Integrated Regional Wetland Monitoring Pilot Project

CALFED Bay-Delta Science Program

Physical Processes and Landscape Ecology “Guiding” Conceptual Models Prior to Integration Effort

11 Jan 2004

1067

Physical Processes Team –	Wetlands and Water Resources Philip Williams and Associates
Landscape Ecology Team –	University of California, Berkeley Wetlands and Water Resources Point Reyes Bird Observatory
Plant Team –	San Francisco State University
Bird Team –	Point Reyes Bird Observatory
Fish/Invertebrate Team –	San Francisco State University University of Washington University of California, Davis U.S. Geological Survey

Compiled by:

Wetlands and Water Resources
1010 B Street, Suite 425
San Rafael, CA 94901
(415) 457-0250; (415) 457-0260 fax
www.swampthing.org

Contents

PHYSICAL PROCESSES CONCEPTUAL MODEL OF TIDAL MARSH RESTORATION EVOLUTION, BASIS FOR SHARED MODELS

This model has been updated to incorporate the salinity gradient graphic re-inserted in Oct 2003. No other changes from Nov 2002 have yet been made. SWS 1/11/04.

In this section we present a three-step sequence of conceptual model – pressure-state-response model – hypotheses. The Conceptual Model describes physical process-ecosystem relationships in established and restored tidal marshes. The Pressure-State-Response (PSR) model provides a framework for applying these relationships (and those presented in the other team's proposals) in a resource management context and, as presented here, provides a starting point in conjunction with the other teams for the effort to develop an integrated model for this Pilot Project. The hypotheses that we propose to test via field data collection and analysis derive from the conceptual model (and those presented in the other team's proposals) and are selected for their potential to aid in applying the PSR model to CALFED's management question.

1.0 Conceptual Model

Inundation, the estuarine salinity gradient and sediment supply are the fundamental external processes that drive tidal marsh evolution and development and abiotic and biotic variability (Mitsch and Gosselink 2000; Warren and French 2001; Zedler 2001; Weinstein and Kreeger 2000). These independent variables can operate and interact in a variety of ways that confound understanding of developing marsh biotic and abiotic characteristics. In general, tidal marshes flourish in intertidal zones wherever and whenever (1) there is adequate protection from destructive waves and storms, (2) the net accumulation of sediments is equal to or greater than the rate of relative sea level rise (including land subsidence), (3) there is suitable plant material available close enough to colonize the site, and (4) substrate is suitable for target flora and fauna (e.g., Redfield 1972, Mitsch 2000).

Marshes consist of unconsolidated sediments and organic matter, so protection from high intensity hydraulic events is essential. Marsh plants flourish in a relatively narrow band of elevations relative to tidal datums, so marshes require a balance between sediment accumulation rates, compaction, and sea level rise. Sediment accumulation is controlled by a number of biotic and abiotic processes. Abiotic processes include the frequency, depth, and duration of over-bank flooding, suspended sediment concentrations, frictional resistance to flow (especially from plants), sediment compaction and consolidation, and, in some instances, salinity-moderated particle flocculation. Biotic processes include the rates of plant matter production and decay, invertebrate production, bird and fish foraging. Finally, the underlying materials may move vertically due to tectonic motions, dewatering, compaction, or other mechanisms, so the net accumulation of sediments must not only accommodate sea level rise relative to "absolute" (geodetic) datums, but also relative to subsidence of the land. In geological time scales these conditions are relatively rare, and tide marshes are not persistent landforms. In ecological terms, however, they can be relatively stable, persisting for thousands of years.

A complication is that these primarily geological phenomena are not independent of the presence or absence of marshes. In fact, the presence or absence of the plants that define marshlands has a significant impact on sedimentation. Thus, although information on sediment supply and dynamics is essential, understanding and forecasting the extent and distribution of marshlands requires collection of extensive data on numerous physical and biotic parameters.

Fundamentally, tidal marsh development is a complex process in which a range of external pressures (e.g., sea level rise, subsidence, anthropogenic actions) and internal state variables interact. Many tidal marshes are characterized by great spatial variations in state variables such as sediment supply, salinity, inundation, substrate character, and biotic metrics. Various temporal scales act on marshes. Water depth and turbulence from wind waves or vertical motions from earthquakes are on the scale of seconds. Eustatic sea level rise, crustal warping and evolution of plant and animal species and communities are on the order of one hundred to a thousand years. Variations due to tidal (12.42 hour, 24.83 hour, and fortnightly), diurnal (24 hour), and seasonal/annual (12 month) forcing functions are common in both ambient or reference sites as well as restoration sites. Inundation regimes, species colonization, biogeochemical processes, reproduction and productivity express themselves over time scales of days to perhaps a year. Thus, defining the interactions between pressures, state variables and responses is difficult, confounded by both the complexity of their interactions but also the spatial and temporal variability in state variables and their associated processes throughout the marsh.

1.1 Pressure-State-Response Model

CALFED has stated that the primary goal for this proposal is to present a plan for assessing the changes in ecosystem process affected by marsh restoration. The Pressure-State-Response (PSR) model advocated by CALFED provides a widely used, robust and useful framework for analyzing the interactions between environmental pressures, states and responses (Fletcher 1999).

