The Geomorphology of Tidal Wetlands

and

Wetland Restoration

Jim Pettigrew

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San Francisco State University

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Abstract

California has lost over ninety percent of its historic estuarine and tidal wetlands to human development. Recent efforts to restore wetlands have provided insight into the complex geomorphic processes involved in wetland evolution, and how to optimize these processes so that future restoration projects will provide more predictable results. Three factors appear to have a profound effect on wetland evolution: suspended sediment supply, erosion of deposited material by wind waves, and the amount of tidal exchange. Two restoration projects were studied: the Sonoma Baylands and the Giacomini Ranch. The Sonoma Baylands restoration utilized dredge spoils to raise the grade of a subsided agricultural impoundment to hasten the establishment of a vegetative marshplain, and incorporated features to minimize the effect of wind waves, but evolution will be hampered by limited tidal exchange due to an undersized inlet channel. The proposed Giacomini Ranch restoration is more complex, as it involves both an estuarine delta and tidal wetland, but it will require no filling or wave mitigation structures. However, the operation of an existing dairy on the site will delay the removal of a controversial dam, and will delay final restoration measures for more than a decade after initial restoration commences in 2007. Both the Sonoma Baylands and Giacomini restoration projects are projected to cost more than $30,000/ha. Also examined is a Louisiana study that proposes slower, long-term wetland restoration by removal of portions of impounding levees at a cost of $1/ha.
Introduction

The Case for Wetland Restoration

Estuarine and tidal wetlands are among the most productive of the planet’s ecosystems, with net biomass productivity approaching that of coral reefs and rainforests (Odum, 1997). Some of the many services provided by wetlands include: wildlife habitat, nurseries for juvenile fish and invertebrate species, erosion controls, pollution filtering, and air purification (Klee, 1999). Yet, beside all the ecosystem services they provide, our society has only recently acknowledged their value. Historically, marshes have been drained and used for agriculture, filled for development, used as garbage dumps and generally seen as unhealthy, mosquito-infested wastelands. In typical human fashion, we have come to realize the importance of wetlands only after most of them are gone, but at least in California that attitude is changing. In the next 20 years, proposals and funding are in place to restore over 14,000 ha of tidal marsh in the San Francisco Bay region (Williams and Orr, 2002). As we move into an era of marshland protection and restoration, it is important that we understand the complex physical processes involved in wetland evolution.

Geomorphic Evolution of Salt Marshes

Estuarine salt marshes and tidal wetlands are relatively young and ephemeral landforms, and the ancient marshes of coastal California were formed 2,000 to 6,000 years ago, when sea level rise associated with the Holocene transgression declined to current rates of 1 to 2mm/yr. The slowing rate of the rising sea created the complex processes that resulted in the formation of modern estuarine salt marshes and tidal wetlands (Lanzoni, 2002). Estuarine salt marshes are defined by the presence of both salt and fresh water flow, and tidal wetlands and sloughs are defined by the absence of fresh water. There is considerable overlap in these definitions, with an example being provided by Elkhorn Slough, which exhibits freshwater flow for only part of the year, and is known as a “full time slough” and a “part-time estuary” (Klee, 1999).

Geomorphic processes controlling wetland evolution include wind wave action (wetlands do not form in the presence of large oceanic waves), tidal flow, sedimentation and resuspension. Suspended silts and clays arrive with the incoming tide, and are deposited when the tide reverses. Deposition of sediment is dependent on the sediment load in the water column, and available sediment can have a significant effect on the rate of wetland formation. For low-elevation marsh
grasses to become established, a threshold elevation of about .05 m NGVD must be reached, and
the concentration of sediment has been shown to have a significant effect on the rate at which a
wetland is established (Figure 1).

Biogenous contribution to marsh morphology begins with initial plant colonizers of
deposited sediments. In California marshes the pioneer plant species of mudflats is marsh
cordgrass (Spartina foliosa). Initial colonization evolves to a vegetated marshplain, and
established Spartina can then extend to lower elevations of ~0.15 NGVD. The presence of
vegetation contributes to vertical accretion by trapping sediment and accumulating organic
matter. Mature marsh systems exhibit soils high in organic matter (peat) and fine silts from
estuarine muds (Williams and Orr, 2002).

