CHANGING DELTA GEOMETRY AND ECOLOGY:

The Effects of Historical Landscape Modification on Water Quality and Ecosystem Structure in Suisun Marsh and the Delta

Proposal to the CALFED Science Program

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I. Background

Efforts to improve biological resources and ecosystem health in highly altered systems such as the San Francisco Bay-Delta have increasingly recognized the need to understand processes and functions at the landscape level (Cissel et al. 1998, Turner 2002). The cumulative effects of local projects cannot be assessed except in the context of understanding large scale patterns in landscape variability. At the same time, as efforts to restore and conserve natural resources have increased in recent years, more specific information about appropriate target endpoints has been needed. There is also a growing recognition that management strategies are often based upon conceptual models derived from relatively short-term observations about how the target systems operate (e.g. National Research Council 1992, Egan and Howell 2001), rather than aiming to establish or reestablish system-level physical processes in the context of changes in climate, geology (including hydrology) and land use that drive system form and function.

The long-term view is essential for distinguishing natural physical process from anthropogenic effects in a system shaped by several generations of landscape modification (Foster et al. 1998). By understanding the relative influences of people and nature on the target system, scientists and managers can identify what people have done, how that has influenced system behavior, and what can be undone or managed to achieve desired kinds and levels of system services. There will always be uncertainty or error in the analyses, but without them managers have little basis for forecasting system response to management actions, or even knowing what to measure as system response.

There are three empirical approaches for developing a long-term record of system response to natural and anthropogenic controls on the behavior of an ecosystem or its component habitats. One approach is to surmise from existing understanding, based mainly on short-term records, what should be measured and then monitor those things into the distant future. Another approach is to construct a long-term view based on data recovery and system reconstruction through the distant past. A third approach is to combine the two, using the historical information to improve models of system behavior, and using these models to identify what should be monitored into the future.

There are risky assumptions underlying all three approaches. By not looking into the past, there is greater risk of misunderstanding the roles of nature and people. This can severely confound later interpretations of system behavior relative to management actions. Forecasting the future based only on historical information assumes that the system will continue to behave as it always has, and that the relative roles of people and nature won't change. This can lead to an inability to foresee thresholds of change that might trigger crises. The combined approach yields the least risk because it involves the most information in setting a course of action and then provides a means of adjusting the course and improving forecasts as actions are taken (Swetnam et al. 1999, Hood and Hinton 2003).

II. Purpose

The purpose of this project is to use distinct yet complementary lines of environmental science to analyze the effects of historical modifications and natural processes on the form and function of the Delta and Suisun Marsh system (DSM). Based on this synthesis, the project will establish a stronger technical basis for the management of drinking water quality and habitat restoration opportunities in the DSM. Specifically, the project will address two sets of fundamental questions about the nature and human history of the DSM:

1) How have alterations to the pre-European hydrodynamic and transport characteristics of the DSM affected its salinity regime? Can strategic restoration of some of the natural hydrographic features of the DSM have significant beneficial effects on the dissipation of tidal energy and distribution of sediment and salt water?

2) What was the ecosystem structure and function that successfully supported native species, through substantial climatic variability, during the past 500 to 1000 years? What was the distribution of critical habitats across the DSM and adjoining estuarine, fluvial, wetland, and upland environments, and what template of physical processes sustained this mosaic of habitats? How might the selection and design of restoration and other management actions strengthen strategies to support critical ecological services in the future?

In this project, we identify a valuable and often untapped resource for understanding both current conditions and future scenarios in highly altered landscapes such as the DSM -- the vast amount of unexamined information about earlier conditions in the region. Extensive materials documenting the pre-settlement characteristics of the Delta and Suisun Marsh are available in numerous local archives, but have not been systematically compiled or analyzed.

When synthesized using a reliable methodology, these data can substantially resolve the difficulty of distinguishing natural process from anthropogenic effect in a system shaped by several generations of landscape modification (Foster et al. 1998). Such comparative analyses of past and present condition have been fundamental components of efforts to reestablish estuarine functions in major estuaries around the country (e.g. Collins et al. 2002, McVoy 2002, Collins and Grossinger 2004), and have the potential to identify a range of previously-unrecognized management options.

The historical data set will be analyzed using an integrated approach of GIS, hydrodynamic modeling, and expert geomorphic and ecological interpretation. While addressing a number of immediate management concerns related to the above questions, we expect that the project will also contribute a valuable spatial/temporal framework for integrating physical and ecological research and ecosystem restoration in the Delta and Suisun Marsh. This landscape framework will also help organize future efforts to address the effects of changing forcing functions, such as sea level rise, estuarine transgression, and watershed yields of sediment and water on alternative management scenarios.

The project will benefit from innovative, interdisciplinary collaborations in historical landscape reconstruction, estuarine modeling, tidal marsh geomorphology, and tidal marsh ecology. An expert team has been assembled through existing collaborations on related topics, and based on reviews of our recent presentations of that work at the Making Science Work for Suisun Marsh Workshop, CALFED Science Conference, Dutch Island Restoration Project, State of the Estuary Conference, annual national meeting of EMAP, Restoring America's Estuaries Conference, and the annual meeting of the Estuarine Research Federation.

The project's conceptual approach is designed to meet a range of management needs for Suisun Marsh and the Delta. Project products will include the following:

- **improved calibration of the RMA 2/11 hydrodynamic model**
- **new hydrodynamic modeling capability for natural wetland features**
- conceptual framework and modeling tools for the **identification of naturalistic hydrodynamic modifications to improve water quality**
- **stronger understanding of appropriate habitat characteristics for key species**, based upon actual historical habitat conditions rather than extrapolation from highly disturbed modern habitats
- technical basis for **performance measures** for habitat restoration and water management
- understanding of **natural spatial variation in DSM habitat characteristics**, as a basis for **sub-regionally appropriate habitat goals**
- **habitat restoration design guidelines**, using direct and modeled information about reference conditions

III. Project Description

This project uses historical landscape reconstruction, hydrodynamic modeling, and ecological/geomorphic interpretation to fill a suite of basic gaps in knowledge about how the Delta and Suisun Marsh operated as natural landscapes prior to Euro-American modification, how these modifications have affected physical processes that naturally control the landscape matrix of aquatic and wetland habitats, and the implications of these effects on future water quality and ecosystem management. This project builds upon existing and emerging science in a number of related fields to test hypotheses at a range of spatial scales, from local restoration projects to the DSM system as a whole.

A. PROJECT ELEMENTS AND CONCEPTUAL FRAMEWORK

Project Element 1: Historical Reconstruction of the Pre-settlement Landscape

Geology, climate, and land use interact at broad scales of time and space to control the distribution, quantity, and quality of estuarine habitats (Figure 1). Certain aspects of geology, especially topography, bathymetry, and hydrology (including sources, transport and storage of both water and sediment) establish the physical template for the formation of estuarine habitats. Climate, especially as it affects sea level rise and fluvial hydrology, controls the natural quantities and timing of water and sediment supplies.

Within estuarine habitats, especially within the intertidal zone, habitats are maintained by dynamic equilibria between inorganic sedimentation and vegetation production as driven by hydrology (variations and trends in seas level rise). An overall physical understanding of habitat characteristics prior to Euro-American modification is particularly useful as it both reveals the interactions between controlling factors under natural conditions during recent centuries and provides a baseline for anticipating and comparing the results of future shifts in climate and land use.

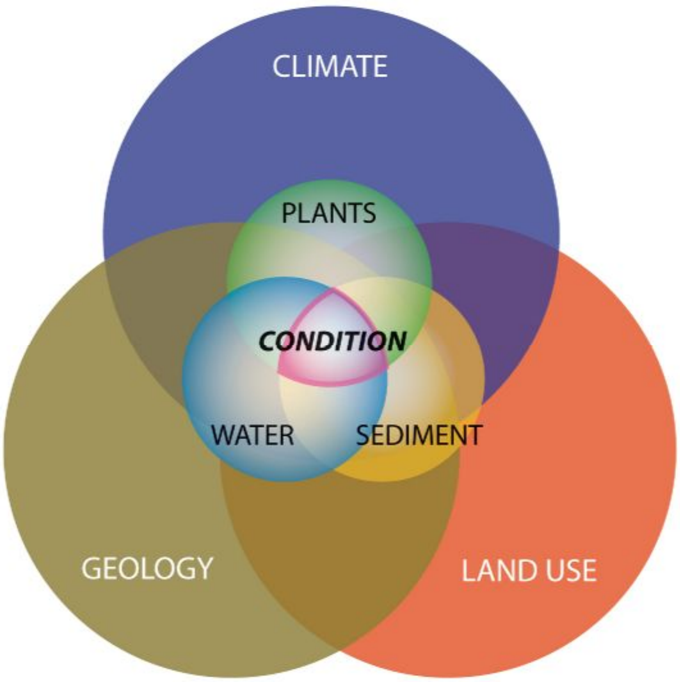

Figure 1: Spatial hierarchy of factors that control the condition of estuarine wetlands and related habitats. Conditions within the wetlands are directly governed by interactions between sediment supplies and water supplies, as mediated by vegetation. These interactions are ultimately controlled by climate, geology, and the specific history of land use.

Understanding these fundamental controls on estuarine form and function is gaining importance as natural resource conservation expands in planning and projects across whole landscapes (e.g. Egan and Howell 2001). The cumulative effects of local projects cannot be assessed except in the context of understanding large scale patterns in landscape variability. There is also a general lack of information about the subregional variation in habitat types to guide regionally appropriate restoration objectives. At the same time, as efforts to restore and conserve natural resources have increased in recent years, more specific information about appropriate target endpoints has been needed. For example, restoration planning at Dutch Slough has been hindered by a lack of information about the natural depth and landscape position of marsh ponds (Mueller-Solger personal communication). Historical information will help explain what kinds of habitats comprised different areas in the estuary and suggest the associated controlling physical processes (Figure 1). As Table 1 shows, almost all of the landscape modifications proposed for analysis in this project have not been previously studied.