OECD (2001) states:

> “This simple PSR framework merely states that ***human activities exert pressures*** (such as pollution emissions or land use changes) on the environment, which can ***induce changes in the state of the environment*** (for example, changes in ambient pollutant levels, habitat diversity, water flows, etc.). ***Society then responds*** to changes in pressures or state with environmental and economic policies and programs intended to prevent, reduce or mitigate pressures and/or environmental damage.”

The PSR model serves as a framework for understanding ecosystem processes in the context of pressures on the system and therefore can provide guidance in identifying state indicators and developing appropriate sampling methodologies.

In applying this model, we have modified it to include both natural and anthropogenic pressures (Figure 1). Examples of natural pressures include sea level rise, flooding and drought, invasive species, disease and subsidence. (Note that human influences can also affect natural processes.) For instance, land subsidence occurs because underlying materials move vertically due to tectonic motions, dewatering, compaction and other mechanisms. Anthropogenic pressures include such activities such as development, channelization, recreation, harvesting, pollution and habitat destruction. If a goal of marsh restoration is to move towards sustainable systems, it needs to consider both natural and anthropogenic pressures in the responses taken.

The “state” represents the conditions that exist and are monitored through measurement of biotic and abiotic indicators. Many of these state indicators are physical processes measurements (e.g., inundation regime, sediment budget, soil chemistry, water chemistry, geomorphology and topography). Others are various biological metrics the quantify the flora and fauna. In the PSR model, measurements of state indicators provide the information to make management responses. Feedback mechanisms in the marsh also create a set of natural responses. These natural responses in essence represent ecological processes such as resource utilization and wildlife population dynamics and more fundamental processes such as nutrient and organic cycling. Marsh restoration, as a management response, addresses pressures and changes the state of a system, resulting in changes in the ecosystem processes, a natural response. Understanding these changes thus addresses the underlying CALFED question.

