried in suspension from a huge watershed reaching into the Sierra Nevada (Krone 1979). These muds are largely a montmorillonite-type clay with high shrink/swell characteristics that exclude air and, together with a high organic content, create the anaerobic conditions suitable for marsh vegetation. Marsh soil accretion results from mineral sediment deposits combined with the organic accumulations of roots and rhizomes. Long-term accretion variation is modified by marsh sediment compaction, the effects of sea-level variation, which can alter tidal regimes, and the density of vegetation that acts as a sediment trap (Pethick 1981). Josselyn estimates that marshes subside from their own weight about 0.06 m (0.2 ft) per century (Josselyn 1982).

Salt marsh vegetation develops readily on the heavy clay and nutrient- and organic-rich mud found in San Francisco Bay. Most plant species have specific requirements for establishment, sustained growth, and reproduction. Little research has been carried out on plant-soil relationships in San Francisco Bay and these relationships are poorly understood.

Soil texture is critical in determining rates of organic matter and nutrient accumulation. Unlike organic matter or nutrient concentrations, the texture of soil does not change over time unless more accumulates on the surface. This is an important consideration with the use of dredge material, which is often too coarse for good plant establishment.

Soil acidity effects plant growth by altering the availability of soil nutrients or by increasing the solubility of metals to toxic levels. Soils with a pH below five are generally stressful to plants. Plants in the wetland-upland transition zone and on constructed peninsulas and dikes are subjected to stressful conditions of increased salinities and poor drainage. Here, plant growth may be stunted and seedling establishment restricted (Josselyn 1982). Plants on constructed islands, peninsulas, or dikes, where pH levels are below five, are mostly restricted to an assemblage of weedy species that usually out-compete native species.

RESTORATION EXPERIENCE

When dikes are breached in areas of former wetland, where salt marsh vegetation has either died out or become ruderal, there is a period where soils adjust to the reintroduced tidal regime. In time, soils again become anaerobic with neutral pH values restored and accumulated salts that inhibit seed germination are leached from the soil. Experiments correcting low pH values with lime suggest that this is not a practical solution. Rather, the establishment of correct elevations, and hence tidal regime, in the project design results in a longer-term solution (Josselyn and Bucholz 1984).

Following tidal restoration of former marsh plain, exposed mud surfaces often form large 0.15 to 0.3 m (6 to 12 in) diameter plates that in the first year or two become covered with assemblages of diatoms. The edges soften and, after another year or so, resume the appearance of a typical bay mudflat. In the first or second season of tidal access, pickleweed seeds become established in the cracks of the mud plates. The rate of plant establishment varies depending on soil and tidal conditions. Cordgrass establishes somewhat more slowly than pickleweed; however, it does establish by seed or by fragments of rhizomes and then spreads vegetatively.

Both natural and restored marshes are sinks for suspended sediments. A study in North Carolina demonstrate that sedimentation rates are greater in younger restored or constructed marshes than in comparable natural or older restored marshes (Craft 2003). As cordgrass becomes established, increasing stem density reduces the velocity of tidal waters and facilitates the deposition of suspended sediments (Knutson 1988). The deposition of both organic and inorganic matter is critical for adding soil nutrients and effects soil structure, bulk density, and porosity as well. Soil organic carbon (C) and nitrogen (N) pools were slow to develop in constructed marshes in North Carolina, so that, after 28 years, there was still significantly less soil organic C and N than in natural marshes (Craft 2003). This type of study has not been carried out in San Francisco Bay and might not apply, as the Bay muds of San Francisco are more nutrient rich than the sandier soils of North Carolina.

Several investigators in other marsh systems have examined the relationship of soil factors of salinity, soil moisture, bulk density, nutrient requirements, and seasonal variations on plant establishment and growth (Phleger 1967; Mall 1969; Pearcy and Ustin 1984; Callaway and Sabraw 1994; Craft 1997; Craft et al. 2002; Zedler and Callaway 2003; Acker et al. 2004). In work in Galveston, Texas, Lindau and Hossner (1981) found that fertilizer applications were not effective; however, naturally settling organic matter and clay particles increased nutrient levels to those of surrounding marshes within two to five years. However, in a pickleweed marsh in Mugu Lagoon in Ventura County, Boyer et al. found that phosphate, and particularly nitrogen enrichment, resulted in a greater biomass of pickleweed during the growing season, with pickleweed branching increasing by over 100 percent (Boyer et al. 2001). Studies outside of San Francisco Bay often involve sandier soils where organic matter and nutrient accumulation is slower and becomes a greater limiting factor for vegetation.

Where daily and seasonal soil moisture conditions fluctuate, soils dry out and become aerated, such as on the high margins of marshes or on constructed islands or peninsulas. Soil acid levels can drop to well below pH 5. However, where full tidal inundation occurs, neutral pH values between 5 and 7 are maintained by the buffering effect of estuarine waters. In monitoring studies at Muzzi Marsh, pH values of marsh plain soils, taken over several years, ranged between 5.7 and 7.2. The exception was an area that remained above regular tidal inundation, where values dropped to 4.1. With restricted tidal regimes, where mud surfaces do not remain under tidal waters, the combination of heavy organic matter and aeration facilitates the reduction of iron and sulfur oxides to form iron and hydrogen sulfides, potentially toxic to plants. Under these conditions, vegetation establishment is inhibited, plant growth is stunted, and the decomposition of roots and buried plant material is slowed.

