

## DRAINAGE CHANNEL DESIGN AND RESTORATION OF INTER-TIDAL MARSHES

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**ABSTRACT:** Geomorphologically, inter-tidal salt marshes are vegetated landforms at elevations slightly greater than mean tidal levels that have distributed channels formed under ebb (drainage) tidal flows that widen and deepen in the seaward direction. The drainage channels enable tidal flows to circulate sediments and nutrients through the marsh system during normal tidal events, while depositing sediments during storm or seismic events. This dynamic system encourages considerable biodiversity while simultaneously providing water quality enhancement features that service marsh terrestrial life and estuary marine life. Reservoir creation, limiting sediment supply, sea level rise as well as agricultural and urban development have resulted in significant loss of inter-tidal marshes and subsequent adverse impacts on waterfowl, infauna and fisheries. The complex and continuously changing marsh channel hydraulics and sedimentary processes have severely constrained quantitative modeling of marsh systems such that restoration/creation efforts remain an empirical science.

The purpose of this paper is to outline current understanding of salt marsh hydrodynamics, sediment accretion processes and subsequent response of marsh vegetation to set the stage for discussion of a marsh restoration/creation effort in San Pablo Bay near San Francisco, California. Several kilometers of drainage channels were constructed in a 410 ha disturbed salt marsh to restore tidal circulation and vegetation so as to enhance habitat for threatened species (e.g. clapper rail, salt marsh harvest mouse, delta smelt and anadromous fish species). Two distinct drainage channel systems ("east" and "west") were installed having similar channel dimensions common to salt marshes in the region, but having design bankfull tidal prism volumes that differed by a factor of two. Following excavation of the channels, main channel tidal flows and sediment loads as well as marsh sediment accretion rates were monitored to assess the relative success of the channel excavation in restoring tidal circulation and vegetation (*Salicornia* spp.) to the marsh. Annual aerial surveys corroborated with ground-truthing indicated that marsh vegetation coverage rapidly expanded, from 40 to 63% coverage following excavation. However, channel surveys and flow measurements indicated that the "east" channel system tidal prism prior to nearly complete siltation of the channels within three years was only about 1,200 m<sup>3</sup>, more than an order of magnitude less than that of the apparently stable "west" channel system. Marsh sediment accretion rates were on the order of 7-8 mm/yr, a rate common to the Pacific coast region that exceeds estimated sea level rise rates of 1-2 mm/yr. East channel network siltation resulted in ponding following storm and spring tidal events and marsh vegetation coverage decreased to 51% of the marsh area and quality of available habitat decreased. These results are considered in terms of the primary inter-tidal marsh factors affecting possible restoration/creation strategies.

### INTRODUCTION

Excessive fatality of the threatened salt marsh harvest mouse and loss of pickleweed

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(*Salicornia* spp.) stand of the inter-tidal marshes on the north side of San Pablo Bay, near San Francisco, California, prompted efforts to restore the marsh "health" such that general habitat improved. Such restoration efforts have become more common in the United States and elsewhere as the value of inter-tidal marsh systems in terms of biodiversity, fisheries and water quality are increasingly recognized, particularly as population pressures increase. A "healthy" marsh ecosystem suggests a system that "realizes its inherent potential, maintains a stable condition and preserves its capacity for self repair when perturbed" (Karr 1993). That is, a near mean tidal elevation vegetated landform having an intricate drainage channel system that is in dynamic equilibrium with changes in sea level and sedimentation such that habitat function is maintained. However, the complexity of inter-tidal marsh system dynamics precludes realistic hydrodynamic and sediment transport modeling such that restoration efforts depend on developing a thorough understanding of inter-tidal marsh processes and analysis of empirical results from restoration efforts. Lack of empirical relationships between tidal channel morphology and ecological function also inhibit marsh restoration efforts. The purpose of this paper is to consider these processes and apply them to analysis of the restoration efforts at San Pablo Bay.

#### WHY RESTORE INTER-TIDAL MARSH SYSTEMS?

Inter-tidal marsh systems have been restored/created for a range of purposes including replacement of lost wetlands, shoreline stabilization and water quality enhancement, facilitating the infauna and fisheries environment, as well as general preservation of biodiversity and habitat. Cumulative estimated losses of tidal marsh systems along the Pacific coast of California, Oregon and Washington exceed 70% in the past 150 years. When combined with their relative isolation, the remaining systems gain importance for their rarity (Onuf et al. 1978). These marsh/wetland systems are essential critical habitat for numerous species during crucial life stages that in turn impact other species commonly considered for human use. In the San Francisco Bay area alone, historical accounts of numerous wildlife species including elk, salmon and waterfowl prior to steady wetland destruction provide an indication of the productivity associated with former marsh systems. The capacity of tidal marshes to retain suspended sediments (Settlemyre and Gardner 1977), nutrients and pollutants from river/estuary systems underscores their importance to water quality concerns stemming from ever-increasing human populations along coastal areas as well (Josselyn et al. 1990).

