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Evolution of Tidal Creek Networks in a High Sedimentation Environment: A 5-year Experiment at Tijuana Estuary, California

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ABSTRACT: In a large (8 ha) salt marsh restoration site, we tested the effects of excavating tidal creeks patterned after reference systems. Our purposes were to enhance understanding of tidal creek networks and to test the need to excavate creeks during salt marsh restoration. We compared geomorphic changes in areas with and without creek networks ($n = 3$; each area 1.3 ha) and monitored creek cross-sectional areas, creek lengths, vertical accretion, and marsh surface elevations for 5 yr that included multiple sedimentation events. We hypothesized that cells with creeks would develop different marsh surface and creek network characteristics (i.e., surface elevation change, sedimentation rate, creek cross-sectional area, length, and drainage density). Marsh surface vertical accretion averaged 1.3 cm yr^{-1} with large storm inputs, providing the opportunity to assess the response of the drainage network to extreme sedimentation rates. The constructed creeks initially filled due to high accretion rates but stabilized at cross-sectional areas matching, or on a trajectory toward, equilibrium values predicted by regional regression equations. Sedimentation on the marsh surface was greatest in low elevation areas and was not directly influenced by creeks. Time required for cross-sectional area stabilization ranged from 0 to > 5 yr, depending on creek order. First-order constructed creeks lengthened rapidly (mean rate of 1.3 m yr^{-1}) in areas of low elevation and low vegetation cover. New (volunteer) creeks formed rapidly in cells without creeks in areas with low elevation, low vegetation cover, and high elevation gradient (mean rate of 6.2 m yr^{-1}). After 5 yr, volunteer creeks were, at most, one-fourth the area of constructed creeks and had not yet reached the upper marsh plain. In just 4 yr, the site's drainage density expanded from 0.018 to reference levels of 0.022 m m^{-2}. Pools also formed on the marsh plain due to sediment resuspension associated with wind-driven waves. We conclude that excavated creeks jump-started the development of drainage density and creek and channel dimensions, and that the tidal prism became similar to those of the reference site in 4–5 yr.

Introduction

Restoration practitioners are often asked to reestablish salt marsh functions, but tidal drainage networks are rarely included or designed to match those in reference marshes. Instead, sites are graded until they are smooth and then replanted, with results that have variable ecological value (Zedler 2001). Without tidal creek networks, restored marshes may lack functions associated with the transfer of biota, water, sediment, and nutrients from the marsh interior to adjacent coastal waters (Reed et al. 1999; Desmond et al. 2000; Crooks et al. 2002). Recent work suggests that tidal creeks should be incorporated into restoration sites to support biological diversity and increase the rate at which target conditions are achieved (Coats et al. 1995; Madon et al. 2002; Morzaria-Luna et al. 2004).

The self-design approach allows low-order creeks to form voluntarily after a higher- order channel is excavated and the site is graded to an elevation that encourages accretion (Haltiner et al. 1997; Crooks et al. 2002; Williams and Orr 2002). This approach has been used in San Francisco Bay and in eastern United States areas, but it may take 4–13 yr for channel dimensions to stabilize (Williams et al. 2002) and 5–20 yr for vegetation to establish (Williams and Orr 2002). Marsh plain sedimentation rates are moderate and available sediment is typically fine-grained, so that once a site accretes to mean higher high water (MHHW) level, there is minimal concern that sedimentation will restrict tidal circulation (Letzsch and Frey 1980; Zeff 1999; Cornu and Sadro 2002; Williams and Orr 2002). Alternatives to self-design (e.g., constructed creeks) are required where restoration goals include short timelines, where low sediment inputs may lead to unacceptably slow development of marsh elevations, or where extreme sedimentation rates (>1.0 cm yr^{-1}, or 5 times the rate of sea-level rise; Munk 2003) are likely (Onuf 1987; Callaway and Zedler 2004; Thrush et al. 2004).

Although tidal creeks should improve vegetation development through improved drainage (Eertman et al. 2002) and fish use of the marsh surface due to improved access (Minello et al. 1994; Desmond et

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al. 2000; Madon et al. 2001), only a few restoration projects have excavated creeks (Minello et al. 1994; Simenstad and Thom 1996; Emmerson et al. 1997; Haltiner et al. 1997). Where constructed, tidal creeks have experienced significant erosion and sedimentation (Simenstad and Thom 1996; Haltiner et al. 1997; Zeff 1999; Eertman et al. 2002; Thom et al. 2002), and their sustainability is uncertain (Desmond et al. 2000). In other restored salt marshes, creeks have formed voluntarily. It is unclear if constructed and volunteer creeks will attain geomorphic conditions comparable to reference wetlands, and if so, how quickly the networks will evolve.

To date, few characterizations of restoration sites document geomorphological development in sufficient detail to determine if drainage networks are comparable to natural reference systems (Coats et al. 1995; Desmond et al. 2000; Callaway 2001; Williams et al. 2002). Geomorphological processes on the marsh surface, such as wind-driven resuspension, have been noted (Cornu and Sadro 2002; Williams et al. 2002) but rarely quantified (Shideler 1984; Ward et al. 1984; Letzsch and Frey 1980; Schoellhamer 1996). With pressure on restorationists to produce desired outcomes and manage costs, it is important to understand how creeks and marsh surfaces develop with and without excavated creeks.

The dimensions and plan forms of tidal creeks in natural systems were initially studied using hydraulic geometry equations (Myrick and Leopold 1963; Pestrong 1965). In an effort to apply these tools and identify regional parameters, researchers in San Francisco Bay, California, expanded upon empirical correlations linking channel dimensions, tidal prism, and drainage area (Allen 2000; Williams et al. 2002). The relationships can be used to assess the extent to which creeks in restoration sites resemble creeks in reference sites, or how far along the evolutionary trajectory they are to the equilibrium morphology (Williams et al. 2002). Emmerson et al. (1997) monitored tidal stage curves to assess morphological and hydraulic development of a site. Additional work on flows in salt marsh tidal creeks (Boon 1975; Bayliss-Smith et al. 1979; Pethick 1980; Pye and Allen 2000; Friedrichs and Perry 2001), tidal prism (French and Stoddart 1992; Lawrence et al. 2004), drainage density (Coats et al. 1995; Zeff 1999; Desmond et al. 2000), and modeling (Allen 2000; Fagherazzi and Furbish 2001; Fagherazzi et al. 2004; D'Alpaos et al. 2005) established a foundation for expanding knowledge in this area.

To enhance our understanding of tidal creek networks and to test the need to excavate creeks, we measured the development of geomorphic features in our 8-ha experimental restoration site (Friendship Marsh) at Tijuana Estuary in southern California (Zedler 2001). Replicate features (three cells with or without creeks) allowed us to quantify the extent and rate of creek developmental change. Following extreme storm events, we assessed the response of tidal creek treatments to sedimentation. We tested the hypothesis that cells with excavated creeks would develop different creek network and marsh surface characteristics by addressing the following questions:

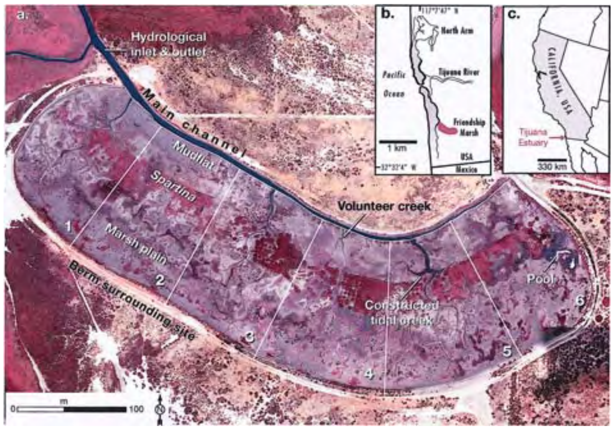

Fig. 1. Friendship Marsh (a) in Tijuana Estuary (b), California, USA (c). Aerial view of adaptive restoration site (a) is from August 1, 2003. Each cell had three habitats: mudflat, *Spartina* (plants appear red), and marsh plain. Pools and volunteer creeks developed within 4 yr.

What variables affect tidal creek development? How do creek cross-sectional area and creek length differ in cells with and without excavated creeks? How, and at what rate, do excavated creeks adjust toward equilibrium morphologies and drainage density of reference systems?

What variables affect marsh surface development? Do vertical accretion and changes in surface elevation differ in areas with and without excavated creeks?

How do excavated creeks affect the development of tidal prism in comparison to reference sites?

STUDY AREA

Tijuana Estuary is a 1,000-ha, marsh-dominated, coastal plain estuary at the mouth of the Tijuana River just north of the U.S.-Mexico border in San Diego County, California (32°35′N, 117°7′W; Fig. 1). This National Estuarine Research Reserve was recently named a Wetland of International Importance (Ramsar unpublished data). Tidal marshes dominate both the north and south arms of the estuary, with vegetation grading from a fringe of *Spartina foliosa* (Pacific cordgrass), to a broad marsh plain dominated by *Salicornia virginica* and *Jaumea carnosa*, a high marsh with subshrubs, and a saline but nontidal transition to coastal scrub.

The tidal regime is semidiurnal mixed tides, and basic flow patterns observed on site follow those of coastal California marshes, as documented by Pestrong (1965, 1972). During the flood tide, flows entering the site are restricted to the confines of the main channel and tidal creeks. Once the banks are topped over, flood flows increase in relation to the rapid increase in tidal prism, and the mudflat, *Spartina* habitat, and marsh plain become inundated, the latter only during above-average tides. During the initial part of the ebb tide, water drains in sheet flow from the marsh to the main channel, with little cross-flow to creeks. As water levels drop, ebb flows of high velocity to tidal creeks become dominant until flows occur only in tidal creeks and as minor bank drainage along the main channel (Bayliss-Smith et al. 1979; Fagherazzi et al. 2004; Lawrence et al. 2004). *Spartina* habitats are inundated twice daily and the marsh plain at least once daily on spring tides. On neap tides, especially in March and September, the marsh plain lacks tidal inundation for several consecutive days (Zedler et al. 2001). Intense storms create surges of seawater that flow into the estuary, including the study area.

The estuary's north arm is the reference site for this study, as it is San Diego County's least fragmented salt marsh and one of the few estuaries in the region with a near-continuous tidal connection (Zedler 2001). The south arm includes Friendship Marsh, which was historically part of a large wetland complex that was buried by sediment and cut off from tidal circulation by the 1950s (estimated from historical aerial photographs (Zedler et al. 1992). Members of the Pacific Estuarine Research Laboratory, Tierra Environmental Services, and Rick Engineering Inc. (unpublished data) planned the restoration of tidal circulation to Friendship Marsh. Restoration began with excavation of approximately 2 m of accumulated sediment in 1999. The exposed marsh soil was compacted but otherwise similar to the reference marsh soil (O'Brien and Zedler in press). Tidal circulation was reestablished in February 2000. To maximize the scientific benefit of this ambitious and costly endeavor, the project was implemented as a replicated ecosystem-scale experiment for studies of tidal creek networks (modeled after a network in the north arm).