Resuspension of deposited sediments occurs through both the action of the ebb flow and
of wind-driven waves. The energy input of wave action can have an inhibiting effect on marsh
development, and the equilibrium form may not proceed beyond that of an intertidal mud flat
(Figure 2).
Geomorphology of Estuarine and Tidal Channels

An Estuary is defined as “a semi-enclosed body of water which has a free connection with the open sea; it is thus strongly affected by tidal action, and within it seawater is mixed (and measurably diluted) with fresh water from land drainage” (PWA, et. al., 1993, page 9). It is where river currents and the tides engage in an interplay of erosion and deposition that creates a funnel-shaped river mouth (Ahnert, 1996). Deposition of suspended load occurs at high tide when the current reverses, with most deposition taking place on the tidal flats. When the tide reverses, the combined flow of the ebb tide and river current concentrates resuspension and erosion in estuarine channels (Ahnert, 1996). When bends exist in an estuary, the ebb or flood current is pushed to the outside of the curve by centrifugal force, and an estuarine meander may be formed. Estuarine meanders do not have the parallel banks of riverine meanders, and are narrowest at the outside of bends, where the paths of the flood and ebb currents cross (Fig. 3).

Tidal channels, or sloughs, differ from estuarine channels in that freshwater flow is negligible, and erosion and deposition are accomplished entirely by tidal flow (Pestrong, 1965). Deposition processes are similar to that of estuarine channels, but ebb tidal currents are less
powerful than the combined ebb and river flow in an estuary, and are less able to resuspend deposited muds and silts (Williams and Orr, 2002).

Tidal and estuarine channels form initially by chance occurrence at extremely small scales, and eventually develop the form that we see by enlargement and bifurcation of initial channels over time. The complex shape of these channels is described as a fractal (Figure 4), which means that their characteristic patterns are found repeatedly at descending scales, so that any part retains the shape of the whole (Mandelbrot, 1977. Capra, 1996).

![Figure 4. A Julia set; an example of a fractal form with morphological similarities to a tidal drainage network.](from North Carolina State University website – www2.ncsu.edu/pams/science_house/bw/chaos)

Estuarine and tidal meanders, and their associated wetlands, constitute parts of a system known as an ecotone that incorporates riverine, estuarine and bay systems, and forms the transition between the land and the sea (Figure 5). An ecotone is not simply a boundary, but a zone of active interaction between two or more ecosystems that displays emergent properties that do not exist in adjacent ecosystems (Odum, 1997).
Anthropogenic Impacts to Wetlands and Restoration Strategies

Wetlands have suffered more from the impacts of human development than perhaps any other habitat. In California, more than 90% of wetlands have been destroyed, and all wetlands are considered to have been altered by human activities (Klee, 1999). Wetlands have been altered by filling for development, or by draining and conversion to agricultural use. The wetlands studied in this paper were drained by constructing levees around their perimeter to inhibit periodic flooding by tidal action. The resulting drained soil is high in organic content and viable for agricultural use, but is subject to subsidence over time due to oxidation of soil organics and mechanical tilling methods (Ford, et al, 1998).
Rehabilitation of diked agricultural wetlands usually involves restoration of estuarine sediments to a level that is consistent for the establishment of colonizing vegetation. Sites that are initially lower take longer to vegetate than those of higher elevations. Three factors have been found to affect the time frame to establish vegetation: limited sediment supply, restricted tidal exchange and erosion and resuspension by wind waves (Williams and Orr, 2002). The restoration examples studied in this paper review several approaches to optimizing the processes affecting wetland restoration.

**Case Study – The Sonoma Baylands Project**

The site of the Sonoma Baylands project is a historic tidal wetland that was leveed and drained for agricultural use around 1900. Although the entire property encompasses 338 ha, only 138 ha was deemed to be suitable for tidal restoration due to the need to maintain levees to protect the Northwestern Pacific railroad bed and Highway 37, both of which run through the property. The restoration of the marshplain is expected to provide habitat for two endangered species, the clapper rail and the salt marsh harvest mouse. Soil subsidence on the restoration parcel was on the order of 1.5-2.1m (Marcus, 2000).