Using salt marsh cordgrass (*Spartina anglica*) to vegetate mudflats, Chung (1989) describes inter-tidal marsh restoration/creation efforts along coastal areas of China. The goals of these efforts were primarily associated with improving the human environment and included coastline stabilization, acceleration of sediment accretion for land reclamation, increasing production of invertebrates, use of the cordgrass as a green manure, animal fodder, fish feed and fuel, and control of waterway pollution. Kramer et al. (1995) demonstrated that restoration of tidal flows to an inter-tidal marsh of San Francisco Bay reduced mosquito (*Aedes dorsalis*) abundance by 98.7% thereby also limiting their potential as disease vectors impacting the local population.

Almost all juvenile salmon migrate into estuarine habitats between mid-winter to late summer along the Pacific coast, with some species having concentrated migration periods (e.g. pink, chum, and sockeye) while other (e.g. coho and chinook) migrations may occur for much longer periods. Estuarine eelgrass beds, macro-algae, emergent marsh vegetation, marsh channels, and tidal flats provide particularly important habitats and nutrient transfer within the estuarine food web as well as a direct source of food for salmon and their prey. Additionally the marsh vegetation, eelgrass beds, and shallow turbid waters of the estuary provide predator

cover for juvenile salmon. Loss of marsh systems has resulted in a dramatic reduction in the emergent plant growth and benthic algae that support the detritally-based food web essential to salmonid outward migration and ocean survival suggesting that their restoration/creation would enhance salmon fisheries as well as improving general habitat.

Simenstad et al. (1995) used examples from the Gulf of Mexico and Pacific coast of the USA in an attempt to infer how tidal channel density, sinuosity, bifurcation, cross-section and slope influence fish, macro-invertebrate and avifauna access, refuge and foraging. Talley and Levin (1999) point out that "lack of ecosystem structure and function forms a major impediment to successful conservation of coastal ecosystems." Josselyn et al. (1990), Zedler (1996) and Zeff (1999) highlight the need for inter-tidal marsh restoration studies that demonstrate successful habitat formation.

## INTER-TIDAL MARSH HYDRODYNAMIC/SEDIMENTATION PROCESSES

Salt marshes may be characterized as vegetated landforms high in the tidal frame having a network of primarily blind-ended channels through which tidal flows transport sediment in and out of the marsh. In the relative short-term, sediments are transported from the Bay (ocean) and adjacent mudflats to the inner marsh during windy conditions. In the longer-term, the primary forcing factors affecting marsh formation, rates of sea level rise and sediment supply, change in both a smooth and episodic fashion. Rates of sediment accumulation in the marsh are also affected by marsh vegetation forming the basis of much of the marsh habitat. Knowledge of the processes affecting salt marsh systems has only recently been developed and at present is being incorporated into models useful for marsh restoration efforts as outlined below.

Building on the original marsh sedimentation studies considered by Postma (1967), Settlemyre and Gardner (1977) and Ward (1981) conducted some of the first comprehensive sediment budgets for a South Carolina marsh. They noted that ephemeral events such as winter storms and wind-induced wave scouring of bay sediment were primarily responsible for maintaining vertical marsh growth requirements, while channel velocity asymmetry is responsible for seaward movement of sediments during non-storm periods. Stumpf (1983) made the same observations at a Delaware marsh and also noted that sediment accretion rates decreased with distance away from channels. Similar distribution of marsh accretion rates found by Stoddart et al. (1989) for a Norfolk, England tidal marsh and Esselink et al. (1998) for a man-made tidal marsh in Dollard Estuary of the Netherlands also supported Stumpf's (1983) and Stevenson et al.'s (1988) observations that actual deposition of fine-grained silts and clays depends on plant trapping rather than settling. Moller et al. (1999) noted that wind generated wave energy dissipation rates were much greater (82% reduction) over vegetated salt marshes as compared to adjacent sand flats (29% reduction). The increase in surface friction provided by the vegetation was the primary factor dissipating wave energy and the relative efficiency of the vegetation in reducing wave energy was greatest for atriplex, secondly, salicornia and lastly spartina. Christiansen et al. (2000) made similar observations and noted that "reduction of turbulence levels within the vegetated canopy promoted particle settling. The role that vegetation plays in trapping sediments, and the relative greater trapping effectiveness of spartina in contrast to salicornia, has also been noted by others (e.g. Weihe 1935; French 1985; Faber 1991; Cahoon et al. 1996; and Zedler 1996). This trapping process by vegetation is reflected in plant density decreasing with distance away from restored tidal channels (Faber 1991).