DESIGN RECOMMENDATIONS

1. Establish correct tidal elevations that assure full tidal inundation of the site and the development of channels throughout the marsh in order to buffer soil acidity.

2. Following dike breaching, assume a period of time for soils to leach and become suitable for natural plant establishment.

3. If the restoration site substrate is Bay mud, it can be assumed that these are sufficient nutrients to support plant growth; therefore, there is little need for nutrient supplements. Future experimental work may provide new information that supports soil enhancement programs, particularly in the transition zone.

4. If the site substrate consists of coarse sandy material or imported upland fill, nutrients may be limited and soil studies should be undertaken to determine whether supplements should be added.

4.11 QUESTION 11: SHOULD PLANTS BE PLANTED?

THE PROBLEM

The plant community is central to the biological functions of a wetland ecosystem: its establishment as a self-sustaining community is a critical goal in wetland restoration. In San Francisco Bay, there is usually an abundant seed source of the most common native salt marsh plants. Seeds and plant fragments are carried to a site by tidal waters and establish where soil and tidal conditions are appropriate. Therefore, planting of common native marsh plain plants may not be necessary.

Historic marshes in San Francisco Bay had greater species diversity than today; diversity has been reduced due to an overall loss of area and fragmentation of wetlands and the extensive diking of the landward margin of marshes. This raises the question whether or not planting is required for rare or endangered species. To date, there has been no systematic attempt in restoration projects to undertake planting for these species.

Historic connections between marshes and their watersheds are almost all gone, thus depriving marshes of winter freshwater runoff and sediments from the watershed. These sediments were a source of diverse substrate particle sizes, ranging from course sand to fine silts, which appear to be important for some plant species, such as the Point Reyes bird's-beak. To date, there have not been experimental efforts to plant less common species or species requiring special conditions, such as unusual soil types or reduced competition from more common species. California sea-blite may have once occurred in the Petaluma Marsh. A population of bush seepweed (*Suaeda moquinii),* more commonly found in the desert, grows in panne-like conditions in the wetland-upland transition zone at the Fremont airport property. There is little experience in San Francisco Bay for developing preconditions for plants, such as selecting imported substrates that will favor certain plants, or timing of breaches to favor species, or weeding of the wetland-upland transition zone to favor healthy establishment of native species.

Several non-native species of cordgrass have been introduced to the Bay because of experimental plantings. Dense-flowered cordgrass (*Spartina densiflora)*, introduced from Humboldt Bay, has established and spread along Corte Madera Creek in Marin County. Saltmeadow cordgrass *(Spartina patens)* was introduced from East Coast salt marshes, established and spread slowly in the Benicia marshes. Seeds of smooth cordgrass, collected from East Coast salt marshes and planted in Pond 3 adjacent to Alameda Creek, established and spread rapidly. It readily hybridizes with the Pacific cordgrass. Pollen from smooth cordgrass is carried by wind and many hybrid forms have developed. Preemptive planting of Pacific cordgrass may be a method for controlling the smooth cordgrass invasion but has not been undertaken or proven at this stage.

Once the tidal saline influence diminishes in the upland transitional zone, non-native plants that are adapted for disturbed conditions tend to flourish and out-compete native species. Pepper grass and

Russian thistle (*Salsola soda*) are two relatively recent aggressive arrivals in this portion of a Bay wetland. Little work has been done to control these species. In brackish areas, pepper grass establishes in the middle zone where there are disturbances. At low elevations, it is easily out-competed by native species such as cattails or bulrush. Strategies for either controlling the spread of exotic species or limiting the possibility for establishment may be developed in the future.

At brackish sites that are not deeply subsided, it may be possible to establish stands of brackish vegetation, such as bulrush and cattails, prior to breaching. With the reintroduction of a tidal regime, stands may keep up with accreting sediments or at least readjust to the new tidal conditions. In this way, native vegetation could be established prior to breaching to preclude colonization by invasive species and increase the stability of the substrate; however, there is no documented experience of this in San Francisco Bay.

EXPERIENCE

Until the early 1970s, it was thought that once a tidal salt marsh was destroyed, it was gone forever. This notion was reversed for San Francisco Bay marshes when native salt marsh plants established naturally in the Faber Tract in South Bay following a dike opening in the early 1970s. The Muzzi Marsh restoration was the first restoration project that relied on the natural establishment of salt marsh plants. Pickleweed first established at higher elevations of the “inner” marsh plain within a year after the dikes were breached and in the next ten years had spread across most of the “inner” marsh. Cordgrass established in several places in the “outer” marsh within three or four years after the restoration of tidal action, with a substantial cover developed after ten or 15 years. Gumplant arrived along the dike transition area 15 years after dike breaching and now, 28 years later, it grows commonly along dike and channel edges within the marsh where in summer and fall, the yellow flowers line the bank tops. Neither arrowgrass (*Triglochin* spp.) nor Point Reyes bird’s-beak, both established on the adjacent fragment of ancient marsh at the Corte Madera Ecological Reserve, have established at Muzzi Marsh, perhaps because of special but unavailable soil requirements or establishment conditions. Pickleweed is replacing cordgrass in the “outer” marsh. As the marsh plain elevation increases, large patches (nine meters (30 ft) or greater) of saltgrass, jaumea, and alkali-heath have established across the marsh plain.