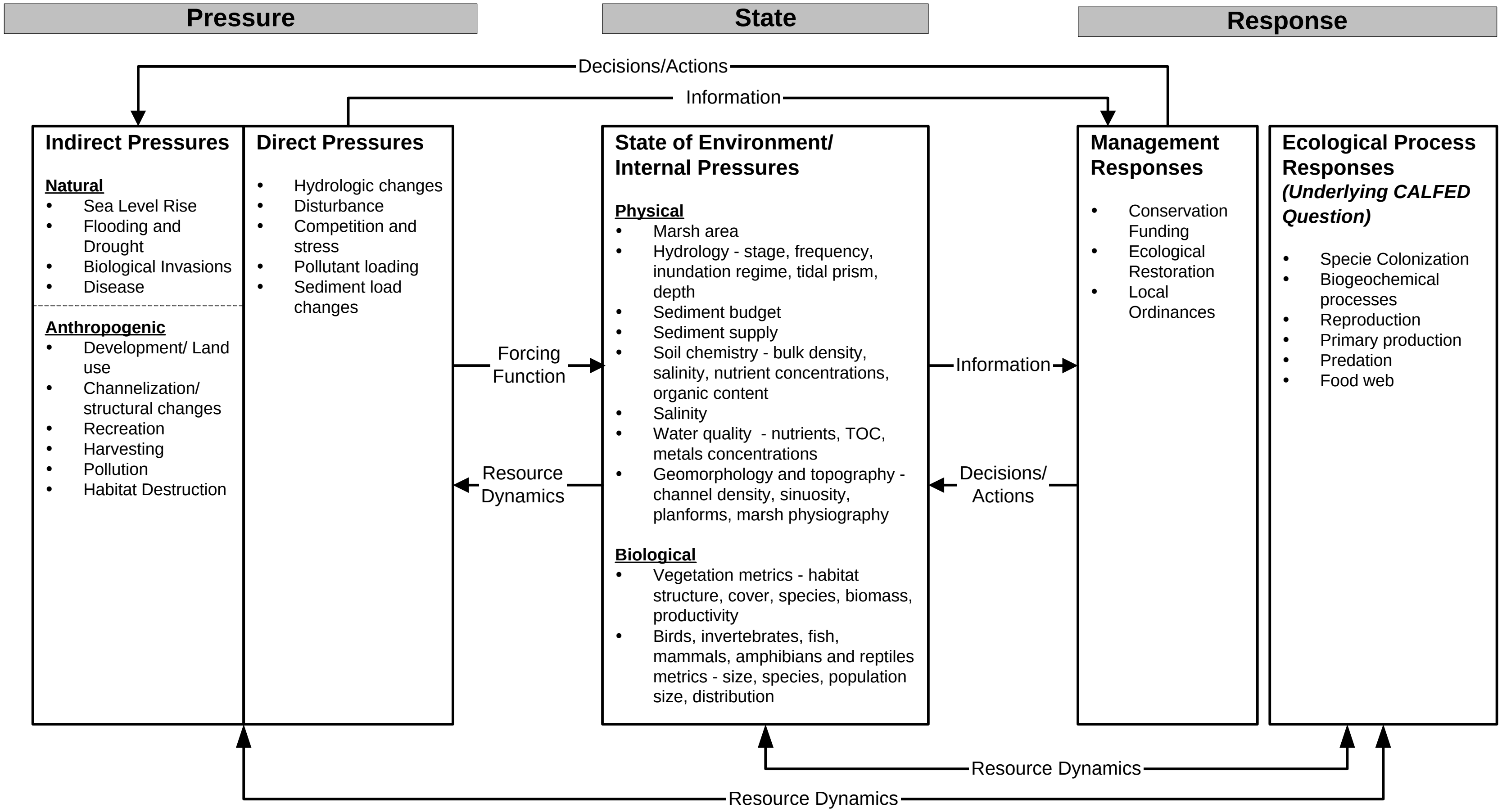
1.2 Causal Relationships

The PSR model does not explicitly address causal relationships and the inherent complexity of tidal marsh systems. Some indicators may be a pressure in one context and a state or response in another (Hart 2000). For instance, tidal statistics (e.g., stage, frequency, water depth) are a state in response to the indirect pressures of sea level rise and channelization and land use, a direct pressure for biotic and abiotic marsh states such as geomorphology, soil chemistry, and vegetation, and an indirect pressure on population dynamics for species from invertebrates through birds and mammals.

In Figure 2, we identify the three fundamental external processes that influence restoration evolution– inundation, estuarine salinity gradient, and sediment supply – The broad horizontal arrow leading from the Golden Gate toward the Delta indicates the primary upstream gradient of decreasing salinity and tidal range, increasing height of high tide datums, decreasing elevation of tidal wetlands, increasing tidal hydroperiod for tidal wetlands, decreasing channel density for tidal wetlands, decreasing amount of tidal flat, and lower intertidal distribution of vascular vegetation. The dark arrow leading from the Golden Gate to Far South Bay indicates increasing salinity and tidal range as part of the primary estuarine gradient. The dashed arrows leading away from the primary gradient indicate secondary gradients into local watershed landscapes. Secondary gradients are steepest in Far South Bay where watersheds drain into very saline conditions. The secondary gradient into Hill Slough from Suisun Slough is unusual in that salinity increases upstream, due to high evaporation rates, scant freshwater inflows, and long residence time for water so far upstream from the primary gradient. The dotted rectangles indicate zones of maximum turbidity, and the circles represent amplification of the tidal range due to standing waves near the mouths of local rivers and streams.

In Figure 3, we model the cascading of pressures and states through a marsh system. In our model, flow from left to right is assumed as the primary direction of pressures through the marsh system. Lines indicate pressure pathways or forcing functions. Dashed lines represent a feedback pressure. States in one context are pressures in another. In our model, external pressures directly affect tidal statistics and sediment loads and concentrations, which affect geomorphology and soil chemistry, which affect vegetation metrics and invertebrate metrics, which finally affect metrics of fish, mammals, reptiles, amphibians and birds. Throughout the model, feedback occurs. For instance, tidal statistics affect geomorphology which affect vegetation. Vegetation provides feedback to physical processes through affecting sediment flow, long-term stability and soil biogeochemistry (see Plant Team proposal). These mechanisms can affect geomorphology which can then affect hydroperiod, a tidal statistic.

Figure 1. Generalized Pressure-State-Response Model Evaluating Ecosystem Response of Marsh Restoration. Various indirect and direct natural and anthropogenic pressures affect the state of the marsh. Physical and biological state indicators can be used to describe the state of the marsh and serve as internal pressures via feedback mechanisms. State indicators provide information to develop appropriate management and design responses and to define resource dynamics that drive ecosystem responses. Model shown here provides examples for the San Francisco Estuary and the Delta.



Notes.
1. Resource Dynamics defined as changes in resource status over time.