Reed et al. (1985) underscored the importance of the storm-driven sediment deposition process during flood tides for a marsh system in Essex, England and noted that no simple re-

relationship exists between channel velocity or flowrate and suspended sediment concentration. The importance of episodic events to marsh accumulation of sediment was verified by Gardner et al. (1989), Reed (1989) and Childers and Day (1990), Wood et al. (1989) and Cahoon et al. (1996) for tidal marshes in South Carolina, Louisiana, Maine and Southern California, respectively. Annual sediment accretion rates found by these studies were surprisingly similar, ranging from 0-17 mm/yr. Day et al. (1999) reported that the greatest sedimentation rates in the Venice Lagoon occurred under storm or flooding events resulting in sediment accretion rates of 2-23 mm/yr. The importance of storm-driven sediment transport can be assessed in part by evaluation of the threshold erosion stress required to suspend mudflat sediments. Houwing (1999) found that the critical stress required to mobilize mudflat sediments along the Wadden Sea ranged from 0.11-0.18 Pa, but found no clear relationship between this threshold and factors such as bed density, moisture content or biological activity. Similarly, Dyer et al. (2000) noted that bay windspeeds in excess of 6 m/sec (as compared to 5 m/sec in earlier studies) reversed flood dominance of sediment flux to ebb dominant, and, in contrast to Houwing's observations, they found that sediment flux was reduced when diatom activity was high. Some of the studies also distinguished between types of sediment and the nutrient load they carried as this may be important to ecological function. For example, in comparing macrofaunal succession and community structure of natural and created salicornia marshes in southern California, Talley and Levin (1999) noted that densities of macrofaunal taxa were most correlated to sediment organic matter levels. French and Stoddart (1992) point out that the net influx of sediments into marsh systems based on sediment budgets developed from the mainstem drainage channel, such as in the studies cited above, may be in error due to seaward sediment transport via ebb-tide overbank sheetflow across the marsh surface. In order to avoid conflicting results of such sediment budget studies, long-term measurements of sediment fluxes (e.g. Suk et al. 1999), measurements of foraminiferal natural tracers to identify net sediment fluxes (Gao and Collins, 1995), or use of the large-scale remote sensing of waterline variability (Mason et al., 1999) should be considered.

Pethick (1981) suggested a conceptual model of salt marsh development that laid a foundation for later studies. In his model, there is a "negative feedback loop in which sediment accretion" results in increased marsh surface elevation thereby decreasing the "depth and period of tidal inundation" such that less sediment is available for deposition and marsh accretion rates decrease. Additional factors affecting this model include possible marsh sediment compaction, changing frequency of storm events, variable rates of sea level rise and changing density/type of marsh vegetation that may trap sediments. Pethick determined marsh accretion rates of up to 17 mm/yr on young (10-yr old) marshes to less than 0.02 mm/yr on very old (>500 years) marshes. In addition, he noted that the maximum marsh elevation was not associated with the maximum tidal level, rather with the most frequently occurring high tidal level (approximately 0.8 m less than the maximum). Furthering Pethick's original work Allen (1997) developed a model of long-term marsh accretion processes and noted that "as a marsh ages, an increasing proportion of a declining tidal prism is transmitted through the [channel] network rather than across the marsh edge". That is, decreasing "hydraulic duty" with increasing marsh elevation relative to sea level "should have a dual expression, geomorphologically on the evolving, active surface of the marsh and stratigraphically [on the] lithology and three-dimensional geometry of the different facies" comprising the marsh. Day et al. (1999) present a model for marsh accretion rates developed for the Venice Lagoon that incorporates measured short-term rates of soil elevation change with the effects of long-term processes of sediment decomposition and compaction to evaluate the effects of storm events and sea-level rise on marsh loss/formation.

Noting similar observations of salt marsh channel morphology by Steers (1959 and 1960) in England, and using channel velocity and morphology measurements in the San Francisco

Bay region, Pestrong (1965) suggested that marsh drainage channels are similar to low-energy terrestrial streams (in terms of sediment transport capability) and that slightly higher elevation ebb-flow channels become incised and stabilized by vegetation. Zeff (1988) notes that higher-order, larger through-flow channels have greater width:depth (W:D) ratios than the more sinuous, low-order dendritic dead-end channels formed on unvegetated, higher elevation areas of a salt marsh in New Jersey. French and Stoddart (1992) outline a dual process marsh channel formation model that includes incision and headward channel migration during regular tidal action while "sedimentation on adjacent surfaces is essentially storm-driven". Moreover, as later noted by Cahoon and Reed (1995) and Allen (1997), they observe that "as marsh elevation increases, tidal prism diminishes, resulting in a redistribution of the energy available for geomorphic work". Leopold et al. (1993) conducted an intensive survey of water levels, water surface profiles, flow velocity and sediment concentration along a 5.8 km estuarine channel in Petaluma Marsh near San Francisco that indicated the complexity of the channel flow regime. Measured water surface profiles having maxima at points in the middle of the channel and suspended sediment concentrations that had no clear relationship to channel velocity were both possibly associated with variations in channel resistance due to bank sloughing. This data set poses severe constraints on verification of hydrodynamic models of flow and sediment transport to be used for restoration studies.

Kamman (1998) and Sivakumaran (1998) suggest that hydrodynamic models of marsh channel hydrodynamics can be developed and used for restoration design while French and Clifford (2000) outline the variety of problems associated with correctly modeling marsh hydrodynamics. Presently, the predictive capability of such physically-based models is quite limited, however, their development assists in the debate related to the theory supporting measurement and testing observations in the environmental sciences. Kamman notes that any models developed should be linked with monitoring efforts to ensure that habitat restoration is actually occurring given the model limitations. Present hydrodynamic models lack the necessary algorithms for changes in channel morphology and roughness associated with sediment deposition during tidal cycles as well as the variability in storm events that drive this process. Time-series analyses of storm events may be helpful in regard to the latter (Gardner et al. 1989 and Warner et al. 1999). At the geomorphic process level, French and Clifford (2000) point out that "higher resolution terrain data and improved model representation of important processes operating at a subelement scale are required". Large-scale "visualization" methods suggested by Smith et al. (2000) may also "inform debates" on marsh processes occurring on decadal time scales.