Table 3. Time Sequence for Species Establishment in Muzzi Marsh (unpublished data)

	Years after dike breaching			
	1-3	4-6	7-10	11-14
Perennial pickleweed (*Salicornia virginica*)	x			
Annual pickleweed (*Salicornia europaea*)	x			
Pacific cordgrass (*Spartina foliosa*)	x			
Salt grass (*Distichlis spicata*)		x		
Grass buttons (*Cotula coronipifolia*)		x		
Sand spurrey (*Spergularaia macrotheca*)		x		
Jaumea (*Jaumea carnosa*)			x	
Alkali heath (*Frankenia salina*)			x	
Fat-hen (*Atriplex triangularis*)			x	
Gumplant (*Grindelia stricta*)				x

At Warm Springs Marsh, saline water—where typical salt marsh species established within the first few years— was replaced by brackish water. Salt marsh species were replaced by dense stands of brackish species, bulrushes, and cattails. Pickleweed is insignificant along with saltgrass, jaumea, alkali-heath, and fat-hen that grow throughout the restoration site, mostly in the higher, mid, and landward portions of the marsh where bulrush is not as dense. Dense stands of gumplant and sea lavender both grow in a higher portion of the site. Seaside arrowgrass (*Triglochin maritima*) was first recorded in 1999, 13 years after the dikes were breached, and has spread to other locations on the site. The annual, small spikerush extensively colonized the mudflat beyond the vegetation in the mid 1990s, mostly disappeared by 2000, and large patches had returned by 2004. Salt marsh fleabane (*Pluchea odorata*) has persisted in one location for four years. These native species have all arrived in tidal waters. The invasive pepper grass grows in several places around the site and in some cases into sparse stands of bulrush; however, its population waxes and wanes—apparently with seasonal variations—and does not appear to exclude other higher marsh native species such as gumplant or sea lavender. In other places in the South Bay and in Suisun Marsh, pepper grass provides 100 percent cover, thus eliminating any species diversity or suitable habitat for native species.

There is limited experience with planting plants in San Francisco Bay. Tom Harvey planted many cordgrass clumps before the dikes were breached at the Faber Tract, demonstrating that cordgrass could be successfully transplanted (Faber 2004 personal communication). A dozen or so cordgrass plants were planted at the "Inner" Muzzi in 1976 and survived but did not expand vegetatively. By 1980, extensive natural colonization of Muzzi Marsh had begun. Curtis Newcombe and Herbert Mason demonstrated that Pacific cordgrass could be successfully transplanted using small plugs or sprigs (five or six culms) or larger clumps (15-30 culms) (Newcombe et al. 1979). This work was of interest for its potential both to speed up restoration projects with large-scale plantings and to stabilize eroding shorelines and dredge spoils. In a study by the USACE at Alameda Creek Pond 3, Paul Knutsen successfully replicated work from the East coast to demonstrate large-scale plantings with seed—but he unfortunately imported smooth cordgrass from Georgia for this work. This species is now considered an aggressive, invasive exotic plant in San Francisco Bay.

Early, small-scale experiments in San Francisco Bay to plant different species of salt marsh plants were frequently unsuccessful because these plantings did not survive and only added to project costs (P. Faber and J. Swanson, personal observations, 1979; Race and Christie 1982). Many questions regarding planting requirements, soil nutrients, differential seed accumulation, and germination requirements have been addressed in the extensive restoration work in the salt marshes of San Diego County (Zedler and Callaway 2003), in experimental fresh water marshes (Vivian-Smith 1997) and work on the East coast using plants to stabilize eroding shorelines (Garbisch et al. 1975; Knutson et al. 1990). Based on a hypothesis that biomass and nitrogen would increase with greater species richness and thus accelerate the evolution of ecosystem function, Callaway, Sullivan, and Zedler examined these parameters for eight native species of common marsh plants. In a three-year study, they found that manipulating the diversity of plantings offers a possible tool for increasing the rate of functional development; however, the long-term advantage of this approach has yet to be demonstrated (Callaway et al. 2003). Josselyn reports success in planting native species in the transition zone to reduce or limit non-native invasions where gypsum and organic matter were used as soil amendments (Josselyn, personal communication, November 2004).

From observing the spread of the introduced species, we know that seeds of cordgrass travel considerable distances. Seeds of Dense-flowered cordgrass traveled from Corte Madera Creek in Marin County across the Bay to Point Pinole. Seeds of smooth cordgrass, experimentally planted in Alameda Creek Pond 3, south of Hayward in the mid-1970s, and later in Alameda, where they established readily and grow vigorously. Smooth cordgrass outcompetes the native Pacific cordgrass because of its vigorous growth and size but also readily hybridizes with the native cordgrass due to its abundant production of pollen. Different forms of hybrids grow at both lower and higher elevations on the marsh plain than the native species, which reduces habitat for native salt marsh plants at higher elevations and for shorebirds at lower elevations. Hybrid forms have spread by several thousand percent in the past several years. If the rapid population expansion of hybrids is allowed to continue, it could endanger the presently abundant Pacific cordgrass by aggressive hybridization. Hybrids that establish at low elevations, replace active feeding grounds for shorebirds and accrete sediment rapidly. High stem density and dense root mats develop, which inhibit channel formation. In the Cogswell Marsh, cordgrass hybrids resulted in truncated channel formation.