Figure 2. Diagram of Primary and Secondary Estuarine Salinity Gradients

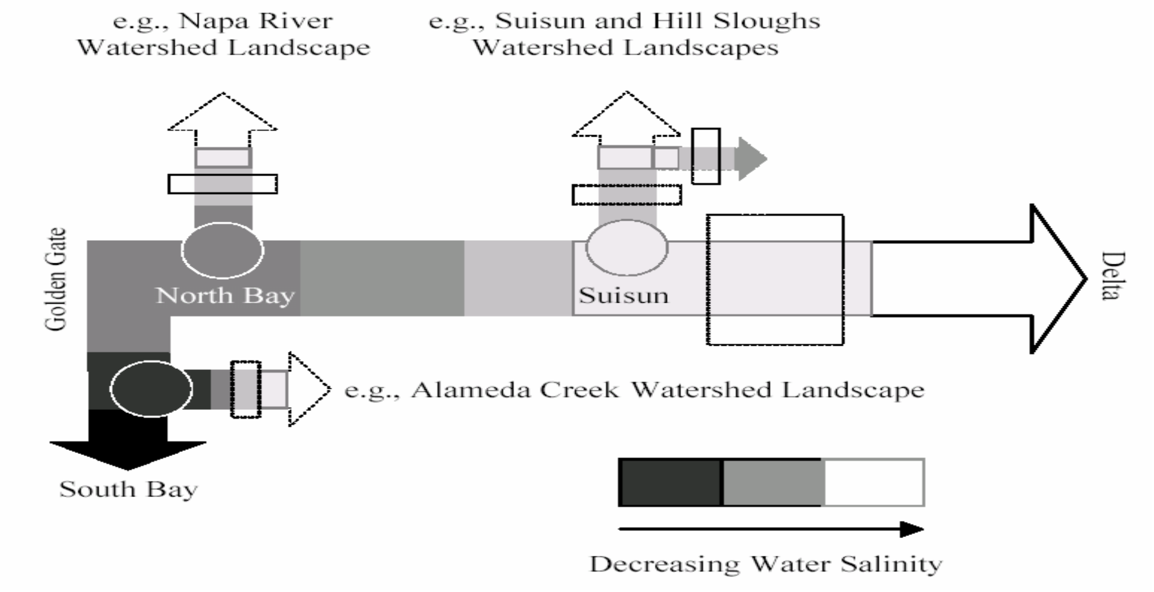
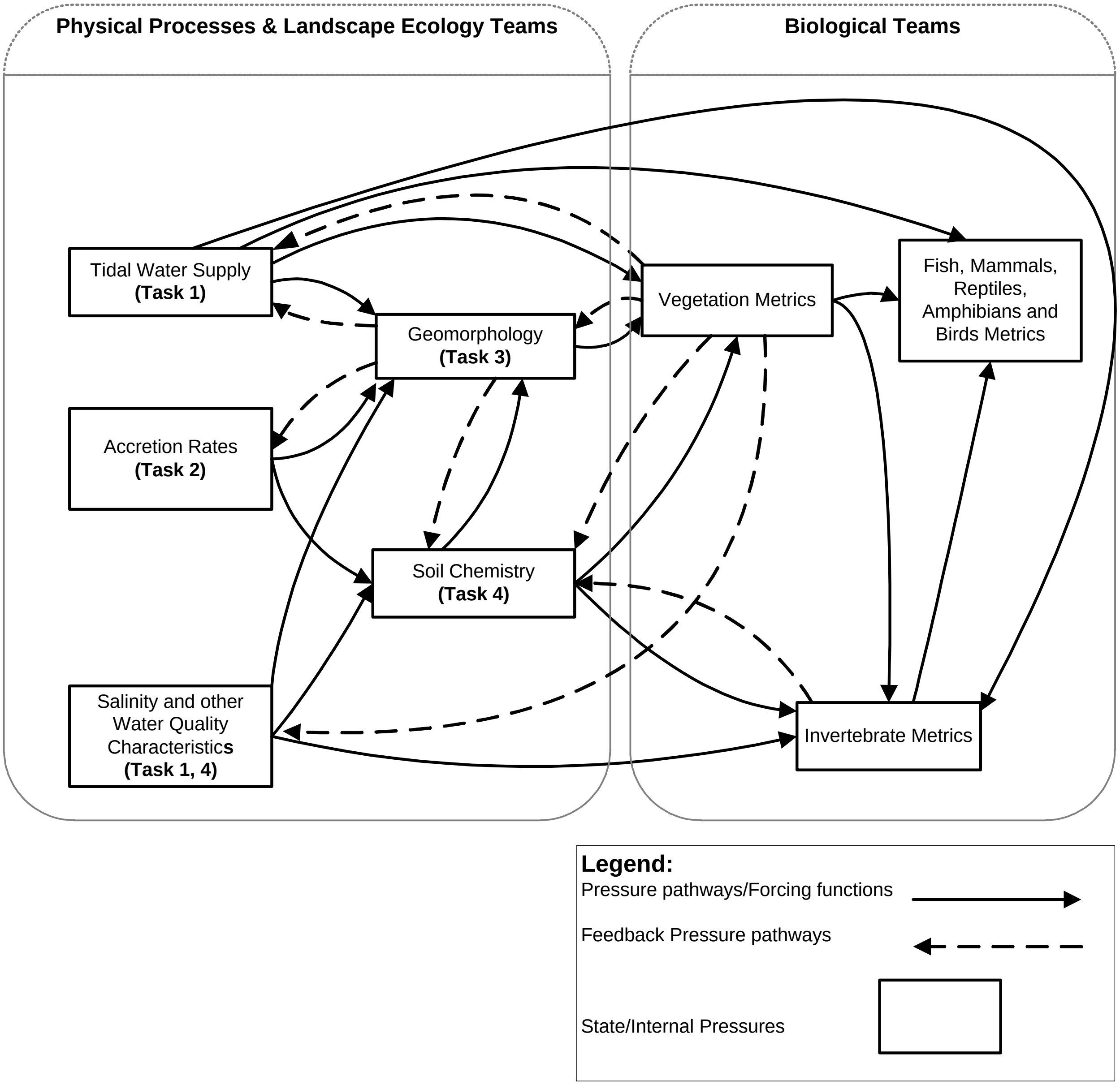


Figure 3. Conceptual Model of "State" Interactions



1.3 Linkage Between Biological and Physical States

This PSR model thus predicts that a number of physical states (hydrology, suspended sediment supply, sediment budget, salinity and water quality, geomorphology, and substrate conditions) drive development of different biological states in the marsh. There is no inherent suggestion in this model of the dominant physical state variable. These biological states then provide feedback pressure to the physical states and thus marsh development is a dynamic system responding not only to external pressures but also adjusting to internal pressures.