Table 1. Some predicted changes in landscape structure for the DSM region as a result of anthropogenic modifications since 1850. Landscape characteristics that have not been previously analyzed or quantified for the region are identified in **bold.**

Historical Landscape Modification	**Previous Analysis**
decrease in tidal marsh area	Atwater et al. 1979, The Bay Institute 1998
shoreline change, i.e. marsh accretion/erosion	NA
loss of tidal channel networks	NA
change in distribution of salinity	NA
change in tidal currents	NA
channel bank erosion	NA
channel filling	NA
loss of shallow, ponded habitat	NA
loss of tidal marsh-upland ecotone	NA
increase in fluvial-tidal channel connectivity	NA

Documentation of the ecology of the historical marsh-upland transitional zones may be of particular importance because the remaining undeveloped areas of this zone and the adjoining uplands are not subsided and may represent much of the future opportunity for restoration, through breaching of peripheral levees and natural estuarine transgression. Modifications in the relationship between adjacent fluvial systems can have particularly significant ramifications on delivery and storage of water and sediment required to develop estuarine wetlands.

The broad latitudinal gradient represented by the watersheds feeding into the DSM also represents a significant gradient in climate. There was historically much less runoff entering the southern reaches of the Delta than its central and northern reaches; the timing of the runoff probably also differed **(**Goodridge 1991, Stahle et. al 2001, Dettinger 2002). These spatial variations in freshwater input around the margins of the historical DSM undoubtedly produced variations in habitat form and function. Understanding the subregional differences in the habitat mosaic as affected by differences in climate will provide a basis for anticipating effects of predicted future climatic changes. To be more specific, we might infer from the historical ecology of the southern reaches of the Delta what would be the overall response of the habitat mosaic to reductions in runoff, whereas the historical ecology of the northern reaches of the Delta may indicate how the southern reaches might respond to increases in runoff (Figure 2).

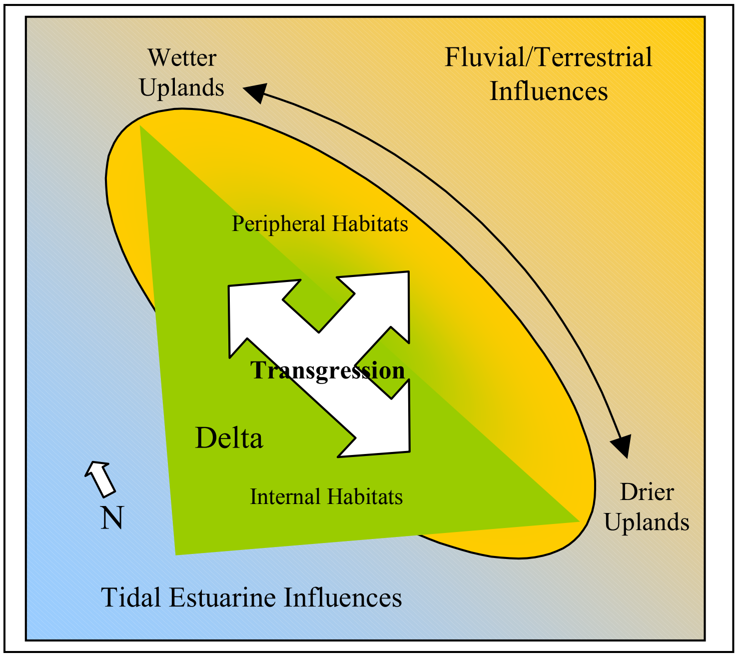

Figure 2: Schematic of delta landscape (green triangle) in the context of fluvial-terrestrial influences (brown shading) and tidal estuarine influences (blue shading), showing that estuarine transgression will move habitat internal to the Delta and peripheral to it inland and upstream into either drier or wetland climatic regimes, depending on latitude and climate change.

With an accurate map of historical, pre-Euro-American settlement conditions as a base, we will be able to analyze subsequent changes as a "retrospective" experiment in landscape response to human and climatic modifications. This portion of the project will involve analyzing the horizontal changes in shoreline position since historical times, before the effects of both diking and hydraulic mining debris. Complementary research has been carried out by USGS on bathymetric changes in Suisun Bay (Cappiella et al. 1999), but no work has addressed corresponding trends in the other side of the system -- the tidal marshlands. To date, there has been no regional baseline analysis to characterize whether marshlands in the region have actually been eroding in recent decades and whether there are variations between and within subregions. Yet accurate historical data sources are available to quantify shoreline change over approximately 50 year intervals since California statehood, with a denser time series for recent decades. This analysis would indicate for the DSM how sensitive the foreshores of tidal marshes, including mid-channel islands, are to changes in sediment supply. We would answer the question of whether perceived erosion/accretion of shorelines tends to be compensatory at any scale.

Recreation of the historical patterns of biogeomorphological outcomes at the Estuary landscape level can provide important background as to the relative importance of the two conceptual mechanisms of tidal marsh channel network formation presented here. Reconstruction of the historic occurrence of tidal marsh landscape features via mapping and narrative description provides a detailed picture of the ways landscape patterns (and biogeomorphologic processes) changed along historical estuarine gradients. This information can subsequently be used to determine to what extent proposed or existing tidal marsh restoration projects conform to historical and regionally important biogeomorphological process within the Estuary. This picture of natural landscape patterns within the Estuary will be of particular relevance to our understanding of potential restoration trajectories, such as the BREACH efforts currently underway (Reed et al. 2004), by providing different models of target marsh form associated with different parts of the Delta.

Project Element 2: Estuarine Habitat Hydrodynamics

With rising sea levels and the large-scale societal dependence on fresh drinking water supplies from the Delta, the inland excursion of saline waters is a major concern for state water management and CALFED research efforts. A major and often overlooked factor in the distribution of salinity is the actual physical form, or geometry, of the Delta and Suisun marsh, which largely controls the dispersion and trapping of tidal waters (Thompson 1957, Enright 2004). Because changes to the Delta took place so early in relation to Delta water management, the system has traditionally been considered relatively physically static. However, a significant component of the management challenges associated with salinity intrusion may be due to early changes in the Delta's geometry, rather than the amount of freshwater flows or diversions (CALFED 2004). Conversely, the identification and reinstallation of historical hydrographic features of the Delta may help manage increasing salinity challenges over the next decades, while making use of self-sustaining physical processes and improving Delta habitat.

In this context, we suggest that the most important changes to the DSM have resulted from alterations of its hydrology. Under natural hydrologic conditions, the development of estuarine habitats tends to be limited by exo- and endogenic sediment supplies (Krone 1987, Byrne et al. 2001, Morris et al. 2002), and salinity gradients vary continuously along the pathways of tidal excursion (Kimmerer 2004). Changes in sediment supplies can profoundly affect the distribution and abundance of estuarine habitats, but these sedimentary changes usually relate directly to changes in hydrology. For example, at the local scale of a tidal marsh drainage system, spatial variations in the relative importance of endogenic (biogenic) and exogenic (water-borne) sediments to marsh development are mainly controlled by tidal hydroperiod (Orr et al. 2003, Collins and Grossinger 2004). Salinity is the other strong immediate control on the nature of estuarine habitats, but it too is mainly controlled by hydrology. Salinity gradients vary continuously along the pathways of tidal excursion (Kimmerer 2004), and intertidal community structure varies strongly with aqueous and soil salinity (Jones & Stokes et al. 1979, Josselyn 1983, Schubel 1992). At the landscape scale, diking has effectively destroyed tidal marshlands, and has probably significantly altered salinity gradients within the remaining distributary channel system. Our study of estuarine habitat controls will therefore focus on hydrology.

The hydrography of the DSM represents a spatially complex physical plan form upon which tidal energy is routed and dissipated nearly two times each solar day. Hydrodynamic interactions between spatial plan form scales (marsh plain, tidal creeks, sloughs, channels, bays) determine sediment erosion, transport, and deposition, and influence salinity gradients, chemical transformations, and biological production (Fischer et al. 1979, Friedrichs and Perry 2001). The distribution of physical morphology ultimately controls dispersion and exchange of chemical and biological constituents between spatial scales (Dyer 1973, Jay et al. 1997).

We infer that native estuarine plants and animals, particularly endemic species that have been difficult to recover such as Sacramento splittail and Delta smelt, are well adapted to this historical morphology and its consequent hydrodynamic and transport complexity, and salinity gradient variability (Schubel 1992, Mount 1995, Bay Institute 1998). The characteristic spatial and temporal diversity of hydrodynamic processes and resultant salinity gradients and scalar transports together create the physical aquatic habitat that successfully supported the native resources that we now seek to recover.

Estuarine transport. A few studies in this region have focused on tidal flow through marsh channels (Leopold et al 1993, Siegel 1993, Warner et al. in press, Fagherazzi et al. 2004). The form of a tidal marsh channel in cross-section, profile, or plan view, and the net direction of sediment transport by channel apparently depends largely on the direction of dominant flow, although sediment grain size, vegetation types, and the bathymetry outside of the channel system are also important (Rinaldo et al. 1999). The following is a compressed version of a conceptual model of estuarine transport with emphasis on the influence of characteristic features like sloughs and channels on dispersion of scalars. The complete conceptual model can be viewed at <*www.sfei.org/CBDA/transport_model.pdf*>.

Estuarine hydrodynamics are observed as potential (stage) and kinetic (velocity) energy playing out a balance between physical energy sources (tides and rivers), and energy sinks (friction due to estuary geometry). Once in motion, water is imbued with momentum proportional to its mass and velocity. The energy from these external "forcings" is ultimately dissipated by frictional interaction with the bed (shear stress) and internally due to viscous dissipation across internal velocity gradients (eddies at all scales). The key concept is that all sources of friction generate velocity gradients. The result is that water parcels in the same channel cross-section will diverge over time because they are moving at different speeds. Gradients of velocity are often referred to as "sheared flow" or "current shear."