A concept plan was developed by Philip Williams Associates (PWA, 1989), and the essence of this plan was to use natural processes wherever possible, and to avoid active management mechanisms such as pumps and tide gates. A review of previously restored wetlands in San Francisco Bay showed that wetland regeneration could be hastened by filling subsided agricultural impoundments prior to levee breaching. Although equilibrium vegetated marshplain exists at MHHW, or about 1.1m NGVD, it was found that early sites filled to this level failed to develop an extensive channel system (Marcus, 2000). Further review revealed that the highest channel density developed in projects filled to a level of about MHW, or 0.6m NGVD, and it was decided that the Sonoma Baylands project was to be filled to an elevation of MHW to provide a template for natural marsh and channel systems to develop. Fill material was to come from a dredging project at the Port of Oakland, and 2.5 million cubic meters of dredge spoils were eventually placed in the baylands site after the fill was determined to be free of hazardous contaminants (Ibid).

Another issue recognized in the concept plan was that the baylands site is subject to strong winds, and that ensuing wind-generated waves could inhibit sedimentation rates by
resuspending material deposited by tidal action. A system of wave-breaker peninsulas was proposed, and eventually constructed (Figure 6). The purpose of the peninsulas, in addition to reducing fetch and encouraging sedimentation, was to provide both additional protection for the railroad levee, and refugia habitat for wildlife species displaced by the return of tidal waters. The peninsulas were built to a level of 1.1 m NGVD, and are expected to erode over time and blend in with accreting marshland (Marcus 2000).

Figure 6. The Sonoma Baylands Project

The concept plan for the Baylands project also recognized the importance of sizing the levee breach to achieve optimal tidal flow, and to encourage sedimentation necessary to establish a vegetated marsh plain. Although the site of the breach is several hundred meters from bay waters and is separated by mature developed salt marsh, the outlet channel was not dredged, as enlargement of the channel would disrupt active habitat for the federally endangered salt marsh harvest mouse. Tidal flows were restored to the site in 1996 by breaching the levee, and natural flows are expected to widen the levee breach and enlarge the outboard slough channel (Marcus, 2000). However, hydraulic constriction by the relatively narrow levee breach and small inlet channel of the Sonoma Baylands will delay the establishment of vegetation by damping tidal
action and preventing full tidal exchange until scouring enlarges the restrictions over time (Williams and Orr, 2002).

The Baylands project concept plan also included provisions for monitoring of restoration results. Monitoring activities are concentrated in a smaller “pilot unit” to provide data to assist in further wetland restoration projects. A recent study compared the Baylands pilot unit to two other restoration projects in San Francisco Bay, the Warm Springs Interior and the Warm Springs Coyote Slough. Among the relationships studied were the effects of channel cross-sectional area and tidal prism (Williams et al, 2002). The Sonoma Baylands pilot unit was classified as having an “undersized, but eroding” channel, increasing in tidal exchange and tidal prism; Coyote Slough was classified as having an eroding tidal channel, adjusting to large but decreasing tidal prism, and Warm Springs Interior was classified as having an “oversized” channel, with decreasing tidal prism, and new channels forming in a depositing mudflat (Ibid). Comparison of the evolutionary trajectories of these three marshlands toward predicted equilibrium illustrates the effect of channel size on tidal prism (Figure 7).

Monitoring of the Baylands pilot unit recorded that the inlet channel tripled in cross-sectional area between 1996 and 2000, and that channel enlargement progressed initially by channel deepening, which was later followed by widening. Deepening occurred rapidly and destabilized

Figure 7. Evolutionary trajectory of channel cross-sectional area and tidal prism at rapidly evolving sites. Number labels indicate the number of years of channel evolution following increase or decrease in tidal prism. Arrows show direction of increasing time. Dashed lines show that channel dimensions should eventually reach the predicted equilibrium, though the exact trajectory toward this endpoint is not known. (from Williams, et. al., 2002)
bank vegetation, and widening was a slower process, and occurred through mass failure of slump block erosion of channel banks (Williams et al, 2002b).