Fluvial inputs to the study site are intermittent but important. Rainfall in the region's mediterranean-type climate averages 30 cm but is episodic and generally restricted to storms between November and March. Summers are warm and dry. Fluvial inputs to different areas of the estuary vary with geomorphic setting. The north arm is surrounded by gently sloping topography, and it becomes inundated by floodwaters from the Tijuana River (Ward et al. 2003). The south arm has a local subwatershed in Mexico, and the steep slopes are composed of loosely consolidated sediments that are continually being cleared of stabilizing vegetation for urban development. Friendship Marsh is connected to a channel that drains the steep slopes and outputs to Tijuana River. During intense storms, sediment-laden floodwaters from the subwatershed flow into the study site. We assume that when such floods coincide with flood tides, on-site sedimentation is enhanced. While sedimentation from tidal sources is low (Weis et al. 2001; Elwany et al. 2003; Ward et al. 2003), fluvial sediment deposition is a primary management challenge for Tijuana Estuary and other wetlands in the region, because it raises the marsh surface and fills creek networks (Onuf 1987; Greer and Stow 2003; Callaway and Zedler 2004). The result is reduced tidal influence.

EXPERIMENTAL DESIGN

The 8-ha Friendship Marsh was constructed to have 3 areas with tidal creek networks and 3 without (referred to as +creek, −creek, or ±creeks cells; Fig. 1). Each cell had a drainage area of 1.3 ha, and those with tidal creeks were patterned after a third-order network in the north arm with a comparable drainage area (tributary order based on Strahler 1964). Creek dimensions were tailored to suit excavation equipment. Cells without creeks had a flat marsh plain with a gradual slope in elevation. The main channel (fourth-order tributary) along the north side of all 6 cells conveys tidal flows into and out of the cells. This channel was designed to hold water continuously and provide fish habitat. The channel's southern bank was relatively short (approximately 0.5 m) where it met the excavated marsh surface, and its northern bank was tall (approximately 2.0 m), steep, and highly erodible. To mimic elevations of the reference site (Zedler 1982), the marsh plain in the cells was excavated to 0.8 m (NGVD 29) and sloped from 0.8 m to the lowest point of the mudflat at 0.3 m. The restored marsh was surrounded by a berm on the west, east, and south sides designed to prevent sediment deposition from floodwaters.

Native halophytes were planted in the cells, with each cell having the same treatments and configuration to avoid confounding the ±creek comparisons (Zedler et al. 2001). Each cell had three habitats: unplanted mudflat (at the lowest elevation, adjacent to the fourth-order channel), a zone of *S. foliosa* planted as plugs at 2-m and 4-m spacings, and a marsh plain planted with five species (following Keer and Zedler 2002; Callaway et al. 2003; Fig. 1). Kelp-amended plots were established in the *Spartina* zone on the east sides of every cell at the time of excavation, as illustrated for cells 5–6 in Fig. 2. The

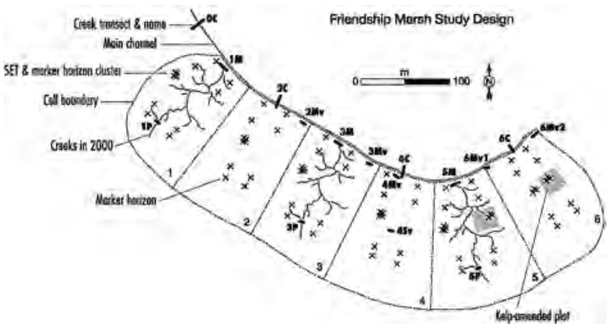

Fig. 2. Map of the experimental design containing six cells (labeled 1–6 in lower right corner): three were +creek, and three were −creek. Every habitat within each cell contained marker horizons for sampling sedimentation. Cells also contained sediment elevation tables (SET) for measuring elevation change. Kelp compost was added to all 6 cells, as illustrated in cells 5 and 6, where SETs were established to test effects of kelp amendment on marsh elevation. Constructed creek profile changes were measured at permanent transects labeled according to cell and habitat: C = main channel, M = mudflat, P = marsh plain, and S = *Spartina*. Volunteer creek transects added in 2004 are labeled v.

top 30-cm layer of soil was removed, mixed with kelp compost, at a 2 : 1 ratio of soil to kelp, and returned to plots. During the first 4 yr (2000–2003), Friendship Marsh was essentially bare (Fig. 1); vegetation was sparse in mudflat and marsh-plain habitats, except for *Spartina*, which covered one-sixth of the 80,000-m^2 marsh surface.

Methods

We investigated geomorphological change in ±creek cells over the first 4–5 yr of restoration by evaluating sedimentation, resuspension, texture, and elevation change on the marsh surface. Creek and channel morphologies were characterized by measuring cross sections using topographic surveys and plan form estimates derived from aerial imagery. We used these data to compare tidal prism, drainage density, and creek and channel dimensions in the constructed marsh to the north arm reference site (Entrix 1991; Desmond et al. 2000) and regression equations in the literature (Williams et al. 2002).

SEDIMENT ACCRETION AND RESUSPENSION ON THE MARSH SURFACE

We used feldspar marker horizons to measure the accumulation of sediments on the marsh surface (Cahoon and Turner 1989). In April 2000, twelve 0.5 × 0.5 m feldspar plots were established in each cell, with 4 per habitat type (Fig. 2). Plots were sampled each spring and fall through April 2004, using a knife to extract two cores per plot. When the sediment was highly unconsolidated or the marker horizon was too deep, we used a cryogenic corer (Cahoon et al. 1996). The depth of sediment deposited above the marker horizon was measured with a caliper (n = 3 per core). Cores were replaced in the plot and marked with a bamboo stake to avoid resampling. Two cores were measured per plot, and means per plot were used for data analysis. Marker horizons were replaced in new locations adjacent to original plots when accretion exceeded the depth of the corer or when plots were lost to erosion.

Increases in depth of sediment between the surface and the marker horizon indicated accretion between sampling intervals. Decreases in depth were interpreted as resuspension. On 19 out of 523 occasions, marker horizons were unclear or absent; we attributed this to bioturbation and did not record a measurement. Because markers could also be lost through resuspension, the frequency of such events may be underestimated.

Resuspension was analyzed first and then combined with accretion events to assess net change. Resuspension data were analyzed by habitat, cell, and season using the descriptive statistics function in Excel 2002 (Microsoft, Redmond, Washington). Marker horizon data were analyzed at the 6-mo, 12-mo, and 42-mo levels from April 2000 through April 2004.

All marker horizons were replaced after the 42nd mo due to high levels of accretion that made core extraction difficult; so 48-mo data were not included in an analysis of cumulative sedimentation. Data from the 42-mo time period were converted into annual averages and analyzed. Because storm inputs were highly variable, we found it difficult to interpret the annual mean, but we chose this approach in order to compare data to other sites. The statistical software R 2.0.1 (R. Foundation, Vienna, Austria) was applied to sedimentation data using a fixed model analysis of variance (ANOVA) accounting for habitat type, presence or absence of creek, and cell (nested within creek feature). In the case of 6-mo data analyses, time was incorporated into the model. Residual plots of 12-mo and 42-mo sediment data displayed heteroskedasticity; log transformations reduced skewness. Since 6-mo data contained negative values (attributed to resuspension), no log transformations were performed. We tested a number of contrasts separately to find standard errors, test statistics, and p values using an alpha = 0.05. Tukey's test was applied to find differences between cells.

The location of each marker horizon plot was determined using real-time kinematic survey methods with a Leica SR530 Global Positioning System (GPS; horizontal and vertical accuracy of ±5 cm) in October 2004. A map of cumulative sedimentation over 42 mo across the site was interpolated from marker horizon data using ordinary kriging functions in ArcGIS 9 (ESRI, Redlands, California). The data were not transformed, and an exponential model, nugget, and all-inclusive neighborhood structure were applied. Prediction error maps were examined to verify the accuracy of interpolated contours.

SEDIMENT TEXTURE

In order to characterize the texture of newly deposited sediment, we collected samples from the top 2 cm of each habitat profile in +creek cells in October 2004 (totaling 9 samples) and analyzed them using the hydrometer method (Gee and Bauder 1986) and sonic sifting. Samples were pretreated for humus fraction by digestion with 30% analytical grade hydrogen peroxide. The program PSA4 (Knox unpublished data) was used to provide percent sand (>0.063 mm), silt (0.002–0.063 mm), and clay (<0.002 mm).

MARSH SURFACE ELEVATION CHANGE

Sediment elevation tables (SET) allowed us to measure changes in marsh surface elevation with millimeter-scale precision (Boumans and Day 1993; Cahoon et al. 1996). In February 2000, 8 SETs were installed as stable benchmarks by driving a 7.5 cm-diameter thin-walled aluminum pipe into the ground until refusal (typically 3–4 m). Changes in wetland surface elevation were measured every 6 mo by attaching the portable SET instrument to the benchmark. Elevations were measured at 36 points using pins at each benchmark (9 points measured with pins on a square grid at each of 4 positions). The SETs were adjacent to marker horizons, and the combined data of sediment accretion and changes in surface elevation allowed us to estimate compaction. One SET was installed in each of the 6 cells in high-density *Spartina* plantings for a comparison of processes in ±creek cells. Two additional SETs were established in kelp-amended, low-density *Spartina* in cell 5 (+creek) and cell 6 (−creek; Fig. 2) to evaluate any potential effect of kelp on surface elevations.

Some SET plots contained footprints, and these were recorded. When analyzing the data, we initially excluded the sample locations with footprints. We later incorporated these locations when footprints were no longer visible, and did not observe any consistent differences in areas measured with and without footprints. We included the data from these locations in our results based on the assumption that tidal action and sedimentation events eliminated effects of footprints over time. SET data were analyzed by graphing the change in the surface elevation against the marker horizon data for each plot. Major differences in data from marker horizons and SETs yielded evidence of compaction. The statistical software R 2.0.1 was applied to SET data at 6-mo levels using a fixed model ANOVA, with alpha = 0.05, accounting for +kelp and −kelp treatments (nested within creek feature), presence or absence of creek, and cell (nested within creek feature).

CREEK AND CHANNEL MORPHOLOGY

Creek and channel cross-section profiles were surveyed at 10 locations with an AutoLevel (vertical and horizontal accuracy of 2–3 cm) prior to tidal restoration in February 2000. Four cross sections were surveyed along the fourth-order main channel: one approximately 10 m west of the breach (cf., cell 0 in Fig. 2), where the main channel connects with a natural channel in an adjacent marsh, and three directly adjacent to the -creek cells. In +creek cells, creek mouth cross sections of each third-order tributary were surveyed 5 m upstream of the main channel. Cross sections of first-order tributaries in headwater areas (adjacent to marsh-plain habitat) were surveyed 10 m downstream of the creek end (Fig. 2). Cross-section end points were monumented by driving 2-cm diameter PVC pipes into the ground until refusal. Elevation positions at approximately 0.25-m intervals were recorded along each transect. Cross sections were surveyed at all locations using an AutoLevel in June 2000, September 2001, April 2002, and April 2003. In October 2004, cross sections of the first-order and third-order transects were surveyed with a Leica SR530 GPS. At this time, 6 additional transects were established at each of 5 volunteer tributaries: 5 transects on the marsh margin and 1 transect in the *Spartina* zone (Fig. 2). The 2004 data set was enhanced by main channel cross sections from Elwany (unpublished data) using a Sokkia Set-5A total station and SDR-33 electronic field data logger (vertical and horizontal accuracy of 2–3 cm). All data were corrected to meters above NGVD 29 and California Coordinates (NAD83).