Smooth cordgrass grows at five times the growth rate of the native species and has 20 percent better seedling recruitment (P. Baye, personal communication, 2004). To date (2004), San Pablo Bay has not been extensively invaded by smooth cordgrass; however, it grows in Tiburon marshes and in 2004, two large clumps were discovered at Muzzi Marsh in Corte Madera. The Central Bay is the most heavily invaded on both sides of the Bay. The California State Coastal Conservancy has established a San Francisco Estuary Invasive *Spartina* Project (CSCC and USFWS 2003), which is planning to extirpate all exotic cordgrass species. Unless this program is successful, the long-term outlook for the San Francisco Bay salt marsh flora may be quite different, with little native cordgrass and altered plant distributions in low, middle and high marsh zones. Work in the field to eliminate the non-native species of cordgrass is presently getting underway.

Marsh plants have been extensively used as wind breaks to stabilize substrate on the East Coast, but have been only experimentally tested in San Francisco Bay. Curtis Newcombe and Herbert Mason found that the Pacific cordgrass would not successfully stabilize high energy scarps— however it could be used with limited success to stabilize 6 to 15 m (20 to 50 ft)-wide benches when planted with sprigs rather than with seed (Newcombe et al. 1979). As an alternative, the use of plant rolls, which are effective in erosion control for stream banks, may provide a new tool to augment or replace peninsulas for damping wave energy.

At Green Point Marsh, an extensive stand of brackish vegetation was established prior to accidental breaching in 1986. However, because the elevations of this managed wetland were too low, the vegetation died. The ensuing mudflat was later recolonized by bulrush when it had achieved appropriate elevations.

DESIGN RECOMMENDATIONS

1. Allow plant establishment to proceed from local native seed sources carried by tidal waters from nearby marshes, and allow time for a full range of common species to establish. Sites that are isolated, geographically or otherwise, may need planting. However, natural plant establishment may be more advantageous biologically and economically.

2. Species diversity should be a goal for restoration.

3. Opportunities to increase diversity of native species or reduce invasions of exotic species may occur in the wetland transition zone by selective planting. Substrate conditions and seed sources need to be fully considered.

4. Because of concern about the rapid spread of the invasive smooth cordgrass and its hybrids, different strategies are appropriate for restoration projects in different parts of the Bay and in accordance with recommendations from the Invasive *Spartina* Project (CSCC and USFWS 2003). Existing invasive vegetation should be removed from a restoration site prior to dike breaching.

5. Monitor and remove non-native cordgrass species that appear in any newly restored marshes.

4.12 QUESTION 12: HOW DO WE PROVIDE HABITAT FEATURES FOR TARGET SPECIES?

The overriding goal of restoring wetlands is to enhance the Bay ecosystem, which encompasses a complex assemblage of physical conditions, habitats, and plant and animal species. Each site is a unique but contributing part of the whole system. Useful information on many endangered species is presented in the Goals Project (2000). Profiles for four species are presented in this document to give a brief idea of aspects to be considered in creating a marsh design to enhance endangered species habitat; however, others could be selected, such as shorebird species or harbor seals.

It is a challenge to balance goals to provide habitat in the near-term for endangered species with goals for the long-term evolution of a healthy ecosystem. As is often the case with endangered species, much is known about individual species, but more knowledge is needed to understand how to best protect them.

THE PROBLEM

Because of the major loss of tidal salt marsh over the past 150 years, plant and animal species that are significantly dependent on these marshes have nearly disappeared. A number of animal species have been designated as endangered by the USFWS and the CDFG, including the clapper rail, the salt marsh harvest mouse, and the salt marsh song sparrow. As species at or near the top of the food web, these organisms provide an indication of the health of the tidal marsh ecosystem. In designing restoration sites, they are used as target species in developing habitat goals. An objective is to provide sustainable habitat that supports these target species. The evolution of the physical conditions at the site will be mirrored by the evolution of vegetation composition. The habitat value for animal species will evolve accordingly: high quality low marsh with continuous expanses of cordgrass and good networks of channels favors clapper rail and extensive stands of pickleweed with good channels and high tide refugia favor salt marsh harvest mice. Each stage in the restoration of a vegetated marsh tends to favor different target species. Rare plant species may also require special soil conditions for establishment. A sizeable, well-buffered transitional marsh with a mix of habitat types best meets the goals for most target species. Many species descriptions for both common and rare species are provided in the Goals Report (2000). However, four species are widely considered as target species in protection and restoration work around San Francisco Bay and are discussed here.

CALIFORNIA CLAPPER RAIL

Of critical concern for the long-term survival of the California clapper rail is the fragmented state of the tidal salt marshes around San Francisco Bay. Small isolated fragments of marsh lead to inbreeding in rails with consequent loss of genetic diversity. Isolated fragments also prevent escape from predators. Quality habitat for self-sustaining populations of rails includes large parcels of tidal marsh at least 100 hectares (250 acres) in size and a network of first order channels. Because rails are cautious, they do not go far into a marsh. Resources are more abundant in "high quality" habitat, thus rails don't need as much area to fulfill their life-cycles and population densities can increase. Rails call to each other to make contact, to advertise their breeding status, and to defend their territories. Stable populations fare best with large contiguous marshes, healthy stands of marsh vegetation, and a well-developed network of tidal channels at the bay edge. Deep channels generally support dense vegetative cover nearby and a complex of smaller channels with corridors to refugia for periods of extreme high tides. Other important features include protection from predators that includes refugia during extreme high tides, and well-buffered marshes isolated from predators emanating from neighboring developed upland areas. Low quality narrow marshes give better access to fox and other terrestrial predators. Such marshes are not used as nesting areas. Successful control of the red fox and feral cats is essential in the near future for the long-term survival of the California clapper rail.