Fischer (1979) divided estuarine scalar transport into two components: transport caused by "advection," and transport caused by "dispersion." *Advection transport* by the net current is essentially the riverine inputs to the estuary. Scalar gradients (like salinity) are compressed by high outflow and decompressed by low outflow. This compression and decompression of the estuarine salinity gradient influences a third scalar transport mechanism called "gravitational circulation" where net river flow moves downstream over the top of a net upstream movement of ocean water, especially in the presence of weak tides and deeper channels (Dyer 1971).

Dispersive transport is caused by velocity gradients (current shear) that form in response to water movement across the essentially stationary but rough and irregularly shaped geometry of the estuary. Tidal forcing, because it is about an order of magnitude larger than movement caused by river flow, wind, or pressure gradients, causes most dispersive transport. Scalar dispersion also depends on the presence of concentration gradients. In order for dispersion (or mixing) to occur, there must be spatial differences in concentration (scalar gradient) to mix. Scalar dispersion is intensified when spatial scalar gradients are high and current shear is strong. Fischer distinguished three categories of tidal dispersion: 1) shear flow dispersion, 2) tidal trapping, and 3) tidal pumping. Each works by enhancing current shear.

Shear flow dispersion is caused by the friction of moving water on the bed that yields velocity gradients in the vertical and horizontal with concomitant mixing of longitudinal scalar gradients.

Shear flow dispersion is enhanced by geometric irregularities, natural or human made. *Tidal trapping* refers to differential tidal propagation in geometric irregularities. The key concept is that the pathway that tidal waves travel affects their propagation. Tidal waves traveling in open channels are called "progressive waves" because their energy is allowed to dissipate completely before being reflected. Tidal waves that enter embayments (or sloughs) are called "standing waves" because they are reflected back before dissipation occurs. Currents in embayments turn (flood to ebb or ebb to flood) sooner than currents in distributary channels. Where embayments and channels intersect, scalar gradients are mixed because of the asymmetry of tidal currents and the scalar gradients therein.

Tidal pumping is distinguished by the time scale of the velocity versus scalar concentration correlation. Tidal pumping is the "net" flow caused by asymmetry of adjacent tidal flows. In looped and braided channel systems like those seen in the modern Delta, the tide can often propagate to the same location by different pathways and arrive at different times. As a result, net flows are generated by a kind pumping action. These three tidal dispersion mechanisms operate together to mix scalar concentration gradients in the presence of current shear caused by geometric irregularities. The magnitude of scalar gradient mixing depends on the morphology of the estuary.

Comparing the pre-settlement and modern estuary geometry. The Delta and Suisun Marsh exhibit complex geometry that includes meandering and looped channels, terminal sloughs, embayments, and tidal creeks, all with different sizes and adjacent land uses. This complexity influences scalar transport by the mechanisms described above.

The fundamental modifications to the DSM plan form are 1) reclamation of low order sloughs by filling, 2) separating uplands from channel connection with levees, 3) removing channel meanders, and 4) cutting new channels between the main rivers. Figure 3 illustrates how former terminal slough and tidal creek systems were transformed into constructed channels that now connect rivers. This example is similar to the fate of False River, which presumably acquired its name from having a large opening to the lower San Joaquin River only to dead end in an extensive dendritic tidal creek system. The slough was leveed along its length, its high order channels filled, and its terminus extended to connect with Old River. Due to its position in the western Delta, and its ability to short-circuit tide propagation to Old River, the "improved" False River likely facilitated significant salinity intrusion into the central Delta.

In addition, ecosystem function that emanates from differential residence time along terminal sloughs was effectively eliminated. Residence time in pre-settlement False River varied with longitudinal position along the slough (Figure 3). At the extreme upper end, water remained in the slough even on extreme low tides. Residence time of this water was at least fortnightly, and exchange with the lower slough depended on wind and boundary layer shear dispersion. Moving downstream, an intermediate zone exchanged with the distributary channel only on spring tides and residence time had a spring-neap signature. Further downstream, residence time near the slough mouth was short, controlled by tidal current direction. Water and scalar exchange with the lower San Joaquin River was a function of tidal asymmetry between slough and channel (discussed above). Variation of residence time was likely to be non-linear from slough mouth (short residence time) to low order creeks (long residence time) with modulation by spring-neap cycle tide strength. Since residence time indexes several biochemical processes, a key goal of the hydrodynamics component is to characterize and map residence time and exchange characteristics as metrics of physical aquatic habitat.

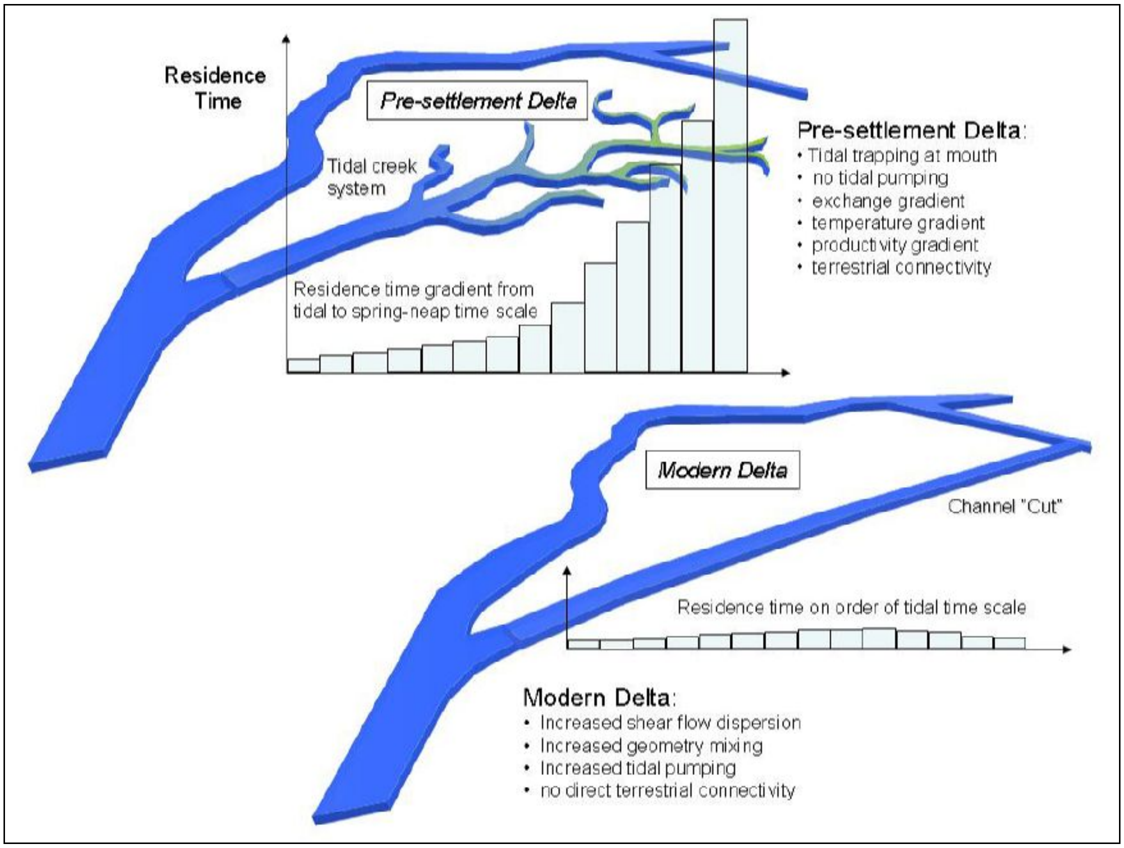

Figure 3. Conceptual model of water residence time in tidal creek system versus modern Delta channel cut. The pre-settlement Delta contained high-density tidal creek systems with differential residence time with position along the creek. The modern Delta reflects modification of tidal creeks into channel cuts with residence time on the order of the tide and extensive exchange with distributary channels.

Distributary channel dynamics have also been modified by addition of channel cuts in the Delta and Suisun Marsh. Distributary channels (e.g. Old and Middle Rivers and Montezuma Sough) are characterized by progressive wave hydrodynamics, long tidal excursions, and less terrestrial linkage. Residence time is short (tidal timescale) but exchange along the channel may be small or large depending on channel connectivity. Old and Middle Rivers were much more distinct in the pre-settlement estuary when tidal excursions were several kilometers but the water stayed (notwithstanding marsh plain interaction) longer in the same river. Channel cuts in the modern Delta and Marsh facilitate rather free tidal exchange of water and scalars between the rivers. The modern Delta is thus a more dispersive environment that tends to homogenize a system where scalar concentrations were likely more patchy.

While this project does not propose a full scenario planning exercise, we will investigate the "sensitivity" of the present-day landscape to the kinds of reverse modifications suggested by the pre-settlement landscape, to identify potential management concepts for modifying system geometry and associated salinity gradients and ecosystem structure.

Project Element 3: Landscape Linkages to Biogeomorphology

The scale of this study dictates that it focus on the dominant habitat types of the brackish and freshwater intertidal zone. These are tidal marsh channels, the marsh plain, tidal pannes or ponds and the intertidal backshore. For reasons explained below, tidal flats tend to be sub-dominant under brackish and fresh conditions and therefore are not emphasized in the proposed research.

Tidal marsh channels. It would be difficult to overemphasize the effect of tidal channels on the form and function of tidal marsh. All materials exchanged between the marshland and the estuary are conveyed via the channels. If the tidal marsh and flats – the "baylands" or intertidal zone - comprise a transition between the uplands and the deep bays or subtidal zone, then the channel banks comprise the immediate boundary. The banks comprise a threshold between aquatic and terrestrial processes. Above and beyond the banks, plants and animals with terrestrial lineage have adapted ways to live near water; below the banks, aquatic species have adapted ways to live near land. Landward of the banks, sedimentary processes are increasingly non-tidal; bayward of the banks, tidal processes control sedimentation. Channel banks are the intersection of air, land, and water. Many functions and services are concentrated within 10m of this intersection (Collins and Grossinger 2004).