We also measured changes in elevation in the creek bed, defined as that portion of the creek bed submerged below low tide. From average water level data in 2003, we defined low tide as 0.15 m NGVD (Elwany et al. 2003). To measure bed levels for each transect from 2000 to 2004, we took the mean of all points below this level; in cases where the creek beds were above this level, we averaged the lowest three points in the bed. To compare bed levels from 2000 to 2004, we subtracted the means. Changes in depth were then compared to marsh surface sedimentation data with permutation tests in R 2.0.1.

Creek cross-sectional area was computed following the methods of Coats et al. (1995), where MHHW (0.88 m NGVD) was defined as the bankfull level. In cases where the top of the bank was below the elevation of MHHW, the top of bank at transect end pipes was projected vertically upward to the MHHW to provide a basis for measurement (Coats et al. 1995). Since no end pipes were established adjacent to volunteer tributaries, we used obvious breaks in the slope as reference points. Cross-sectional area was defined as area between MHHW and the survey points along the creek profile, and computed using geometrical formulas.

Tributary lengths were estimated from August 1, 2003, color-infrared orthophoto mosaic with 0.5 m (1.5 ft) pixels (Wild RC30 camera, Kodak Aerochrome III Infrared film 1443, Estar Base; courtesy of Rick Engineering, Inc. (San Diego, California) Cal Zone 406, units ft) and 2000 design drawings in ArcGIS 9. Following the methods of Desmond et al. (2000) and Coats et al. (1995), we assigned tributary orders according to Strahler's (1964) modified rules of the Horton (1945) classification system. Tributary lengths were estimated using a program written in ArcView 3.0 (ESRI, Redlands, California). Length data were evaluated by order, habitat, cell, and site levels using descriptive statistics in Excel 2002.

Drainage densities were calculated by dividing the total tributary length by the contributing drainage area at cell (1.3 ha) and site levels. Calculations incorporated the main channel lengths draining the edge of each cell. Densities were compared to values observed in the north arm reference marsh (Desmond et al. 2000) and to design standards for California marshes (Coats et al. 1995).

TIDAL PRISM

Potential mean diurnal tidal prism is defined as the combined storage volume of the marsh surface and tributaries between MHHW and mean lower low water upstream of a location in the channel system (Coats et al. 1995). It represents the volume of tidal water that is exchanged during an average tide assuming no restrictions on ebb or flood. The tidal prism of the marsh surface (mudflat + *Spartina* zone + marsh plain) was calculated by multiplying its area (8 ha–surface area of tributaries) by the depth of water at MHHW (= MHHW − mean marsh elevation). The design and as-built surveys provided marsh surface elevations for 2000 that were then averaged. Marsh surface elevation estimates for 2003 were found by adding cumulative accretion data to 2000 values and cross-referencing estimates with subsoil compaction data. Tidal creek tidal prism was calculated using the equation for the volume of cone frustums (Coats et al. 1995) using area and width data from transects and length data from 2000 and 2003 digital imagery. Creek network tidal prisms were underestimated, since they were calculated from only two transects per cell, excluding many second-order and first-order tributaries. Tidal prisms for cell and site levels were calculated by summing marsh plain and tributary volumes for 2000 and 2003.

We applied hydraulic geometry regression equations established by Williams et al. (2002) to test how well tidal prism and drainage area predicted 2003 cross-sectional areas. The regression equations represent equilibrium dimensions of stable creeks in salt marshes of California. The tidal prism regression equation used was $y = 0.0284x^{0.649}$ where y = tributary cross-sectional area (m^2) and x = tidal prism (m^3). The equation relying on drainage area to predict tributary cross-sectional area was $y = 2.4x^{0.772}$ where y = cross-sectional area (m^2) and x = drainage area (m^2). Regression formulas were computed in Excel 2002. The relatively flat topography made it difficult to identify drainage area and tidal prism boundaries. In the absence of a high-resolution digital elevation model or hydraulic model, we developed a range of probable drainage area and associated tidal prism for the three constructed creek networks. In identifying this range, we considered contribution to the tidal prism from the tidal creeks as well as over the marsh margin. Previous field work and models have identified that tidal creeks can contribute 30–40% of the total tidal prism to a drainage basin within the marsh (French and Stoddart 1992; Lawrence et al. 2004). For the minimum value of the range, we selected the drainage area for each creek's cell (1.3 ha) and a minimum tidal prism corresponding to this area that was 40% of the total tidal prism. The maximum value of the range corresponded to the maximum marsh surface area and volume that would drain through each of the three creek mouths. We selected the following drainage areas that extended beyond the cell boundary for each creek: Creek 1 could potentially drain all of cell 1 and the western half of cell 2. Creek 3 could drain all of cell 3, the eastern half of cell 2, and the western half of cell 4. Creek 5 could drain all of cells 5 and 6, the eastern half of cell 4, and all of cell 6. These high-end estimates assume that no water drains directly across the marsh margin; rather, all of it drains through a creek mouth. At some high tidal stages, we know water drains across the marsh margin. While this may overestimate the role of creeks, it sets an upper boundary for these cells. Actual drainage area and tidal prism should fall within the range provided. We conducted an additional assessment representing the middle of our range using the maximum drainage area, but with the assumption that 40% of the tidal prism

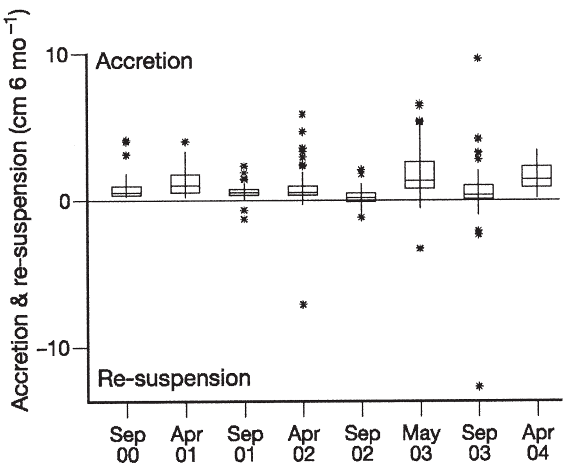

Fig. 3. Box-plot for sediment accumulation and resuspension on the marsh surface through time (n = 523). Processes were episodic with higher sedimentation occurring in winter and most of the resuspension occurring in summer. Data outside of the first and third quartiles are indicated with *.

would move through the creeks and 60% would move across the margin, with the expectation that this third scenario would best simulate field conditions. First-order tributaries were not assessed, since regression equations apply to third-order creeks and higher (Williams et al. 2002).

Results

Our specific findings follow for sedimentation, resuspension, elevation, and changes in cross-sectional area in areas ±creeks. After presenting the site-specific data, we compare drainage density, creek and channel dimensions, and tidal prism in the restored site to reference conditions.

MARSH SURFACE SEDIMENTATION AND RESUSPENSION

Marker horizon data indicate that the dominant surface process at the site was accretion with periodic resuspension. Major sedimentation events occurred in winters (maximum 6-mo accretion = 9.5 cm), with lower accretion and resuspension values in summer (minimum 6-mo = −12.8 cm; Fig. 3). Net accretion rates for all habitats from 2000 to 2004 had a mean 6-mo value of 0.8 ± 0.06 cm (n = 523) and an annual mean of 1.3 ± 0.12 cm (n = 68). After accreting sediments from February 2000 to April 2001, all habitats and cells experienced some resuspension (10–20% of the observations in all cells). Mudflat, *Spartina*, and marsh-plain habitats experienced resuspension 14%, 9%, and 16% of the time, respectively. Most (58 of 67) resuspension events were observed in the summer, suggesting a seasonal pattern, although the sample size was too small to show statistical significance. Resuspension values ranged from −0.01 to −12.8 cm over a 6-mo period, with a mean of −0.8 ± −0.22 cm. Resuspension occurred frequently (19 of 67 observations in 4 yr) in cell 6 at the east end of the site.

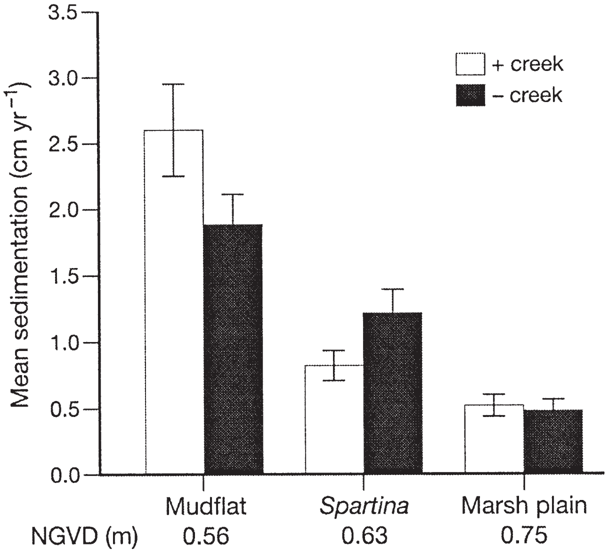

Fig. 4. Mean (± SE) sedimentation according to habitat (n = 23, 22, and 23 for mudflat, *Spartina*, and marsh plain, respectively). Sedimentation was significantly different between habitats ($p < 0.001$, n = 68) and decreased with elevation. There was a marginal interaction between creeks and habitat ($p = 0.052$, n = 68) such that +creek cells experienced more accumulation in the mudflat but less accumulation in *Spartina* habitats compared to −creek cells. Letters indicate significant differences at alpha = 0.05 level. Elevation units are meters NGVD 29.