In the North Bay, there are populations of clapper rail in Muzzi Marsh, Bahia Marsh, and along the Petaluma River. These populations are thought to be stable because of a number of factors. A fringing border of cordgrass marsh that grows along the Corte Madera waterfront to the Tiburon waterfront enables clapper rails to move between marshes to establish new territories in otherwise non-contiguous marshes. Surrounding roadways and houses appear to limit red fox access but increase cat and raccoon access. Other urban tidal marshes with stable populations of clapper rail include the San Bruno and Arrowhead marshes. Low numbers in Sonoma Baylands reflects a regional decline in clapper rail, though there is a population at Carl's Marsh and the nearby silted in marina (J. Evens, personal communication, July 2004).

DESIGN RECOMMENDATIONS

1. Provide large contiguous areas of tidal marsh with corridors of cordgrass along the bayfront.

2. Restore a complex sinuous tidal drainage system with deep and sinuous channels that foster vigorous cordgrass establishment.

3. Wherever possible, isolate the marsh plain from predators such as red fox and domestic and feral cats.

SALT MARSH HARVEST MOUSE

Salt marsh harvest mice are dependent on the thick perennial vegetative cover of salt marshes and only leave the marshes in late spring and summer if the marsh connects with grasslands, and then only when the plants are green and provide good cover. These mice live primarily in the middle of the pickleweed and upper (or "peripheral halophyte" zone as it is called by Shellhammer 1982; Shellhammer 2000) or high marsh zones of marshes; they need the latter zone to escape from high tides. They are cover-dependent animals that swim well but are exposed to aerial predators when they are forced out of vegetation to swim or to cross bare ground. Their usual method of escape from both tides and predators is to seek the dense cover of the less-flooded upper tide zone of marshes or the bushes along channels within marshes. The upper zone of marshes, the high marsh, was once much more abundant in San Francisco Bay, but is now present in most tidal marshes as 1-2 m (3-6 ft)-worth of mixed halophytes distributed along the steep sides of outboard dikes. The loss of this essential escape cover has resulted in marshes with sizable pickleweed (i.e. middle) zones that lack populations of this endangered mouse. Upper marsh zones have become highly fragmented, thus making it difficult for populations to persist and movements to occur between marshes. Isolation and reduction in size of habitat usually results in extinction.

There are few areas around the Bay today where grasslands adjoin tidal marshes. Most marshes end in abrupt dikes, salt ponds, and filled areas that are either barren or developed. There are few places where cats and red foxes do not have relatively easy access to the marshes. The higher, and especially the highest tides, attract raptors that feed on mice of all species that have been forced to move upland by the tides. Our ability to plan for protection of the salt marsh harvest mouse is impeded by a lack of knowledge. Areas needing better answers include the population genetics of the mouse. How much genetic variation does a population have and what parameters of marshes, such as size, complexity, escape cover, etc., are necessary to prevent the loss of genetic variability over time? How much or what kinds of predator control measures are necessary? What is the impact of pepper grass, which is becoming dense and extensive throughout many parts of the mouse's range? Nothing is known about the level of toxics and the health of mouse populations.

Most of the marshes of the South San Francisco Bay have undergone some to considerable amounts of subsidence during the last 50 years and many have become much less saline. Much of the southern part of South San Francisco Bay has shifted from cordgrass-pickleweed marshes to brackish species marshes filled with bulrush and cattails. Shellhammer (personal communication, 2004) concluded that the salt marsh harvest mouse southern subspecies prefer saline hydrophytes such as pickleweed. Recent studies in Suisun Bay indicate that mice belonging to the northern subspecies prefer brackish marsh plant species.

DESIGN RECOMMENDATIONS

1. Provide large contiguous areas of pickleweed marsh connected by migration corridors.

2. Provide adequate areas of high tide refugia with abundant cover.

3. Wherever possible, isolate the marsh plain from predators such as red fox, raccoons and domestic and feral cats.

SONG SPARROW

There are three distinct subspecies of song sparrow that are year-round residents of tidal wetlands of the San Francisco Bay Area or closely adjacent lands: *Melospiza melodia samuelis* of San Pablo Bay and northern San Francisco Bay (south to Sausalito and north Richmond); *M.m. pusillula* of the balance of San Francisco Bay shores; and *M.m. maxillaris* of the Suisun Bay marsh complex and west to South Hampton Bay. These are three narrow endemics with distinct morphological and behavioral differences, the latter primarily observed for nest timing differences. These marsh songbirds stake out small territories in the pickleweed zone, as many as 25 per hectare (ten per acre) in a "good" marsh. Song sparrows tend to stake out their territories close to where they were hatched. They are found above the cordgrass in the pickleweed zone and along tidal sloughs where gumplant grows. They use this plant effectively as song perches and for nesting sites. Preferred feeding sites within the marsh include the muddy edges of small channels where they forage in the intertidal mud for small mollusks and other marine invertebrates as well as the seeds of gumplant and pickleweed. Nesting losses result from extreme high tides, parental desertion, and from predators, such as the Norway rat, garter snake, and especially the red fox.