Incipient tidal marsh channels tend to form on tidal mudflats as the result of largely stochastic processes coupling micro-scale topographical variation and ebb-tide drainage (e.g. Pestrong 1965). Small rivulets draining mudflat ponds or depressions provide conduits for delivery of tidal water to and from depressional back-marsh areas, and tend to concentrate hydraulic energies, particularly on ebb tides. These concentrated energies result in local erosion within and immediately adjacent to the enlarging incipient channels and in the establishment of a more-or-less stable channel network plan form on the emerging mudflat (assuming actively accumulating sediment). These small (generally no larger than a few centimeters wide or deep), newly-established channel networks are subject to modification or elimination via meteorological and tidal conditions such as sustained rains, winds, and tides. Stabilization of these mudflats and the channel networks within them depends upon subsequent colonization by emergent vegetation, which further improves sediment deposition conditions within the growing vegetation. In this way sediments and vegetation are linked in a feedback loop to promote active evolution of the mudflat and subsequently colonized tidal marsh plain. The marsh plain accumulates sediments upward and around the established tidal channel networks.

By similar mechanisms, tidal channels will form on existing land surfaces due to sea level rise and estuarine transgression. Under this scenario, newly tidally inundated lands become inscribed with incipient channels as floodwaters coalesce into rivulets on the ebb tide and erosion of the existing land surface begins. Initial erosion and formation of incipient channels on existing land surfaces in this case proceed in a fashion more dependent on the erodibility of the existing land surface. The erodibility is dependent on the nature and structure of the soils comprising that land surface, and as a result can be greatly dependent upon the overlying vegetation community whose roots play a large role in binding soils and resisting local erosional forces. In this way erosion and vegetation are linked in a feedback loop to foster development of an eroded tidal channel network accommodating the incident tidal prism and subsequent modification of the soil profile (via increased frequency and duration of inundation).

Studies from outside the region suggest that the larger channels on tidal flats become fixed in place as their natural levees or banks become colonized by vascular plants (Beeftink and Rozema 1988). For any salinity regime the density of channels decreases as the marsh plain evolves upward through the tidal range (Ahrnet 1960, Steel and Pye 1997). Higher marshes obviously have less water to drain, and channel networks tend to adjust in capacity to changes in tidal prism.

Considerable work has been done on the hydraulic geometry of tidal channels, meaning the relationship between tidal prism or drainage area and channel form in cross-section, profile, and plan view, usually in the context of designing channels for restoration projects (e.g., Collins et al. 1987, Collins and Orr 1988, Coates et al. 1989, PWA 1995, Siegel 1993). The typical log-log plots of hydraulic geometry reveal large variability around trends of increasing cross-section with tidal prism. For the systems studied, channels with base elevations above low tide gain cross-sectional area in the downstream direction due mainly to increases in depth. Further downstream, where base elevations are below low tide, the gains in area are mainly due to increases in channel width. The cross-sectional form of the high-order channels is complicated by slump blocks that occur on the outside of meanders and along both banks of straight reaches (Collins et al. 1987, Fagherazzi et al. 2004). The transition in cross-sectional form and downstream hydraulic geometry between third- and fourth-order channels seems to coincide with the transition from channels that evolved with the marsh plain to antecedent channels that evolved on the predecessor mudflat.

The relationships between plan form geometry and channel order has been examined across salinity regimes ranging from saline in far South Bay to fresh-brackish at the eastern end of Suisun (Collins and Grossinger 2004). Channel width, curvature, and wavelength tend to increase progressively from first- to sixth-order channels, although there is much variability within each channel order. These parameters do not seem to be affected by salinity regime. For each channel order, however, meander amplitude is greatest under the freshest conditions. Channel density for marsh islands (sensu Novakowski et al. 2004) is strongly correlated to island area, and tends to increase from fresh-brackish to saline conditions. Drainage area also tends to be greatest under fresher conditions, especially for the larger channel orders.

Amplified tidal ranges have been observed within zones of barotropic convergence, where the flood flow from two sources is combined (Collins et al. 1987, Warner et al. in press). This happens along the middle reaches of a “looped” channel that is open at both ends to tidal inflow. The amplification is due to increases in high tide, rather than decreases in low tide. The convergence happens within an elongated zone rather than a point because of the diurnal inequality of the high tide. If sediment supplies are great enough, the suspended load that is deposited in the convergence zone can lead to division of the channel into two drainage systems with independent tidal sources (Collins et al. 1987).

Marsh plain. As a tidal marsh matures, it gains elevation, its overall gradient flattens, its tidal prism decreases (Ahnert 1960, Redfield 1972), the total extent and cross-sectional area of its channels therefore eventually decrease (Steel and Pye 1997), the area of poorly drained marsh plain increases, and, for saline or brackish marshes, soil salinity on the plain probably also increases.

Studies of the physical nature of the tidal marsh plain have focused on sedimentary processes (Krone 1987, Collins et al. 1987, Culberson 2001, Callaway et al. 1996, Williams and Orr 2002, Siegel 2002, Watson 2004), including vertical accretion of tidal marshlands and its inland transgression during Holocene sea level rise (e.g., Byrne et al. 1994, Wells and Gorman 1994). As the marsh plain builds upward through the tidal range, the frequency and duration of inundation decrease, and the ability of the channel network to decant suspended sediment increases, such that less and less sediment is delivered to the marsh plain. As the plant cover becomes denser, it functions to filter sediment from the flows of water across the marsh plain, such that the inorganic sediment is trapped near the channel banks (Collins et al 1987, Culberson 2001, Eisma and Dilkema 1997, Culberson et al. 2004). In advanced stages of tidal marsh development, inorganic sedimentation is largely restricted to areas within a few meters of the channel banks. In the middle reaches of very large drainage divides, organic matter accounts for most of the volume of the sediment pile, indicating very little input of inorganic sediment. At the landscape scale, this model predicts that soils in the interior reaches of the Delta would be more organic than at the edges. Sediment cores and subsidence patterns support this prediction (DWR 1993).

Marsh ponds. Marsh ponds or pannes are topographic depressions on the plains of mature tidal marshlands. In this region, marsh pannes are most common at places most distant from any tidal source, as measured along the pathway of tidal excursion within a marsh. They exist on drainage divides between channel networks, and near the backsides of natural levees (Collins and Grossinger 2004).

Different formative processes have been identified for marsh pannes in different climates (Yapp et al. 1917, Kesel and Smith 1978, Pethnic 1974, Pethnic 1992, Christie et al. 2002, Ewanchuck and Bertness 2004). In all cases the feature is sustained by the entrapment of salts and persistent saturation of the benthic sediments that inhibits plant growth. The feature must also be isolated from supplies of in-filling suspended sediment. The larger pannes form away from any tidal source, where the inputs of inorganic sediment are minimal, and marsh accretion is largely due to organic sedimentation. Isolated topographic depressions in these areas might result from differential rates of peat production. Marsh pannes vary in number and size in relation to tidal salinity regime, with fewer but larger pannes existing under fresher conditions (Grossinger 1995). However, the historical condition of freshwater tidal marshlands typical of the Delta has yet to be described. Whether or not these marshlands have a greater amount of ponding per unit area of marsh plain, as predicted by the model, remains to be determined.

Intertidal backshore. The backshore is defined as the ecotones between the tidal marshland and the adjoining upland. Its breadth is directly proportional to the steepness of the upland terrain. Where the estuary was transgressing over flatlands, such as the Central Valley, the historical backshore was undoubtedly very broad. For Santa Clara Valley in South Bay, which historically rose very gradually from the tidal marshlands, the backshore was miles broad (Collins and

Grossinger 2004). The onshore surface winds that are typical for the Santa Clara Valley and the Delta can broaden the backshore by the aeolian deposition of salts carried inland from the estuary. Thus, the backshore can extend inland beyond the direct influence of the highest tides.

Restoration of intertidal habitats in the historical peatlands of the western and central Delta is challenged by their severe subsidence (CDWR 1993). Sea level rise will continue to elevate the challenge in the future. In contrast, sea level rise and estuarine transgression may represent an opportunity to restore intertidal and related habitats of the backshore. Existing and proposed land uses within and around the Delta will constrain opportunities for backshore restoration. Nevertheless, we suggest that an examination of the nature of the historical backshore is necessary to define the restoration opportunities that might exist. Elsewhere in the estuary, where tidal marsh and aquatic habitat restoration is proceeding at large scale, backshore restoration is gaining emphasis. We expect that a study of the historical extent and structure of the backshore of the Delta will result in discoveries of its past ecological functions that will significantly help shape restoration planning in the future. That has been our experience elsewhere in this estuary and in other coastal systems

Tidal marsh dynamics. Marshes that achieve equilibrium with sea level rise are not static. Although the larger channels (fourth-order and larger) migrate so slowly (Fagherazzi et al. 2004) that modern aerial images and historical maps of them overlay almost exactly (Grossinger 1995), there is a dynamic relationship between plant growth and tidal flows that is manifest as more rapid changes in the distribution of smaller channels and marsh pannes (Collins et al. 1987). For very large drainage systems (fourth-order and larger) in saline marshes, channel retrogression at the ends of some channels tends to be compensated by headward erosion in other channels, such that there is no net change in channel capacity for the system as a whole. In general, the retrogression happens in small tributaries, and the headward erosion happens as an extension of the mainstem. The mechanism for this compensation between channel loss and gain is not well understood. In these large systems the ongoing loss of some small channels is evidently insufficient to affect a change in the cross-section of the tidal source; the amount of tidal prism equal to the amount of channel lost is apparently shunted along the hydraulic gradient of the flood flow from the retrogressed tributaries to the end of the mainstem that subsequently erodes headward to accommodate the increase in tidal prism (Collins and Grossinger 2004). If this process of tidal prism conservation is real, then it follows that naturalistic systems of fourth-order or larger are minimal to sustain all the ecological and hydrological services ascribed to channels large and small. According to Collins and Grossinger (2004), the drainage area of saline marshland encompassing such systems ranges from 0.5 km^2 (fourth-order) to 0.75 km^2 (fifth-order). If the same mechanism of tidal prism conservation exists in brackish marshes, then the minimum size of sustainable marsh drainages might be 0.25 km^2 (fourth-order) to 1.5 km^2 (fifth-order). The patch size for freshwater tidal systems is unknown.