The tidal inlet channel of the main unit of the Sonoma Baylands project is, like the pilot unit, classified as being hydraulically constricted (Williams and Orr, 2002). Although innovative measures (wave-breaker peninsulas, filling of subsided land) have been taken to enhance wetland evolution, the undersized tidal channel will retard development of the marsh until it erodes to a channel large enough to provide full tidal exchange. A logical answer to this would be to enlarge the channel through dredging, but as that would damage active habitat of endangered species, it is an unlikely solution.

**The Role of Marsh Biota**

After examining the rate of wetland evolution of earlier projects from the 1970’s, designers of the Sonoma Baylands project discovered that raising the grade to that of a mature marshplain actually hindered marsh development, and that optimal development occurred when a template of an immature wetland is created. This realization acknowledges the role marshland biota plays in geomorphic evolution, as colonization by marsh grasses precedes the formation of tidal channels (Williams and Orr, 2002). Indeed, life forms may impact evolutionary processes prior to the establishment of *Spartina*, as the distribution of benthic microalga plays a role in vertical accretion of sediments (Philips, 1999). Another life form affecting development of the Baylands project is the salt marsh harvest mouse. Ironically, the evolution of the marsh is hampered by concerns over disturbance of current habitat, but one of the main purposes of the project is to create habitat for this and other endangered species. Of this conundrum the mouse is blissfully ignorant.

Monitoring of the progress of the Sonoma Baylands project is scheduled to continue until 2016, and the data could provide insight into future wetland restoration endeavors. Total cost for the restoration, including land purchase, is about $35,000/ha (Marcus, 2000).

**Case Study – The Giacomini Ranch Restoration**

The Giacomini Ranch is a 227 ha parcel at the southern terminus of Tomales Bay which was purchased by the National Parks Service in 2000. Current dairy ranching operations will continue until 2007, after which work will commence to restore the ranch to estuarine tidal
wetland habitat (PWA, et. al., 1993). Like the Sonoma Baylands, the Giacomini Ranch is a reclaimed tidal marsh that was converted to pasture in 1947 through the construction of levees.

**Geomorphic Evolution of the Giacomini Ranch Site**

Tomales Bay is a 2700 ha estuary that was formed about ten thousand years ago when rising sea level flooded the rift valley of the San Andreas fault (Daetwyler, 1966). The morphology of Tomales Bay has evolved over time by influence of rising sea level, accretion of sediment from its watershed and sediment movement due to tidal and wave action. Littoral transport delivers coarse sands to northern Tomales Bay, and they accumulate mainly as shoals close to the bay mouth, and do not affect the southern two thirds of the bay.

Streams carrying an alluvial mixture of sand, silt and mud provide most of the sediment to Tomales Bay (PWA, et. al., 1993). The coarser material, carried by flood event flows, is deposited at the mouth of Lagunitas Creek, and forms a delta. Finer materials are deposited on shallow mudflats, which are subject to wave action, which resuspends sediment; the resuspended material is then transported by tidal currents to be redeposited in other parts of the bay (Ibid). Sediment discharge to the bay is variable, and most sediment inflow occurs during infrequent large flood events such as the 1982 storm, which delivered approximately 160 acre feet of sediment to the bay (Anima, et. al., 1983).

The processes of sedimentation, resuspension and deposition by both tidal flow and freshwater flow from Lagunitas Creek have contributed to the morphology of both a deltaic salt marsh and tidal slough channels in southern Tomales Bay. The salt marsh delta is formed by flood flows depositing coarser alluvial sediments onto the intertidal mud and sand flats (PWA, et. al., 1993). Natural levees, typically 30 to 60m wide are created by the coarser material, and as the levees extend into the bay, they create backwater areas that are protected from wind wave action, which enables deposition of fine estuarine muds and the evolution of a vegetated marsh plain. Tidal slough channels are formed in the backwater areas by the scouring of the ebb and flood tides, and their geometry is related to the tidal prism and the marshplain they drain (Coats and Williams, 1987). Prior to levee construction, three main distributary channels existed in the Lagunitas Creek delta, each with low natural levees extending into the bay. The westernmost of these distributaries was disconnected from Lagunitas Creek when the marsh was converted to agricultural use (PWA, et. al., 1993).
Anthropogenic Alteration of Southern Tomales Bay

When Tomales Bay was first mapped in 1862, the site of the Giacomini Ranch was a mixture of salt marshes, intertidal mudflats and slough channels (Figure 8). When the area was settled during the latter half of the 19th century, agriculture, logging and grazing greatly increased sediment delivery to the bay, and by the 1980’s the southern part of Tomales Bay had largely filled with sediment (Evens, 1993).