Until such models can be developed and integrated with the longer-term sediment deposition processes described above and outlined by Allen (1997), restoration efforts will depend on observations such as that by Coats et al. (1995), Haltiner et al. (1997) and Zeff (1999) who relate the parameters associated with intact tidal marsh channel networks (e.g. stream order, bifurcation ratio, W:D ratios, length and channel sinuosity) with marsh area and projected tidal prism volumes. The importance of the processes outlined above to tidal marsh restoration efforts was highlighted by Winfield et al. (1995) in a review of marsh restoration efforts on dredged soils. They found that successful formation of adequate marsh channel density and morphology and subsequent ecological function was dependent on the initial surface elevation, while Day et al. (1999) noted that dredged soil elevations tend to decrease more quickly than adjacent natural deposits due to compaction. Inlet channel stability to the marsh is critical to maintaining tidal prism circulation. Gao and Collins (1994) showed that sediment transport conditions and flood/ebb tide durations across the marsh inlet were critical to establishing inlet stability. In the same vein, Sanderson et al. (2000) reported the importance of tidal marsh channels to establishment of dense, diverse marsh vegetation. They found that channel influence (distance from channel) on marsh vegetation depended upon channel type and order;

significantly greater species diversity was found adjacent to natural channels as opposed to constructed channels. In their comparison of created and natural salt marshes, Talley and Levin (1999) found that though created marsh systems generally had greater macrofaunal densities, faunal recovery following salicornia marsh creation may require ten or more years. The purpose of the work considered here is to extend that empirical knowledge needed for successful marsh restoration efforts while also providing field parameters for future numerical model developments.

## INTER-TIDAL MARSH RESTORATION/CREATION - METHODOLOGY

The northern San Pablo Bay salt marsh near San Francisco, California comprises approximately 410 ha. It is bounded to the north by Highway 37 and bisected by a deep intake channel developed to supply salt ponds further north in the early 1900's. The eastern portion of this salt marsh, bordered by Mare Island shipyard, had developed wave landform features (relic beaches) resulting in ponding, loss of vegetation and habitat as well as subsequent mosquito control problems. Due to its relative hydrologic isolation, the marsh has no freshwater drainage channels, or significant groundwater flows often important to wetland systems (Grismer 1999). The western portion supports a dense pickleweed (*Salicornia* spp.) stand and diverse habitat apparently as a result of numerous small drainage channels directly connected to the Bay. Historically, San Pablo Bay has been a dynamic site for sediment supply and deposition (Atwater et al. 1979). From 1856 to the late 1800s, San Pablo Bay was inundated with 263 million m<sup>3</sup> of hydraulic gold mining debris resulting in a three-fold increase in tidal mudflat area. From 1887 to 1898, sediment deposition slowed as hydraulic mining ceased by Congressional order in 1884. During this period, approximately 3 million m<sup>3</sup> of sediment was deposited, however, shallow, mudflat areas became unstable and then erosional decreasing in area at an average of 100 ha/yr. San Pablo Bay continued to fill with sediment from 1898 to 1951, at a rate of only 2 million m<sup>3</sup>/yr, but tidal mudflat areas continued to decrease. During 1951 to 1983, the Bay again became an erosional environment as upstream sediment supply was limited by dam construction. Tidal mudflat area decreased at the rate of 0.75 ha/yr. However, the north and northeast areas of the Bay where this project is situated did not lose mudflat area. In fact, bathymetric maps prepared by the USGS show little change in this area from 1887 to 1983.

Two surface drainage systems ("west" and "east") were designed and installed the eastern portion of the marsh in October 1996 as a means of improving tidal cycling as well as the drainage of excess surface waters in a disturbed eastern portion of the marsh. The "west" drainage system included a pre-existing 2,900 m main drainage channel running roughly parallel to and near the northern boundary for about the western one-third of the marsh. This channel is connected to the Bay via an existing salt pond intake channel. Nine sinusoidal smaller lateral channels, each extending roughly 1,000 m south to southeast from the main channel at regularly-spaced intervals were added to the main channel to facilitate drainage to the north and tidal flushing. The "east" drainage system consists of a 3,600 m main channel that originates in the Bay mudflats to the south and continues north then northwest with two small irregular lateral channels having a total length of about 1,800 m. The drainage channel design was based on observations of channel size and density in relatively "undisturbed" inter-tidal marshes in the San Francisco Bay region. Inter-tidal marsh channels had base widths on the order of 1 m, depths ranging from Mean Low to Mean High Water (MLW to MHW) and radii of curvature on the order of 20-30 m. The channel dimensions were also based on consideration of tidal prism volumes, anticipated flowrates and available land slopes. Furthermore, wildlife managers desired only partial drainage of the site in order to facilitate lim-

ited ponding for threatened clapper rail and other wildlife habitat.