The three subspecies of song sparrow all require productive tidal salt marshes where there is sufficient vegetation to provide suitable nest sites, food, and cover. Ideal habitat for *M.m. pusillula* and *M.m. samuelis* appears to be large expanses of fully tidal salt marsh with numerous small channels. Ideal habitat for *M.m. maxillaris* is large expanses of fully tidal brackish marshes where bulrush grow along with pickleweed and gumplant (Goals Project 1999). Continuity of habitat appears to be of great importance though no studies of size of marsh required are reported. Temporary aggregations at the upper fringes of marshes have been noted during high tide periods. However, birds return to their territories when the tide recedes. The use of various types of diked wetlands is poorly understood and needs further study; however, the only mud available for nest building by May is in adjacent tidal or diked-off marshes. Ecological studies of the use of diked marshes by the different subspecies is needed to reveal if nesting can be successful or if the birds simply use the dikes as dispersal corridors. Continuous marsh/mud interfaces are essential for dispersal in the late summer.

DESIGN RECOMMENDATIONS

1. Design to achieve extensive stands of dense marsh plain vegetation.

2. Wherever possible, isolate the marsh plain from predators such as red fox, raccoons and domestic and feral cats.

SOFT BIRD'S-BEAK (*CORDYLANTHUS MOLLIS* SSP. *MOLLIS*)

Soft bird’s-beak is an annual semi-parasitic herb in the figwort family and is considered “rare” by the State of California and “endangered” by the Federal government. It is known from fewer than 20 populations and is found in the upper and mid zones of tidal brackish salt marshes around the Napa River, Carquinez Straits, and the Suisun marshes. It is presumed extirpated from the Petaluma River marshes. These populations are found in the upper and mid zones of marshes. Point Reyes bird’s-beak, another semi-parasitic annual, is also considered rare and endangered throughout its range of coastal tidal salt marshes. It is found in several marshes from Sausalito to Las Gallinas in Marin County but has been extirpated from marshes in San Mateo and Santa Clara counties. The elimination of tidal and brackish salt marshes has drastically reduced available habitat for both species but populations are now further reduced by development, foot traffic, non-native plants, altered hydrology, and cattle grazing.

Both species of bird’s-beak are annuals with germination and establishment of seedlings dependent of adequate annual rainfall, both in quantity and timing. In Marin County where marshes have been protected and disturbances reduced, Point Reyes bird’s-beak populations have increased and in some years, the number of plants is quite abundant in the few areas where it grows. It has not been found growing in any restoration sites yet, but some of these sites appear to have the right conditions for bird’s-beak establishment and there are nearby populations in older marshes as sources of seed. Both species of bird’s-beak appear to grow best in relatively course, sandy, silty or even gravel-silt, often in upper marsh areas on poorly drained flats, depressions, or areas with sparse or little emergent vegetation. For a portion of its life cycle, both bird’s-beak species are parasitic on common species such as pickleweed; however, it apparently does these species little harm. This genus is considered to be a variable complex and is in an active state of speciation in California with species varying taxonomically and as a result habitat races are limited in distribution. For this reason the extirpation of a subspecies with very limited distribution such as the soft bird’s-beak is a greater loss for the longevity of the entire genus. Natural establishment in restored marshes has not been observed to date. Studies to better understand population genetics and habitat requirements, including special soil conditions, would improve conservation and management strategies.

DESIGN RECOMMENDATIONS

1. Broad wetland-upland transition zones need to be established with maximum plant species diversity.

4.13 QUESTION 13: HOW SHOULD PUBLIC ACCESS BE PROVIDED?

THE PROBLEM

Public access is often an important component of restoration projects and the San Francisco Bay Conservation and Development Commission (BCDC), the USFWS, and the CDFG all encourage recreational opportunities for the public. Good public access encourages better protection of natural resources by an interested public; however, public access can have adverse impacts on wildlife. Adverse effects on wildlife may be direct, such as harassment or killing, or may be indirect and result in modification of habitat usage, such as with nest or site abandonment. Long-term effects may be reduced reproductive success and reduced populations within species or species distributions. Some wildlife species do adapt to the presence of humans although this may leave them more vulnerable. Balancing public access and natural resource protection is a complex aspect of public policy and choices are often difficult (BCDC 2001a, b).

Design decisions on the location of pathways can have a significant influence on other restoration objectives. For example, paths are often located on existing levees and the levee's preservation may conflict with the opportunity to restore full connection to the estuary. The abutments of bridges may constrict tidal flows.

Negative impacts can include impacts on populations of endangered species, impacts on breeding and foraging areas, or fragmentation of wildlife corridors. Migratory birds do not attain the energy reserves essential to a successful migration if foraging is disturbed. Human access also provides access to predators such as cats, dogs, raccoons, and foxes that use the same trails. On the other hand, public access that is well designed can provide considerable protection for wildlife since human presence can discourage vandalism and illegal hunting. Many birds do become acclimated to trail users even during migratory stopovers. Intrusions into the marsh plain should not be allowed except for specific purposes such as research or occasional teaching needs. In those cases, care must be taken not to create worn pathways that alter tidal flows across the marsh plain. Where extensive use is panned, a boardwalk over the marsh reduces damage to the marsh and provides easier access for teaching purposes.

RESTORATION EXPERIENCE

At the Warm Springs, a public trail was constructed along the new inboard levee. The design of this trail was not integrated with the wetland design and included exotic plantings and a viewing platform that was quickly engulfed in vegetation (Figure 53). Nevertheless, the trail supports high recreational use and appears to create minimal impact on the high bird use of adjacent mudflats.