In the period from 1861 to 1957, sedimentation reduced the total estuarine volume of Tomales Bay by about 20%, and an average of 1.2 ha/year of salt marsh was created. However, dam construction over the last 40 years to create reservoirs has greatly reduced sediment inputs, and protection of the upper watershed from disturbance will further reduce long-term sediment delivery to Tomales Bay (PWA, et. al., 1993).

In 1946 Waldo Giacomini began construction of a series of levees to drain marshland for conversion to dairy pasture. Since levee construction, much of the former marshplain has subsided due to compaction, drying and oxidation. Subsidence has been on the order of 0.3-0.6m. The levees have also subsided up to 2m due to settlement and compaction of underlying estuarine sediment (PWA, et. al., 1993). The channelization of Lagunitas Creek by levees has
contributed to a cycle of aggradation between flood events followed by scouring during floods, with a long-term trend of aggradation. Channelization has also contributed to the northward advance of the Lagunitas Creek delta. The shallow mudflats at the mouth of the creek appear to have reached an equilibrium depth limited by wave energy, and the most rapid sedimentation may be occurring in deeper water to the north of the creek mouth (PWA, et. al., 1993).

Perhaps the most adverse and controversial impact the Giacomini Ranch has had on Tomales Bay is the construction of a seasonal gravel dam across Lagunitas Creek (Figure 9). This dam is typically built in mid-May and is removed or washed out by mid-November; its purpose is to provide irrigation water for pasture grasses, which are sensitive to salinity. The temporary structure is about 3m high, 30m long and 2.5m wide at the top; upstream water level is controlled by an overflow weir, and a permanent fish ladder is installed (PWA, 1993). As Lagunitas Creek is home to 10% of the threatened central California coho salmon population (Evens, 1993), the controversy surrounding the seasonal dam was one of the reasons the National Parks Service decided to purchase the land and restore it to its former state.

**Restoration of the Giacomini Ranch**

In 1993, Philip Williams and Associates (PWA) prepared a report evaluating the feasibility of wetland restoration on the Giacomini Ranch. Several attributes of the property were identified as being conducive to viable wetland restoration: Most of the land is at an elevation suitable for tidal marsh restoration without the need for grading or filling; Removing levees along Lagunitas Creek would restore a natural area of sediment deposition, which would reduce transport of coarse sediments to Tomales Bay; and setting back levees along the Lagunitas Creek would allow for the restoration of riparian corridor vegetation on both banks of the creek. The eventual development of a gradient from low tidal to high marsh to upland vegetation would provide rare habitat for endangered species such as the California black rail (PWA, et. al., 1993).

Several proposals were considered and the option recommended by PWA utilizes a phased, adaptive management approach. The phased tidal restoration (Alternative E) would first restore the non-irrigated pasture to the west of Lagunitas Creek by breaching the levee at the northwest corner of the property and by lowering the levee constraining Lagunitas Creek (Figure 9). The 57ha parcel of the Phase 1 site would be monitored for approximately 5 years to best determine restoration strategies for the Phase 2 area. In the second phase, 35ha of less productive eastern
pasture would be restored to tidal action through the removal of a control structure and by breaching a levee. A temporary levee would also be constructed at this time to allow dairy operations to continue in the final restoration area. In Phase 3, the dairy would be decommissioned and the remaining 93 ha would be restored as tidal and riparian habitat. This would involve eliminating the seasonal dam, lowering the levee on the north side of Lagunitas Creek, and excavating preliminary slough channels to encourage tidal flow. A large portion of the levee on the east side of Lagunitas Creek would be retained as refugia for species displaced from wetland restoration. This approach is currently favored because it provides greater certainty of achieving desired restoration goals because it provides for feedback from monitoring activities at each stage to enhance the design for the next stage. The phased alternative also offers flexibility in timing of implementation and it allows for the optimal use in the investments made in dairy infrastructure while the restoration is under way.