Sedimentation (combined accretion and resuspension values) varied with habitats (p always < 0.001) and cells ($p < 0.05$ at cumulative and annual level) but not in direct response to creeks ($p = 0.23$, 0.99, and 0.41 at seasonal, annual, and cumulative levels, respectively). Sedimentation was greatest in mudflat, followed by *Spartina* and marsh-plain habitats ($p < 0.001$; untransformed annual means were 2.2 ± 0.12 versus 1.0 ± 0.12 versus 0.5 ± 0.06 cm, respectively). Over 4 yr, the central cell (3, +creeks) experienced the greatest sedimentation (mean = 5.9 ± 1.39 cm), while cells 1 and 6 experienced the least (mean = 2.7 ± 0.10 and 3.0 ± 0.53 cm, respectively). Although sedimentation was not directly linked to the creek treatment, the combination of creeks and habitats did marginally affect annual sedimentation in the linear model ($p = 0.052$); the gradient in sedimentation from mudflat to *Spartina* was greater in +creek cells due to higher levels of accretion in the mudflat and lower levels in the *Spartina* habitat (Fig. 4). Cells without creeks had a less dramatic decrease in sedimentation from mudflat to *Spartina* habitats. In other words, the difference from the mudflat to *Spartina* in +creek cells (untransformed annual

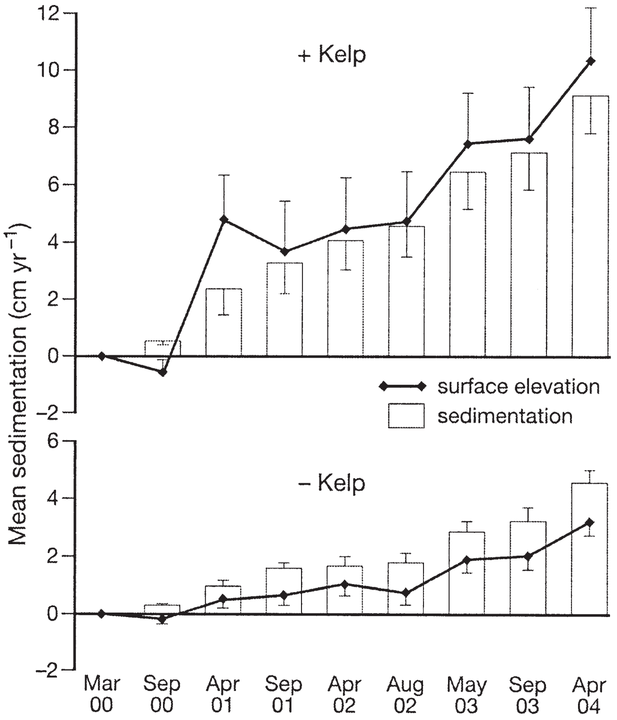

Fig. 5. Cumulative mean surface elevation and sedimentation over time for kelp treatments. Data depicted are from SETs (mean ± SE; n ranges from 3 to 7 per time interval) and marker horizons (mean ± SE; n ranges from 2 to 5 per time interval) in *Spartina* habitats of cell 5. Note that kelp amendment areas experienced increases in surface elevations that exceeded sediment accumulation. In −kelp treatments, surface elevation lagged behind sedimentation indicating compaction.

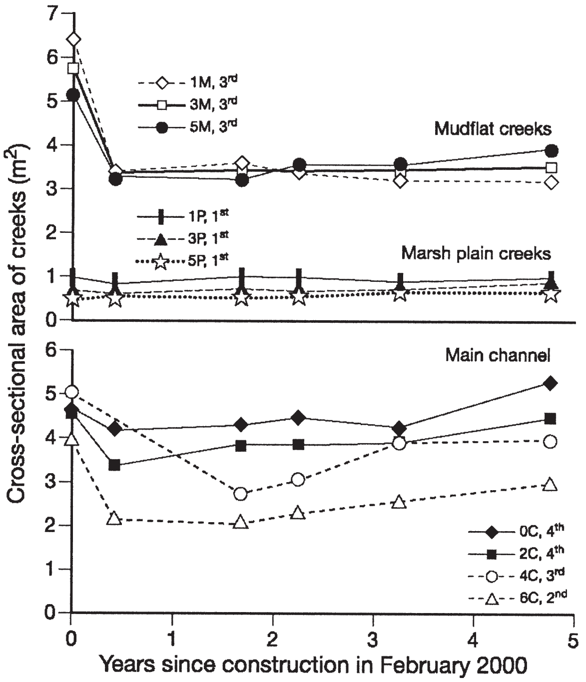

Fig. 6. Cross-sectional areas of constructed creek profiles at marsh plain, mudflat, and main channel positions over time. Profiles in the marsh plain did not experience significant change. Creek mouths in mudflats experienced initial reduction in area followed by stabilization around 3.5 m^2. Main channels experienced initial reduction followed by an increase in cross-sectional area.

means = 2.6 ± 0.4 versus 0.8 ± 0.1 cm) was significantly higher than in −creek cells ($p = 0.038$; 1.2 ± 0.2 cm). This relationship was also evident at the 6-mo level ($p = 0.007$).

Sediment Texture

The sediment accumulating on the marsh surface (depths 0–2 cm) between February 2000 and October 2004 had a mean of 15 ± 9% sand, 65 ± 8% silt, and 20 ± 7% clay when samples from all habitats were combined. Silt content was lower in the mudflat and *Spartina* habitats compared to the marsh plain (49 ± 18% versus 59 ± 7% versus 88 ± 6%, respectively). Clay was present in the mudflat and *Spartina* sediments (22 ± 15% versus 38 ± 8%, respectively) but was absent from the marsh plain (0%). The highly variable sand content in the mudflat (29 ± 26%) was not observed in *Spartina*, but the marsh plain did have a sand component (12 ± 6%). From west to east across the site, mean clay content shifted from 10% to 35%, mean sand content shifted from 36% to 1%, and mean silt content ranged from 54% to 79%.

Surface Elevation Change

We found an increase in marsh surface elevation in all cells. Data from SETs indicated that absolute elevation increases were less than accretion in all but cell 2, with the difference ranging from 1.4 to 4.0 cm over the 42-mo period. Cells with creeks displayed higher rates of subsoil compaction than −creek cells (mean change in elevation = −0.9 ± 0.2 versus −0.4 ± 0.3 cm per 6 mo, respectively; $p = 0.08$). Compared to areas of −kelp treatment, +kelp areas experienced elevation increases greater than accretion, suggesting greater accumulation of organic matter in the soil with kelp additions (Fig. 5; $p < 0.001$; mean change in surface elevation = 0.8 ± 0.2 cm in +kelp versus −1.1 ± 0.2 cm in −kelp).

Creek and Channel Cross Sections

Shortly after tidal introduction (February 2000 and 2001), the main channel and constructed creek mouths lost up to 47% of their cross-sectional area (Fig. 6). Following this, the cross-sectional area values in third-order mudflat creeks stabilized, while the main channel became wider (Table 1). Cross-sectional area changes varied with creek order and geomorphic position. The eastern main channel

TABLE 1. Cross-sectional area (Xc), bed level, and morphologic change in creeks. Cr = creek, P = marsh plain, M = mudflat, C = main channel, S = *Spartina*, and v = volunteer.

		Change from 2000 to 2003			Change from 2003 to 2004			Net change from 2000 to 2004		
Order	Transect (cell and habitat)	Xc area (m^2)	Bed level (m)	Morphologic change	Xc area (m^2)	Bed level (m)	Morphologic change	Xc area (m^2)	Bed level (m)	Morphologic change
Constructed creeks										
1°	1P	−0.04	0.03	Minimal	0.07	−0.02	Minimal	0.03	0.01	Minimal
1°	3P	0.03	0.05		0.18	−0.08	Scoured bed	0.21	−0.02	
1°	5P	0.21	−0.05		0.00	0.00	Minimal	0.21	−0.05	
3°	1M	−3.16	0.23	Cr fills	−0.06	−0.09	Levees developed, Scoured banks and bed	−3.21	0.13	Cr narrows and fills
3°	3M	−2.29	0.25		0.07	−0.12		−2.21	0.13	
3°	5M	−1.59	0.13	Scoured banks, bed fills	0.39	−0.15	Scoured banks and bed	−1.20	−0.02	Cr narrows
4°	OC	−0.45	0.13	Cr shifts laterally, bed fills	1.07	−0.10	Scoured banks and bed	0.62	0.03	Cr widens
4°	2C	−0.70	0.06		0.57	0.02		−0.14	0.07	Cr shifts laterally and fills
3°	4C	−1.14	0.16		0.04	−0.04	Minimal	−1.10	0.13	Cr narrows and fills
1°, 2°	6C	−1.41	0.35		0.41	−0.02	Scoured banks and bed	−1.00	0.32	
Volunteer										
1°	4Sv							0.22		Cr scours
2°	4Mv							0.71		
1°	2Mv							0.42		
1°	3Mv							0.42		
1°	$6Mv_1$							0.66		
1°	$6Mv_2$							0.34		

cross sections farthest from the mouth, near cells 4 and 6, experienced channel narrowing due to deposition from the adjacent unstable bank (net loss = 1.1 and 1.0 m^2, respectively in cells 4 and 6; Fig. 1). Main channel cross sections near the mouth (cells 0 and 2) experienced widening, lateral shifting, and filling (net change <0.65 m^2). Third-order creek cross sections in the mudflat also experienced narrowing and filling (losses ranged from 3.2 to 1.2 m^2; Table 1), and levees developed in later years (Fig. 7). Headwater cross sections on the marsh plain did not experience notable changes. Correlated with the loss in cross-sectional area, the creek bed levels increased in elevation, and sediment accumulation rates were three times higher than for mudflat, *Spartina*, and marsh plain combined ($p < 0.001$; mean = 13.4 ± 3.8 cm [n = 10] in creek beds versus 4.4 ± 0.43 cm [n = 68] on the marsh surface over 3 yr).

While filling of constructed creeks was widespread, we also witnessed some erosion. Ten creeks initiated voluntarily along the marsh margin and were first visible in 2002. By 2004, one volunteer creek elongated into a headwater area, and its cross-sectional area was 24% of that for constructed creeks in similar positions. The six volunteer creeks at the marsh margin averaged 14% of the cross-sectional area of constructed creek mouths (Table 1). Volunteer creeks were meandering dendritic (Wallace personal observation), a form typical of mudflats in natural systems (Allen 2000).

LENGTH AND DRAINAGE DENSITY

Total creek length increased from 5,020 to 6,160 m (Table 2), and overall drainage density increased 23% from 2000 to 2003, equaling that of the reference site (0.018–0.022 m m^{-2}; Desmond et al. 2000). We attribute this increase in density to the headward expansion of first-order and second-order constructed creeks and volunteer first-order creeks

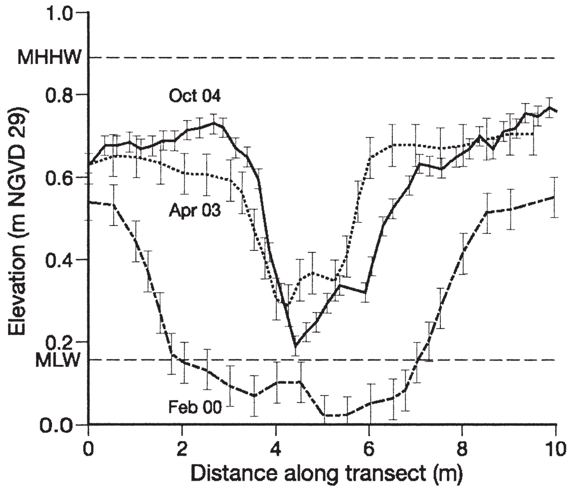

Fig. 7. Cross-sectional profiles from the creek mouth position in cell 1. This profile demonstrates how a constructed mudflat creek experienced filling, narrowing, and levee development from 2000 to 2004 (a total loss of 3.2 m^2 in cross-sectional area).