Thus in assessing the effort required in measuring the various physical states, an understanding of the relative importance of each physical state in controlling biotic and abiotic marsh processes is required.

1.4 Discussion of State Variables

We assess the relative importance of each physical process based upon a review of the literature in this section.

1.4.1 Hydrology and Geomorphology

Hydrology and geomorphology are tightly coupled. Tidal regimes interacting with marsh geomorphology determine the hydroperiod and inundation frequencies.

Inundation Regime

A first approximation to marsh form and function emphasizes the similarities of marsh “plains” to other intertidal zones (Rozas 1995). In this conceptual model element, the tides rise above the marsh plain whenever tidal stage in the adjoining deep water exceeds the marsh plain elevation, and drain off the marsh plain as open water stage drops below that “bank-full” height. The patterns of this flooding and draining define the inundation regime, also referred to as hydroperiod. Therefore, lower areas flood with greater frequency, duration, and depth than higher areas and the marsh will be essentially divided into zones based on elevations relative to tidal datums (also taking into account attenuation away from the tidal source). Because plants (and thus animal habitats) appear to demonstrate vertical zonation with inundation, this model is a basis for much of the stratification of tidal marsh as a sampling universe (see Plant Team proposal)

This model requires three major assumptions:

- The ocean is an infinite source and sink of tidal water and energy relative to the quantities exchanged with the marshlands
- Conveyance capacity is great enough and friction low enough that rising water stages are conveyed everywhere on the marsh without head loss
- No topographic or other barriers to drainage impede dropping tides.

Unfortunately, distance from the tidal source to more remote sections of marshes; insufficient channel capacity for tides with high range or low absolute stage; and vegetation, irregular topography, and other surface roughness together probably ensure that these assumptions are never strictly met. In particular, attenuation of the tidal signal headward along channels and across the marsh plain is known to occur (e.g., Leopold *et al.* 1993).

Tidal Network Morphology

A more complex and subtle model emphasizes channels as controls on marsh form and function. Channels are the conduits for moving water, sediment, nutrients, and aquatic organisms between the oceanic (or estuarine) tidal source/sink and the marsh plain (Allen 2000, French and Reed 2001, Siegel 2002). Secondarily, they influence the deposition of mineral sediments and thus the distribution both of soils and landforms (e.g., levees). Channel density, capacity, and plan-form are basic parameters of marsh physiography, and distance from channels of various sizes becomes a significant influence on processes of the marsh plain.

Causal Relationships

Together, hydrology and geomorphology directly affect soil chemistry, vegetation, bird and animal use (Figure 2). Vegetation colonizes along inundation gradients with vegetation communities in lower elevation marsh different than that in higher elevation marsh (Mahall and Park 1976a,b,c; Plant Team proposal). Invertebrate population dynamics are affected by hydrology as well. Flooding frequency and duration affect nutrient and organics cycling and thus affect invertebrate population density (Allen 2001, Mitsch and Gosselink 2000, Weinstein and Kreeger 2000). Water birds, whether they are waterfowl, shorebirds or seabirds, prefer certain hydrologic regimes for different activities (e.g. roosting, foraging, nesting) and can be either exposed or protected from predators (see Bird Team proposal), thus hydrology directly affects their population dynamics.

1.4.2 Sediment Load, Concentration and Aggradation

Sediment loads and concentrations drive geomorphological development of marshes and can determine whether a marsh is sustainable. These internal pressures directly affect geomorphology and soil chemistry because of sediment deposition and erosion (Figure 2). Sediment deposition characteristics within a marsh will likely depend not only upon the sediment supply, hydrologic characteristics and marsh geomorphology but also on the spatial variations in marsh form and function. Subsequent sediment accumulation or erosion will affect development of vegetation and invertebrate communities (French and Reed 2001, Weinstein and Kreeger 2000, Zedler 2001, Figure 2).

Spatial Variations in Marsh Form and Function

Tidal marshes can demonstrate large variations across space, especially along gradients of salinity, tidal range, elevation, distance from tidal source, and major sediment sources. In the context of sediment deposition and erosion, both will depend upon a number of variables including sediment concentration, hydraulic loading, frequency of over-bank flooding, and inundation regimes as discussed previously. Because estuaries are characterized by simultaneous gradients of salinity and tidal range, it can be difficult to separate these effects on the large-scale geographic distribution of marsh patterns. Elevation, sediment concentration and sediment loading gradients, in contrast, are usually observed not between marshes but within marsh areas with essentially uniform boundary conditions of salinity and tidal datums.

1.4.3 Salinity and Other Water Quality Parameters

Salinity and other water quality variables directly affects soil chemistry, invertebrates, fish, reptiles and amphibians (Figure 2).