Table 1 San Pablo Bay tidal marsh restoration project drainage system characteristics.

Description	Channel length (m)		Average dimensions (m)		Channel volume (m <sup>3</sup> )		Channel sinuosity	
	Design	Install	Width	Depth	Design	Install	Design	Install
West system								
Main channel	2,896	2,713	3.0	1.5	13,445	12,582	1.00	1.00
Lateral #1	549	527	1.2	0.9	617	592	1.25	1.25
Lateral #2	610	683	1.2	0.9	678	765	1.28	1.30
Lateral #3	610	634	1.2	0.9	678	703	1.28	1.30
Lateral #4	549	529	1.2	0.9	617	592	1.32	1.35
Lateral #5	567	406	1.2	0.9	629	456	1.29	1.25
Lateral #6	622	385	1.2	0.9	691	432	1.28	1.20
Lateral #7	549	333	1.2	0.9	617	370	1.25	1.01
Lateral #8	488	323	1.2	0.9	543	358	1.52	1.01
Lateral #9	488	272	1.2	0.9	543	308	1.25	1.01
Totals	7,927	6,805			19,119	17,146		
East system								
Main channel	3,598	2,916	2.1	1.2	9,350	7,586	1.45	1.16
Lateral #1	744	496	0.9	0.5	308	210	1.45	1.05
Lateral #2	915	680	0.9	0.5	382	284	1.40	1.05
Totals	5,256	4,093			10,041	8,079		

Details of the drainage channel networks constructed in the eastern portion of the northern San Pablo Bay salt marsh are summarized in Table 1 and an aerial view of the marsh channel systems is provided in Fig. 1. In the approximately 200-ha site, nearly 11.6 km of drainage channels (82.7% of design) having a surface area of roughly 20,000 m<sup>2</sup> were installed (~14,000 m<sup>2</sup> and 6,000 m<sup>2</sup> for the west and east systems, respectively). Corresponding hydraulic duties (HD = ratio of tidal prism to channel surface area) were nearly equal (HD~1.3 m) for both channel systems; a value that exceeded the minimum HD required for “stable” channel systems as suggested by Allen (1997). Channel W:D ratios ranged from 2-4 for channel dimensions of 0.3-5 m base widths and 1 m depths with vertical (1:1), or steep (2:1) side slopes. This W:D ratio is less than that suggested from regression analyses of marsh data by Coats et al. (1995) for tidal marshes of this size (i.e. W:D ~ 7-10). Drainage densities for the site expressed in length terms (approximately 58 m/ha), or area terms (approximately 91 m<sup>2</sup>/ha) were also less than that of other natural sites (99–190 m/ha). This was due to excavation and budget constraints and the desire to maintain some flooding (approximately 35-40%) of the marsh so as to encourage natural drainage channel development. The bank-full tidal prism volume of the west drainage system was about twice that of the east system (i.e. approximately 17,100 vs. 8,100 m<sup>3</sup>) enabling investigation of the effects of prism volume (i.e. channel discharge or velocity) on channel stability. This volume is an order of magnitude less than that suggested by Coats et al. (1995) analyses, however input of the design prism volume above into their regression analyses results in a main channel depth similar to that installed. In contrast, use of the regression analyses to estimate prism volume based on main channel cross-sectional area results in a volume that is 30-50% of that measured. Similarly, the main channel maximum top width of 4.9 m results in an estimated prism volume of only 15% of that actually measured. Nonetheless, the design guidelines proposed by Coats et al. (1995) provide a starting point from which to develop specific restoration channel designs for particular marsh systems.





Note: The photo longitudinal axis is oriented east-west with the Bay to the right (south).

Fig. 1 Aerial view of San Pablo Bay marsh restoration project



Pre-channel construction air photos and infrared surveys from the NASA high-altitude ER-2 at low tide were used to initially characterize the site in terms of vegetation coverage (Johnson and Ustin 1999). These images were digitized and calibrated with ground-truth frame surveys to establish that the pre-construction (September 1996) site conditions were 60% bare soil and 40% vegetation by area. Similarly, in September 1997, 1998 and 1999, digital camera airborne surveys of the site (using a Nikon/Kodak 420 at a height such that 0.5-1.0 m<sup>2</sup> pixels resulted) were conducted and corroborated with ground-truth frame surveys as done in the initial 1996 survey.

Marsh field measurements included a land survey of marsh elevations and channel cross-sections following channel construction, regular flow and suspended sediment (TSS) measurements during several tidal cycles (May through October, 1998) at established stations on the main channels of each drainage system, and sediment accretion rate measurements near the drainage channels. Swiffer propeller flow meters were used to measure flow velocities at the a depth of 0.6 times the flow depth at several cross-section points across the channel at 15-30 minute intervals during the tidal cycle. Suspended sediment samples (1 L) were collected using an integrated depth sampler at the same time flow measurements were taken. TSS concentrations were determined by filtering the samples and drying the filters and weighing the mass of sediment trapped on the filters. Finally, sediment accretion rates in the marsh were determined through measurement of sediment depths accumulated on 20 small (50 mm square by 4 mm thick) plexi-glass plates anchored to the marsh using PVC pipes following Faber (1991). The plates were deployed in October 1998 and sediment depths were measured 3 and 9 months later. Plates were not randomly distributed through the marsh rather they were located on unvegetated areas and salt pans alongside main, lateral and "natural" drainage channels at distances of 1-42 m from the channels.