TABLE 2. Comparison of morphometry data between cells with and without creeks and in different habitats over 4 yr. Ch = main channel; it was designed to fourth-order dimensions but according to Strahler (1964), ranged from first to fourth along its length between 2000 and 2003. M = mudflat, S = *Spartina*, P = marsh plain. * North arm data from Desmond et al. 2000. ** Drainage density values are provided in ft ft^{-2} for comparison with Coats et al. (1995) design standard of 0.010 to 0.020 ft ft^{-2}.

Treatment	Date		Mean number of creeks	Mean length [m (± SE)]	Mean drainage density (m m^{-2})	Mean drainage density (ft ft^{-2})	Mean tidal prism (m^3)
		Order					
+Creek cells (n = 3)	2000	1°	14	13.22 (1.0)	0.032	0.010	2,805
		2°	5	17.7 (3.4)			
		3°	1	77.46*			
		Ch	1	65.8 (12.6)			
	2003	1°	13	17.3 (1.9)	0.034	0.010	2,185
		2°	4	22.1 (6.4)			
		3°	2	66.5 (14.1)			
		Ch	1	71.6 (14.1)			
−Creek cells (n = 3)	2000	1°	0	na	0.005	0.002	2,774
		2°	0	na			
		Ch	1	69.6 (5.8)			
	2003	1°	4	18.5 (6.8)	0.012	0.004	2,218
		2°	1	41.5*			
		Ch	1	86.4 (8.1)			
		Habitat					
+Creek cells (n = 3)	2000	M	6	12.1 (3.3)	0.019	0.006	
		S	7	11.0 (2.0)	0.027	0.008	
		P	6	20.7 (4.6)	0.016	0.005	
	2003	M	10	14.7 (2.2)	0.040	0.012	
		S	4	14.2 (1.9)	0.018	0.006	
		P	6	18.6 (2.2)	0.014	0.004	
−Creek cells (n = 3)	2000	M	0	0	0	0	
		S	0				
		P	0				
	2003	M	7	53.1 (8.3)	0.031	0.010	
		S	0				
		P	0				
Entire site	2000				0.018	0.005	18,340
	2003				0.022	0.007	14,630
North arm, Tijuana Estuary*					0.022	0.007	
Design standard**						0.010–0.020	

initiating at the marsh margin (Fig. 8). Cells with creeks experienced a mean increase in drainage density of 7% (from 0.032 to 0.034 m m^{-2}), with the greatest increase occurring in cells farthest from the mouth. Cells without creeks saw a mean increase of 140% (0.05 to 0.012 m m^{-2}), though total length remained much smaller than in +creek cells.

First-order creeks grew over time, with the total number increasing from 43 to 49 creeks and length increasing from 658 to 870 m. Second-order creeks decreased in total number (5 to 4) while increasing 69% in total length (266 to 460 m) and 82% in mean length (18 to 32 m). Third-order segments decreased in total and mean length (368 to 335 m and 92 to 84 m, respectively) due to filling in the third-order creek in cell 3. The main channel (designed to fourth-order capacity) did not change in length.

The change in segments varied across habitats for all cells. The mudflat habitat experienced an increase in number of segments (18 to 31), total segment length (715 to 1,494 m), and mean length (40 ± 10.9 to 48 ± 7.2 m). The number of segments and their lengths decreased in *Spartina* and marsh-plain habitats (Table 2).

TIDAL PRISM

Potential mean diurnal tidal prism was reduced from 18,340 to 14,630 m^3 due to sedimentation from 2000 to 2003. The majority of the tidal prism was on the marsh surface (15,802 and 12,548 m^3 in 2000 and 2003, respectively), rather than in the drainage network (2,538 versus 2,082 m^3 in 2000 and 2003, respectively). Most (88%) of the volume lost was attributed to sedimentation-induced increases in elevation of the marsh surface; while the remaining loss was attributed to filling in the main channel (accounting for 5% of the volume lost) and to filling of the tributaries on the marsh plain (based on two cross sections per cell, such filling contributed 7% of the volume lost). To calculate the effect of surface elevation changes on tidal prism, we assessed the portion of the surface that increased in elevation by

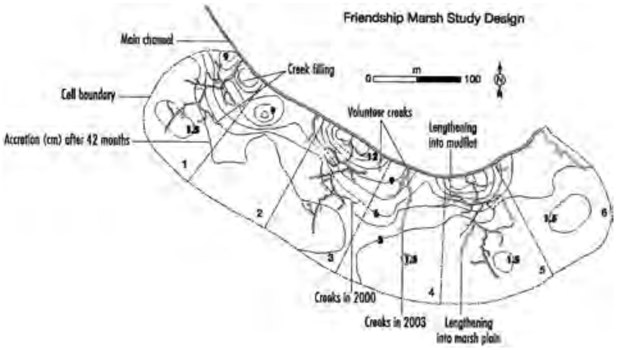

Fig. 8. Map of sediment accretion contours, changes to the constructed creeks, and volunteer creek formation. After 42 mo, the entire site accreted sediment ranging from 1.5 to 13.5 cm with highest levels occurring in mudflats and lowest levels on the marsh plain. Cells with creeks experienced both filling of constructed creek segments and lengthening in others. Cells without creeks gained volunteer creeks extending from the edge of the main channel into the mudflat.

a mean of 4.6 cm due to kelp amendments (7% of the site area), in combination with the remaining areas (93% of site area) that experienced compaction of 1.1 cm. We found that the calculated subsoil compaction would cause tidal prism changes to vary by 3.5% for the 3-yr period.

Compared to the equilibrium values of Williams et al. (2002; tidal prism = 7–15% the product of marsh area and diurnal tide range), the tidal prism at Friendship Marsh was 12% of the product of marsh area and diurnal tide range in 2000 and 10% in 2003. Using data of Entrix et al. (1991) for tidal range, area, and volume of Tijuana Estuary's north and south arms, we calculated reference tidal prisms that were 16% and 12%, respectively, of the product of marsh area and diurnal tide range.

MORPHOMETRY REGRESSIONS FOR CONSTRUCTED CREEK SYSTEMS

We observed that the third-order creek cross-sectional areas stabilized by 2003 (Fig. 6) and asked how the measured cross-sectional areas compared to regression equations of Williams et al. (2002). We found that 2003 tidal prisms for each constructed creek network predicted a range of cross-sectional areas that included the observed dimensions. Moderate tidal prism estimates where networks drained 40% of nearby cells (ranging from 1,377 to 2,235 m^3 per +creek network) predicted cross-sectional areas of 3.1–4.2 m^2 that closely matched the observed third-order tributary values of 3.2–3.9 m^2. Regression equations using minimum tidal prism values, where each creek network was limited to draining only 40% volume of the 1.3-ha area (prism ranging from 817 to 948 m^3), predicted cross-sectional areas of 2.2–2.4 m^2. Using maximum tidal prism estimates (where networks drained 100% volume of nearby cells, ranging from 3,444 to 5,588 m^3), we predicted third-order cross-sectional areas of 5.6–7.6 m^2. The drainage area regression equation (Williams et al. 2002) predicted a range of cross-sectional areas that included the measured values. Minimum drainage area estimates (1.3 ha-$cell^{-1}$) predicted creek mouth areas of 2.9 m^2 compared to the observed values of 3.2, 3.5, and 3.9 m^2. Maximum drainage area values (from 1.95 to 3.25 ha) predicted cross-sectional areas of 4.0–6.0 m^2.

When analyzing the cross-sectional areas of the fourth-order main channel outlet (transect 0C; Fig. 6), we observed that the channel area initially decreased but then continued to expand from 2000 to 2004, indicating that it had not reached equilibrium morphology. We compared the cross-sectional area values predicted by the regression equations of Williams et al. (2002) as a test to see how far away from an equilibrium dimension the channel might have been in 2003. A tidal prism of 14,630 m^3 for the entire site predicted a main channel fourth-order outlet area of 14.3 m^2 versus the measured value of 5.2 m^2. The entire site drainage area of 8.6 ha (8.0 ha for the marsh + 0.6 ha for the main channel) predicted a fourth-order main channel outlet area of 12.6 m^2 compared to the 5.2 m^2 measurement.

Discussion

Tidal creek networks are critical to the structure and functioning of coastal salt marshes (Pethick 1984; Allen 2000; Friedrichs and Perry 2001; Vivian-Smith 2001; Williams and Desmond 2001), yet only a few restoration projects have designed and excavated creeks (Minello et al. 1994; Simenstad and Thom 1996; Emmerson et al. 1997; Cornu and Sadro 2002; Eertman et al. 2002). Few projects have documented the dynamics of constructed creeks or formation of volunteer creeks (Coats et al. 1995; Williams et al. 2002). It remains unclear whether creeks need to be constructed or if volunteer creeks will attain geomorphic conditions comparable to reference sites. The rates of geomorphic evolution are also poorly known.

By designing our restoration site to include replicate cells with and without mimics of a naturally-occurring creek network, we were able to compare geomorphic development and state. Because the site experienced extreme sedimentation, we were able to evaluate resilience to disturbance with and without creeks. Our results for the first 5 yr indicate that the constructed creeks allowed the site to develop geomorphic characteristics (drainage density, tidal prism, and creek dimensions) that were comparable to the reference system. Cells with only volunteer creeks developed much lower drainage density and established tidal creek circulation only in the low-elevation habitats. By examining additional factors that contribute to drainage network evolution, we discuss how reference site geomorphic conditions may be achieved.

TIDAL CREEK DEVELOPMENT

Cross-sectional area measurements indicated that excavated creek profiles initially contracted and then stabilized at values closely matching those predicted by regression equations. We discuss how tributaries of different order approached equilibrium dimensions at varying rates according to flows and sediment load. While creek profiles were stabilizing, the drainage network increased in length and density.

Previous authors have observed that newly excavated channels respond to hydraulic forces by slumping and filling as they adjust toward equilibrium morphologies (Coats et al. 1995; Haltiner et al. 1997; Zeff 1999; Eertman et al. 2002; Thom et al. 2002). At Friendship Marsh, the eastern section of the main channel experienced filling that we attribute to slumping of unstable bank materials and also over-sized fourth-order dimensions, where second-order dimensions would have served the small drainage area (1.3 ha). Slumped material in the main channel bed was likely reworked throughout the site and combined with heavy sediment loading from the local subwatershed, resulting in initial accumulation in the excavated creek networks. In San Francisco Bay, Williams et al. (2002) described existing, rapidly evolving channels that moved toward equilibrium morphologies in 4–13 yr. After the third-order and fourth-order tributaries in Friendship Marsh filled with sediment, they stabilized at cross-sectional areas matching, or on a trajectory toward, equilibrium values predicted by regression equations developed from natural salt marshes of California. At Friendship Marsh, adjustment periods increased with creek order, with first-order tributaries on the marsh plain stable throughout the study, third-order creek mouths stabilizing after 6 mo, and the western section of the main channel steadily increasing in area over the 5-yr period. Cross-sectional areas of properly designed and excavated creeks (third order and lower) stabilized within 6 mo.