As has been shown by previous researchers (Atwater and Hedel 1976, Harvey et. al 1977, Culberson 2001) vegetation communities change with soil salinity gradients characteristic of the Estuary. Owing to the underlying importance of plants and their effect on the processes of tidal channel formation outlined above, we expect to find landscape-level relationships between tidal marsh geomorphology and plant community composition. We refer to these relations as being bio-geomorphological because they represent the strong geomorphic influences of biological or biogenic processes, especially plant growth on tidal marsh geomorphology. For example, we know that the species composition of marsh vegetation along channels and the foreshore changes with salinity regime, and that the vegetation grows at lower elevations under fresher conditions (Atwater and Hedel 1976). Under fresh-tidal conditions, native plants can thrive near MLLW, whereas native plants in saline conditions seldom grow at elevation lower than MSL. This means that the extent of tidal flats decreases as salinity decreases. The lower intertidal zone between MSL and MLW that would be tidal flat under saline conditions is low marshland under freshwater conditions. This also means that the beds of tidal marsh channels seldom extend much above MLLW under freshwater conditions. Consequently, the lengths of low-order channels and the overall density of channels are probably less under fresh conditions than saline conditions. It follows that channels in saline marshland would be more sinuous, networks would be more complex (higher-order), and drainage divides would be smaller than comparable areas of marshland   The larger drainage divides predicted for freshwater marshes would represent larger areas poorly serviced by channels, and thus might account for the larger pannes or ponds that are also predicted for freshwater tidal marshlands.

The geography of the Delta and its watersheds provides a special opportunity to describe the possible effects of alternative climate change scenarios on the future Delta ecosystem. From South to North in watersheds draining to the Delta, there was historically almost 100% increase in mean annul precipitation and presumably runoff (Goodridge 1991). The drier conditions of southern backshore must have affected its plant and animal communities. The ecology of the natural levees along the main tidal channels were probably also affected. For example, a cursory investigation of the tidal-fluvial riparian overstory as depicted on historical lithographs indicates that southern channels were bordered by oaks, whereas northern channels supported cottonwoods. Thus, the historical differences in community structure along the north-south moisture gradient of the backshore and riparian zones may provide basic clues about future ecological responses to increases or decreases in precipitation and runoff.

B. METHODS AND PRODUCTS

Project Element 1: Historical Reconstruction of the Pre-settlement Landscape

Reconstructions of landscape characteristics prior to extensive Euro-American modification have been developed in recent years to guide major ecosystem restoration efforts for many of the most important wetland systems in the United States.

In the Puget Sound, a multiyear project to develop a GIS of the historical lowland rivers and delta systems is a foundation component of the Puget Sound Nearshore Ecosystem Restoration Study, the multiagency program to develop a regional restoration plan. The Puget Sound River History Project involves georectification of historical maps and photography, development of a GIS, and analysis of changes to geomorphic/hydrologic processes and fisheries habitat (Collins et al. 2003).

In South Florida, a number of collaborative efforts have been developed as part of the USGS South Florida Ecosystem Program to understand the interrelated effects of changes in hydrology, vegetation, and species support functions. Schaffranek et al. (2001) summarize the use of historical documents to identify hydrological and ecological changes and the application of GIS and numerical model techniques to assess flow modifications (McVoy 1996). Related efforts in the Florida Ecosystem History Project are designed to document subregional variation in the historical ecosystem and differences in response to modification (Willard 1996).

Similar efforts have been integral to regional wetland management efforts in the San Francisco Bay Area. A GIS-based historical reconstruction of the tidal marshland ecosystem downstream of the Delta provided technical foundation, numerous insights into ecosystem function, and a basis for regional thinking for the Bay Area Wetland Ecosystem Goals Project (SFEI 1998; Goals Project 1999). Subsequently, SFEI was asked by the Science Team of the South Bay Salt Pond Restoration Project to extend the regional assessment to provide a more detailed analysis of pre-modification tidal hydrography and ecosystem function for South San Francisco Bay. This analysis reported on numerous previously undocumented aspects of the South Bay ecosystem, including the complexity and subregional variation of tidal channel networks, the discontinuous relationship to local streams, and the historical existence of a range of forgotten habitat types that supported native species of concern (Collins and Grossinger 2004, Grossinger 2004). The editors of *Estuary and Watershed Science* have solicited publication of Collins and Grossinger (2004) for publication in 2005.

Grossinger (2004; also summarized in Brown 2004) described the preliminary state of knowledge about the natural landscape characteristics and functions of Suisun Marsh, particularly the limited information about natural waterfowl support and salinity/habitat characteristics of the middle and eastern parts of the marsh. Initial investigations suggest that historical data are available to support equivalent efforts in the Delta and Suisun Marsh. However, these data have not yet been assembled and compiled in a rigorous way to support quantitative and functional analyses.

The historical reconstruction of the DSM system will build upon earlier, partial efforts by several researchers by incorporating numerous additional historical data sources. Thompson (1957) carried out a voluminous study of historical land use, with extensive references and some descriptions of historical conditions. As part of a USGS geological mapping of the Delta, Atwater (1982) used historical maps and aerial photographs to map many of the smaller historical channels of the central and southern part of the Delta. Bingham (1996) provided a qualitative overview of the history of the Delta. Vorster and others (Bay Institute 1998) compiled several sources, including SFEI maps, to produce general historical maps of the San Francisco Bay Delta system from the Golden Gate to streams of the Sierra Nevada, including the Delta and Suisun Marsh. SFEI compiled initial historical data for Suisun Marsh as part of the San Francisco Bay regional wetland mapping (SFEI 1999, Grossinger 2004b).

While these previous studies provide a strong foundation for the present work, they focused on coarse scale ecological description and used a limited number of data sources. Through this effort a fuller, locally-oriented analysis will be carried out, reflecting the full range of historical data available and providing the detail/accuracy of necessary to address technical management questions.

To create a reliable historical assessment, a wide range of data sources must be collected. Patterns and trends become visible only with a substantial volume of historical data. The crossreferencing of documents of different type and origin also provides the most objective way to determine the accuracy of historical data. SFEI will use existing relationships developed over the past 10 years with most of the key archives pertaining to the San Francisco Bay-Delta to create a robust data set, including the Bancroft Library, the California State Library, California State Lands Commission, National Ocean Survey, National Archives Records Administration, and many others.

For plan form information about presettlement DSM geometry, historical USGS quadrangles (early 1900s), Tide Lands Commission maps (circa 1870), Debris Commission maps, city and county surveys, and “ghost images” in early aerial photography will be consulted. Navigation maps and hydrographic surveys will be collected for channel depths and cross-sectional information. Numerous additional sources will be obtained for valuable descriptive information that can be associated with specific locations and extended more broadly. Some examples are shown in Figure 4.

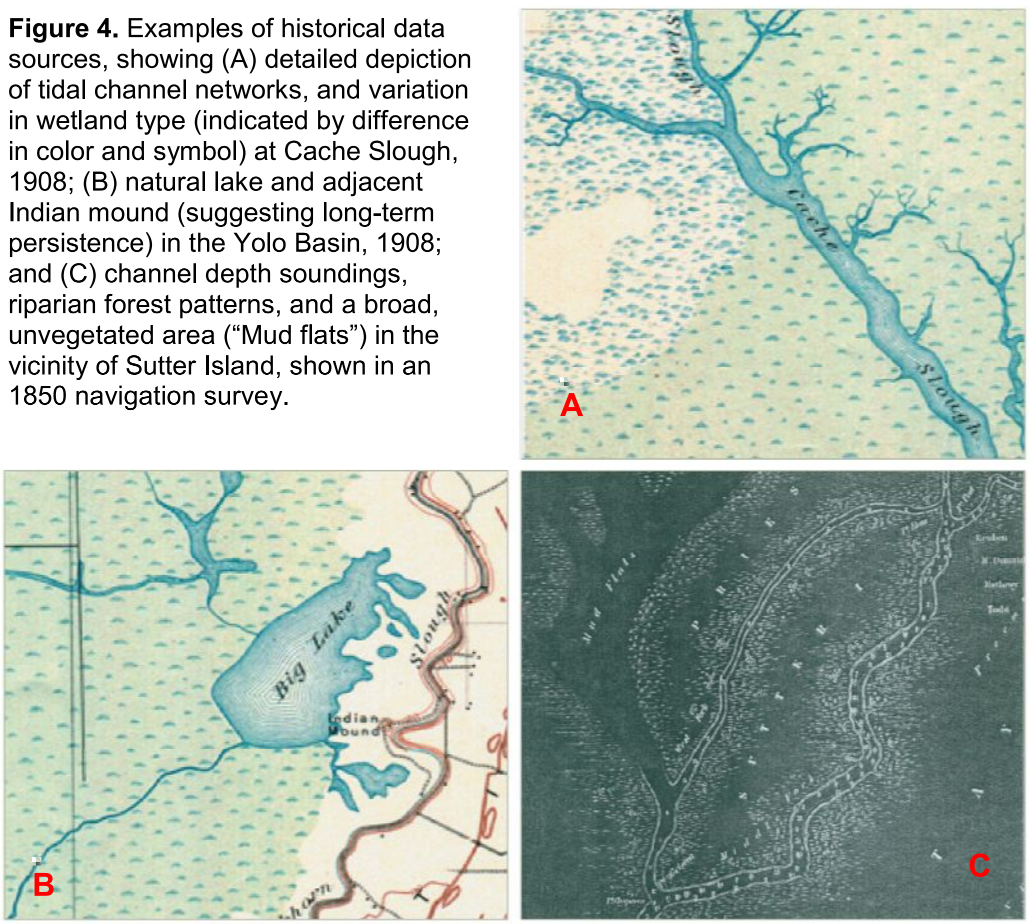

Figure 4. Examples of historical data sources, showing (A) detailed depiction of tidal channel networks, and variation in wetland type (indicated by difference in color and symbol) at Cache Slough, 1908; (B) natural lake and adjacent Indian mound (suggesting long-term persistence) in the Yolo Basin, 1908; and (C) channel depth soundings, riparian forest patterns, and a broad, unvegetated area (“Mud flats”) in the vicinity of Sutter Island, shown in an 1850 navigation survey.