Salinity

Vegetation gradients establish along salinity gradients (Atwater *et al.* 1979). Invertebrates, amphibians, reptiles, mammals, fish and birds can vary along salinity gradients for several reasons some of which are physiological tolerance to salt, physiological tolerance of prey items to salt, and characteristic marsh structure and its influence on species colonization. Salinity also can dramatically affect soil chemistry. Increasing surface water salinity results in soils themselves becoming more saline. Under hypersaline conditions, salts such as gypsum and calcium carbonate precipitate (Ver Planck 1958).

Nutrients and Organic Cycling

Water column nutrient concentrations can both affect and reflect soil nutrient levels because of nutrient cycling, sequestration and transport (Mitsch and Gosselink 2000, Tate 1995, Kadlec and Knight 1996, Qualls and Richardson 1995, Vaithiyanathan and Richardson 1997). High surface water nutrient concentrations can lead to algal blooms, anoxia and fish kills. These levels are likely not to be found at the restoration sites.

1.4.4 Soil Chemistry

Soil chemistry, especially organics, nitrogen and phosphorus, can affect vegetation community composition. Vegetation composition in turn can affect peat accretion rates as well as marsh fauna (Mitsch and Gosselink 2000, Weinstein and Kreeger 2000, Zedler 2001).

1.4.5 Marsh Evolution

Marsh evolution and development are a response to the external pressures and state variable interactions at a site (Figure 2). As such, evolution in an undisturbed vs. disturbed site will differ.

Marsh Evolution in “Undisturbed” Sites

The process of marsh evolution in sites where anthropogenic influences are minimal is generally described as sediment accretion (mineral and peat) raising the marsh surface, which decreases the frequency of over-bank flooding and increases the frequency of drying events (French and Reed 2001, Mitsch and Gosselink 2000, Weinstein and Kreeger 2000). Processes of accumulation and loss of material become balanced and the marsh surface elevation achieves a rough dynamic equilibrium relative to tidal datums. This geomorphic process is accompanied by a suite of changes to the flora, traditionally described as “succession,” which interacts with the geomorphic “maturation” of the site by changing the organic matter availability, sediment trapping, overbank flow rates, etc. (Weinstein and Kreeger 2000). In general, young marshes are associated with low elevations in the tidal range and a flora that is tolerant of long, deep, and frequent flooding. Older marshes are associated with higher elevations, and a flora tolerant of less frequent flooding, longer dry periods, and periodic high salinity caused by evaporative concentration. Channel density and size tend to decrease with tidal prism as a marsh rises through the intertidal zone.

Marsh Evolution Following Restoration Activities

Sites chosen for tidal marsh restoration in the San Francisco Estuary generally have been disturbed through diking, ditching, grading, and drainage in some combination. Their resulting hydrology can vary from permanently impounded (salt ponds) to seasonally flooded and drained (duck clubs) to almost-permanently drained (agricultural areas; some ruderal areas drained for flood protection). There is almost always some surface subsidence following prolonged periods of drying and the resulting oxidation and/or wind erosion. Subsidence is often accompanied by the development of significant soil cracks.

Because disturbances to marshes vary, so do restoration activities. However, the primary activity in most restoration projects is breaching or removal of dikes. These activities are usually followed by responses on four primary time scales (Malamud-Roam 2000):

- Rapid modification of hydrology reflecting a greater tidal influence. This invariably means a greater frequency of both wetting and drying. Depending on conditions prior to restoration, this will also mean changes in the duration and depth of flood and dry events. Usually the durations of the longest flood and dry events are reduced.

- Changes in the distribution of animals and then vegetation in response to the changed hydrology.

- Increases in mean surface elevation in response to increased deposition and possibly decreased oxidation/erosion of sediments.

- Changes in the distribution of plants and then animals in response to the changed hydrology.

Rapid actions of such magnitude are relatively atypical in the formation of natural marshes, especially in the context of the San Francisco Estuary and the Delta. This time scale of change is likely reflected in the ecosystem processes that follow restoration.

1.5 Development of Tasks for Supporting Studies of Other Teams

From the Pressure-State-Response Model and an understanding of state variable interactions, we have developed a set of four tasks to quantify the physical processes state variables. Quantifying these state variables is necessary to provide the information required by the biological teams to investigate pressures and test hypotheses. The four tasks are identified in Figure 2 and listed below:

Task 1. Tidal Water Supply
Task 2. Accretion Rates
Task 3. Geomorphology and Topography for Inundation
Task 4. Soil and Pore Water Chemistry

Methods to implement these tasks are described in detail in the Work Plan (Section 4). These tasks are referenced in development of the hypotheses that are detailed below.

2.0 Hypotheses

This monitoring project is focusing on the role of tidal marsh restoration efforts in affecting ecosystem function at different scales. In order to develop hypotheses from the Conceptual Model and Pressure-State-Response Model presented above, we need one final piece of information, an understanding of the range of baseline conditions at restoration sites in the Estuary and Delta.