The increased time required for higher order creeks to reach stabilized cross sections is supported by the work of Friedrichs and Perry (2001), who indicate that smaller creeks are generally more dynamic and that the evolution rate of creek cross sections decreases with increasing channel size. Recent modeling indicates that the development of creek cross-sectional area is controlled by the balance of sedimentation and erosion related to spring tide ebb and flood flows and the autoconsolidation of cohesive sediments that limit downward cutting (Fagherazzi and Furbish 2001). Flood tides introduce sediment to creek networks (Pestrong 1972; Christiansen et al. 2000; Voulgaris and Meyers 2004) and, in Friendship Marsh, loads are likely highest when a storm event combines fluvial flows with tidal flows. During such floods, high velocity flows would carry sediments from the main channel into creek beds. When flood flows overtopped creek banks, sediments would be redistributed to the marsh surface. In the first 5 yr, first-order tributaries likely experienced minimal cross-sectional changes compared to third-order tributaries, because they received fewer flood flows that would deposit sediment and cause filling and experienced less frequent inundation and more frequent exposure, which would increase cohesiveness of the creek bed and limit down-cutting. Filling of third-order tributaries continued for 6 mo until equilibrium dimensions were reached between the flood tide sedimentation and the ebb tide erosion. The main channel took longer to adjust, since coarse bed load sediments (observed in sandbars and ripples; Wallace personal observation) took longer to flush out of the site and the deepening of the channel was likely constrained by baselevels imposed by larger tidal inlets (French and Stoddart 1992).

Is it necessary to excavate an entire creek network? Based on data from third-order systems along the California coast, Coats et al. (1995) hypothesized that constructing 80% of the drainage network would allow the remaining 20% to develop volunteer first-order creeks. Following the initial contraction in our fourth-order system, the constructed and volunteer creeks elongated 23% in just 4 yr, primarily through first-order creek elongation. Drainage density increased from 2000 to 2003 to the level of our reference system (Table 2, Fig. 8). We attribute the high drainage density to constructed creeks that established higher baseline values and natural creek development that occurred via slumping and headward elongation (Gabet 1998; Friedrichs and Perry 2001). We agree with Coats et al. (1995) that creeks readily form and extend on their own when adjacent to an excavated fourth-order channel or third-order creek network. Decisions to excavate fewer, larger creeks versus an entire creek network should rely on project goals and also site characteristics that affect creek elongation.

Topographic and hydraulic gradients, sediment texture (Zeff 1999), and vegetation cover (Garofalo 1980) all affect creek elongation rates, according to several studies. Positive topographic gradients affected creek size in an experimental restoration in Coos Bay, Oregon (Cornu and Sadro 2002). We observed similar patterns; constructed creeks elongated headward and volunteer creeks initiated primarily in the mudflat where a steep topographic and associated hydraulic gradient occurred between the mudflat and the main channel bed. Sediment texture affects both shear strength and water content (Crooks and Pye 2000; Crooks et al. 2002), and sandy reference systems are known to reach maximum channel densities sooner than finer sediment systems (Allen 2000). The parent substrate at the Friendship Marsh was dominated by sands (62% sands, 38% fines; Thorbjarnarson and Stuart 1998) while material accumulating on the marsh surface was finer (15% sand, 65% silt, and 20% clay at 0–2 cm depths). Textures at the reference site were even finer (0–10 cm depths were 66–71% clay, 24–26% silt, and 4–20% sand; Weis et al. 2001; Ward et al. 2003). Differences in texture are likely due to geomorphic position; the reference site receives sediment from Tijuana River and a gently sloping floodplain, while Friendship Marsh receives coarse sediment from a local watershed with highly-erodible slopes (Battalio and DeTemple 1998; Elwany et al. 2003). Given its coarse parent substrate, Friendship Marsh might exceed the drainage density of the reference site over time, although the evolution rate will slow as fine sediments accrete and the marsh surface elevates, according to models depicting the dynamic equilibrium of young marshes (Pethick 1981; French and Stoddart 1992; Allen 2000). Expanding vegetation will also affect future creek development as it binds sediments, slows erosion, reduces lateral migration of creeks, and dissipates flows (Ward et al. 1984; Gabet 1998; Micheli et al. 2002; Lawrence et al. 2004). Creeks typically originate in tidal flats as the ebb tidal flow incises mud and sedimentation on mudflats elevates creeks to a level where vegetation stabilizes flats (Pestrong 1965; Allen 2000). At Friendship Marsh, we observed that the longest volunteer creek (65 m in length) elongated through sparse *Spartina* habitat (4-m spaced plantings). Other biota might have contributed to tidal creek erosion, as found for polychaetes in southeast England (Morris et al. 2004; Paramor and Hughes 2004), crabs in Argentina (Perillo 2003), and decapods in eastern U.S. (Letzsch and Frey 1980). In our study, development of constructed and volunteer creeks followed patterns described for other marshes such that initiation and elongation occurred in the low elevations in conjunction with high gradients and according to vegetation cover and bioturbators, although we lack data on the latter.

FACTORS AFFECTING MARSH SURFACE AND TIDAL PRISM CHANGE

On the marsh surface, accretion occurred at high magnitudes in winter and continued at lower levels through all seasons from 2000 to 2004 (Fig. 3). Peak and long-term rates were comparable to those at the north arm reference site (9.5 cm per storm season in this site versus 1.9–12.7 cm in the north arm; Ward et al. 2003; and long-term rates of 1.3 in this study versus 0.71–1.23 cm yr^{-1} in the north arm; Weis et al. 2001). We attribute high sedimentation rates to abundant sediment sources and settling lag effects, discussed below.

Following other work (Hatton et al. 1983; French and Spencer 1993; Callaway et al. 1997), we observed that sedimentation decreased with increasing elevation (Fig. 4). Rising tides inundated the mudflat, and flood flows likely lost power as they reached higher elevations, so less sediment was accreted in *Spartina* and marsh-plain habitats (Christiansen et al. 2000; Voulgaris and Meyers 2004). Flood flows spilling over creek banks can develop levees at creek edges (Letzsch and Frey 1980), but we did not observe this until yr 5 (Fig. 7). Still, areas distant from creek margins were not significantly affected by the presence or absence of a creek network within the cell ($p = 0.23$ at the 6-mo level). This result agrees with the finding of Reed et al. (1999) that sedimentation decreased an order of magnitude within 20 m of creek edge.

Constructed creeks did not directly affect sedimentation at marker horizons, but there was an interaction with habitat type. While shallow flows across the marsh surface can be highly complex and time dependent (Lawrence et al. 2004), the differences we found in sediment deposition between mudflat and *Spartina* habitats in +creek versus −creek cells (2.6 versus 0.8 cm and 1.9 versus 1.2 in 12 mo, respectively) can be explained by drainage patterns. Mudflats in +creek cells experienced flood flows from two sources and directions (creek banks and marsh margin), while mudflats in −creek cells primarily received flows from the marsh margin. Greater volumes of water meeting on the mudflats adjacent to creeks deposited more sediment, which may have depleted the suspended load before flows inundated the *Spartina* habitat. Because habitats in −creek cells received flow from only one direction, the sedimentation gradient from low to high elevations was gentler (Fig. 4).

As with creek elongation rates, high sedimentation rates were likely accentuated by the texture of local sediment sources. Net deposition of material indicates that ebb tides were not strong enough to flush out the sediments brought in during floods (Pethick 1980; Schostak et al. 2002); this tidal discharge asymmetry has a long-term influence on the transport of sediment in natural marshes (Myrick and Leopold 1963; Boon 1975; French and Spencer 1993). According to Postma (1961), net accretion increases as particles react slowly to velocity changes, and they are transported further in the flood direction than would be the case if settling were instantaneous. Particles brought in with flood tides can settle in places where the ebb tides are too weak to carry them away. Sediments at the sand-silt boundary that characterize Friendship Marsh are especially susceptible to such lag effects, as demonstrated by sedimentation in the Gradyb tidal area of western Denmark (Bartholdy 2000). Compared to finer particles, higher velocities are necessary to carry sand and silt, and these high velocity flows can project particles further into the marsh, where they are not easily resuspended (Bartholdy 2000).

Changes induced by wind-wave activity can also substantially affect geomorphic development in restoration sites (Williams and Orr 2002). At Friendship Marsh, resuspension events occurred in all habitats but most often in the marsh plain (27 versus 18 versus 22 events for marsh plain, *Spartina*, and mudflat, respectively). We interpret this pattern of resuspension to wind waves as opposed to tidal currents, because strong tidal currents were lacking in the marsh plain (Mickelson personal communication). Wave-induced bed shear stress is a function of wave power; it depends on fetch length, wind velocity, and the inverse of water depth (USACE 1984). Shallow water depths in the marsh plain were more vulnerable to resuspension than deeper *Spartina* and mudflat areas; the marsh plain was mostly devoid of vegetation that would have reduced resuspension. The prevailing winds blow west to east, and transportation of material by wind-driven waves was evidenced by higher accumulations of wrack in eastern cells (Morzaria-Luna 2004). We would expect wave energy to increase with fetch length from west to east over the site, and this corresponds with the higher frequency of resuspension events observed in the eastern cells (15% and 19% frequency in cells 5 and 6, respectively). Wind speeds, water depth, and fetch at Friendship Marsh are capable of generating waves on the marsh plain that could resuspend local sediment. With mean wind speeds of 12.1 km h^{-1} west northwest (San Diego-Lindbergh field unpublished data), water levels ranging from 0.0 to 0.8 m (2001–2003; NERR 2005), and average wind fetch of 500 m, wind waves on the marsh plain would be generated at heights and associated velocities that exceed the threshold necessary to resuspend individual silt and sand grains. The range of wave heights generated at the study area was 0.1 to 0.19 m with a period of 0.65–1.17 s. Resuspension of sand particles < 0.15 mm would require a wave height of 0.09 m in the maximum period and water depth (1.17 s and 0.8 m, respectively; USACE 1984). We lack data on suspended sediment, but it is possible that resuspension of clay particles (as opposed to flocs) would occur first, and once suspended, such particles could be transported off-site by the gentlest of tidal flows (Letzsch and Frey 1980), explaining the scarcity of clay-sized particles on the sparsely vegetated marsh plain. Resuspension was more commonly documented in summer periods and might be explained by increased bioturbation of sediment left from winter storms (Letzsch and Frey 1980).

We link resuspension processes to the formation of pools throughout the site. Pools would be accentuated where wrack deposition impedes drainage. Because plants dissipate wave energy and bind sediment (Ward et al. 1984; Onuf 1987; Van Proosdij 2000), resuspension was lower in the *Spartina* habitat and more frequent in bare areas on the marsh plain and mudflat. We attribute the formation of large marsh-plain pools in the eastern cells (Fig. 1) to higher resuspension frequency and net transport of clay off-site.