An important source that is generally overlooked is the Spanish/Mexican era documentation associated with the land grant cases. A number of land grants are located along the outer Delta and should provide specific legal testimony about early features as part of efforts to establish land boundaries. This information will be particularly useful for questions about the tidal marsh-upland ecotone.

Historical data will be converted into accurate geographic data sets and associated attribute files using established techniques for georectification and synthesis (Grossinger 2001). Selected historical maps and aerial imagery will be georectified to a high degree of precision using ArcGIS and ERDAS software packages. A recognized leader in historical mapping, SFEI recently converted a set of 1850s era Coast Survey maps for the South Bay into modern coordinates with correspondence <15m in most places (Grossinger et al. 2004).

Data synthesis will involve interpreting historical cartographic, visual, and textual representations into modern wetland and geomorphic classification systems. SFEI has carried out similar work in the San Francisco Bay and is currently leading the National Wetlands Inventory for the region. The habitat type classification system will be developed in concert with the TAG. As in other advanced historical reconstruction efforts, mapped features will be coded on a feature-by-feature basis for certainty level (Table 2) and source information (Grossinger 2001). This critical step allows other researchers to assess the accuracy and origin of features of interest in future research efforts.

Table 2. Typical Certainty Levels for GIS-based Historical Landscape Reconstruction (after Grossinger 2001).

	Interpretation	**Size/Shape**	**Geo-rectification**
High	"Definite"	+/- 10%	Within 100 feet
Medium	"Probable"	+/- 50%	Within 500 feet
Low	"Possible"	Defined by case	Within 2000 feet

Based upon the results of GIS development, a range of landscape ecological metrics will be calculated for the historical landscape. These will include relative abundance, subregional variation in habitat distribution, habitat associations or "complexes", and other standard measures (Table 3). A significant measure of overall system function may be the calculation of amount of shoreline, or "edge" (Collins et. al 2004).

Table 3. Some of the expected habitat characteristics of the pre-settlement landscape and likely historical source data, based upon previous research.

Habitat Characteristic	**Source materials**
Channel density, channel width/number vs. distance upstream	USGS, US Coast Survey, early aerials
Channel depth, cross-section	Hydrographic surveys, Army Corps, narrative descriptions
Tidal marsh-upland ecotone	Spanish land grant case materials, landscape painting/photography, ranching/agricultural history, soil surveys
Tidal marsh ponds, pond size, pond depth	USGS, US Coast Survey, hunting descriptions, indigenous information
Riparian forest extent and width, location/size of sausals (willow groves)	Spanish maps, Gold Rush era maps, travelers descriptions

On the Suisun and Contra Costa shorelines, where larger or fringing tidal marshes still exist, changes in shoreline position will be analyzed at 20 to 40 year intervals, between 1866 and 2005, using a combination of historical maps and aerial photography, with special attention to tide levels and datums. These analyses will represent the first time most of these variables have been measured for the DSM system. All analyses will be reported with assessments of certainty level.

Deliverables

1. **Annotated bibliographic database.** Database will catalog historical reference materials of use to DSM environmental research (Endnote and/or other standard database format).
2. **Technical memorandum** describing historical data acquired, technical topics addressed by the data, and data gaps.
3. **GIS documenting pre-Euro-American settlement conditions in the DSM.** GIS coverages, associated attribute tables, georectified imagery in standard ESRI ArcMap Shapefile and geo-tiff formats, with standard metadata.

Project Element 2: Hydrodynamics and Transport Modeling

We will describe the essential physical attributes of the pre-settlement DSM and submit this data to an advanced finite element estuary model to develop metrics of hydrodynamics and transport habitat for the pre-settlement estuarine plan form and bathymetry. These physical habitat metrics will integrate a variety of spatial and temporal dimensions amenable to geographic quantification and display. We will compare the derived physical habitat metrics to the same metric suite observed in the modern DSM plan form. We suggest that the differences in physical habitat metric expression between the modern and historical plan forms are candidate performance measures for ecosystem restoration initiatives in the DSM.

We propose to leverage a mature numerical modeling system that has been extensively tested and applied in the San Francisco Estuary. The RMA 2/11 finite element model is a full-featured hydrodynamics/water quality modeling system of the full Bay-Delta estuary. It is (and continues to be) calibrated and validated against all available historical velocity/flow and salinity data (for example, CALFED 2001). Preliminary investigations into the changes in plan form and cross-section of the Delta and Suisun Marsh have been undertaken by Chris Enright, using the RMA 2/11 hydrodynamics/water quality model and preliminary historical data. The model is capable of solving the shallow water and advection-dispersion equations in one, two, or three dimensions.

The RMA 2/11 models include the following essential features: 1) They are calibrated and verified on a grid that includes the full Bay-Delta Estuary with downstream boundary at the Golden Gate, and upstream flow boundaries at the limit of tidal propagation (approximately Sacramento, Vernalis and other eastern Delta rivers.); 2) Modules for bed and suspended sediment transport estimation are included; 3) The model allows a moving “wetting and drying” boundary for inter-tidal areas; 4) All computational points, both inputs and output, have geographical reference; 5) The model facilitates process analysis with tools for signal processing, Eulerian and Lagrangian tidal excursion, wave characteristics, tidal datum, and tidally averaged current and transport. Static and animation displays are seamlessly integrated because they are essential for comparative transport process understanding.

However, recent analyses using the RMA 2/11 models have been limited by the lack of a reliable historical data set. Using the data from the presettlement reconstruction, we will model the effects of reductions in channel extent, density and position; changes in channel depth; and the series of human-made channel cuts, shipping channels, and subsided open water areas. By isolating the effects of these different physical modifications to the system (produced during different eras for different purposes and with varying present-day value), we expect to be able to identify potential future scenarios for managing Delta geometry to maximize ecological and water quality benefits.

Model applications for process analysis. The RMA 2/11 model has extensive output post-processing capability designed to support transport mechanism and comparative analysis. The Project team expects to work collaboratively through regular meetings on landscape process science. To support and elucidate emerging hypotheses, we will prepare simulations of pre-settlement and modern Delta and Marsh plan forms with identical boundary conditions (river and creek flows, Golden Gate tide, and facilities operations). We will provide the team with executable animations of predicted tidal and residual velocity and salinity fields along with spatial maps and animations of the tidal datum, wave progressivity, tidal excursion, and unit and cross-section salinity fluxes. In conjunction with *in situ* data, these products encapsulate complex hydrodynamics and transport processes and support mechanistic analysis among the PI’s.

Model advancement. This project will contribute significant advancement of the RMA 2/11 model, currently a critical tool for hydrodynamic analysis of the Bay-Delta system, by increasing its ability to represent the complex tidal marsh features characterizing both the historical landscape and the presumptive results of current and proposed restoration projects. Model validation for the historical data set will significantly improve the modeling of tidal channel networks, nontidal channels, and other natural hydrographic features, which will be useful for many other efforts. The comparative past/present application of the model is likely to initiate greater use of comparative, scenario-testing efforts in the future.

Physical habitat metrics. We propose to use the RMA 2/11 model to compare the modern and pre-settlement Delta and Marsh by developing several metrics of physical aquatic habitat.

1. <u>Residence time</u>. We will use Lagrangian particle tracking to and numerical tracers to map water residence time in the pre and modern systems. Residence time is a fundamental physical index because it is correlated with temperature, dissolved oxygen, and primary productivity, as well as providing physical refugia for less motile invertebrates and small or early life-stage fish.
2. <u>Wave progressivity.</u> Correlation between tide height and tidal currents indicate the wave progressivity. Currents and stage height are less correlated in sloughs and more in channels. Slough-channel connections are locations where tidal trapping occurs. We will map the spatial extent of wave progression gradients as a metric of tidal trapping tendency.
3. <u>Salinity gradients.</u> Tidal trapping in tends to “trap” ebb tide water at the head of sloughs while slough mouths tend to track mean channel salinity. Sloughs can thus provide relatively larger salinity gradients over shorter distance than channels. We will generate a metric of salinity gradient “compression” to characterize local salinity variability.
4. <u>Hydraulic convergence zones</u>. Looped channel networks offer alternative pathways for tide propagation to the same location (Collins et al. 1987). Regions where tides converge exhibit low and chaotic velocity signals. They are loci for sediment and perhaps contaminant concentration. There approximate location can be identified as narrow reaches of looped channels in plan view (Collins et al. 1987, Collins and Grossinger 2004). We will develop a metric of current velocity to describe the occurrence of tidal convergence zones in hydraulic terms.
5. <u>Tidal excursion/bifurcation index.</u> The relation of tidal water excursion in channels to the characteristic distance between channel bifurcations (i.e., the average length of channels of each order) controls exchange between distributary channels within the channel network.
6. <u>Tidal pumping.</u> Tidal pumping is a residual current transport mechanism caused by tidal current asymmetry.
7. <u>Flood-</u> and ebb-domination. The dominant flow direction within channels can control the net direction of sediment transport within tidal marsh channels. We will test meander asymmetry (Rinaldo et. al 1999) as an indicator of dominant flow direction.
8. <u>Flux decomposition.</u> *Fluxes* are Eulerian metrics that integrate scalar transport in time. Flux measurements reveal not only how much mass crosses geographical boundaries, but they can also elucidate transport mechanisms. High frequency data collected *in situ* will be processed using digital filters and timescale correlations between flow and scalar concentration to determine the contribution to flux from advection and dispersion processes.