2.1 Restoration Configurations

In the San Francisco Estuary, sites with potential for restoration to tidal marsh are largely diked baylands with land uses that fall into the following categories: farmed (e.g., much of San Pablo and Delta sites), salt pond (Napa complex), managed wetlands (primarily Suisun), and unmanaged wetland (“abandoned” diked wetland and relatively common along the southern Suisun Bay shoreline). Each of these categories, in turn, creates common sets of physical and biological characteristics that influence the ecological outcome of restoration efforts. Important physical characteristics include degree of subsidence (amount of sedimentation needed, whether elevations and initial substrate conditions suitable for plant colonization exist at the outset), distance from and constraints on tidal source (ability to obtain unrestricted tidal exchange), exposure to long wind fetches (sediment resuspension), sediment supply (sedimentation rates), soil salinity and contaminants (substrate suitability), adjacent land use (e.g., island versus upland, streams for surface and subsurface freshwater inputs), and infrastructure constraints. Important biological characteristics include possible seed banks, existing vegetation, proximity to other wetlands (propagule sources), displacement of biological resources, adjacent land use (wetland-upland transition potential), and structural diversity (habitat availability). The most important of these attributes are shown in Table 1.

Table 1. Characteristics of Initial Conditions at Potential Restoration Sites.

Initial Condition	Regions of Occurrence	Degree of Subsidence	Geomorphic Heterogeneity	Existing Plants for Revegetation	Substrate Suitability for Revegetation
Farm	San Pablo, Delta	Usually considerable	Usually converted to drainage ditches, some swales	None; if exists, typically will be buried	No concern
Salt pond	San Pablo	Usually little	Often preserved channel networks; depressions may be common	None	Potentially major concern
Managed wetland	Suisun, some San Pablo	Usually little	Varies; either converted to drainage ditches with some swales or preserved channel network and broad depressions	Some; controlled species composition	Could pose concern
Unmanaged wetland	Suisun, some San Pablo	Varies depending on prior land uses	Highly variable depending on prior land uses	Some; varied species composition; buried at deeply subsided site; important at minimally subsided sites	Could pose concern

2.2 Linkage to Conceptual Model

The conceptual model presented above states that general marsh evolution derives from four fundamental forcing functions: inundation regime, surface water salinity, sediment supply, and substrate. Many important biological processes derive from and feed back into these forcing functions. These four forcing functions, in turn, are controlled by the following processes:

- **Inundation** is controlled by site topography (primary, internal state), tidal range (secondary from estuarine position, external state), and degree of tidal restriction (assumed secondary from morphology of tidal connection to open bay waters, external state).
- **Surface water salinity** is controlled by large-scale climate and water use factors (external state).
- **Sediment supply** is controlled by many factors, including proximity of mudflats, wind regimes, proximity of watershed and Delta outflow inputs, and morphology of tidal connection (all external states).
- **Substrate** is controlled by site history prior to restoration including degree of subsidence, prior inundation regime, and dredged material placement if part of a restoration project (all internal states).

Because inundation regime and substrate are the only general evolutionary forcing functions that are controlled by baseline restoration site conditions, we have opted to use them as our basis for developing hypotheses.

2.3 Hypothesis: Threshold Baseline Elevation

We propose the Threshold Baseline Elevation Hypothesis, which states that there exists a baseline topographic threshold at which dependent state variables of vegetation colonization and geomorphic evolution diverge. We have derived this hypothesis from the conceptual model presented above, from literature reviews (e.g., Siegel 1993), and from our field observations of restoration sites around San Francisco Estuary.

The threshold baseline elevation acts through its control on inundation and substrate conditions. These controls derive internal and external to the site and exert primary and secondary control, as shown in Table 2.

Table 2. Origin and relative importance of independent state variables in controlling site evolution following restoration

Relative Importance	Independent State Variables that Control Biotic and Abiotic Evolution Based on Initial Elevation: Below Threshold Elevation	Independent State Variables that Control Biotic and Abiotic Evolution Based on Initial Elevation: Above Threshold Elevation
Primary Controls		
Originate Internal to Site		• Existing site vegetation • Initial substrate conditions • Initial topographic variability
Originate External to Site	• Sediment accretion as controlled by sediment supply, wind-wave regime, site configuration	• Surface water salinity (via affect on plant species composition)
Secondary Controls		
Originate Internal to Site	• Topographic variability	
Originate External to Site	• Surface water salinity (via flocculation)	

This hypothesis predicts the following two evolutionary trajectories in vegetation colonization and geomorphic evolution, as shown in Table 3.

Table 3. Predictions of baseline elevation hypothesis

Process	Baseline Below Threshold	Baseline Above Threshold
Sediment Accretion	Entirely physical-process based until reach vegetation colonization elevations	Combined physical and biological processes
Role of Initial Site Topography on Evolution	Can influence	Fundamental control
Role of Initial Substrate Conditions on Evolution	Minimal if any influence	Potentially very important
Vegetation Colonization Process	Entirely externally-derived propagules	Combined external propagules and internal seed banks and rhizome propagation

This hypothesis further predicts that once a “below the threshold” site accretes to vegetation colonization elevation, then position in estuary relative to the salinity gradient influences restoration trajectory via physiological control on vegetation species composition and the relative influence of different species on subsequent geomorphic evolution and ecological function.