At Muzzi Marsh, high public use of the perimeter pathways on dikes appears to have reduced disturbances by illegal hunters and hunting dogs. In 1980, as part of an adaptive management project, channels were excavated to limit intrusion onto the marsh plain by bicycles, motorcycles, cats and dogs. As designed, these channels have been effective barriers—however, they have also brought channel habitat close to disturbance from human activities on the dikes.

Because of its urban location, the Crissy Field project probably receives the highest public use of any restoration project in the Bay Area. Here, public access was fully integrated into the design and appears to be successful in limiting human and pet intrusion in a small site in an urban setting. A boardwalk and bridge allows access into the site and perimeter paths are separated from the wetland by both low fences and extensive native plantings in a buffer zone (Figure 54). The promenade across the entrance channel was bridged by a 20 m (70 ft) clear span to allow unimpeded migration of the tidal channel beneath.

DESIGN RECOMMENDATIONS

1. Avoid public access to sensitive areas for plants or wildlife in marshes where access is required.

2. Where any human activity is anticipated, provide buffer zones around the perimeter of the site.

3. Where access across a salt marsh is required, a boardwalk is advisable to reduce physical alteration of the marsh plain from foot traffic. Use of boardwalks should be kept to a minimum as their presence alters the vegetation below.

4. Where paths cross tidal channels, use clear span bridges that are adequately sized for the anticipated tidal prism within the site (see Section 4.3 Question 3: Should a levee breach and outboard channel be excavated?).

5. Provide educational interpretive signs that enhance the experience and support respectful visits.

4.14 QUESTION 14: HOW SHOULD WE INTEGRATE FLOOD MANAGEMENT ISSUES?

THE PROBLEM

The potential impact on flooding and draining of adjacent property, and the opportunity to reduce flood hazards, has to be considered in all restoration projects. Two types of flooding have to be considered: coastal flooding due to levee erosion and overtopping from storm surges and high waves, and flooding from the watershed due to rainstorms.

Most restoration sites require breaching a levee that formerly was the primary defense against coastal flooding. Therefore, it is essential that a new inboard levee be constructed that provides equal or better protection than the original levee. Moving the primary flood defense levee inland can modify the drainage system on adjacent low-lying land. This drainage system may rely on passive discharge of runoff that is stored in ditches and retention areas through tidal flap gates. If the storage volume is reduced by levee setbacks, improvements will need to be made to compensate for the potential increase in ponded water level. In addition, the restoration may temporarily change the tidal range outboard of flap gates by reducing or preventing discharge on the ebb tide.

In many instances, tidal wetland restoration projects can help reduce flood hazards. Many existing bayfront levees are former agricultural levees that are now in poor condition. Rebuilding a new levee inland provides an opportunity to improve the degree of protection for adjacent areas. Re-establishing a new vegetated marsh outboard of a relocated levee can significantly reduce the risk of erosion damage and the need for costly riprap erosion protection.

In many instances, restoration sites are located adjacent to where creeks discharge to the Bay. Whereas these creeks formerly discharged into natural slough channels that meandered through marshes before connecting to the Bay, their flows are now usually confined within a leveed tidal channel. Many of these tidal flood channels accumulate estuarine and alluvial sediments, requiring frequent expensive maintenance dredging to retain their design flood conveyance capacity. Restoring tidal action to restored marshes can significantly increase natural scouring and reduce the need for maintenance. On the other hand, increased tidal scouring might also widen the channel and undermine existing levees downstream. In addition, removal, lowering, or setting back levees along these tidal flood channels can also increase flood conveyance and reduce flood hazards upstream.

RESTORATION EXPERIENCE

At Muzzi Marsh, a new inboard levee was constructed prior to breaching the old bayfront levee. The extensive vegetated marsh plain helps protect the new levee from erosion. Over the last 25 years, the original levee has eroded (Figure 45). If the restoration project had not taken place, this levee, or a new inboard levee, would have had to be reinforced with riprap.

At Warm Springs, the reintroduction of tidal action from the project into Coyote Slough caused rapid scouring and has doubled its cross-sectional area and significantly increased its flood conveyance capacity (Figure 27 and Figure 28). However, this benefit was incidental and not incorporated into the planning of the project. Restoring tidal action to this site reduced the passive flood storage area for the adjacent property. To compensate for the lost volume, a flood basin was excavated inboard of the new levee (Figure 22) and new tide gates installed. Unfortunately, these tide gates discharged into an artificial embayment instead of directly into a tidal channel. This resulted in the need for frequent maintenance dredging to keep the tide gates clear.

At the Warm Springs site, a graded intertidal bench, 30 m (100 ft)-wide, protected the inboard levee. In the first few years, up to nine meters (30 ft) of this bench eroded due to wave action until a vegetation fringe was firmly established; since then, erosion has been negligible (PWA and LSA Associates 1998).

At Tolay Creek, reintroduction of tidal action at the end of a long, constricted channel changed the tidal characteristics, increasing mean tide and low tide elevations. This meant that drainage from adjacent properties was impeded, causing waterlogging and ponding. High standing water levels and strong wind wave action has caused erosion of the adjacent roadway, Highway 37 (Figure 55).

As part of the Napa Flood Management Project, a 160-hectare (400–acre) tidal wetland was restored at the mouth of the Napa River. Part of this design included lowering the levees to allow flood flows to dissipate across the wetland, thereby reducing flood elevations upstream in the City of Napa.

DESIGN RECOMMENDATIONS

1. The potential impact of tidal restoration on flood hazards and drainage of adjacent land needs to be analyzed and integrated in the design plan.