Deliverables.
In addition to collaborative modeling to elucidate emerging hypotheses among the project team, several stand-alone modeling tasks will be completed:

1. **Model Validation Report.** Report documenting the validation/calibration of the RMA model to field velocity and stage data.
2. **GIS Analyses.** GIS based metrics maps that quantify the spatial and temporal differences between physical habitat metrics in the pre-settlement and modern Delta/Suisun Marsh. This includes wet and dry hydrology maps of residence time, wave progressivity, hydraulic convergences, tidal excursion/bifurcation, flux decomposition components (advective and dispersive transport), salinity gradients, and a suite of landscape ecology metrics.

Project Element 3: Landscape Linkages to Biogeomorphology

In this component of the project, the new findings about the characteristics and distribution of pre-settlement habitats will be analyzed from a geomorphic and ecological perspective. The bio-geomorphic processes, as influenced by salinity and tidal prism, create and sustain a mosaic of habitats for native and introduced plants and animals throughout the estuary. We expect that discoveries will be made about the historical extent of habitats, the number of habitat types, and the complexity of habitat mosaics at various scales ranging from restoration projects and tidal Delta islands to the DSM system as a whole. The habitat preferences for many key species are well known and are documented through the primary literature and major conservation plans (e.g., USFWS 1992, Goals Project 2000, Moyle 2002).

To describe the likely ecological functions of the historical DSM, information will need to be extrapolated from the modern mosaic that has been studied to the historical mosaic that represents restoration potentials. We intend to translate the matrix of historical major habitat types into expected support functions for key species of plants and animals, based on best professional judgment. To achieve this, we will work through our TAG to access wildlife experts who can annotate the matrix and supporting maps. The product will be a GIS coverage of expected ecological support functions of each major habitat of the historical DSM ecosystem, with spatial variations as warranted by expert advice. In other regions (Goals Project 1999), this has been a successful method of synthesizing bio-geomorphic analyses and historical ecology into a picture of potential ecosystem support that can be readily understood by resource managers, serve as a reference against which future habitat matrices can be compared, and easily revised based on new information.

Deliverables

1. **Two technical memoranda** with preliminary interpretation results, timed for Technical Advisory Group meetings**.**

2. **A GIS coverage** of historical habitat types with their expected ecological functions for selected species.

C. TECHNICAL ADVISORY GROUP

The project will rely on a specially assembled, interdisciplinary Technical Advisory Group (TAG). The TAG will serve two purposes: (1) to advise the project team on specific technical issues, and (2) to connect and integrate the project with appropriate related efforts within the CALFED and broader scientific community. Given the interdisciplinary scope of research, experts from a diverse range of fields have been, or will be, recruited. The TAG will consist of scientists and resource managers specializing in Delta and Suisun Marsh ecology, geomorphology, hydrology, sediment transport, land use history, conservation, restoration, and water project operations.

TAG members will receive quarterly project updates and meet with project team members once a year to discuss and refine the project work plan (year 1 and 2) and analysis and interpretation of project results (year 2 and 3). With their breadth of knowledge about Delta and Suisun Marsh research, management, and history, TAG members will ensure that this project meets its goals of delivering high-quality and timely information that will answer current management questions and provide the basis for a new, integrative ecological and ecosystem restoration framework for the Delta and Suisun Marsh. The TAG currently includes the following technical experts who have already agreed to contribute; additional members will be contacted upon project initiation.

Initial Technical Advisory Group Members

Brenda J. Grewell, Ph.D., USDA	*Wetland Plant Ecology*
Professor Matt Kondolf, UC Berkeley	*Fluvial Geomorphology*
Professor Peter Moyle, UC Davis	*Ecology, Fisheries Biology*
Peter Vorster, The Bay Institute	*Hydrology, Bay-Delta History*

Deliverables

Technical advisory committee meeting summaries

D. ANALYSIS AND REPORTING

Project results will be summarized and presented in several forms. The technical products of the historical landscape reconstruction and model validation will be presented as new tools for estuary science, made available to other researchers through the project web site. Results of the interdisciplinary analysis, including the contributions of the TAG, will be presented as technical findings with management implications, in the scientific literature. Broader public access will be provided through general-audience historical images, map products, and project information on the web site. We will also propose a special session at the CALFED Science Conference to present the interdisciplinary results of the project.

Deliverables

1. **Technical Reporting.** The summary report will present project methods, findings, and implications, in the form of coordinated journal submissions to peer reviewed technical publications in the appropriate fields, including *Estuary and Watershed Science.*
2. **Local Presentation of Findings.** Submissions to IEP newsletter and *CALFED* Science *Conference* presentation.
3. **Project Website.** SFEI will host a project website providing extensive access to project materials, including a project description, general-audience press release, selected historical imagery, and all project deliverables. GIS files will be available for download. Website design will be based on popular SFEI websites such as the South Bay Salt Pond Restoration Project site and the Bay Area Stream Fishes site.

IV. Priority Questions

This section demonstrates in more detail how the goals of the project address current management issues.

A. WATER OPERATIONS AND KEY SPECIES

There is a substantial and growing interest in addressing issues of water operations and their effects on key species in the Delta at the level of system processes (rather than solely the immediate localized effects of pumps and diversions), to ensure long-term population-level success. The Science Program has identified this issue as a central priority in the 2004 PSP. A number of relevant, exemplary questions have been presented in the PSP. This proposal will directly address many of those questions, albeit from a new, previously unexamined perspective, with applications at both the system-wide and local levels. Several examples are listed below.

What are the population-level effects of large and small water diversions in the Delta and small diversions throughout the Bay-Delta system on salmonids and delta smelt at different life stages?

Creating a robust, habitat-level picture of pre-modification conditions in the Delta will establish a functional understanding of the habitat types and mosaics that successfully supported populations of salmonids and delta smelt during recent centuries, with varying levels of water input. Currently, assessment of population level processes in these species is based on observations of their habitat use in a highly disturbed, fragmentary ecosystem. The study will establish a much better understanding of the actual habitat characteristics (tidal slough geometry, currents, salinity, vegetation) that supported different stages in the life history of key species. Secondly, in the modeling component we will be able to directly compare the effects of water diversions of different size and spatial arrangement on the pre-modification and current landscapes, indicating the sensitivity of the present-day regional habitat structure to water operations, and suggesting scenarios for improvement.

What are the ecological benefits of the different uses of environmental water assets in streams, rivers, Suisun marsh, and the Delta?

As this proposal hypothesizes, the physical geometry of channels, marshes, islands, and tidal marshes largely determines the fate, i.e. the spatial distribution and residence time, of freshwater provided to the system through streams and rivers. Modifications to the DSM geometry, whether by design (restoration of channel networks, removal of “cut-throughs”) or by accident (channel erosion/aggradation, island flooding), may have a greater effect on determining the ecological benefits of delivered water than the actual water quantity or timing. It is therefore difficult to establish accurate ecological expectations for water inputs without the ability to compare different scenarios of DSM geometry and resulting habitat. This project will provide a knowledge base and set of practical GIS and modeling tools to assess the interrelated effects of landscape structure and water delivery/withdrawal on ecological resources.

How do environmental processes and water operations combine to affect the distribution, fate, and population success of at-risk or other native species?

This project will allow the science and management community to use the pre-modification landscape, which successfully supported these species in the recent past, as a demonstration system to evaluate the relative importance of landscape modifications and water operations on the distribution of key habitat conditions such as current, salinity, and vegetation. For example, we may find that a prevalence of dead-end sloughs in a particular part of the Delta may provide high-quality habitat that is less susceptible to the effects of diversions or invasive species. Using the historical pattern and modeling tools, we can test these scenarios.

Why are Delta habitats and ecological processes beneficial for many species but not for others?

The Delta has undergone major changes to its habitat structure. In response, substantial financial resources are being expended to recover some of its original species support functions. However, the scientific understanding of the original habitat structure and function is notably superficial, given the level of modification and social expenditure. It is highly likely that this project will identify a number of overlooked but significant ecological features and associated processes that characterized the Delta and supported key species. As in SFEI's San Francisco Bay studies downstream, we expect to discover "forgotten habitat types" (Grossinger 2001), many of which may be substantially recoverable.

Help improve existing approaches or develop new ones for substantiating cause-and-effect relationships between multiple CALFED actions and specific program goals. Improve predictions of the performance of combinations of CALFED actions.

This project will create an integrating spatial and temporal framework linking habitat structure, human modification, and system evolution at the landscape level. This information will provide a much stronger basis for identifying the causes of current problems and setting appropriate goals and performance measures (Hood and Hinton 2002). The expanded modeling tools, comparing "natural" and current conditions, will improve predictive abilities for CALFED actions, in particular for the interrelated effects of landscape modification and water operations.

What are the implications of forecasted changes in precipitation, the hydrologic cycle, and water temperature for Delta habitats, ecological processes, and important management factors (such as salt concentrations and flux and key species abundance and distribution)?

First, one of the premises of this project is that modeling the hydrodynamics of the pre-settlement landscape is likely to identify achievable landscape modifications (such as the reestablishment of complex tidal slough networks at less subsided sites, and the potential strategic removal of channel connections) that may reduce the effects of sea level rise/precipitation change on Delta salinity. Secondly, understanding the geographic variation of habitat conditions within the Delta under natural, but spatially variable, conditions may provide a model for response to anticipated climatic changes. With decreasing summer water supplies, the pre-modification South Delta, which was supplied by the drier San Joaquin River system, may be illustrative of future conditions that will characterize much broader portions of the Delta, even with restoration. Understanding the historical template of spatial variation will help the science and management community to distinguish natural, restored conditions from anthropogenic effects.