## ANALYSIS OF SAN PABLO BAY SALT MARSH RESTORATION

We consider the impacts of restoration of tidal circulation to the San Pablo Bay salt marsh in terms of the drainage system hydrologic response, sediment movement and accretion and vegetation response in the marsh.

In post-construction surveys conducted approximately 18 months after channel excavation, we found that the "west" drainage channels were stable, nearly rectangular in cross-section and had not become filled with sediment. In contrast, the "east" drainage channels lacking pickleweed growth adjacent to the channels had filled in substantially and taken on a broad V-shaped cross section. Within three years following channel construction, the east drainage system main channel had largely filled in precluding continued flow measurements and subsequently trapping large tidal flows within the marsh. Several "natural" channels, varying in cross-section from tens of cm wide and a few deep to approximately 0.6 m wide and 0.15 m deep, had formed in the flooded, relatively bare areas of the excavation spoils. Extensions of some of the excavated drainage channels had also developed. Though subject to similar flood/ebb tide inflow/outflow periods of 2-4 and 10-13 hours, flowrates and prism volumes in the main channels of the two drainage systems were quite different. Measured tidal prism volumes ranged from 1,011 to 1,628 m<sup>3</sup> for changes in tide height in the east main drainage channel of 0.24 and 0.37 m, respectively. Similarly, measured tidal prism volumes ranged from 7,092 to 65,870 m<sup>3</sup> for changes in tide height in the west main drainage channel of 0.25 and 0.58 m, respectively. Corresponding hydraulic duties (ratio of prism volume to channel surface area; Allen 1997) ranged from 1-4 m for the west system and only about 0.3 m for the east system. Based on numerical modeling of organic and mineral deposition for the inter-tidal region of the Severn Estuary in England, Allen (1997) indicates that marsh channel

systems in dynamic equilibrium with a sea level rise of 2 mm/yr have a hydraulic duty between approximately 0.7 and 1.2 m. This observation suggests that the east drainage system had insufficient hydraulic capacity to maintain channel form as was noted in field measurements. That is, the larger tidal volumes passing through the west drainage system appear to have maintained the channel dimensions with minimal silt deposition as compared to that for the east drainage system. Ebb tidal prism volumes were 2-4 times greater than flood volumes indicating there was drainage geomorphological control of marsh channel dimensions as in terrestrial fluvial systems. Though outflow from both drainage systems began shortly after high tide levels were reached in the Bay, outflow continued for several hours after low tide in the Bay until sufficient flood tide elevation in the Bay was reached to cover the mudflats and reverse channel flows.

Sediment accumulation rates were highly variable across the marsh and did not appear to depend on distances from channels as found by several other authors though the sampling may have been inadequate to display this dependence. Accumulation rates ranged from near zero to 19 mm/yr with average rates of 7.6 and 8.1 mm/yr associated with plates near the west and east drainage systems, respectively. These rates do not significantly differ despite increased ponding in the vicinity of the east drainage system and are consistent with those measured elsewhere while exceeding estimated rates of sea level rise (1-2 mm/yr) in the San Francisco Bay region.

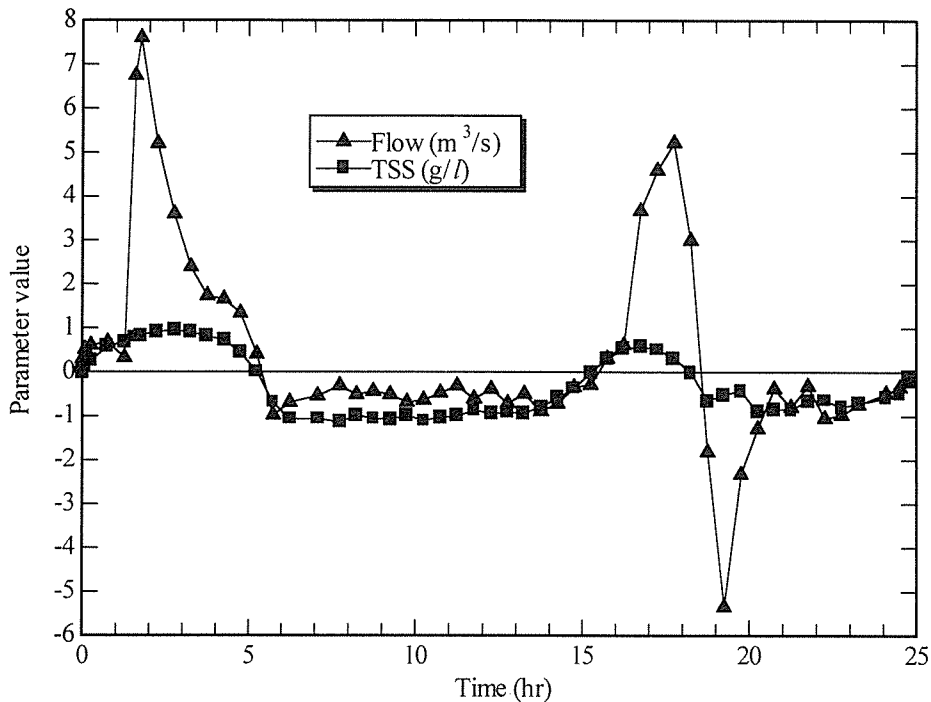


Fig. 2 Windy flood (+) / ebb (-) cycle (8/8-9/98) flow and suspended sediment conditions in main channel of west drainage system