2. Opportunities for reducing flood hazards and drainage should be considered and incorporated into the plan wherever possible.

3. Wherever possible, the design should reduce erosion hazards to flood control levees by establishing vegetated marsh to reduce wave energy.

4. Restoration of tidal action can also be designed to increase scouring of flood control channels to increase their flow capacity during flood events.

5. Lowering of levees along flood control channels can reduce flood elevations upstream by increasing channel conveyance and storage.

5. GENERAL RECOMMENDATIONS AND CONCLUSIONS

5.1 CONCLUSIONS

- In general, restoration projects around San Francisco Bay have evolved in geomorphically explicable ways. The ecologic response to the physical evolution of the wetland has been less predictable.

- Many early restoration projects had unrealistic expectations of the rate at which a fully vegetated marsh would form. We should expect restoring wetland sites to take at least several decades to evolve towards a mature state in balance with sea level rise and sedimentation.

- Restoration projects (and unplanned restorations) that took advantage of natural sedimentary processes to form an accretionary marsh that evolved over time have performed as well or better than highly engineered projects that attempted to replicate the form of a mature marsh.

- The design of many early restoration projects was focused on the achievement of vegetated marsh functions as rapidly as possible and, in doing so, discounted the value of interim habitats and the value of a mosaic of evolving habitats.

- Monitoring periods of five to ten years, commonly required as permit conditions, may provide valuable information on whether the site is evolving as anticipated. However, this period is generally not long enough to inform improvements in planning and design of future projects.

- Early restoration projects were not planned and designed following a rigorous methodology that clearly established the linkage between design decisions and predictions of how the site would evolve to meet restoration objectives. This has sometimes made it difficult to assess performance in a way that would help us improve design decisions.

- Some early restoration projects were based on goals for developing suitable habitat for a particular target species. Overall project objectives should be clear at the outset with due consideration given to the needs of other target species and the marsh as a part of the whole ecosystem.

- Although there has been more than three decades of restoration experience in San Francisco Bay, and more than ten projects have been systematically monitored, we still have little experience of how large, deeply subsided restoration sites will perform.

- Almost all the restoration sites around San Francisco Bay have had most of all types of their transition zone removed or used for dikes or paths. Habitat values and other functions of the transition zone, such as sediment filtration, have not been well studied. Likewise, buffers have not been well-studied to determine an optimum width for varying urban or rural conditions or for differing functions such as water quality protection or disturbance.

- Apart from land acquisition, the largest restoration cost is usually earth moving. Many design decisions have significant grading cost implications yet are based on very limited data and analysis.

- Recreating historic wetland landscapes and functions on restoration sites is often constrained by the legacy of past human interventions as well as long-term changes in physical processes. These include: levees, property boundaries, subsidence, and sea level rise.

- Care needs to be exercised in the use of vertical datums around the Bay given the degree of subsidence and tectonic movement in the area.

5.2 RECOMMENDATIONS

There is a significant opportunity to continue to improve design decisions by incorporating explicit adaptive management experiments within future restoration projects. These experiments can address uncertainties in project design that significantly effect cost, feasibility, and ecologic performance. These uncertainties include for example:

- The rate of evolution of a subsided site to a mature marshplain.

- The importance of the size of tidal channels within the marsh to support estuarine fish.

- The degree to which internally generated wind waves effect sediment dynamics and vegetation colonization.

- The evolution and functioning of tidal pannes at the marsh margin.

- The rate of natural establishment for a full range of salt marsh plant species.

- The impact of exotic species on tidal marsh habitat for a range of species.

Useful adaptive management experiments that should be incorporated in future restoration projects include:

- Examine the tradeoff between the amounts of fill required in a subsided site and the rate of evolution of desired wetland functions.

- Predict more accurately the rate of evolution of wetland form and function for different erosional and sedimentary environments that take into account consolidation, organic accretion, future sea level rise, changes in sediment budget, and changes in estuarine sediment dynamics.

- Assess more completely the functional differences between restoring marshes of different ages, as well as the tradeoffs between subtidal, intertidal mudflat, and vegetated marsh habitats in an evolving system.

- Design improvements such as the size and spacing of wave breaks, cost effective ways to create channel systems in dredged materials, outboard channel excavation requirements, or use of offshore marshes to prevent levee erosion.

- Investigate the role of vegetation in reducing wave energy, erosion, and resuspension.

- Understand the benefits of grading more heterogeneous habitat within the site—particularly integrating transitional wetland/upland habitat in the site design.

- Understand the requirements of plants and the use of soil amendments that enable successful planting programs to occur where appropriate.

- Develop techniques for controlling aggressive non-native plants that limit or replace native species.

- Better understand the effect of human activities on wildlife and develop strategies to protect the wildlife.

- Develop better means to inventory endangered wildlife species such as the harvest mouse and strategies to enhance the extent and quality of their habitat.

Restoration practice is an applied science that is now maturing. We now understand tidal wetlands as vital components in a larger estuarine ecosystem that is continually evolving in response to human and natural physical processes and that this context has to be taken into account if we are to achieve sustainable long-term benefits from restoration. We also now perceive that many restoration projects are best planned and designed as multi-objective projects that integrate social and ecologic objectives in a rigorous, explicit, planning methodology. This allows us to objectively assess performance by monitoring pre-selected indicators. In this way, we can continue to improve our design decisions based on experience and, sometime in the future, produce an updated version of this report.

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