Although the tidal prism was sustained within a range of reference system values during the study, the volume between the marsh surface and MHHW did decrease as sedimentation and elevation increased. The volume will likely continue to decrease, but we expect the marsh surface to build until the shortened period of inundation limits sedimentation, leading to a stable marsh surface elevation below the highest annual tide. The time to stabilization will depend on the rate of sea-level rise, sediment inputs, plant matter accumulation, and autocompaction (Pethick 1981; Allen 2000). Because creek network size and complexity are an increasing function of the marsh surface height and age (Allen 2000), we might also expect loss of marsh surface tidal prism to be compensated by increased creek volume (Haltiner personal communication). It appears that creek drainage density and the cross-sectional area of the fourth-order creeks were expanding to compensate for lost volume on the marsh surface. Simultaneously, vegetation and biogenic processing of the surface were increasing roughness, thereby increasing lateral flow to the creeks as they elongated (Lawrence et al. 2004). Creek elongation would allow an increasing proportion of the marsh surface tidal prism to be routed through creeks instead of the marsh margin. As indicated by French and Stoddart (1992), elongation of creeks is most rapid during early phases of marsh development, and by maturity most of the prism is in a stable creek network. While the cross-sectional areas of third-order creeks did not increase, they might in the future, depending on sedimentation, storms, changes in roughness of the marsh surface, and tidal circulation. Despite recent modeling of creek cross-sectional development (Fagherazzi and Furbish 2001), further field research is needed to understand how marsh surface tidal prism affects the development of tidal creek networks in restoration settings.

RECOMMENDATIONS

A key first step in planning for restoration of tidal wetlands is to identify factors that will affect geomorphic development. Sedimentation and resuspension will affect creek dimensions, tidal prism, pool formation, and levee development. Relative elevation, grain sizes, and vegetation will affect the location and rate of elongation of tidal creeks. It is not sufficient to focus on biological targets and physical characteristics of reference sites.

Plans for creek excavation should be directed toward establishing a basic creek template for elongation and accelerating creek development in higher elevation areas where they are less likely to develop on their own compared to the mudflat position. By comparing ±creeks cells, we observed that volunteer creeks in −creek cells did not achieve restoration targets for drainage density and creek dimensions within 5 yr. If we had not excavated creeks, volunteer creeks would likely have formed along the marsh margin but would not have elongated onto the marsh plain. In a setting where catastrophic sedimentation events were likely, the worst-case scenario might have been the development of a fine-grained levee at the marsh margin that severely limited tidal flushing across the marsh surface. To enhance restoration site functioning, creeks need to be built into restoration sites or at least jump-started.

To encourage creek elongation in higher elevations, we recommend leaving unplanted corridors, where erosion can occur without encountering roots and rhizomes. Elevation gradients and vegetation plantings can be manipulated to promote creek elongation through careful grading and the use of kelp amendments. Surface elevation data indicated that kelp amendments reduced the bulk density of the soil and accelerated *Spartina* growth (O'Brien and Zedler in press), counteracting compaction processes dominating elsewhere (Fig. 5).

We encourage others to document creek and channel dimensions, drainage density, sedimentation, resuspension, and elevation change to increase the understanding of how restored ecosystems develop over time. We also encourage the design of projects to support adaptive restoration, wherein options can be tested in an experimental framework. Tidal creeks support habitat and biological diversity (Coats et al. 1995; Madon et al. 2001; Morzaria-Luna et al. 2004), and the excavation of tidal creek networks can aid the development of a drainage network comparable to reference systems.

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LITERATURE CITED

ALLEN, J. R. L. 2000. Morphodynamics of Holocene salt marshes: A review sketch from the Atlantic and Southern North Sea coasts of Europe. *Quaternary Science Reviews* 19:1155–1231.

BARTHOLDY, J. 2000. Processes controlling import of fine-grained sediment to tidal areas: A simulation model, p. 13–30. *In* K. Pye and J. R. L. Allen (eds.), Coastal and Estuarine Environments: Sedimentology, Geomorphology, and Geoarchaeology, Volume 175. Geological Society, Special Publications, London, U.K.

BATTALIO, R. AND B. DETEMPLE. 1998. The Preliminary Feasibility of a Conceptual Sediment Management and Enhancement Plan for Goat Canyon Creek. Philip Williams and Associates, Corte Madera, California.

BAYLISS-SMITH, T. P, R. HEALEY, R. LAILEY, T. SPENCER, AND D. R. STODDART. 1979. Tidal flows in salt marsh creeks. *Estuarine and Coastal Marine Science* 9:235–255.

BOON, III, J. D. 1975. Tidal discharge asymmetry in a salt marsh drainage system. *Limnology and Oceanography* 20:71–80.

BOUMANS, R. M. J. AND J. W. DAY. 1993. High precision measurements of sediment elevation in shallow coastal areas using a sedimentation-erosion table. *Estuaries* 16:375–380.

CAHOON, D. R., J. C. LYNCH, AND A. N. POWELL. 1996. Marsh vertical accretion in a southern California estuary, U.S.A. *Estuarine Coastal and Shelf Science* 43:19–32.

CAHOON, D. R. AND R. E. TURNER. 1989. Accretion and canal impacts in a rapidly subsiding wetland. II. Feldspar marker horizon technique. *Estuaries* 12:260–268.

CALLAWAY, J. C. 2001. Hydrology and substrate, p. 89–118. *In* J. B. Zedler (ed.), Handbook for Restoring Tidal Wetlands. CRC Press, Boca Raton, Florida.

CALLAWAY, J. C., R. D. DELAUNE, AND W. H. PATRICK, JR. 1997. Sediment accretion rates from four coastal wetlands along the Gulf of Mexico. *Journal of Coastal Research* 13:181–191.

CALLAWAY, J. C., G. SULLIVAN, AND J. B. ZEDLER. 2003. Species-rich plantings increase biomass and nitrogen accumulation in a wetland restoration experiment. *Ecological Applications* 13: 1626–1639.

CALLAWAY, J. C. AND J. B. ZEDLER. 2004. Restoration of urban salt marshes: Lessons from southern California. *Urban Ecosystems* 7:133–150.

CHRISTIANSEN, T., P. L. WIBERG, AND T. G. MILLIGAN. 2000. Flow and sediment transport on a tidal salt marsh surface. *Estuarine Coastal and Shelf Science* 50:315–331.

Coats, R. N., P. G. Williams, C. K. Cuffe, J. B. Zedler, D. Reed, S. M. Waltry, and J. S. Stratton Noller. 1995. Design guidelines for tidal channels in coastal wetlands. Prepared for U.S. Army Corps of Engineers Waterways Experiment Station. Phillip Williams and Associates, Ltd. Report #934. San Francisco, California.

Cornu, C. and S. Sadro. 2002. Physical and functional responses to experimental marsh surface elevation manipulation in Coos Bay's South Slough. *Restoration Ecology* 10:474–486.

Crooks, S. and K. Pye. 2000. Sedimentological controls on the erosion and morphology of salt marshes: Implications for flood defence and habitat recreation, p. 207–222. *In* K. Pye and J. R. L. Allen (eds.), Coastal and Estuarine Environments: Sedimentology, Geomorphology, and Geoarchaeology, Volume 175. Geological Society, Special Publications, London, U.K.

Crooks, S., J. Schutten, G. D. Sheern, K. Pye, and A. J. Davy. 2002. Drainage and elevation as factors in the restoration of salt marsh in Britain. *Restoration Ecology* 10:591–602.

D'Alpaos, A., S. Lanzoni, M. Marani, S. Fagherazzi, and A. Rinaldo. 2005. Tidal network ontogeny: Channel initiation and early development, Volume 110. *Journal of Geophysical Research* F02001, doi:10.1029/2004JF000182.

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

Eertman, R. H. M., B. A. Kornman, E. Stikvoort, and H. verBeek. 2002. Restoration of the Sierperda tidal marsh in the Scheldt Estuary, the Netherlands. *Restoration Ecology* 10:438–449.

Elwany, H., D. Hansen, N. Marshall, R. McCreight, K. Marshall, and M. Jilka. 2003. Tijuana Estuary Model Marsh Sedimentation and Hydraulic Evaluation. Coastal Environments, CE No. 03-02, La Jolla, California.

Emmerson, R. H. C., J. M. A. Manatunge, C. L. Macleod, and J. N. Lester. 1997. Tidal exchanges between Orplands managed retreat site and the Blackwater estuary, Essex. *Journal of Water and Environmental Management* 11:363–372.

Entrix Inc., Pacific Estuarine Research Laboratory and Philip Williams and Associates, Ltd. 1991. Tijuana Estuary tidal restoration program. Draft Environmental Impact Report and Environmental Impact Statement. Volume 1–3. State Coastal Conservacy, Oakland, California.

Fagherazzi, S. and D. J. Furbish. 2001. On the shape and widening of salt marsh creeks. *Journal of Geophysical Research* 106:991–1003.

Fagherazzi, S., E. J. Gabet, and D. J. Furbish. 2004. The effect of bidirectional flow on tidal channel planforms. *Earth Surface Processes and Landforms* 29:295–309.

French, J. R. and T. Spencer. 1993. Dynamics of sedimentation in a tide-dominated backbarrier saltmarsh, Norfolk, U.K. *Marine Geology* 110:315–331.

French, J. R. and D. R. Stoddart. 1992. Hydrodynamics of salt marsh creek systems: Implications for marsh morphological development and material exchange. *Earth Surface Processes and Landforms* 17:235–252.

Friedrichs, C. T. and J. E. Perry. 2001. Tidal salt marsh morphodynamics: A synthesis. *Journal of Coastal Research* 27:7–37.

Gabet, E. J. 1998. Lateral migration and bank erosion in a salt marsh tidal channel in San Francisco Bay, California. *Estuaries* 21:745–753.

Garofalo, D. 1980. The influence of wetland vegetation on tidal stream channel migration and morphology. *Estuaries* 3:258–270.

Gee, G. W. and J. W. Bauder. 1986. Particle-size analysis, p. 383–411. *In* A. Klute (ed.), Methods of Soil Analysis: Part I: Physical and Mineralogical Methods. American Society of Agronomy, Madison, Wisconsin.

Greer, K. and D. Stow. 2003. Vegetation type conversion in Los Peñasquitos Lagoon, California: An examination of the role of watershed urbanization. *Environmental Management* 31:489–503.

Haltiner, J., J. B. Zedler, K. E. Boyer, G. D. Williams, and J. C. Callaway. 1997. Influence of physical processes on the design, functioning, and evolution of restored tidal wetlands in California (USA). *Wetlands Ecology and Management* 4:73–92.

Hatton, R. S., R. D. DeLaune, and W. H. Patrick, Jr. 1983. Sedimentation, accretion, and subsidence in marshes of Barataria Basin, Louisiana. *Limnology and Oceanography* 28: 494–502.

Horton, R. E. 1945. Erosional development of streams and their drainage basins; hydrophysical approach to quantitative morphology. *Bulletin of the Geological Society of America* 56:275–370.

Keer, G. H. and J. B. Zedler. 2002. Salt marsh canopy architecture differs with the number and composition of species. *Ecological Applications* 12:456–473.