Sediment movement and average channel velocities in San Pablo Bay salt marsh was similar to that observed in similar size channels of other inter-tidal marshes (Leopold et al. 1993). Figures 2 and 3 illustrate TSS concentrations and average channel flowrates through similar tidal cycles in the main channel of the west drainage system during windy and non-windy Bay conditions, respectively. Note that the average flowrates are similar ( $\sim 1$  m<sup>3</sup>/s) in both cases, however, the TSS concentrations differ by nearly an order of magnitude. Fitting a linear relationship between TSS concentration and average channel velocity (i.e. TSS (mg/l) =

$1.123 \cdot \text{Velocity (m/s)} + 0.122$ ) resulted in a regression coefficient of 0.38 for all flood/ebb tide data when wind conditions in the Bay were mild. Suk et al. (1999) also obtained a significant correlation between TSS and V from long-term measurements for TSS concentrations in the low range of 5-15 mg/l. However, inclusion of TSS data associated with flood tides on windy days at San Pablo Bay marsh precluded determination of a linear regression coefficient because it added TSS data ranging from 1-8 mg/l centered on an average velocity of 0.15 m/s. The Bay wind conditions had little or no effect on ebb-tide TSS concentrations. Clearly, from a hydrodynamic modeling perspective, information is required about the time series variation in Bay wind shear strength (Warner et al. 1999) in order to estimate rates of sediment transport into the salt marsh as well as estimating marsh sediment balance conditions.

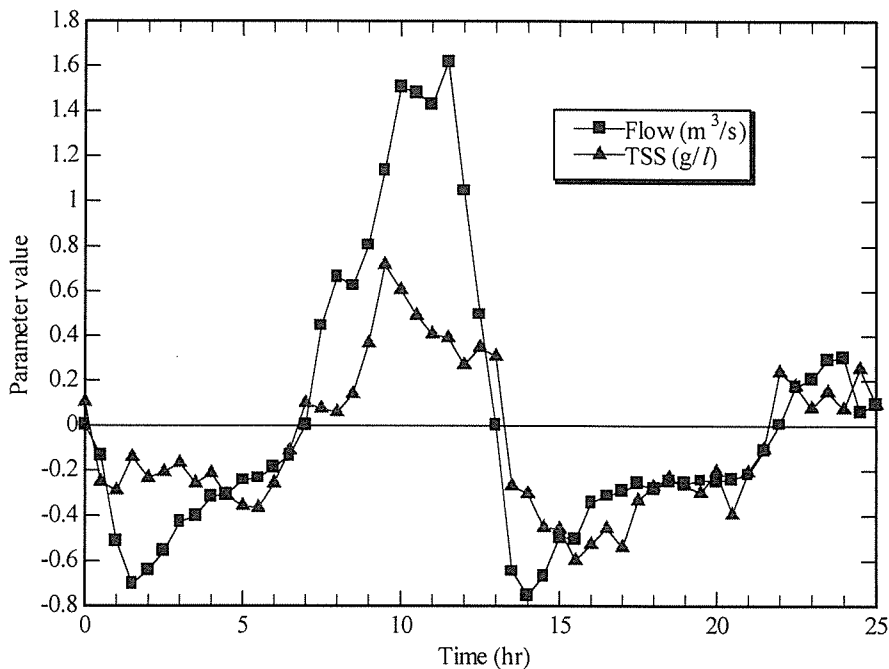


Fig. 3 Non-windy flood (+)/ebb(-) cycle (9/12-13/98) flow and suspended sediment conditions in main channel of west drainage system

In comparing the product of channel flowrate and TSS mass in Figs. 2 and 3 (note reduction in scale), it is evident that the flood tide contains considerably more suspended sediment than that leaving the marsh in the ebb tide. This occurs despite an ebbflow water volume of 46,800 m<sup>3</sup> under windy conditions that exceeding the flood flow volume of 16,640 m<sup>3</sup> by nearly three times. Under windy Bay conditions, only 57.4% of the flood tide suspended sediments returned to the Bay, whereas 71.8% of the flood tide sediments returned to the Bay under non-windy conditions. This relative sediment balance under non-windy conditions is more consistent with the relative balance in ebb/flood water volumes of 22,300 m<sup>3</sup> and 19,600 m<sup>3</sup>, respectively. This result is similar to that described by others as discussed above in that sediment accretion in tidal marshes is largely storm, or seismic event driven.