As in the Sonoma Baylands Project, the Giacomini Ranch restoration is also hindered by an animal; in this case it is the milk cow. Although the ecology of Tomales Bay will benefit greatly from the restoration of its southern marshlands, the continued operations of the dairy will delay the benefits of restored marshes by at least a decade, and there is always the possibility that funds could become unavailable or that political fortunes may change. Linkage of the viability of the ranch to a dam across Lagunitas Creek is essentially choosing habitat for cows over endangered salmon.

The projected cost of the restoration project, including land acquisition, is similar to that of the Sonoma Baylands project, about $30,000–40,000 per hectare (PWA, et. al., 1993).
Figure 9. Phased Tidal Restoration
(From PWA, et. al., 1993)
**Additional Restoration Studies**

Like California, the State of Louisiana is also experiencing the effects of subsiding leveed agricultural lands, and over 80,000 ha of agricultural impoundments in the southern Mississippi delta have been abandoned due to saltwater intrusion or excessive subsidence. In 1995 a study was conducted by Trepagnier, Kogas and Turner, which examined aerial photos of the abandoned farmlands in 1978 and 1988 to determine the percentage of open water, as related to the percentage of the levee that was absent from active removal or natural deterioration. Open water on fields was usually associated with intact levees, as levees serve to inhibit sedimentation, and establishing vegetated marshland correlated with levee breaches, which allowed sediment to accumulate. A multiple regression model was developed to predict the statistical relationship between the change in open water over 10 years, and the independent variables of impoundment size and changes in levee enclosures. Results indicated that removal of 12% of levees could result in natural wetland restoration at a very low cost ($1/ha), although the rate of restoration was expected to be between 1% and 2% annually (Trepagnier, et. al., 1995).

Another study from Louisiana, in concept similar to the Sonoma Baylands project, examined a way to combine dredging and marsh soil replenishment as a unified process. The technology, named Jet-Spray®, deposits a thin later of material directly on coastal marsh by means of high-pressure spray dredging (Figure 10). This method was found to be effective at restoring marsh elevation and increasing vegetative cover (Ford, et. al., 1999).

![Figure 10. Application of Jet-Spray® technology in a Louisiana marsh](from Ford, et. al., 1999)
Conclusions

Upon reviewing current approaches to wetland restoration, it becomes clear that the geomorphic processes involved are complex, and that our knowledge seems to be evolving at about the same rate as the landforms, which is certainly rare in geomorphology.

The Sonoma Baylands project utilizes the most current understanding of marshland evolution, in that grass species colonization begins at a lower grade that climax marshplain, and that channel density is highest when this relationship is acknowledged. The construction of wave-breaker peninsulas is unique to this project, and the success of their role in hastening sedimentation rates is likely to have an effect of future restoration designs. However the damping effect of an undersized outlet channel will make isolation of the effect of wave mitigation difficult.

The proposed Giacomini Ranch project is more complex than the Sonoma Baylands in the geomorphic processes encountered, but simpler and more passive in design and construction. The long time of the phased implementation can both serve to optimize local knowledge of ideal restoration practices, but could also leave the project vulnerable to the winds of political change and a potential loss of funding.

The perspectives of the Louisiana studies provide low-budget alternatives to marsh restoration, but further research into the available sediment supply would need to be made before estimating the efficacy of applying the approach of Trepagnier, et. al. to California marshland restoration.

There is another experiment that can possibly have a profound effect on wetland restoration projects, and that is the effect of anthropogenic influences on climate, which is unfortunately an experiment with no control. Rising sea level caused by climate change could proceed far in advance of the adaptability of endangered marshland species, and wetland restoration projects like the ones examined in this paper may seem one day in the future to be nothing more than the quaint, futile acts of a time gone by.
Jim Pettigrew, Geography 810 - References