Lawrence, D. S. L., J. R. L. Allen, and G. M. Havelock. 2004. Salt marsh morphodynamics: An investigation of tidal flows and marsh channel equilibrium. *Journal of Coastal Research* 20: 301–316.

Letzsch, W. S. and R. W. Frey. 1980. Deposition and erosion in a Holocene salt marsh, Sapelo Island, Georgia. *Journal of Sedimentary Petrology* 50:529–542.

Madon, S. P., J. West, and J. B. Zedler. 2002. Responses of fish to topographic heterogeneity in an experimental marsh (California). *Ecological Restoration* 20:56–58.

Madon, S. P., G. D. Williams, J. M. West, and J. B. Zedler. 2001. The importance of marsh access to growth of the California killifish, *Fundulus parvipinnis*, evaluated through bioenergetics modeling. *Ecological Modelling* 136:149–165.

Micheli, E. R. and J. W. Kirchner. 2002. Effects of wet meadow riparian vegetation on streambank erosion. *Earth Surface Processes and Landforms* 27:687–697.

Minello, T. J., R. J. Zimmerman, and R. Medina. 1994. The importance of edge for natant macrofauna in a created salt marsh. *Wetlands* 14:184–198.

Morris, R. K. A., I. S. Reach, M. J. Duffy, I. S. Collins, and R. N. Leafe. 2004. Forum: On the loss of saltmarshes in south-east England and the relationship with *Nereis diversicolor*. *Journal of Applied Ecology* 41:787–791.

Morzaria-Luna, H. 2004. Determinants of plant species assemblages in the California marsh plain: Implications for restoration of ecosystem function. Ph.D. Dissertation, University of Wisconsin, Madison, Wisconsin.

Morzaria-Luna, H., J. C. Callaway, G. Sullivan, and J. B. Zedler. 2004. Relationships between topographic heterogeneity and vegetation patterns in a Californian salt marsh. *Journal of Vegetation Science* 14:523–530.

Munk, W. 2003. Ocean-freshening, sea level rising. *Science* 300: 2041–2043.

Myrick, R. M. and L. B. Leopold. 1963. Hydraulic geometry of a small tidal estuary. Geological survey professional paper 422-B:B1-B18. U.S. Government Printing Office, Washington, D.C.

O'Brien, E. and J. B. Zedler. 2005. Accelerating the restoration of vegetation in a southern California salt marsh. *Wetlands Ecology and Management* in press.

Onuf, C. P. 1987. The Ecology of Mugu Lagoon, California: An Estuarine Profile. Biological, U.S. Department of Interior, Fish and Wildlife Service, National Wetlands Research Center, Report 85 (7.15). Washington, D.C.

Paramor, O. A. L. and R. G. Hughes. 2004. The effects of bioturbation and herbivory by the polychaete *Nereis diversicolor* on loss of saltmarsh in south-east England. *Journal of Applied Ecology* 41:449–463.

Perillo, G. M. E. 2003. New mechanisms studied for creek formation in tidal flats: From crabs to tidal channels. *Eos Transactions American Geophysical Union* 84:1–5.

Pestrong, R. 1965. The development of drainage patterns on tidal marshes. *Stanford University Publications, Geological Sciences* 10:1–87.

Pestrong, R. 1972. Tidal-flat sedimentation at Cooley Landing, southwest San Francisco Bay. *Sedimentary Geology* 8:251–288.

PETHICK, J. S. 1980. Velocity surges and asymmetry in tidal channels. *Estuarine and Coastal Marine Science* 11:331–345.

PETHICK, J. S. 1981. Long-term accretion rates on tidal salt marshes. *Journal of Sedimentary Petrology* 51:571–577.

PETHICK, J. S. 1984. An Introduction to Coastal Geomorphology. Butler and Tanner Ltd, Frome Somerset, U.K.

POSTMA, H. 1961. Transport and accumulation of suspended matter in the Dutch Wadden Sea. *Netherlands Journal of Sea Research* 1:148–190.

PYE, K. AND J. R. L. ALLEN. 2000. Past, present, and future interactions, management challenges and research needs in coastal and estuarine environments, p. 1–4. *In* K. Pye and J. R. L. Allen (eds.), Coastal and Estuarine Environments: Sedimentology, Geomorphology, and Geoarchaeology, Volume 175. Geological Society, Special Publications, London, U.K.

REED, D. J., T. SPENCER, A. L. MURRAY, J. R. FRENCH, AND L. LEONARD. 1999. Marsh surface sediment deposition and the role of tidal creeks: Implications for created and managed coastal marshes. *Journal of Coastal Conservation* 5:81–90.

SCHOELLHAMER, D. H. 1996. Factors affecting suspended-solids concentrations in south San Francisco Bay, California. *Journal of Geophysical Research* 101:12087–12095.

SCHOSTAK, L. E., R. G. D. DAVIDSON-ARNOTT, J. OLLERHEAD, AND R. A. KOSTASCHUK. 2002. Patterns of flow and suspended sediment concentration in a macrotidal saltmarsh creek, Bay of Fundy, Canada, p. 59–74. *In* K. Pye and J. R. L. Allen (eds.), Coastal and Estuarine Environments: Sedimentology, Geomorphology and Geoarchaeology, Volume 175. Geological Society, Special Publications, London, U.K.

SHIDELER, G. L. 1984. Suspended sediment responses in a wind-dominated estuary of the Texas Gulf Coast. *Journal of Sedimentary Petrology* 54:731–745.

SIMENSTAD, C. A. AND R. M. THOM. 1996. Functional equivalency trajectories of the restored Gog-Le-Hi-Te estuarine wetland. *Ecological Applications* 6:38–58.

STRAHLER, A. N. 1964. Quantitative geomorphology of drainage basins and channel networks, p. 439–476. *In* V. T. Chow (ed.), Handbook of Applied Hydrology. McGraw-Hill, New York.

THOM, R. G., R. ZEIGLER, AND A. B. BORDE. 2002. Floristic development patterns in a restored Elk River estuarine marsh, Grays Harbor, Washington. *Restoration Ecology* 10:487–498.

THORBJARNARSON, K. AND S. STUART. 1998. Sediment grain size characterization for the Model Marsh region of the Tijuana Estuary. Department of Geological Sciences, San Diego State University, San Diego, California.

THRUSH, S. F., J. E. HEWITT, V. J. CUMMINGS, J. I. ELLIS, C. HATTON, A. LOHRER, AND A. NORKKO. 2004. Muddy waters: Elevating sediment input to coastal estuarine habitats. *Frontiers in Ecology* 2:299–306.

U.S. Army Corps of Engineers (USACE), Waterways Experiment Station. 1984. Shore protection manual. Volume 1. U.S. Government Printing Office, Washington, D.C.

VAN PROOSDIJ, D., J. OLLERHEAD, AND R. G. D. DAVID-ARNOTT. 2000. Controls on suspended sediment deposition over single tidal cycles in a macrotidal saltmarsh, Bay of Fundy, Canada, p. 43–58. *In* K. Pye and J. R. L. Allen (eds.), Coastal and Estuarine Environments: Sedimentology, Geomorphology and Geoarchaeology, Volume 175. Geological Society, Special Publications, London, U.K.

VIVIAN-SMITH, G. 2001. Developing a framework for restoration, p. 39–88. *In* J. B. Zedler (ed.), Handbook for Restoring Tidal Wetlands. CRC Press, Boca Raton, Florida.

VOULGARIS, G. AND S. MEYERS. 2004. Temporal variability of hydrodynamics, sediment concentration and sediment settling velocity in a tidal creek. *Continental Shelf Research* 24:1659–1683.

WARD, K. M., J. C. CALLAWAY, AND J. B. ZEDLER. 2003. Episodic colonization of an intertidal mudflat by native cordgrass (*Spartina foliosa*) at Tijuana Estuary. *Estuaries* 26:116–130.

WARD, L. G., W. M. KEMP, AND W. R. BOYNTON. 1984. The influence of waves and seagrass communities on suspended particulates in an estuarine embayment. *Marine Geology* 10:85–103.

WEIS, D. A., J. C. CALLAWAY, AND R. M. GERSBERG. 2001. Vertical accretion rates and heavy metal chronologies in wetland sediment of the Tijuana Estuary. *Estuaries* 24:840–850.

WILLIAMS, G. D. AND J. S. DESMOND. 2001. Restoring assemblages of invertebrates and fishes, p. 235–270. *In* J. B. Zedler (ed.), Handbook for Restoring Tidal Wetlands. CRC Press, Boca Raton, Florida.

WILLIAMS, P. B. AND M. K. ORR. 2002. Physical evolution of restored breached levee salt marshes in the San Francisco Bay estuary. *Restoration Ecology* 10:527–542.

WILLIAMS, P. B., M. K. ORR, AND N. J. GARRITY. 2002. Hydraulic geometry: A geomorphic design tool for tidal marsh channel evolution in wetland restoration projects. *Restoration Ecology* 10:577–590.

ZEDLER, J. B. 1982. The Ecology of Southern California Coastal Salt Marshes: A Community Profile. U.S. Fish and Wildlife Service, FWS/OBS-81/54, Washington, D.C.

ZEDLER, J. B. (ed.). 2001, Handbook for Restoring Tidal Wetlands. CRC Press, Boca Raton, Florida.

ZEDLER, J. B., J. C. CALLAWAY, AND G. SULLIVAN. 2001. Declining biodiversity: Why species matter and how their functions might be restored in Californian tidal marshes. *BioScience* 51: 1005–1017.

ZEDLER, J. B., C. S. NORDBY, AND B. E. KUS. 1992. The Ecology of Tijuana Estuary: A National Estuarine Research Reserve. National Oceanic and Atmospheric Administration Office of Coastal Resource Management, Sanctuaries and Reserves Division, Washington, D.C.

ZEFF, M. L. 1999. Salt marsh tidal channel morphometry: Applications for wetland creation and restoration. *Restoration Ecology* 7:205–211.

SOURCES OF UNPUBLISHED MATERIALS

ELWANY, H. unpublished data. Coastal Environments, Inc. 2166 Avenida de la Playa, Suite E, La Jolla, California 92037.

HALTINER, J. personal communication. Geomorphologist, Philip Williams and Associates, Inc. 720 California Street, 6th Floor, San Francisco, California 94108-2404.

KNOX, J. unpublished data. PSA4, program for particle size analysis. Geomorphology Laboratory, Department of Geography, 550 N Park Street, Madison, Wisconsin 53706-1491.

MICKELSON, D. personal communication. Department of Geology and Geophysics, University of Wisconsin, 1215 W Dayton Street, Madison, Wisconsin 53706-1692.

National Estuarine Reserve Centralized Data Management Office (NERR). 2005. unpublished data. cdmo.baruch.sc.edu/Maps/TJRMap.htm

San Diego-Lindbergh field, California. 1999–2002. unpublished data. Monthly average wind speeds. www.wrcc.dri.edu/htmlfiles/westwind.final.html

RAMSAR. 2005. unpublished data. Ramsar list. www.ramsar.org.

Rick Engineering Inc. 2003. unpublished data. Digital imagery. 5620 Friars Road, San Diego, California 92110.

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