Results of the aerial surveys of land coverage as fractions of total marsh area are summarized in Table 2. Following the original pre-construction survey, non-vegetated areas were distinguished between original bare marsh areas and those areas covered by water (“inundation”) and excavation “spoils” sidecast up to 75 m from the channels to depths not to exceed 0.2 m. From both field observations and the results of image classification, introduction of tidal flows to the wetlands combined with improved winter drainage encouraged significant re-emergence of the pickleweed through vegetative growth (no reseeding) within the first year

(1997) following channel construction. Some areas of the marsh, however, do not appear to be responding and some areas remain flooded as designed. However, vegetation coverage declined to 57% in 1998 and to 51% in 1999. Areas that have 'regressed' appear to be between relic beaches, or waveforms (pannes) subject to fresh and salt water ponding without subsequent drainage. The absence of drainage in these areas during the 1998 El Nino winter season may have resulted in persistent ponding unsuitable for *Salicornia* growth (Mahal and Park, 1976). In fact, pickleweed grows best when periods of emergence are greater than or equal to periods of tidal submergence (Josselyn, 1983); that is, growth is favored by periods of low streamflow and submergence times less than that for *Spartina* (Zedler, 1996). It was noted during the preflight panel installation that areas of good *Salicornia* growth on the relic beach tops, and particularly along the beach behind the active strand line, appeared to have exceptional flower production. Large areas were thickly covered with flowers and/or post-inflorescence products. From a habitat development perspective, it was interesting to note in field surveys that the bare marsh areas were covered by extensive tracking and were active foraging areas for shore birds and small mammals.

Table 2 Summary of annual (September) land coverage conditions at San Pablo Bay salt marsh site following drainage channel excavation in October 1996

Year	Vegetation (%)	Bare marsh (%)	Spoils (%)	Inundated (%)
1996	40.0	60.0	na	na
1997	62.7	23.3		14.0
1998	57.4	26.8	10.3	5.5
1999	51.1	29.7		19.3

As part of the aerial survey process, the shoreline of the "intact" salt marsh west of the salt pond intake channel was surveyed. During the traverse it was observed that this marsh had in excess of 40 "intake" channels from the ocean (rather than only two) and no relic wave landforms to restrict the regular seawater inundation/drainage of the marsh during tidal cycles as occurred in the project marsh. Towards the west end of this marsh, channels were closely spaced and approximately 1 m wide and up to 2 m deep. In addition, a large channel at the western end of the west marsh was about 3 m deep over 3 m wide, considerably larger than the corresponding "west" system main channel in the project site. Also, the shoreline was extensively covered by *spartina* that at some points extended more than 200 m from the mudflats into the marsh interior. As an apparent result, there were no noticeable strand lines of oceanic debris as found at the project site marsh, presumably the *spartina* played some role in stabilizing this shoreline.

## SUMMARY AND CONCLUSIONS

Inter-tidal marshes provide an important function in the landscape for both human and wildlife needs. However, their maintenance and restoration is a complex endeavor requiring knowledge of estuary hydraulics, sediment supply and transport, and factors affecting marsh accretion rates and channel morphology. Restoration efforts presume that successful establishment of tidal circulation to an inter-tidal zone area will result in vegetation establishment (if not already pre-seeded to trap sediments), and creation of functional habitat useful to fisheries, waterfowl, infauna and other terrestrial species. Such restoration efforts must also consider development of sediment accretion rates, or rates of marsh elevation rise that exceed the

5-7 mm/yr rates of sea-level rise projected by the United Nations Intergovernmental Panel on Climate Change (2001). Here, the key processes important to restoration efforts are briefly outlined and considered in their application to restoration efforts at San Pablo Bay, California.

Two different types of drainage channel networks were installed in the northeastern inter-tidal marsh of San Pablo Bay. The “west” system consisted of multiple channels and a tidal prism volume of approximately 17,000 m<sup>3</sup> while the “east” system was comprised of a single channel with two small branches and an initial prism volume of about 8,000 m<sup>3</sup>. Though sediment accumulation rates across the marsh were quite variable with no apparent pattern of distribution across the west and east drainage networks, the east system channels filled in with sediment within three years. The west system channels appeared stable and had a “hydraulic duty” consistent with that estimated for “equilibrium” marsh systems by Allen (1997). The channel W:D ratios, bifurcation frequency, and sinuosity seemed to have little effect on channel hydraulic performance or stability and seem to be of less importance in that regard as compared to maintaining minimal tidal flow volumes. These channel factors may be important to overall habitat function, but did not affect dramatic re-establishment of pickleweed vegetation. It appears that the factors controlling effective re-establishment of pickleweed habitat were more related to relationships between tidal prism volume, channel area/density and marsh area as well as the topographic features of the marsh that restrict tidal circulation and result in excessive ponding. Some information is also required about the relative magnitude of sediment sources in the Bay and their circulation such that marsh accretion rates could be estimated and compared to those estimates of sea-level rise. Hydrodynamic models need to include changing channel conditions (dimensions and roughness) as tidal circulation in a marsh is restored (see French and Clifford, 2000). Until such algorithms are available it may be necessary to rely on empirical approaches such as those presented here and by Coats et al. (1995).

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