Our ability to test this hypothesis, in conjunction with data from the other teams, depends on site selection and availability of necessary baseline data for selected study sites. This requirement highlights the importance of site selection in terms of testing categorical initial site conditions representative of potential restoration sites throughout the Estuary and Delta and thus our ability to extrapolate (see LET proposal).

Our monitored state indicators are relative heterogeneity of geomorphic attributes (as measured by abundance and distribution) of marsh plain near and far from channels, tidal channel network, and depressions (ponds and pannes). These attributes are of interest because of their ecological support functions for all species of interest. The vegetation team, in turn, is examining the vegetation colonization component of this hypothesis.

LANDSCAPE ECOLOGY CONCEPTUAL MODEL OF TIDAL MARSH RESTORATION EVOLUTION, FOR SCALE ISSUES

The conceptual model of the Landscape Ecology Team uses the landscape ecology approach. This approach asserts that landscapes are a mosaic of patches that can be defined by their structure, their function and change (Bell et al. 1997; Forman 1995; Forman 1997; Turner 1990). Our conceptual approach defines the bayshore and watershed landscapes in San Pablo Bay and the Delta by their structure (meaning the spatial relationship among distinct wetland patches or their elements), their function (meaning the flow of mineral nutrients, water, energy, or species among component patches or between landscapes), and change (meaning the temporal alterations in the structure and function of landscapes or their components). The processes of interest are varied, and overlap with those of the other teams that prepared this integrated Regional Wetland Monitoring Pilot Program (IRWM) proposal to CALFED.

Our premise is that the structure, function and change of patches across landscape mosaics affect fundamental ecosystem processes, which determine the trajectories of wetland restoration. Therefore, the quantification of landscape structure and measurements of change to that structure are important precursors to understanding functional effects of change (Kelly 2001; Semlitsch and Bodie 1998; Tischendorf 2001). At the site scale, the structure of a wetland patch can be related to topography and other spatial attributes such as channel density and pattern and heterogeneity of vegetation types (Zedler et al. 1999). At the landscape scale, the spatial configuration of wetland patches—e.g., their size, shape and connectivity—and the composition of surrounding uplands are the key components of structure.

One method to quantify structure employs the use of spatial “metrics” (Jones et al. 2001; Narumalani et al. 1997; Schuft et al. 1999; Wu et al. 2000). Relevant metrics that we intend to generate are summarized in Table 1, and include both site- and landscape-scale characteristics. Spatial structure metrics can be linked to function through a variety of analyses including regression-based and other types of statistical models and sensitivity analyses (Tischendorf 2001). For example, a tidal marsh-dependent vertebrate species might require connectivity with other wetland patches for dispersal and recruitment purposes, or may experience higher rates of predation in marshes with a high ratio of edge to interior habitat. Measurement of landscape context metrics may reveal adjacent land uses as potential stressors, or hint at exchange rates across ecotones.

For this proposal, spatial characteristics will be calculated for important wetland features at the site and landscape scales and tied to ecological functions through interactions with other IRWM teams (described below). Remotely sensed satellite and low-altitude aerial photographic data combined with Geographic Information Systems (GIS) have proven to be an approach successful in mapping wetlands (Henderson et al. 1999; Kasischke and Bourgeau-Chavez 1997; Phinn et al. 1996; Phinn et al. 1999; Rao et al. 1999; Siegel 2002; Townsend 2001); and in measuring broad-scale landscape patterns and correlating such patterns with ecological functional changes (Frohn 1998; Kelly 2001). Furthermore, such methods have been proven in mapping wetland habitat in settings similar to the SF Bay. For example, Phinn et al. (1999) and (1996) found that several important biophysical properties of coastal wetland vegetation in Southern California could be estimated with accuracy from high-resolution imagery. They found standard spectral classification techniques could be used to delimit individual and mixed species stands within a wetland patch (Phinn et al. 1996), and that cover could be mapped in a non-invasive manner (Phinn et al. 1999). Similar results were found in San Pablo Bay using hand-held spectrometers, and a courser resolution imagery source (Zhang et al. 1997).

Scale is very important here and we treat it in the following manner. We define the site scale at the level of the monitored field sites (six monitored by these collective proposals). The landscape scale incorporates a range of spatial scales relevant to understanding ecosystem processes in the San Francisco Estuary, from the lands immediately surrounding each marsh study site to estuarine subregions (San Pablo, Suisun, Delta) to the entire estuarine region from San Pablo Bay through the Delta. As these landscape elements operate at multiple scales, changes can be overlooked or even exacerbated by a management regime that focuses on a particular scale in its operation (Bedford 1999). Thus, effects of restoring individual wetlands should be examined in a larger context, using a synoptic landscape approach. The LET wetland monitoring activities proposed here are organized around this scaling approach.

The LET sees itself partly as a service team, and thus is the provider of geospatial techniques and products for other teams. There is much precedent for using these techniques for marsh monitoring and management. Indeed, many aspects of wetland management are increasingly utilizing these spatial techniques: for example, wetland restoration siting, wetland restoration monitoring, and wetland inventory have recently benefited from the use of GIS and remote sensing (Barrette et al. 2000; Cedfeldt et al. 2000; Guo and Psuty 1997; Llewellyn et al. 1995; Moorehead 1999; Siegel 2002).