B. HABITAT DESIGN

As larger scale efforts to restore habitat have been initiated in recent years, more specific information about appropriate target habitat characteristics has been needed. The following questions have been fielded by the Historical Ecology Program at SFEI in the past year from practitioners in restoration and management of the DSM and will be addressed through the project.

- How were habitat elements such as channel side riparian habitat, stand-alone willow groves (sausals), and other poorly documented but ecologically significant features distributed within Suisun Marsh, the Delta, and the transition to fluvial and upland habitats?

- To what extent were large, shallow marsh pannes, such as those found historically in western Suisun Marsh, prevalent in the Delta? Did habitats such as these, which provided high quality waterfowl support in Suisun, provide significant water bird habitat? Were there other types of pond morphology in the Delta, such as deeper features associated with the ends of channels?

- What was the extent, or density, of tidal marsh channel networks in the Delta? How did basic morphological characteristics vary with distance upstream, and north to south: channel density, channel number, channel width, channel sinuosity, radius of curvature, etc.

- What kinds of habitats were associated with the tidal marsh-upland edge? Which species support functions could benefit from their restoration?

- Which streams connected directly into tidal channels and conversely, which distributed flows and sediment onto the adjacent alluvial plain? How have these modifications affected transport characteristics and habitat?

V. Expression of Project Findings to Broader Public

The process of identifying and acquiring historical data is inherently participatory. One of the benefits of this research approach is that numerous local residents, many of them with substantial and relevant expertise, will be contacted through libraries, historical societies, oral histories, and interviews. In our previous research in Suisun Marsh, for example, valuable information has been obtained from longtime local landowners, and the interactions have been mutually appreciated (Frost personal communication). If conducted with appropriate respect and credit, this exchange between local and scientific expertise is a particularly valuable public education component of historical research (Grossinger 2001).

To express the project results to a broader community, if this proposal is funded we expect to develop an additional interpretive and educational component. SFEI has existing relationships with a number of local foundations that have supported the translation our historical ecology research into diverse media for general audiences. The highly visual and intriguing aspect of historical ecology/landscape change can be a very effective way of engaging the public in the scientific process of ecosystem management. Within this proposal we will produce and announce a public-friendly website with a wide range of compelling maps and images. Through collaborative efforts, we anticipate one or more exhibits or public events in association with libraries, historical societies, and other local groups, leveraging CALFED funding for broader community education and participation.

A recent example was the popular *BayBoards* campaign, which used donated commercial billboards and bus shelter posters to reveal the history of local wetlands and bayside habitats, based upon previous historical landscape analysis (Figure 5). These were seen by hundreds of thousands of residents, featured in exhibits at the Lawrence Hall of Science and San Francisco Public Library, and received extensive media coverage including the *San Francisco Chronicle, Oakland Tribune, Landscape Journal,* and others. The project was funded by the Creative Work Fund, supported by Haas Foundation and Columbia Foundation. Public exhibits and classroom materials similarly leveraging SFEI landscape research have also been supported by the Strong Foundation for Environmental Values and the Center for EcoLiteracy.

Figure 5. Albany Hill BayBoard, illustrating historical shoreline and modern remnants (SFEI, February 2004).

SFEI has also partnered successfully with *Bay Nature* magazine, most recently to present our South Bay historical analysis in the special issue on Salt Pond Restoration. The richly illustrated, six-page spread is a featured component of the Coastal Conservancy outreach efforts and has recently been reproduced in poster format as a series of exhibits for local libraries. The magazine has already expressed interest in a special section about the results of this project. We will also explore the development of a map/poster about the project for distribution to local schools and libraries through the Oakland Museum of California Map Series, which is currently producing a poster based upon SFEI's South Bay wetlands research.

VI. Collaborative Proposal Approach, Timing, and Feasibility

While this project brings together several distinct research disciplines in new ways, it builds upon the strong collaborative abilities of the PI's. It also builds upon established research collaborations, demonstrated by previous jointly authored publications by team members (Table 4).

Table 4. Recent collaborative publications by team members.

Culberson (Wetlands Geomorphology) and Enright (Hydrodynamics)	*Culberson et al. 2004b*
Collins (Wetlands Geomorphology) and Grossinger (Historical Ecology)	*Collins and Grossinger 2004; Striplen et al. 2004*
Culberson (DWR) and Collins (SFEI)	*Culberson et al. 2004a*

We feel this project team is well selected to generate new ideas and insights through collaborative research, while managing the challenges of institutional and professional collaboration. SFEI is well experienced in managing complex interdisciplinary and multi-institution projects, carrying out such projects routinely as part of our mandate. SFEI has numerous existing collaborations with state agencies, including DWR. SFEI Contract Manager Lynne Curry has experience establishing subcontracting relationships with the State of California.

Project Manager Grossinger has extensive experience guiding joint project teams as Director of the inherently interdisciplinary Historical Ecology Program. He currently leads the Santa Clara Valley Historical Ecology Project ($479,000 budget) , which involves three related projects and collaborations with Santa Clara University, Tetra Tech, and Philip Williams and Associates. Co-PI Josh Collins currently leads the San Francisco Bay component of the National Wetlands Inventory and California State Wetlands and Riparian Inventory, with USFWS and San Francisco State University, and a number of other research collaborations. Collins (Methyl Mercury Processes in Wetlands), Culberson (Sacramento Splittail), and Enright (Sacramento Splittail) are each investigators on current CALFED-sponsored projects.

The project team anticipates no significant hindrances to project timing and sequencing. Tools and methodologies for the historical reconstruction, GIS development, and hydrodynamic modeling have already been developed through previous projects and are ready for use. Additionally, the focus on archival data precludes delays associated with weather or season. SFEI's existing relationships with most major archives should minimize any potential delays in data acquisition. The use of certainty levels in the pre-settlement landscape reconstruction will allow us to identify areas of greater and lesser available information.

Figure 6 illustrates the mechanisms established to ensure consistent coordination and timely synthesis between SFEI, DWR, and the Technical Advisory Group. The 36 month schedule allows sufficient time for both the parallel and sequential components (Figure 7).

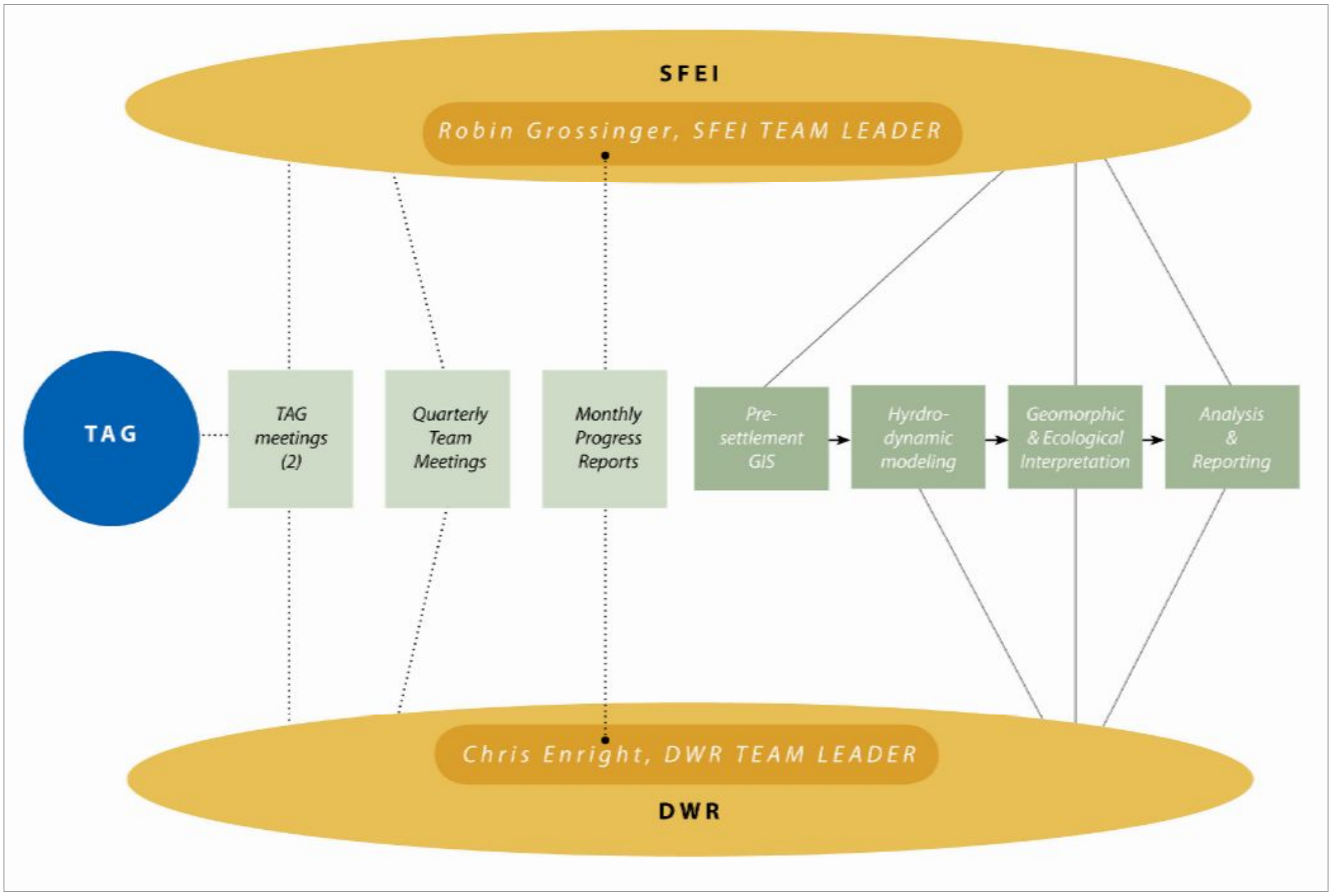

Figure 6. Team Linkages, Responsibilities, and Work Sequencing.

Figure 7. Overview of Project Timeline.

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